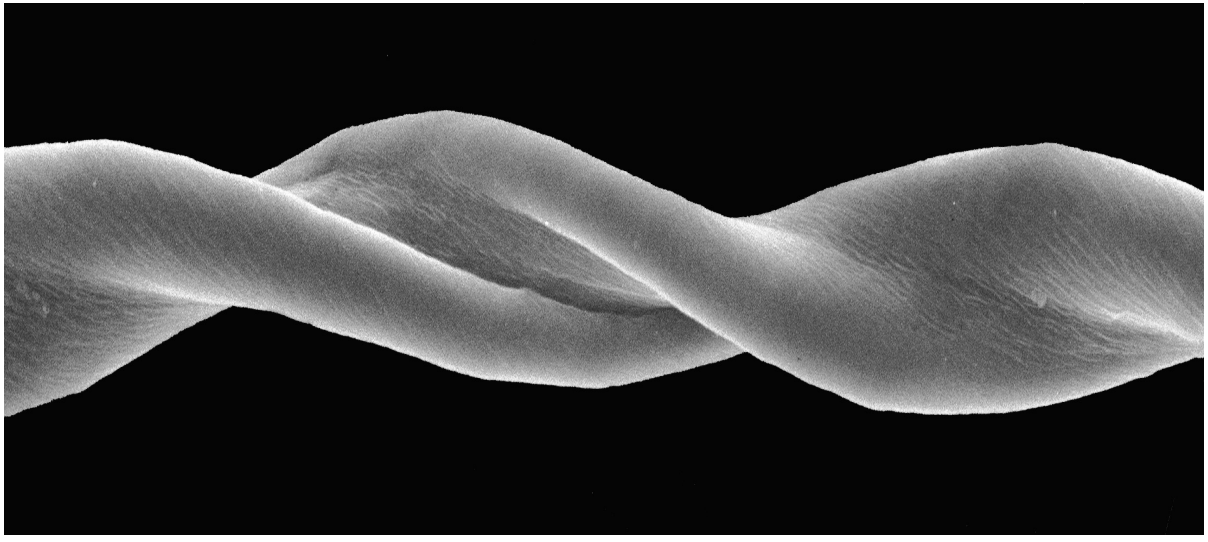
COTTON FIBER DEVELOPMENT AND PROCESSING



AN ILLUSTRATED OVERVIEW

project funded by Cotton Incorporated

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COTTON FIBER DEVELOPMENT AND PROCESSING
AN ILLUSTRATED OVERVIEW

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A Joint Project of
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INTRODUCTION

JAMES McD. STEWART, Ph.D.

When we hear the word "cotton", pleasant memories and mental images of soft sheets and comfortable garments run through our head. From the earliest historical times, cotton has had a significant role in many of the world's human cultures. Even the Egyptian pharaohs had cotton. Our modern day word for "cotton" is derived from the old Arabic word "al qatn".

Unknown to most people is the true miracle of the cotton fiber, especially its origin and biological characteristics. Each cotton fiber is a single plant hair. Each hair is only one single cell that develops from the surface of a cotton seed with each seed producing from 10,000 to 20,000 fibers. The presence of hairs on plant seeds is not an unusual event, but the characteristics of the seed hairs on the wild plants that became cotton are unique. They alone, of the world's plant hairs, have the combination of length, strength and three dimensional structural characteristics in the dried state that enable them to be spun into yarn or thread.

This book provides an illustrated summary of the developmental and structural features of the cotton plant and fiber, and of the machines that have been developed around the utilization of cotton. The pictures and discussions have been donated and compiled by a group of dedicated cotton enthusiasts to convey some of the beauty and unusual features that contribute to the unparalleled utility of cotton fibers so that the general layman can develop an appreciation of the wonder of cotton.

ORIGIN OF COTTON

The development of seed hairs with structural characteristics that enabled them to be spun into yarn or thread has occurred only once in nature. This was in an ancient line growing on the African continent in the cotton genus now known as *Gossypium*. This ancient line diverged into at least three different species that retained the ability to produce the unique seed hairs. Over time each of these lines migrated to different parts of the world.

