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Plant fibres: cell wall and structure of cellulose

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Learning outcome

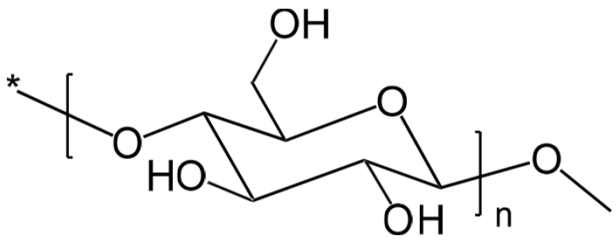
After this lecture, you will be able to :

- Answer the questions: where does cellulose come from?
- Distinguish herbaceous and woody plants (main source of cellulose)
- Describe the main points of cell wall ultrastructure: chemistry, morphology, and hierarchy

Contents

What is cellulose

- Cellulose is a polysaccharide biosynthesized in nature
- Main structural (load bearing) component of all plants
- The most abundant biopolymer on earth (10^{12} tons produced per year)

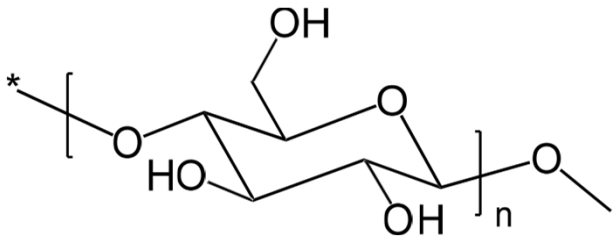


- Poly (1,4-β-D-glucopyranose)
- Linear homopolymer
- Forms semi-crystalline microfibrils
- Recalcitrant
- Insoluble

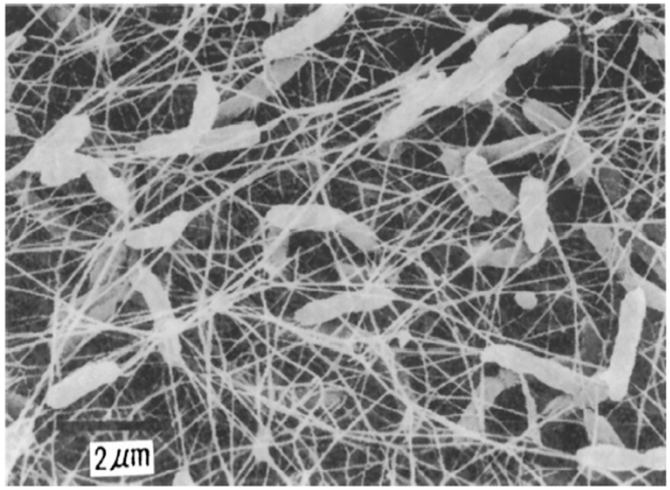
Sources of cellulose

Cellulose is produced via biosynthesis in nature

There are three known sources of cellulose:
(1) Certain species of bacteria (bacterial cellulose)
(2) Tunicates (animal cellulose)
(3) Plants (plant cellulose)



Bacterial cellulose



- Some species of bacteria are able to biosynthesize cellulose (notably *acetobacteria xylinum*)
- The cellulose is extracellular, it is not in the bacteria but extruded by the bacteria
- Bacterial cellulose is the only pure form of cellulose in nature, no other components are synthesized with cellulose
- Microfibrils in bacterial cellulose are generally larger than in other cellulose grades

Tunicate cellulose

- Tunicates are small marine animals
- They are the *only species of animals* that biosynthesize cellulose
- The body of a tunicate is surrounded by a test or a tunic where the cellulose is produced
- Tunicate cellulose is in the form of microfibrils that are highly crystalline compared with most plant celluloses

Plants

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What is a plant?

