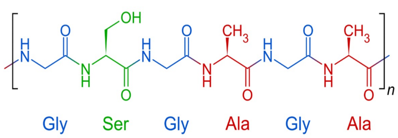
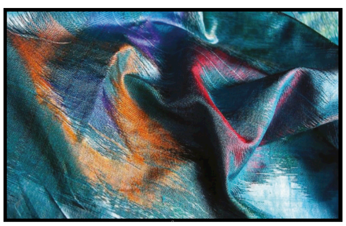
HERE WE GO 'ROUND THE MULBERRY BUSH
SPHEX CLUB
January 22, 2026
David W. Frantz, MD, FACS

SLIDE OF SILK PROTEIN MOLECULE



I know the best way to get you to settle in and start to nod off is to show a picture of an organic molecule. This substance however has ancient origins and very exciting prospects for future uses in both engineering applications and particularly biomedical devices.

This is a protein comprised of a string of amino acids in a simple repeating pattern. You can see its sequences of just 4 of the 20 amino acids: glycine, serine, another glycine, alanine, another glycine, and again alanine, repeated in a long chain. These fold and crosslink forming a structure known as a "beta sheet". A triangular, crystalline shape is what gives this substance its characteristic sheen as well as its strength.



SLIDE OF SILK FABRIC

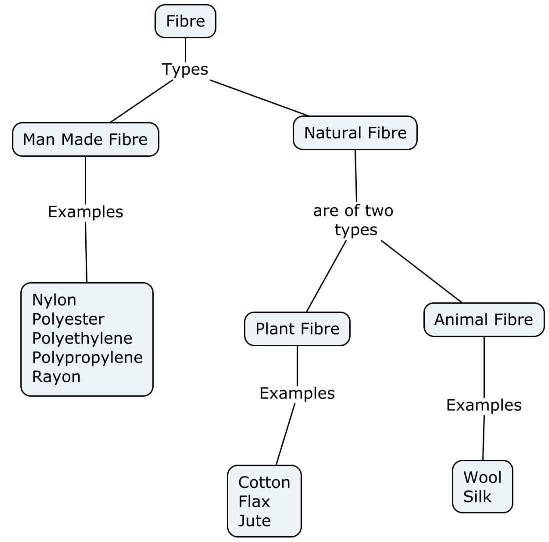
It's more easily identified as a fabric of unique characteristics being extremely strong, absorptive, lightweight, flexible and takes dyes well. It is soft against the skin and has a beautiful ability to drape in gentle folds.

SLIDE OF SILK DRESS

Now that could be polyester, but as you may have guessed, we're talking about silk. A thread of similar weight is stronger than a steel wire. It can absorb up to 30% of its weight in water but loses 20% of it's strength when wet. It has some elasticity but will deform if over-stretched. Washing will shrink it 8%, but even dry cleaning will shrink by about 4%. It will burn but tends to self-extinguish. However, it's beauty, luxurious feel and scarcity it has made it the most coveted of fabrics, at times restricted only to emperors and royalty. It was frequently seen as emblematic of the power and wealth of the wearer.

SLIDE OF SILK INTRO

In 2003 in an area of southern Lebanon there was discovered a short thread with droplets of glue just like a modern-day spider web. This, however, was buried in amber and was estimated to be 130 to 135 million years old. It represents the oldest known specimen of silk. The use of silk fibers to make fabrics is so ancient that any details have long been lost or reduced to legends. Yet we now look at silk as an incredibly versatile material with multiple possible future applications in medicine, engineering, and manufacturing.



SLIDE OF TEXTILE FAMILY TREE

As much as we're going to talk about silk, we have to know where it falls in the hierarchy of world-wide textile production. Today, synthetic fibers, which are petroleum based, clearly dominate, with about 65-70% of world production. The natural fibers are either plant based, like cotton and are about 20% of production. Which leaves very little for the animal-based products, like wool and silk. Silk production is estimated to be less than 1%.

