

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.

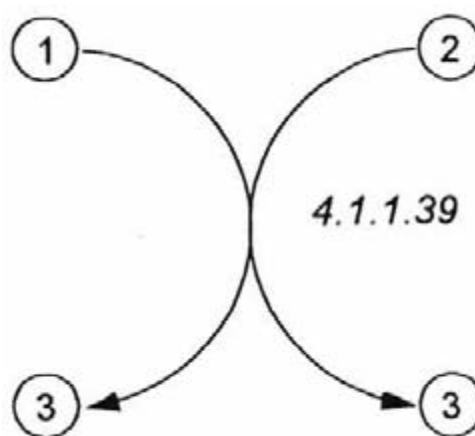
The most important **intermediates** are shown with numbers in the charts. The corresponding compounds can be identified using the table on the same page.

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.

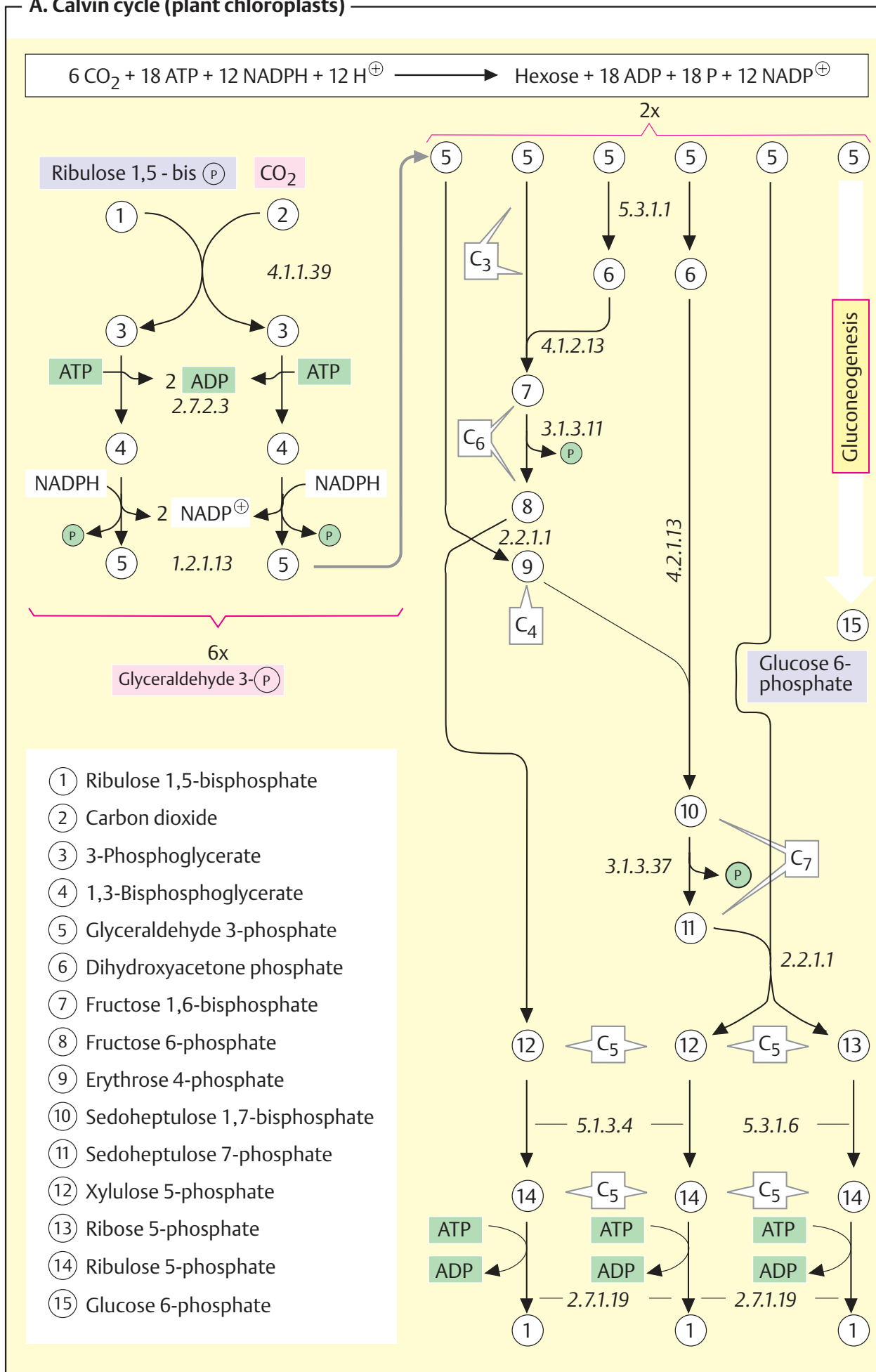
Example

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

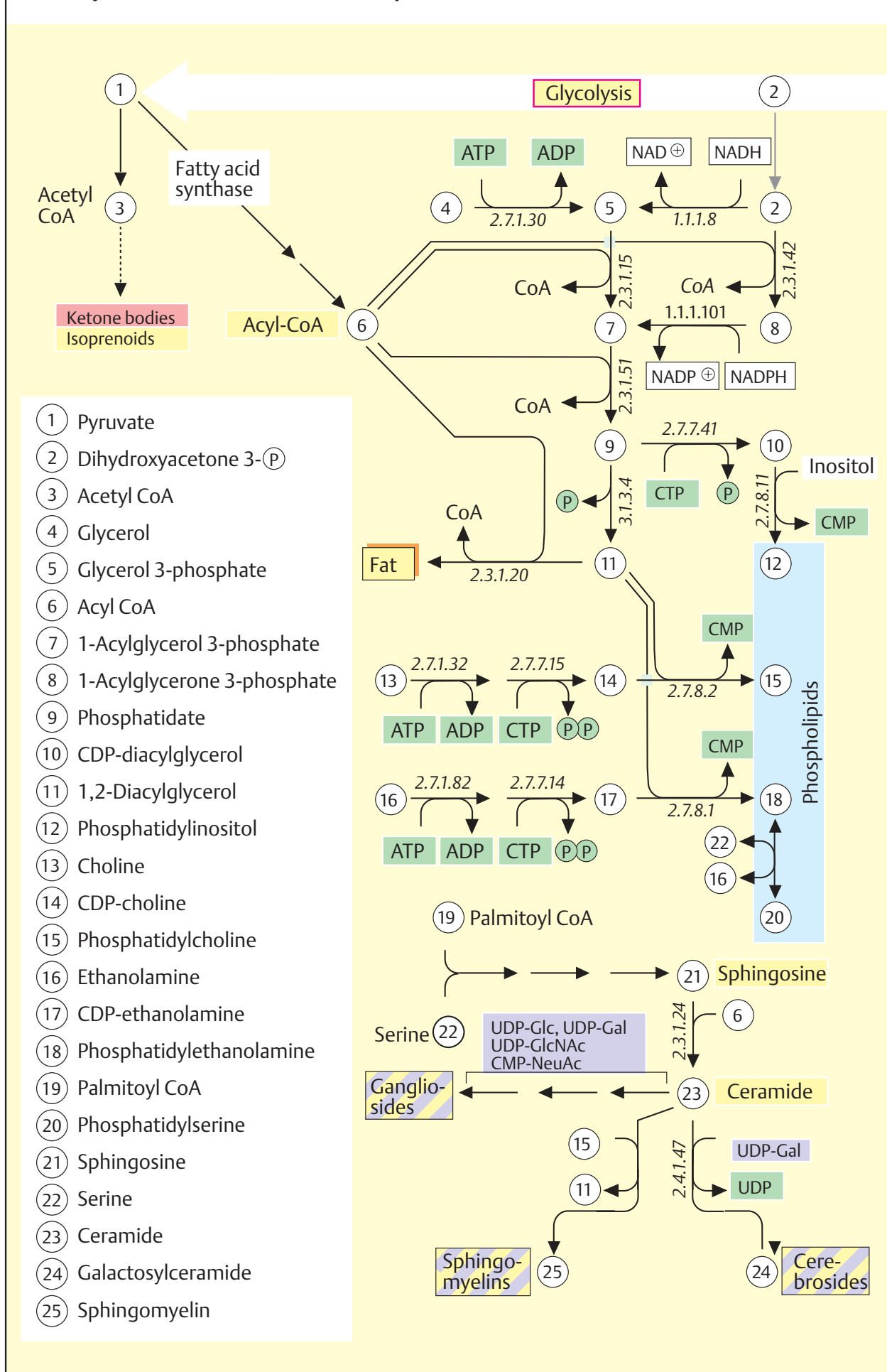


