17

A large diversity of isoprenoids has multiple functions in plant metabolism

Isoprenoids are present in all living organisms, but with a remarkable diversity in plants. More than 40,000 different plant isoprenoids are known and new compounds are being constantly identified. These isoprenoids have many different functions (Table 17.1). In primary metabolism, they function as membrane constituents, photosynthetic pigments, electron transport carriers, growth substances, and plant hormones. They act as glucosyl carriers in glucosylation reactions and are involved in the regulation of cell growth.

Plant isoprenoids (also known as **terpenoids**) are important commercially, for example as aroma substances for food, beverages, and cosmetics, as vitamins (A, D, and E), natural insecticides (e.g., pyrethrin), solvents (e.g., turpentine), and as rubber and gutta-percha. The plant isoprenoids also comprise important natural compounds, which are utilized as pharmaceuticals or their precursors. Investigations are in progress to increase the ability of plants to synthesize isoprenoids by genetic engineering.

Plant ethereal oils have long been of interest to chemists. A number of mainly cyclic compounds containing 10, 15, 20, or correspondingly more C atoms have been isolated from turpentine oil. Such substances have been found in many plants and were given the collective name **terpenes**. Figure 17.1 shows some examples of terpenes. Limonene, an aromatic substance from lemon oil, is a terpene with 10 C atoms and is called a monoterpene. Carotene, with 40 C atoms, is accordingly a tetraterpene**.** Rubber is a polyterpene with about 1,500 C atoms. It is obtained from the latex of the rubber tree *Hevea brasiliensis*.

Table 17.1: Isoprenoids of higher plants

Precursor	Class	Example	Function
C_5: Dimethylallyl-PP	Hemiterpene	Isoprene	Protection of the photosynthetic apparatus against heat
Isopentenyl-PP		Side chain of cytokinin	Growth regulator
C_{10}: Geranyl-PP	Monoterpene	Pinene	Defense substance attractant
		Linalool	
C_{15}: Farnesyl-PP	Sesquiterpene	Capsidiol	Phytoalexin
C_{20}: Geranylgeranyl-PP	Diterpene	Gibberellin	Plant hormone
		Phorbol	Defense substance
		Casbene	Phytoalexin
C_{30}: 2 Farnesyl-PP	Triterpene	Cholesterol	Membrane constituents
		Sitosterol	
C_{40}: 2 Geranylgeranyl-PP	Tetraterpene	Carotenoids	Photosynthesis pigments
n Geranylgeranyl-PP or *n* Farnesyl-PP	Polyprenols	Prenylated proteins	Regulation of cell growth
		Prenylation of plastoquinone, ubiquinone, chlorophyll, cyt *a*	Membrane solubility of photosynthesis pigments and electron transport carriers
		Dolichols	Glucosyl carrier
		Rubber	

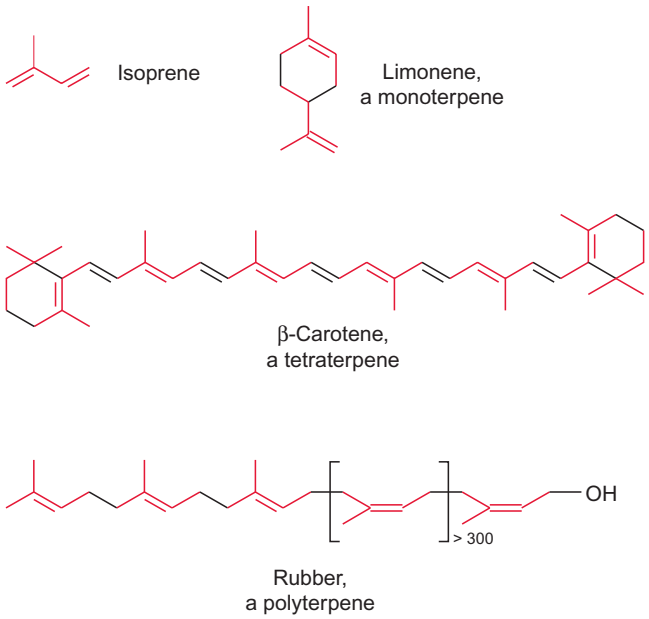


Figure 17.1
Various isoprenoids.

Otto Wallach (Bonn, Göttingen), who in 1910 was awarded the Nobel Prize in Chemistry for his basic studies on terpenes, recognized that isoprene is the basic constituent of terpenes (Fig. 17.1). Continuing these studies, Leopold Ruzicka (Zürich) found that isoprene is the universal basic element for the synthesis of many natural compounds, including steroids, and for this he was awarded the Nobel Prize in Chemistry in 1939. He postulated the biogenic isoprene rule, according to which all terpenoids (derivatives of terpenes) are synthesized via a hypothetical precursor, which he named **active isoprene**. This speculation was verified by Feodor Lynen in Munich (1964 Nobel Prize in Medicine), when he identified **isopentenyl pyrophosphate** to be the "active isoprene."

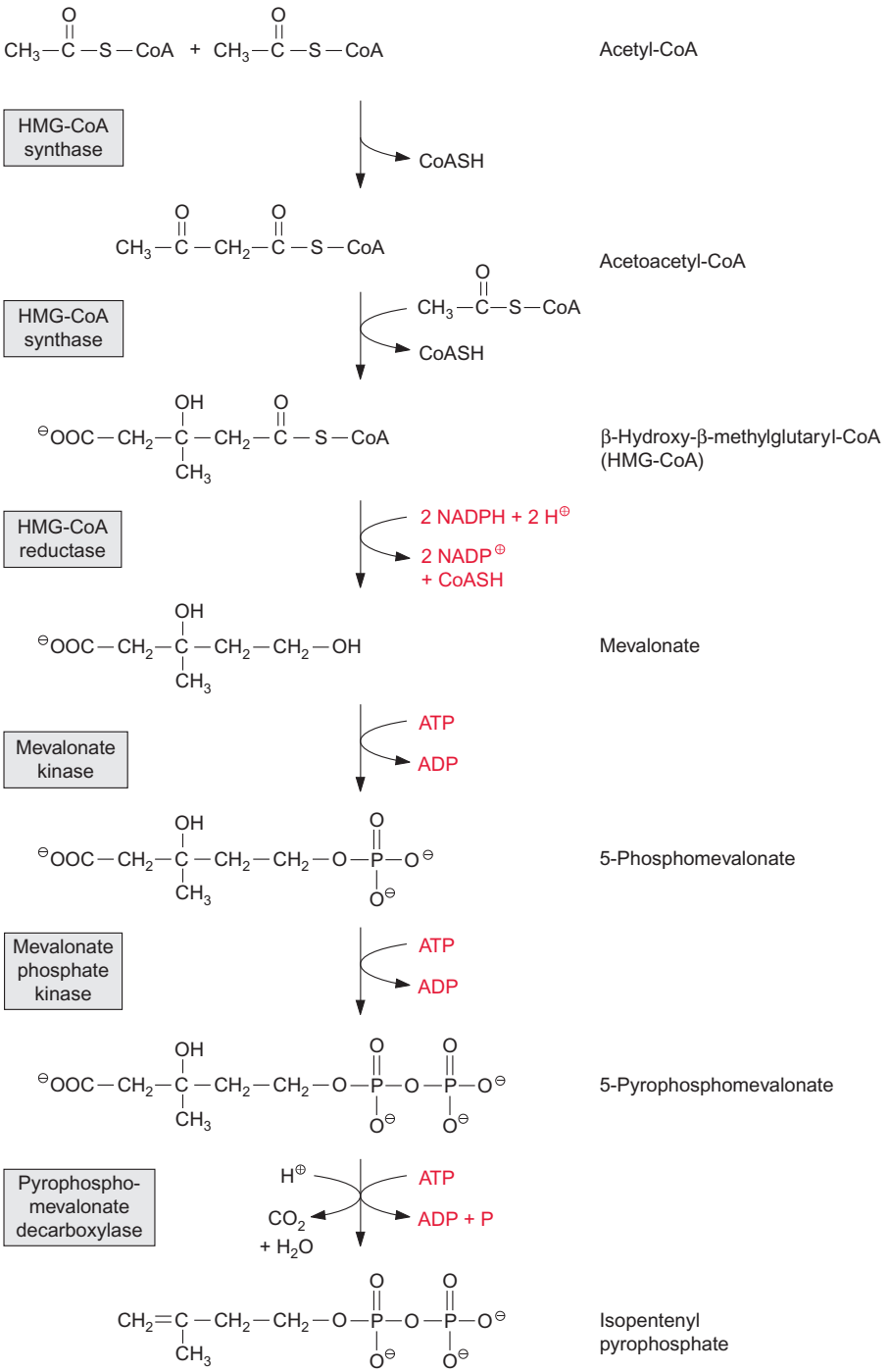
17.1 Higher plants have two different synthesis pathways for isoprenoids

