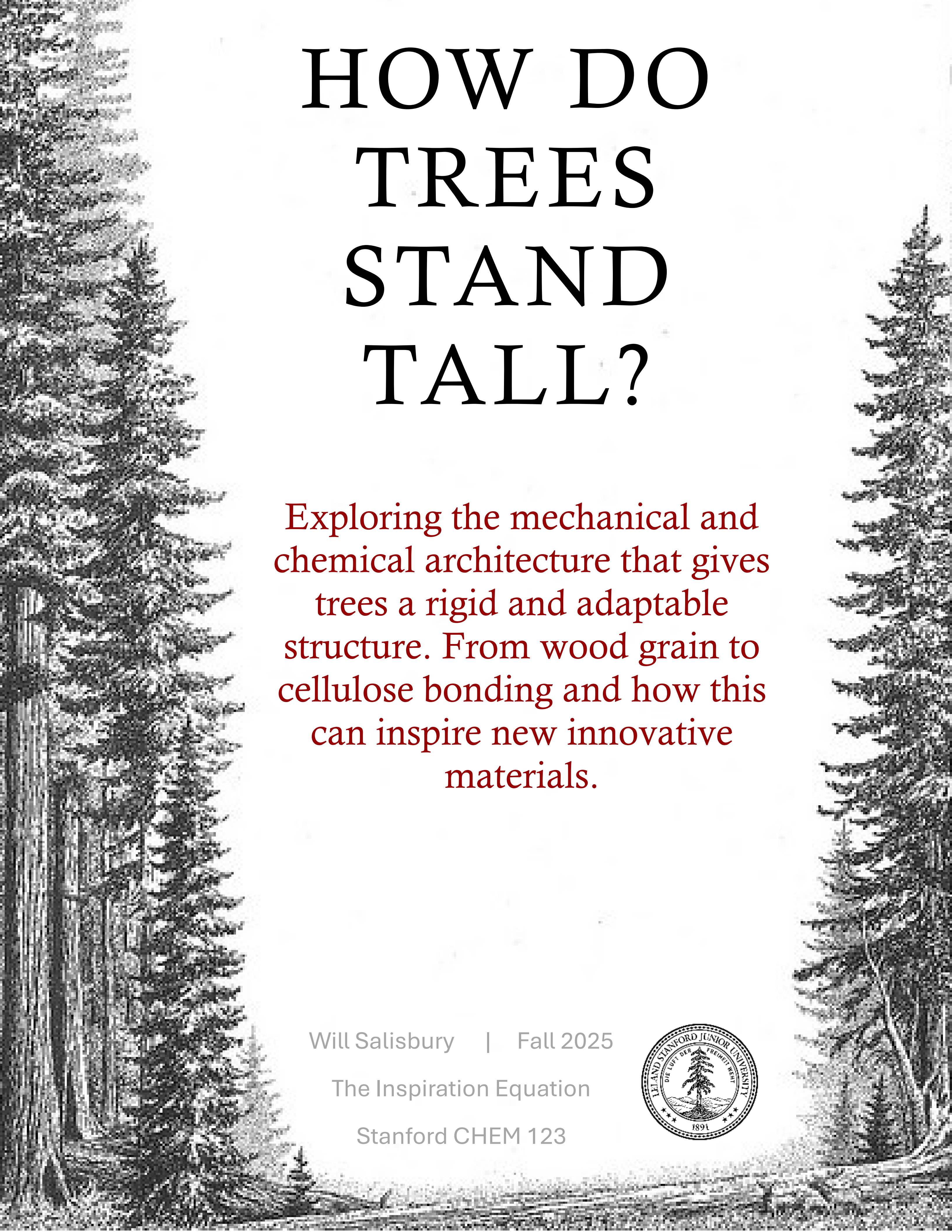


HOW DO TREES STAND TALL?

Exploring the mechanical and chemical architecture that gives trees a rigid and adaptable structure. From wood grain to cellulose bonding and how this can inspire new innovative materials.

Will Salisbury | Fall 2025

The Inspiration Equation

Stanford CHEM 123

1891

Abstract

This paper will explore the chemical structure of plant matter that gives trees their impressive mechanical properties, allowing them to weather storms, stand hundreds of feet tall, and to continuously grow. At the chemical level, trees are made of a bio-composite of three components: cellulose, hemi-cellulose, and lignin. Cellulose is a polysaccharide of glucose units bonded together to make a polymer that can carry large tensile stresses, analogous to rebar in buildings. Lignin and hemicellulose are complex and disorganized aromatic structures that act as the cement, holding the fibrils of cellulose together. This paper will explore the mechanism of “growing” the cellulose chains, known as polymerization, and review the anomeric effects of cellulose bonding that make long chains possible and avoids chain termination. In addition, the binding interactions between lignin/hemi-cellulose and cellulose will be reviewed. Hydrogen bonding between the cellulose -OH groups keep fibrils together but also interact with phenolic and aliphatic groups in lignin. Lignin can be bonded directly to hemi-cellulose through ester or ether bonds, which in turn can bridge to cellulose creating an indirect bonding between lignin and cellulose. Finally, we’ll look at how these natural bonding mechanisms can be translated into innovative material systems that humans could use for everything from buildings to cars.

Trees are awesome. It’s important you agree before continuing so let me convince you. For us humans, trees provide oxygen, shade, and natural beauty; they provide wood for building and pulping for paper. Wood can be burned for heat, used to make biofuels, and is the material of choice for tools, furniture, and homes. For the animals that we live here with, trees are homes, protection, storage, and hunting grounds. For the fungus and microbes that power the natural world, decomposing trees are a buffet of nutrient rich organic matter. For the planet, trees capture carbon dioxide gas, balance temperature by absorbing sunlight, and reduce effects of soil erosion. If you are thinking “trees aren’t that important” I challenge you: imagine your bathroom without any paper products.

Now, let’s explore the mechanical and chemical structure that make wood one of the most common and versatile materials on the planet.

First, we’ll study the strength of a redwood tree.