By plants, people usually refer to *green plants*:

- Flowering plants (angiosperms)
- Gymnosperms
- Mosses
- Clubmosses
- Hornworts
- Liverworts
- Ferns
- Green algae

Two main features of all plants:

- Possess cell walls with cellulose as the main structural material
- Get most of their energy from photosynthesis

Categorisation of plants

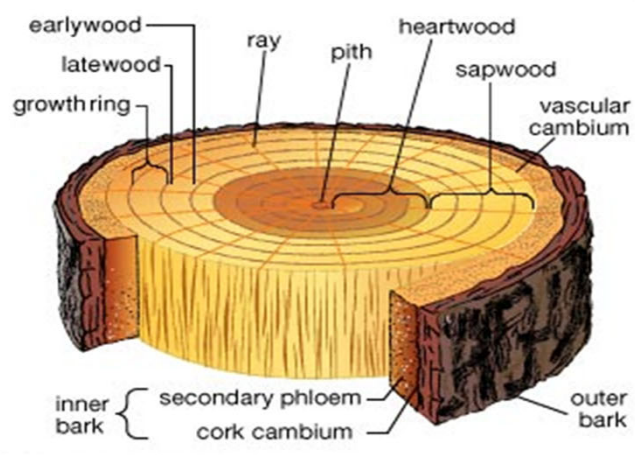
Plants can be categorised in many ways; however, from the point of view of fibre materials, the most sensible division is to:

- **Herbaceous plants**
  - Agro fibres
  - At least the part above ground dies after the growing season
- **Woody plants**
  - Wood fibres
  - Remain alive during dormant season; reinforced by secondary xylem