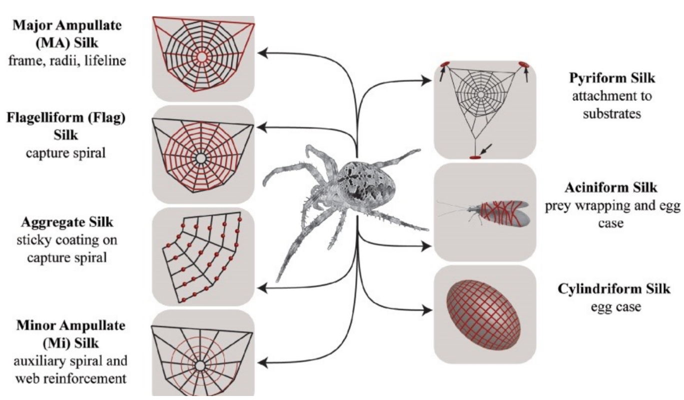
SLIDE OF SPIDER WEBS

You noticed that I mentioned a spider fiber earlier. There are many insects that produce fibers that can properly be called "silk". Among these are spiders, moths, butterflies, mites, centipedes, millipedes and wasps. There are even some marine shrimp-like animals producing fibers. The strongest silks are certainly from spiders as their webs have been known to catch bats, small birds and even tree snakes. Spider silk has from time to time been woven into fabrics, its strength obviously an attribute.

SLIDE OF SPIDER SILK CAPE DETAIL

This is a picture of detail from a silk Cape was made from the silk of Madagascar spiders. It's exhibited at the Metropolitan Museum in New York. Took four years to make and 1.2 million fibers.

SLIDE OF DIFFERENT SPIDER SILKS



So the difficulty with the spider silk is first it's availability in any kind of volume. It's also true that individual spiders can make up to 9 different kinds of silk for different uses. The uniformity and the characteristics of the fiber would be highly variable. As well, the spiders are notoriously territorial and cannibalistic, so trying to get them together for mass production has been impossible.

SLIDE OF MOTH SPECIES

So we'll turn to lepidoptera. This is the genus of moths and butterflies. There are at least 150,000 different species. These are comprised of many more moths than butterfly species. The moths are concentrated in the tropics and it's believed they're actually many more species that are yet to be discovered. About 40

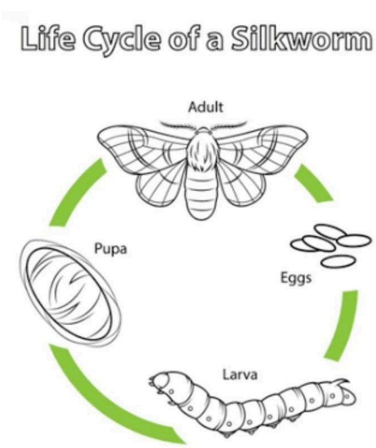
have been used for silk production and there are 12 that have been used with some regularity, most of them producing what's referred to as “wild silk” differentiating it from the product of the common silkworm. This slide depicts several species of moths whose silk has some uses. At the bottom is the Chinese oak silk moth, above it the cecropia silk moth, then the polyphemus moth, followed by the tussar silk moth (used extensively in India), then the Atlanthus silk moth, and then finally the star of our show the common silk moth, that is, bombyx Mori.

This month is unique in that it has been cultivated so for so many thousands of years that it no longer exists in the wild. It is totally dependent on human intervention and silk production for its survival. You can see it has no particular camouflage to protect it from predators and in fact neither the male nor the female can fly. They don’t even move around much because there is no need while they are cultivated by humans.

SLIDE OF TWO SILKWORMS

Although bombyx Mori is often referred to as the “common silkworm”, we obviously have to point out that none of these caterpillars are worms. In fact, they're the larval stage for these insects that have 4 parts to their life cycle.

SLIDE OF SILKWORM LIFE CYCLE



If we start with the winged moth emerging from the cocoon. The abdomens of the females are already full of eggs, and these are almost immediately fertilized by the male and she deposits them very close to where she emerged, often on the old cocoon. They develop over a period of at least 7 days, although without careful temperature control they could “overwinter” until hatching in the spring. With cultivation, however, up to 6 lifecycles can be obtained in a year, so these eggs are pushed to hatch in a week and the very small (2-3 mm) caterpillars start a period of voracious eating. Although there is some variation in different parts of the world, the white mulberry, a native to China is the normally the single foodstuff for these larvae.

They are starting at a tenth of an inch, and then go thru exactly 4 molts, shedding their outer skin. At the end of about 6 weeks, they are now about 3 inches or 7 cm and begin spinning the cocoon around their bodies. The silk emanates from paired, specialized salivary glands below their mouth. The spinning process take 2-3 days to be complete.

SLIDE OF THE COCOONS

This is the product. Completed cocoons, BEFORE the moth has emerged. The normal process is for the moth to secret an enzyme that dissolves the end of the cocoon and allows it to emerge after about 6 weeks. This severely damages the silk, however. The prized characteristic of the common silkworm cocoon is that it is spun from long, continuous strand, that can be completely reeled off the cocoon intact. Total length varies according to sex of the larva,

general health and other factors, but can be up to 900 meters, averaging about 600 in length. And yet it still takes 4000-9000 cocoons to make one kg of silk fabric. A single silk kimono would require the production of about 5000 silkworms and they would have consumed about 150 kg of mulberry leaves in the course of short life.

