

Review

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A brief overview on the development of wood research

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Abstract: Wood science covers in particular the areas of the formation and composition as well as the chemical, biological and physical-mechanical properties of wood. First comprehensive studies have already been published in the last century. Detailed knowledge of wood is required for the processing of wood, the production of wood-based materials, and the utilization of wood and wood-based materials as buildings and various other products such as furniture. This review gives a brief overview on the progress in wood chemistry, wood biology (including photosynthesis and biodeterioration), and physical-mechanical properties of wood and wood-based materials. These fundamentals are also essential for understanding technological processes and product development.

Keywords: historical development; institutions; wood biology; wood chemistry; wood physics; wood science.

1 A short introduction to wood science

Wood is one of the most remarkable natural products and has been used by humans for thousands of years. With the development of powerful civilizations in ancient times, wood played an important role in their daily life

and the demand for wood for buildings, as fuel, for the construction of ships, etc. was constantly increasing. Over time, this led to severe regional and transregional deforestation, as in Mesopotamia in the Middle East or in the Mediterranean region during the ancient Greek and Roman eras (Dotterweich 2013; Hughes 2011; Kaplan et al. 2009), followed by soil erosion, karstification or even desertification. Later, especially in the seventeenth and eighteenth century, an increasing demand for construction, the mining industry, as firewood in Central Europe as well as an increasing conversion of forest land into farm land led to a dramatic decline in forested areas. As a consequence, these devastating environmental changes were accompanied by massive timber shortages. Hans Carl von Carlowitz (1645–1714) developed the visionary concept of sustainability with the reforestation of cleared forest sites to ensure production of sufficient quantities of timber for the future. At the transition from the eighteenth to the nineteenth century, the importance of forest management knowledge and establishment of sustainability strategies led to the foundation of the first academic forestry institutions in several European countries such as in Russia, France, Germany, Sweden and former Austria-Hungary. At this time, basic knowledge in wood science was increasingly included in forestry education programmes. Kisser et al. (1967) provided details on the historical development of wood anatomy with numerous pioneering contributions already from the nineteenth century, followed by excellent microscopic descriptions in the first half of the twentieth century. Until the early twentieth century, however, there was no targeted wood research with corresponding research institutes. Research was still more or less focused on forestry and forest utilization. According to Köstler et al. (1960), modern wood research began in 1910 with the foundation of the Forest Products Laboratory in Madison/Wisconsin in the United States (see book on 100 years FPL Madison), see also Anderson (2010). Earlier, in 1906, a Forest Products Research Institute was founded in Dehradun, India. In Germany, the first real wood research institute was founded in 1932 at the Technical University of Darmstadt and in 1934 as the Prussian Wood Research Institute in Eberswalde (later the “Reichsanstalt für

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Holzforschung”) under the direction of Franz Kollmann (1906–1987). At this time, numerous wood research institutes were established in almost all industrialized countries (Table 1). Nowadays, wood science is subdivided in great detail, either into techniques such as molecular biology and its related biotechnological approaches, or into other specific areas adopted from botany, e.g., taxonomy, cell biology, physiology and pathology. Wood science education programs are in most cases part of

Bachelor and Master programmes at several universities worldwide with degrees directly in wood science or wood materials science, in sub-disciplines such as wood technology or in combination with other programmes such as forestry with a degree in forestry and wood science. In addition to these educational wood institutes, numerous wood research institutions were established, which are nowadays mostly integrated into larger units for research in the field of natural resources and they are associated

Table 1: Overview of wood research institutes in different countries (Niemz. 1993, Niemz and Sonderegger 2021).

Country	Year	Institute
India	1906	Forest Products Research Institute Dehradun
USA	1910	Forest Products Laboratory Madison/Wisconsin
Germany	1913	Institute of Wood and Pulp Chemistry Eberswalde (from 1934 Prussian Wood Research Institute, 1939 to 1945 «Reichsanstalt für Holzforschung» (German Central Institute for Wood Research)
Canada	1913	Forest Products Laboratory Montreal (since 1927 Ottawa)
	1918	Forest Products Laboratory Vancouver (since 2007: FPIInnovations Quebec and Vancouver)
Australia	1919	Forest Products Laboratory Melbourne
Great Britain	1920	Forest Products Laboratory Princes Risborough
Russia	1929	Institute for Wood Science and Technology Leningrad (St. Petersburg), strong orientation on wood chemistry with a Faculty of Wood Chemistry
Latvia (former Soviet Union)	1946	Latvian Academy of Sciences, Institute of Wood Chemistry (coordinated all wood chemistry research in former Soviet Union)
Russia	1932	Union Research and Development Association “Soyuzmetdrewprom” Arkhangelsk (with the Research Institute of Mechanical Processing of Wood (ZNIIMOD)), today: Nautschdrewprom-ZNIIMOD Arkhangelsk
France	1933	Institut National du Bois Paris (French National Wood Research Institute)
Finland	1942	Laboratory of Wood Technology Helsinki
Switzerland	1943	Wood Department of the Swiss Federal Laboratories for Materials Testing Zurich (today: Cellulose & Wood Materials, EMPA, Dübendorf)
Sweden	1944	Svenska Träforskningsinstitutet (STFI), [Swedish Forest Products Research Laboratory], Stockholm. The Swedish Institute of Wood Technology Research (TRÅTEK), today a part of RISE – Research Institutes of Sweden.
Germany	1946	Institute for Wood Research of the Association for Technical Wood Questions (Verein für technische Holzfragen e. V. Braunschweig), today: Fraunhofer Institute for Wood Research (WKI)
Slovakia	1947	State Wood Research Institute Bratislava (no longer exists in this form, today part of the Institute for Paper Technology)
New Zealand	1947	Forest Research Institute, Rotorua (today: Scion)
Germany	1950	Federal Institute for Forestry and Forest Products, Reinbek near Hamburg (today: Thünen Institute with its Institute of Wood Research, Hamburg) in cooperation with the University of Hamburg
	1952	Institute for Wood Technology and Fibers Dresden, today: Institute for Wood Technology Dresden (Institut für Holztechnologie Dresden (IHD))
Austria	1953	Austrian Wood Research Institute Vienna (today: Holzforschung Austria)
Germany	1954	Institute for Wood Research and Wood Technology at the University of Munich (today: Wood Research Munich (Technical University Munich))
Russia	1962	VNIIDrev (Union Research and Production Association), then in addition 1971 “Sojusnautschplitprom” Podreskowo (with the research institute Balabanowo), since 1990: Institute for the planning of facilities for wood-based materials “NIPKIDREVPLIT” Podreskowo
Worldwide	Since about 1960	Founding of research institutes in the field of wood research at many universities and also universities of applied science (Institute of Wood Technology and Renewable Resources of the University of Natural Resources and Life Sciences Vienna (today in Tulln) Austria; ENSTIB, Epinal, France; University of British Columbia, Vancouver/Canada; University of Laval/Canada; University of Maine/USA; Oregon State University; Bern University of Applied Sciences, Biel/Switzerland; Chinese Academy of Forestry in Beijing, Universities in Nanjing, Kunming, Harbin/China, etc. Considerable research capacities are also available in Japan (e.g., universities in Nagoya and Kyoto), as well as in South Korea, New Zealand, Australia, Brazil and Chile. Large wood research areas are also established at the universities in the former Eastern European countries (Poland, Hungary, Czech Republic, Slovakia, Romania, Bulgaria, Serbia, Slovenia and other countries)

with units for, e.g., forestry, agriculture, geology, or even fisheries. These often national institutes provide science-based support for policy and decision-makers, are involved in monitoring activities and represent their countries in international scientific commissions.

2 Wood chemistry

Wood chemistry is primarily concerned with the chemical compounds that make up wood, particularly the xylem. These compounds are structural polymers (“lignocellulose”) of the cell wall (cellulose, hemicelluloses, lignin) and various low molecular weight compounds (mostly organic), the extractives. The most important extractives (phenolics, terpenoids) are secondary plant compounds that can strongly influence the properties of wood. Primary plant compounds, which mostly occur in lumens of living wood cells (parenchyma cells), may also determine the wood properties, but are less considered in wood chemistry.

