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DO THE TWIST: A BRIEF HISTORICAL INTRODUCTION TO THE PHYSICS AND CHEMISTRY OF YARN SCIENCE

Twisted fiber yarns revolutionized human culture. Improvements in technology were made throughout the common era, but serious attempts to understand the structure and properties of textile yarns date only from the 17th century. In this paper, visual evidence of the structure of textile filaments will be presented from 1665 to 1977. Major advances were made in the 20th century thanks to the development of X-ray crystallography. The study of the mechanical properties of textile filaments dates from the 19th century and continues in the present.

Historical introduction to yarn science

One of the most important items of human culture is "fabric." Humans take items found in nature and modify them to create "yarn." Yarn is then "woven" together to make fabric. While this sounds simple, and humans have been doing this longer than formal writing, the subject of yarn science is so complicated that only technical experts are willing to invest the time and energy to even try to understand at an appropriate level what is happening. Nevertheless, the subject can be addressed in a systematic way **[1]**.

The story of fabrics starts with the observation that there are structures in nature that are constructed from filamentous elements such as spider webs. Silk worms conveniently manufacture such filaments and silk fabrics were manufactured more than 4,000 years ago. Very little in nature is found in a pure form. The silk fibers are part of "cocoons" that are part of the life cycle of the silk moth. In order to prepare the "bare" silk fibers, they need to be processed both chemically and mechanically. After the fabric is woven, degumming the silk fibers is accomplished with a washing process involving natural soap and washing soda **[2]**. The "gum" is a group of soluble glycoproteins called "sericin." Rather than becoming a "waste product," sericin is recovered and used in the cosmetic industry!

The individual silk fiber is composed of two fibroin filaments and the binding agent known as sericin. The fibroin filaments are complicated and contain three different forms, including a glycoprotein P25 **[3]**. The extended scaffolding of the filament is based on two anti-parallel beta sheets of the protein polymer

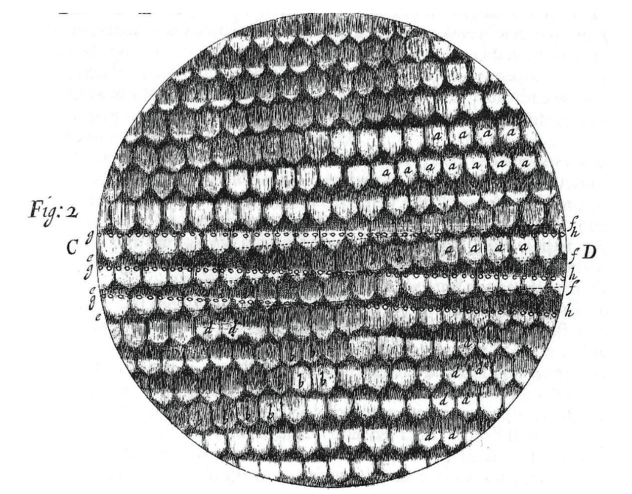


Fig. 1 - Hooke's drawing of the image of a piece of watered silk under the microscope (scanned from my copy of *Micrographia*)

(Glycine-Serine-Glycine-Alanine-Glycine-Alanine)$_n$. A light chain version binds to the main chain by disulfide bonds. While human agents have crafted silk fabrics for 4,000 years, the molecular level basis for this material is a 20th century discovery.

Robert Hooke and microscopy

The beginning of fabric science dates from the work of Robert Hooke (1635-1703). His classic study of the microscopic world, *Micrographia* (1665) **[4]**, includes a drawn image of watered silk (Fig. 1), known for its remarkable optical properties. Hooke discusses this phenomenon in terms of interference between light rays refracted by the regular structure of the fabric. In addition, he notes that the individual silk filaments are not round.