If the cocoon is to be harvested, the demise of the pupa inside the cocoon is usually accomplished with hot or boiling water. This also softens the cocoon and the glue-like substance, sericin, that holds it together. That allows reeling to be accomplished. Of course, a certain number of moths have to be allowed to emerge each cycle to provide the eggs for the next generation.

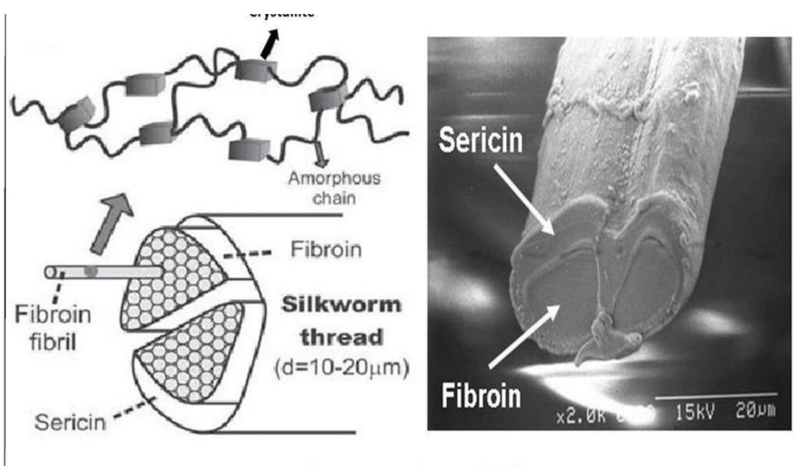
SLIDE OF MALE AND FEMALE MOTHS

If the lifecycle is allowed to be completed, the moths then emerge in close proximity to each other. The attraction to the females is immediate, and the observation of this phenomenon led to the discovery of the first pheromone. Bombykol was isolated and identified in1959. Pheromones are the organic compounds used to signal between individuals of a species, usually a sexual attractant. For the silkmoth, that pheromone can be detected by the male over a mile away.

SLIDE OF PUPA ON SERVING BOARD

The remaining pupa are eaten in many parts of Asia, or they may be used for fertilizer for the mulberry trees. The necessity of killing the silkworm pupa is a problem for some. In fact Mahatma Gandhi at one time lead a movement to oppose this. The only alternative is “peace silk”, of lower quality, but spun from shorter fibers obtained from the damaged cocoons after emergence, sparing the moth.

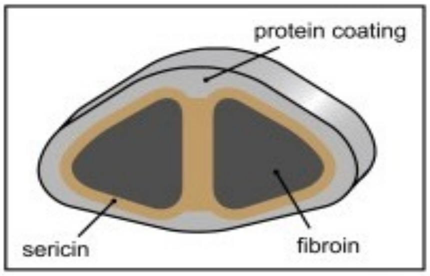
SLIDE OF SILK FIBER PHOTO



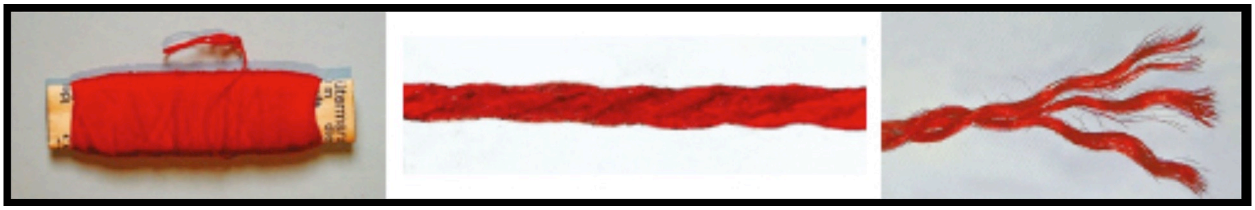
The composition of a strand of silk fiber is deceptively simple. It is composed of a double strand of fibroin, which is the protein polymer that we saw earlier. That is surrounded by the “glue” which is the sericin, another protein. It is washed off during the processing of the cocoon, allowing the fibers to be unwound (reeling), each measuring about 20 micrometers in diameter. That would be approximately ¼ the diameter of a human hair.

SIMPLIFIED DIAGRAM

Simplified a little, the silk strand is 2 columns of fibroin surrounded be sericin and a thin protein coat



SLIDE OF RED SILK THREAD



“Thread” is a misnomer for what comes off the cocoon, as usually 4-12 strands of silk are twisted together to form a silk thread, which is a process called “throwing”. The individual threads and then be further twisted together, depending on type of garment and the finest of weave required. Some fabrics may have over 50 strands of silk in their thread.