The French chemist Anselme Payen (1795–1871) coined the term *cellulose* in 1838 (Payen 1938) (Figure 1). In the years 1837–1842, he discovered that all plants contain a white substance with the same composition as starch (about 44% carbon, 6% hydrogen, and 49% oxygen) and distinguished between “la cellulose” und “l’incrustation ligneuse”. He also found cellulose in cotton and decomposed it into glucose *via* sulfuric acid hydrolysis. Emil Fischer (1852–1919, Nobel Prize in 1902) at the University of Berlin (nowadays Humboldt University, Germany) performed pioneering work in the area of sugar chemistry. In 1891, he elucidated the structure of D-glucose, D-mannose and D-arabinose and the stereochemistry of sugars. Fischer developed the nomenclature of linear monosaccharides (“Fischer nomenclature”) and the three-dimensional presentation method (“Fischer projection”). Walter Norman Haworth (1883–1950, Nobel Prize in 1937) at the University of Birmingham (UK) elucidated the ring (glucopyranose) structure of the sugar units in the polysaccharides and developed the three-dimensional presentation method of five- and six-membered monosaccharide rings (“Haworth-projection”). Karl Freudenberg at the University of Heidelberg (1886–1983) and Haworth provided strong evidence for the β -1,4-glycosidic linkages in cellulose. Hermann Staudinger (1881–1965, Nobel Prize in 1953), the father of polymer chemistry at the University of Freiburg (Germany), established the polymeric structure and the final chain conformation of cellulose. He and his co-worker H. Eilers found that the structural difference between cellulose and starch relies on the conformation of the

anomeric glucose unit, which leads to α -glycosidic (starch) and β -glycosidic bonds (cellulose) (Staudinger and Eilers 1936). The elucidation of the crystalline structure of cellulose began with the development of X-ray crystallography by Max von Laue in Germany (Nobel Prize in 1914). In 1913, Shōji Nishikawa (1884–1952) and his fellow student S. Ono in Japan were the first who showed that cellulose exhibits definite diffraction rings formed by rod-like shaped crystallites and Nishikawa later postulated the discontinuous nature of cellulose (Nishikawa and Ono 1913). Reginald Herzog and his collaborator Willi Jancke at the Kaiser Wilhelm Institute for Fibre Chemistry in Berlin (Germany) used the Debye–Scherrer-procedure to confirm the crystalline structure of cellulose in widely different sources such as cotton, ramie, wood, jute, and flax, which has become commonly known as the “native” cellulose form (Hon 1994). In the 1920th, Michael Polanyi at the Kaiser Wilhelm Institute for Fibre Chemistry in Berlin, Olenus Lee Sponsler at the University of California in Los Angeles (USA) and Haworth (1928) have published early intensive studies on the composition of cellulose and on its elementary unit cell. In 1928/29, Meyer and Mark were the first to postulate a monoclinic unit cell for native cellulose. Albert Frey-Wyssling at ETH Zürich (Switzerland) has developed a frequently cited model for the ultra-structure of cellulose and studied the orientation of microfibrils in the different cell wall layers of wood. He described distinct crystalline and amorphous sections in native cellulose. In contrast, Reginald D. Preston at the University of Leeds (UK) postulated that native cellulose is a continuous crystalline polymer with occasional dislocations (lattice distortions), meaning that the amorphous parts do not form discrete domains. In 1937, Kurt H. Meyer and Lore Misch at the University of Geneva (Switzerland) determined the dimensions of the unit cell of ramie cellulose by X-ray diffractometry (Meyer and Misch 1937). In their model, the glucan chains are located at the four edges of the unit cell and run in one direction (parallel), while the central chain runs in the opposite direction (anti-parallel) (Gardner and Blackwall 1974). In 1974, however, the groups of Anatole Sarko at SUNY ESF (College of Environmental Science and Forestry), Syracuse (USA) and John Blackwell at the Case Western Reserve University, Cleveland (USA) showed independently that all the chains in the unit cell of native cellulose run parallel. For regenerated celluloses (cellulose II), however, both groups reported an anti-parallel orientation of the centre chain, which is now both widely accepted.

In 1984, Rajai H. Atalla at the Institute of Paper Chemistry, Appleton (USA) and David L. Vanderhart of the National Bureau of Standards, Washington (USA) first



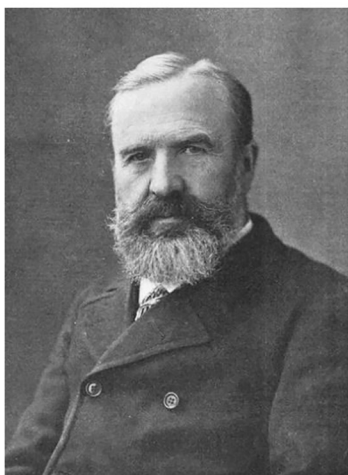
Augustin-Pyrame de Candolle
(1778-1841)



Anselme Payen
(1795-1871)



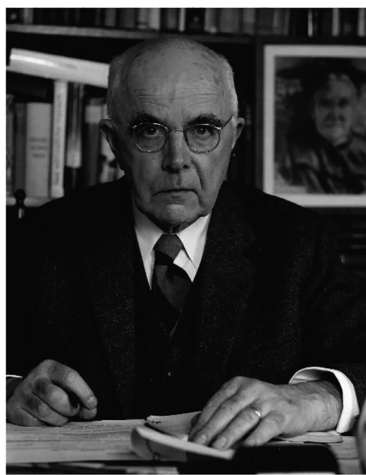
Ernst Schulze
(1840-1912)



Peter Klason
(1848-1937)



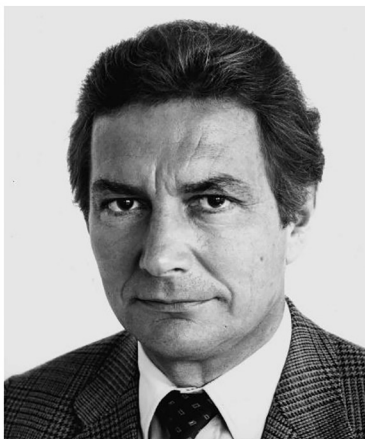
Hermann Staudinger
(1881-1965)



Karl Freudenberg
(1886-1983)



Takayoshi Higuchi
(1927-2017)



Horst Nimz
(1930-2013)



Gösta Brunow
(1936-2013)

Figure 1: Selected scientists from the field of wood chemistry. Copyright: *Freudenberg*: Archive of Freudenberg & Co. KG Weinheim/Germany; *Higuchi*: courtesy of Satoru Tsuchikawa, Kyoto University/Japan; *Brunow*: courtesy of Stefan Brunow, Sweden; all others: Wikimedia Commons.

reported the existence of two distinct crystalline forms of native cellulose based on ^{13}C -NMR data – cellulose I_α (dominant in bacteria and algae) and cellulose I_β (dominant in higher plants such as wood). In 1992, Shiro Kobayashi and Shin-ichiro Shoda from the Tohoku University in Sendai (Japan) reported the first synthesis of cellulose *via* a non-biosynthetic path by using β -D-cellobiosyl fluoride as substrate for cellulose in an organic solvent mixture (Kobashi et al. 1992).

The industrial exploitation of cellulose fibres from wood (mostly together with the hemicelluloses) relies on chemical pulping according to the sulphite process and the sulphate process. The sulphite process using calcium bisulphite was first patented by Benjamin Chew Tilghman (USA) in 1867. Based on studies of Carl Daniel Ekman, the first industrial magnesium sulphite pulp mill started operation at Bergvik, Sweden. The first calcium sulphite pulp mill in Germany started production in Hannoversch Münden in 1879 based on the developments of Alexander Mitscherlich. Sulphate cooking was invented by Carl F. Dahl in 1879 in Danzig, Prussia (then Germany), who called it “kraft” process from the Germany word *Kraft* (strength). In 1890, the process was first applied in a pulp mill in Sweden.