Herbaceous *vs.* woody plants

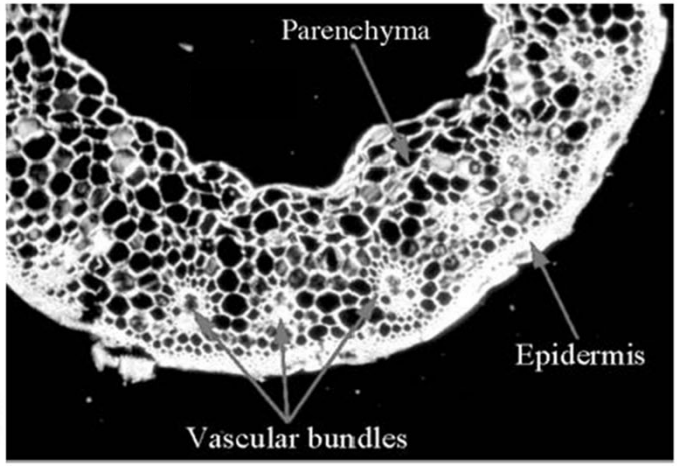
Localization of growth

(a) Woody plant



Growth occurs by cell division in vascular cambium

(b) Herbaceous plant

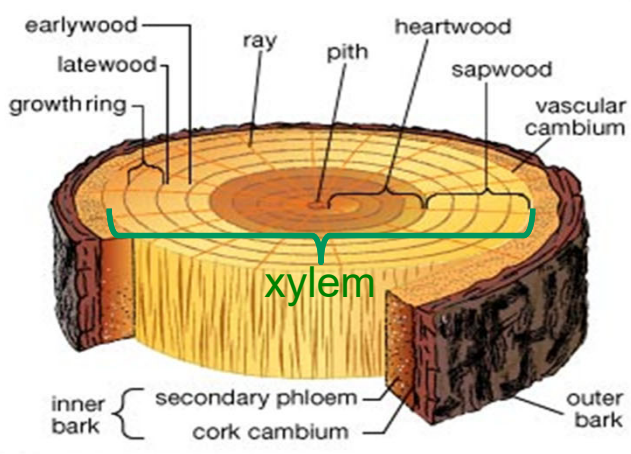


Growth occurs by cell division in vascular bundles

Herbaceous *vs.* woody plants

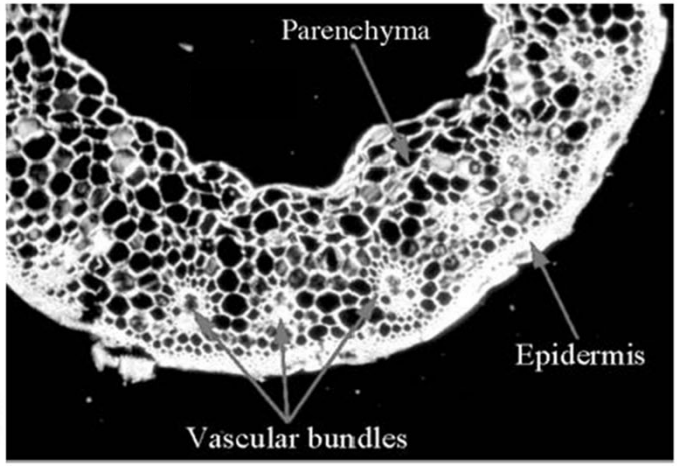
Strength distribution

(a) Woody plant



Strength provided by fibres all over the xylem

(b) Herbaceous plant

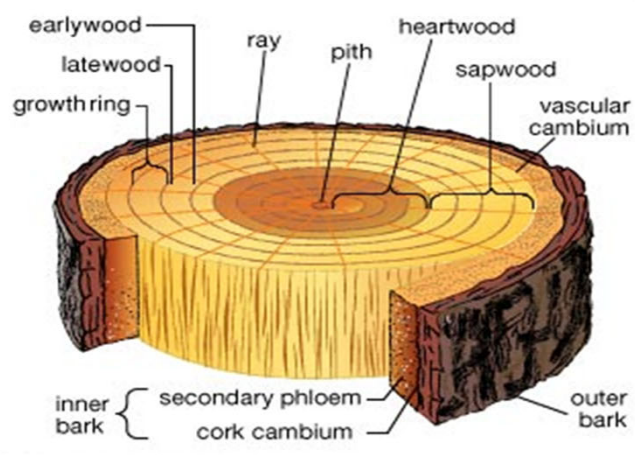


Much of the strength provided by epidermis (cellulose+silica) and fibres

Herbaceous *vs.* woody plants

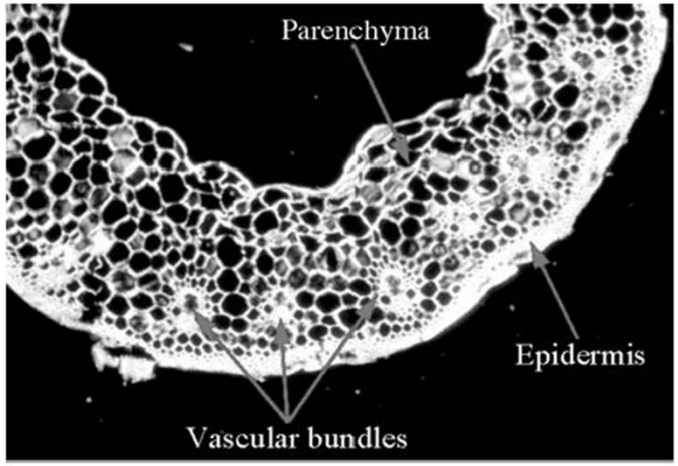
Water transport

(a) Woody plant



Water transport occurs through xylem fibres

(b) Herbaceous plant



Water transport occurs mainly through vascular bundles

Common plants in fibre technology

Woody plants:

- Trees
- Shrubs

Herbaceous plants:

- Flax
- Cotton
- Jute
- Kenaf
- Bamboo
- Ramie
- Sisal

Wood structure and plant cell types

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Heartwood and sapwood

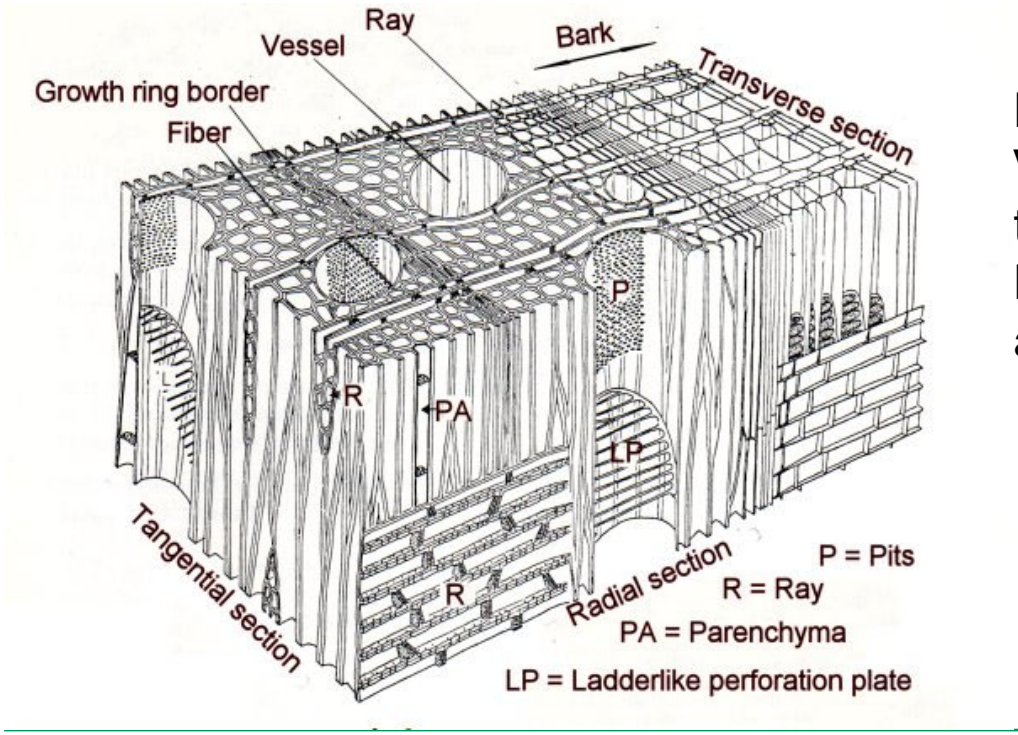
SAPWOOD
- conducts water and minerals nutrients
- has (also) living tissue

→ active tissue

HEARTWOOD
- does not take part in water conduction
- high extractives content

→ inactive tissue
- protects wood against rot or insect decay

Fibres, vessels, parenchyma cells



Fibres: strength, water transport
Vessels: water and nutrition transport
Parenchyma: storage of water and nutrition

Softwood *vs.* hardwood

Softwood: from coniferous trees (evergreens, ones that have needles)
Hardwood: from deciduous trees (ones that have leaves)

Softwood *vs.* hardwood

SOFTWOOD	HARDWOOD
EARLYWOOD AND LATEWOOD DISTINCTION	NO CLEAR DISTINCTION
~90% OF WOOD CELLS ARE TRACHEIDS (FIBRES)	WIDER VARIETY OF WOOD CELLS - ONLY 30-70% FIBRES
	WIDER CHEMICAL DIVERSITY

Ultrastructure of plant fibres

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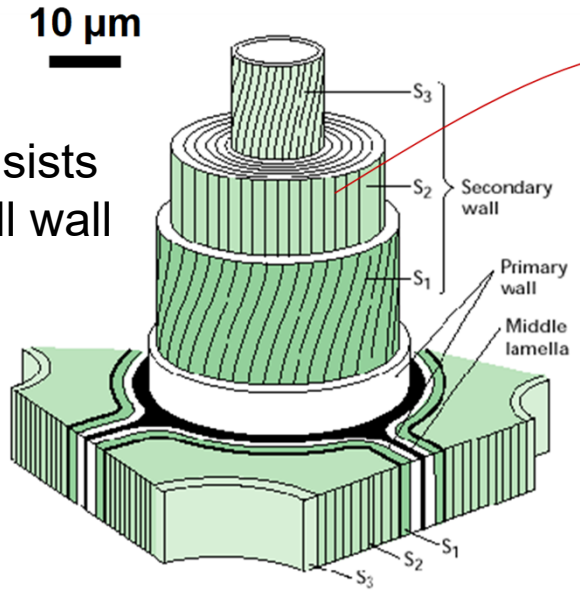
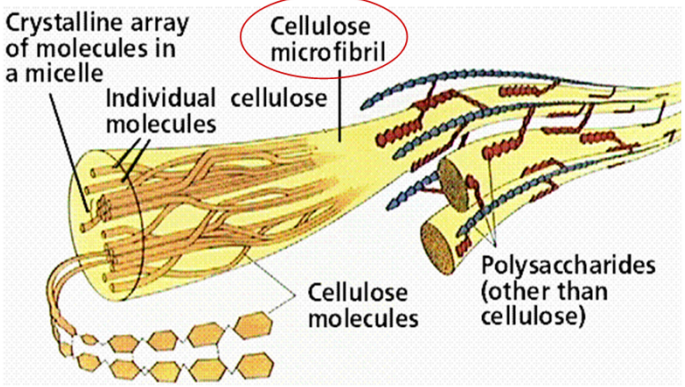
Wood fibre

