

7.4. Fiber Analysis

Learning Goals and Objectives

Fibers are all around us in our clothes, carpets, curtains, and all sorts of fabrics and fillers. In order to understand how fiber analysis can be used, you will need to develop an understanding of:

- the types of natural and man-made fibers, their composition and formation;
- how fibers in cloth can provide production and history information of the cloth;

Introduction. While manmade and natural fibers, other than hair and fur, are not formally biological materials derived from skin, they are often quite similar in their overall structure and function to hair. Fibers are frequently woven together into cloth to form both insulating and protective layers that lie adjacent to our skin, in some respects enhancing the capabilities of our skin. But our uses for fibers goes well beyond our needs simply for cloth. Fibers are twisted into ropes, embedded within other materials to form composites, pressed into sheets of hardboard, paper, or felt, spun into building materials, and employed in biomedical applications from surgical dressings to artificial skin. Because we use fibers for so many everyday functions, they often find their ways into forensic investigations and are employed as evidence very similarly to the way that hair evidence is typically considered. For these reasons, fibers will be considered in this chapter along with skin and hair analysis.

What Are Fibers? Fibers can be defined simply as long, thin filaments in which their lengths are very much greater than their widths, at least a 100-fold longer. Fibers can be classified into one of three main groupings depending upon how they are produced: (1) natural fibers, (2) regenerated (sometimes called reconstituted) fibers, and (3) manmade or synthetic fibers. Examples of each of these types is illustrated in Figure 7.4.1.

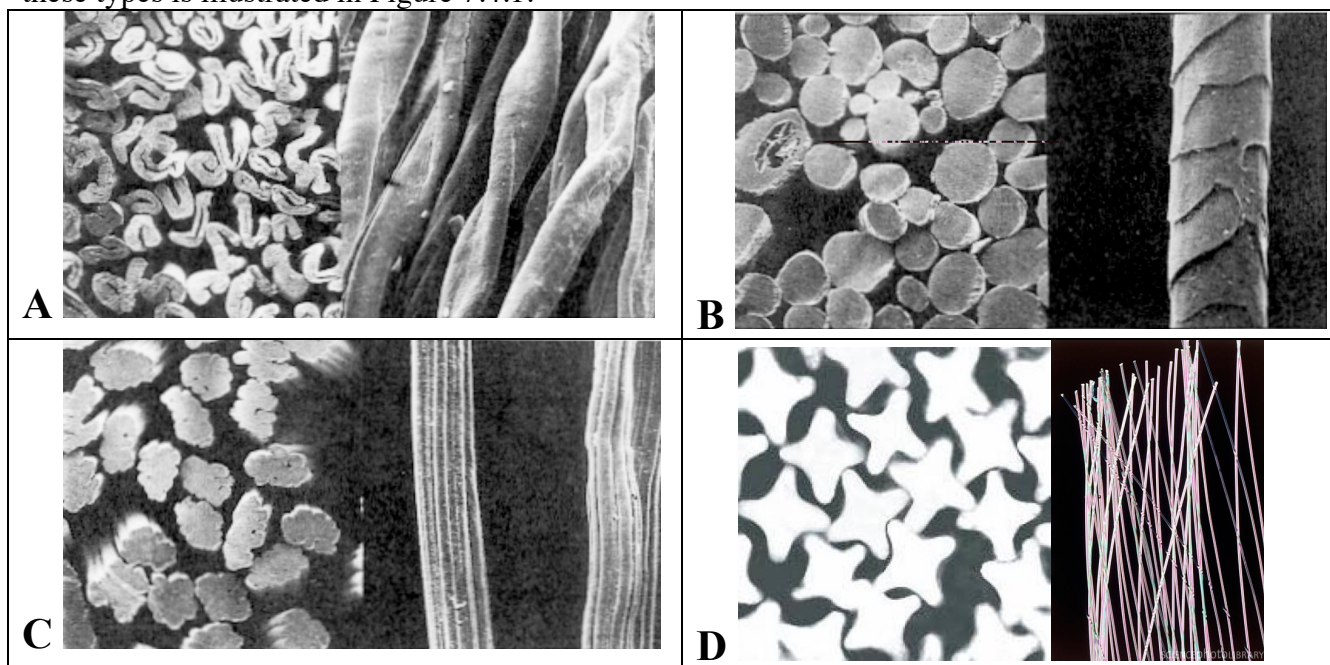


Figure 7.4.1. Natural, regenerated, and synthetic fibers shown in cross-section and lengthwise: (A) Natural plant fiber cotton, (B) Natural animal fiber wool, (C) regenerated rayon fiber, and (D) synthetic nylon fiber. (sources: A-C Unknown, D www.taiwantrade.com.tw/80/EP/Products.do?Method=showProductDetail&catalogId=260739&company=acclon&company_id=10812&setLangCode=en&come_soon=0&locale=2 and sciencephoto.com).

Natural Fibers: Natural fibers are very common and were the first type of fibers to be used by man to make objects for skin protection and insulation. Wool and dyed flax fibers that were used by humans have been found that date over 35,000 years old. These natural fibers come from many different sources including plants, such as cotton in cloth, wood found in paper, hemp in rope, from insects, such as in silk fabrics, from animals (besides hair and fur), as found in catgut and spider's silk, and from inorganic materials or minerals, such as asbestos found in older types of home insulation and glass in fiberglass and spun glass materials. Several examples of natural fibers are shown in Figure 7.4.2.

