



Finland has more than 230,000 sq km of forest land, and its tree canopy increases every year.

SUSTAINABILITY

Looking for Finland's future in its forests

Researchers at Aalto University hope new scientific ideas can revitalize one of the country's traditional economic engines

SAM LEMONICK, C&EN WEST COAST

Thick stands of pine, spruce, and birch cover three-quarters of Finland, Europe's most forested nation.

So it's no surprise that paper and other wood products are a cornerstone of the Finnish economy. What might be a surprise is that today only 20% of Finland's exports come from its forests—down from 80% in the early 20th century.

The world's been changing. Newspapers are closing their doors, taking with them the demand for paper. Metals and composites are replacing wood in building materials. Even the rise of online shopping and the resulting boom in cardboard hasn't stopped the slide. A sector that had grown consistently for 100 years plateaued in 2000.

That might have spelled disaster for Finland. But the forested nation had seen the writing on the wall for a long time. In the late 1990s, representatives from industry, academia, and government in Finland gathered multiple times to lay out a plan. Finland had already seen the value of embracing new technology demonstrated in one of its greatest success stories: Nokia. The Finnish industrial giant—which,

incidentally, started as a paper company—shed its tire, computer, and other divisions to go all in on mobile phones, a decision that made Nokia a household name around the world. Maybe, Finland's leaders thought, the timber industry could pivot too. And maybe science and technology could help.

Last year, one piece of the plan that stemmed from those meetings came to fruition. Aalto University, located just outside Helsinki, opened the doors of its department of bioproducts and biosystems, known among the researchers who work there as Bio².

The university's department of forest

Aalto's department of bioproducts and biosystems (Bio²) at a glance

- ▶ **Year established:** 2017
- ▶ **External funding:** \$7.8 million
- ▶ **Professors:** 18
- ▶ **Ph.D. students:** 67
- ▶ **Papers published in 2017:** 200

products technology combined with its biochemistry and biotechnology groups to create the new unit. Chair Herbert Sixta explains that the move brought researchers together to think innovatively about wood and its chemistry.

The focus of Bio²—finding new and better ways to use wood—isn't that much different from the work that had been carried out by the department of forest products technology, Sixta says, "but the tools we have now in our hands are not limited to engineering and chemistry. They've been extended to biotechnology and biochemistry."

Revamped, the department looks far beyond paper. Sixta's research focuses on making textiles from wood fibers. His colleagues are using wood to make nanocrystals and nanoparticles that can deliver drugs, facilitate reactions, and filter chemicals. They're trying to inject new life into the forest products field.

"Aalto is one of the leading universities in this area, both in Finland and in Europe. They've been doing very well," says Mika Aalto, who runs the enterprise and innovation department at the Finnish Ministry of Employment & the Economy. (Aalto

is a common family name in Finland.)

The formation of Bio² mirrors larger changes happening in Finland. Aalto University is less than a decade old, founded in 2010 by combining Helsinki University of Technology, the Helsinki School of Economics, and the University of Art & Design Helsinki, each of which was more than a century old.

Named after perhaps Finland's most famous son, the architect Alvar Aalto, the adolescent university is seen as part of the country's transition to a high-tech economy. Microsoft, Nokia, and other companies have incubators on or near its campus, formerly the site of the 1952 Summer Olympics.

Attracting corporations, researchers, and money from outside Finland is part of Aalto's lofty goals. Like the timber industry, the university is hoping to reinvent itself for a new century.

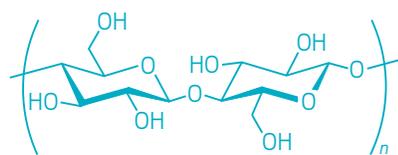
To facilitate that, Finland has fostered a collaborative exchange of ideas and money among its universities, corporations, and government research agencies. Bio²'s website lists dozens of industry partners. One is Metsä Fibre, which makes pulp and other bioproducts from wood. "I think in a small country like Finland, close cooperation is one key to success," says Niklas von Weymarn, vice president of research at Metsä, which relies heavily on Aalto and other university R&D facilities to support its product innovation.