Precursor for the synthesis of isoprenoids is isopentenyl pyrophosphate. Its synthesis proceeds in higher plants and some groups of algae in two different ways, one located in the cytosol and the other in the plastids.

Acetyl CoA is a precursor for the synthesis of isoprenoids in the cytosol

The basis for the elucidation of this isoprenoid biosynthesis pathway was the discovery by Konrad Bloch (USA, likewise a joint winner of the Nobel Prize in Medicine in 1964) that **acetyl CoA** is a precursor for the biosynthesis of steroids. Figure 17.2 shows the synthesis of the intermediary product isopentenyl pyrophosphate: two molecules of acetyl CoA react to produce **acetoacetyl CoA** and then with another acetyl CoA yielding **β-hydroxy-β-methylglutaryl CoA** (HMG CoA). In yeast and animals, these reactions are catalyzed by two different enzymes, whereas in plants a single enzyme, **HMG CoA synthase**, catalyzes both reactions. The esterified carboxyl group of HMG CoA is reduced by two molecules of NADPH to a hydroxyl group, accompanied by hydrolysis of the energy-rich thioester bond. Thus **mevalonate** is formed in an irreversible reaction. The formation of mevalonate from HMG CoA is an important regulatory step of isoprenoid synthesis in animals. It has not yet been resolved whether this also applies to plants. A pyrophosphate ester is formed in two successive phosphorylation steps, catalyzed by two different kinases. With consumption of a third molecule of ATP, involving the transitory formation of a phosphate

Figure 17.2 Isopentenyl pyrophosphate synthesis in the cytosol proceeds via the acetate-mevalonate pathway.



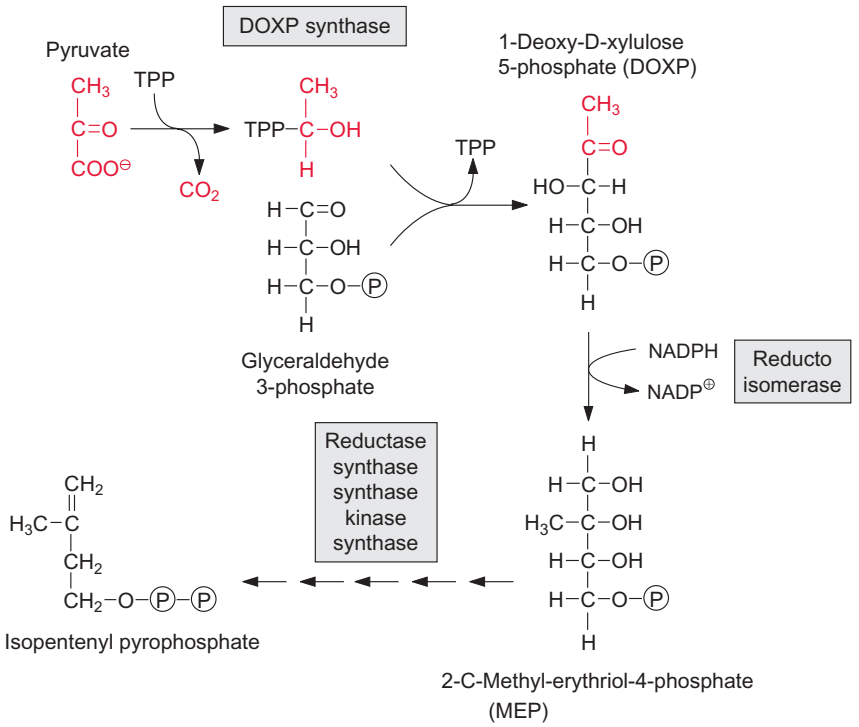


Figure 17.3
The isopentenyl pyrophosphate synthesis in the plastids proceeds via the 2-methyl erythriol 4-phosphate pathway (MEP). For the conversion of MEP to isopentenyl pyrophosphate only the enzymes involved are listed, the intermediates are not shown.

ester, a carbon-carbon double bond is generated and the remaining carboxyl group is removed. Isopentenyl pyrophosphate thus formed is the basic element for the formation of an isoprenoid chain. This synthesis of isopentenyl pyrophosphate, termed the **acetate-mevalonate pathway**, is located in the cytosol. It is responsible for the synthesis of sterols, certain sesquiterpenes, and the side chain of ubiquinone.

Pyruvate and D-glyceraldehyde-3-phosphate are the precursors for the synthesis of isopentyl pyrophosphate in plastids

The acetate-mevalonate pathway can be blocked by **mevilonin**, a very specific inhibitor of HMG CoA reductase. Experiments with plants showed that mevilonin inhibits the isoprenoid synthesis in the cytosol, but not in the plastids. These findings led to the discovery that the synthesis of isopentenyl pyrophosphate in the plastids follows a different pathway from that in the cytosol (Fig. 17.3). For the plastidal synthesis pathway, the precursors are **pyruvate** and **D-glyceraldehyde-3-phosphate**. As in the pyruvate dehydrogenase reaction (Fig. 5.4), pyruvate is decarboxylated via thiamine pyrophosphate (TPP), and then, as in the transketolase reaction (Fig. 6.17), is transferred

to D-glyceraldehyde-3-phosphate to yield **1-deoxy-D-xylulose-5-phosphate** (**DOXP**). After isomerization and reduction by NADPH, 2-C-methyl-D-erythritol-4-phosphate (**MEP**) is synthesized. MEP is then activated by reacting with CTP to yield CDP methyl erythriol. Two further reduction steps, followed by dehydration and phosphorylation, finally yield **isopentenyl pyrophosphate**. The **MEP-synthase pathway** for isoprenoids is present in bacteria, algae, and plants, but not in animals. A large part of plant isoprenoids, including the hemiterpene isoprene, monoterpenes like pinene and limonene, diterpenes (e.g., phytol chains, gibberellin, abietic acid as oleoresin constituent) as well as tetraterpenes (carotenoids) are synthesized via the MEP synthase pathway located in the plastids. Also, the side chains of chlorophyll and plastoquinone are synthesized by this pathway. Sesquiterpenes and triterpenes, on the other hand, according to our present knowledge are synthesized by the mevalonate pathway in the cytosol (Fig. 17.2).