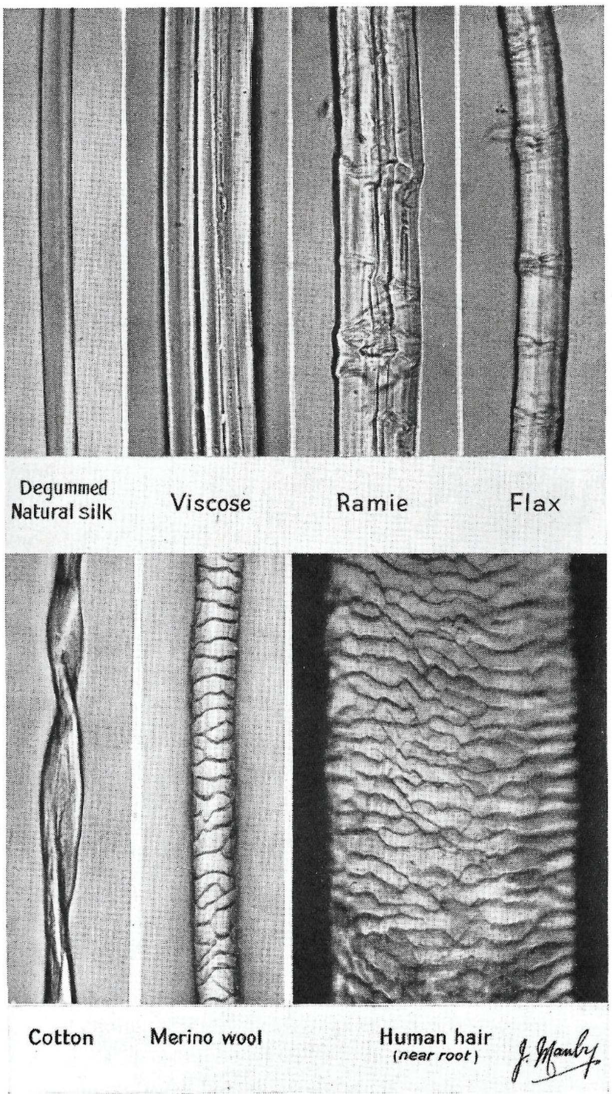
Flax: the earliest textile fiber

One of the earliest "natural" fibers to be used in the production of fabrics is flax. The stem of the *Linum usitatissimum* plant contains long cellulose filaments. The filaments are pure crystalline cellulose, a classic polysaccharide. They are arranged in a regular pattern in the stem **[4]**. A good illustration of the details of the flax stalk structure can be found at: **https://textilestudycenter.com/flax-fiber-properties/**.

The process of extracting the desired bast filaments is at least 30,000 years old **[4]**! The plant is pulled up completely, including the roots, so that no length of fiber is lost. Typical flax plants are 1 meter in height. The plants are then allowed to dry and the seeds, which are highly nutritious, are removed. One key "unit operation" is "retting" of the stalks in water. This process can take from a few weeks to a few months. Retting breaks down the structure of the stalk and facilitates "hackling" of the stem to separate the Bast filaments.

The structure of silk filaments

Natural fibers already require substantial human processing to prepare them for the production of textiles. They are constructed by their vegetable or animal organism to produce unique properties through complex structures. One of the most important books in the history of fiber science is *Fundamentals of Fibre Structure* (1932) by W.T. Astbury



TYPICAL TEXTILE FIBRES as viewed under the microscope in ordinary light at a magnification of 400 times

Fig. 2 - Textile fibers under x400 magnification (scanned from my copy of *Fundamentals of Fibre Structure*) **[5]**

(1898-1961), Professor of Textile Physics at the University of Leeds (UK) **[5]**. In addition to seminal X-ray studies of biological materials, he studied the textile fibers by high resolution microscopy (Fig. 2).

Under such a microscope, the silk fiber looks quite "smooth." Astbury subjected such fibers to X-ray crystallography and obtained the following pattern (Fig. 3). This is the characteristic pattern for an oriented uniaxial crystal. A discussion of the relationship between silk filament structure and its mechanical properties is given below.

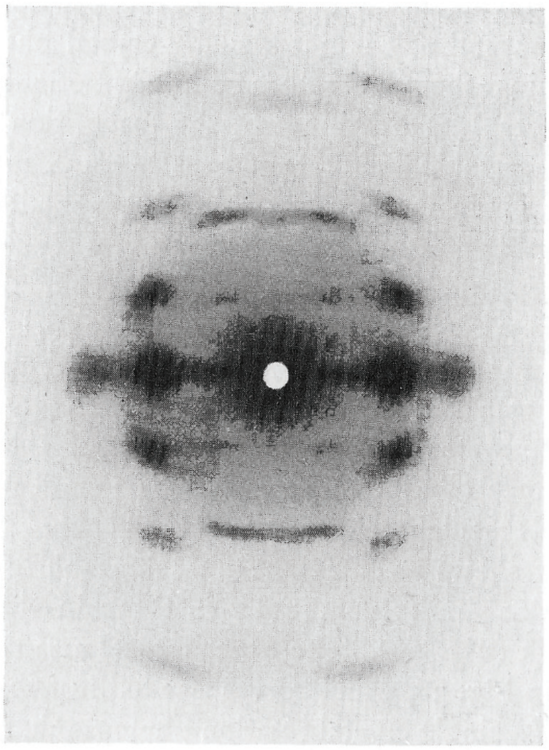


FIG. 36. X-ray 'fibre photograph' of natural silk (fibroin).