Giant sequoia redwood trees can grow to be over 200 ft, one of the tallest being the General Sherman tree, standing proudly at 275 ft in Sequoia National Park. The tree is 36.5 ft wide at the base, and 14 ft wide 180 ft above ground level. Assuming a tapered circular cross section, the volume of the tree is then 52,513 ft^3 with the total weight of the tree at 1,312,825 lbs. (that's a heavy tree). The stress at the base from the weight of the tree is 8.7 psi. The highest recorded wind speed in the Sierra Nevada is 130 mph. The drag from the wind acting on the tree (figure at right) will be concentrated at the base, equating to about 28 psi. The combined force of the wind and the weight of the tree is about 36 psi in compression. To put this in perspective, your car tires are inflated to about 32 psi. This highlights the excellent architecture of redwood trees. **Even an 800-mph windstorm wouldn't break the trunk of the General Sherman tree**.

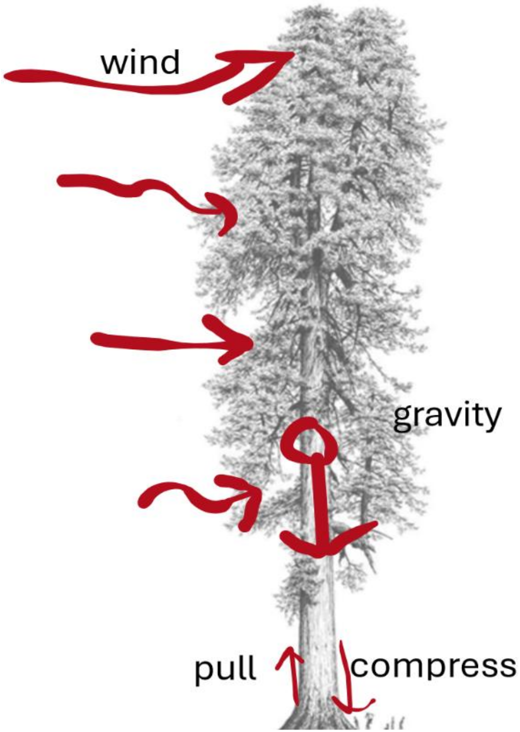


Figure 2. Tree mechanics

This extreme resilience stems from two key attributes, geometry and chemical structure. **Geometry**: the tree's wide base spreads out the forces efficiently, and the taper reduces the amount of wind the tree experiences higher up. Millions of years of evolution have naturally engineered redwood trees to endure heavy winds. **Chemical structure**: trees are a complex and strong cellular *composite* of cellulose, lignin, and hemi-cellulose. The interactions between these different molecular structures give wood its impressive strength, capable of withstanding 500 psi in compression for a new growth redwood tree [1].

Trees are a composite. What does that mean?

A composite is a combination of two or more materials that have greater properties than the individual materials. A great example is rebar and concrete: concrete is excellent for compression but terrible at tension, but add rebar? This combination created an extremely versatile material that has become a cornerstone of human infrastructure. Wood is a composite, in a way, but on a much smaller scale and from complex chemical interactions.

Consider the grain of wood

What you can see and feel. The sometimes linear and sometimes swirly pattern that gives wood its texture. This grain is a collection of individual fibers made up of plant cells. The cells are very simple compared to human or animal cells, and one of their primary functions is to provide rigidity to the tree. The cells get this rigidity from their cell walls, which make up most of the cellular system.

The cell walls run in the axial direction, up and down the height of the tree. Within the cell wall, we find molecular chains of cellulose, hemi-cellulose and lignin. These three components make up most of a plant's mass.

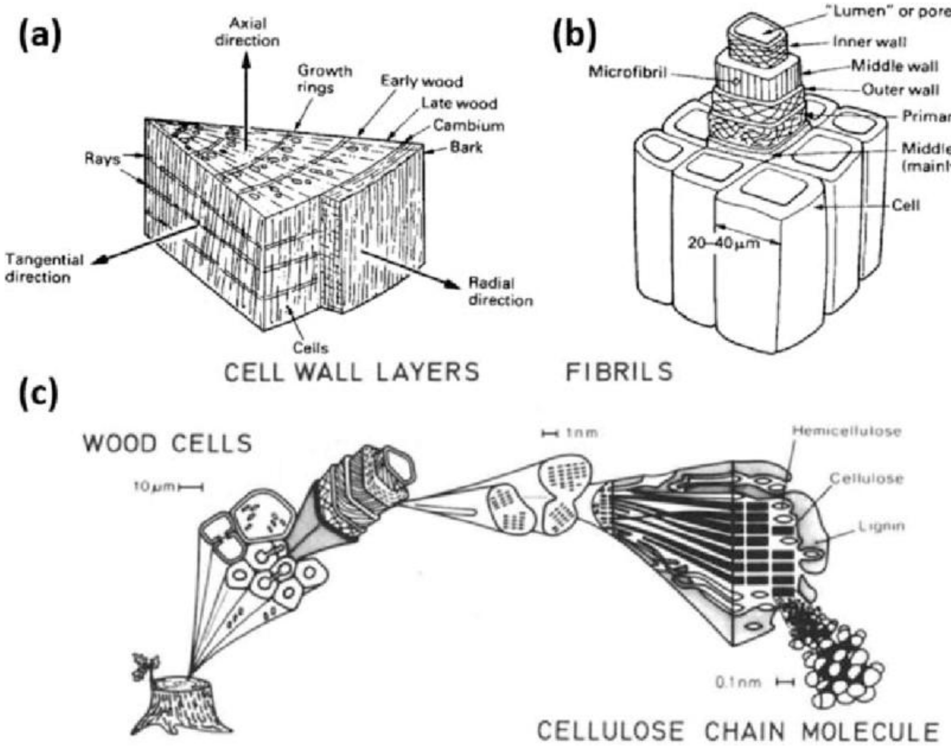


Figure 3. Chemical and cellular structure of wood

If we continue to zoom in, we see that cellulose is organized in bundles of individual fibers, that are held together by the interactions it has with between cellulose fibers, and its bonds with hemi-cellulose and lignin. Cellulose acts as the primary fibrous component, giving strength in the axial direction. Hemi-cellulose bonds indirectly to the surface and then to lignin. It holds the fibrils together and acts as a bridge that transfers force between the components. Lignin acts as a sort of glue that holds everything together. As an amorphous matrix, lignin can absorb compressive stress, which the cellulose alone is not capable of [2]. The complex bio-composite is a wonderful example of how multiple components working together can provide remarkable properties. Let's look a bit closer at the chemical structures. How are the components assembled? Why are they strong? How do the components interact?

