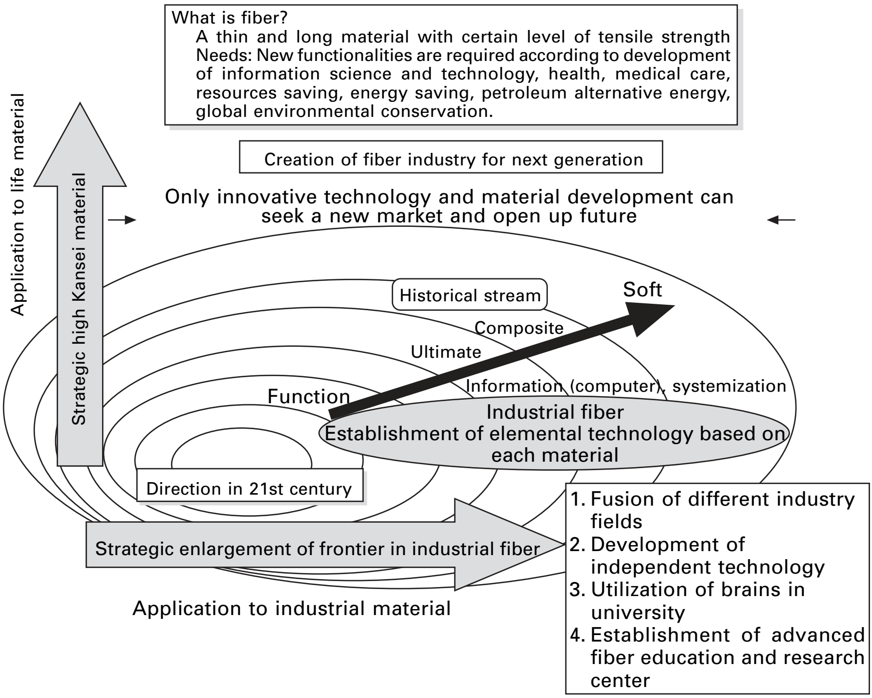
1
Searching the roots of fibers

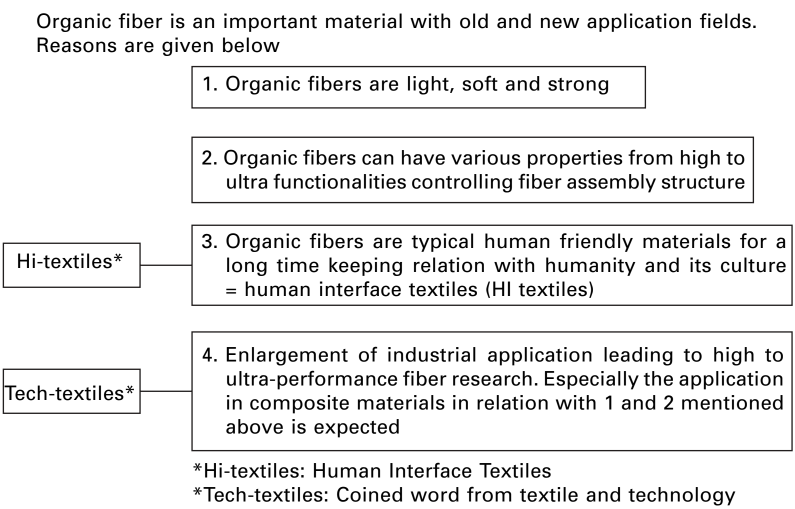
1.1 The importance of fiber in human life

An instinctive reaction is that organic fiber is nothing like as strong as metal. However, nylon, a superfiber, appeared which was stronger than metal in terms of tensile strength per unit cross-section. Organic fibers are light, but since some organic fibers possess a high tenacity/high modulus and much-improved heat resistance, these fibers have expanded into new industrial uses. When these fibers are incorporated into a resin to produce a composite material, the resulting advanced composite material (ACM) is light, strong and deform-resilient. This material surpasses metal, to some extent, in its mechanical properties. These ACMs are applied widely in the aero and space industries to replace aluminum alloys. ACMs are also being used increasingly in the civil engineering and construction industries. For example, in Kansai International Airport, which was built on land reclaimed from the sea, the ACMs have been used as geotextiles following the Kobe earthquake. Although the term 'fiber' tends to have old-fashioned connotations, the fact is that these new fibers have reached new performance levels and found new functions, which match social needs. Now fiber is applied widely in so many fields, which could not have been imagined even a decade ago. This book will describe this new range of fibers.

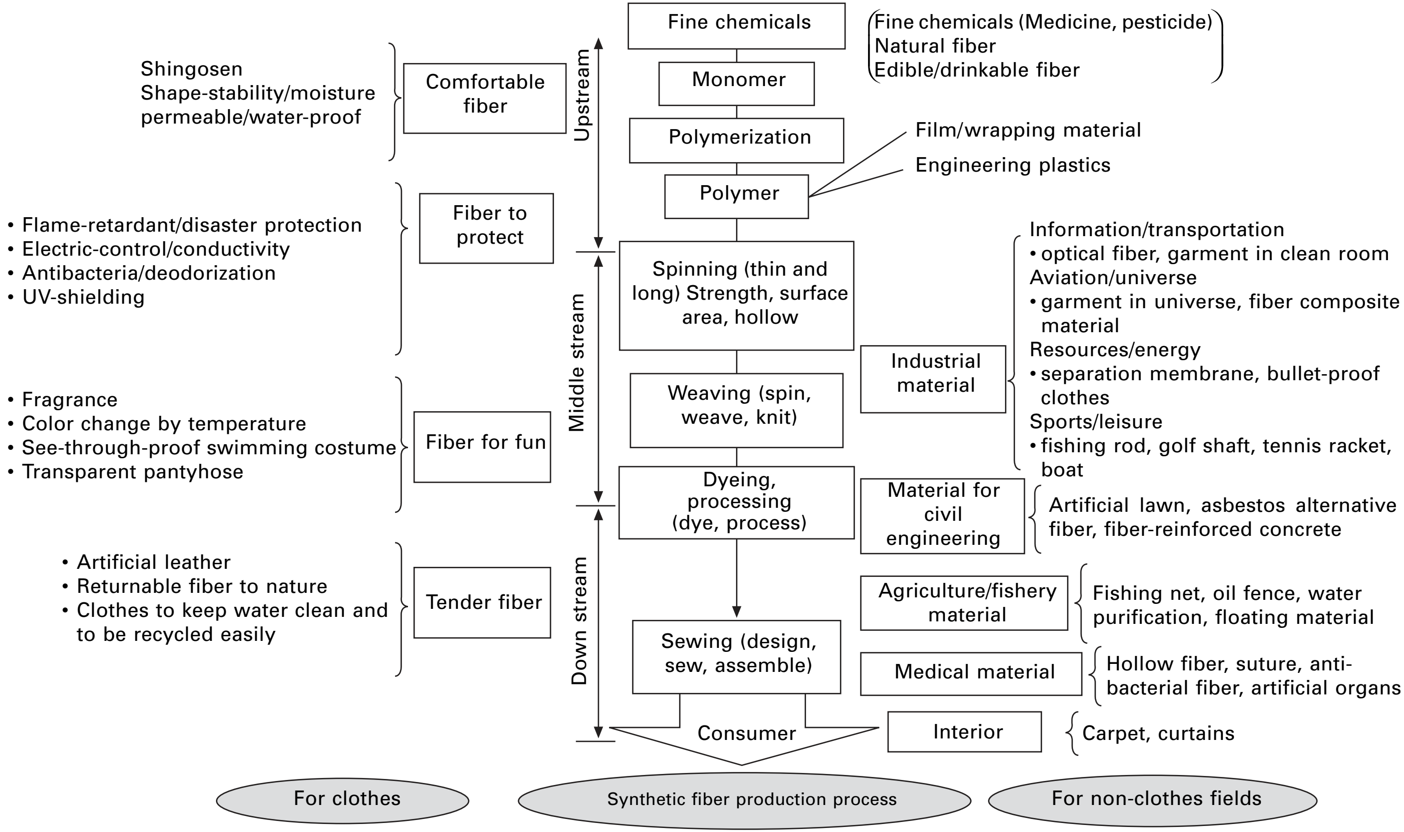
Tech-textile denotes the textiles applied in the high technology area, including the aero/space industry (as primary and secondary structural materials), the transportation industry (as tyres), the marine industry (as ropes and fishing nets), the civil engineering and construction industry (as reinforcing materials) and the sports industry (as tennis rackets, golf shafts and ski plates). The term 'Tech-textile', implying integrating technology into textiles, was first introduced at the EXPO for industrial textile materials at Frankfurt, and later at the EXPO in Japan. Figure 1.1 shows the development prospects of the fiber industry for the next generation. Figures 1.2 and 1.3 demonstrate the importance of fiber as materials and the expansion of advanced fiber technology into diverse industrial areas. New fibers have appeared in