17.2 Prenyl transferases catalyze the association of isoprene units

Dimethylallyl pyrophosphate, which is formed by isomerization of isopentenyl pyrophosphate, is the acceptor for successive transfers of isopentenyl moieties (Fig. 17.4). With the liberation of the pyrophosphate residue, dimethylallyl-PP condenses with isopentenyl-PP to produce geranyl-PP. In an analogous way, chain elongation is attained by further head-to-tail condensations with isopentenyl-PP, and so farnesyl-PP and geranylgeranyl-PP are formed one after the other.

The transfer of the isopentenyl moieties is catalyzed by **prenyl transferases**. Prenyl residues are a collective term for isoprene or polyisoprene residues. A special prenyl transferase is required for the production of each of the prenyl pyrophosphates mentioned. For example, the prenyl transferase termed **geranyl-PP synthase** catalyzes only the synthesis of geranyl-PP. However, **farnesyl-PP synthase** synthesizes farnesyl-PP in two discrete steps: from dimethylallyl-PP and isopentenyl-PP, first geranyl-PP is formed, but this intermediate remains bound to the enzyme and reacts further with another isopentenyl-PP to produce farnesyl-PP. Analogously, **geranylgeranyl-PP synthase** catalyzes all three steps of the formation of geranylgeranyl-PP. Table 17.1 shows that each of these prenyl pyrophosphates is the precursor for the synthesis of structurally and functionally specific isoprenoids, including hemiterpenes, monoterpenes, and sesquiterpenes. As these prenyl pyrophosphates are synthesized by different enzymes, the synthesis of a certain prenyl

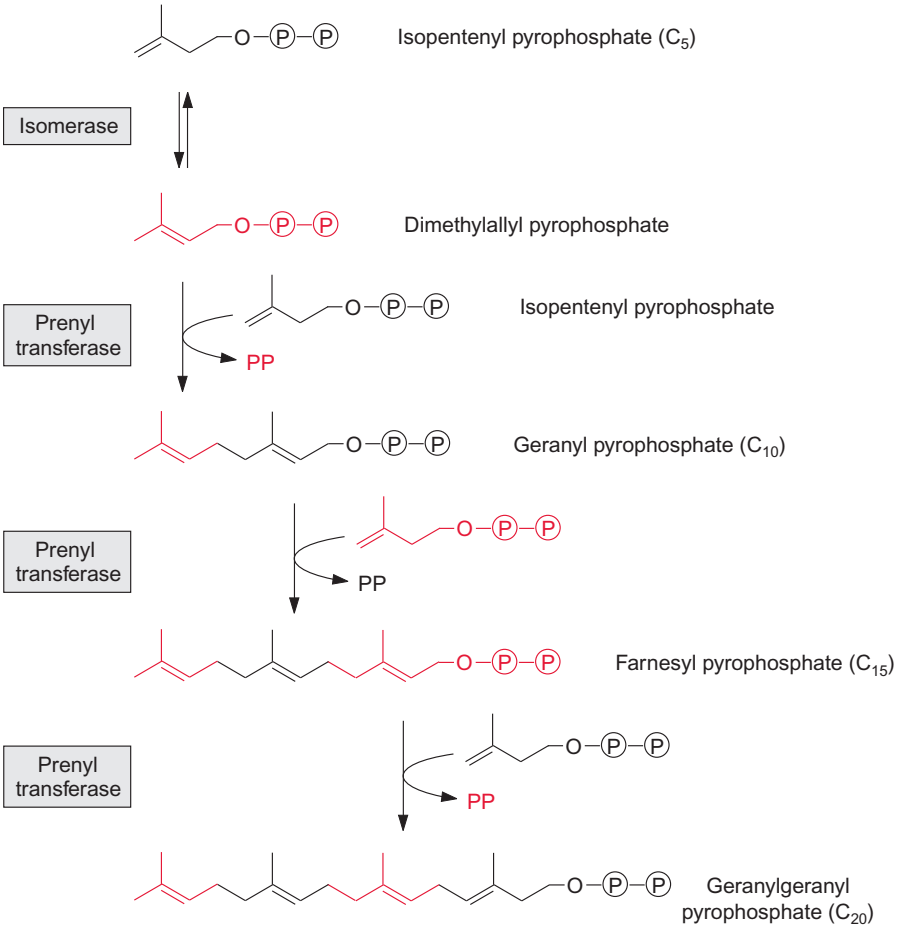


Figure 17.4 Higher molecular prenyl phosphates are formed by head-to-tail addition of active isoprene units.

pyrophosphate can be regulated by induction or repression of the corresponding enzyme. It appears that there is a synthesis pathway from isopentenyl pyrophosphate to geranylgeranyl pyrophosphate, not only in the cytosol but also in the plastids. The differences between these two pathways have not yet been resolved in detail.

The formation of a C-C linkage between two isoprenes proceeds by nucleophilic substitution (Fig. 17.5): an Mg^{++} ion, bound to the prenyl transferase, facilitates the release of the negatively charged pyrophosphate residue from the acceptor molecule, whereby a positive charge remains at the terminal C atom (C-1), which is stabilized by the neighboring double bond. The allyl cation thus formed reacts with the terminal C-C double bond of the donor molecule and a new C-C bond is formed with the release of a proton. According to the same reaction mechanism, not only isoprene chains, but also rings are formed, leading to the exceptional diversity of isoprenoids.

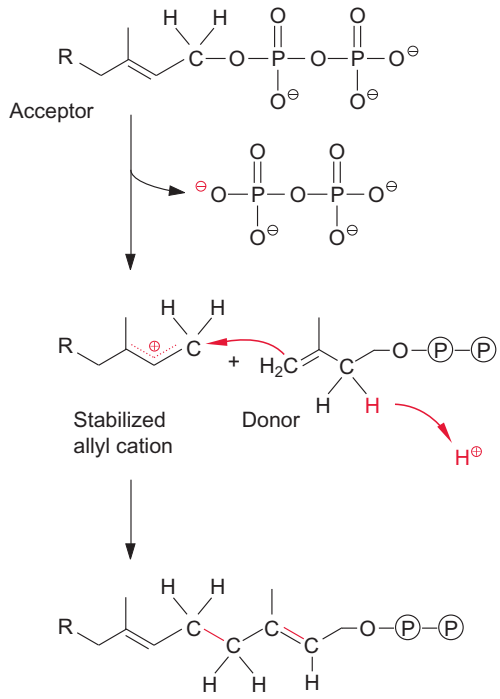


Figure 17.5 The head-to-tail addition of two prenyl phosphates by prenyl transferase is a nucleophilic substitution according to the S_N1 mechanism. First, pyrophosphate is released from the acceptor molecule. An allyl cation is formed, which reacts with the double bond of the donor molecule and forms a new C-C bond. The double bond is restored by release of a proton, but it is shifted by one C atom. The reaction scheme is simplified.

17.3 Some plants emit isoprenes into the air

The **hemiterpene** isoprene is formed from dimethyallyl-PP upon the release of pyrophosphate by an **isoprene synthase**, which is present in many plants (Fig. 17.6). Isoprene is volatile (boiling point 33°C) and leaks from the plant in gaseous form. Trees, such as oak, willow, planes, and poplar, emit isoprene during the day at temperatures of 30°C to 40°C. At such high temperatures, as much as 5% of the photosynthetically fixed carbon in oak leaves can be emitted as isoprene. Isoprene emissions of up to 20% of the total photoassimilate have been observed for the kudzu vine (*Pueraria lobota*), a climbing plant that is grown in Asia for fodder. Together with monoterpenes and other compounds, isoprene emission is responsible for the blue haze that can be observed over forests during hot weather.