Fig. 3 - X-ray fibre photograph of natural silk (scanned from personal copy of Astbury) [5]. This is a historically important image and is reproduced in high resolution. The image is an accurate reflection of the actual sample structure

The structure of wool fibers

Wool fibers are much more complicated. A modern "cartoon" for a wool fiber is reported in Fig. 4.
At the heart of the fiber is a complicated protein chain called keratin. In its relaxed state it forms predominantly an "alpha helix". Wool fibers can be stretched like natural rubber filaments. Astbury studied the X-ray patterns corresponding to the relaxed and fully stretched state of wool fibers. The characteristic repeated distance along the fibril axis changed as the chain stretched. It is now known that the alpha helix becomes a fully stretched polypeptide chain. If the stretching is carried out under 0% relative humidity, the stretched state can be retained for extended periods of time after the stress is removed. But, if the wool is exposed to water, it will return to its initial state. Astbury, in 1932, correctly compared this to the behavior of natural rubber [6]. Stretched rubber crystallizes and heat is given off. If the rubber

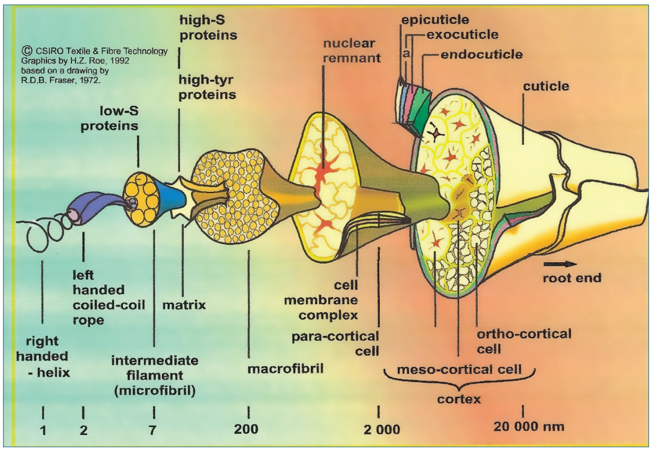


Fig. 4 - Schematic diagram of a wool fiber showing the complicated biological structure. (https://csiropedia.csiro.au/wp-content/uploads/2015/01/6229343.pdf)

is cooled under tension the crystalline state is stable. Natural rubber will crystallize spontaneously if it is cooled sufficiently.

The structure of cotton fibers

Crystalline materials often exist in multiple forms. One of the most famous textile chemists, John Mercer (1791-1866), discovered that cellulose fibers could exist in two forms [7]. When he used cellulose cloth to filter a strong lye solution, he noticed that the fibers became shorter and stronger. This process, now known as "mercerization", is still a standard procedure for preparing strong cotton thread.
Such fibers have also been studied by X-ray crystallography. Four polymorphs are now known for the cellulose crystal form [8]. They are all based on the extended cellulose structure that forms microcrystals of folded chains, but the packing is different.
The basic filaments of natural textile fibers are all based on crystalline forms of biomacromolecules. The technology needed to isolate the structure needed to form yarns has been known for millennia, but the molecular details are 20th century discoveries. In spite of "modern" synthetic textile fibers, all four classical textile fibers are still an important part of human culture!

Turning textile fibers into yarn

Early fabric technology was tedious but people with lots of time could devote their energy to such activities. Eventually, fabric production became a stand-

Fig. 5 - Portrait of a lady spinning with a flyer and wheel. Maerten van Heemskerck (1531), Museo Thyssen-Bornemisza, public domain

ard "home industry" and the distaff was a staple in most houses (**https://en.wikipedia.org/wiki/Distaff**). While the spinner was not fully aware of the technological significance of their craft, they knew that in order to create good fabrics, the yarn needed a "twist."

Spinning wheels

The origins of the "spinning wheel" are disputed, but regions that produced lots of fabrics from wool and cotton, such as India and Persia, were employing this technology by around 1000 CE **[9]** (Fig. 5).