1.1 Development prospects of the fiber industry for the next generation.



1.2 Importance of fibers as materials.



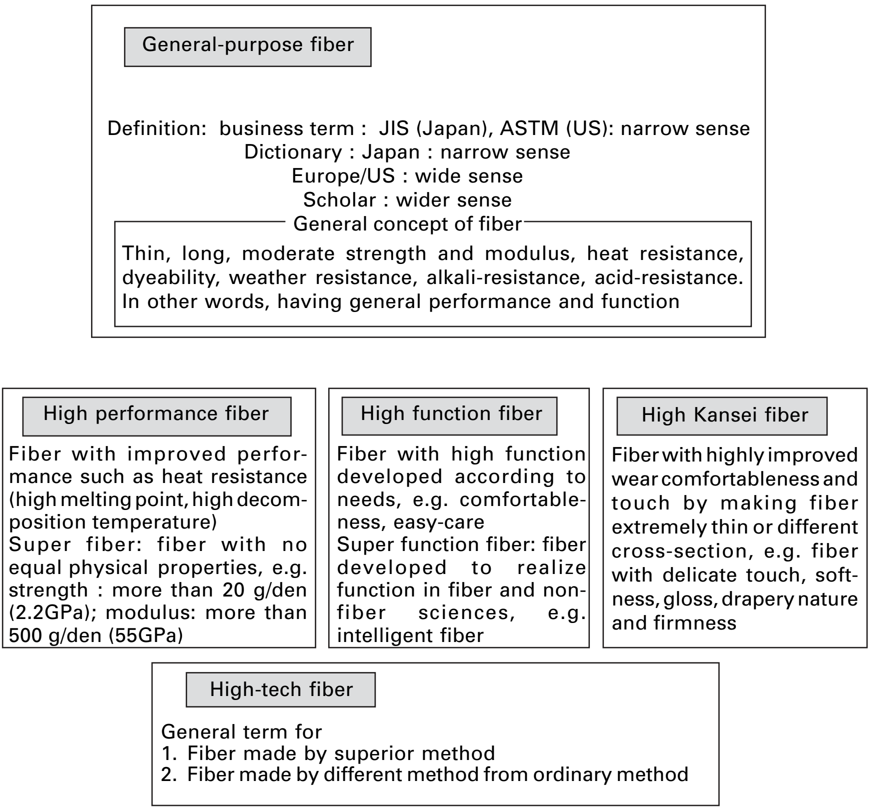
1.3 Expansion of synthetic fiber technology in diverse industrial areas.

order to meet the changing social needs over the past thirty years, including superfiber, advanced composite materials, optical fiber, shingosen (ultra fine fiber), various functional fibers, comfort/healthcare fiber, etc.

1.2 What is high-tech fiber?

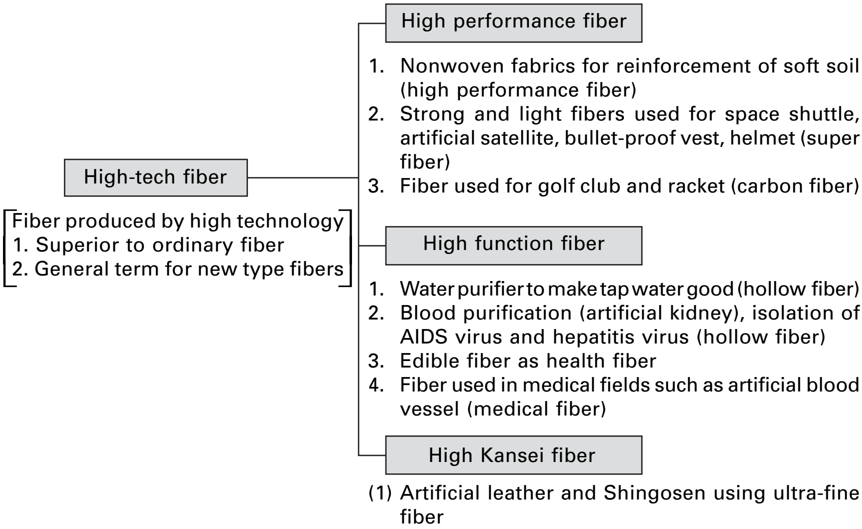
High-tech fiber is an expressive way to indicate that advanced science and technology have been used to produce this fiber. High performance fibers, such as the superfiber, high function fiber, which functions as a sensor and actuator, and high touch fiber which possesses a new hand feel, as exemplified by shingosen, are examples of high-tech fiber. The concept of new fibers is summarized in Fig. 1.4, and their applications are found in diverse areas as shown in Fig. 1.5 and summarized in Fig. 1.6. Figure 1.7 illustrates examples of high-tech fiber.

High performance fiber, which has improved physical properties compared with conventional fibers, needs to be distinguished from superfibers. In general,

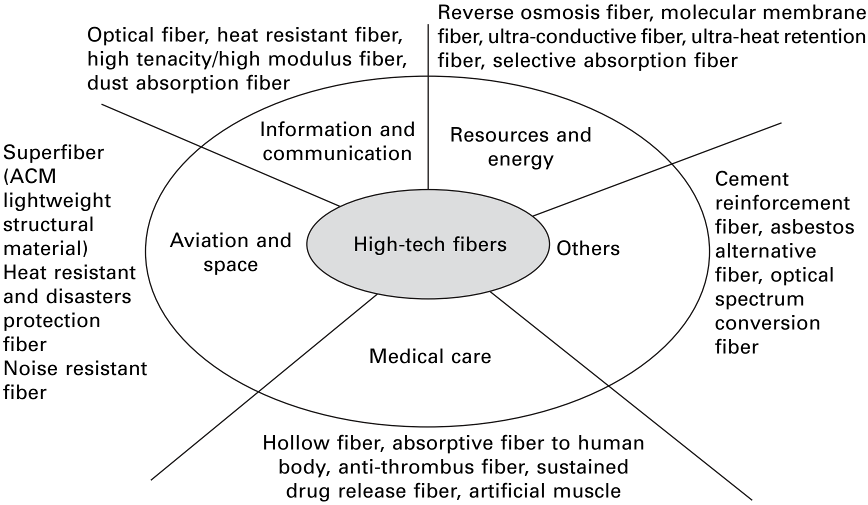


1.4 Concept of new fibers.

1.5 Utilization of fiber in various fields.



1.6 Applications of high-tech fibers.



1.7 Applied examples of high-tech fiber (from short to middle term).

fibers for commodity purposes need to possess appropriate physical properties including such mechanical properties as tensile strength and Young's modulus, heat resistance, dyeability, weather resistance, alkaline resistance and acid resistance. A superfiber, which needs to be superior to high performance fiber, must have a tensile strength larger than 20 g/denier (or 2.2 GPa) and a Young's modulus higher than 500 g/denier (or 55 GPa). Typical examples of superfiber are listed in Table 1.1. GPa (giga Pascal) is the international unit

Table 1.1 Typical examples of superfiber

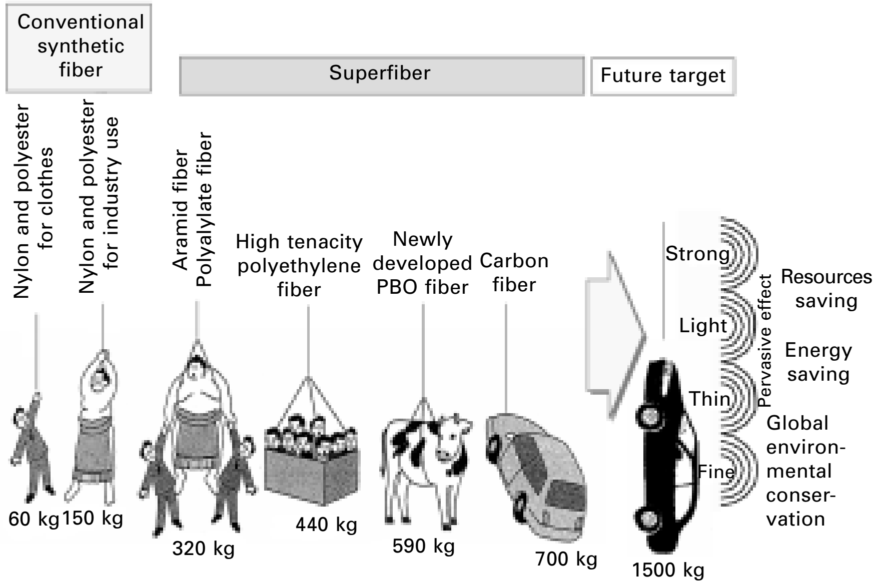
Fiber	Trade name	Strength (g/den)	Modulus (g/den)
Measure of superfiber		More thn 20 Satisfy both at the same time	More than 500
para-aramid*1	Kevlar 49 (Du Pont)	22	850
	Twaron*2 (Teijin Twaron)	22	850
	Technora (Teijin)	28	560
All aromatic polyester	Bectran (Kuraray)	29	670
Polyethylene fiber	Dyneema (Toyobo) SK60	30–40	1000–1400
	High tenacity product	40–45	1200–1600
PAN-based carbon fiber*2 (liquid crystal)	TORAYCA (Toray) Besfight (Toho Tenax) Pyrofil (Mitsubishi Rayon)	20–45	1400–3500
Pitch-based carbon fiber (liquid crystal pitch)	Glanoc (NGF) Dialead (Mitsubishi Chemical)	13–19	700–4500
PBO fiber	ZYLON® (Toyobo)	42	2000

(*Note*)
*1There are *para*-aramid (high tenacity and high modulus) and *meta*-aramid (heat resistance). *para*- and *meta*-types belong to super and high function fibers, respectively.
*2There are isotropic (for general use) and liquid crystalline pitch (high performance). Liquid crystalline pitch belongs to superfiber.

to express the strength and modulus of a material, and 1 GPa corresponds to the load of approximately 100 kg per 1 mm^2, which can suspend two persons. Currently much effort is focused on producing superfibers from polyvinyl alcohol, poly acrylonitrile, polyacetal, nylon and polyester. The tensile strength of various super fibers is compared in Fig. 1.8.