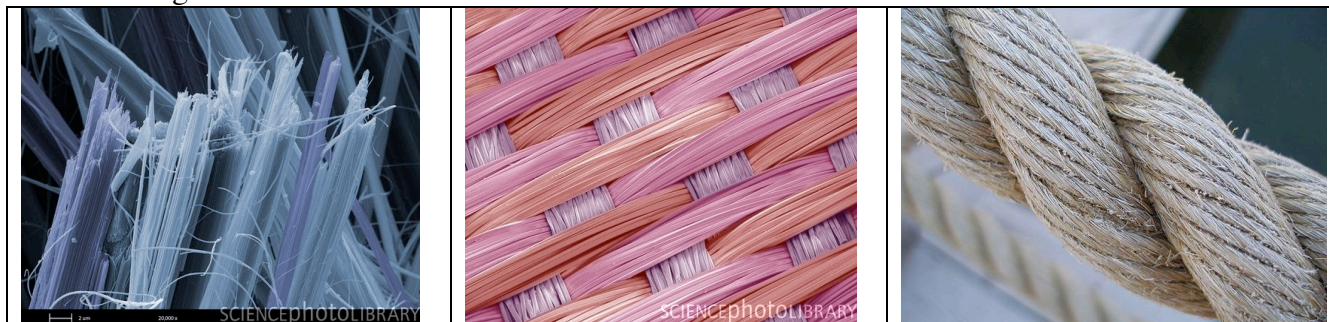


Figure 7.4.2. Examples of natural fibers: (Left) fibers of the mineral asbestos (sciencephoto.com Image C004/8624), (Center) woven silk fibers made by silk worms (sciencephoto.com Image C002/9469), and (Right) manila rope fibers (http://cdn-www.trails.com/Cms/images/GlobalPhoto/Articles/1905/195907-main_Full.jpg).

Plant-based fibers may be either carbohydrate-based or protein-based. Many plant-derived fibers are composed largely of the carbohydrate polymer molecule cellulose, a complex sugar or polysaccharide molecule (“poly” meaning many and “saccharide” meaning sugar). The chemical structure of cellulose, shown in Figure 7.4.3, consists of many smaller sugar units (the six-membered rings) strung together to form a very long chain. These long chains can be intertwined and chemically attracted to one another through hydrogen bonds between adjacent strands to give a strong and sturdy fiber (Figure 7.4.4).

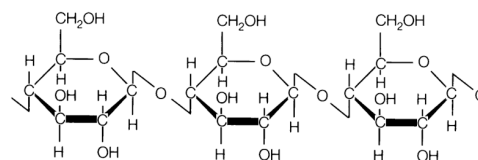


Figure 7.4.3. Structure of Cellulose (www.greenspirit.org.uk/Resources/cellulose.gif).

Animal derived fibers are typically composed largely of protein, such as keratin and silk-related proteins. Like cellulose, these proteins are polymeric materials built from the smaller units linked together, in this case amino acid building blocks. These fibers can be both very physically strong and highly resistant to chemical attack, and some can be remarkably elastic. Probably the most common animal protein fiber is silk, obtained from the cocoons of silk moths. Silk protein is largely built from the amino acid glycine, up to about 50% glycine, that provides many of the desired properties to silk such as strength, sheen, and texture.

Mineral fibers, such as asbestos, can have a variety of compositions and are used primarily for composites and building components. They, nonetheless, appear in forensic investigations relatively often.

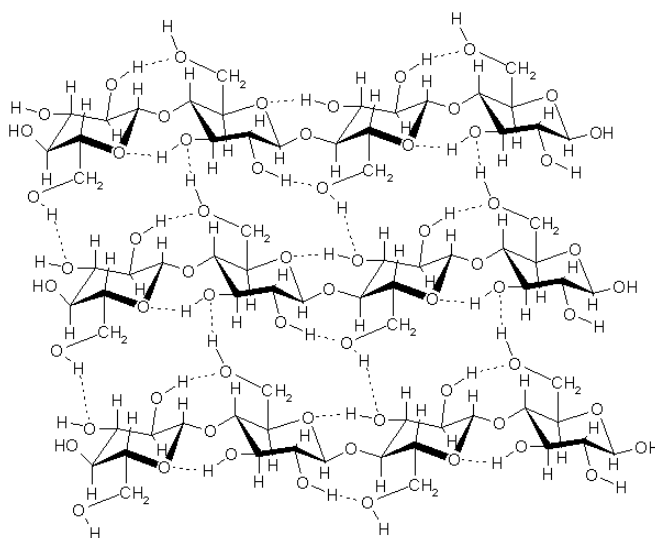


Figure 7.4.4. Hydrogen bonds holding together strands of cellulose polymers (www.doitpoms.ac.uk/tlplib/wood/figures/cellulose.png).

Regenerated Fibers: Regenerated fibers are those that are made by chemically processing naturally occurring materials into fibers of desired shape and structure. Rayon and acetate are two very common examples of regenerated fibers made from cellulose, Figure 7.4.5.

Regenerated fibers can be classified as either deriving from cellulose-based or protein-based starting materials, but both typically come from plant materials. The first commercial regenerated fiber was rayon, originally called “artificial silk”, and discovered in 1855 and later produced in large scale beginning in the 1890s. It was, however, far from the material we use today but through modification in the production and chemical modifications, in 1924, a very stable, durable, and desirable form of the artificial silk, renamed rayon, was introduced to the market.

In the production of Rayon and its analogs, cellulose from trees and other plants is first dissolved or suspended in a solvent and chemically purified and treated before being formed into threads and fibers through a variety of manufacturing processes. In one common process for forming these fibers, the wood from trees are first chopped into small pieces that are chemically treated to both remove non-cellulose components and bleached to remove any coloration from the material. The cellulose is then dissolved in a basic solution, bathed in carbon disulfide (CS₂), extruded from a shower head-like device (spinneret), and ultimately stretched to produce the characteristic thin threads. The final stretching process helps to realign the long cellulose molecules along the length of the fiber.