In this reaction, one molecule of ribulose-1,5-bisphosphate (metabolite 1) and one molecule of CO₂ (metabolite 2) give rise to two molecules of 3-phosphoglycerate (metabolite 3). The enzyme responsible has the EC number 4.1.1.39. The annotated enzyme list shows that this refers to *ribulose bisphosphate 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]).

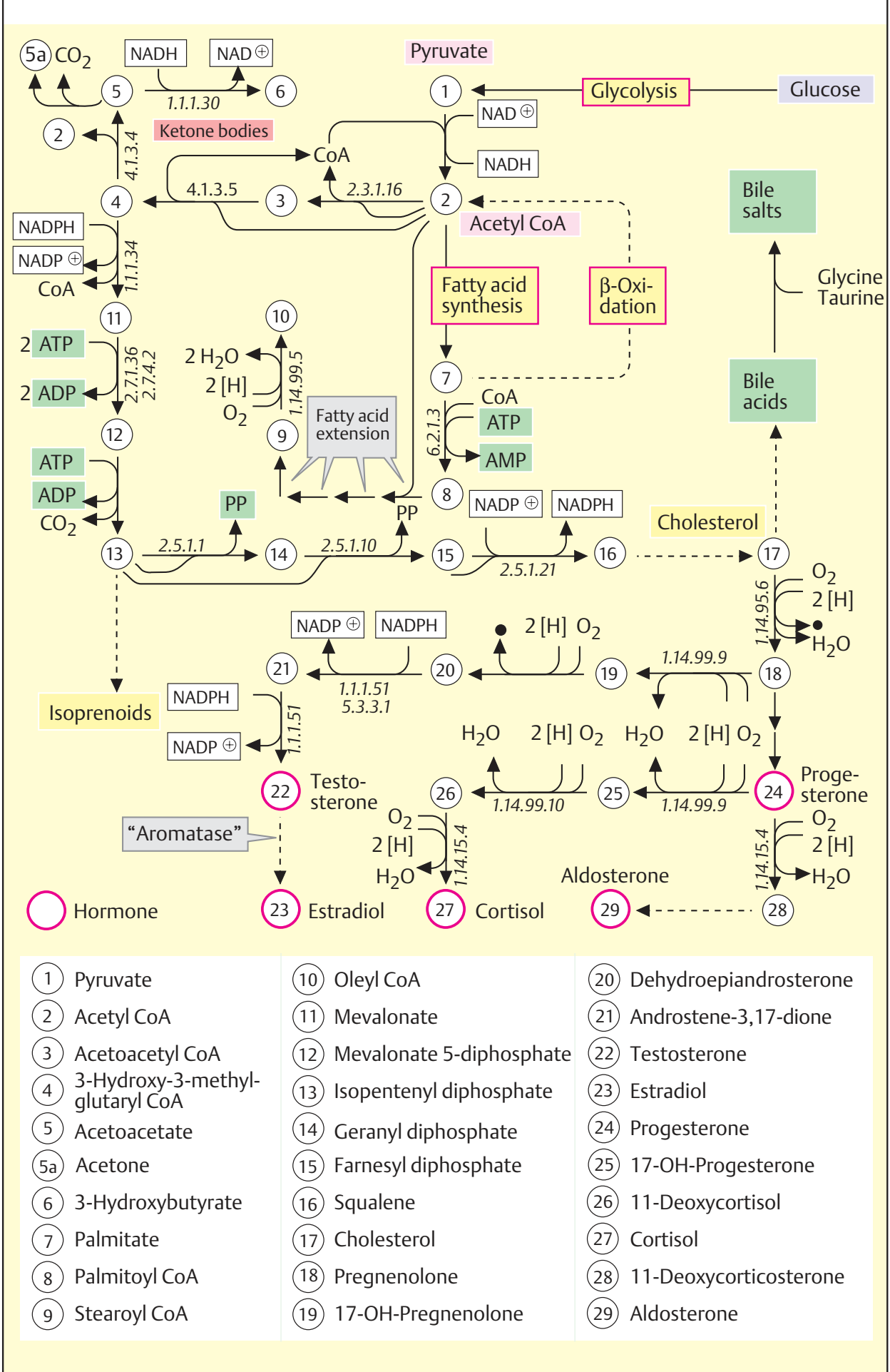
A. Calvin cycle (plant chloroplasts)