SLIDE FOR SILK SERVICULTURE

As mentioned the origins of the use of silk is obscured by time. The legend is that Empress Ti Ling She, wife of the Yellow Emperor, sat under a tree in 2640 BCE. A cocoon fell into her hot tea and she was surprisingly able to unwind the strand of the soaked fibers, resulting in the development of silk fabric. The reality may be even older, with silk protein found in the soil of a residence from about 6000 BCE. The earliest actual silk garment found was a child’s shroud, dating from 3600 BCE. We therefore know that silk textiles have been made for at least 5000 years.

SLIDE OF THE SILK ROAD

“Sericulture” refers to the cultivation of silkworms, processing of silk and manufacturing of textiles. It is derived from the Latin : “sericum” in turn derived from the Greek: “serikos”. This probably refers to the people of East Asia known as “Seres” with whom they had contact and probably obtained silk.

The Emperors of China tried mightily to keep the process of sericulture secret and succeeded for about 3000 years. Exportation of silk worms, eggs or mulberry seeds was prohibited. Silk was an important source of wealth as taxes were paid on the silk production.

The silk itself could be used as a form of currency.   Soldiers were sometimes paid in bolts of silk. Only the nobility and family, however, were allowed to wear silk garments. Although the process was a tightly kept secret, the product began to spread far and wide. With the long distance trade along the Silk Road beginning approximately 1000 BCE, we see the appearance of silks as far away as Egypt, found in the hair of a mummy, circa 1070 BCE. The <u>techniques</u> for production meanwhile were gradually smuggled out of the region later, first spreading to Korea about 200 BCE, and into India about 140 CE. Various nefarious techniques were used to finally steal the secrets of production. Khotan was a large kingdom to the northwest. The prince there received his silk technology via a Chinese princess bride. Silkworms were smuggled out, hidden in the bride's hair, as part of her dowry. The demand continued to rise, as commerce along the silk road was peaking in about 400-500 AD, with silk textiles perhaps the most valuable commodity.

The Roman world received the secret of silk production via the Byzantine Empire. Justinian I, in Constantinople, induced two Christian monks, returning from China, to smuggle out silkworms hidden in their hollow canes about 600 AD. From there, the production of silk, and the necessary propagation of white mulberry trees spread through the Mediterranean, centering first in Turkey and then spreading to Europe, with a strong presence in Italy. France also developed silk production and weaving, and by 1460 Lyon in the Rhone valley was the center of the industry in Europe. Despite extensive efforts, success in Britain was very limited as the white mulberry did not thrive and the native black mulberry was not as well suited.

Britain was very anxious for sericulture to succeed in the New World. In fact, silkworms and trees arrived in Jamestown in 1609 and 1622 with instructions from James I to establish a silk industry. There was considerable effort and silk was eventually produced all along the East Coast, from Pennsylvania to Georgia. For a while there was even enough for export. Martha Washington was said to have worn an entirely domestic silk dress at George's inauguration.

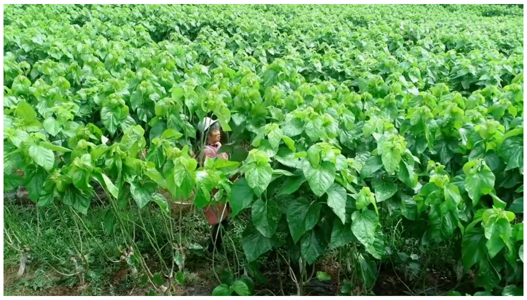
However, there was intense competition for the land and labor that was required. In Virginia, it was tobacco that competed. In South Carolina, and in Georgia it was indigo and rice, even though Savannah at one time produced significant amounts of silk. In the New World, it is only Brazil that has maintained a significant silk industry, although always overshadowed by the Far East.

SLIDE OF SILK REELING IN FLORENCE, 1500'S

The process has always been labor-intensive. This is Florence in the 1500's. Here you see the major steps of processing the cocoons, with hot or boiling water heated by the fire, to kill the pupa and soften the fibers.   Then the gentle unrolling (reeling) of the cocoons with multiple fibers being combined into thread on the spools. The fibers are then dyed either before or after the cloth is woven.

SLIDE OF MORE MODERN COTTAGE INDUSTRY

For much of the world, silk production has remained a cottage industry with families either raising the moths and selling the cocoons to brokers or producing fabric and garments to complete the process. This is particularly true across India and Africa.