Isoprene is produced in the chloroplasts from dimethylallyl pyrophosphate, which is formed via the MEP synthase pathway (Fig. 17.3). Isoprene synthase is induced when leaves are exposed to high temperatures. The physiological function of isoprene formation is still a matter of debate. There are indications that low amounts of isoprene stabilize photosynthetic membranes against high temperature damage. The global isoprene emission

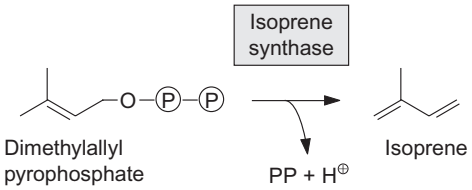


Figure 17.6 Via isoprene synthase some leaves form isoprene, which escapes as a volatile.

by plants is considerable. It is estimated to be about as high as the global methane emission. But, in contrast to methane, isoprene decomposes in the atmosphere rather rapidly.

17.4 Many aromatic compounds derive from geranyl pyrophosphate

The monoterpenes comprise a large number of open chain and cyclic isoprenoids, many of which, due to their high volatility and their lipid character, are classified as essential oils. Many of them have a distinctive, often pleasant odor and are, for example, responsible for the typical scents of pine needles, thyme, lavender, roses, and lily of the valley. Flower scents attract insects for the distribution of pollen, but in addition some volatiles also repel insects and other animals and thus protect the plants from herbivores.

The hydrolysis of geranyl-PP results in the formation of the alcohol geraniol (Fig. 17.7), the main constituent of rose oil. Geraniol has the typical scent of freshly cut geraniums. Geranyl-PP is a precursor for the synthesis of monoterpenes via monoterpene synthases. These enzymes belong to a common enzyme family, which typically possess characteristic sequence motifs and similar active centers, and produce a great variety of products. Figure 17.8 shows the products of two closely related monoterpene synthases. Whereas the linalool synthase from *Nicotiana alata* produces only one product linalool, the cineol synthase from *Nicotiana suaveolens*, as a multiproduct enzyme, yields eight products (60% cineol, 10% each myrcene, limonene and sabinene and 2% each ocimen, terpineol, α-pinene and β-pinene). Thus a variety of compounds can be synthesized by a single enzyme. Monoterpenes occur as scents in flowers to lure insects, but they are also contained in plants as insect repellent. The monoterpenes myrcene, limonene, α-pinene and β-pinene are major constituents of the resin (termed **olioresin**) of conifers. They are toxic for many insects and thus act as a protection against herbivores. Conifers respond to an attack by bark beetles with a strong increase of

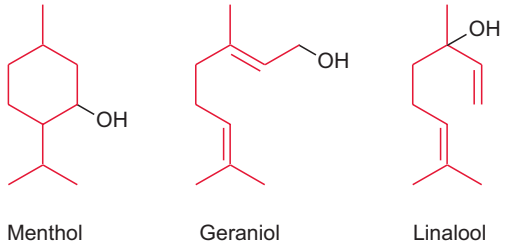


Figure 17.7 Menthol, a constituent of peppermint oil; geraniol, a constituent of rose oil as well as an aromatic compound in geranium scent; and linalool, an aromatic compound of the *Compositae*.

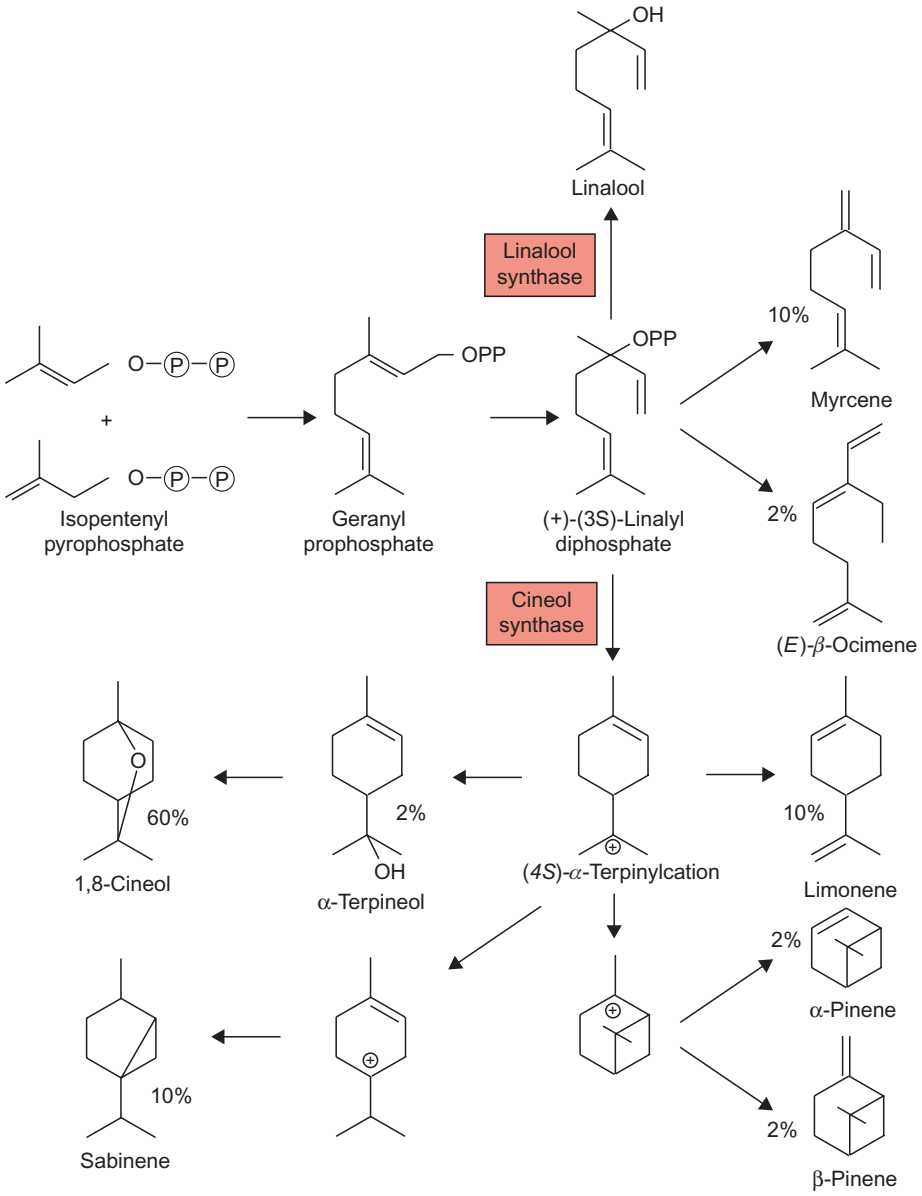


Figure 17.8 Example for the reaction products of two monoterpene synthases. The conversion of linalyl diphosphate, as catalyzed by the linalool synthase from *Nicotiana alata*, yields a single product, whereas the conversion by the cineol synthase of *Nicotiana suaveolens* results in eight products (yields are indicated in %).

cyclase activity, which results in enhanced formation of cyclic monoterpenes, e.g., pinene, limonene. Limonene is also found in the leaves and peel of lemons. Another example of a monoterpene is menthol (Fig. 17.7), the main constituent of peppermint oil. It serves the plant as an insect repellent. Many other monoterpenes containing carbonyl and carboxyl groups can be synthesized by plants, which are not discussed here.