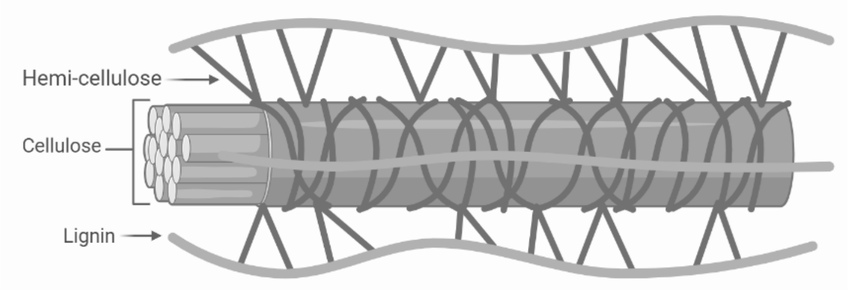


Figure 4. Cellulose bio-composite

Let’s start with Cellulose

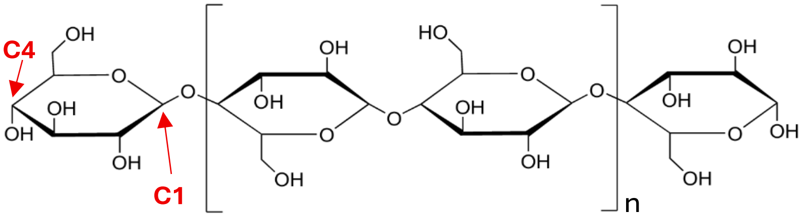


Figure 5. Cellulose structure

Cellulose is a highly linear polymer (which means “many units”) of covalently bonded glucose units, which are a product of photosynthesis (plants make glucose from light, water, and CO_2!). Cellulose is produced by plants on the order of several billion tons per year across the globe, making it the most abundant biopolymer on earth, and arguably our best carbon capture tool. A single chain of cellulose has between 300 and 15000 glucose units that are rotated 180° relative to the previous unit [3].

This alternating pattern allows for a very straight polymer whereas most synthetic polymers are coiled, like a cooked spaghetti compared to a bundle of uncooked spaghetti. The cellulose chains are straight because of the alternating conformation glucose and the hydrogen bonding that this allows. Hydrogens can interact through-space with the groups on neighboring cellulose chains to stabilize the chain. The highly linear chains maximize the availability of OH groups, providing the most opportunity for hydrogen bonding. The result are regions of crystal-like bundles of cellulose chains [3].

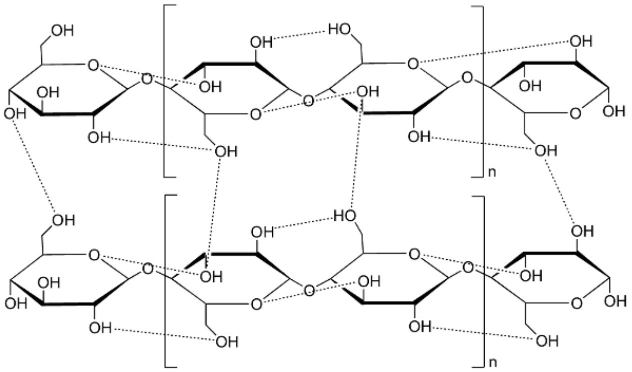


Figure 6. Cellulose chain hydrogen bonding

So, how does cellulose get assembled? It’s a great question that has an unfortunately complex answer. To start, we need a glucose unit that is functional. A regular old glucose unit can’t really do much, so we need to add something to kick things off. Plant biology has evolved to produce this catalyst, called UDP or uridine diphosphate [4]. Let’s walk through the synthesis by starting with a glucose unit.