In addition to the utilization of cellulose for paper production, regenerated cellulose and cellulose derivatives have been produced from dissolving pulp after about 1850. This class of products provided basic materials for the textile and chemical industry. In 1857, Matthias E. Schweizer (1818–1860) at the University of Zürich (Switzerland) discovered that cellulose dissolves in aqueous tetraamine-copper-(II)-hydroxid (cuprammonium solution, also called Schweizer’s reagent). Max Fremery and Johann Urban filed a patent in 1897 on the procedure to gain filaments from this solution by reprecipitation of the cellulose, but initially only used the filaments in light bulbs. In 1899, the industrial production of cuprammonium rayon (“Cupro”) for textiles started in the Vereinigte Glanzstoff-Fabriken AG in Wuppertal-Elberfeld (Germany). In 1901, Edmund Thiele developed a spinning process at the J. P. Bemberg AG in Wuppertal-Oberbarmen (Germany) to produce “artificial silk” based on the cuprammonium process. Charles Frederick Cross, Edward John Bevan and Clayton Beadle patented the viscose process (“viscose” due to the highly viscous mixture) to produce “artificial silk” in 1894. The process is based on solubilisation of cellulose as cellulose xanthate and subsequent reprecipitation. The company Courtaulds Fibres (UK) produced the first commercial viscose rayon in 1905. The development of the Lyocell process, which relies on dissolving bleached wood pulp, started in 1972 at the American Enka Company, Enka (USA).

The first cellulose derivative was nitrocellulose (cellulose nitrate) produced with nitric acid. Its unstable precursor “xyloidine” was first synthesized in 1832 by the French chemist Henri Braconnot. In 1845, Christian Schönbein in Germany was able to produce the first stable nitrocellulose using a mixture of nitric acid and sulfuric acid. Georges Audemars in France produced the first cellulose textile fibre by using solutions of nitrocellulose in alcohol-ether mixtures in 1855 and called it “rayon”. In 1889, the French chemist Hilaire de Chardonnet patented a nitrocellulose fibre marketed as “artificial silk”. Commercial production of Chardonnet’s silk started in 1891. In 1869, John W. Hyatt (USA) developed celluloid, a nitrocellulose softened with camphor and obtained the patent to produce billiard balls from celluloid. The French chemist Paul Schützenberger produced the first cellulose acetate by reaction of cotton with acetic anhydride in 1865. The process was further developed by the Dutch chemist Antoine Paul Nicolas Franchimont, who used sulfuric acid or zinc chloride as a catalyst in 1879. Other approaches of cellulose derivatisation involved graft-copolymerization of the cellulose backbone with synthetic polymers such as polystyrene or polyacrylonitrile. Vivian T. Stannett of North Carolina State University (USA) published early works in this area. The liquid crystalline behaviour of cellulose derivatives was studied by Derek G. Gray at McGill University, Montreal (Canada) and Peter Zugenmaier at Clausthal University of Technology (Germany) starting around 1982.

Research studies related to microcrystalline cellulose and nanocellulose started in the 1950s, when O. A. Battista at the Textile Research Institute, Princeton (USA) obtained microcrystalline cellulose by controlled hydrolysis of cellulose fibres and subsequent sonification treatment (Battista 1950). This led to the first commercialisation of microcrystalline cellulose.

At about the same time, B. Rånby from the Royal Institute of Technology (KTH), Stockholm (Sweden) for the first time reported the generation of colloidal suspensions of cellulose nanocrystals (one type of nanocellulose) after hydrolysis of cellulose. The production of microfibrillated cellulose (another type of nanocellulose) was first described in patents by F. W. Herrick and by A. F. Turbak and co-workers from the ITT Rayonier labs in Whippany (USA). The company commercialized the production of microfibrillated cellulose.

Today, the chemical and semi-crystalline structure of cellulose has been largely elucidated. Future basic research is therefore likely to focus primarily on the interactions of cellulose with other cell wall components and the elucidation of the three-dimensional cell wall structure. Further developments in instrumental analysis will play an

important role in this. Recent and expected future developments regarding the utilisation will focus on the functionalisation of cellulose, especially nanocellulose, to produce materials that are responsive and adaptive towards changing ambient conditions for medicine and engineering (“smart materials”). Novel innovative composites based on cellulose derivatives will be produced. In addition, research will continue into the targeted decomposition of polysaccharides to produce biofuels (“biorefinery”) and various platform chemicals.

The German chemist Ernst Schulze at the University of Zürich (Switzerland) first used the term *hemicelluloses* in 1891 (Schulze 1891) for all sugars of the plant cell wall that are released during hydrolysis by weak mineral acids, such as galactose, mannose, arabinose or xylose. Schulze falsely believed that these sugars were precursors to cellulose. Since the late 1950s, Tore E. Timell and his co-workers at the College of Forestry in Syracuse (USA) have elucidated the chemical composition and structure of hemicelluloses from softwoods (Timell 1967) (arabinoglucuronoxylans and galactoglucomannans) and hardwoods (glucuronoxylans and glucomannans). Several other researchers have studied hemicelluloses with respect to their chemical behaviour during alkaline sulphate pulping (e.g., its endwise degradation). Horace S. Isbell at the National Bureau of Standards, Washington D.C. (USA), Olof Samuelson at Chalmers University of Technology (Sweden), Kuniyoshi Shimizu at Kyushu University, Fukuoka (Japan) and Eero Sjöström at Helsinki University of Technology (Finland) provided significant findings in this area. As for cellulose, recent and possible future research fields are functionalisation, finding novel medical and technical applications (e.g., food amendments, gels, paper sizing agents) and targeted decomposition of hemicelluloses (biofuels, platform chemicals).

The term *lignin* was first introduced by the Swiss botanist Augustin Pyramus de Candolle (1778–1841) at the University of Geneva (Switzerland) in 1813 (de Candolle 1813). It derives from the Latin word for wood *lignum*. In 1856, Franz Ferdinand Schulze at the University of Rostock (Germany) used the term lignin for the non-hydrolysable constituent of wood (Schulze 1856). The beginnings of lignin chemistry date back to 1874, when Ferdinand Tieemann and Wilhelm Haarmann at the Friedrich-Wilhelms-University of Berlin (nowadays Humboldt-University of Berlin) isolated coniferin from the cambial sap of Norway spruce wood and developed a process to produce vanillin from coniferin. Around 1893, Peter Klason (1848–1937) began systematic studies on lignin chemistry at the KTH Royal Institute of Technology in Stockholm (Sweden). He was the first to suggest that lignin is a polymer of coniferyl

alcohol, which made him the “father of lignin chemistry”. Klason also developed the first method to determine the lignin content of wood (“Klason lignin”). Around 1933, Holgar Erdtman at the Stockholm University (Sweden) developed the idea that lignification proceeds *via* radical coupling of substances similar to coniferyl alcohol. He dehydrogenated isoeugenol with crude fungal extract (containing laccase) and identified a dimer with a phenylcumarane bond (β -5 bond). Based on Erdtman’s studies, Karl Freudenberg (1886–1983) at the University of Heidelberg (Germany) further elucidated the structure and synthesis of lignin (Freudenberg and Neish 1968). He and his co-workers were able to synthesise an artificial lignin (dehydrogenated product, DHP) from coniferyl alcohol using oxidative, radical-inducing enzymes (laccase, peroxidase), which displayed similar properties as lignin isolated from Norway spruce wood. Freudenberg distinguished two types of synthesis methods that produced different types of polymers by a free radical coupling mechanism: the “Zutropfexperiment” yielded an “end-wise” polymer and the “Zulaufexperiment” yielded a “bulk polymer”. Studies on the structure and constitution of lignin were continued in Germany by Horst Nimz at the Universities of Heidelberg, Karlsruhe and Hamburg. Nimz described the occurrence of the β -1 bond in lignin for the first time in 1965 (Nimz 1965), which was later shown to derive from a spirodienone structure by John Ralph’s group at the University of Wisconsin (USA).