17.5 Farnesyl pyrophosphate is the precursor for the synthesis of sesquiterpenes

The number of possible products is even larger for the cyclization of farnesyl-PP, according to the same mechanism of cyclization of geranyl-PP (Fig. 17.8). This is illustrated in Figure 17.9. The reaction of the intermediary carbonium ion with the two double bonds of the molecule alone can lead

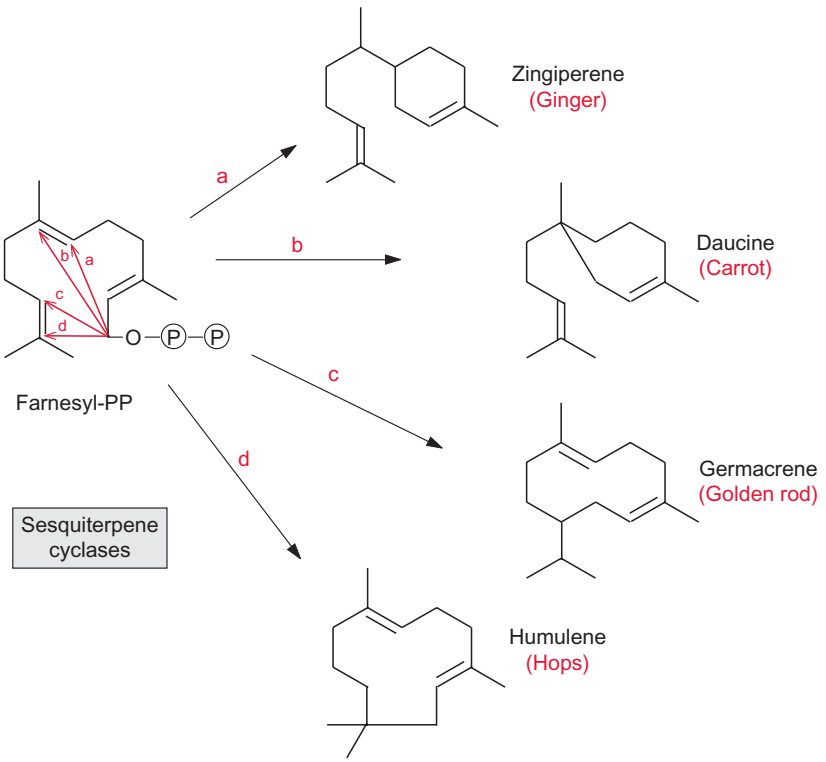
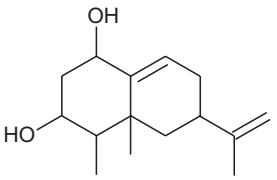


Figure 17.9 Without rearrangement of the double bonds there are four different possibilities for the cyclization of farnesyl pyrophosphate.



Capsidiol

Figure 17.10 Some sesquiterpenes.

to four different products. The number of possible products is multiplied by simultaneous rearrangements. Sesquiterpenes form the largest group of isoprenoids; they comprise more than 200 different ring structures. The sesquiterpenes include many aromatic compounds such as valencene of oranges, caryophyllene of carnations and several constituents of hops and eucalyptus oil. Capsidiol (Fig. 17.10), a phytoalexin (section 16.1) synthesized in pepper and tobacco, is a sesquiterpene.

Steroids are synthesized from farnesyl pyrophosphate

The triterpene squalene is formed from two molecules of farnesyl-PP by an NADPH-dependent **reductive head-to-head condensation** (Fig. 17.11). Squalene is the precursor for membrane constituents such as cholesterol and sitosterol, the functions of which have been discussed in section 15.1, and also for **brassinosteroids**, which function as phytohormones (section 19.8).

A class of glucosylated steroids, named **saponins** because of their soap-like properties (Fig. 17.12), functions in plants as toxins against herbivores and fungi. The glucosyl moiety of the saponins consists of a branched oligosaccharide built from glucose, galactose, xylose, and other hexoses. The hydrophilic polysaccharide chain and the hydrophobic steroid give the saponins the properties of a **detergent**. Saponins are toxic, as they dissolve the plasma membranes of fungi and cause hemolysis of the red blood cells in animals. Some grasses contain saponins and are therefore a hazard for grazing cattle. **Yamonin**, a saponin from the yam plant (*Dioscorea*), is used in the pharmaceutical industry as a precursor for the synthesis of progesterones, a component of contraceptive pills. A number of very toxic glucosylated steroids called **cardenolides**, which inhibit the **Na^+/K^+ pump** present in animals, also belong to the saponins. A well-known member of this class of compounds is **digitoxigenin** (Fig. 17.12), a poison from foxglove. Larvae of certain butterflies can ingest cardenolides without being harmed. They store these compounds, which then make them poisonous for birds. In low doses, cardenolides are widely used as a medicine against heart disease. Other plant defense substances are the **phytoecdysones**, a

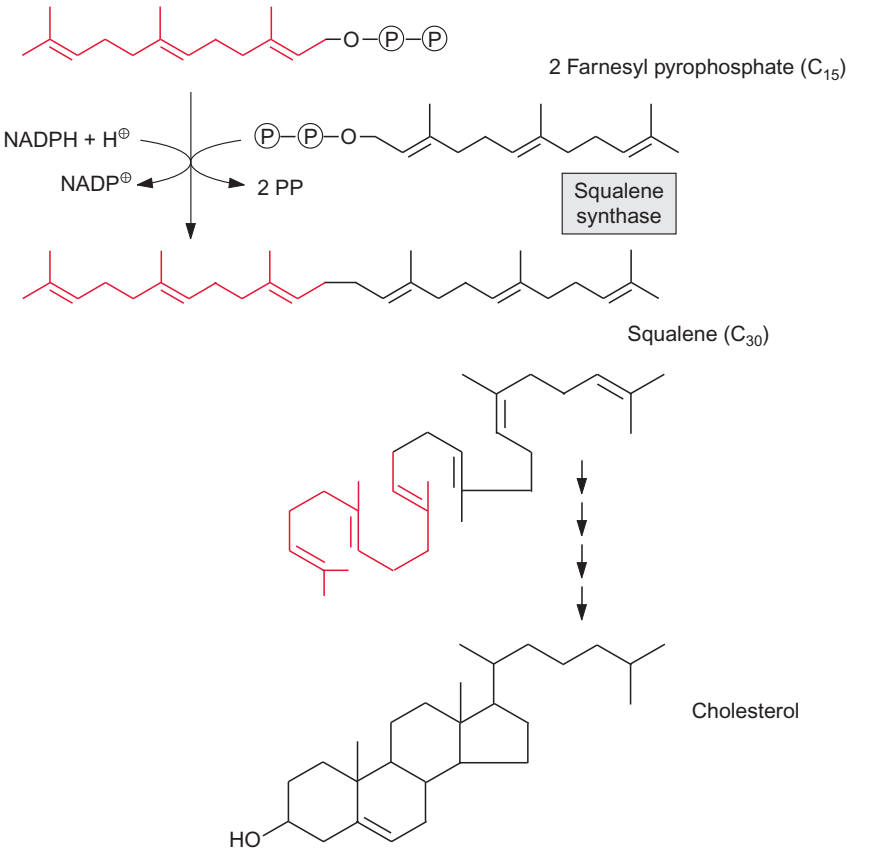


Figure 17.11 Squalene is formed from two farnesyl-PP molecules by head-to-head addition, accompanied by a reduction. After the introduction of an -OH group by a monooxygenase and cyclizations, cholesterol is formed in several reaction steps.