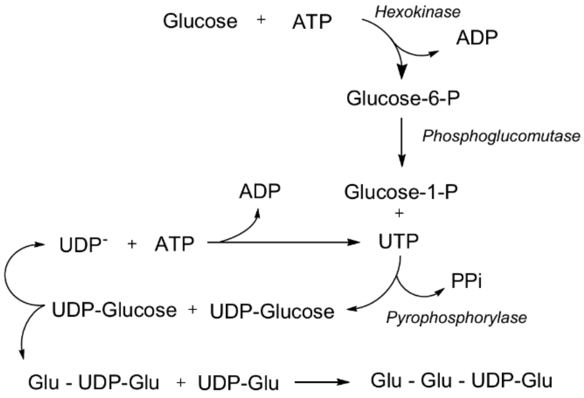


Figure 7. General formation of cellulose

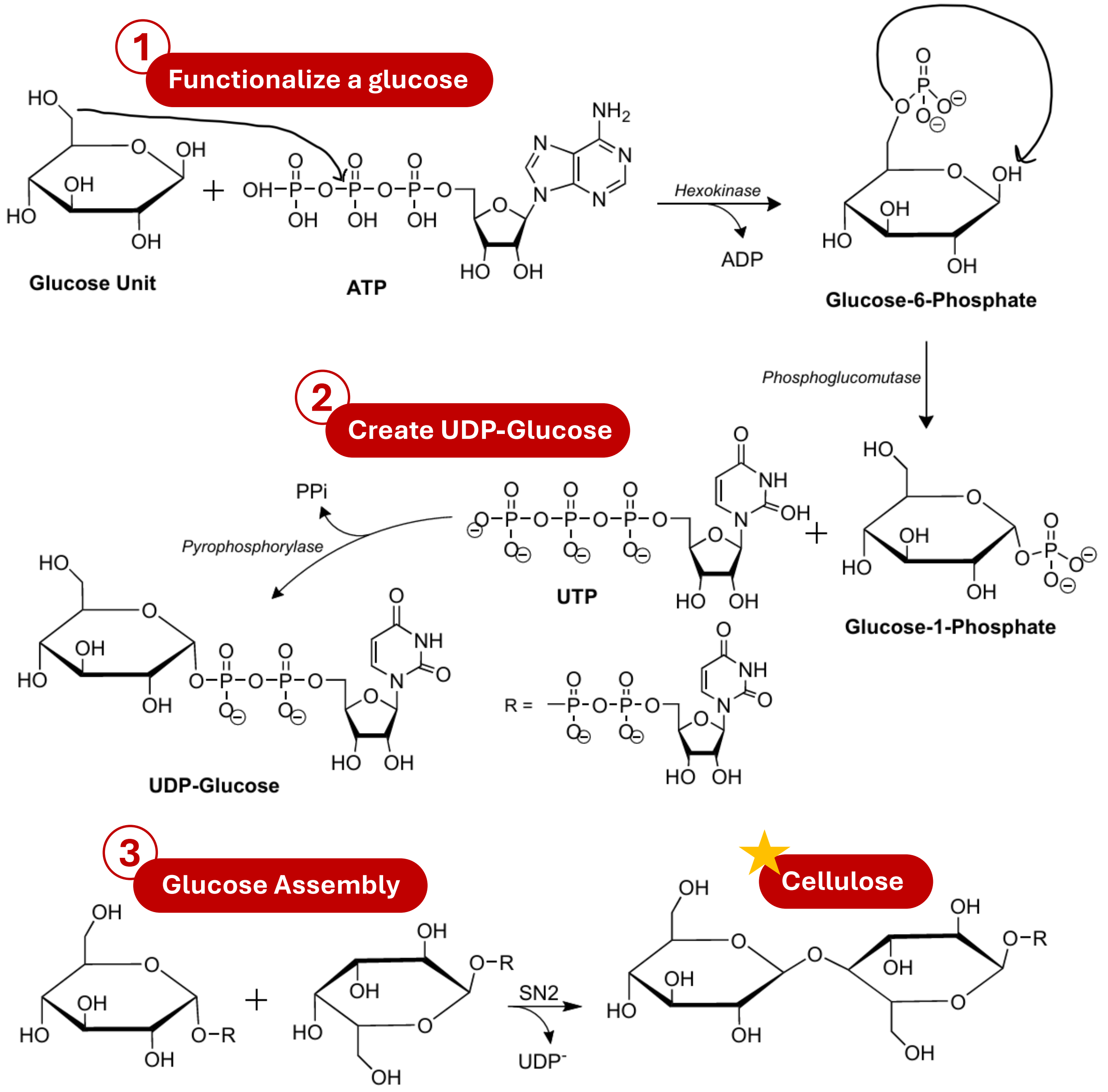


Figure 8. Overview on the synthesis of cellulose

The graphic above gives a mechanistic overview of how the reaction proceeds. ATP, which is essentially cellular energy, reacts enzymatically to attach a phosphate group to the exocyclic -CH^2-OH group. Then, a second enzyme transfers the phosphate group to the position 1 carbon (hence the name glucose-1-phosphate). Next, UTP is enzymatically added to the C1 unit, in an SN2-like reaction with PPi as a leaving group. Now we have UDP-glucose, the fundamental and reactive building block for cellulose [5]. Let's look a bit closer at the actual assembly mechanism that bonds two UDP glucose units together.

First, an enzymatically generated base deprotonates (removes a hydrogen atom) from the C4 of a UDP glucose. This base reaction turns the -OH group into an -O^-, called an alkoxide which is strongly nucleophilic, meaning it will want to donate its electrons to an electron-poor atom. The diphosphate (P-O-P) unit of UDP acts as a strong electron withdrawing group, pulling electron density away from the C1. This creates a partial positive charge on the C1 carbon, denoted as δ^+. The polarized C1 acts as an electrophile; it is electron poor and wants a negative charge, enter the alkoxide.

SN2-Like Attack

The alkoxide is drawn to the polarized carbon. It proceeds in a substitution reaction, where the O- attacks the backside of the C1 atom. The UDP group leaves the atom at the time the -O- bond is formed. This reaction is called SN2, a substitution with a leaving group. UDP- is a good leaving group because the oxygen groups provide resonance stability.

Rinse and repeat

The reaction continues to progress. A new UDP-glucose attacks the C1 position of the previous unit. This reaction can happen thousands of times on one chain, producing cellulose that is made up of thousands of glucose units.