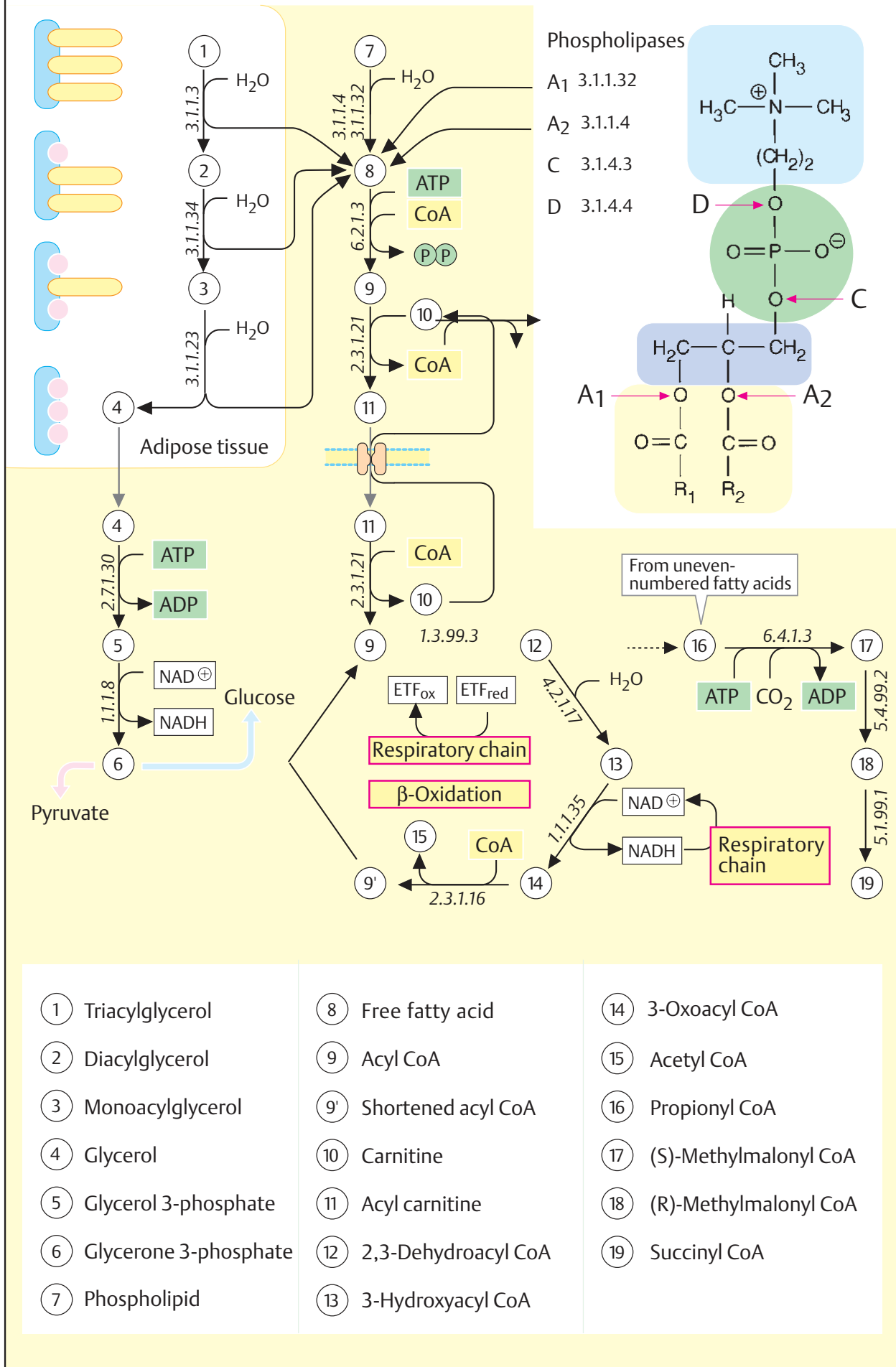
A. Biosynthesis of fats and membrane lipids



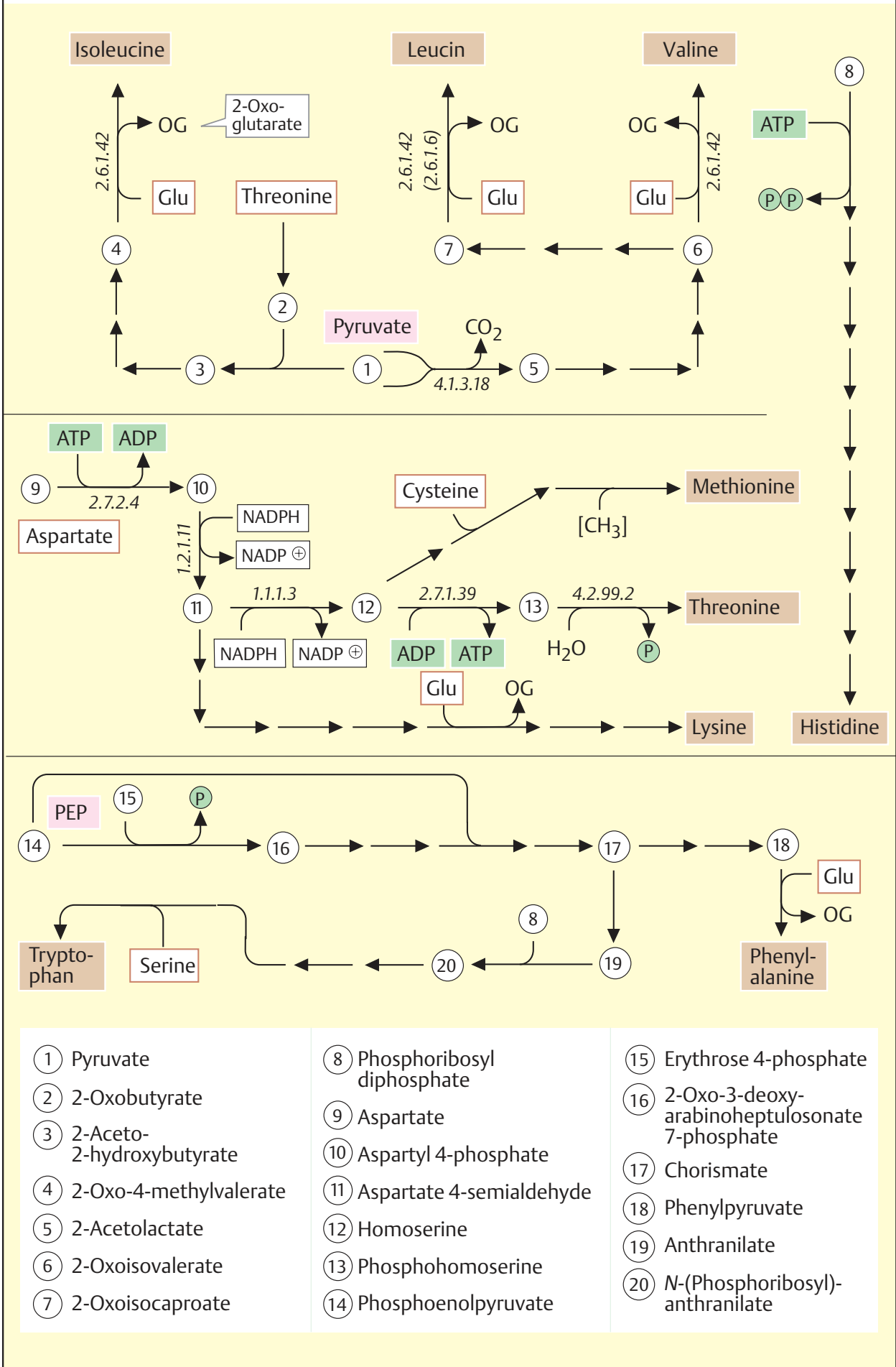
A. Synthesis of ketone bodies and steroids