In his study, Nimz collaborated with Hans-Dietrich Lüdemann from the University of Regensburg (Germany) who conducted the identification of lignin structures by Nuclear-Magnetic Resonance (NMR) spectroscopy. Several other researchers have further elucidated the structure and reactions of lignin by ^{13}C -NMR and other more advanced NMR techniques such as Charles H. Ludwig at Georgia Pacific Corporation Bellingham, Washington (USA), Josef Gierer at the Swedish Pulp and Paper Research Institute - STFI (Sweden), Larry Landucci at the USDA Forest Products Laboratory (USA), Josef Gratzl and Dimitris Argyropoulos at North Carolina State University (USA), Knut Lundquist at Chalmers University of Technology (Sweden) and John Ralph at the University of Wisconsin (USA). Oskar Faix at the Federal Research Institute for Forestry and Forest Products (now Thünen Institute of Wood Research in Hamburg (Germany) has done pioneering work on infrared (IR) spectroscopy. Another important method to analyse the composition of lignin is thioacidolysis developed by Catherine Lapierre at INRA (France) around 1985. In 1995, Gösta Brunow (1936–2013) and his co-workers from the University of Helsinki have first described the dibenzodioxocin (octagonal) structure in lignin (Karhunen

et al. 1995). Several groups have studied the structure, biosynthesis and fungal biodegradation of lignin such as Kyosti S. Sarkanen at the University of Washington (USA), David A. I. Goring at the Pulp and Paper Research Institute, Montreal (Canada), Takayoshi Higuchi at the University of Kyoto (Japan), Karl-Erik Erickson at STFI (Sweden) as well as the University of Georgia (USA), Kent Kirk at the USDA Forest Products Laboratory in Madison (WI), Michael H. Gold at the Oregon Graduate Institute of Science and Technology (USA), Bernard Monties and Bernard Kurek at INRA (France), Jean-Paul Joseleau and Katia Ruel at the University of Grenoble (France), as well as Wolfgang Fritzsche and Martin Hofrichter at the University of Jena (Hofrichter later at the International Graduate School Zittau), (Germany).

With the emergence of molecular biological methods, the research base on lignin biosynthesis has expanded considerably. Extensive research has been carried out by the groups of Wout Boerjan at Ghent University (Belgium) and Marie Baucher at the University of Brussels (Belgium). For a long time, the coupling of enzymatically induced radicals during lignification has been considered a random process in which the already formed polysaccharide matrix serves as a template. From 1995 to 2000, however, Norman G. Lewis and his co-workers at Washington State University (USA) sparked controversy when they postulated the existence of dirigent proteins that may exert a specific control over the lignification process. In recent years, lignin valorisation has become an increasingly important issue, as the emergence of lignin as a by-product will predictably increase due to the bio-economic utilization of all wood constituents. Several approaches to lignin utilisation have previously been elaborated. The groups of Horst Nimz in Hamburg, Alois Hüttermann at the University of Göttingen and Gerhard Kühne at the Technical University of Dresden (all Germany) were probably the first to produce particleboards with a lignin-based adhesive - the two latter by applying laccase as catalyst. Wolfgang Glasser at the Polytechnical Institute of Virginia (USA) is a pioneer in the field of chemical modification of lignin to produce graft-copolymers to form polyurethane foams, adhesives, and coatings (Glasser and Sarkanen 1989).

Recently, there has been a renaissance in lignin research driven by aim to produce biofuels from lignocellulose. For the future, further research efforts are expected with regard to the genetic modification of lignin as well as the investigation of lignin composition and the interaction of lignin with other cell wall components. As is already the case today, the valorisation of the technical lignin obtained as a by-product of pulp and biofuel will gain in importance in the future. Possible utilisations

of technical lignin are as polymer materials, carbon fibres, activated carbon, antioxidant, antimicrobial actives, biochemical and smart materials.

The use of wood *extractives* and tree exudates partly dates back to Neolithic times. Examples are exudates (as varnishes, lacquers, gums), tannins, dyes, perfumes, rubber, and medicines. Special types of extractives are “naval stores”, a term that has been used since the 17th century. These materials, derived from pine resin, were originally applied as tar and pitch used in building and maintaining wooden sailing ships (Hillis 1989). The major constituents of softwood resins belong to the chemical class of terpenes. Inspired by early studies of the French Chemist Pierre Eugène Marcelin Berthelot, August Kekulé (1829–1896) at the Universities of Gent (Belgium) and Bonn (Germany) coined the name “terpenes” for the hydrocarbons occurring in turpentine oil (German “Terpentin”) around 1860 (Dev 1989). Later on, the term was extended also to other related compounds (the isoprenoids). Since 1955, the term “terpenoid” has gradually become the preferred generic name for this chemical class. “Terpenoid” is nowadays used synonymously with “terpene”. Otto Wallach at the Universities of Bonn and Göttingen (Germany) conducted pioneer studies and elucidated the chemical structure of terpenes. He discovered that terpenes are composed of isoprene (C_5H_8) units and received the Nobel Prize in 1910. Wallach’s findings were published in the book “Terpene und Campher” (Wallach 1909). Another pioneer of terpene chemistry was Adolf von Baeyer (1835–1917, Nobel Prize in 1905) at the University of Munich (Germany), who conducted comprehensive investigations on cyclic terpenes. Friedrich Wilhelm Semmler at the Polytechnic University of Breslau (then Germany) for the first time elucidated the chemical formula of a sesquiterpene, santalene, in 1910. Based on earlier findings of Berthelot and Wallach, Leopold Ružička (Nobel Prize in 1939) at ETH Zürich (Switzerland) formulated the “biogenetic isoprene rule” for terpenes (isoprenoids) in 1922. In the field of isoprenoids, Ružička mainly studied the chemistry of higher terpenes and steroids. Feodor Lynen at the Max Planck Institute for Cell Chemistry (nowadays Max Planck Institute of Biochemistry) in Munich as well as the University of Munich (Germany) and Konrad Bloch at Harvard University in Cambridge (USA) elucidated the biosynthesis of terpenes. In 1964, both researchers received the Nobel Prize of Physiology of Medicine in equal shares.

Tannins are a major group of polyphenols that can strongly influence certain properties of wood such as dimensional stability and durability. The term “tannin” derives from the ability of these compounds to turn animal skin into leather. Most probably, the Ancient Greeks of the

archaic period (ca. 800–500 BC) first used this process with tannin preparations from oak galls. The structural elucidation of hydrolysable tannins started with the isolation of gallic acid from oak-galls by the Swedish chemist Carl Wilhelm Scheele in 1786. Gallic acid received its name from the French chemist Henri Braconnot (because of its origin from oak-galls), who also discovered ellagic acid and pyrogalllic acid in 1831 at the University of Nancy (France). Julius Löwe at the University of Gießen (Germany) succeeded in the first synthesis of ellagic acid from gallic acid in 1868. Maximilian Nierenstein at the University of Bristol isolated ellagic acid from oak bark and other sources in 1905. Emil Fischer, Max Bergmann und Karl Freudenberg at the University of Berlin (Germany) showed that hydrolysable tannins are derivatives of glucose and digallic acid. In 1920, Freudenberg divided the tannins into the flavonoid-derived condensed tannins and into hydrolysable tannins. He also discovered the catechin structure and the synthesis of epicatechin (both structural units in condensed tannins) in 1925. Richard Willstätter at the Kaiser-Wilhelm-Institute of Chemistry, Berlin (Germany) prepared pure anthocyanin in 1915 and Robert Robinson at the University of Oxford (UK) for the first time synthesised an anthocyanin in 1931.