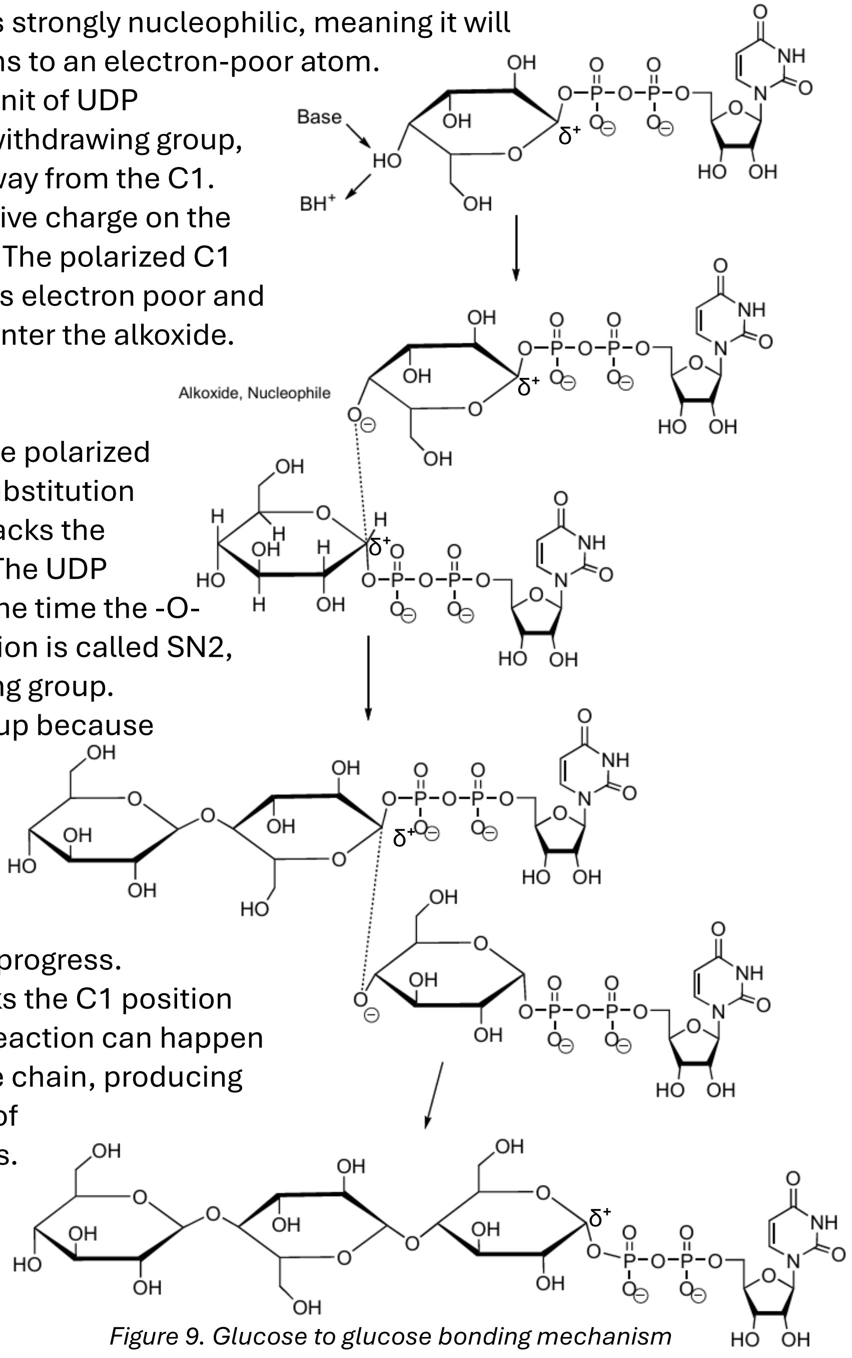


Figure 9. Glucose to glucose bonding mechanism

One of the coolest parts of this reaction is the UDP leaving group. After it departs, UDP can react with ATP to create UTP, which then reacts with glucose to make UDP glucose. The modified glucose now add to the chain! It’s an elegant way that biological systems recycle atoms to repeat reactions without consuming the compounds necessary for synthesis. [6]

Lignin and Hemi-cellulose

Hemi-cellulose is closely related to cellulose, and the structure looks remarkably similar. It does not bond directly with cellulose, but it does chemically and physically interact with cellulose through hydrogen bonds, Van der Waals forces, and physical entanglement. Van der Waals forces are weak intermolecular interactions from the attraction between nearby atoms. Hemi-cellulose is wrapped within and around cellulose, this physical entanglement provides strength between the two chemical compounds.

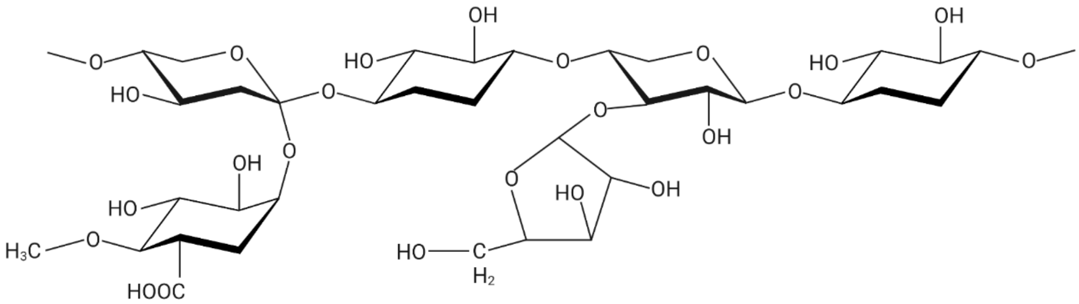


Figure 10. Chemical structure of hemi-cellulose

Lignin is far more complex in its disorder than hemi-cellulose or cellulose, much about its synthesis is still not well understood. It is network of bonded aromatic phenolic units that are joined through a specific type of bonding called radical coupling. The primary units are called monolignols, shown in the figure below as p-coumaryl, coniferyl, and sinapyl alcohol [7].

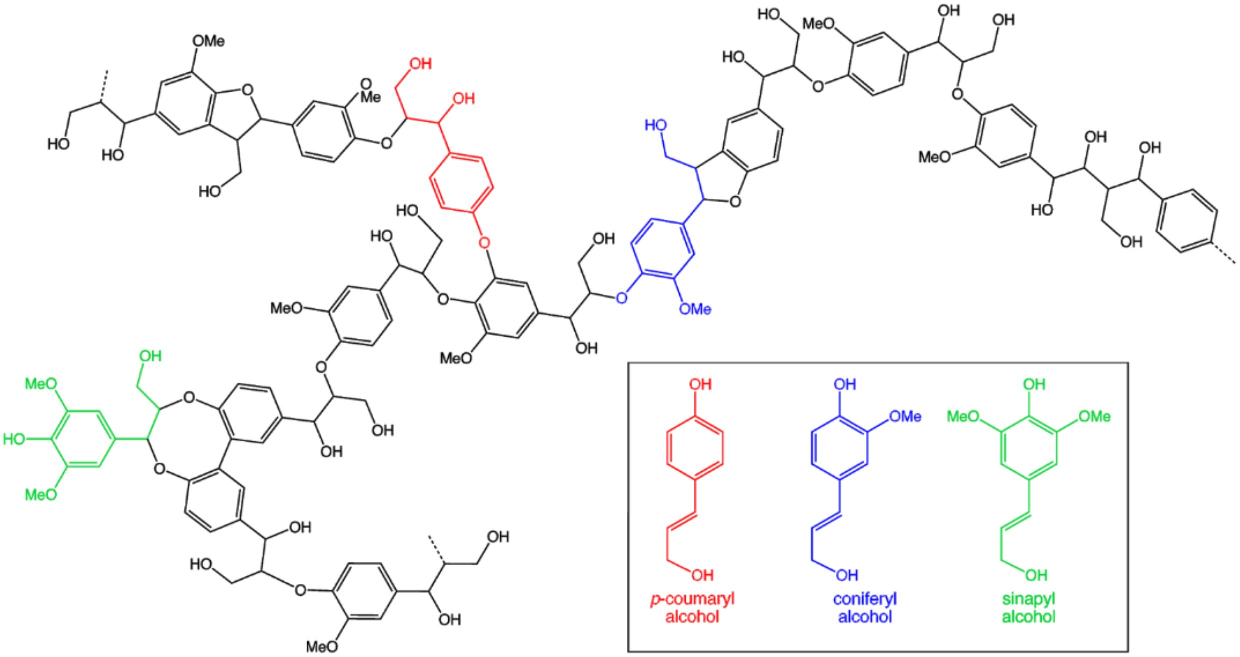


Figure 11. Chemical structure of lignin

Coupling is initiated by oxidation of a monolignol -OH group. An enzyme, laccase or peroxidase, removes the proton, H$^+$, and an electron, e$^-$, leaving the oxygen atom with an unpaired electron. The unpaired electron is called a radical, it is unstable and reactive. The radical coupling allows lignin to be a highly adaptable. It can easily form structure around the cellulose and hemi-cellulose chains, acting as a sort of concrete that binds everything together [8] [9]. Where a lignin unit is needed, radical coupling can bond it.