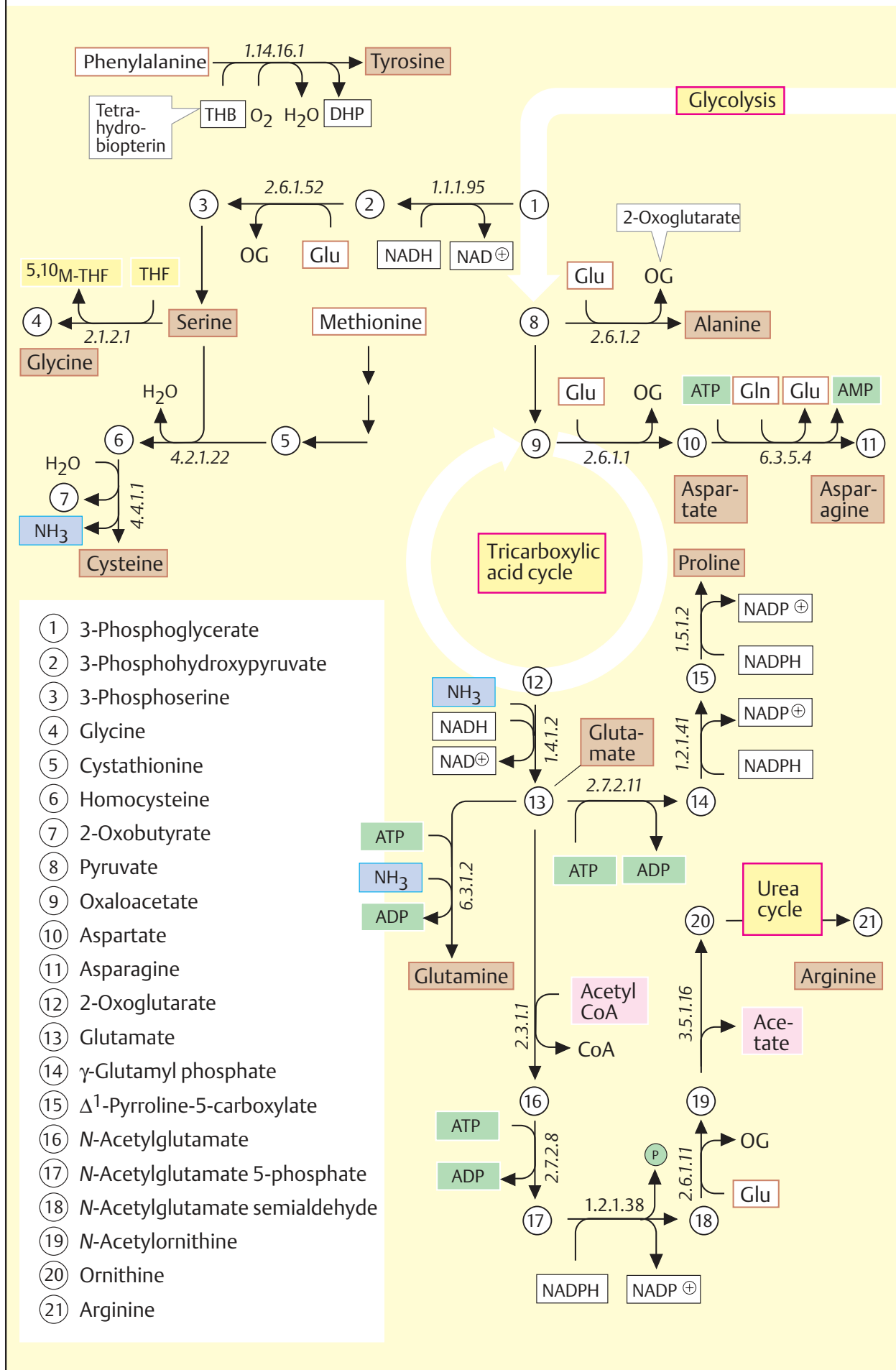
A. Degradation of fats and phospholipids



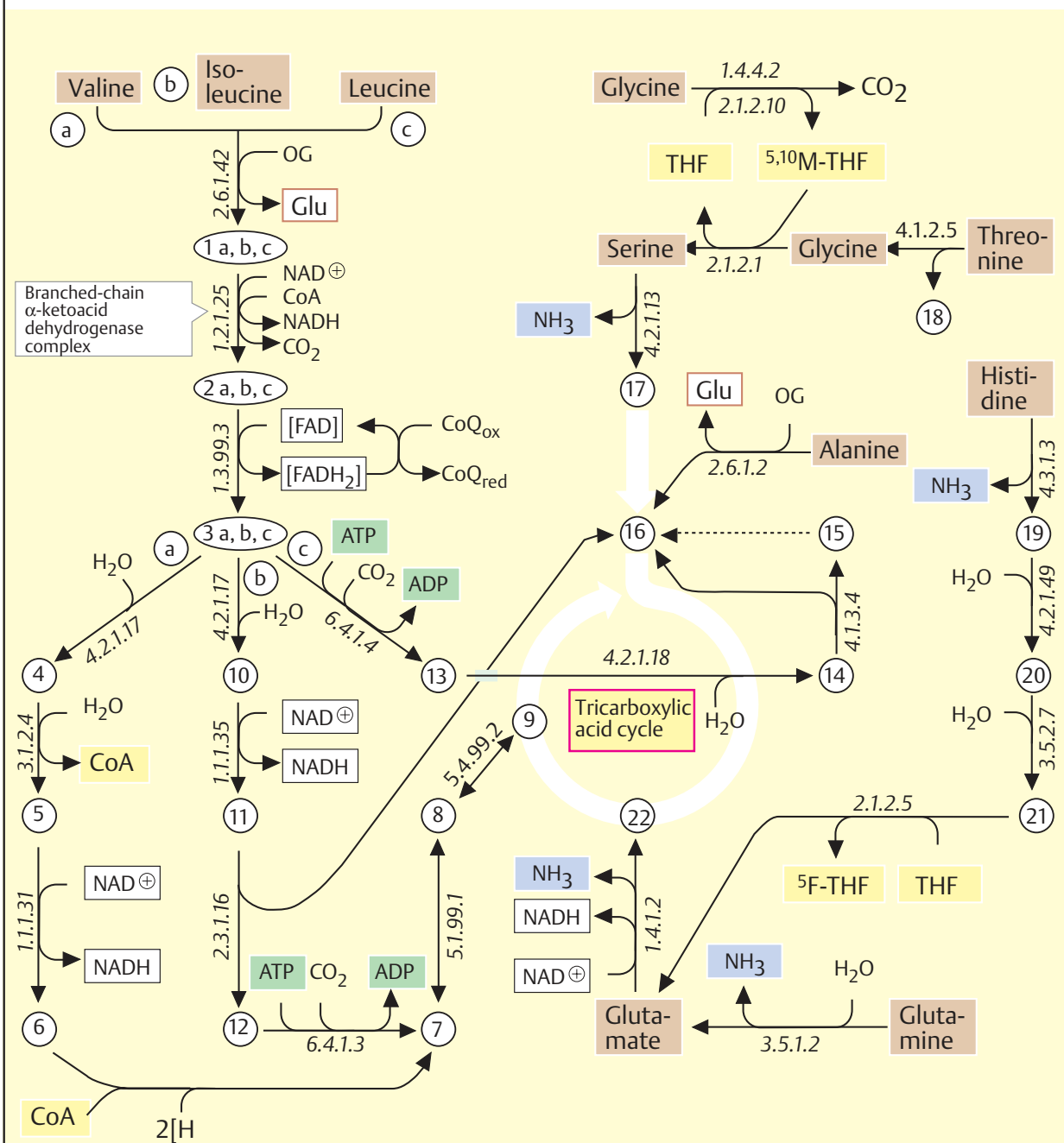
A. Biosynthesis of the essential amino acids