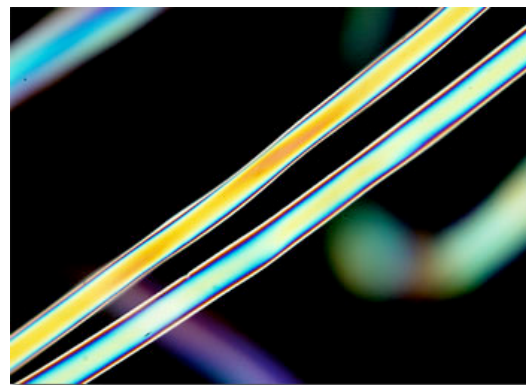


Figure 7.4.5. Micrograph of a form of rayon fiber, cuprammonium rayon, that closely resembles silk

(micro.magnet.fsu.edu/primer/techniques/polarized/gallery/pages/cuprammonium)



Figure 7.4.6. Fiber made from soy beans
(www.swicofil.com/soybeanproteinfiberproperties.html).

There are a number of new and increasingly important regenerated fibers that originate from plant or animal protein rather than from cellulose. For example, the protein from corn, soy, peanut or milk (casein) can be used to form strong, stable and occasionally biodegradable fibers (Figure 7.4.6). For example, soybean fibers are smooth, light, and soft, similar to the natural fiber cashmere. Some of these fibers have the advantage of being produced in a more environmentally-friendly fashion.

Synthetic Fibers: Synthetic fibers are prepared from chemical feedstocks, often petrochemicals, rather than from natural fiber sources, and are typically formed through polymerization reactions that lead to long chain

molecules. Common synthetic fibers are nylon, polyethylene, acrylic polyesters, PVC fiber, and polyurethane. The properties of the synthetic fibers vary widely.

Some synthetic polymers have special elastic properties, called **elastomers** (e.g., spandex, polyurethane, neoprene, and others). Silicones, compounds composed of chains of silicon, carbon, and oxygen atoms, make particularly good elastomers since the chemical backbone chain is very flexible. Lycra (spandex) is a polyurethane polymer that has both rigid and flexible subunits repeated in its structure. The combination of these subunits provide a strong material, derived largely from the rigid parts, that is quite elastic, derived from the flexible units that can “unwind”.

Synthetics are among the strongest of the known fibers. Additionally, many regenerated and synthetic fibers are **thermoplastic** – they melt or soften easily. This allows them to be easily molded into a variety of shapes by heating – shapes that they retain after cooling (pleats, creases, solid objects, and many more). A plastic material, by definition, is simply something that can be shaped or molded. Today, however, the term plastic has become synonymous with synthetic thermoplastics.

Polymers: In Chapter 4 on DNA, the general idea of polymeric molecules was presented. Fibers, whether natural, regenerated or synthetic, are also typically composed of long polymer molecules, of which DNA is just one very important specific example.

Polymers are, by definition, long chain molecules that are composed of smaller units, called monomers, strung together. These chains are typically very long. To get a sense of this, a typical polymer made up of 10,000 monomers strung together would be comparable in length-to-thickness ratio to a 6-inch rope (15 cm) over a mile long (1.6 km).

One convenient way to subdivide the vast array of known polymers is to consider natural polymers and synthetic polymers. Natural polymers include biopolymers, such as proteins, polysaccharides, nucleic acids, and inorganic polymers, such as asbestos and graphite. Synthetic polymers are most often prepared by linking together a variety of small organic monomers.

Polymers display an amazing array of properties that are put to an equally large variety of uses, ranging from soft pliable materials to extremely hard, structural components. Polymers now fit needs that NO other materials can fit - from artificial skin to high strength composites. There are, however, a few key features that dictate most of the observed properties of the polymer.

Probably the most important feature is the identity of the small monomer molecules. Often, thousands or even millions of monomers are linked together to form a single polymer strand. The chemical structure of the individual monomers dictate what structures are possible in the full polymer. A few examples of monomers and the polymers that they form are shown in Figure 7.4.7 and include, among many other examples:

- Amino acids form proteins;
- Sugar molecules (such as glucose) form polysaccharides;
- Nucleotides (composed of a phosphate, a sugar, and a nitrogen base) form DNA and RNA;
- Ethylene forms polyethylene;
- An organic di-acid molecule coupled with a diamine forms nylon;
- Carbon forms diamond, buckminsterfullerene, and nanotubes.