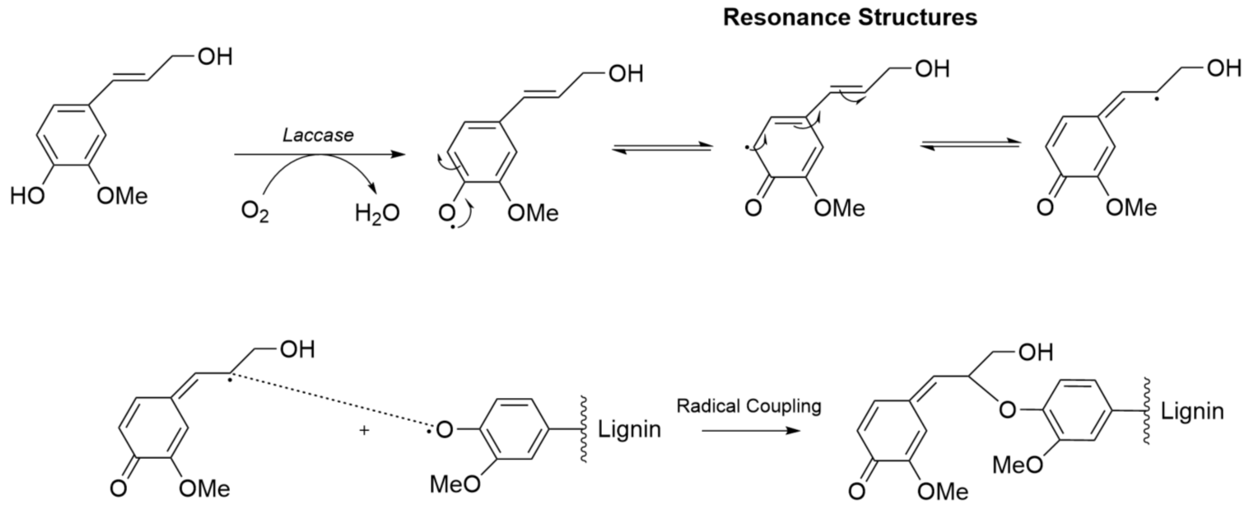


Figure 12. Radical coupling of lignin

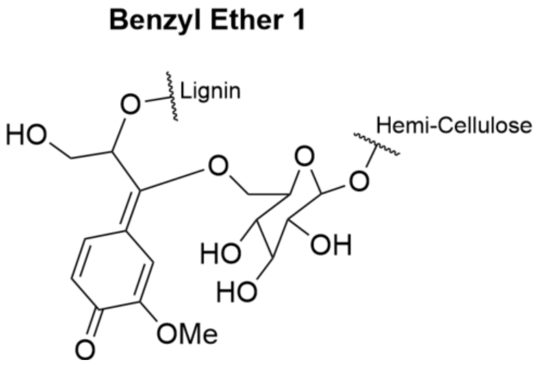


Figure 13. Lignin to hemi-cellulose bonds

Lignin can covalently bond to hemi-cellulose, in much the same way that in bonds to itself. This is perhaps the most important interaction in the bio-composite and ties the whole system together. Lignin-hemi-cellulose bonds are called lignin-carbohydrate complexes (LCCs). In this benzyl ether 1 bond, we see that a hemi-cellulose OH group has attacked the radical of a lignin unit, forming a strong covalent bond between the two plant chemical structures [10].

Bringing it all together

Long chains of cellulose provide strength in tension. It's entanglement with hemicellulose transmits and redistributes forces through reversible hydrogen bonding, and the amorphous lignin matrix resists loads by compressing. The coupled responses of the three distinct components yield wood's remarkable combination of stiffness, toughness, and compressive strength.

How can this organic bio-composite inspire new materials?

You may or may now know that humans already make our own synthetic composites. We talked about concrete and rebar earlier, but human-made composites go back way further than modern buildings. For example, ancient Egyptians figured out that adding straw to clay made their bricks much stronger [11]. Today, we use many different types of composites. The most common type is fiberglass and resin, where thin glass fibers are held within a resin matrix. Even stronger are carbon fibers in an epoxy-resin matrix, which we use for some of the highest performance applications, like formula one or rocket components.

But composites are not always amazing. They have a few pressing issues:

- Strength depends on fiber orientation
- Hard to recycle[1]
- Not strong in compression
- High-cost materials
- Complex manufacturing techniques
- Volatile chemistries

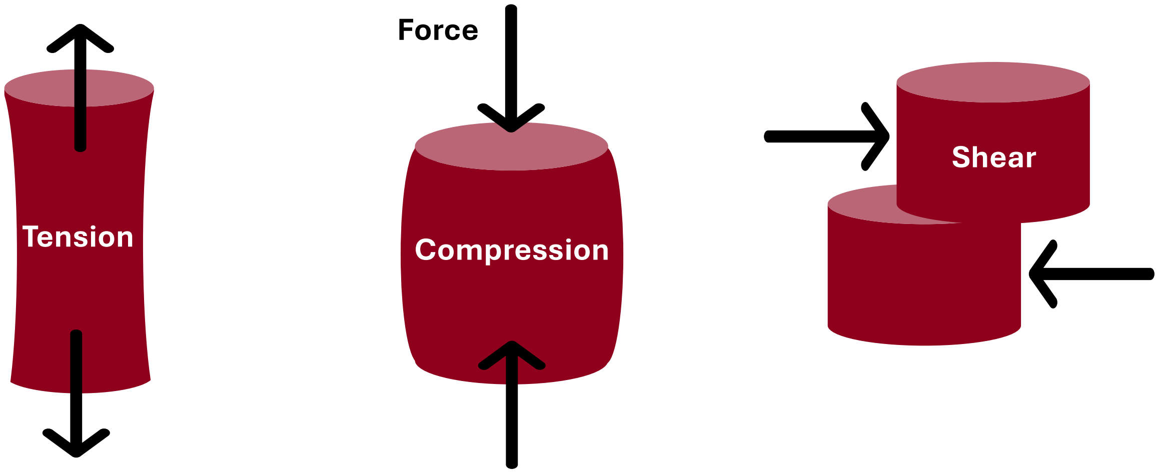


Figure 14. Mechanical forces

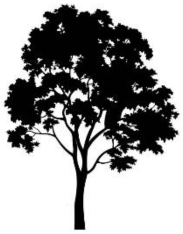
The highly aligned molecular chains that make up fibers are very strong in tension. Imagine holding a rope with both hands. By pulling outwards, you are putting tensile stress on the rope, and it will be nearly impossible to snap. Now, imagine pushing your hands together, the rope will not resist at all. These same rules generally apply to modern composites. Carbon or glass fiber composites rely on the matrix for compressive strength, and most of our matrices are not particularly strong in compression. We could use a ceramic matrix, which totally works and is currently how many heat shields for space vehicles are made. But these ceramic composites are extremely hard to make and very expensive.