A. Biosynthesis of the non-essential amino acids

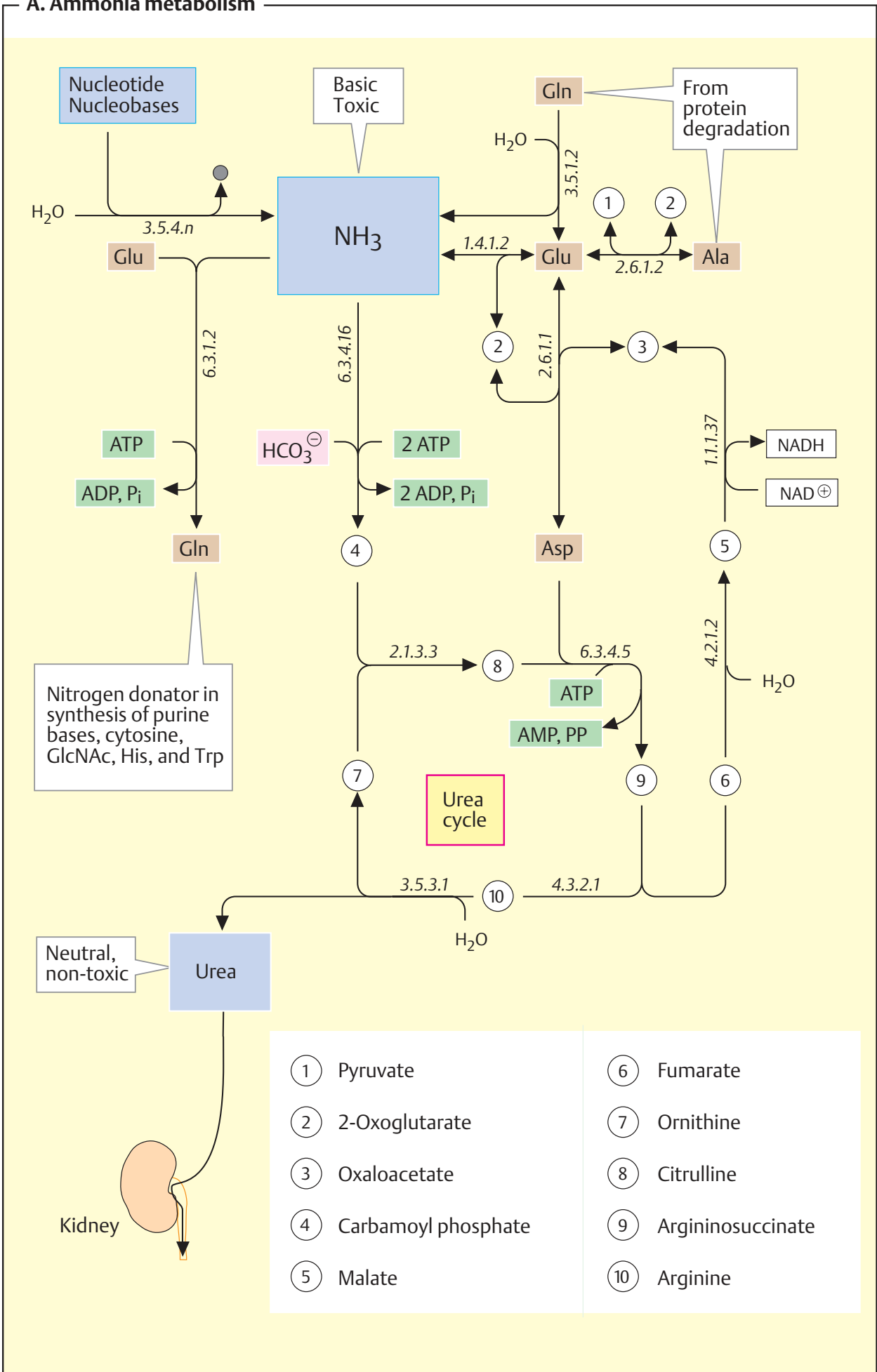


A. Amino acid degradation I

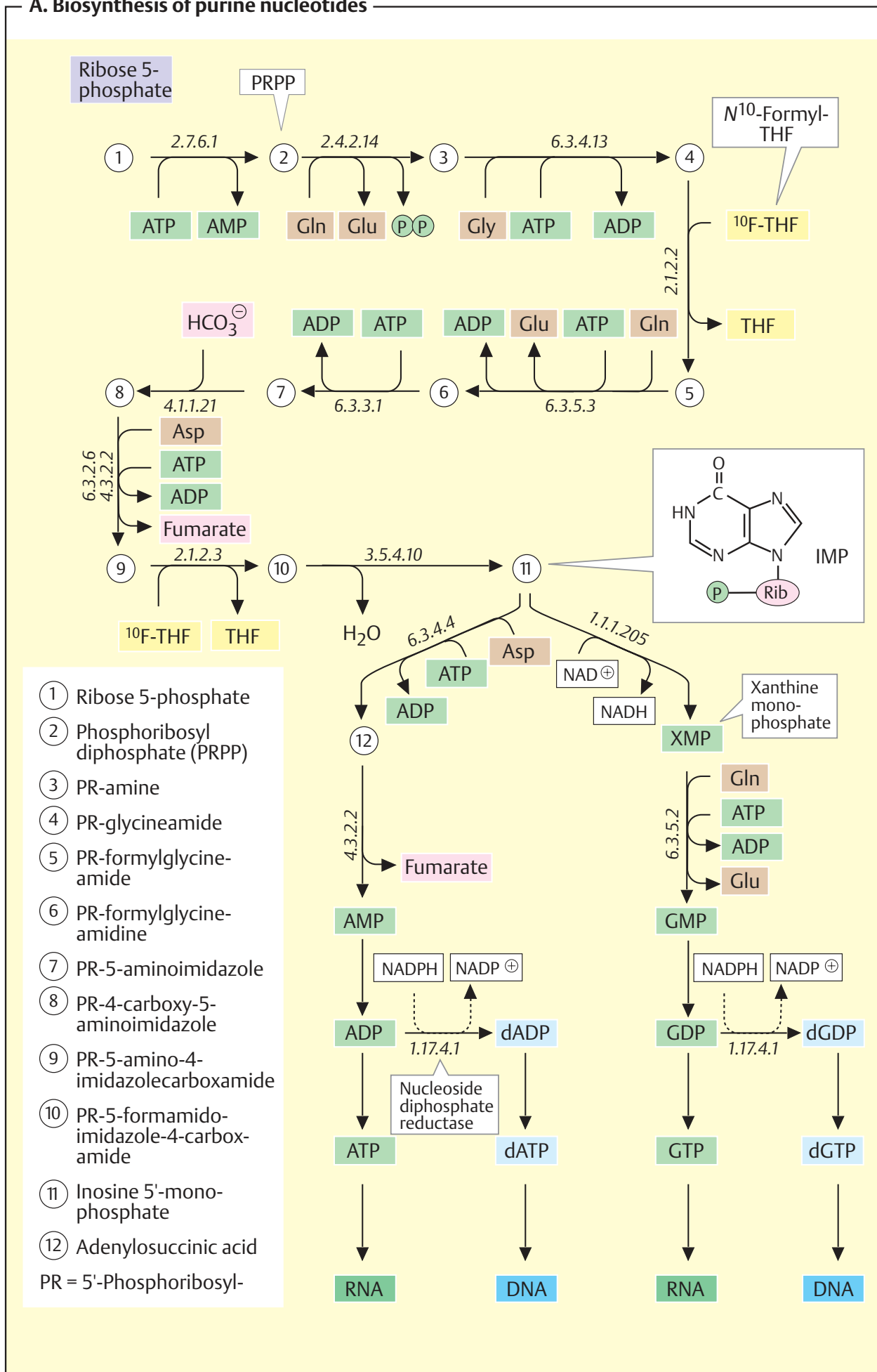


- | | | | | | |
|----|-------------------------|---|--------------------------------|---|--------------------------|