Generally superfibers are defined as the fiber whose strength is more than *ca*. 2 GPa, and elastic constant more than *ca*. 50 GPa. The strength and the elastic constant of the general-purpose fibers are usually represented in units of cN/dtex (centi-Newton/deci-tex). For the superfibers, a unit of GPa is often used. The value in cN/dtex represents the load per unit line density. On the other hand, the value in GPa represents the load per unit sectional area and is larger than that in cN/dtex. For the Para-aramid superfiber a strength of 20 cN/dtex and elastic constant 500 cN/dtex (density = *ca*. 1.44 g/cm^3) corresponds to 2.9 GPa and 72 GPa, respectively.

Conventional nylon or polyester fibers for apparels have tensile strength 4.5~6.5 g/denier, and that for industrial use 6.5~10.0 g/denier, both of which



1.8 Strength of superfibers (How many kilograms can a fiber with 1 mm^2 cross-section support?).

are well below the superfiber. Superfiber is used for ropes, monofilament fishing string, in the composite for helmets, tennis rackets and golf shafts, and is also used as a structural advanced composite material for airplanes and space shuttles. Since the superfibers are generally used on the inside of structures, they are rarely evident to the public eye.

Although all fibers have a role within products, functional fiber should additionally possess some distinctive chemical functions. Fiber is usually defined as a thin and long structure. Three features are generally used to characterize a fiber:

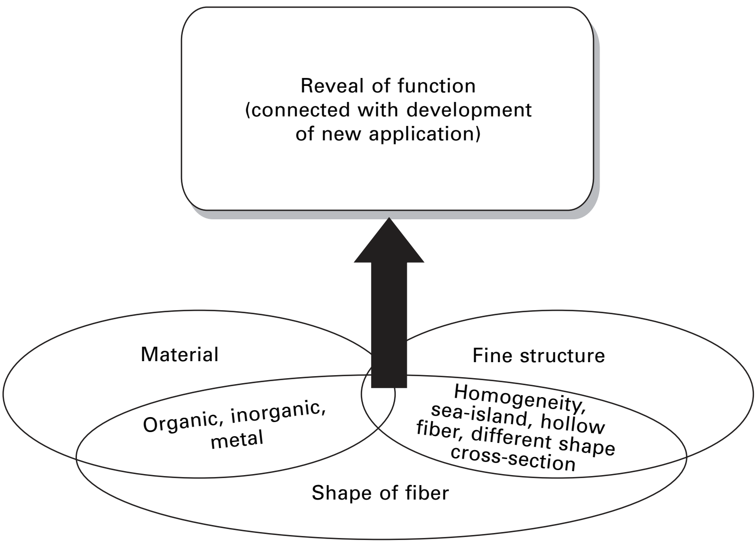
(1) The material which makes up the fiber, which could be organic or inorganic, a biomaterial, a nanofiber, such as DNA or a synthetic polymer.
(2) The shape of cross-section can be circular or non-circular.
(3) The fiber microstructure: homogeneous or non-homogeneous, a hollow fiber or a composite fiber.

As the three elements of melody, rhythm and harmony can amalgamate to produce music and move the human heart, so also can the three elements of materials, shape and microstructure in fiber stimulate human emotion through the five senses. For example, shingosen has a characteristic feel which people had never previously experienced and fall in love with. We may be able to produce something even more advanced than shingosen, since no synthetic fiber has yet been produced with a similar feel to animal hair, such as alpaca, angora, cashmere, vicuna, mohair, and camel. The characteristics of these animal hairs are summarized in Table 1.2. Figure 1.9 shows how three elements of fiber are amalgamated to reveal new functions.

Chemical fiber is produced by extruding a polymer through a nozzle, so that the fiber cross-section is more homogeneous. Natural fibers, on the other hand, possess non-homogeneous cross-sections, indicating that we need

Table 1.2 Animal hair and characteristics

Variety	Characteristics (touch)	The habitat
Alpaca	Glossy and smooth	Peru
Angora	Glossy and soft Impossible to spin because of no crimp Spun with wool	Hair from Angora rabbit
Cashmere	Glossy, thin and soft Glossy long hair like silk	Native goat in Indian Kashmir and Tibet
Vicuna	Thinnest and softest among animal hair Expensive	Hair of vicuna living in Cordillera de los Andes
Mohair	Glossy as silk Strong and elastic	Hair of Angora goat in Turkey
Camel	Soft as cashmere Dark brown Impossible to decolorize	Hair of camel in Asia



1.9 Three elements of fiber to reveal new functions.

to learn much more from nature. The requirements for fibers are diverse and beyond conventional concepts. Thus, it is likely that more complex and sophisticated fiber will appear in the future.

1.3 Natural versus synthetic fiber

The main difference between natural and synthetic fiber is in structure. Synthetic fiber is produced by extruding a polymer through a nozzle and subsequent drawing. The resulting fiber has a simple structure. The fiber structure of most synthetic fibers is characterized by the *shish kebab* structure, as in the example of polyethylene.

Natural fibers such as cotton, wool, and silk have a non-even non-homogeneous surface. Those fibers also possess a multi-phase structure, which results in specific functions. The simple structure of a synthetic fiber could be suitable for high performance, but not for high function applications.

The silkworm eats mulberry leaves, which are converted by enzymes into two proteins (fibroin and sericin) in its body. Recent research has described how it drags out silk thread to make a cocoon, but the mechanism for how it produces the two proteins is still unknown. Moreover, the chemical structure of silk is complicated and the cross-section of its filament is not circular. Silk possesses a specific luster, warm touch, deep color, and moisture-absorption characteristics, which no synthetic fiber possesses.

The chemical structure of wool, a protein produced by sheep, has a complicated and cunning bilateral structure. Wool is cool in summer and warm in winter. The complicated wool structure gives wool this property, and also good resilience, high bulkiness, and water repellency. No artificial fiber can compare with wool with respect to those properties, which makes wool so suitable for clothing.

A similar argument can be applied to cotton, made up of cellulose photosynthesized from carbon dioxide in air and water. It is a homopolysaccharide with a relatively simple chemical structure. However, its morphological structure is ingenious such that no synthetic fiber can compare with cotton with respect to its moisture absorbency, dyeability and moisture maintainability.

Lentinan, a similar simple but branched fibrous polysaccharide, can be extracted, separated, and purified from a type of fungi, a polypore. It has anti-tumor activity because it increases the level of body immunity. This polysaccharide (Lentinan®) is now commercially available from Taitro Pharmaceutical (Manufactured by Ajinomoto) as an anti-tumor agent.

Why is synthetic fiber different from natural fiber? Why cannot synthetic fibers emulate natural fibers? One of the reasons is that their mode and speed of formation are quite different. Silk thread is produced from the silkworm mouth at the rate of 1 m/min. Wool or cotton has a much slower growing rate of around 10^{-6} m/min. The spinning speed of a synthetic fiber is steadily increasing with the development of fiber manufacturing technology, and has now reached the speed of the jet plane. Silkworms, sheep or cotton produce natural fiber in order to protect their bodies, so need to maintain enough function to cope with the environment where those living creatures live. Synthetic fiber, on the other hand, beats natural fiber with respect to its physical performance (tensile strength, heat resistance, durability at extremely low temperatures, etc.) and production efficiency (spinning speed, etc.).