Seeing the tree for its molecules

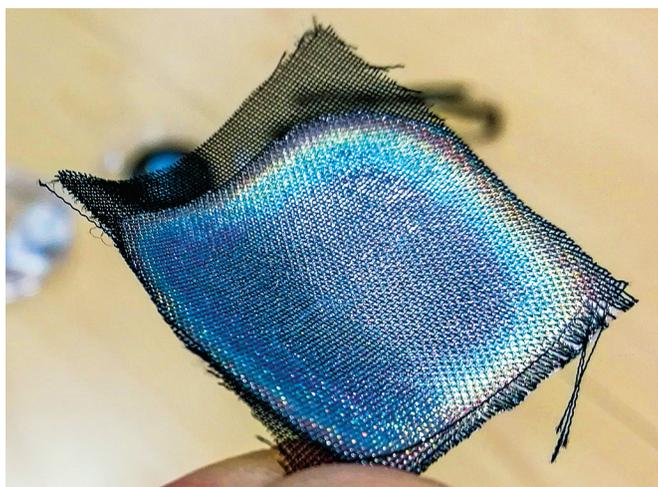
To understand what's happening in Finland, you first have to understand wood. It has two major structural components: cellulose and lignin.

"When you look at wood and bark, nature has made beautiful molecules," says Timo Heikka, a vice president in research and development at Stora Enso, a Finnish pulp and paper company.

Cellulose is a linear polysaccharide of D-glucose molecules that makes up



Cellulose



Cellulose nanocrystals create iridescent structural color on a fabric swatch.

about half of wood by mass. It's the longest known natural polymer, and it provides wood's tensile strength—how much a material can be pulled on before it breaks.

Lignin is a class of molecules that give wood its compressive strength—how much load a material can bear before it breaks. Between one-fifth and one-third of wood's dry mass is lignin. Chemically, lignins are cross-linked, phenolic polymers.

The rest of wood's mass is filled with the branched polysaccharide hemicellulose, which has so far found fewer uses in industry. Separating cellulose, lignin, and hemicellulose is the first step of wood processing. Felled trees are ground into chips. These can be cooked in a basic solution of sodium hydroxide and sodium sulfide or an acidic solution of sulfurous acid; both approaches can break down and dissolve lignin and hemicellulose to form a goo. What remains is mostly cellulose pulp, which is rolled and dried to make paper.

Traditionally, pulping factories burn the goo, a hydrocarbon mixture called black liquor, as fuel in boilers or generators.

The philosophy underlying what's happening in Finland right now is that, given the structural complexity and properties of the molecules that make up wood, scientists can do better than black liquor and wood pulp.

Take Sixta's textiles lab. Making fiber from wood isn't a new idea. The French scientist Hilaire de Chardonnet made an "artificial silk"—what we now call rayon—by extruding a cellulose mixture in the 1880s.

Rayon from wood cellulose had long been a feature of Finland's wood products industry, but the last legacy plant that was manufacturing it closed in the 1990s. It was old, inefficient, and environmentally unfriendly. "But demand is still growing

because the population is still growing, and the average quality of life is increasing," von Weymarn says. "So where do we get fibers? This is where the forest industry sees new opportunity."

Sixta has come up with one possibility for a more energy-efficient process: using an ionic liquid to dissolve cellulose, which can then be spun into rayon fibers. He's experimented with 1,5-diazabicyclo[4.3.0]non-5-enium acetate, developed with Ilkka Kilpeläinen at the University of Helsinki.

The ionic liquid can dissolve cellulose from wood pulp at temperatures below 90 °C. The researchers spin the resulting solution into fibers. According to published results, this so-called Ioncell process produces fibers with better physical properties than other cellulose-derived fibers (*Textile Res. J.* 2015, DOI: 10.1177/00405175155591774). And Sixta is working to perfect a recycling process for the ionic liquid, boosting Ioncell's green cred.



Finnish designer Marimekko created dresses from cellulose fibers made with Sixta's Ioncell process.

CREDIT: ORLANDO ROJAS (FABRIC); MARIMEKKO (DRESS)

Aalto researchers demonstrated their new fibers in a 2014 fashion show, debuting dresses by the Finnish design company Marimekko. Now companies like Metsä Fibre are working with Sixta to figure out how to commercialize the Ioncell process.

“This is a very good example where research communities flagged opportunity and companies [capitalized],” von Weymarn says.

Using cellulose to make fibers is a natural choice, but it’s not the only option. Aalto University chemical engineer Orlando Rojas works with cellulose in a different form: as nanocrystals and nanofibrils.

In wood and other plants, cellulose polymers bundle together to form fibrils, which in turn assemble into larger strands that make bulk cellulose fibers. These fibrils have tightly packed crystalline regions along with less-ordered amorphous sections.