| ①a | 2-Oxoisovalerate | ⑤ | 3-Hydroxyisobutyrate | ⑮ | Acetoacetate |
| ①b | 2-Oxo-3-methylvalerate | ⑥ | Methylmalonyl-semialdehyde | ⑯ | Acetyl CoA |
| ①c | 2-Oxoisocaproate | ⑦ |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

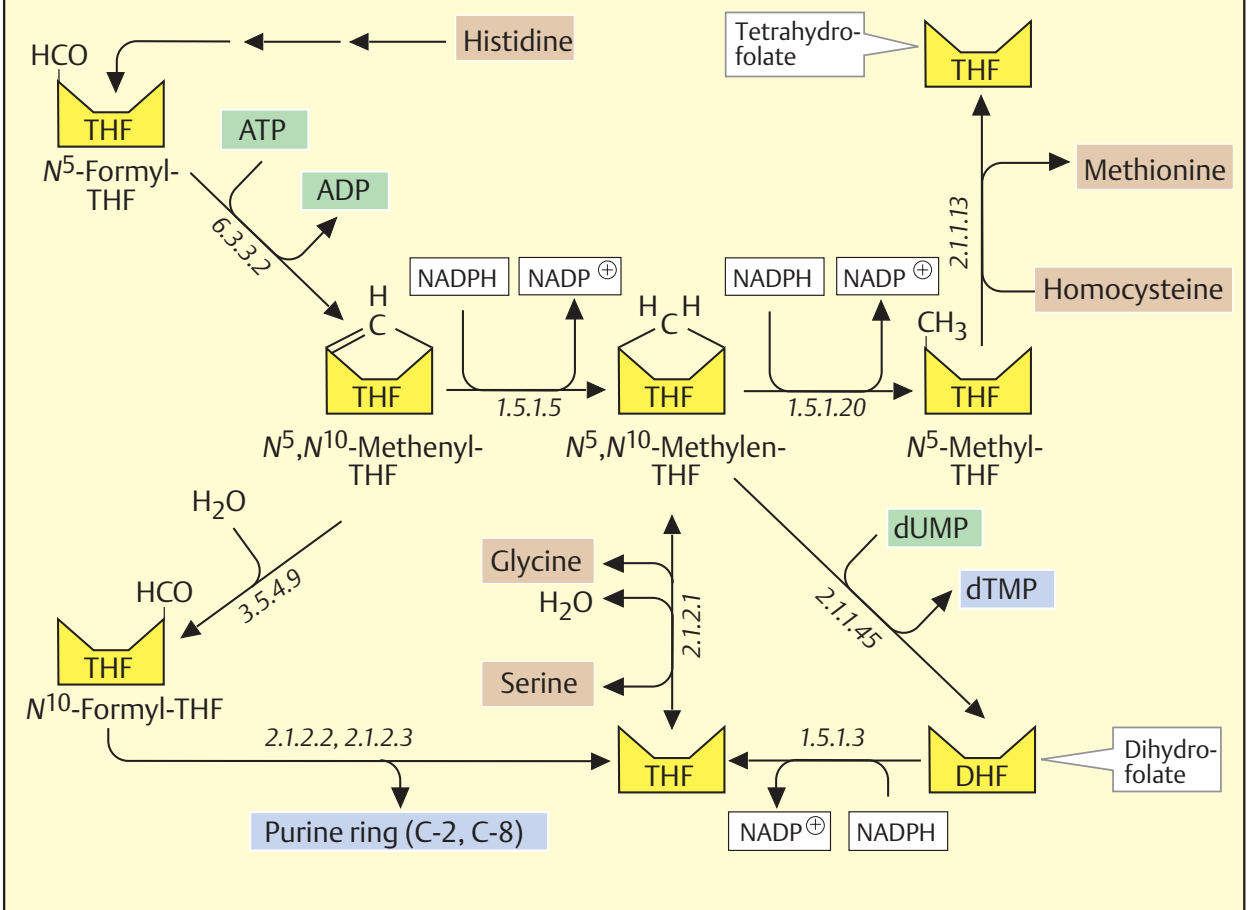
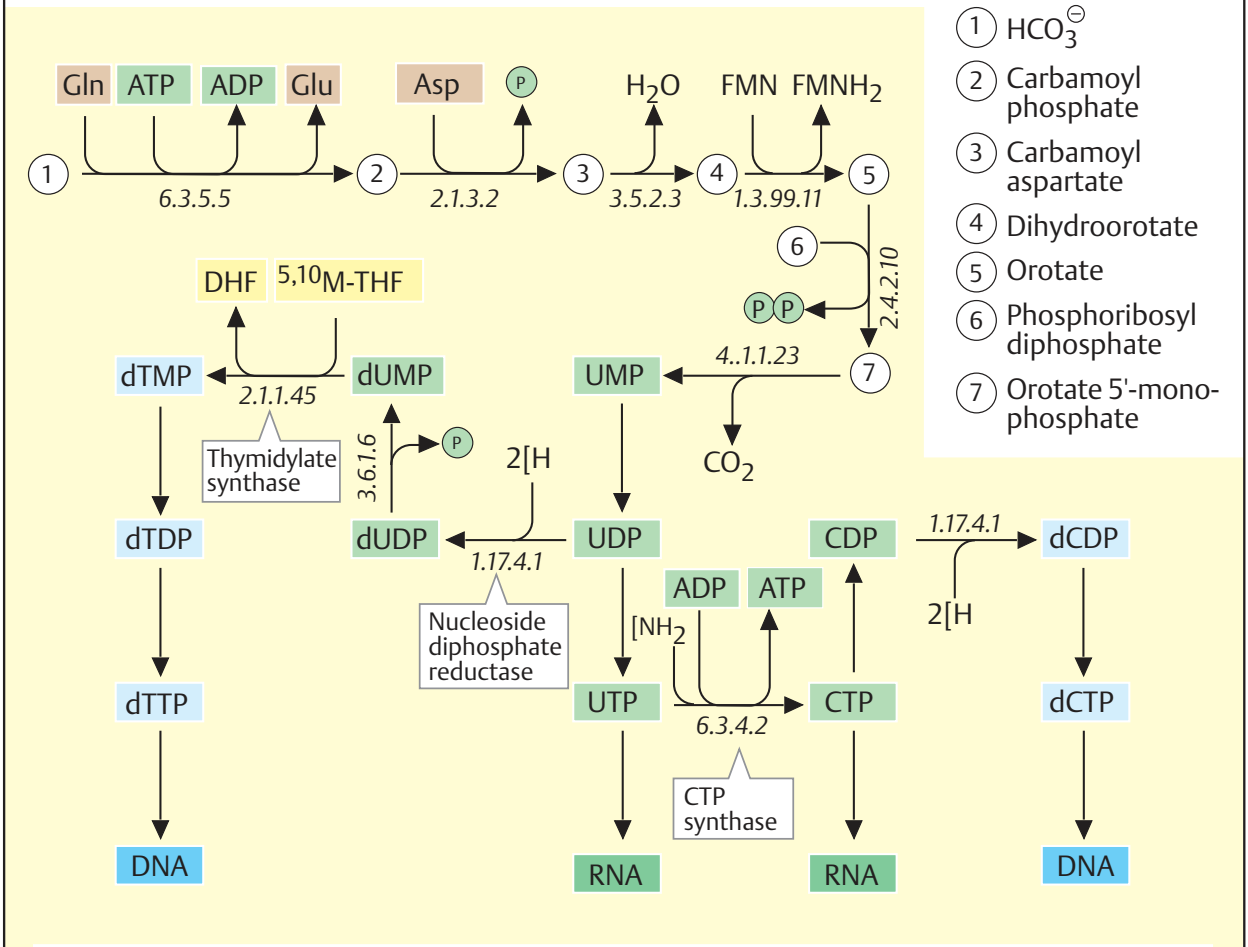
A. Ammonia metabolism