Table 1.3 lists the differences between natural (cotton) and synthetic fibers. As seen from Table 1.3, natural fiber and synthetic fiber can be classified as high-function fiber and high performance fiber, respectively. Synthetic fibers were developed initially as copies of silk, wool, or cotton. At present, there

Table 1.3 Difference between natural and synthetic fibers

	Natural fiber (cotton)*	Synthetic fiber
Raw materials	Water, light and carbon dioxide	Petroleum (monomer)
Production method Rate	Photosynthesis Less than 8×10^{-7} m/min	Polymerization and spinning More than 1×10^{3} m/min
Characteristics: Structure	Inhomogeneous, precise, complicated (multiphase structure)	Homogeneous and simple, *shish kebab* structure
Property	Show excellent properties in daily environment	Show excellent structure even in specific environment
Usage	Mainly used for clothes	For clothes and industrial materials
Prospect for next generation	1. High functionality 2. Reformation of production technology by biotechnology (fiber production after insects and spiders) 3. New natural fiber (spinning mechanism of spiders and silkworms)	1. Precise control of molecular orientation produces higher dimensional structure materials and composite materials 2. Contribute to human technology and fibers with ultimate functions and environmental response 3. Contribute to clarification of tissue structure and function

*Plants derived natural fibers with higher dimensional fibrous structures are synthesized from water, carbon dioxide and light by biochemical processes in plants. The excellent water absorbency/releasing properties are not easily copied by synthetic fibers, and will have different application fields from those of synthetic fibers even if superior development of synthetic fibers. Wool and silk are synthesized by biological processes in sheep and silkworms using plants as raw materials. The structures are more complicated and precise than those of plants derived from natural fibers.

is no way to produce high function natural fiber with a speed comparable with synthetic fiber.

Synthetic fibers are no longer copies of natural fibers such as silk, wool, and cotton. To create synthetic fiber possessing new functions that even natural fibers do not have, research needs to develop a new method of simultaneous polymerization and spinning since wool is produced in such a way. Synthetic fiber indeed surpasses natural fiber, to some extent, as exemplified by ultra-fine fiber, high tenacity/high modulus fiber, water-absorbent fiber, and heat-resistant fiber. A new paradigm shift such as the application of biotechnology is needed to develop super high function fiber.

1.4 Artificial fiber by biomimetics

Most synthesized materials including synthetic fibers have been developed by science and sometimes by chance in the past, whereas natural materials are produced as a consequence of biological processes. These approaches have now been integrated.

1.4.1 Plant fiber synthesized from carbon dioxide

Plants produce carbohydrates by photosynthesis. Air contains only about 0.3% carbon dioxide. Yet plants utilize this small amount of carbon dioxide with water to produce cellulose by photosynthesis. The structure of the resulting fiber cross-section is non-homogeneous, and is composed of complex multi-layers, whereas that of the artificial fiber is homogeneous. Cellulose could be termed 'carbon dioxide fiber', and gives a hint as to how to produce an environmentally friendly fiber without using fossil energy if we could learn from nature.

1.4.2 Lessons from the silkworm

Rayon appeared about a century ago as the first chemical fiber mimicking silk. Rayon filament is made from wood pulp that is dissolved and wet-spun. Rayon is thus chemically composed of the same component (cellulose) as wood pulp. Then nylon appeared about a half a century later. Nylon was aimed to mimic silk chemically, and has similar amide groups. Fifty years after the invention of nylon (around 1988), a synthetic fiber reached a new stage of development when the combined yarn processing technology (the blends of filaments of different shrinkage characteristics) was developed to produce high bulky polyester fiber fabric with a characteristic feel different from natural silk. However, not all of silk's features were reconstructed. For example, the characteristic luster, moisture-absorbent characteristic and bright dyeability of silk have not yet been achieved.

Dr J. Magoshi at the National Institute of Agrobiological Science (NIAS) in Japan has elucidated the mechanism of *in vivo* synthesis of silk in silkworm. It was not previously known how the silkworm makes silk from mulberry leaves. Mulberry leaves are digested to amino acids, which are concentrated in the silk gland where a two-layered silk protein is produced at room temperature. Gel-like fibroin solution is formed by calcium ions in the silk gland. Gel is transformed to sol by carbon dioxide in air, and becomes liquid crystalline in a narrow tube. Sol is transferred slowly to the spinning tube and is spun to silk filament.

The silk gland corresponds to the polymerization/spinning tank in terms of the synthetic fiber production. Silk filament is produced enzymatically at room temperature. This high technology required for the precise control of such a molecular assembly has not yet been achieved by human beings.

The process is now being reconstructed on an industrial scale. A bio-spinning factory is expected to develop to a commercial scale on the basis of the elucidated bio-mechanism of spinning soon as a substitute for oil-based fibers. The silkworm spins fibroin, not by extrusion, but by drawing. The silkworm fixes the end of fibroin on to the ground, and swings its head in the manner of a number ‘8’ to draw fibroin. In conventional industrial spinning of synthetic fiber, the nozzle is fixed and extruded filaments are drawn, whereas the silkworm moves the nozzle (mouth) to draw out filament. Silk filament is crimpled, and its assembly is bulky. In effect, silk has good properties such as heat insulation, moisture absorption and a good feel. The silk filaments assemble and synchronize to achieve high functionality. Now the filaments can be designed to synchronize and promote the same specific functions artificially.

1.4.3 Learning simultaneous polymerization and spinning from nature

The process of human hair or wool growth is not well understood. However, human hair or wool grows simultaneously as it is polymerized from amino acids. Since human hair or wool is spun immediately when polymerized, no entanglement occurs during fiber formation. With synthetic fibers, the polymer melt is stored and then spun through a nozzle. We should learn how to spin a new type of synthetic fiber using a similar process to hair production in nature.

The regeneration of human hair is now being investigated. Modern biotechnology has made it possible to manipulate the cells responsible for hair to grow *in vivo*. If the hair growing mechanism can be duplicated, then wool can be produced artificially by biotechnology in the future.

Spider silk is another interesting material. For a synthetic fiber the tenacity is inversely proportional to the elongation at break. In order to improve the tenacity, molecules should be oriented in the direction of the fiber axis. When molecules are more oriented in a fiber, the tenacity increases but the elongation at break decreases. Spider silk in warp has a good tenacity close to Kevlar, and the elongation at break is as high as 35%. Spider silk in weft is coated with adhesive liquid to catch insects, and elongates surprisingly effectively when wet. The spider has the means to remove this liquid in order to walk to its prey without adhering. Now investigations are focused on explaining the structure of spider silk and its relation to its physical properties.

1.4.4 From homogeneous intelligent materials to non-homogeneous intelligent materials

As has been indicated ‘biomimetics’ (the art of learning from the bio-system) could be the key to developing new materials. Applying information from biomimetics has in fact led to the development of new chemical fibers. Biomimetics is expected to lead to the next generation of materials. Non-homogeneous materials can be developed with this technology, whereas only homogeneous material such as chemical fibers were the main target of the twentieth century. For example, new functions may emerge from mimicking the insect shell wing composed of liquid-crystal protein reinforced with chitin, which cuts out infra-red radiation in a hot desert. Bamboo is a natural fiber-reinforced composite material composed of alternating parts of stalk and joint. Its cross-section reveals the distribution of fibrous materials, where the outside is dense and hard while the inside is coarse and soft. A bamboo has a non-homogeneous structure (with density gradient) from the same material, and is thus resilient to very windy and heavy snow conditions. Professor T. Kikutani (Tokyo Institute of Technology) has succeeded in producing a composite with the same density gradient by mimicking the cross-section of bamboo.

There are many examples of materials having density gradients around us in nature. A cap of a turbo shell is an example of a composite reinforced with micro-particles. In this example, the composite is made of a protein matrix and calcium carbide micro-particles. The density of the cap decreases gradually from the surface to the inside. The cap should grow as a turbo (*Turbo cornutus*) grows, and protects it from enemies. The disk-shaped cap has an amorphous layer structure, and grows in its radial direction as the turbo grows. No artificial system yet follows this type of processing, but we may expect to develop new processing methods for plastic materials in this way. The control of the non-homogeneous structure seems a key technology to developing the intelligent fiber.

One of the most demanded characteristics is the ultimate strength of materials as exemplified by high tenacity/high modulus fiber. In order to explore the ideal potential of the polymer material, we should increase the molecular weight of the polymer to almost infinity and reduce the molecular defects. The new spinning and processing technology to achieve this should also be innovative enough to cope with the control of molecular orientation with predetermined precision. In nature, we find proteins of high molecular weight over 2,000,000, but the molecular weight of synthesized polyamide is at most 200,000. There is therefore much to gain by learning the mechanism where by nature synthesizes extremely high molecular weight polymer and spins high-oriented fiber with precision.

1.5 Definition of fibrous materials

The field of fibers and textiles covers a very broad range of science and technology. Since people generally regard this as a limited subject, it may be useful here to reconsider what fiber really is.

1.5.1 Narrow and broad definitions of fiber

Fiber can be defined in more than one way. A narrow definition of fiber can be found in JIS (Japanese Industrial Standards) L0204-1979, which specifies a fiber to be the structural units constituting yarn, fabric, etc., which are flexible, thin and long enough with respect to its thickness. The shape of fibrous materials is specified by the aspect ratio defined by L/D with L and D being the length and cross-sectional diameter, respectively, and the aspect ratio is over 1,000 in general for fiber. However, JIS does not specify this aspect ratio for fiber explicitly. The fiber characteristics are revealed when the aspect ratio exceeds 100 as exemplified by monofilaments of cotton linter or beaten wood pulp. ASTM (American Society for Testing and Materials) defines textiles to be, ‘a generic term for any one of the various types of matter that form the basic elements of a textile and that is characterized by having a length at least 100 times its diameter’ (D123-91a).