[1] The resins we use are known as thermosets, which involve an irreversible reaction forming strong chemical bonds that require lots of energy to break. Our best methods for recycling epoxy-carbon fiber composites are by burning the hell out of them, destroying the matrix, and recovering some of the degraded fibers. Even more, there are not simple natural pathways that are good at breaking these strong chemical bonds, hence the wind turbine blade graveyards you've probably seen. Some of these composites will last thousands of years.

So, what can we do? We can follow nature's lead. We know that wood is similarly strong in compression and tension [1]. We've learned about the interactions between lignin, hemi-cellulose, and cellulose. The interconnected and hydrogen-bonded network is strongly linked. Cellulose carries the tension, lignin can be compressed, and the hemi-cellulose intermediate transfers stresses between the components.

725 psi

Tensile strength perpendicular to grain



Black Maple

Green (not dried)

594 psi

Compressive strength perpendicular to grain

Figure 15. Mechanical strength of maple wood

We can modify our current composites to better handle stresses in all directions and make strong bonds between fibers and the resins we use. To explore this, let's look at the chemical structure of carbon fiber [12]. The fiber is a lattice of 6-membered carbon rings that is extremely strong in tension but not strong in compression.

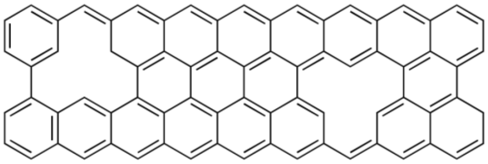


Figure 16. Carbon fiber (non-PAN based)

The interface between carbon fibers and resins is critical. The strength of the bonding between the surface of the fibers will determine the overall strength of the composite. Engineers have been hard at work on dozens of chemistries to promote better bonds at the interface [13]. The tried-and-true method is coating the surface in a polymeric material that interacts better with the resin in a process known as sizing. This is a strong mechanical system, but we can use our inspiration from the natural bio-composite to come up with a new chemistry.

Graft cellulose to carbon fiber

We can graft cellulose nanofibers to the oxidized surface of carbon fiber to create a type of "fuzzy" fiber. These "nano-arms" can reach further into the resin matrix to provide extra area for resin-fiber interaction, greatly strengthening the composite. This is like the way hemi-cellulose acts as a mechanical intermediate between cellulose and lignin.

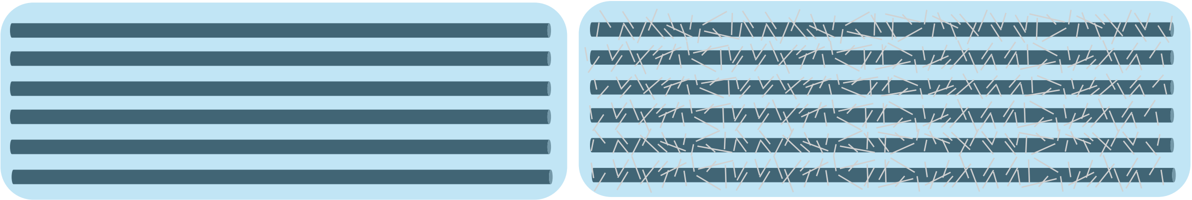


Figure 17. Carbon fiber with and without cellulose grafting
(black = fibers, blue = resin, grey = cellulose nano fibers)

There’s load of chemical interactions that would make this grafting possible, but we’ll use a mechanism like the way glucose units are joined to make cellulose. The reaction begins by oxidizing carbon fiber to add functional units to its surface. We then protonate the $-CH_2-OH$ groups with acetic acid to create $-H_2O^+$, which will act as a good leaving group for a substitution reaction. Next, water departs, leaving $-CH_2^+$, which is prime for a reaction with the lone pair of electrons on cellulose’s $-CH^2-OH$ group. The result is a covalently bonded cellulose fiber to the surface of carbon fiber. It’s worth noting that rehydration is possible; after water leaves it could easily and more readily attack the -CH+ compared to the bulky cellulose fibers. To combat this, this reaction should occur in low water/high solvent conditions and with high concentrations of cellulose fibers.