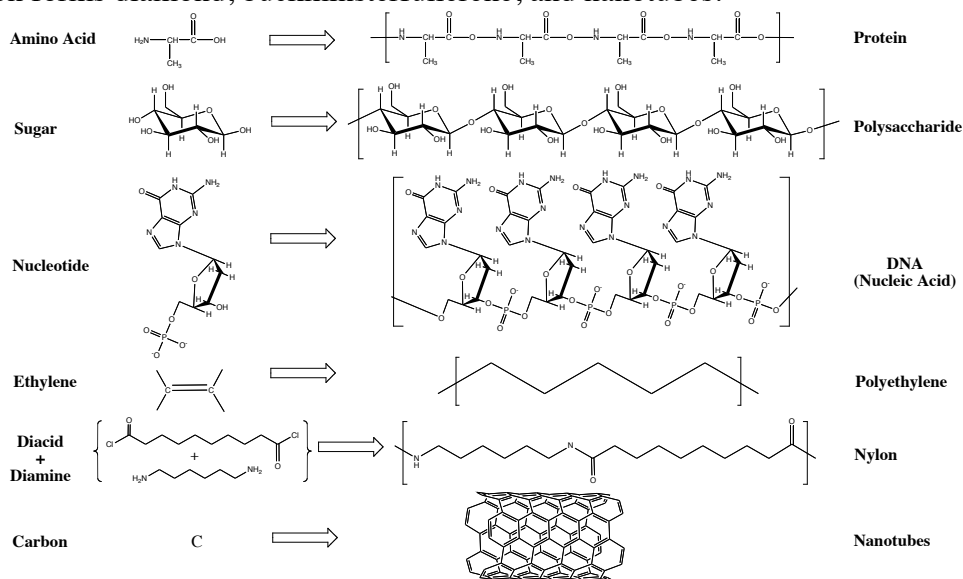


Figure 7.4.7. Various monomers that combine to make important polymers (unlabeled junctures between the lines indicate carbon atoms).

Today, most of our synthetic polymers are composed of just five monomers: ethylene, vinyl chloride, styrene, propylene and terephthalic acid

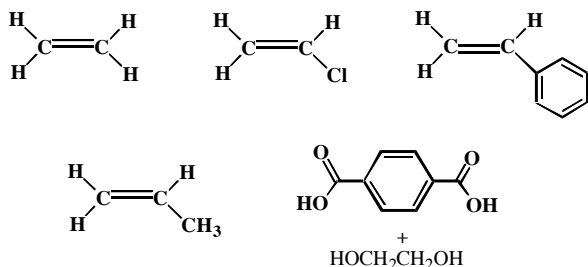


Figure 7.4.8. The most common monomers for making synthetic polymers today are (clockwise from upper left): ethylene, vinyl chloride, styrene, propylene, and terephthalic acid.

(with ethylene glycol). The structures of these five small molecular monomers is shown in Figure 7.4.8. The first four of these monomers form long chains through direct chemical polymerization reactions brought about by **catalysts**, special chemical reagents that can cause a chemical reaction to occur or to accelerate without being ultimately changed itself. These reactions are often called **addition** reactions since the net result is to simply add the monomers together without the loss of any portion of the monomer. These reactions account for millions of tons of polymers produced annually in the US alone, with polyethylene the number one polymer produced.

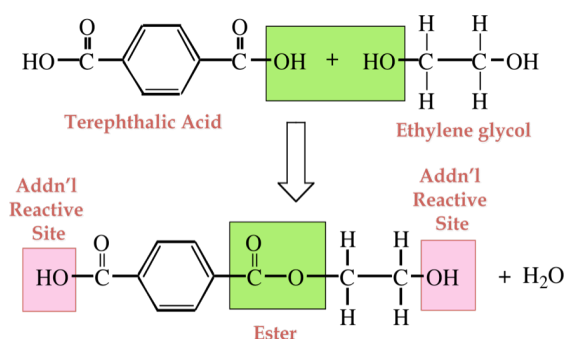


Figure 7.4.9. Formation of a polyester: the polymer polyethylene terephthalate from a condensation reaction through the loss of water.

The other most common way to form a polymer from monomers occurs through a reaction called **condensation**, a reaction that involves the loss of a small molecule, such as water, from the reaction. For example, the reaction of terephthalic acid with ethylene glycol results in the elimination of H_2O to form the condensation polymer polyethylene terephthalate (Figure 7.4.9). To say that this type of reaction is important in forming critically needed biopolymers would be an extreme understatement. Condensation reactions are used to build proteins from amino acid building blocks, polysaccharides from simple sugars, and DNA from individual nucleotides (Figure 7.4.10). Clearly, without this single type of polymerization reaction, life would not be possible as we know it.

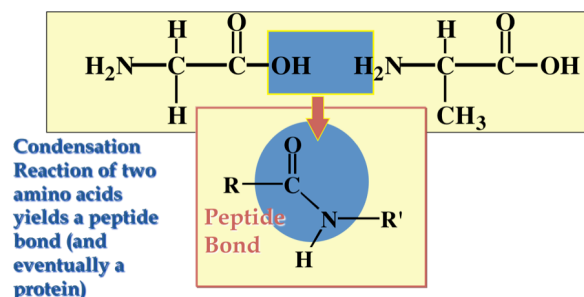


Figure 7.4.10. Formation of a peptide bond, the bond linking amino acids together, to form a protein biopolymer.

The properties of polymer molecules are clearly controlled largely by the monomeric units. The key controllable properties include:

- Chemical composition of the monomers;
- Formation of straight or branched chains;
- Length of the chains;
- Orientation of the monomers within the chains;
- Bonding between the chains;
- Introduction of co-polymers.

Some monomers can only link to form a straight chain, like a railroad train, while others can branch out, forming tree-like structures. Their ability to branch strongly affects the chemical and physical properties of the resultant polymer. For example, high density polyethylene (HDPE) is made up almost entirely of straight chains. This allows the chains to stack together very well to form dense, tightly packed materials, similar to the way boards in a lumberyard or straight logs can be

efficiently stacked in a pile (Figure 7.4.11). Low density polyethylene (LDPE), on the other hand, is made up of branched chains that does not allow the individual chains to pack together very well. This would be similar to trying to stack trees together with all of the branches still attached, resulting



Figure 7.4.11. Schematic of the polymer stacking in HDPE *versus* LDPE (left) and the analogous stacking of logs *versus* branched trees (pics: logs trees http://www.northerngrid.org/ngflwebsite/chopwell/images/photographs/log_stack.jpg; and http://www.istockphoto.com/file_closeup/nature/4814662-christmas-trees-fresh-cut-pile-stacked.php?id=4814662).

in an inefficient stack with lots of open air-spaces between the tree trunks. The result of this kind of packing is that HDPE forms very strong, rigid, dense and high-strength materials, used in applications such as water pipes, snow boards, and storage sheds, while LDPE forms softer, low density, flexible, low melting polymers, such as found frequently in plastic bags, milk containers, and plastic laminate.