SLIDE OF MULBERRY TREES

Now, however, the major players, particularly China have automated much of the process, establishing first vast mulberry orchards that can produce the enormous amounts of leaves that are required. They then automate as much of the process as possible, providing the environment where the worms can go through 6 generations in a year,
rather than one.

SLIDE OF LEAF BEDS

The leaves are mulched and spread onto extensive indoor beds.

SLIDE OF LEAVES AND WORMS

The larvae are then spread onto the beds and munch continuously for about 6 weeks.

SLIDE OF LEAF MACHINE

They must be provided continuously with fresh mulberry leaves as they increase dramatically in size. When needed, artificial feed can be used, providing all the components of mulberry leaves, allowing year-round feeding.

SLIDE OF FRAMES OVER BEDS

When ready to pupate, frames are lowered and the larva climb to find a place to attach and start spinning.

SLIDE OF REMOVAL FROM FRAMES

Well before they complete their metamorphosis and emerge, (which would ruin the cocoon) they are harvested from the frames with an automated process or by hand for sorting.

SLIDE OF COCOON SORTERS

Hand labor is still needed to sort the cocoons, removing poor quality larva, but the rest of the process requires much less labor, and the Chinese in particular have been adept at automating as many processes as possible.

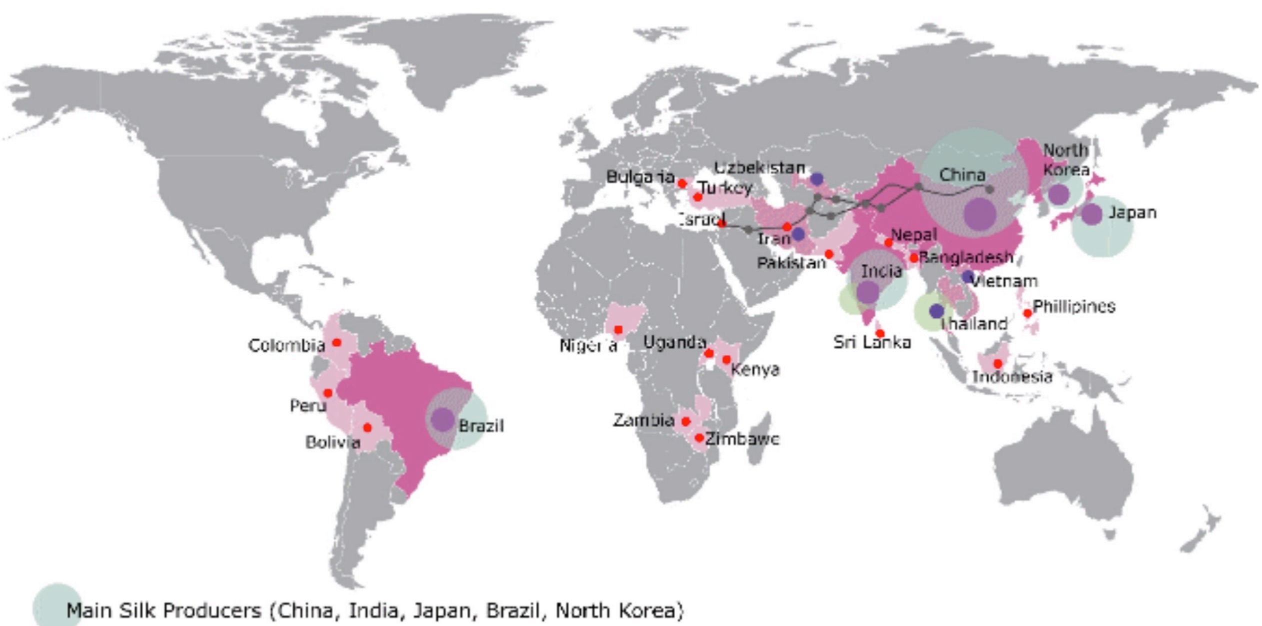
SLIDE OF REELING MACHINES

Reeling was one of the earliest stages to lend itself to automation, with these machines able to unwind multiple cocoons and combine the strands into threads.

