===== Commercial Polymers Saved Elephants (0:00) =====

Charles Darwin was a big fan of billiards. He loved his billiard table; it was one of his prized possessions and one of the most valuable things he owned.

Well - not the actual table itself. In fact, it was the balls that were so valuable. Pure ivory carved from the tusks of elephants, only the wealthiest could afford a full set. Luckily he was married to an heiress. A full set of sixteen billiard balls would require at least one, possibly two, full elephants worth of ivory.

The idea that any bar in the world might contain a billiard table available for anyone to play, and not like run out of the bar with your pockets full of valuable ivory would have sounded insane in 1850. And the billiard industry was well aware of this problem. Billiard balls were getting more expensive, elephants were getting more rare. It was thus not with an environmental motive, that in 1867 the Phelan and Collender Pool Supply Company offered ten thousand dollars to anyone who could come up with a substitute material that worked as well as ivory, but could be produced more quickly and sustainably then dead elephants.

An inventor named John Wesley Hyatt took on that challenge. He used nitrocellulose, a flammable solid, created by mixing cotton with nitric acid to create a hard, shiny, white sphere. The properties were extremely similar to ivory billiard balls. The company never gave him the prize. But he did patent the technique, using it to create billiard balls, piano keys and even teeth, becoming pretty dang wealthy in the process.
Also he pretty much created the industry that made all of the polymer materials that surround you right now, and that we'll be discussing today in Crash Course Chemistry. Also elephants didn't go extinct, so that's a plus.

[Crash Chemistry Theme]

The polymer that John Hyatt worked on was, somewhat unsurprisingly, kinda crummy. It worked well once it was created, but the manufacturing process was dangerous because nitrated cellulose can explode in a warm breeze.

So luckily, some replacements started creeping in. Replacements with some names you probably recognize, like polyvinyl chloride or PVC, Bakelite, polystyrene, polyester, and nylon. These are all polymers; huge chains or sometimes three dimensional networks of repeating organic units called monomers. Each polymer has a monomer, but they're all relatively simple at that basic one unit level. The trick is that they bond to each other on each side potentially forever, though in reality the chains are sometimes hundreds, sometimes thousands, sometimes hundreds of thousands of units long.

===== Ethene aka Ethylene(2:29) =====

In order to make a polymer all you need is a molecule that can easily bond to another identical molecule at two points. And the simplest of those is ethene, also known as ethylene. It's polymer, you'll be unsurprised to hear is polyethylene, which you've probably heard about. We'll talk more about the specifics in a second, but basically because pi bounds in the double bond are weaker than sigma bonds they can be broken and new monomers can be added.

Just to note to avoid confusion: polyethylene has that "-ene" sound in it, right, but it's not an alkene because all those double bonds get broken to form new sigma bonds. It's a polymerized alkene, but the molecule itself is an alkane. It's confusing so I thought it's worth pointing out.

===== Addition Reactions (3:08) =====

Now chemists might want a bunch of different things out of their polymers; maybe they want it to be stretchy, maybe strong, maybe transparent, maybe recyclable. Polyethylene is transparent and thermoplastic, meaning it can be melted and reformed. Making it recyclable. Some other polymers like polyurethane or Bakelite are thermoset. Which means that they change chemically during some kind of curing process and cannot be melted down and reformed. Polyethylene can actually be converted into a thermoset polymer by introducing cross-links, basically molecular bridges between those polymer chains. Any plumbers out there probably have heard of cross-linked ethylene or PEX pipe. Which is what this is. It's extra, super strong because of those cross-links.

Polyethylene is also nice because it's strength can be varied by changing the size of the molecules. If they are allowed to polymerize until they are tens of thousands of monomers long the plastic they will form will be all knotted up in these ultra long chains and it will be extremely strong. That is why this HDPE, high density polyethylene, is a strong bottle. Whereas this is much squishier, this is low density polyethylene.

However those ultra long chains also make it much more viscous when heated and thus more difficult to process. It also loses some of its opacity, and becomes more of that milky white color. Now polyethylene is great. It's really great, so great that it's the most common plastic in the world. We produce over eighty million tons of it per year. But we want a lot out of our plastics - strength, color, elasticity, resilience, recyclability - we need everything from saran wrap to car tires. All of these are traits that chemists work tirelessly to create in the early to middle twentieth century and continue to work on even today. One of the earliest techniques they used to try and bring out new properties was to change the substituents on the ethylene monomer. Just to see what would happen.