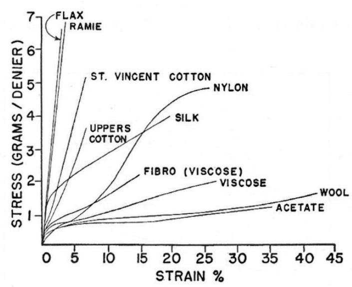
The distaff is now more elegant, but it still provides convenient unreeling of the not yet twisted fibers. The wheel provides the motive power, and in this version is controlled directly by the right hand (later versions were driven by a treadle mechanism). The major improvement is the flyer mechanism that incorporates the twist. Leonardo Da Vinci played an important role in the perfection of this mechanism. The fibers from the distaff are gathered and twisted by the spinner. Handwork remained the key to good yarn. The hand-twisted yarn is fed into the hollow axle of the flyer and up through a hole. The yarn is then threaded through the hooks on one side of the flyer and onto the bobbin. The drive-wheel band is twisted so that there are two strands available for spinning. The whorl spins more slowly than the bobbin, due to the different diameter of the drive groove. This allows the proper tension to be maintained. When the process is completed, the whorl is unscrewed and the bobbin removed (the whorl-nut threads are counter-rotational from the spinning direction). A nice diagram of the modern flyer can be found at: **http://rovingcrafters.com/2015/05/06/how-to-pick-a-spinning-wheel-that-you-will-love-part-1/**.

The physics of yarn strength

It has been known for many millennia that twisted yarns are stronger than single filaments. But it has only been in the 20th century that a coherent theory of yarn strength has been developed. There are many levels of theory that can be applied to this problem, but they all start with a single filament. Measurements of the stress and strain of a single textile filament look like Fig. 6.

Flax and ramie are "stiff" filaments, while, by comparison, wool is "soft." The "tenacity" of the filament is obtained from the slope of the curve. The range of tenacities for the filaments considered here are **[10]**:

Flax 2.4-7.0 g/D
Silk 2.2-4.6 g/D
Cotton 2.0-5.0 g/D
Wool 1.1-1.5 g/D



Graph 5. Stress-strain curves of typical fibers.* (*From Meredith,*[8] *"Tensile Behavior of Cotton."*)

Fig. 6 - Stress-strain curves for typical textile fibers **[10]**

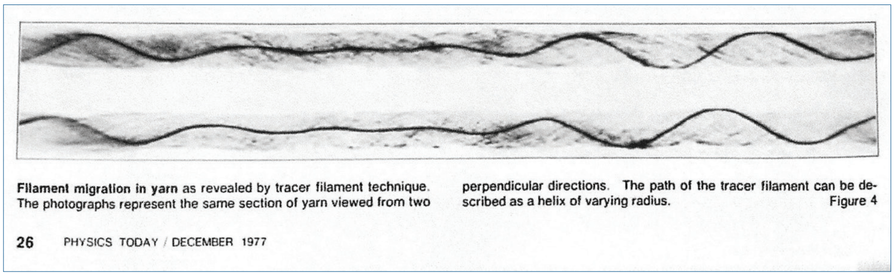


Fig. 7 - Filament migration in a twisted yarn. The filaments are flexible and can sample the full cross section of the fiber. This complex structure is fully consistent with the known structure of polymers like polyethylene in the oriented liquid state [11]

Another important measure of the filament is its percent elongation at rupture. Flax and ramie break at only 3-7% elongation, while wool can elongate by up to 50% of its initial length. As discussed above, wool undergoes a conformational transition from alpha helix to extended chain that allows it to extend under tension.

Yarns contain many filaments. Consider an "ideal" straight cylindrical filament of cross-sectional area A and length L. If a group of N of these filaments are contained in a cylindrical vessel with a cross section substantially exceeding NA, but still small enough to restrict the direction of the filaments, a single filament can be pulled out of the "bundle" with minimal force (think of a package of spaghetti). But, if the bundle is subjected to a cylindrical pressure, it will be difficult to remove a single piece. The neighboring cylinders provide a frictional force that resists movement of the "test piece." If the frictional force is large enough, pulling on a single piece will result in extensional failure of the test filament.

Individual filaments have cross-sectional areas in the micron range, while filament length can be macroscopic. While dry spaghetti looks like a rigid rod, any textile filament at room temperature will look like a writhing snake. Inter-filament forces are strong enough to bind the bundle together like a liquid crystal. With only a small external tensile force, the "preferred direction" for the filaments can be established. Raw silk filaments are mated with others in a process of reeling that creates a structure where there are many filaments oriented preferentially along the contour of the yarn. Intrinsic inter-filament forces stabilize the bundle.