Wood fibres, like many other plants fibres, contain a secondary wall that yields exceptional strength to the fibre

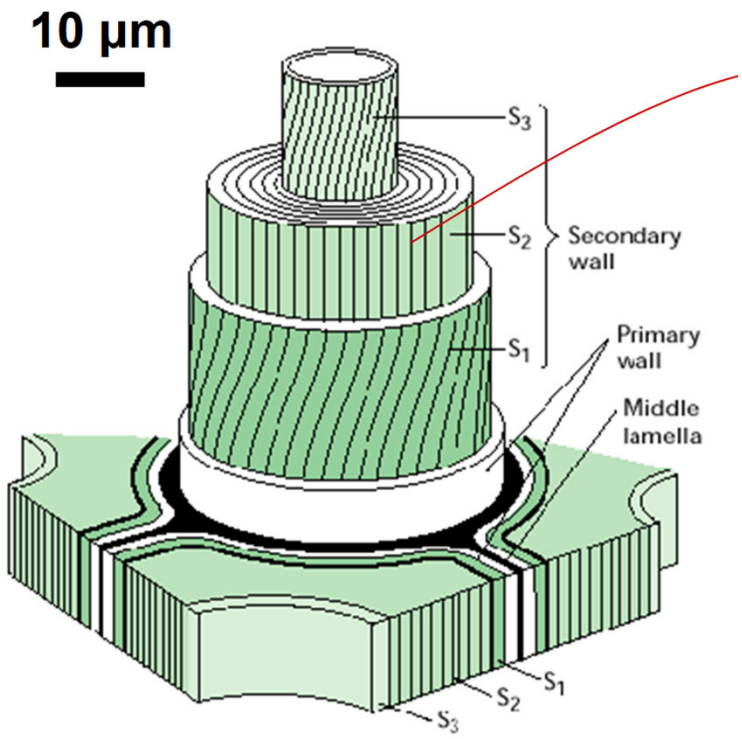
Wood fibre consists of a layered cell wall matrix



Cellulose microfibril
Diameter: **3-20 nm**
(In wood: 3-4 nm)

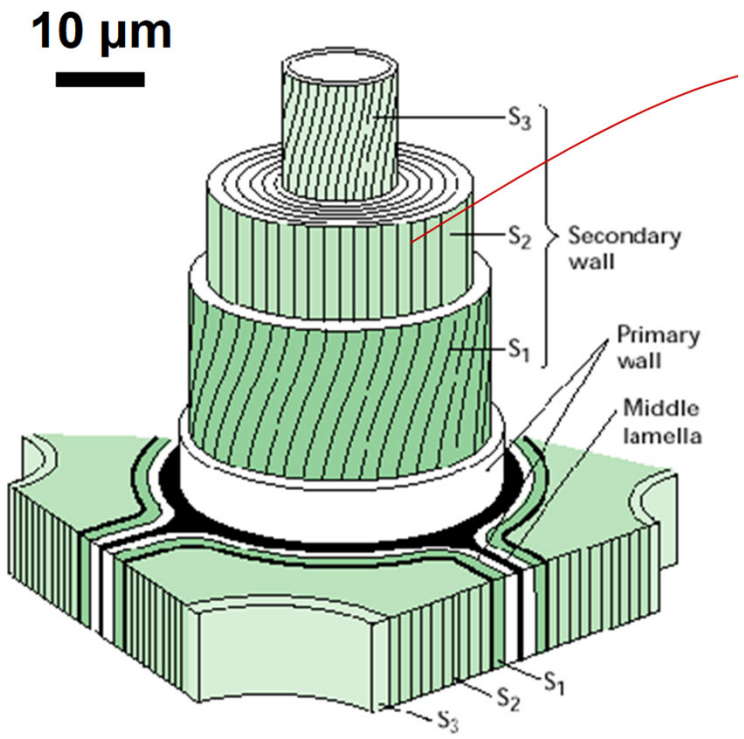


Wood fibre



Wood fibre cell wall consists of semi-crystalline cellulose microfibrils with amorphous lignin and hemicellulose in between.