Although fiber and textile are not well distinguished in Japan, textile is defined explicitly in ASTM as a general term for the fabric or product composed of fiber or fiber assembly. The definition of fiber/textile in JIS or ASTM is an important matter for the textile industries in Japan or the US, and includes no concept of molecules. However, a more general concept of fiber will be found, for example, in the Oxford Advanced Learner’s Dictionary:

- the part of food that one’s body cannot digest but which helps the body to function well (for example, cellulose and pectin that stimulate peristalsis in the intestine)
- a material made from a mass of thin threads
- any of the thin threads from which many animals and plant tissues are formed.

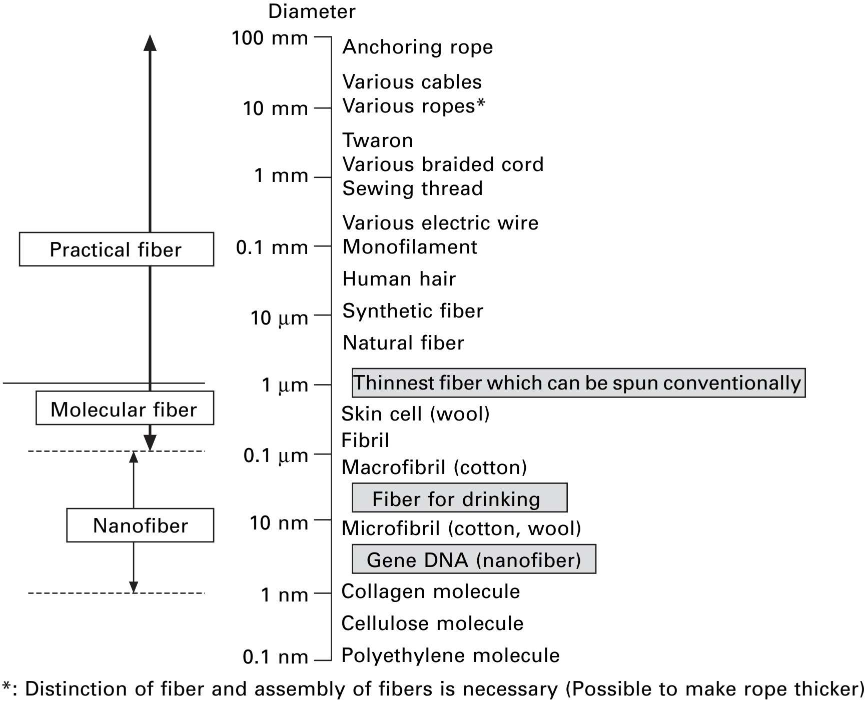
1.5.2 The concept of fiber according to its thickness

Fiber can be classified according to its cross-sectional diameter. A practical fiber has a cross-sectional diameter over 1 μm, and fiber with a smaller diameter would be classified as a molecular fiber. A practical fiber includes an anchoring rope (a cross-sectional diameter over 100 mm) various cables/ropes (a cross-sectional diameter varying from 10 mm to 50 mm), a sewing thread (a cross-sectional diameter around 1 mm), synthetic and natural fiber (a cross-sectional diameter from 10 μm to 50 μm), and a microfiber (a cross-sectional diameter less than 0.1 μm). Dietary fiber and molecular fibers, such as DNA, can be regarded as a nanofiber of a cross-sectional diameter of the order of nm. When the fiber is defined as a material with a large aspect ratio, fiber and textile are hierarchically classified according to their diameter as shown in Fig. 1.10.

1.6 Fiber: characteristics and shapes

1.6.1 Three characteristics and three shapes

Professor Emeritus S. Ohya (Kyoto Institute of Technology) has his own concept of fiber. He considers the aspect ratio and freedom, energy and



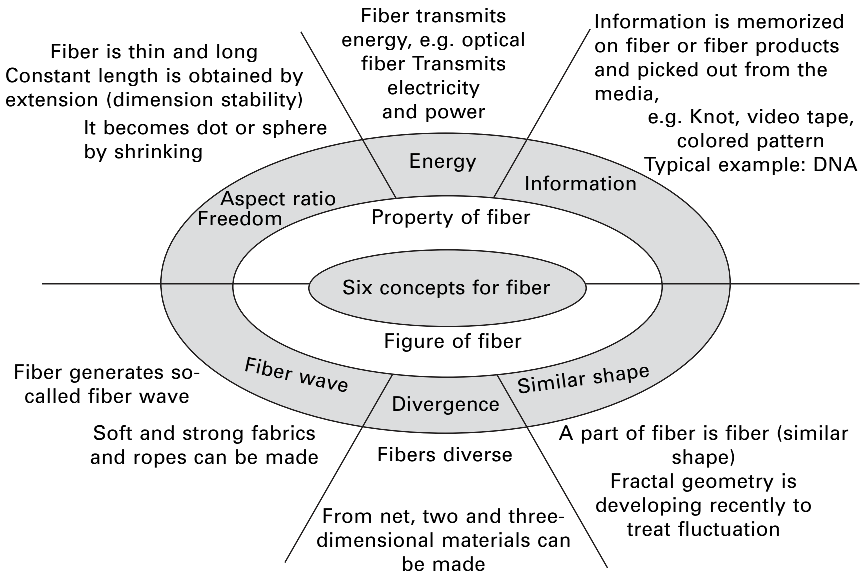
1.10 Classification of fiber according to diameter.

information as three characteristics, which are related to the shapes of fiber, specified as parallelism, branching, and fibrous wave. Fiber is defined as a slender solid with a large aspect ratio. He considers that the concept of fiber should now be extended to include energy, if energy is transmitted over a long distance through a long thin medium such as optical fiber or electric wire. In this concept, linearly propagating information such as music is a type of fiber. Music is thus treated as a fibrous wave. He also argues that fiber and textiles are tools to input/output information. This concept of fiber and textile is summarized in Fig. 1.11

1.6.2 Peace of mind and natural remedy

Fiber science and technology have been concerned mostly with the physical performance or function. Now, textiles for healthcare and comfortable clothing comfort have been developed. Here comfort is not only an important factor with regard to wear, but also people consider how they can appeal to other people. Thus, human sensibility is becoming a big issue to be investigated in developing new fibers and textiles.

Professor Emeritus T. Musha (Tokyo Institute of Technology) found a characteristic rhythm in the sound of birds and the wind, a river murmuring, a heart beating, and in brain waves when people were relaxed. These rhythmic sounds appear irregular at first sight, but really have a characteristics fluctuation inversely proportional to the frequency, specified as the 1/f fluctuation. This



1.11 Concept of fiber and textile.

fluctuation brings peace of mind. The natural rhythm was analyzed by computer and applied to an electric fan to produce a natural breeze.

Many people suffer from the stress caused by a constantly changing society. They show symptoms of mental disorder and are confused by the rhythm of everyday life. The natural rhythm applied to textile products can provide a compensating function, such as with deodorant or anti-bacteria clothes, but the function is to refresh the mind. Another type of textile with a similar effect is also available, where the function is produced by certain minerals blended in fiber and properly processed, and which generate a negative ion or anion as in the forest. Wavy magic® (Kurabo), Shizen-no-Yuragi® (Nisshinbo) and Biosound® (Toyobo) are examples of the application of the theory of 1/f fluctuation. Holic® (Shikibo) and Stayers® (Fujibo) are the commercial products which can refresh the human mind using the forest rhythm effect.

The theories of the 1/f fluctuation, the fractal, and the bio-sound seem to be applied in different ways to the knitted or woven fabrics by each manufacturer, but all these textiles have a certain effect to refresh the mind. Starting from comfort and health, the target for developing textiles has advanced to mental fulfillment much needed in the modern day and age.

1.6.3 Product value generated by human senses

The research target has now been expanded from the objective world to the subjective world. Production efficiency has been the most important factor in operating a factory. The change of lifestyle and values is forcing a shift from this product-led policy to a market-led one, since a comfortable and private life becomes the primary concern. Although in the initial stages, investigation has started into the quantitative evaluation of the in-cloth climate by monitoring the heat and moisture transfer from the inside to the outside of the cloth under various ambient conditions. The fast progress in this new field resulted in the establishment of two research units in Nara Women's University (Laboratory of Apparel Science) and Shinshu University (Department of Kansei Engineering), in 1993 and 1995, respectively. These two research units are now very active in this new field.