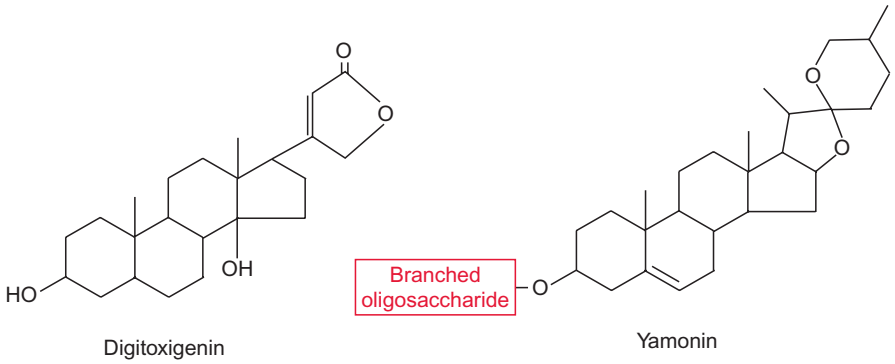


Figure 17.12 Digitoxigenin, a cardenolide, and yamonin, a saponin.

group of steroids with a structure similar to that of the insect hormone ecdysone. Ecdysone controls the pupation of larvae. When insects eat plants which accumulate phytoecdysone, the pupation process is disturbed and the larvae die.

17.6 Geranylgeranyl pyrophosphate is the precursor for defense compounds, phytohormones, and carotenoids

The cyclization of geranylgeranyl-PP leads to the formation of the diterpene casbene (Fig. 17.13). Casbene is a phytoalexin (section 16.1) of castor bean (*Ricinus communis*). The diterpene phorbol is an ester in the latex of plants of the spurge family (*Euphorbiae*). Phorbol acts as a toxin against herbivores; even skin contact causes severe inflammation. Since phorbol esters induce the formation of tumors, they are widely used in medical research. Geranylgeranyl-PP is also the precursor for the synthesis of gibberellins, a group of phytohormones (section 19.4).

Oleoresins protect trees from parasites

In forests of the temperate zone, conifers are widely spread and often reach an old age, some species being far over 1,000 years old. This demonstrates that conifers have been very successful in protecting themselves from browsing enemies. One of the greatest threats is the bark beetle, which not only causes damage itself, but also opens the destroyed bark to fungal infections.

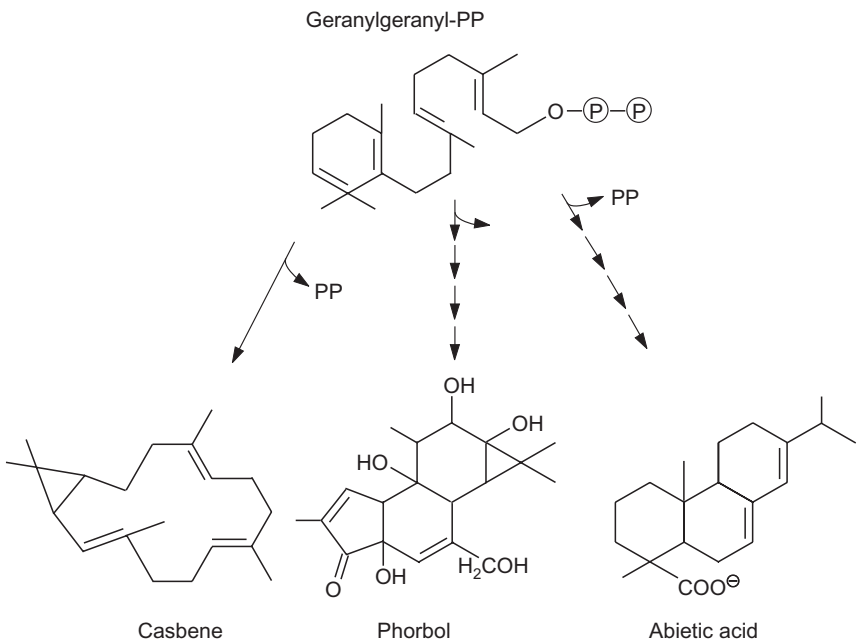


Figure 17.13 The phytoalexin casbene is formed in one step by cyclization from geranylgeranyl pyrophosphate. The synthesis of the defense compound phorbol requires several steps, including hydroxylations, some of which are catalyzed by monooxygenases. Abietic acid, which is also synthesized from geranylgeranyl pyrophosphate, is one of the main components of oleoresins.

To protect themselves, the trees secrete **oleoresins** (tree resins), which seal the wound site and kill insects and fungi. The conifer oleoresins are a complex mixture of terpenoids, about half of which consist of a volatile **turpentine fraction** (many monoterpenes and some sesquiterpenes) and the other half of a non-volatile **rosin fraction** (diterpenes). The turpentine fraction contains a number of compounds that are toxic for insects and fungi (e.g., **limonene** (Fig. 17.5)). The rosin fraction is comprised of resin acids, the main component of which is **abietic acid** (Fig. 17.13). When the tree is wounded, stored oleoresin leaks through channels or is synthesized directly at the infected sites. It is presently being investigated how the toxic properties of the different components of the oleoresins affect different insects and fungi. Scientists are hopeful that such knowledge will make it possible to employ genetic engineering to enhance the parasite resistance of trees growing in large forests.

Carotene synthesis delivers pigments to plants and provides an important vitamin for humans

The function of **carotenoids** in photosynthesis has been discussed in detail in Chapters 2 and 3. Additionally, carotenoids function as pigments, e.g., in flowers and fruits (tomato, bell pepper). The synthesis of carotenoids requires two molecules of geranylgeranyl-PP, which, as in the synthesis of squalene, are linked by head-to-head condensation (Fig. 17.14). Upon release of the first pyrophosphate, the intermediate pre-phytoene pyrophosphate is formed, and the subsequent release of the second pyrophosphate results in the formation of **phytoene**, where the two prenyl residues are linked to each other by a carbon-carbon double bond. Catalyzed by two different desaturases, phytoene is converted to **lycopene**. According to recent results, these desaturations proceed via dehydrogenation reactions, in which hydrogen is transferred via FAD to O_2. Cyclization of lycopene then results in the formation of **β-carotene**. Another cyclase generates α-carotene. The hydroxylation of β-carotene leads to the xanthophyll **zeaxanthin**. The formation of the xanthophyll violaxanthin from zeaxanthin is described in Figure 3.41.

β-Carotene is the precursor for the synthesis of the visual pigment **rhodopsin**. Since β-carotene cannot be synthesized by humans, it is as **provitaminA** an essential part of the human diet. Hundreds of millions of people, especially in Asia, where rice dominates the diet and there is a lack of β-carotene in the food supply, suffer from severe provitaminA deficiency. Because of this, many children become blind. A recent success was the introduction of all the enzymes of the synthesis pathway from geranylgeranyl pyrophosphate to β-carotene into the endosperm of rice grains by genetic engineering. These transgenic rice lines produce β-carotene containing grains, with a yellowish color, and have therefore been called "**golden**