After the Second World War, tannins and other polyphenols have been studied with increasing intensity in various plant-related scientific fields such as agriculture, ecology, food science and nutrition, and medicine rather than in wood science. Around 1950, Edgar Charles Bate-Smith and Tony Swain at the University of Cambridge (UK) investigated the phenolic constituents of plants using paper chromatography and suggested hexahydroxydiphenic acid to be part of the hydrolysable tannins. In 1956, Otto T. Schmidt and Walter Mayer at the University of Heidelberg (Germany) postulated that hexahydroxydiphenoyl esters are formed by oxidative coupling of galloyl ester groups. In 1951, Bate-Smith for the first time developed a coloration method to detect condensed tannins in plant materials. Early works of Bate-Smith and Swain as well as David G. Roux at the University of Orange Free State, Bloemfontein (South Africa) and of others revealed that condensed tannins are essentially polymers composed of flavanoid units. Tannins and other polyphenols have also been intensively studied by Edwin Haslam at the University of Sheffield (UK), who provided the first comprehensive definition of plant polyphenols referred to as the White–Bate-Smith–Swain–Haslam (WBSSH) definition in 1966 (Quideau 2011). In wood technology, tannins found practical application as adhesives with low formaldehyde emission for wood-based panels. Antonio Pizzi at the University of Lorraine in Nancy (France) and Edmone Roffael at the University of

Göttingen (Germany) have done important research in this area.

Suberin is a hydrophobic (lipophilic) substance typically found in the bark of the cork oak (*Quercus suber*), which is associated with a complex mixture of waxes. Robert Hooke first described suberin layers in 1665, when he examined suberised cork cells from the bark of *Q. suber* (Kolattukudy and Espelie 1989). In 1877, Franz von Höhnell discovered the lamellar structure of suberin (von Höhnell 1877). More than 60 years later, I. Ribas and E. Blasco found that glycerol is a part of suberin (Ribas and Blasco 1940). Since the 1980s, the chemical structure of suberin with its aliphatic and phenolic (lignin-like) domain has been progressively elucidated with pioneer work being done by the group of Pappachan E. Kolattukudy at Washington State University, Pullman and at Ohio State University, Columbus, USA (Kolattukudy 1980; Kolattukudy and Espelie 1989).

In the future, wood and lignocellulose will be used to produce platform chemicals that can replace petroleum-based basic chemicals currently used in the chemical industry. In this way, lignocelluloses could gradually replace petroleum as a source of raw materials for the chemical industry, thus placing wood chemistry at the centre of the chemical industry. This can be seen as a significant step in the economic transformation toward a bioeconomy. In addition to wood-based platform chemicals, also cell wall-based polymers and composites might play a pivotal role in future material research. Novel wood-based materials that respond and adapt to changing environmental conditions could become more important in the future data-driven society. By developing tunable materials, novel building blocks could be created that can be integrated into more complex future technologies.

3 Wood biology

Wood is defined as the tissue formed by the cambium through a periodical release of new cells to the inside thus forming growth increments. Such wood tissue is responsible for mechanical support of trees and shrubs, for the axial and radial transport of water and mineral solutes as well as for storage of reserve material. The botanical term for wood is “xylem”. Wood biology is a sub-discipline of wood science and deals with the formation and structure of xylem tissues and is based on analyses on macroscopic, microscopic, and molecular levels. Cambium and its activities as the meristematic tissue responsible for xylem formation generally are included in wood biological research. Wood biology also comprehends the physiological processes of wood-forming plants during their entire

life, their interactions with the environment as well as endogenically driven processes, including obligatory heartwood formation representing secondary changes as the final step in the life cycle of xylem tissue of many tree species. Other secondary changes such as facultative heartwood formation and discolouration of wood in the living or freshly felled tree are associated with the biology of wood and may be caused by active responses of living tissue, by invading microorganisms or by biochemical reactions. Pathological aspects such as attack and decay by microorganisms play an important role in the understanding of the biology of wood. Xylem with annual layers may variously be used as an archive for interactions with the environment and climate. The scientific sub-discipline recording and interpreting such information is called dendrochronology, which allows the exact dating of tree-rings to the year they were formed. Dendroclimatology as one subfield of dendrochronology focusses on the reconstruction of present and past climates, whereas the other subfield called dendroecology deals with changes in local forest environments. Taxonomy is part of wood biological research using anatomical, chemical and genetic characteristics.

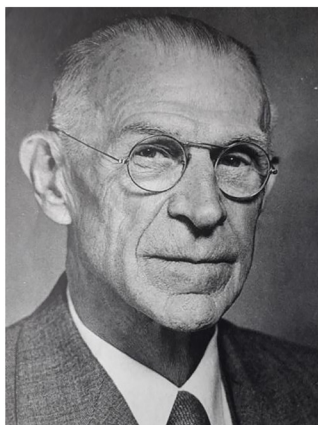
Scientific progress in wood biology was in the past and nowadays still is closely related to the methodological progress in biological sciences. A central point for such a relation in earlier times is the development of microscopy. In parallel to the improvement of light microscopy in the nineteenth and twentieth century, the introduction of electron microscopy in the 50s of the twentieth century, as well as the application of spectroscopic methods and synchrotron radiation during the last decades revealed more and more details on the tissue, cell, and molecular level. In the following, an overview on the history of wood biology is given, which is often combined with studies on general plant anatomy.

The beginnings date back into the seventeenth century, where Robert C. Hooke, Marcello Malpighi, Nehemiah Grew and Antoni van Leeuwenhoek were the first to start using simple light microscopes (Figure 2). Hooke (1635–1703), as a universal microscopist, used his enormous technical skills for improving microscope quality, especially through optimized illumination and control of height and angle. He finally achieved magnifications of up to 50× and examined a variety of objects. In 1665, Robert C. Hooke published the book “*Micrographia*“, which contains details on the porosity of charcoal and the structure of cork. Hooke prepared thin hand sections and was able to identify “empty spaces” surrounded by “walls”. For the first time the term “cells” was used for those units. Around the same time, in the second half of the 17th century, Marcello

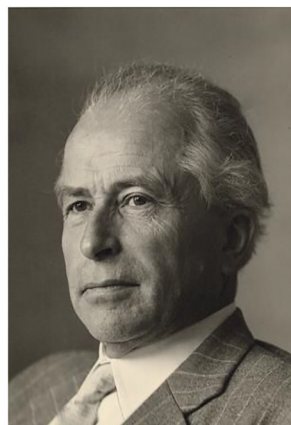
Malpighi (1628–1694) and Nehemiah Grew (1628–1711) began a systematic approach to studying plant anatomy. Marcello Malpighi published his macroscopic and microscopic observations on plant structures in 1675 in the book entitled “*Anatome Plantarum*”. The rough inner structure of the bark could be revealed, vessels with spiral thickenings were identified as well as the ray system and some for this time astonishing details like bordered pits in softwoods and tyloses in hardwoods. With regard to the physiological role of the discovered plant structures, however, Malpighi oriented himself too much to animal tissue, which led him to too speculative and false interpretations (Freund 1951; Metcalfe 1979). A few years later, in 1682, Nehemiah Grew published his principle work “*The Anatomy of Plants*” with comparative microscopic descriptions of the internal structure of hardwood and softwood species in relation to their three-dimensional appearance. Although Grew, like Malpighi, made some misinterpretations regarding structure-function relationships, he observed “little bladders” (or “cells”) evidencing the cellular structure of the plant body. Grew also demonstrated the existence of vessels in the “ligneous body” (i.e. xylem), bark fibres, pith tissue, and the so-called “inserted pieces” (i.e. the rays) (Freund 1951; Metcalfe 1979). Especially, Grew clearly stated that his work should have the aim to search for common and distinguishing anatomical characteristics, which can be understood as the initiation of systematic plant anatomy. Antoni van Leeuwenhoek (1632–1722), the third pioneer of microscopical plant anatomy, described characteristics of numerous hardwoods and some softwoods. With his self-made and perfected microscope lenses, van Leeuwenhoek was able to recognize details such as bordered pits, perforation rims in vessels, and a macrofibrillar substructure of the cell wall (Baas 1982a, b). Additionally, he recognized relationships between tree-ring widths and wood quality when studying fast-growing ring-porous hardwoods with wide rings displaying better quality than slow-growing ring-porous trees with narrow rings; van Leeuwenhoek also realized that these relationships are the opposite in softwoods. As already mentioned for Malpighi and Grew, also van Leeuwenhoek compared some plant structures and their functions with those in animals, which in turn led to a number of misinterpretations. Nevertheless, van Leeuwenhoek’s achievements undoubtedly have to be acknowledged so that Malpighi, Grew and van Leeuwenhoek can be regarded as the fathers of wood anatomy and wood biology (Baas 1982a). As the 18th century was one of stagnation without significant progress in wood biology, the next milestones were reached in the 19th century with the work of several well-known botanists like