With some monomers, the two

“ends” of the building blocks where they connect together have different chemical components. When they are assembled into a polymer, there are two ways that the building blocks can be assembled; head-to-head and head-to-tail, as illustrated in Figure 7.5.12. These differences lead to different chemical and physical properties of the polymer, although head-to-tail arrangements are far more common.

The properties of polymers can often be changed by building bridges between adjacent chains through cross-linking. This process is what usually happens when a resin or polymeric precursor is cured or hardened after it is applied in a soft or liquid moldable form. During the hardening process, the bridges between the polymeric strands are created that form a three-dimensional lattice of interwoven strands and bridges throughout the material (Figure 7.4.13). These bridges

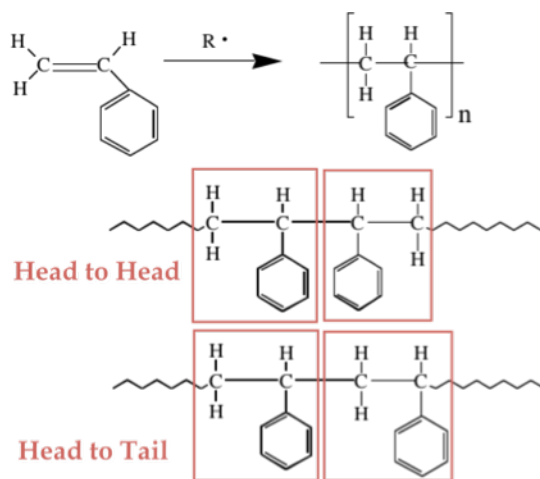


Figure 7.4.12. Orientation differences in forming synthetic polymers.

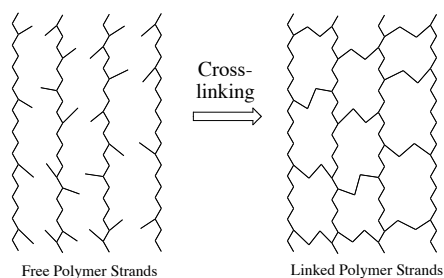


Figure 7.4.13. Cross-linking of individual polymer molecules.

can also occur at several levels. Most commonly, cross-linking is considered at the molecular level, but larger strands can also be cross-linked at the macroscopic level to give a three-dimensional web-like structure, such as shown for a cross-linked styrene-based polymer in Figure 7.4.14. The degree of

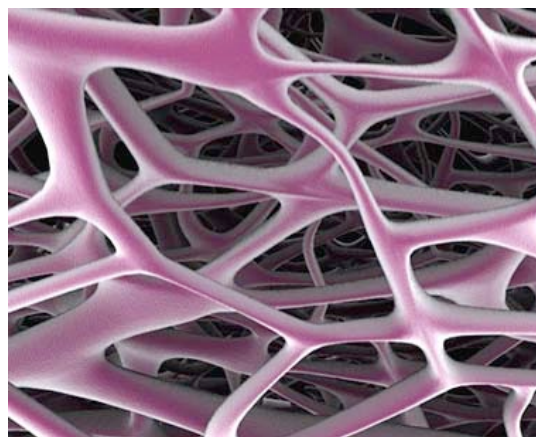


Figure 7.4.14. Crosslinked polymer lattice of the acrylonitrile, styrene, and butadiene terpolymer (<http://retr0bright.wikispaces.com/ABS+Plastic>).

cross-linking imparts important features to the polymer. For example, permanent press fabrics have relatively few cross-linkages, resulting in a soft and pliable fabric but one that also retains its shape. Rigid polymers, such as Bakelite (the world's first synthetic plastic), are heavily cross-linked, forming exceptionally hard, inflexible, and brittle materials.

Polymers can also be made from a blend of different monomers. The resulting polymer is referred to as a co-polymer, in contrast to a polymer made from just one type of monomer called a homopolymer. The very popular Saran wrap, used for preserving food because of its very low permeability to gases such as oxygen and moisture that speeds food spoilage, is an example of a copolymer made from polyvinylidene chloride and other monomers such as acrylic esters. Many variations on the co-polymer idea have been developed for specific applications.

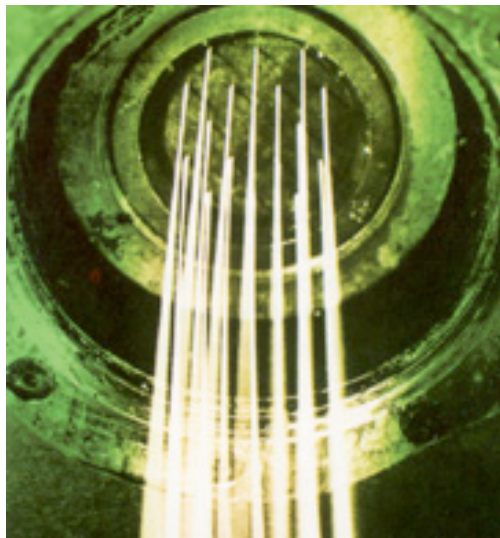


Figure 7.4.15. Fiber extrusion process
e.g., nylon, polyester, etc.
(www.fibersource.com/f-tutor/techpag.htm)

Forming Polymer Fibers: Many methods have been developed over the years to form reconstituted or synthetic polymers into useful fibers. Probably the most common, however, involves some type of extrusion process.