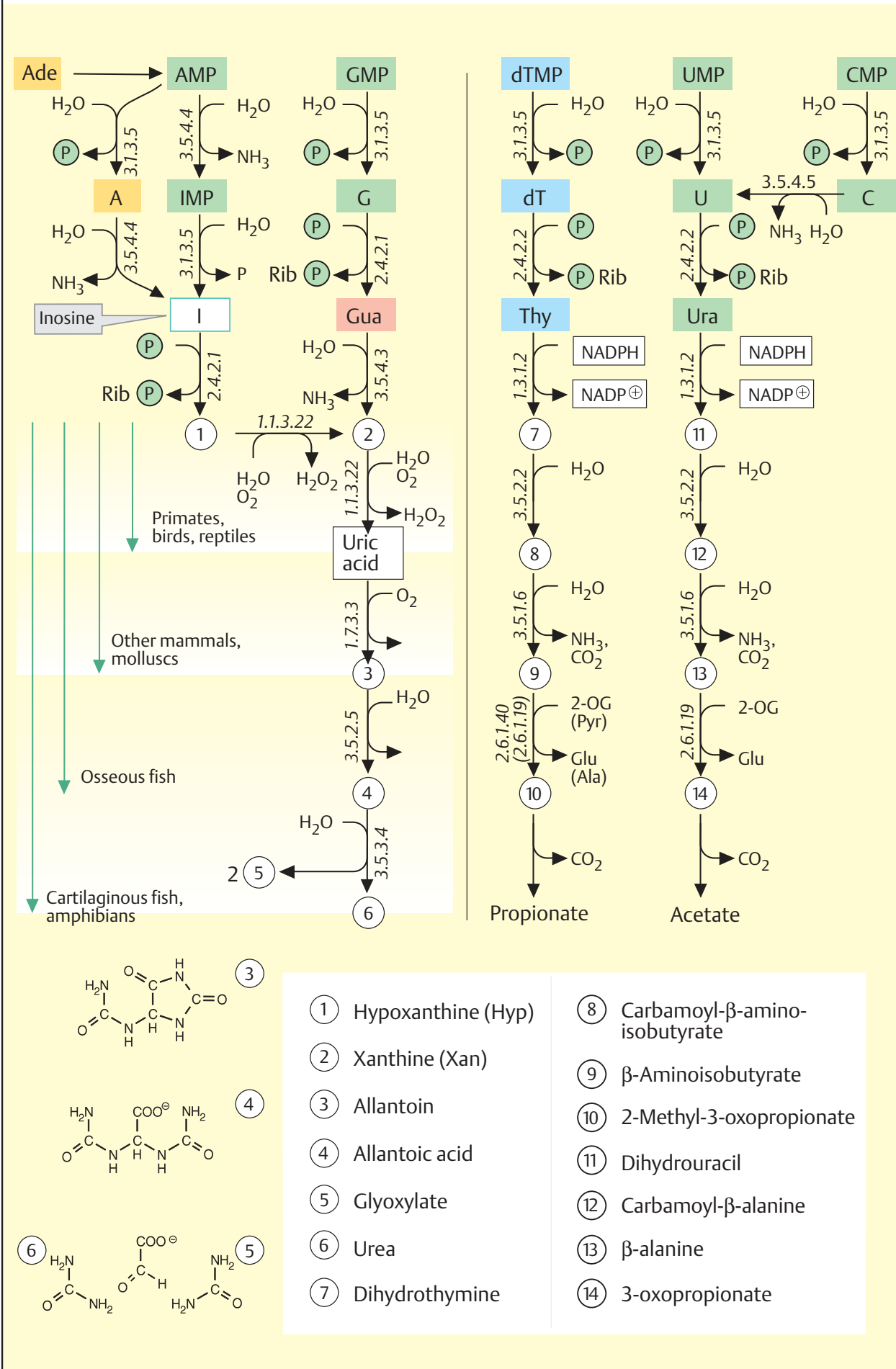
A. Biosynthesis of purine nucleotides



A. Biosynthesis of the pyrimidine nucleotides and C₁ metabolism



A. Nucleotide degradation



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 official *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 [Zn²⁺]
- 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-Δ⁵-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, Fe₂S₂, Fe₄S₄], “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 [Fe₄S₄]
 1.5.99.8 Proline dehydrogenase [FAD]
- 1.6 NAD(P)H is the donor**
 1.6.4.2 Glutathione reductase (NADPH) [FAD]
 1.6.4.5 Thioredoxin reductase (NADPH) [FAD]
 1.6.5.3 NADH dehydrogenase (ubiquinone) [FAD, Fe₂S₂, Fe₄S₄]—“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, Fe₂S₂]—“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 Calcdiol 1-monooxygenase [heme]
- 1.14.15.4 Steroid 11 β -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 17 α -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 -CH₂ 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, Fe₄S₄]