Carl Wilhelm von Nägeli
(1817-1891)



Irving Widmer Bailey
(1884-1967)



Albert Friedrich Frey-Wyssling
(1900-1988)



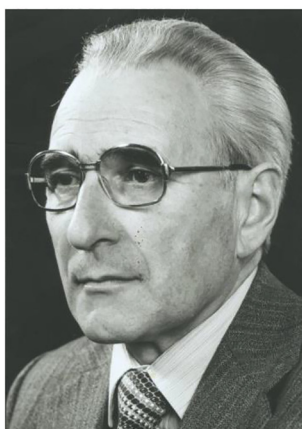
Johannes Liese
(1891-1952)



Herbert Eric Dadswell
(1903-1964)



Alan Buchanan Wardrop
(1921-2003)



Hans Heinrich Bosshard
(1925-1996)



William Edwin (Ted) Hillis
(1921-2008)



Fritz Hans Schweingruber
(1936-2020)

Figure 2: Selected scientists from the field of wood biology (see also Figure 4 with portraits of G.L. Hartig and R. Hartig). Copyright: *von Nägeli*: Wikimedia Commons; *Bailey*: Collection of Historical Sci. Instr., Harvard University/USA; *Frey-Wyssling*: ETH Zürich/Switzerland; *Johannes Liese*: courtesy of Walter Liese, Hamburg/Germany; *Dadswell*: CSIRO Melbourne/Australia; *Wardrop*: CSIRO Melbourne/Australia; *Bosshard*: ETH Zürich/Switzerland; *Hillis*: courtesy of Jugo Ilic, Melbourne/Australia; *Schweingruber*: WSL Birmensdorf/Switzerland.

Anton de Bary (1831–1888), Gottlieb Haberlandt (1854–1945), Theodor Hartig (1805–1880), Robert Hartig (1839–1901), Charles Francois Brisseau de Mirbel (1776–1854), Hugo von Mohl (1805–1872), Carl Wilhelm von Nägeli (1817–1891), Anselme Payen (1795–1871), Johann Evangelist Purkinje (1787–1869), Ludwig Radlkofer (1829–1927), Julius von Sachs (1832–1897), Karl Gustav Sanio (1832–1891), Hermann Schacht (1814–1864), Matthias Jakob Schleiden (1804–1881), Franz Joseph Unger (1800–1870), Julien Vesque (1848–1895), and Julius Wilhelm Albert Wigand (1821–1886). The discovery of the cambium and its description as a “building tissue” has to be highlighted as an important step in understanding and explaining secondary tree growth. A more detailed overview on the development of the concept of cambium as a cellular tissue responsible for wood and bark formation is given in Larson (1994). Based on the early observations by de Mirbel and the use of Grew’s term “cambium”, the work of Unger, Schleiden, von Mohl, Purkinje, and especially von Nägeli substantially contributed to the understanding of the role of the cambium through the discovery of cell division as the central process for secondary growth and the protoplasm as the cell content responsible for all activities of living cells. Schleiden focused his work on the cytological aspects of plant cells creating the new field of plant cytology.

Already at that time, increasing attention was paid to the structure of woody cell walls. Von Mohl was the first to describe the lamellar structure of a woody cell wall by applying polarized light microscopy, distinguishing only between primary and secondary lamellae without recognizing the tertiary lamella, which was identified later by Theodor Hartig; also, most structural details of bordered pits in conifers have been correctly shown by von Mohl. Payen has taken a chemical approach to the woody cell wall introducing the term “cellulose” for one of the constituents, which is “similar to starch”. Von Nägeli identified the cell wall consisting of crystalline cellulose and Mulder used the term “lignin” for “another constituent different to cellulose”. In 1850, Wigand resolved the problem of how two adjacent plant cells adhere to each other and was the first to identify a common middle lamella, which was confirmed a few years later by Sanio. Around 1870, some principles of formation and structure of woody cell walls have already been known. During the last decades of the 19th century, Robert Hartig established the new scientific branch of forest pathology and also published the first descriptions of fungal wood decay.

The twentieth century brought manifold technical progress, so that microstructural and chemical characteristics as well as physiological processes could be analyzed in much greater detail. Using conventional light

microscopy as well as so called indirect methods such as polarization microscopy, X-ray diffraction and staining techniques, Irving W. Bailey (1884–1967) made a name for himself in the early decades and published several papers on the fine structure of wood tissues. He established the uninucleate condition of the fusiform cambial initials; together with his co-workers Kerr, Vestal and Berkley, Bailey also revealed details of the fine structure of the wood cell wall, especially the non-cellulosic nature of the middle lamella (Scott 1955; Kerr and Bailey 1934). These studies finally aimed at an early and rather precise model of wood cell wall layering (Kerr and Bailey 1934). Albert Frey-Wyssling (1900–1988) and Reginald Dawson Preston (1908–2000) substantially contributed to the knowledge about the fine structure of the wood cell wall by using light microscopy-based techniques. Johannes Liese (1891–1952) combined his knowledge on wood anatomy and decay mechanisms with intense studies on wood protection. Johannes Liese’s research in this field aimed at detailed descriptions of standardized testing methods for natural durability and wood preservatives.

With the introduction of the electron microscope to wood biology at around 1950, this novel tool opened a new dimension of structural wood biology. Pioneers in this field, who steadily improved preparation procedures, were Walter Liese (Germany) (*1926), Hiroshi Harada (Japan) (1923–1991), Wilfred Arthur Côté (USA) (1924–2012), Reginald Dawson Preston (UK), Alan Buchanan Wardrop (1921–2003), and Herbert Eric Dadswell (Australia) (1903–1964), Albert Frey-Wyssling, Kurt Mühlethaler (1919–2002) and Hans Heinrich Bosshard (Switzerland) (1925–1996). These early electron microscopic observations revealed numerous details of wood cell walls, such as precise wall layering, orientation of cellulose microfibrils, fine structure of pit membranes, and the occurrence of warts (Liese and Côté 1960; Nimz 1965). The first electron micrograph of a pine bordered pit membrane (Figure 3) taken in 1950 by Walter Liese at the institute of Ernst and Helmut Ruska in Berlin (in 1986 E. Ruska received the Nobel prize in physics for “his fundamental work in electron optics and for the design of the first electron microscope”). Central torus and peripheral margo fibrils are well visible. In the second half of the 20th century, Sherwin Carlquist (USA) (*1930), William Edwin (Ted) Hillis (Australia) (1921–2008), and Fritz Hans Schweingruber (Switzerland) (1936–2020) in particular made significant contributions to wood anatomy, representative for a number of other wood scientists all around the world working in the frame of the International Association of Wood Anatomists (IAWA).