1.7 Fibers as hierarchical structures

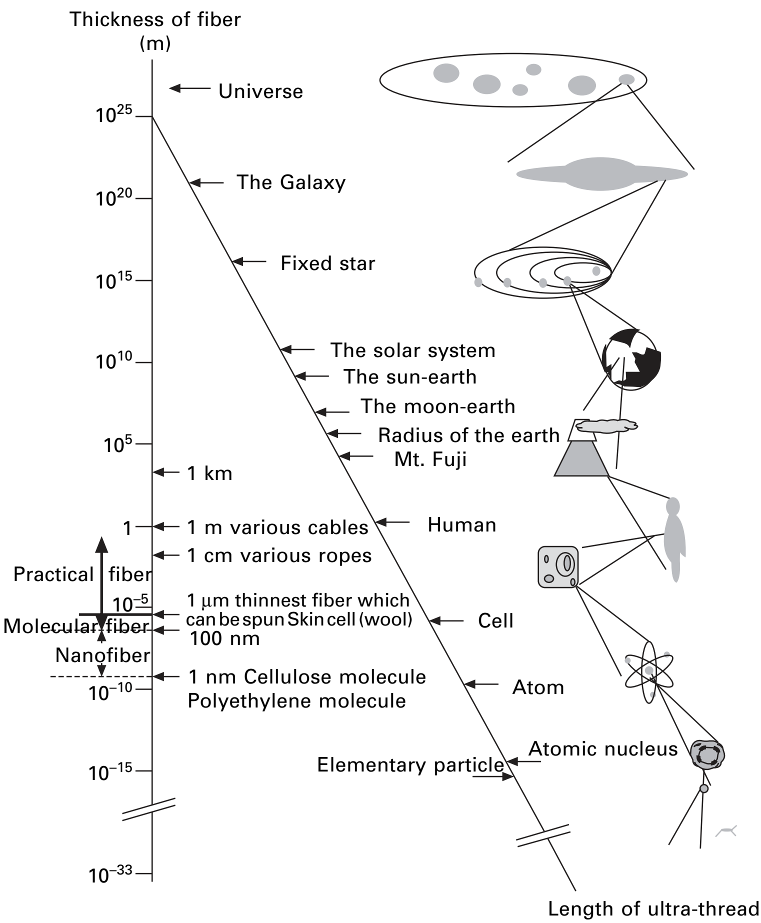
Fiber, as noted, can extend from a molecular fiber to an anchoring rope (a cross-sectional diameter over 100 mm). When fiber is classified according to its diameter, fiber and textile products are included in a geometric similarity.

The fibrous system can be considered as a continuous phase. This concept implies that a series of hierarchical structures constitute a whole structure as observed often in ecosystems. A thread is the fibrous system constituted of fibers, which are the assemblies of fibrils composed of microfibrils. More examples will be found in natural fibers such as cotton, wool, and silk which have continuous hierarchical structures. This concept covers various systems from the universe and animals/plants to molecules, atoms and elementary particles as demonstrated in Fig. 1.12.

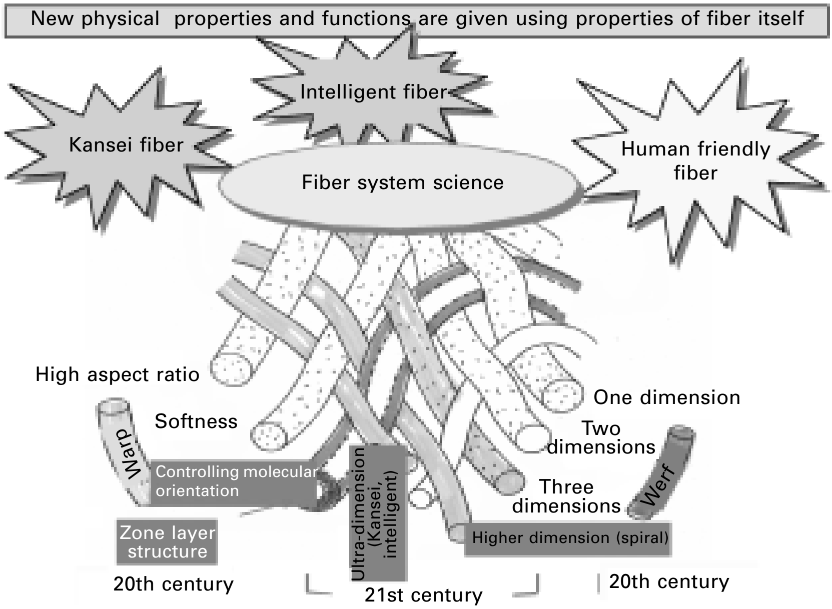
1.8 What should we investigate in the field of fiber and textiles?

1.8.1 Systematic fiber/textile science has a warp and weft

How we can activate fiber and textile science? Fiber/textile science can be regarded as a woven fabric composed of warp and weft. Figure 1.13 shows

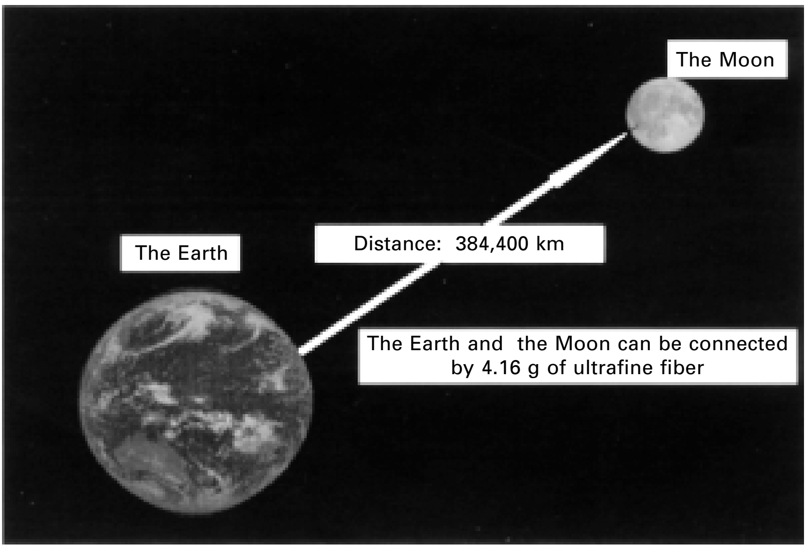


1.12 Classification of fiber by thickness and hierarchical structures of materials.



1.13 Dimensional fiber science.

the warp and weft within fiber/textile science. The warp represents the characteristics of fibrous materials, including high aspect ratio, flexibility and molecular orientation. A high aspect ratio is exemplified by a 4.16 g microfilament reaching from the earth to the moon (see Fig. 1.14), an optical



1.14 Image of ultrafine fiber thickness.

fiber or a nerve fiber. The hollow fiber applied for water purification, artificial kidney and artificial liver are other examples of a high aspect ratio. A genetic code can be stored in fibrous DNA (nanofiber) and another example is carbon-nanotube.

1.8.2 Flexibility

Since fibrous materials are long and thin, they are flexible. How can we apply this flexibility to the technology? Soft and flexible materials are not well adapted to the technology except for clothes. NASA (National Aeronautics and Space Administration) launched the Mars explorer Mars Pathfinder. This explorer had a unique landing device made of an airbag. The airbag was made of the superfiber Vectran® woven fabric (Kuraray), and had the shape of a beach ball. This soft and flexible ball was basically shapeless, making it possible for it to land on any surface.

Softness is one of the basic characteristics of human-friendly fiber/textile. Bulkiness and heat insulation of the fabric are also important characteristics induced by a synergistic effect of fiber and air. Thus the technology to utilize such materials requires a new 'shapeless' approach.

The physical properties of polymer materials depend on the molecular orientation of component polymers. The control of molecular orientation in the polymer materials is thus a key technology to develop high performance (e.g., superfiber) or high function (e.g., healthcare) fiber. The hybrid of natural and synthetic fiber could possess a high physical performance as well as environmentally-friendly characteristics, and the biodegradable fiber is developed in this context.

In conventional fibers, molecules are oriented relatively in one direction along the fiber axis. Professor C. Kajiyama (Kyushu University) proposed a fiber with the multi-layered structure at the NEDO (New Energy and Industrial Technology Development Organization) Meeting in 1999. When the polymer molecules are oriented in both lateral and radial directions with respect to the fiber axis, such a fiber can have a high tensile strength in both directions. The two-layer structure in the fiber axis can also improve the light-transmittance efficiency of optical fiber. The lateral orientation can be controlled during the spinning and drawing process. If the radial orientation can also be controlled, the potential of polymer materials is optimized in the form of fiber, and we can improve the mechanical, electric, magnetic, and optical properties of fibrous materials.