Wood fibre



- Cellulose microfibrils are oriented in the secondary wall and arbitrarily aligned in the middle lamella
- The “fibril angle” affects the tensile strength of fibres a great deal

Chemical composition of fibres: the lowest hierarchical level

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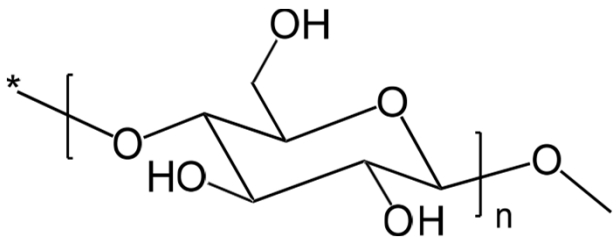
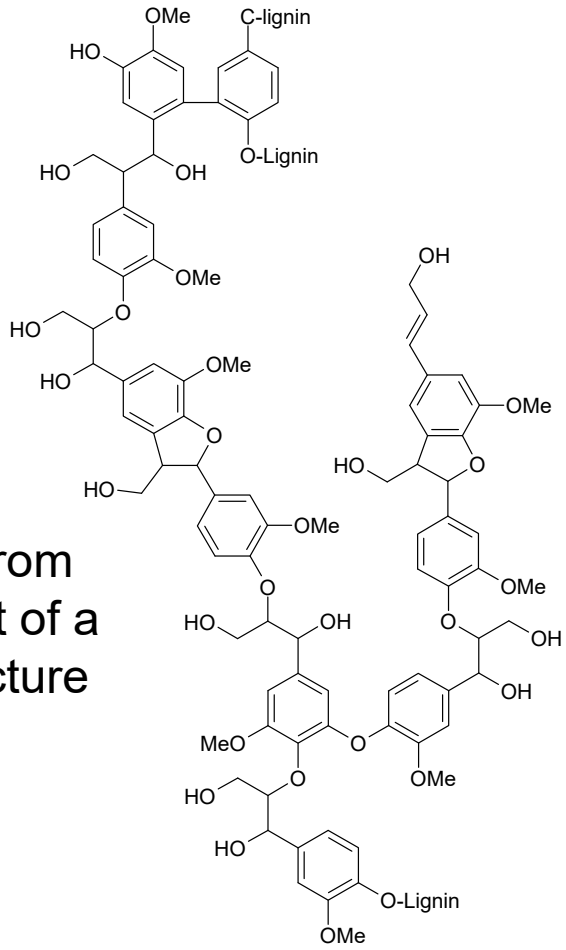
Cellulose: main structural element



- Poly (1,4-β-D-glucopyranose)
- Linear homopolymer
- Forms semi-crystalline microfibrils
- Recalcitrant
- Insoluble

Lignin

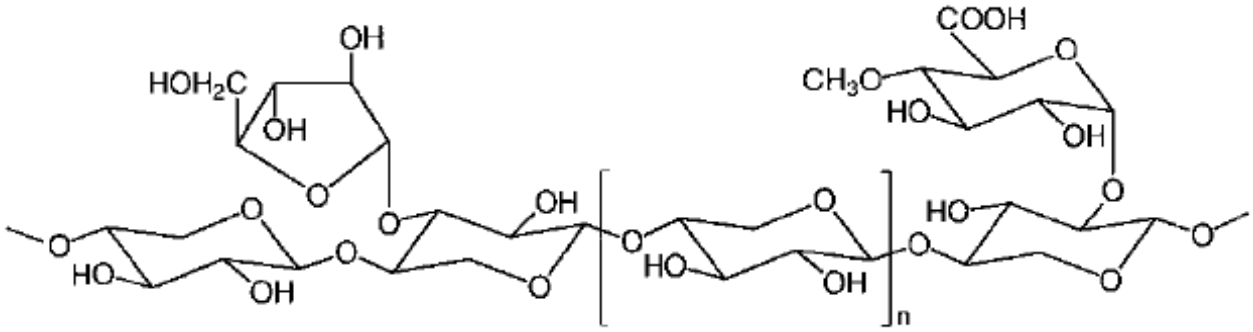


Example from a fragment of a lignin structure

- Non-linear polyphenol
- Structurally extremely diverse
- Glues fibres together as the main component in middle lamella
- Hydrophobic: controls the amount of water inside the cell wall
- Responsible for the brown colour of wood (pulping and papermaking aim at removing lignin as completely as possible)