SLIDE OF PILES OF COCOONS

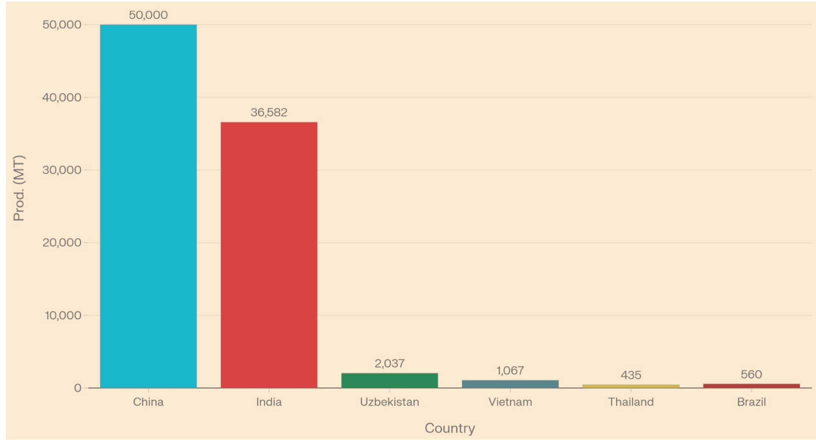
The volume of production becomes exponentially greater.

SLIDE OF WORDWIDE DISTRIBUTION



Sericulture spread across the world, but obviously limited by climate and labor and the tolerances of the mulberry trees and the silkworms. China, however, with the climate and a cultural heritage, as well as government support and a push toward automation, has dwarfed the rest of the world in production.

SLIDE OF PRODUCTION NUMBERS



Today's world wide production is clearly dominated by China. Japan previously had been the largest producer, but this capacity was destroyed by WWII. It was revived after the war but suffered from the competition of Chinese and other southeast Asian producers. Japan currently has no significant output. The introduction of the synthetic fabrics at about the same time had a dramatic effect on the demand for silk not only for Japan but for other producers as well. It remains a niche product, as we noted, accounting for less than 1% of the world's total textile output.

SLIDE OF COCOON TO SILK TO FABRIC

However, on the horizon are the prospects for new, fascinating ways to use the silk protein fibroin, not as a fiber but as a building block for other products. We would no longer be just going from cocoon to silk fiber to fabric.

SLIDE OF NEW SILK PRODUCTS

- GENETIC ENGINEERING OF SILK WORMS
  - Add spider genes
- GENETIC ENGINEERING OF SPIDERS
  - Add silkworm genes
- REFORMULATE SILK PROTEIN (fibroin)
  - Recycle
  - Liquify, mold, extrude, 3-D print

There are 2 avenues of potential expanded use of silk. One is to use it still as a fiber, but by genetically engineering the common silk moth or another species, you alter the characteristics of their silk. So if you identify spider silk characteristics that you want incorporated in your silkworm silk, you identify and transfer the genetic coding to produce a new kind of silk. Or conversely, you could choose desirable traits of silkworm silk and introduce those genes into the DNA of spider egg, using the CRISPR 9 gene editing techniques.

The second avenue is to take advantage of the properties of the silk protein fibroin as it is currently produced by the silkworm and reformulate it. You wash off the surrounding sericin glue, then dissolve the protein into a broth. It could be reformulated into new fabric with recycling of silk. However, there is a very limited supply of silk waste. (only 1% of fabric manufacturing). Recycled silk containing dyes presents additional problems and would limit it's uses. However, if you regard the virgin silk protein as just a building block for other materials, then it opens up a world of other possibilities. The silk can be liquified, creating a "soup" of fibroin. It can remain a liquid or be further manipulated to almost any form. It has the possibility of being formed into a sheet, or molded into any 3-dimensional form, even to be used in a 3-D printer.

SLIDE OF COMMON HOUSE SPIDER

Here's a proof of concept for the genetic engineering idea from work done in just May of this year (2025) by a team in Germany. Using a common house spider, they introduced genes that would cause it to make fluorescent silk. It was therefore easy to identify that those genes were being expressed.

SLIDE "GOT SILK"

Tufts University is my medical alma mater in Boston. I was introduced into this new world of silk research just by a tantalizing article an alumni magazine, with a clever little marketing hook on the cover. This described how Dr. Fiorenzo Omenetto, one of their faculty, had establish this fascinating basic research lab with multiple disciplines exploring all these different possibilities for the silk protein.

SLIDE BIOCOMPATIBLE, BIODEGRADABLE, STABILIZING

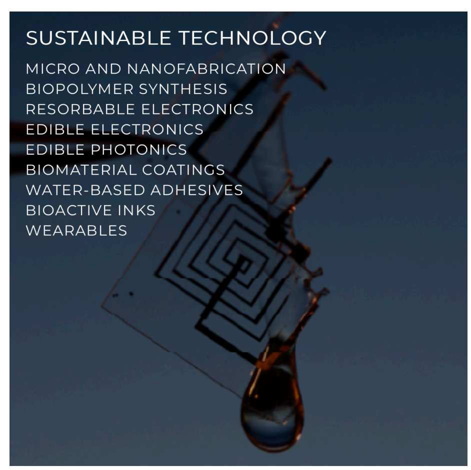
These are the characteristics of fibroin, the silk protein, that make it so exciting as building block for other products.