In this research on fibrous materials, one should keep in mind three factors as the characteristics of fibrous materials:

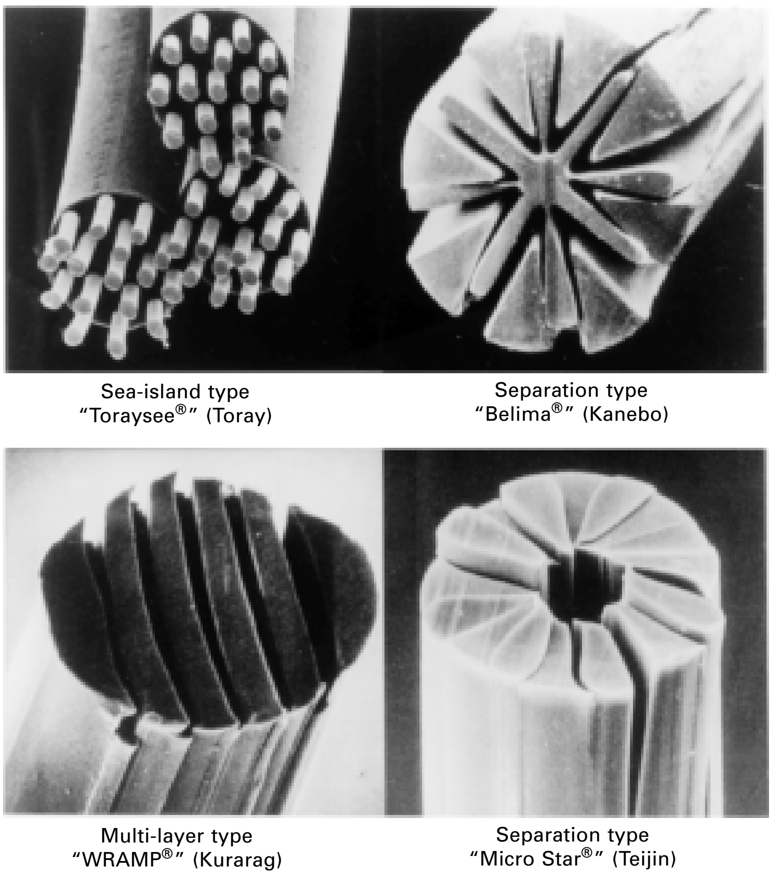
(1) a high aspect ratio to express the shape characteristic of long and thin fiber

(2) a softness and bulkiness to take into account a physical property of flexible and soft fiber as an industrial material
(3) a molecular design and molecular orientation to optimize the performance and function.

1.8.3 Structural control in the fiber cross-section

Fiber is a one-dimensional long, thin material. Now an ultra-microfiber can be produced, which reaches from the earth to the moon with a total weight of 4.16 g. This microfiber contains about 40,000 polymer molecules in its cross-section. When a fiber has a cross-section less than a certain value, a living body can no longer recognize it as a foreign object.

When spun through a nozzle, the fiber cross-section becomes circular because of surface tension. The non-circular cross-section became popular when shingosen first appeared. Various kinds of Microdenier (ultrafine) fibers are shown in Fig. 1.15.

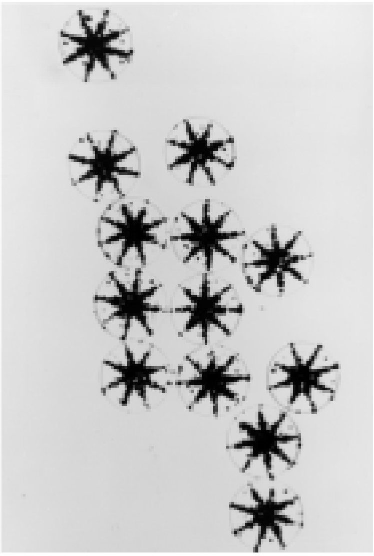


1.15 Various kinds of microdenier (ultrafine) fibers.

Non-transparent effect by a non-circular cross-section component incorporated into fibers

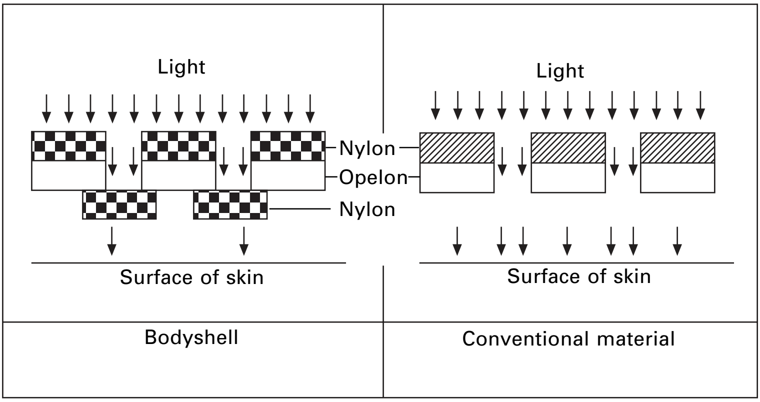
A non-transparent effect was achieved by incorporating non-circular components in filaments. Toray developed a non-transparent white swimming costume (Bodyshell®) by combining conjugate spinning and non-circular cross-section technology. Why does a white swimming costume become transparent? When wet, fiber transmits light from inside and becomes transparent. Bodyshell® appeared on the market in summer 1994, and became a big seller. As shown in the cross-sectional view of Bodyshell® original filament in Fig. 1.16, the filament is composed of a star-shaped core containing white pigment (titanium oxide). Titanium oxide is a white powder, which reflects light (non-light transmitting), is stable against light, does not turn yellow, and can be processed into very fine particles. Since the core polymer containing white pigment has an eight-edge star shape, and screens light, incident light from any direction is randomly reflected, and in consequence the swimming costume becomes non-transparent.

A conventional swimming costume is made of two-layer knits, but Bodyshell® has a special three-layer structure as shown in Fig. 1.17. The extra layer prevents light transmittance through an opening of stretched knit fabric. This two-step device suppresses light transmittance to 40% in comparison with a conventional swimming costume. White pigment (titanium oxide) is also used in cosmetics because it has a UV-blocking effect.



The cross-sectional of original fiber

1.16 Bodyshell® (Toray).



1.17 Characteristics of Bodyshell® (Toray).

Multi-layer structures in nature

There are many examples of multi-layer structures in nature. Morphos in the upper Amazon in Brazil have metallic cobalt blue on their wings. This color is caused by light interference due to the multi-layer structure of scales on the wing. The principle of light interference was applied to Morphotex® (developed by Teijin), a polyester fiber with a multi-layer structure. Details about Morphotex® will be given in Chapter 9.

If we can introduce scales on to a fiber like wool, the friction coefficient becomes dependent on the direction of applied force. The mechanical and optical properties of fiber can be designed precisely by adjusting the molecular orientation in the radial direction. The precise control of the molecular orientation and composite structure enables the production of new fibrous materials with multi-layer structures in a radial direction.

Optical fiber supporting today's information technology society

Optical fiber transmits light where the refractive index varies in the radial direction. Fiber itself is one-dimensional, but light cannot be transmitted unless the structure is two-dimensionally controlled. Optical fiber is a powerful tool to transfer a large amount of information quickly, and plays a key role in supporting today's information technology society. A fine optical fiber like a hair can transmit information equivalent to 6000 telephone circuits. Although the cost of optical fiber is higher than copper wire, the optical fiber is lighter in weight, higher in capacity and lower in the transmittance loss. An optical fiber is a fine filament, 0.1 mm in diameter, and transmits 95% of input light as far as 1 km. An optical fiber has a two-layer structure of core and clad. A core part is composed of the material with a high refractive index, and a clad part with a low refractive index. Light input in the core part reflects at the circumference with the clad part and is transmitted without leaking outside, because of the refractive index difference. Three types of light transmittance are available and can be classified as:

- the step index (SI) type,
- the graded index (GI) type, and
- the single mode (SM) type (see Fig. 1.18).

Optical fiber is made of

- quartz,
- multi-component glass or
- plastics

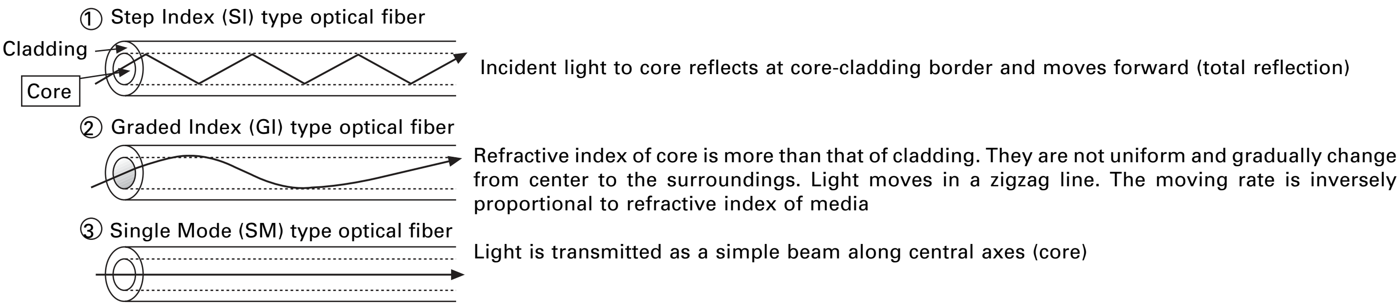
which are applied to a suitable field depending on the transmittance scale and distance as shown in Fig. 1.19

Although quartz is expensive, its transmittance distance is long and is used for transmittance over medium to long distances. The light transmittance of plastic is not so good as quartz, but is easier for handling. Its cost is low, and it is used as a guideline over short distances in applications such as in the control equipment for a measuring instrument, and for office and factory automation. For example, the main optical highway from Asahikawa (Hokkaido) to Kagoshima (Kyushu) is laid with single mode quartz optical fiber, but superfiber is incorporated in order to protect the brittle quartz. Plastic optical fiber (POF) is easy to handle for branching and connecting, and a big market is expected for POF to replace the present in-house telephone circuit if its intrinsic performance is improved. A genuine multi-media society will be realized when the optical fiber network is widespread in all households. POF, for domestic use, will complement the glass-type (quartz or multi-component glass) optical fiber for long distance optical highways. ‘Fiber to the home’ has become the catchphrase of the POF network by fixing the peripheral technology complementary to the high-speed/large-scale transmittance technology using a single mode.