Acids can penetrate the disordered segments and hydrolyze the polymer, cleaving off tiny, stiff, rodlike segments referred to as cellulose nanocrystals. Rojas has found a number of ways to use these cellulose nanocrystals, just one member of a larger class of materials called nanocellulose. In water, they network to form viscous hydrogels. Rojas has a patent, filed with the oil company Halliburton, that uses the crystals to increase the viscosity of drilling fluids for better insulation, lubrication, or hydraulic fracturing.

That’s probably the least elegant application for the abundant wood molecule. Because cellulose is composed entirely of D-glucose, the nanocrystals are inherently chiral. That makes it possible to use them for filtering or detecting enantiomeric compounds. Rojas’s colleague Mark MacLachlan at the University of British Columbia has demonstrated that cellulose nanocrystals can act as templates for making such filters, yielding silica films with chiral pores (*Nature* 2010, DOI: 10.1038/nature09540).

They can also be used to give materials color. Insects like beetles and butterflies are famous for using nanostructures in their shells and wings to generate shimmering colors. These structures rely on chitin to refract light and produce new hues, but cellulose nanocrystals can do the same thing.

Their chirality lends the tiny rodlike particles a helical twist; tuning their lengths tunes the different colors they produce. The more hydrolyzed the source cellulose was, Rojas found, the smaller

and more crystalline the nanocrystals were, and the shorter the wavelengths of light reflected, producing colors from blue to white (*Small* 2017, DOI: 10.1002/sml.201702084).

Cellulose is not all that ties Rojas and Sixta together. Both are outsiders in Finland. Originally from Venezuela, Rojas came to Bio² by way of North Carolina State University, and Sixta hails from Austria. That’s a theme in their department at Aalto, where Dean Janne Laine says only two members of the original forest prod-

ucts technology department remain.

The push to modernize Finland’s wood products industry is happening at the same time that Aalto is trying to bring itself more in line with other Western universities. Sixta says proudly that about 65% of the department’s funding—some \$7.8 million—comes from external competitive grants, many of them from the European Union.

Lignin has usually played second fiddle to cellulose. Ninety-five percent of the lignin extracted from trees and plants is

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burned to generate electricity. Lignin can be a pain, chemically; whereas cellulose is ordered and homogeneous, lignin is a chemically diverse mess.

"Its structure might not ever be known," Monika Österberg, a chemist at Bio², says of lignin's complexity.

But that messiness gives Österberg a lot to work with. She's found a way to make lignin nanoparticles and to modify their characteristics so they can be useful in various applications.

Making these nanoparticles turns out to be relatively simple. Österberg dissolves lignin in tetrahydrofuran, then adds the resulting solution to water, where the lignin molecules self-assemble into globules—the nanoparticles—by turning their

hydrophilic parts outward.

She was surprised to discover that's all it took. Previous researchers have resorted to bombarding lignin with ultrasonic waves to turn it into nanoparticles. Others have acetylated the polymer with acetyl bromide, a fairly nasty chemical to work with. These different experiences may partly depend on how the lignin is processed or what type of wood it comes from, Österberg says, something she's seen in her lab.

Lignin has inherently useful properties that researchers at Aalto are interested in exploiting. It scavenges ultraviolet photons thanks to its extensive aromaticity, which means in nanoparticle form, it could work as a sunscreen ingredient. And

Österberg, along with colleagues at Aalto and the Finnish National Institute for Health & Welfare, found that milled lignin effectively stopped methicillin-resistant *Staphylococcus aureus* from growing, possibly due to guaiacyl, syringyl, carboxyl, and other groups on the polymer (*BioResources* 2017, DOI: 10.15376/biores.12.4.7601-7614).