Hemicellulose

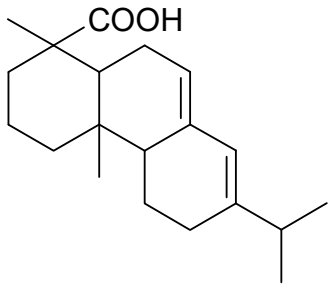
Example from a structure of arabinoglucuronoxylan, a common hemicellulose in conifers



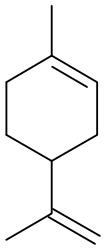
Hemicelluloses are heteropolysaccharides with low DP (<200) and they form amorphous structures in the cell wall

Extractives

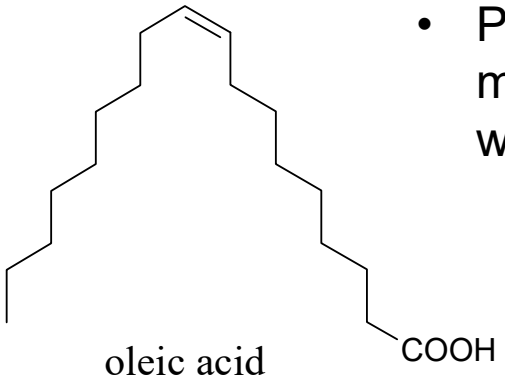
Some examples of common extractives



abietic acid
(diterpenoid)



limonene
(monoterpene)



oleic acid
(fatty acid)

- Part of the wood matrix, not part of the wood cell wall *per se*

- Small molecular (not polymers) organic compounds that can be extracted with an organic solvent
- Thousands of different extractives abound

Chemical composition of wood

	Softwood	Hardwood
CELLULOSE	40 %	40-50 %
LIGNIN	27-33 %	19-25 %
HEMICELLULOSE	23-30 %	23-40 %
EXTRACTIVES	5-10 %	5-10 %

Isolation of fibres

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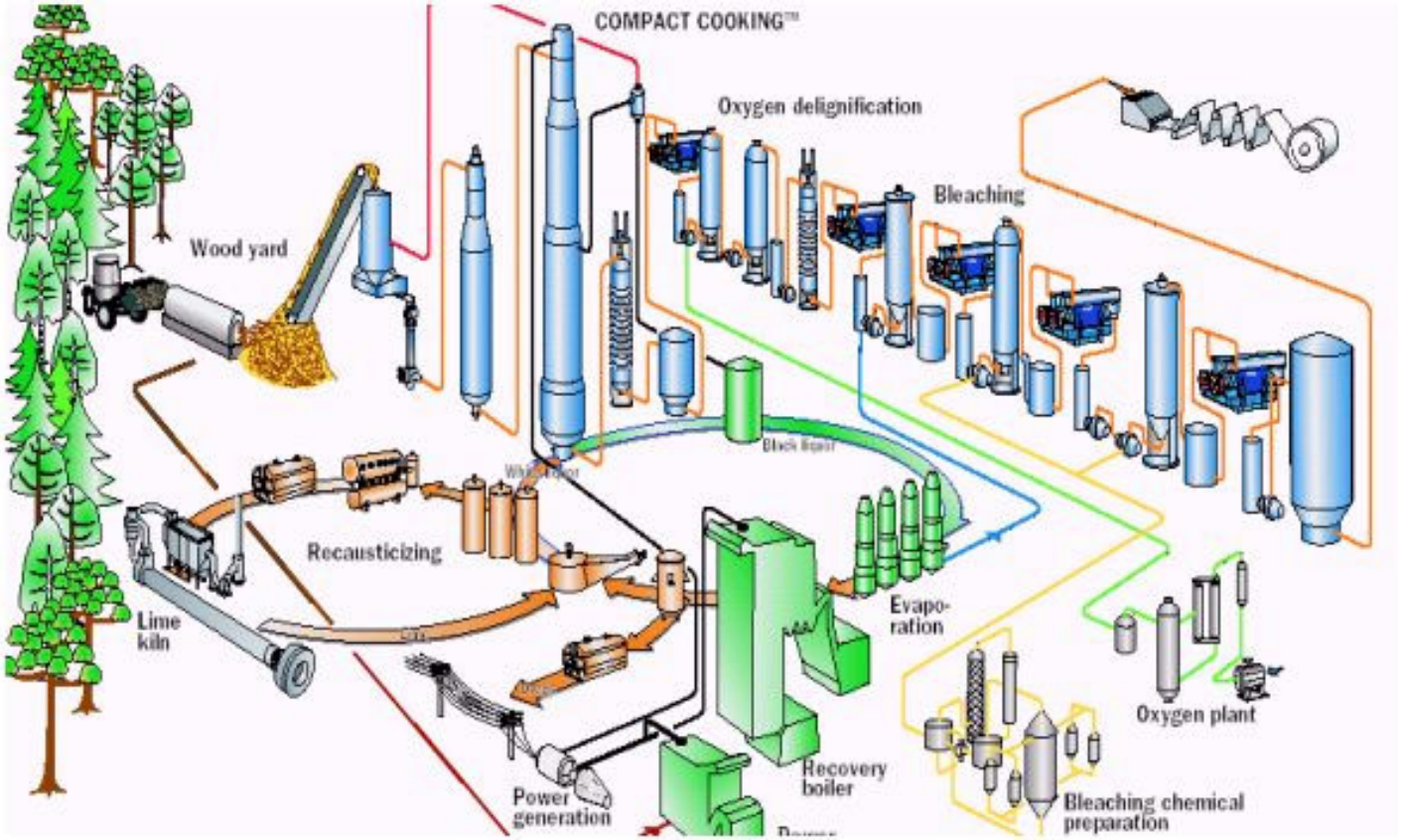
Basic isolation methods