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

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

- 2.1 A C₁ 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 [Zn²⁺]
- 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 Acylglycerol-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 Acetyloronithine 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 Ketohehexokinase
 - 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-1-phosphate uridylyltransferase
 - 2.7.7.12 Hexose-1-phosphate uridylyltransferase
 - 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-acetyl-glycerol 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 A₂
 3.1.1.7 Acetylcholinesterase
 3.1.1.13 Cholesterol esterase
 3.1.1.17 Gluconolactonase
 3.1.1.32 Phospholipase A₁
 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 [Zn²⁺]
 3.1.3.2 Acid phosphatase
 3.1.3.4 Phosphatidate phosphatase
 3.1.3.9 Glucose 6-phosphatase
 3.1.3.11 Fructose biphosphatase
 3.1.3.13 Bisphosphoglycerate phosphatase
 3.1.3.16 Phosphoprotein phosphatase
 3.1.3.37 Sedoheptulose biphosphatase
 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 biphosphate 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-NH₃ ligase—“glutamine synthetase”
 6.3.2.6 Phosphoribosylaminoimidazolesuccinocarboxamide synthase (*sorry!*)
 6.3.3.1 Phosphoribosylformylglycinamide 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 (NH₃)
 6.3.5.2 GMP synthase (glutamine-hydrolyzing)
 6.3.5.3 Phosphoribosylformylglycinamide 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	FAD	Flavin adenine dinucleotide
ACE	Angiotensin-converting enzyme (peptidyl-dipeptidase A)	Fd	Ferredoxin
ACP	Acyl carrier protein	FFA	Free fatty acid
ACTH	Adrenocorticotropic hormone (corticotropin)	fMet	<i>N</i> -formylmethionine
ADH	Antidiuretic hormone (adiuretin, vasopressin)	FMN	Flavin mononucleotide
ADP	Adenosine 5'-diphosphate	Fp	Flavoprotein (containing FMN or FAD)
AIDS	Acquired immunodeficiency syndrome	GABA	γ -Aminobutyric acid
ALA	5-Aminolevulinic acid	GDP	Guanosine 5'-diphosphate
AMP	Adenosine 5'-monophosphate	Glut	Glucose transporter
ANF	Atrial natriuretic factor	GMP	Guanosine 5'-monophosphate
ANP	Atrial natriuretic peptide (= ANF)	GSH	Reduced glutathione
ATP	Adenosine 5'-triphosphate	GSSG	Oxidized glutathione
AVP	Arginine vasopressin	GTP	Guanosine 5'-triphosphate
b	Base	h	hour
bp	Base pair	HAT medium	Medium containing hypoxanthine, aminopterin, and thymidine
BPG	2,3-Bisphosphoglycerate	Hb	Hemoglobin
cAMP	3',5'-Cyclic AMP	HDL	High-density lipoprotein
CAP	Catabolite activator protein	HIV	Human immunodeficiency virus
CDK	Cyclin-dependent protein kinase (in cell cycle)	HLA	Human leukocyte-associated antigen
cDNA	Complementary DNA	HMG-CoA	3-Hydroxy-3-methylglutaryl-CoA
CDP	Cytidine 5'-diphosphate	HMP	Hexose monophosphate pathway
cGMP	3',5'-Cyclic GMP	hnRNA	Heterogeneous nuclear ribonucleic acid
CIA	Chemoluminescence immunoassay	HPLC	High-performance liquid chromatography
CMP	Cytidine 5'-monophosphate	hsp	Heat-shock protein
CoA	Coenzyme A	IDL	Intermediate-density lipoprotein
CoQ	Coenzyme Q (ubiquinone)	IF	Intermediary filament
CSF	colony-stimulating factor	IFN	Interferon
CTP	Cytidine 5'-triphosphate	Ig	Immunoglobulin
d	Deoxy-	IL	Interleukin
Da	Dalton (atomic mass unit)	InsP ₃	Inositol 1,4,5-trisphosphate
DAG	Diacylglycerol	IPTG	Isopropylthiogalactoside
dd	Dideoxy-	IRS	Insulin-receptor substrate
DH	Dehydrogenase	kDa	Kilodalton (10 ³ atomic mass units)
DNA	Deoxyribonucleic acid	K _m	Michaelis constant
dsDNA	Double-stranded DNA		
EA	Ethanolamine		
EIA	Enzyme-linked immunoassay		
ER	Endoplasmic reticulum		

LDH	Lactate dehydrogenase	QH ₂	Reduced coenzyme Q (ubiquinol)
LDL	Low-density lipoprotein	R	Gas constant
M	Molarity (mol L ⁻¹)	rER	Rough endoplasmic reticulum
Mab	Monoclonal antibody	RES	Reticuloendothelial system
MAP kinase	Mitogen-activated protein kinase	RFLP	Restriction fragment length polymorphism
MHC	Major histocompatibility complex	RIA	Radioimmunoassay
MPF	Maturation-promoting factor	RNA	Ribonucleic acid
mRNA	Messenger ribonucleic acid	ROS	Reactive oxygen species
N	Nucleotide with any base	RP	Reversed phase (of silica gel)
NAD ⁺	Oxidized nicotinamide adenine dinucleotide	rRNA	Ribosomal ribonucleic acid
NADH	Reduced nicotinamide adenine dinucleotide	S	Svedberg (unit of sedimentation coefficient)
NADP ⁺	Oxidized nicotinamide adenine dinucleotide phosphate	SAH	S-adenosyl L-homocysteine
NADPH	Reduced nicotinamide adenine dinucleotide phosphate	SAM	S-adenosyl L-methionine
NeuAc	<i>N</i> -acetylneuraminic acid	SDS	Sodium dodecylsulfate
nm	Nanometer (10 ⁻⁹ m)	sER	Smooth endoplasmic reticulum
ODH	2-Oxoglutarate dehydrogenase	sn	Stereospecific numbering
PAGE	Polyacrylamide gel electrophoresis	snRNA	Small nuclear ribonucleic acid
Pan	Pantetheine	SR	Sarcoplasmic reticulum
PAPS	Phosphoadenosine phosphosulfate	ssDNA	Single-stranded DNA
PCR	Polymerase chain reaction	TBG	Thyroxine-binding globulin
PDH	Pyruvate dehydrogenase	THB	Tetrahydrobiopterin
PEG	Polyethylene glycol	THF	Tetrahydrofolate
PEP	Phosphoenolpyruvate	TLC	Thin-layer chromatography
pH	pH value	TPP	Thiamine diphosphate
P _i	Inorganic phosphate	TRH	Thyrotropin-releasing hormone (thyroliberin)
PK	Protein kinase	Tris	Tris(hydroxymethyl)aminomethane
PLP	Pyridoxal phosphate	tRNA	Transfer ribonucleic acid
PP	Protein phosphatase	TSH	Thyroid-stimulating hormone (thyrotropin)
PPP	Pentose phosphate pathway	UDP	Uridine 5'-diphosphate
PQ	Plastoquinone	UMP	Uridine 5'-monophosphate
PRPP	5-Phosphoribosyl 1-diphosphate	UTP	Uridine 5'-triphosphate
PS	Photosystem	UV	Ultraviolet radiation
PTH	Parathyroid hormone	V _{max} , V	Maximal velocity (of an enzyme)
Q	Oxidized coenzyme Q (ubiquinone)	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 1 pound (lb) = 0.4536 kg
Mass	Kilogram	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 coefficient	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	N = 6.0225 10 ²³
(number of particles per mol)	
Faraday constant F	F = 96480 C mol ⁻¹

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333	B	Voet D, Voet JG. Biochemistry. New York: Wiley, 1990, p. 1126, Fig. 34–55
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