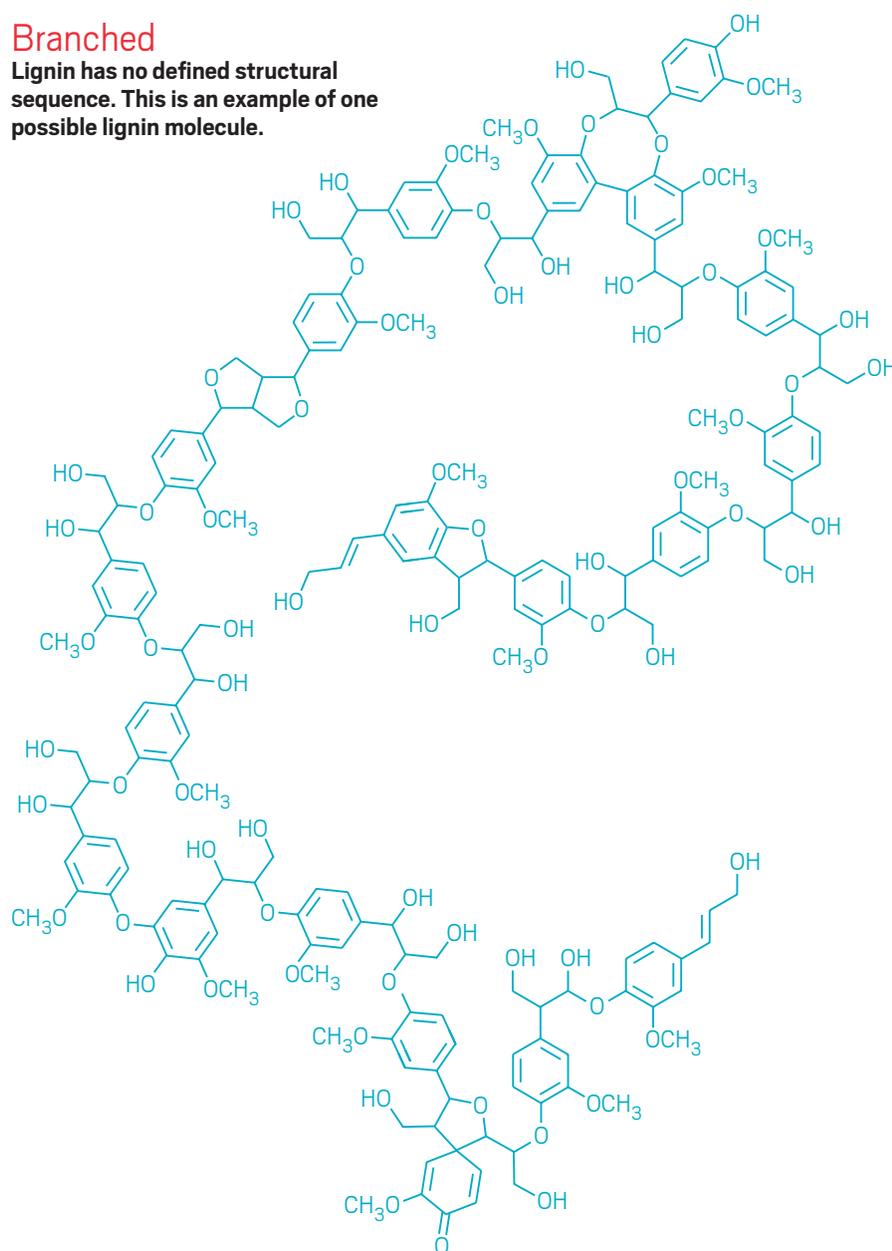
Österberg's Aalto colleague Mauri Kostiaainen has also been working on lignin nanoparticles. His, he hopes, will fight cancer.

Targeted drug delivery with nanoparticles could soon be mainstream medicine, but right now the raw materials for the particles come from oil and gas. A better option, think Kostiaainen and Österberg, might be sustainable, renewable lignin.

Working with physical chemist Hélder A. Santos of the University of Helsinki, Kostiaainen carboxylates lignin, which he then makes into nanoparticles using the same method as Österberg. The carboxylate groups allow the researchers to functionalize the lignin nanoparticles with cell-penetrating proteins and pH-responsive polymers to help deliver anticancer drugs into tumor cells. Loaded with benzazulene, a poorly soluble drug, the nanoparticles are effective at killing cancer cells in cultures and remain intact under conditions meant to simulate the body (*Nanomedicine* 2017, DOI: 10.2217/nnm-2017-0219).

Branched

Lignin has no defined structural sequence. This is an example of one possible lignin molecule.



Wood in the new millennium

Other intriguing possibilities in wood are waiting to be realized. Aalto scientists talk about carbon fiber made from or reinforced with cellulose and lignin. And they envision flexible, transparent films that could be used in displays or conductive, wood-based polymers for electronics.

It is impossible to say how long we have been harvesting wood but easy to imagine that we've been using it at least since we became humans. Chimpanzees, after all, are known to use sticks as tools. The oldest written story in human history describes the king Gilgamesh in the third millennium BCE cutting down a forest to make a raft.

We are in a different age today, vastly different even from the world of a few centuries ago. We have materials at our disposal—plastics, carbon fiber, metal alloys—that would be almost unrecognizable to our ancestors. But in Finland, at least, people still see a crucial resource in their forests and trees. Not just for the past and the present, but for the future as well. ■