With the further improvement of methodology in recent decades, wood scientists and also botanists

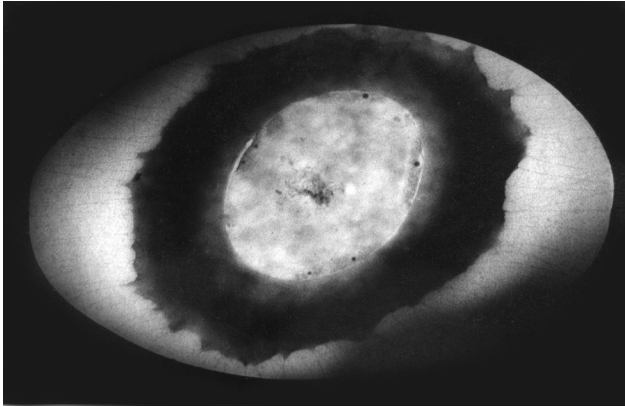


Figure 3: First electron micrograph of a pine bordered pit membrane (photo courtesy of Walter Liese, Hamburg/Germany).

increasingly focused on biochemical as well as molecular aspects of wood formation (Fromm 2013). Biochemistry in general deals with the structure and function of biological molecules such as proteins, nucleic acids, carbohydrates and lipids in all processes in a living tree, whereas molecular biology is usually defined as a subdiscipline of biochemistry that focuses only on the nucleic acids. A breakthrough in molecular biology has been achieved during the last 10–15 years by sequencing whole genomes of trees. Complete DNA sequences of forest trees were first published in 2006 for *Populus trichocarpa* (Tuskan et al. 2006) and in 2014 for *Eucalyptus grandis* (Myburg et al. 2014). As the first conifer species, *Picea abies* was sequenced in 2013 (Nystedt et al. 2013). Since then, the sequencing of several more tree genomes has been completed.

In the future, such molecular techniques open a new dimension of genetic engineering, primarily aiming at developing transgenic trees with modified characteristics, such as resistance to insect pests and harsh environmental conditions, improved growth for higher biomass production or even altered lignin contents (e.g., less lignin for chemical pulp production and more lignin for energy purposes). Another technique uses DNA markers for precisely tracing the origin of traded wood. This is very promising to further strengthen future activities to combat illegal logging. Besides these molecular techniques also classical macroscopic and microscopic wood identification are indispensable for supporting authorities in the control of globally traded wood. This is also true for the identification of CITES-protected species (CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora). Within the next few decades, it is expected that a high number of so-called lesser-known species will be increasingly traded, therefore existing databases on wood

identification have to be continuously extended. Currently, in several laboratories scientists are working on the development of reliable automatic identification systems. Wood biology with its diverse research fields, e.g., on cell wall formation processes, on cell wall fine structure, and aspects on structure-function relationships, remains important also through large overlapping with research activities in wood chemistry and wood physics.

4 Wood physics

Wood physics is an integral part of wood science. It is based on the findings of

- wood chemistry
- wood anatomy and biology as well as
- classical physics, mechanics and strength of materials

Wood physics is understood as the “theory of the physical and mechanical properties of wood and wood-based materials”. Figure 4 shows selected important scientists.

Important areas of wood physics are:

- the behaviour of wood related to moisture (basics of moisture sorption, swelling and shrinkage)
- the influence of temperature on the wood properties, the heat conduction and the heat storage and
- the mechanical, rheological and acoustic properties of wood and wood-based materials.

Wood physics also deals with the theory of the relationships between structure and properties of solid wood and wood-based materials and their modelling. Due to the natural character of wood as a biological material, a number of material-specific properties are to be taken into account compared to other materials such as steel and concrete. Some examples are inhomogeneity, anisotropy and hygroscopic behaviour of wood. All wood properties depend on wood moisture, temperature and time.

Knowledge of the mechanical-physical properties is an important basis for the production of timber and wood-based materials, their processing and appropriate use. The development and the use of modern manufacturing processes and computer-aided manufacturing also require comprehensive knowledge of the physical-mechanical properties of wood and wood-based materials.

In industrial manufacturing, physical effects or properties are increasingly used for quality control. Examples include lumber grading, colorimetry and detection of wood defects (e.g., tracheid effect). In the field of quality control, today, e.g., sound propagation, eigenfrequency measurement, colorimetry, X-ray radiation, laser technology and



Henri Louis Du Hamel du
Monceau
(1700-1782)



Heinrich Cotta
(1763-1844)



Georg Ludwig Hartig
(1764-1837)



Robert Hartig
(1839-1901)



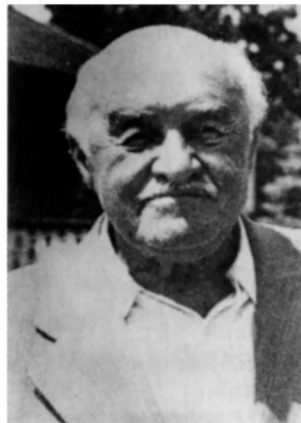
Tadeusz Perkitny
(1902-1986)



Herbert Flemming
(1903-1963)



Wilhelm Klauditz
(1903-1965)



Leopold Vorreiter
(1904-1984)



Franz Kollmann
(1906-1987)

Figure 4: Selected scientists from the fields of wood physics and wood based materials (with a focus on wood physics). Copyright: *Duhamel de Monceau, Cotta, R. Hartig, P. Hartig, Perkitny, Flemming, Klauditz, Vorreiter, Trendelenburg, Keylwerth, Bodig*: Niemz and Sonderegger (2021); *Ugolev*: P. Niemz; *Schneider, Kollmann*: Holzforschung München/Germany; *Skaar, Siau, Maloney, Stamm*: Forest Products Laboratory, Madison/USA.



Reinhard Trendelenburg
(1907-1941)



Rudolf Keylwerth
(1912-1964)



Thomas M. Maloney
(1931-2014)



Josef Bodig
(1934-2007)



Boris N. Ugolev
(1925-2015)



Christen Skaar
(1919-2006)



Alfred Stamm
(1934-2007)



John Siau
(1922-1996)



Adolf Schneider
(1919-1991)

Figure 4: Continued.

NIR spectroscopy as well as electrical property measurements (for humidity measurement) are used. Almost all methods of classical material research are used in wood

research today (nanoindentation, atomic force microscopy, mechanical testing in the environmental scanning microscope, spectroscopy (e.g., IR, NIR, FTIR, RAMAN)

including correlations with physical and mechanical properties. Various optical methods of strain measurement are state of the art today (e.g., based on photogrammetry as digital image correlation).

The first scientific approaches to characterize physico-mechanical properties of wood date back to e.g., Henri Louis Duhamel du Monceau (1700–1782) and Georges-Louis Leclerc de Buffon (1707–1788). Leclerc de Buffon was the first to describe the correlation between wood density and strength (Köstler et al. 1960). He already carried out tests to compare the properties of small specimens with those of large ones. But, a lot of basic work was also done earlier (material characteristics, density measurements), which is described in older encyclopaedias [e.g., Johann Georg Krünitz (1728–1796), “Oekonomische Encyclopädie” (The Oeconomic Encyclopaedia), published between 1773 and 1858, 242 volumes with 600–800 pages each] (Matejak and Niemz 2011).

Between 1750 and 1830 there was a flood of publications on wood production and utilization (Beckmann 1780). In particular, works by Georg Ludwig Hartig (1764–1837) and Heinrich Cotta (1763–1844) with the focus on strength properties should be mentioned here. During this time, the linear thermal expansion of wood was also investigated for the first time (Struwe, Glatzel, Villari), however, the hygroscopic behaviour of wood was not yet sufficiently taken into account. Building on all this work, Karl Karmarsch published an overview on the properties and processing (technology) of wood in the “Handbook of Mechanical Technology” in 1837 (Karmarsch 1851). Academic education at universities in the field of forest and wood dates back to this time. In Germany, the first forestry departments were founded at the beginning of the nineteenth century (e.g., in Tharandt, Hannoversch-Münden) (Scamoni 1960).

Extensive work on recording the properties of wood began in the middle of the nineteenth century (Hartig 1885). Nördlinger published detailed properties of wood in 1860 (Nördlinger 1860). The work of B. Volbehr in Kiel, Germany (1896), on wood swelling should also be mentioned. At the beginning of the twentieth century, Janka in Austria carried out extensive studies on wood hardness and strength (Köstler et al. 1960). In this way, many elements of today’s wood science were developed, but there was not yet a “science of wood” in the true sense. This is not least due to the fact that there was no targeted wood research in corresponding research institutes until 1910. The research was more or less focused on forestry or forest utilization. This is still the case today in some countries.