Biocompatible means it's not going to react if it's placed in the body. No rejection or immune reaction. We've use silk sutures for over a century now, so there is some experience with this characteristic.

Biodegradable implies that it will gradually breakdown in the body to non-toxic substances that will be absorbed and removed with nothing left behind. What's important for silk in this regard is that the breakdown can be modulated with the addition of enzymes, so it could occur in days, weeks, or years, according to the need of the implant. Devices placed to stabilized a fracture could be "programmed" with the right enzyme to disappear at the appropriate time.

Fibroin seems to be able to **stabilize** other molecules that are imbedded in its structure, preserving them until triggered by the dissolution of the fibroin or contact with another specific molecule. Chemotherapy drugs or a vaccine could be delivered to the body over a prescribed period of time as the fibroin degrades underneath or in the patient's skin

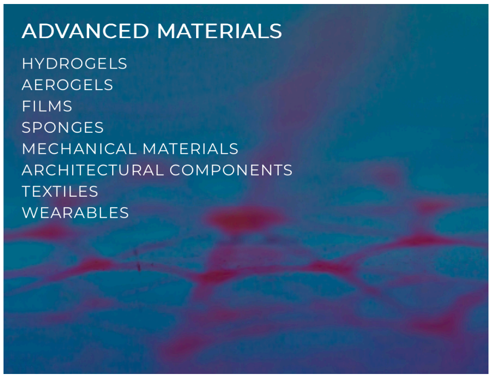
SLIDE OF SUSTAINABLE TECHNOLOGY



If you go to the Tufts Silklab website, there is a "wish list" of where they think silk research may lead them. They have cast a wide net. For Sustainable Technology, they see possibilities in all types of manufacturing, particularly nano (that is, extremely small) manufacturing. Edible electronics? A little easier to understand would be water-based adhesives. They already have glue that will polymerize and stick in underwater conditions. Bioactive inks may be put onto clothing or patches to turn colors when your glucose gets too high or your lactate level goes up with exercising.

SLIDE ADVANCED MATERIALS

We know the fibroin can be fashioned to be in any shape, so the possibilities in manufacturing are extensive, from gels to sponges, to wearable sensors. It may once again be used in textiles as reformulated silk.



SLIDE GLOBAL HEALTH

The frontier in health applications is perhaps most exciting, due to those biocompatible, biodegradable and stabilizing abilities.

I am not sure what a “wireless tattoo” would do for you, but “absorbable therapies” is exciting. Instead of treating severe fractures with rods, or plates and screws, you might stabilize the bones with absorbable screws that would never have to be removed.

A chemotherapy drug, a contraceptive or an antibiotic would be implanted within the fibroin and released as it is slowly re-absorbed.

“Biological detection” implies that an ink containing a sensing compound, stabilized with fibroin, would turn colors when exposed to bacteria, identifying a contaminated surgical field or dressings.

And fibroin films might preserve food and prevent contamination, preventing food borne illnesses and food waste.

SLIDE MOVIE OF WALLET

Let me try to show you some of these medical and non-medical potential uses for which I have images. This is a 1 ½ minute promotional from the Tufts Silklab, promoting how fibroin can be used to produce leather-like products.

https://youtu.be/YI8957ZdAFs?si=RCyQtqqdBg5fpepv

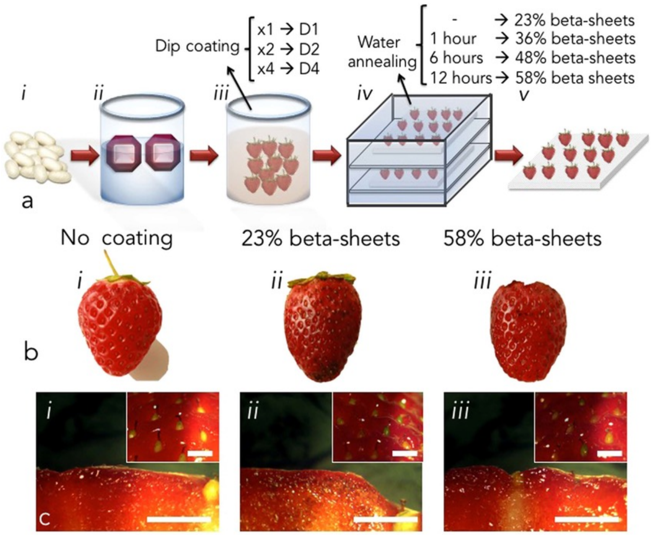
SLIDE OF WINDSHIELD

The fibroin molecule is described as amphiphilic, meaning parts of the structure attach to water and other portions repel. This means it can be used here, on a windshield as a water repellent, but is also critical in manufacturing where water is an important solvent. Nanomanufacturing can be described as “water based” and fibroin is being discovered as an important surfactant, breaking down surface tension in the process.