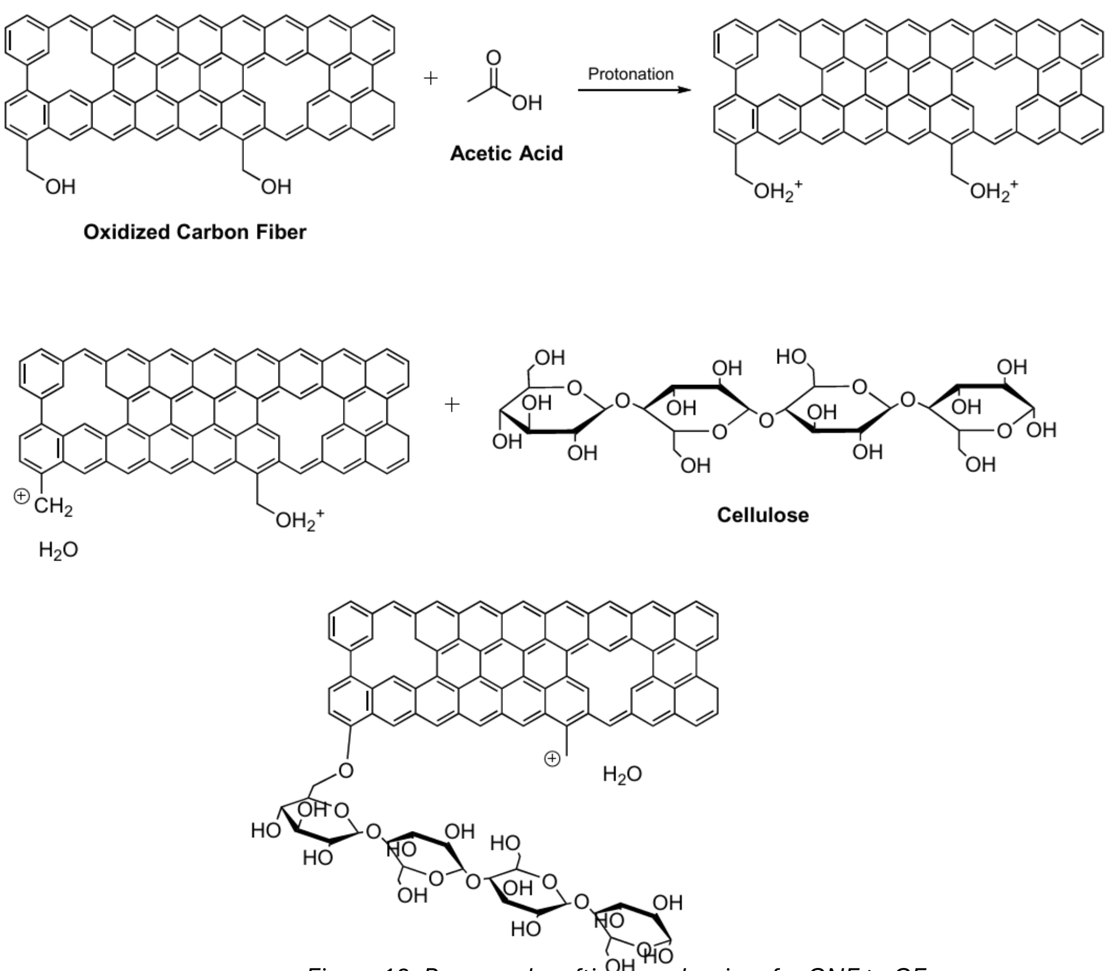


Figure 18. Proposed grafting mechanism for CNF to CF

So, how do trees stand tall?

I hope that now you can tell me.

Graphics in the order they appear:

Bibliography:

[1] D. E. Kretschmann, “Mechanical Properties of Wood”.

[2] A. Wiedenhoeft, “Structure and Function of Wood”.

[3] “(PDF) Biopolymer-Based Materials from Polysaccharides: Properties, Processing, Characterization and Sorption Applications,” in *ResearchGate*. doi: 10.5772/intechopen.80898.

[4] G. B. Pedersen, L. Blaschek, K. E. H. Frandsen, L. C. Noack, and S. Persson, “Cellulose synthesis in land plants,” *Mol. Plant*, vol. 16, no. 1, pp. 206–231, Jan. 2023, doi: 10.1016/j.molp.2022.12.015.

[5] S. Li, L. Bashline, L. Lei, and Y. Gu, “Cellulose Synthesis and Its Regulation,” *Arab. Book Am. Soc. Plant Biol.*, vol. 12, p. e0169, Jan. 2014, doi: 10.1199/tab.0169.

[6] J. T. McNamara, J. L. W. Morgan, and J. Zimmer, “A Molecular Description of Cellulose Biosynthesis,” *Annu. Rev. Biochem.*, vol. 84, pp. 895–921, 2015, doi: 10.1146/annurev-biochem-060614-033930.

[7] Unknown, “How about Lignin?: Lignin structure,” How about Lignin? Accessed: Nov. 20, 2025. [Online]. Available: https://howaboutlignin.blogspot.com/2013/07/lignin-structure.html

[8] J. Yun, Q. Yang, and G. Liu, “Mechanisms of lignin degradation and persistent free radical formation under light or thermal exposure,” *Cell Rep. Sustain.*, vol. 2, no. 1, p. 100267, Jan. 2025, doi: 10.1016/j.crsus.2024.100267.

[9] Y. Tobimatsu and M. Schuetz, “Lignin polymerization: how do plants manage the chemistry so well?,” *Curr. Opin. Biotechnol.*, vol. 56, pp. 75–81, Apr. 2019, doi: 10.1016/j.copbio.2018.10.001.

[10] N. Giummarella, S. Koutaniemi, M. Balakshin, A. Kärkönen, and M. Lawoko, “Nativity of Lignin Carbohydrate Bonds substantiated by Biomimetic Synthesis,” *J. Exp. Bot.*, vol. 70, July 2019, doi: 10.1093/jxb/erz324.

[11] J. Hays, “Mud-Brick Construction in Ancient Egypt | Middle East And North Africa — Facts and Details.” Accessed: Oct. 22, 2025. [Online]. Available: https://africame.factsanddetails.com/article/entry-168.html

[12] “(PDF) Tailoring the Stabilization and Pyrolysis Processes of Carbon Molecular Sieve Membrane Derived from Polyacrylonitrile for Ethylene/Ethane Separation.” Accessed: Nov. 20, 2025. [Online]. Available: https://www.researchgate.net/publication/357882775_Tailoring_the_Stabilization_and_Pyrolysis_Processes_of_Carbon_Molecular_Sieve_Membrane_Derived_from_Polyacrylonitrile_for_EthyleneEthane_Separation?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6Il9kaXJlY3QifX0

[13] Y. Li *et al.*, “Revisiting the sequential evolution of sizing agents in CFRP manufacturing to guide cross-scale synergistic optimization of interphase gradient and infiltration,” *Compos. Part B Eng.*, vol. 287, p. 111825, Dec. 2024, doi: 10.1016/j.compositesb.2024.111825.

[14] “Pin on Redwood Tattoo,” Pinterest. Accessed: Nov. 20, 2025. [Online]. Available: https://www.pinterest.com/pin/798896421381815314/

[15] “Pin on Sequoia Tree Tattoo,” Pinterest. Accessed: Nov. 20, 2025. [Online]. Available: https://www.pinterest.com/pin/332281278732331829/

[16] C. Chan *et al.*, “Composites of Wood and Biodegradable Thermoplastics: A Review,” *Polym. Rev.*, vol. 58, pp. 00–00, Sept. 2017, doi: 10.1080/15583724.2017.1380039.

[17] “Redwood Cliparts #2899027 | Clipart Library.” Accessed: Nov. 21, 2025. [Online]. Available: https://clipart-library.com/clipart/82677.htm