===== Ethene-based Polymers (4:44) =====

Like, what if we swapped out one of the hydrogens for chlorine? Well you get polychloroethene, kinda, that's not what we call it. Okay so remember how benzene when attached to a chain is a phenyl group, and how those two words have nothing to do with each other. Well the same thing goes for the ethene functional group, which is called a vinyl group. It's an old word, super old, it comes from the Greek word for wine. And that is why chloroethene is more commonly called vinyl chloride. And polychloroethene is more commonly called polyvinyl chloride, or PVC. Which is what this little ducky is made out of and also what records are made out of; which is why we call them vinyl.

Now what happens when we change out a hydrogen for a methyl group? Well then suddenly this molecule is a propene or, if you are using ye old ways, a propylene. And, yes, if you polymerize it, it becomes polypropylene.

If one of the hydrogens is replaced with a phenyl group, well that chemical was first derived from trees in the Styrax family, so it's called styrene. Polymerize it, polystyrene. Make a foam out of it, Styrofoam.

Now if you change all four of the hydrogens on the base ethylene with fluorine it becomes tetrafluoroethylene. Polymerize that and instead of hydrogens that polymer is bound entirely to fluorines. Fluorine as we could guess from its spot on the periodic table, love electrons. It is extremely electronegative. So because it holds onto it's electrons so tightly, and is so satisfied in this polymerized chain the electrons are unavailable for even minimal interactions with any other molecules. I'm not just saying this stuff is super difficult to difficult to react with, or it's really stable. It's more than that the electrons aren't even available for the sort of interactions that make things stick to each other, or cause friction. Which is why you have heard of polymerized tetrafluoroethylene, because it's super useful, either by its abbreviation, PTFE, or by its brand name Teflon.

===== Addition Polymerization & Condensation Reactions (6:32) =====

So how do we actually make these things? Well, ethene based polymers form through a process called addition polymerization. The monomers are simply added together and no by products are formed. In order to get the process kicked off you have to introduce a free radical. To me, that always sounded like some crazy freedom-fighter diving into battle without much thought for what would come after he was consumed in the firefight. And, that's kinda what they are; free radicals are atoms or ions that have a single unpaired electron. This is crazy unstable. It's basically like having half of covalent bond dangling off the atom.

Anywhere this can form a bond, it's going to form a bond. And, in the case of addition polymerization it attacks the double bond and joins one of the carbons, while the other carbon is itself left with an unpaired electron. The molecule itself is now a newly formed free radical, and it attack another nearby pi bond, joining with another molecule of ethene, forming another radical. This process continues until two radicals meet each other consuming both free radicals without producing any more, thus, ending polymerization.

There are, of course, other sorts of polymerization, as well. Sometimes a hydroxyl group from one molecule is happy to join up with a hydrogen from another, forming water. The water will break away as a byproduct, leaving the two molecules bound together. The often occurs when an amine group, with its loosely held hydrogen, meets a carboxylic acid, with its loosely held -OH group. This is just what happens when hexamethylenediamine meets adipic acid forming another branded polymer, nylon. By dissolving hexamethylenediamine and adipic acid into two different immiscible, or un-mixable, solvents we actually create nylon right here. The nylon forms at the interface between the two immiscible liquids. And, we can literally grab it and pull it out of the vial. Twisting and spooling it until we get a nice glob of nylon. This works because hexamethylenediamine has an amine group on each end and adipic acid has a carboxylic acid on both ends. Thus when the two monomer unit, called a dimer, is formed there is still a carboxylic acid on one end and an amine group on the other, allowing for further polymerization.

===== Proteins & Other Natural Polymers (8:33) =====

These amine acid condensation polymerizations also allow for the creation of possibly the most important polymers on the planet; natural polymers being created inside of you right now out of monomers that we call amino acids. Did you see that one coming?

Amino acids polymerize through condensation reactions guide by the code in your DNA and some very complicated enzymes to form basically you. Other important polymers in your body include: polysaccharides, which we use to store energy; and yeah DNA and RNA, which we use to encode information for the formation of proteins. But that would be back to biology, which is a whole other Crash Course. Which to be clear is available if you'd like to watch it. And thank you for watching this episode of Crash Course Chemistry, in it you learned:

- The first commercial polymer ever saved the lives of a lot of elephants.
- That ethene is sometimes called ethylene.
- And, that a huge variety of polymers is based on the addition reaction of ethene based monomers, including Teflon. Which so friction-less because of fluorine's extreme electronegativity.
- You also learned how addition polymerization reactions work.
- And, that other polymers are formed by condensation reactions. Including the polymerization of amino acids monomers, which along with other polymers like DNA and RNA, and glycogen, make up a lot of the stuff that is you.

This episode of Crash Course was written by me, Hank Green, edited by Blake de Pastino, and our chemistry consultant was Dr. Heiko Langner. It was filmed, edited and directed by Nicholas Jenkins. Our script supervisor was Stefan Chin. Our sound designer was Michael Aranda. And, our graphics team is Thought Café.