In this technique, the polymer in a pliable form, such as in solution or as a viscous liquid, is forced through the small openings of a showerhead-like device called a spinneret (Figure 7.4.15). The spinneret may have from a few to hundreds of holes of varying shape. Often, the shapes of the small openings dictates the cross-sectional shape of the fiber produced (Figure 7.4.1). As the fiber is pushed out of the holes, it solidifies to produce the filaments. Often, the fibers are stretched while they are after they have hardened to align the polymer molecules along the length of the fiber, producing a stronger fiber.

Forensic Analysis of Fibers: There are several important questions that are often asked as part of forensic investigations when considering fibers, including:

- *What is the composition of the fiber?* This can often be answered through a chemical analysis of the fiber using the analytical tools that will be described in later chapters. The goal is to determine the chemical components of that make up the fiber (the component monomers) and to determine the specific features of the molecular structure of the chains. This would involve discovering the identity of the monomer(s) employed, whether the sample is a copolymer, what is the relative orientation of the monomers to each other, and the degree of cross-linking formed between the chains. The chemical analysis would also determine the presence of plasticizers and other additives included in the polymer to help it be more pliable or stable. A simple flow chart has been developed that can help in describing the chemical/structural composition of fiber and is shown in Figure 7.4.16.
- *What are the physical properties of the fiber?* This typically involves determining the melting properties (e.g., softening temperature, melting temperature, glass transition temperature (T_g), and the sharpness of the melting point), the degree of crystallinity, the refractive index, and chain length in the fiber sample. Other information of interest might involve features such as birefringence, whether the refractive index is the same in all directions of the fiber (anisotropy), and opacity (whether light can pass through the fiber) depending upon the sample.
- *What is the shape, or morphology, of the fiber?* This can usually best be answered by observing the structure of the fiber at the microscopic level. Both light and electron

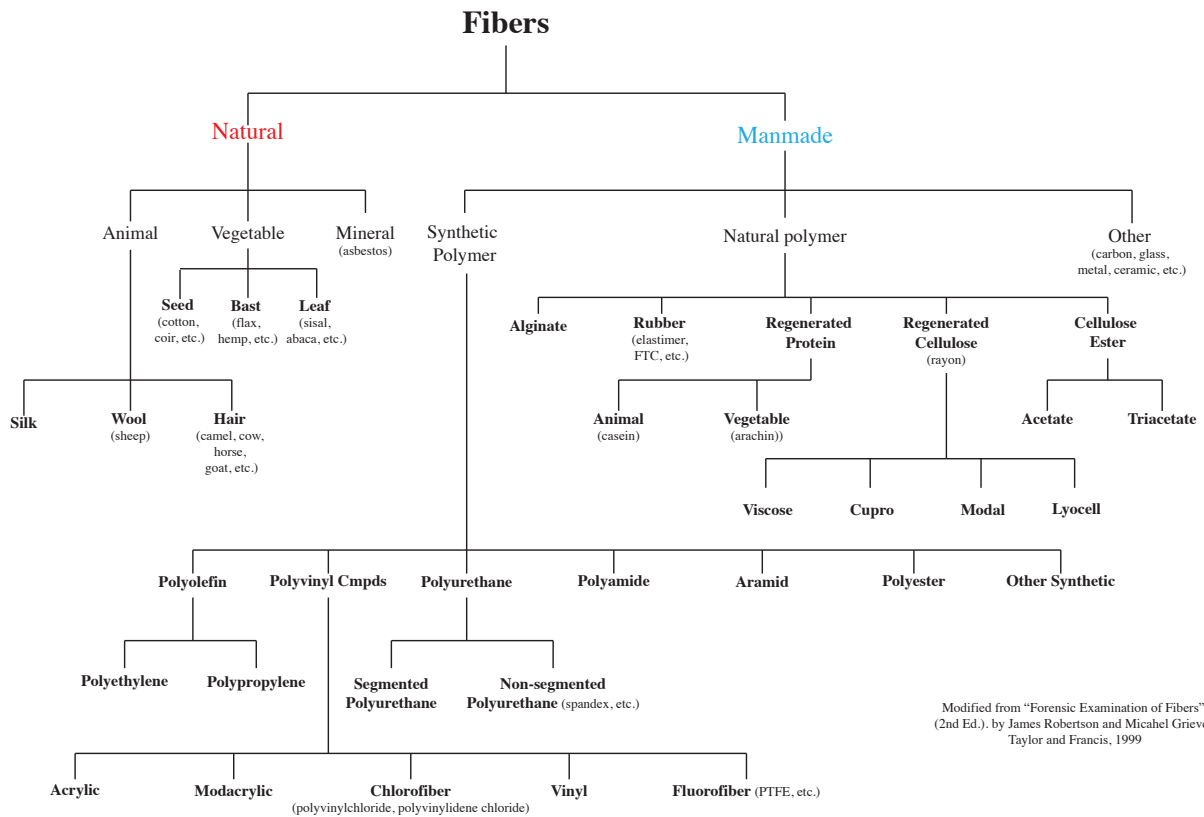


Figure 7.4.16. Flow chart for the classification of fibers (Modified from “Forensic Examination of Fibers” (2nd Ed.), by James Robertson and Micahel Grieve; Taylor and Francis, 1999).

microscopic investigations are possible, including comparison microscopic techniques to evaluate the similarities and differences between two fibers.

- *Is the fiber part of a larger piece of evidence?* This refers to the possibility of the fiber being part of a particular collection of fibers, or piece of cloth, with the likelihood of dyeing and/or coloration of the fiber as part of a pattern or design on the cloth.
- *Are there any uniquely identifying features of the fiber?* This involves looking for unique features of the fiber or cloth that would separate it from all other similar samples, such as striations, cutting marks, extrusion shapes, and other considered below.