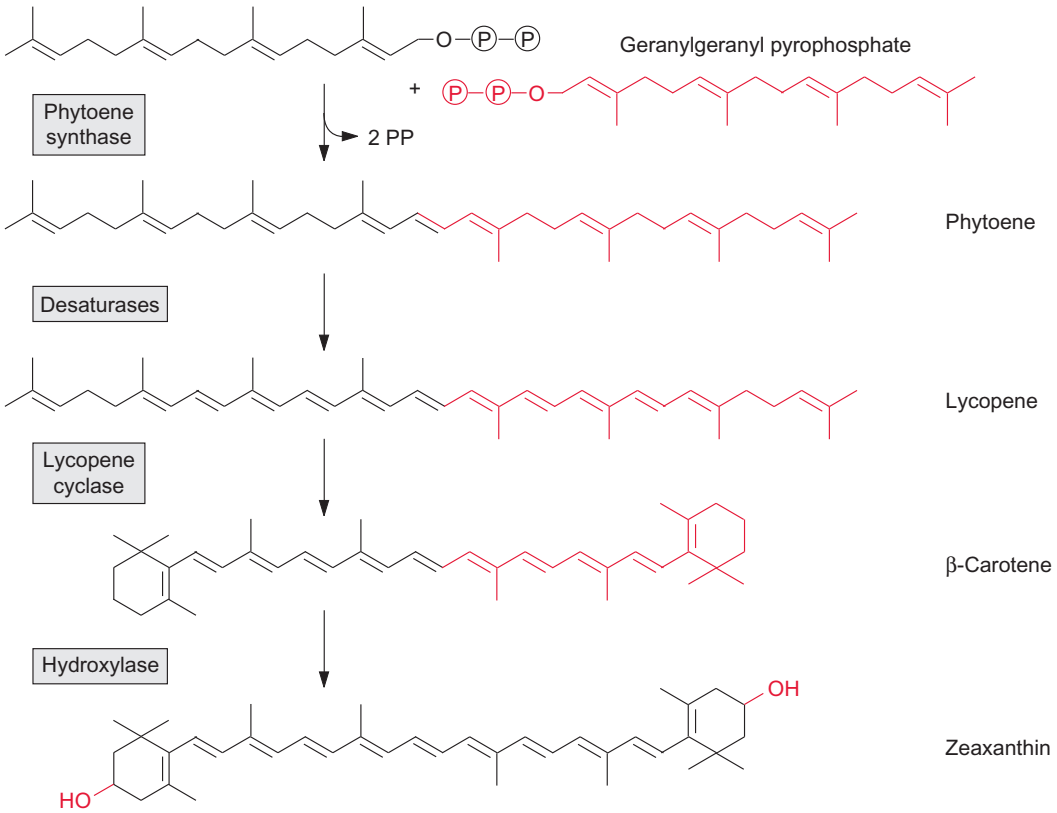


Figure 17.14 Carotenoid biosynthesis. The phytoene synthase catalyzes the head-to-head addition of two molecules of geranylgeranyl-PP to phytoene. The latter is converted by desaturases with neurosporene as the intermediate (not shown) to lycopene. β-Carotene is formed by cyclization and zeaxanthin by additional hydroxylation.

rice." Non-profit organizations have placed these transgenic rice lines at the disposal of many breeding stations in Asian countries, where they are at present crossed with local rice varieties. It is hoped that the serious provitaminA deficiency in wide parts of the world populations can be overcome through the cultivation of "golden rice."

17.7 A Prenyl chain renders compounds lipid-soluble

Ubiquinone (Fig. 3.5), plastoquinone (Fig. 3.19), and cytochrome-*a* (Fig. 3.24) are anchored in membranes by isoprenoid chains of various sizes. At the biosynthesis of these electron carriers, the **prenyl chains** are

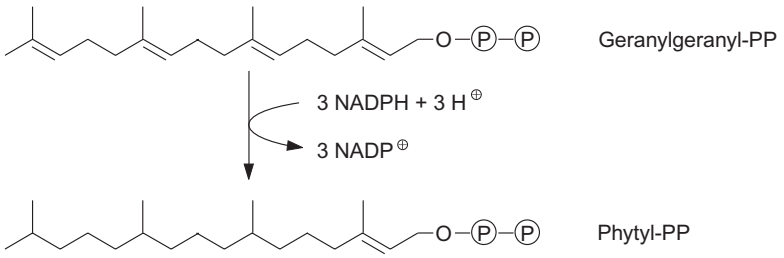


Figure 17.15 Synthesis of phytyl-PP from geranylgeranyl-PP.

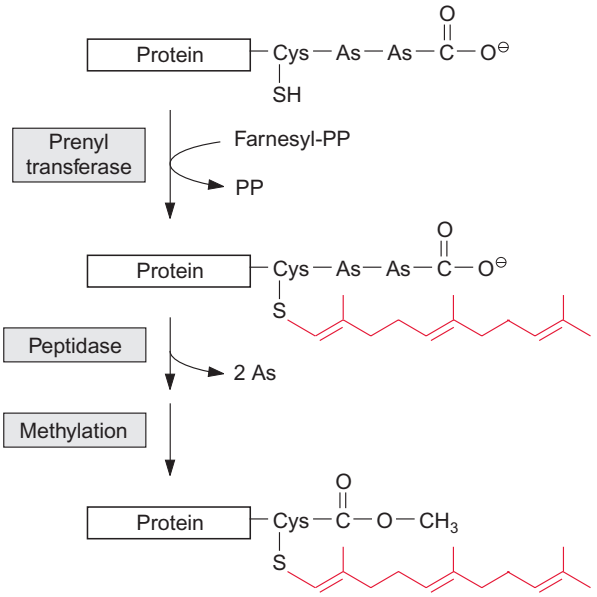


Figure 17.16 Prenylation of a protein. A farnesyl residue is transferred to the -SH group of a cysteine residue at the C terminus of the protein by a prenyl transferase. After hydrolytic release of the terminal amino acids (AS), the carboxyl group of the cysteine is methylated. The prenyl residue provides the protein with a membrane anchor.

introduced from prenyl phosphates by reactions similar to those catalyzed by **prenyl transferases**. Chlorophyll (Fig. 2.4), tocopherols, and phylloquinone (Fig. 3.32), on the other hand, contain phytol side chains. These are synthesized from geranylgeranyl-PP by reduction with NADPH and are incorporated correspondingly (Fig. 17.15).

Proteins can be anchored in a membrane by prenylation

A large number of membrane proteins present in yeast and animals possess a characteristic C terminal sequence with a cysteine, which binds a farnesyl or geranyl residue via a thioether (Fig. 17.16). The connection of these molecules is catalyzed by a specific prenyl transferase. In many cases, the terminal amino acids following the cysteine residue are eliminated after

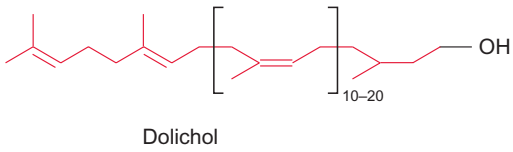


Figure 17.17 Dolichol, a polyprenol.

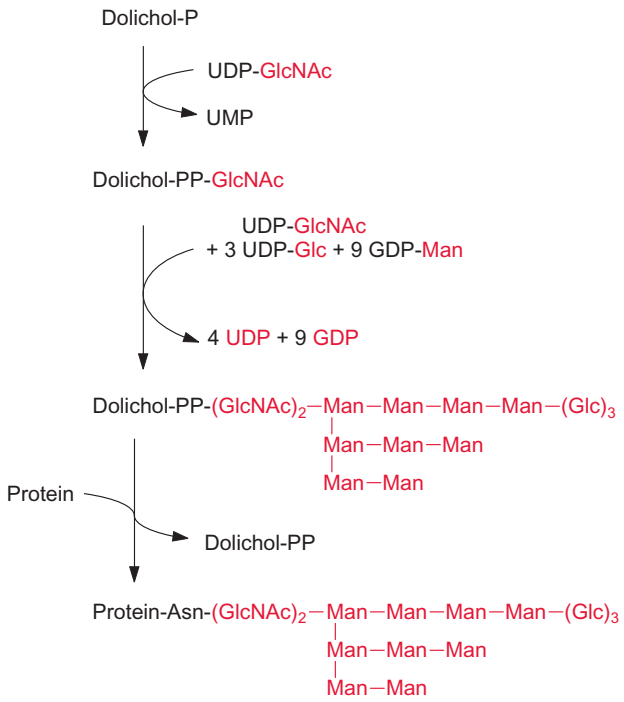


Figure 17.18 Dolichol as glucosyl carrier. For the synthesis of a branched oligosaccharide, successively sugar moieties are added from *N*-acetylglucosamine (GlcNAc), the corresponding UDP- and GDP-hexoses mannose (Man) and glucose (Glc) to dolichol. The first *N*-acetylglucose residue is attached to the -OH group of the dolichol via a pyrophosphate group. The complete oligosaccharide is then transferred to an asparagine residue of a protein. Asn = asparagine.

prenylation by a peptidase, and the carboxylic group of the cysteine is methylated. Prenylation and methylation modify the protein so that it becomes lipid-soluble and can be anchored in a membrane. Recent results indicate that this prenylation of proteins plays important roles in plants.