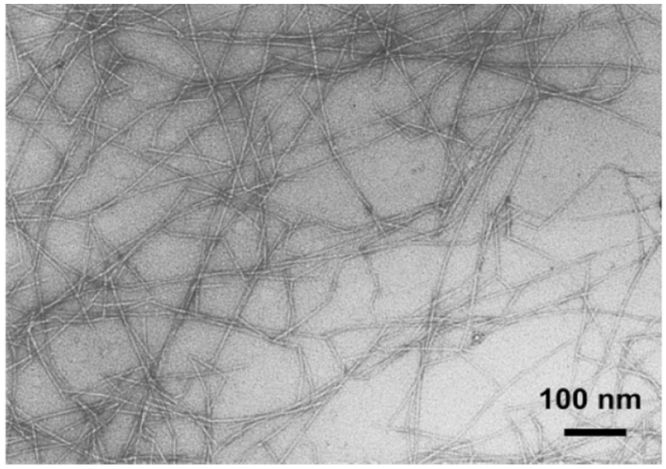
- In order to utilize fibres, they must be isolated from a plant matrix that confines them to a rigid template
- Wood fibres are generally isolated by:
  - Mechanical force (mechanical pulping)
  - Chemical means (chemical pulping)

Kraft process plant

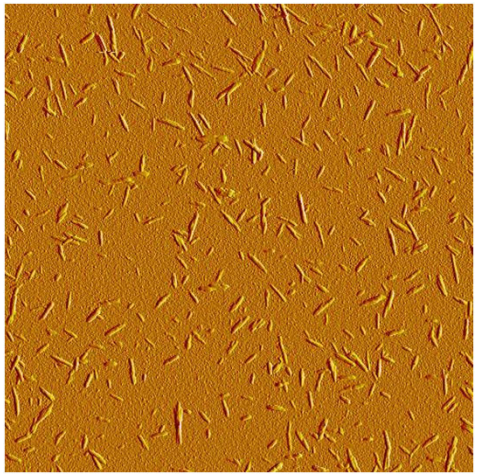


Note: isolation of nanocellulose

Cellulose nanofibres



Cellulose nanocrystals



- At present, isolated plant fibres are further disintegrated to nanocellulose
- Nanocelluloses are also made mechanically and/or chemically
- Promising new materials in future applications

Summary on plant cells and cellulose

- Plant fibres stem from woody or herbaceous plants
- Tracheids (fibres), vessels, and parenchyma are the main types of plant cells
- Plant cell is a hierarchical construction made of cellulose, hemicellulose, and lignin
- Wood fibres are separated by either mechanical or chemical pulping
- Disintegration of wood fibres results in nanocellulose