Collections of Fibers in Larger Pieces: One of the key reasons why fibers are of such great important and so very commonly found in forensic investigations is their fabrication into larger collections to form cloth, rope, paper, and many other items. Of particular importance is the use of fibers to form cloth.

Cloth, or textile, is a network of fibers that can be shaped into a two-dimensional layer for a variety of uses. While these two terms are often used interchangeably, they have subtly different meanings; a textile is a material made from interlacing fibers while the term cloth refers to a fabric that has been made into a finished piece such as a shirt or pants. Typically, textiles are made through the use of yarns,

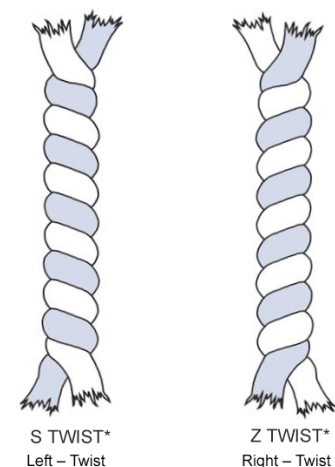


Figure 7.4.17. Types of twists in yarn production (www.fennerprecision.com/images/timing-belts_yarn-twist.gif).

long segments of fibers that are twisted or grouped together to form a relatively strong, interlocking array. Yarns are often formed by twisting shorter lengths of fibers together and the manner of twisting can help identify a particular yarn. For example, the yarn can be characterized by whether it is twisted clockwise or counter clockwise (Figure 7.4.17), how tightly it is twisted (e.g., number of twists per inch), the number of fibers in the thickness of the yarn, and how it is colored. Importantly, yarns are often made by blending together different types of fibers. For example, a textile used in clothing might be a blend of 20% cotton, 30% wool, and 50% synthetic polymer.

Yarns may be made stronger by taking smaller yarns and twisting them together to make thicker units. For example, taking two previously formed yarn strands and twisting them together makes a thicker, stronger, 2-ply yarn. The “ply” number indicates how many single spun yarns are twisted together to make the thicker yarn (Figure 7.4.18).

Yarns are often woven together in intricate patterns to form cloth. An analysis of these weaving patterns can readily show that two samples are not from a common origin if they have different weaves. There are hundreds of weave patterns known, just a few are illustrated in Figure 7.4.19.

Yarns of different colors can be woven into a cloth in particular ways to give pattern and design to the cloth, such as found in plaids, stripes, and similar arrangements. It is also common, however, for yarns to be woven together first to form an unpatterned cloth and then a design incorporated into or onto the fabric using dyes and other forms of coloration. This can be done by printing, resist dyeing, tie-dyeing, and



Figure 7.4.18. Twisted rope, made up of seven three-ply yarns. In the picture, the three plies of the left-most core yarn are spread apart (upload.wikimedia.org/wikipedia/commons/1/1a/Kernmantle_climbing_rop_e_dynamic_Sterling_10.7mm_internal_yarns_and_plyes.jpg).

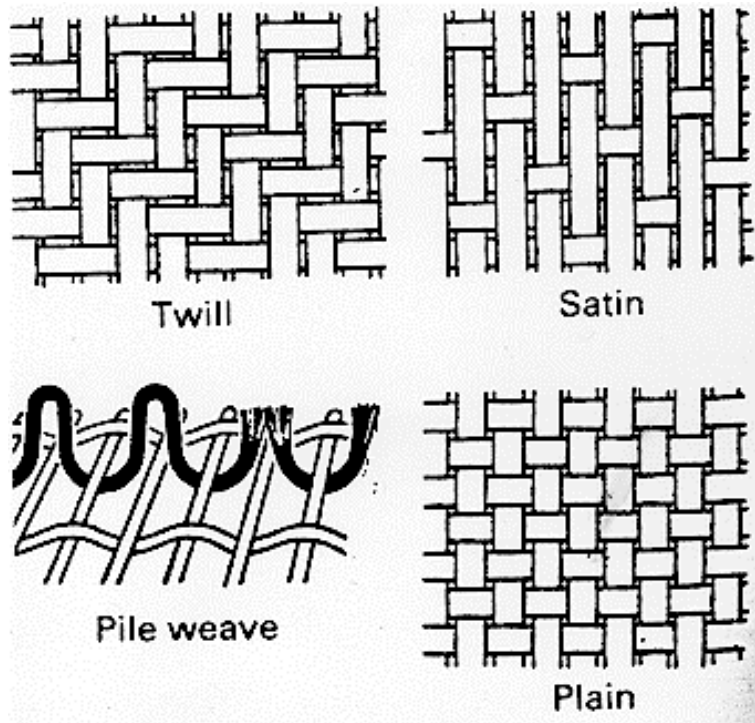


Figure 7.4.19. Example weave patterns found in cloth (source unknown)



Figure 7.4.20. Intricately embroidered Chinese fabric

(<http://topic.chinaa2z.com/topics/?c=index&f=topicalone&ename=Chinese%20Embroidery>).

through many other methods. Colored thread can also be stitched into the final cloth (embroidery) to provide intricate

patterns (Figure 7.4.20). In effect, each of these later treatments helps to individualize the piece of cloth as to its origin and use.

Besides patterns in coloration, there are a number of ways that a piece of cloth can be individualized and two fragments associated with a crime connected. Occasionally, a piece of cloth is ripped or otherwise damaged before or during a crime. It may be possible to fit these torn or damaged pieces together (Figure 7.4.21).