Dolichols mediate the glucosylation of proteins

Dolichols (Fig. 17.17) are isoprenoids with a very long chain length, occurring in the membranes of the endoplasmatic reticulum and the Golgi network. They have an important function in the **transfer of oligosaccharides**. Many membrane proteins and secretory proteins are *N*-glucosylated by branched oligosaccharide chains. This glucosylation proceeds in the endoplasmatic reticulum utilizing membrane-bound dolichol (Fig. 17.18). The oligosaccharide structure is successively synthesized at the dolichol molecule,

and after completion it is transferred to an asparagine residue of the protein to be glucosylated. By subsequent modification in the Golgi network, in which certain carbohydrate residues are split off and others are added, a large variety of oligosaccharide structures are generated.

17.8 The regulation of isoprenoid synthesis

In plants, isoprenoids are synthesized in different organs and tissues according to the specific demand. Large amounts of hydrophobic isoprenoids are synthesized in specialized tissues such as the glandular and epidermis cells of leaves and the osmophores of flowers. The enzymes for synthesis of isoprenoids are present in the plastids, the cytosol, and the mitochondria. Each of these cellular compartments is essentially self-sufficient with respect to its isoprenoid content. Some isoprenoids, such as the phytohormone gibberellic acid, are synthesized in the plastids and then supplied to the cytosol of the cell. As mentioned in section 17.2, the various prenyl pyrophosphates, from which all the other isoprenoids are derived, are synthesized by different enzymes.

This spatial distribution of the synthetic pathways makes it possible that, despite their very large diversity, the different isoprenoids synthesized by basically similar processes, can be efficiently controlled in their rate of synthesis via regulation of the corresponding enzyme activities (e.g., terpene synthases) in the various compartments. Results so far indicate that the synthesis of the different isoprenoids is regulated primarily at the level of gene expression. This is especially obvious when, after infections or wounding, the isoprenoid metabolism is very rapidly activated by elicitor-controlled gene expression (section 16.1). Competition may occur between isoprenoid synthesis for maintenance and for defense. In tobacco, for instance, the fungal elicitor induced phytoalexin synthesis blocks steroid synthesis. In such a case, the cell focuses its capacity for isoprenoid synthesis on defense.

17.9 Isoprenoids are very stable and persistent substances

Little is known about the catabolism of isoprenoids in plants. Biologically active compounds, such as phytohormones, are converted by the introduction of additional hydroxyl groups and glucosylation into inactive derivatives,

which are often deposited in the vacuole. It is questionable whether, after degradation, isoprenoids can be recycled in a plant. Some isoprenoids are remarkably stable. Large amounts of isoprenoids are found as relics of early life in practically all sedimentary rocks as well as in crude oil. In archaebacteria, the plasma membranes contain glycerol ethers with isoprenoid chains instead of fatty acid glycerol esters. Isoprenoids are probably constituents of very early forms of life.

Further reading

Eisenreich, W., Rohdich, F., Bacher, A. Deoxyxylulose phosphate pathway. Trends in Plant Science 6, 78–84 (2001).

Hirschberg, J. Carotinoid biosynthesis in flowering plants. Current Opinion in Plant Biology 4, 210–218 (2001).

Holopainen, J. K. Multiple functions of inducible plant volatiles. Trends in Plant Science 9, 529–533 (2004).

Hunter, W. N. The non-mevalonate pathway of isoprenoid precursor biosynthesis. Journal Biological Chemistry 282, 21573–21577 (2007).

Knudsen, J. T., Eriksson, R., Gershenzon, J., Stahl, B. Diversity and distribution of floral scent. The Botanical Review 72, 1–120 (2006).

Lichtenthaler, H. K. The 1-deoxy-D-xylulose-5-phosphate pathway of isoprenoid biosynthesis in plants. Annual Review of Plant Physiology and Plant Molecular Biology 50, 47–65 (1999).

Lichtenthaler, H. K. Biosynthesis, accumulation and emission of carotenoids, alpha-tocopherol, plastoquinone, and isoprene in leaves under high photosynthetic irradiance. Photosynthesis Research 92, 163–179 (2007).

McGarvey, D. J., Croteau, R. Terpenoid metabolism. The Plant Cell 7, 1015–1026 (1995).

Osbourn, A. Saponins and plant defence—a soap story. Trends in Plant Science 1, 4–9 (1996).

Peñueales, J., Munné-Bosch, S. Isoprenoids: an evolutionary pool for photoprotection. Trends in Plant Science 10, 166–169 (2005).

Roeder, S., Hartmann, A. M., Effmert, U., Piechulla, B. Regulation of simultaneous synthesis of floral scent terpenoids by the 1.8 cineole synthase of *Nicotiana suaveolens*. Plant Molecular Biology 65, 107–124 (2007).

Römer, S., Fraser, P. D. Recent advances in carotenoid biosynthesis, regulation and manipulation. Planta 221, 305–308 (2005).

Sharkey, T. D., Wiberley, A. E., Donohue, A. R. Isoprene emission from plants: Why and how. Annals Botany (London) 101, 5–18 (2008).

Strack, D., Fester, T. Isoprenoid metabolism and plastid reorganization in arbuscular mycorrhizal roots. New Phytologist 172, 22–34 (2006).

Tholl, D. Terpene synthases and the regulation, diversity and biological roles of terpene metabolism. Current Opinion Plant Biology 9, 297–304 (2006).

Trapp, S., Croteau, R. Defensive resin biosynthesis in conifers. Annual Review of Plant Physiology and Plant Molecular Biology 52, 689–724 (2001).

Ye, X., Al-Babili, S., Kloeti, A., Thang, J., Lucca, P., Beyer, P., Potrykus, I. Engineering the provitamin A (β-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 287, 303–305 (2000).

18

Phenylpropanoids comprise a multitude of plant secondary metabolites and cell wall components

Plants contain a large variety of phenolic derivatives, which contain a phenyl ring and a C_3 side chain and are collectively termed **phenylpropanoids**. As well as simple phenols, these comprise flavonoids, stilbenes, tannins, lignans and lignin (Fig. 18.1). Together with long chain carboxylic acids, phenylpropanoids are also components of suberin and cutin. These rather structurally divergent compounds have important functions as antibiotics, natural pesticides, signal substances for the establishment of symbiosis with rhizobia, attractants for pollinators, protective agents against ultraviolet (UV) light, insulating materials to make cell walls impermeable to gases and water, and structural material to assist plant stability (Table 18.1). All these substances are derived from phenylalanine, and in some plants also from tyrosine. Phenylalanine and tyrosine are synthesized by the **shikimate pathway**, described in section 10.4. The flavonoids, including flavones,

Table 18.1: Some functions of phenylpropanoids

Coumarins	Antibiotics, toxins against browsing animals
Lignan	Antibiotics, toxins against browsing animals
Lignin	Cell wall constituent
Suberin and cutin	Formation of impermeable layers
Stilbenes	Antibiotics, especially fungicides
Flavonoids	Antibiotics, signal for interaction with symbionts, flower pigments, light protection substances
Tannin	Tannins, fungicides, protection against herbivores