If a "raw" yarn is simply allowed to exist as a tangled mess, it devolves in many ways. Natural Brownian motion allows the chemical chains to "sample" possible arrangements. Filaments on the outside of the yarn can start to deviate from the preferred direction and eventually "reptate" away! This process is facilitated by ambient moisture. The water molecules provide both a "heat bath" and a Brownian force. We should celebrate the woman who observed that if the yarn is kept reeled, it will be stable longer. Re-reeling reinforces the preferred direction and allows some defects to be eliminated.

Nevertheless, untwisted yarns have a definite "shelf life." Some dear soul discovered that if the yarn is twisted, the structure is both stronger and more persistent. This is not the only technological miracle that remained a mystery for millennia, but it required both the theoretical advances of the 19th century and the analytical advances of the 20th century to begin to understand the phenomenon.

One of the most important theoretical and experimental insights is the actual paths traversed by single filaments along the length of the yarn. Riding and Treloar [11] have measured the trajectories for a single filament using tracer techniques. The actual path meanders with respect to the radial location even as it progresses in the axial direction (Fig. 7).

The twisting of the yarn "compacts" the bundle creating a liquid crystalline-like environment. The preferred direction is along the axis of the yarn, but individual filaments have much more freedom in the transverse direction. One of the key macroscopic characteristics of the yarn is its "anisotropy." The optical anisotropy of textile fibers was known by Robert Hooke. Treloar discusses the mechanical anisotropy that is so important to textile science. The tensile modulus of a yarn is very high, but the torsional modulus is low. It is much easier to "twist" yarn than to stretch it! But, when the yarn is fully compacted by twisting, additional torsional strain will produce internal stresses that weaken the structure.

One of the most remarkable theoretical studies that illustrates this effect was published in 1942 in the *Journal of Applied Physics* [12]. The yarn strength

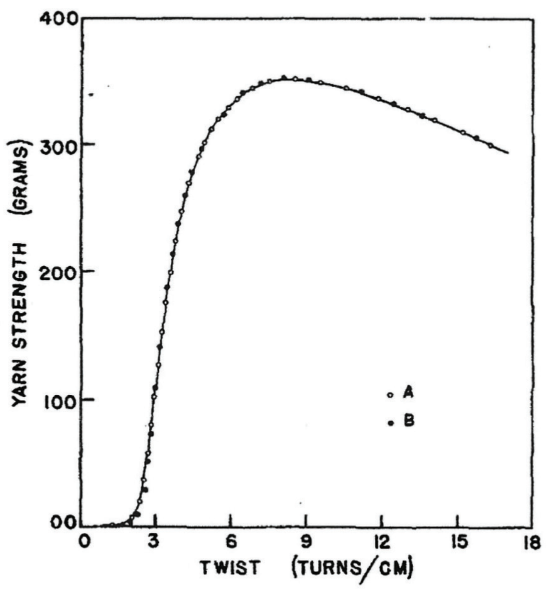


FIG. 5. The parallel-fiber yarns of Fig. 4 have been twisted and the resulting yarn strengths plotted as functions of the twist. The constant external pressure, p_0, is 0.6 g/cm². δ'=unity. Points A are for fiber properties variable. Points B are for all fibers alike.

Fig. 8 - Calculated yarn strength as a function of twist in a model yarn [12]

was calculated as a function of twist (Fig. 8). The key physical phenomenon involved is the friction experienced by a filament as a function of twist. At low twist, it is still relatively easy to pull out the test filament (it is still relatively easy to pull out a test strand of spaghetti from a pot of boiling water). As the twist increases, the test strand is more confined and at the point where there is less "free volume" than needed to avoid close contact the friction produces a much stronger multi-filament structure. But, at much higher twist, little new compaction occurs and local stresses can now produce failure due to breakage of the filaments themselves!

Real textile yarns may introduce many additional complications, but the combination of molecular mechanics, condensed matter physics and polymer science account for most of the phenomenology.

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Facciamo il "twist": breve introduzione storica alla fisica e alla chimica della scienza del filato

I filati in fibra ritorta hanno rivoluzionato la cultura umana. I miglioramenti nella tecnologia sono stati compiuti durante l'era volgare, ma concreti tentativi di comprendere la struttura e le proprietà dei filati tessili risalgono solo al XVII secolo. Nel presente articolo verranno presentate prove visive della struttura dei filamenti tessili dal 1665 al 1977. Grandi progressi si sono poi avuti nel XX secolo grazie allo sviluppo della cristallografia a raggi X. Lo studio delle proprietà meccaniche dei filamenti tessili risalgono al XIX secolo e continuano nel presente.