First summaries of the state of the art of wood science were presented in 1936 by Franz Kollmann (1906–1987), (Kollmann 1936) and in 1939 by Reinhard Trendelenburg (1907–1941) (Trendelenburg 1939). In this context, the work of Leopold Vorreiter (1904–1984) published in 1949 should also be mentioned (Vorreiter 1949). Kollmann’s book in the second, greatly expanded edition under the title “Technology of Wood and Wood-Based Materials” (in German) is still a standard work in wood research today (Kollmann 1951). This has primarily documented the status of the scientific work. In collaboration with Wilfred Arthur Côté Jr, it also was published in an English version (Kollmann and Côté 1968). In the USA, the Wood Handbook of the Forest Products Laboratory was first issued in 1935 and slightly revised in 1939. The most recent edition was published in 2010, which is available online. The focus of this book to date has been on the transfer of scientific knowledge into the practice of wood use. Alfred Stamm (Stamm 1964) summarized in particular the physical properties of wood in his book “Wood and Cellulose Science”. Joachim Radkau published a very interesting overview of the history of timber use (in German: Radkau 2007; in English: Radkau 2012).

The founding of wood research institutes, the industrialisation of wood processing, the increased use of wood in construction and the development of wood materials (plywood since 1900 in Germany, fibreboard since 1900 in England, particleboard since 1940 in Germany), led to a large number of publications in the field of wood physics.

From the beginning to the middle of the twentieth century, wood physics research was intensively pursued in the field of mechanical engineering and aviation engineering. Many well-known scientists were active in this field. Particularly worth mentioning are Franz Kollmann (Germany), Rudolf Keylwerth (Germany), R. L. Hankinson (USA), and Arvo Ylinen (Finland). Well-known contributions also came from the physics itself such as the study of piezoelectric properties by Alexei V. Shubnikov (Shubnikov 1946) and Eiichi Fukada (Fukada 1955). A trend that is increasingly appreciated today.

Many studies on mechanics date back to the period around Second World War, when a great deal of wood research was carried out worldwide (Anderson 2010; Steinsiek 2008). After the Second World War physical research focused on the physics of wood-based materials (Rudolf Keylwerth (1912–1969), Wilhelm Klauditz (1903–1963) both Germany, Fred Fahrni Switzerland (1907–1979)). Thomas Maloney (1938–2014) made a major contribution to the development of wood-based materials in the United States at Washington State University (Maloney 1999).

Research into the fundamentals of the basics of structural mechanics and fracture behaviour has gained

considerable importance, in particular through the use of modern computational methods (e.g., finite element method, multi-scale modelling), see e.g. Kent Persson (2000). Substantial work has been done in particular in the

USA, Japan, Germany, Austria, Switzerland, Russia (e.g., Ugolev 1986, 2014), and Sweden (Table 2).

In 1982, Bodig (1934–2007) and Jayne published the first overview of the structural and fracture mechanics of

Table 2: Overview of selected works on wood physics (Niemz 1993; Niemz and Sonderegger 2021).

Year	Scientist	Research area
Eighteenth century	Duhamel du Monceau	Fundamentals of forest utilization
	Leclerc de Buffon	Mechanical properties of wood
1848	Chevandier/Wertheim	Relation between moisture and density of wood
1850	Struwe	Measurement of thermal expansion of wood
1882	Sachs/Hartig	Cell-wall density
1885–1895	Hartig	Relation between annual ring width and strength Relation of heartwood formation to density and water uptake, density distribution in the log
1896	Volbehr	Swelling and shrinking of wood
1906/1907	Tiemann	Fibre saturation point
1907–1927	Stamm	Electrical properties of wood
1921	Hankinson	Influence of grain angle: Hankinson's equation (slope of grain)
1922	Baumann	Relation between fibre direction and tensile strength, calculation of shear moduli, influence of knots on the strength of wood
1923–1935	Hörig	Theory of elastic properties of wood/generalized Hooke's law for orthotropic materials
1924	Baumann/Bach	Influence of shear deformation on Young's modulus
1928	Huber	Measurements of shear modulus of wood
Since 1930	Kraemer/Winter	Strength of laminated wood
1932	Mörath	Hardness and dielectric properties
1934	Schmidt	Measurement of the logarithmic decrement of wood
1935	Roth	Rheological properties of wood
1936	Kollmann	Book "Technologie des Holzes" (Wood Technology), 1st edition
1938	Ivanov	Duration of load
1938	Nilakantan	Investigations on the magnetic properties of wood
1944	Kollmann/Dosoudil	Fatigue of wood and wood-based materials (vibration tests)
1946	Weatherwax/Stamm	Thermal properties
Around 1950	Keylwerth/Perkitny/Raczkowski/Schneider, Siau, Skaar, Ugolev	Swelling, sorption, hindered swelling, mechanical properties
About 1950	Klauditz/Kollmann/Keylwerth/Fahrni/Himmelheber/Fischer/Kehr/Plath/Maloney	Physical-mechanical properties of particleboards
About 1958	Keylwerth/Flemming/Bodig/Jayne/Plath/Fahrni/Maloney	Structure mechanics of particleboards
About 1966	Pellerin/James/Bucur/Ross/Beall	Acoustic properties of wood and wood-based materials for the calculation of mechanical properties
About 1968	Beall/Ansell/Landis/Niemz	Acoustic emission (cracks induced by mechanical stress and drying)
About 1970	Funt/Bryant/Conners/James/Knuffel/Hirai/Fukada/Morén/Hansson	Intensified research on wood physical properties for purposes of quality control (optoelectronic, electrical, acoustic, X-ray, laser)
About 1980	Martensson/Ranta-Maunus/Hunt/Morlier/Gressel/Hanhijärvi	Creep of wood and wood-based materials, mechano-sorption
About 1990	Meder/Tsuchikawa	Research on spectrometric properties of wood (mechanical properties, adhesive content, thermal treatment)
About 2000	Salmen/Burgert/Navi/Stanzl-Tschegg/Gindl-Altmutter/Wimmer	Micromechanical tests (nanoindentation, DMA, Raman spectroscopy, X-ray diffraction, AFM)
About 2005	Bucur/Forsberg/Van den Bulke/Niemz/Van Acker/Kamke	X-ray microtomography, synchrotron light, <i>in-situ</i> mechanical tests, colour for industrial quality control
About 2005	Harrington/Serrano/Persson/Gustafsson/Nairn/Svensson/Navi/Gamstedt/Landis/Kaliske/Eberhardsteiner	Modelling (properties of wood and wood-based materials, swelling, multi-scale modelling)

wood and wood-based materials in their book “Mechanics of Wood and Wood Composites” (Bodig and Jayne 1982).

Main research topics of the past decades were:

- The rheological properties of wood (e.g., Roth (1935), Dinwoodie, Niemz (1982), Martensson, Ranta-Maunus, Hunt, Gressel (1972), Hanhijärvi (1995))
- The fracture behaviour of wood and wood-based materials by means of scanning electron microscopy (SEM) and acoustic emission analysis (e.g., Beall, Kitayama, Nogouchi, Landis),
- The determination of defects and quality control of wood and wood-based materials on the basis of wood-physical effects (especially in USA: Galligan, Pellerin, Beall, and Japan: Fukada, Tsuchikawa)
- Colour measurements
- Grading and quality control of wood and wood-based materials (strength, internal defects, colour deviations, structural defects, e.g., Glos, TU Munich/Germany).

In recent years, research has also been increasingly devoted to the microscopic, submicroscopic and molecular fields (e.g., Bodig and Jayne 1982; Geitman and Gril 2018).

Modern wood physics research requires cooperation of experts from different disciplines (e.g., wood science, physics, chemistry, mechanics, materials science) (Geitman and Gril 2018; Montero et al. 2012). Only in this way can methods such as computed tomography in the synchrotron, X-ray microtomography, neutron tomography or wave propagation in wood be successfully applied.

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