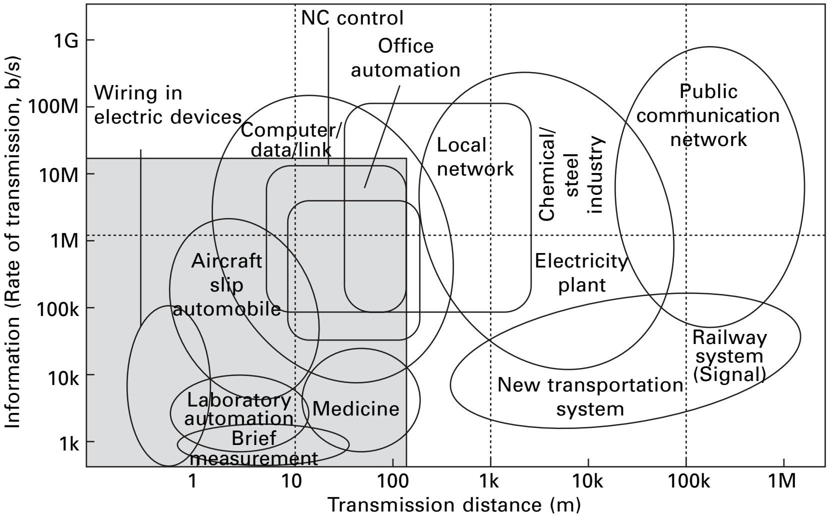
A SI-type POF (see Fig. 1.20) has a two-layer structure composed of high-purity poly(methylmethacrylate) resin with a high refractive index in the core part and fluorocarbon polymer with a low refractive index in the clad part. Since the clad part has a lower refractive index than the core part, the incident beam will reflect totally at the boundary and propagate to the other end.

Recently POF made of whole fluorocarbon polymer has been developed by Professor Y. Koike (Keio University) and appeared on the market (Lukina® from Asahi Glass). Whole fluorocarbon POF has an advantage over the quartz optical fiber in two respects. Fluorocarbon-type POF has a larger core size for light transmittance and is more flexible than the quartz optical fiber. The latest developments in a GI-type whole fluorocarbon POF are very remarkable, and have received much attention.

Material	Core	Cladding	Way of transmission	Properties (db/km)
Quartz glass fiber	Quartz glass	Quartz glass	SI type, GI type, SM type (5-62.5 μm)	Advantage: good optical property, transparent, less loss Disadvantage: expensive (10–15)
Multi components glass	Multi components glass	Multi components glass		
Plastic fiber (POF)	Plastic	Plastic	(Fiber to the home)	
	PMMA	Special fluorine resin	SI type (100–1000 μm)	Advantage: soft and easy to process, large diameter Disadvantage: (100–150)
	Fluorine resin	Fluorine resin	GI type (100–1000 μm)	Optimization of refractive index distribution cause equal arrival rate of information Simple connector makes reduction of error (10–15)

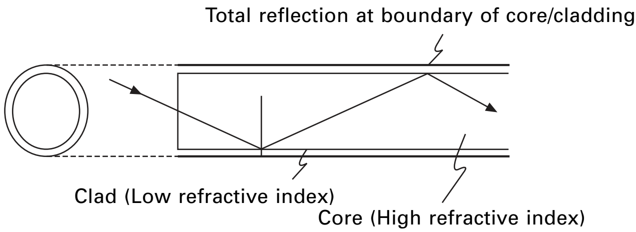


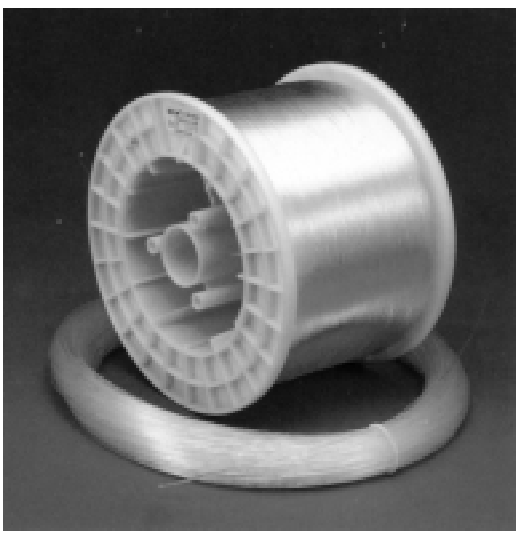
1.18 Kinds of optical fibers supporting information technology and way of transmission.



Note: Plastic optical fiber is available only in gray zone (bottom left) because of transmission loss.

1.19 Application field of optical communication.





1.20 Structure of plastic optical fiber and bulk fiber (Mitsubishi Rayon).

Although POF, in general, has a shorter transmittance distance than quartz optical fiber, it is light, flexible, easily processed, and durable. Thus POF can be widely applied in various fields from industrial use to all-purpose domestic use, including light guide (spot illumination, display), light sensor (optical measuring instruments, medical appliances), the short distance transmittance system (in-house automation, office automation, and factory automation), automobile/house electric appliance, etc. Soon telephone circuits will be replaced by POF and real-time pictures may be transmitted by telephone, thus improving the quality of our life.

1.8.4 New fiber science

Three-dimensional textiles

Arisawa Manuf. Co. and Shikishima Textile Co. produce three-dimensional fabrics for advanced composite materials applied in the aero-/space motor, machinery, and civil engineering industries.

Human- and environmentally-friendly intelligent fiber

Fibers can possess intelligence and can function as a sensor to detect external stimuli, as a processor to evaluate external stimuli, and as an actuator to respond/control actively according to the external stimuli. Figure 1.21 shows the concept of the human- and environmentally-friendly intelligent fiber.

Fibrous materials for intelligent fibers are being developed. Sportswear should have a good heat insulation with low conductivity when a body is still cold, but have a good sweat permeability to prevent the body from being steamed up when the body is hot and sweaty. Intelligent sportswear controls ventilation through its texture.

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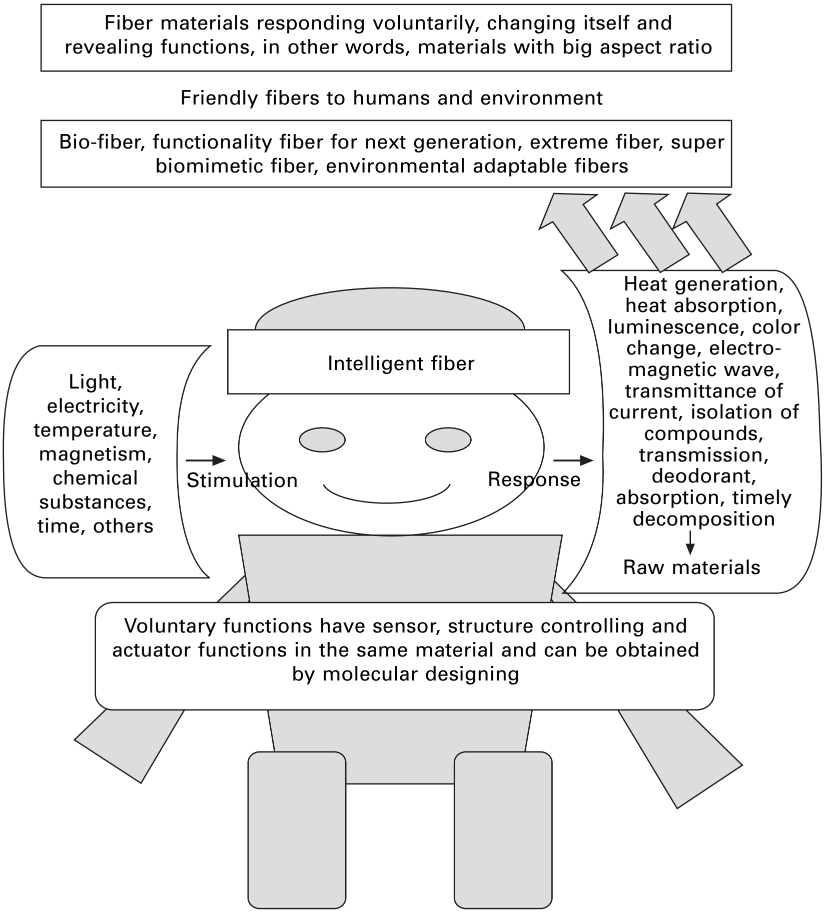

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Morphos-structured fibrils

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