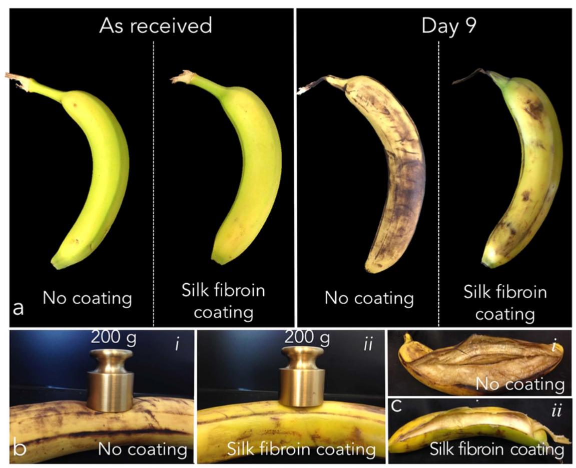
SLIDE OF GLUE AND BEAKER

This is a demonstration of their fibroin based glue that can set up underwater. In this case, they are demonstrating the ability to “shoot” the glue to an object and have it adhere and develop a strong fiber attachment. (Spiderman)

SLIDE OF STRAWBERRIES



Food protection and preservation are a major area of potential use. Because the fibroin solution can be applied as a liquid, you could dip fruit or vegetables and allow it to cover as a film. It could then provide preservation and ultimately be completely edible.



SLIDE OF BANANAS

The same could be true of bananas. One is dipped, the other is not. At 9 days (mine don’t last that long on the counter) the covered one looks pretty good, and even passes the “smush” test in the bottom panels

SLIDE OF SCREWS

This what absorbable screws or fixation devices might look like. Able to be screwed into bone at a fracture site, than gradually reabsorb as the bone repairs.

SLIDE OF SCREWS AND DIME

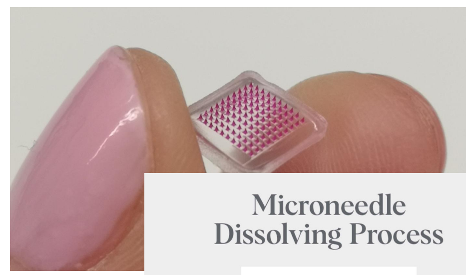
This gives you an idea of scale with larger, or very small devices possible.

SLIDE OF GLOVE

There are numerable uses for bioactive inks that act as sensors. In this case the ink is activated on a surgical glove if it senses the presence of bacterial proteins, alerting you to a contaminated surgical field or dressing.

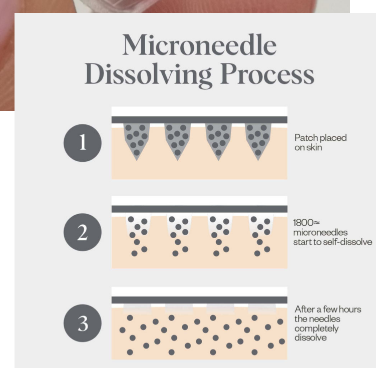
SLIDE OF MICRONEEDLE PATCH

One of the most exciting things is the idea of delivering vaccines via absorbable microneedle patch. This is interesting both in the idea of how the vaccine is administered via these tiny needles thru the skin, (which reportedly don't hurt) as well as the fact the vaccine is imbedded in the fibroin needle and is release as the needle dissolves. Perhaps most importantly, the vaccine would be stabilized in the fibroin needles of the patch until applied, obviating the need for refrigeration. This would have major logistical implications, particularly in providing vaccines in low resource countries.



SLIDE OF NEEDLE PATCH STRUCTURE

This how the idea works. The patch and stays on your skin for perhaps a few hours, as the needles dissolve, releasing the vaccine, or other medication.



SLIDE FROM VAXESS (to 1:30 mark)

This a minute and a half presentation by a startup called Vaxess, who has a product that they have demonstrated works but is not yet on the market.

https://youtu.be/zmVt2-od5ME?si=pG7oXtlF0C6GAGPQ

SLIDE OF MOTH

As much as this guy is a hero in textiles, and may have been at it for 3000 years, the next step may be to cut him out of the picture entirely.   As our genetic engineering advances, we are now able to program E. coli and other bacteria to produce organic compounds at our direction. It may be that bacteria, fungi or yeast one day produce all the fibroin we need for these multiple applications.