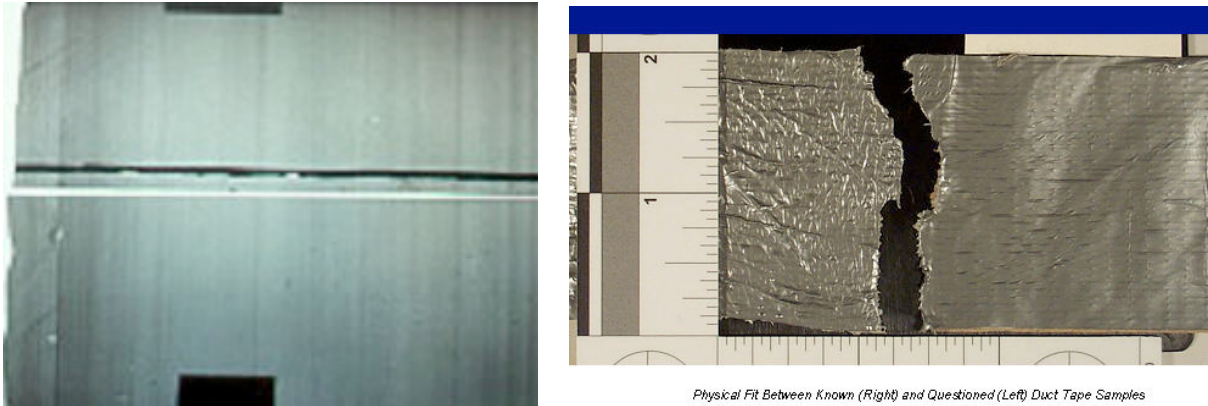


Figure 7.4.21. Striations in plastic polymer bags (top) and in fibers and polymer backing of duct tape (bottom) between known and questioned samples (www.state.nj.us/njsp/divorg/invest/criminalistics.html).

Many other objects made of fibers and polymers may also play a role in forensic investigations. Rope, twine, cord, paper, fiberboard and many others can transfer fibers *a la* Locard’s Principle. Rope is simply thick, and therefore stronger, versions of cord – both composed of fibers that can be characterized using the methods already described. Various kinds of rope, cord, and thread are possible and their analysis is very similar to that described for yarns. Additionally, polymeric materials, including sheet plastic, tapes (with and without added fibers) can also carry unique markings, such as striation formed during the manufacturing process, that can individualize a sample.



Two Cases Hanging By A Fiber

The Wayne Williams Case

From 1979 to 1981, the City of Atlanta, Georgia was plagued by a number of unsolved murders that appeared to be the works of one person, sometimes referred to as “child murders” although all of the victims were not children. The victims were murdered in a variety of ways including being shot, bludgeoned, stabbed, asphyxiated, and traumatized. A number of the later bodies had been pulled from nearby rivers, leading desperate investigators to use night surveillance of area bridges in the remote hopes of catching the murder disposing of the body of the most recent victim. On May 21, 1981, an officer stationed under the Chattahoochee River Bridge heard a splash in the river and heard a car drive by. The car, driven by Wayne Williams, was stopped by officers near the bridge and after several hours of interrogation and the search of his car, he was released. Several days later, however, the body of a victim was found downstream from the Chattahoochee Bridge and all attention was focused upon Wayne Williams.

The case was complex and difficult, with much testimony and various types of evidence. The key pieces of evidence, however, turned out to involve fibers. Expert fiber testimony connected several types of carpet fibers found in Williams’ home with fibers found on several of the victims. Additionally, some of the victims were found with fibers linked to the trunk liners of two cars of the Williams’ family. The difficulty was that these types of fibers were common in carpeting used both in homes and cars in the Atlanta area. Prosecutors

had to show that the fibers found on the victims had a high probability of coming from Williams' home and car. Investigators examined the structure and colors of the fibers and determined how common these fibers were in the Atlanta area and determined the odds of a random match of these fibers at about 1 in 30,000,000. In the end, they were able to convince the jury that there was enough of a link between the two sets of fibers to convict Wayne Williams of two of the homicides.

There remains, however, some unanswered questions in this case to many people. It appears that the car from which the fibers were deemed to match was not available to Williams at the time of the crimes. The fibers were relatively commonly found in hotels, homes and other residential buildings. And Williams himself has maintained his innocence throughout his imprisonment.

Jeffrey MacDonald Case

Early on the morning of Feb. 17, 1970, military police on Fort Bragg were called to a reported violent attack. At the home of Capt. Jeffrey MacDonald, a doctor on the base, they found a violent scene with MacDonald's wife and two small children dead. They had been violently attacked and repeatedly stabbed and beaten. MacDonald was found wounded but none of his wounds were life threatening.

The case quickly centered upon Dr. MacDonald as the prime suspect since investigators felt that Dr. MacDonald's account did not seem to match the physical evidence. MacDonald's account was that intruders had broken into his home and had done the crime.

A great deal of evidence was collected but, once again, fiber analysis proved important to the case. Investigators were able to find fiber fibers from MacDonald's pajama tops in several places at the crime scene and number of hole in the cloth. He had said that he used the top to wrap around his hands to help ward off the blows from the ice-pick wielding attacker. The tears in the cloth, both in location and in the smooth nature of the holes, were, however, thought not to be consistent with a defensive posture but more consistent with MacDonald attacking his wife with the pajama top laid over her.

Capt. MacDonald was convicted on Aug. 29, 1979 and sentenced to life imprisonment. Capt. MacDonald continues to declare his innocence and has lodged a number of unsuccessful appeals. Subsequent DNA analysis has failed to turn up any connection with someone other than a member of the MacDonald household.