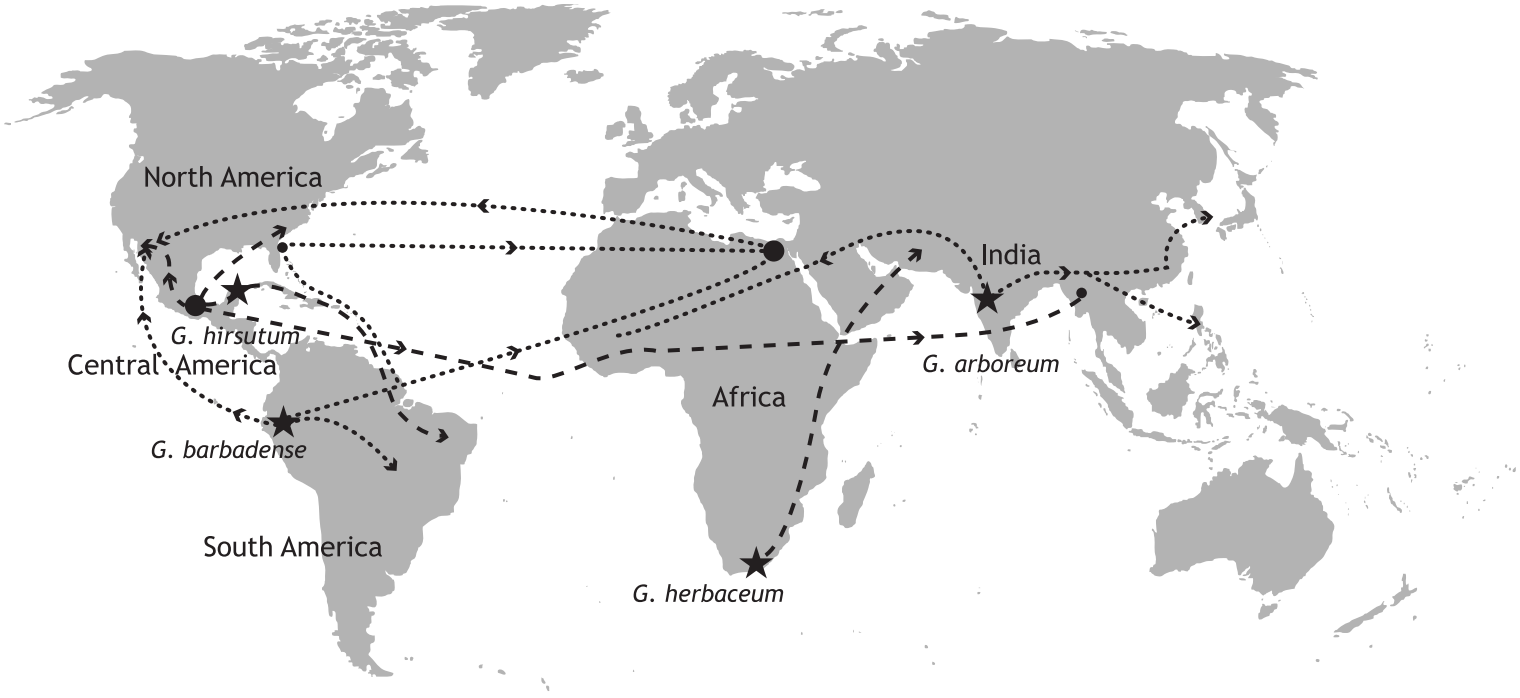


Figure 1. Major dispersals of cultivated cotton prior to mid-20th century

One species became established in southern Asia and is now known as *Gossypium arboreum*. A second is found wild in southern Africa and is known as *Gossypium herbaceum*. The third apparently does not survive today but indirect evidence indicates that it managed by some means to cross the ocean to the Western Hemisphere between 1 and 2 million years ago. During the time this immigrant was able to grow in the Western Hemisphere, it hybridized with one of the native *Gossypium* species and the chromosomes in that hybrid doubled in number. This resulted

in a new polyploid species that had a complete set of both the African species chromosomes and the New World species chromosomes. When combined with the native American species, the new arrival retained the ability to produce spinnable fibers, resulting in a vigorous hybrid line that became established and radiated out to different parts of the Western Hemisphere.

Following migration of the polyploid to new areas (Figure 1) and subsequent isolation there was divergence into 5 species, each with seed hairs. Today these species are known as *G. darwinii* native to the Galapagos Islands, *G. mustelinum* native to northeast Brazil (Figure 2), *G. tomentosum* native to the Hawaiian Islands (Figure 3), *G. barbadense* native to Peru, and *G. hirsutum* native to the Yucatan Peninsula.

Our early ancestors originally "domesticated" from wild native plants all crops and food plants that we take for granted today. Cotton is no exception. A remarkable testimony to the importance of cotton to human enterprise is the independent domestication of four different *Gossypium* species in four different parts of the world.

Two of these species are the "Old World" or "Asiatic" cottons. These were direct descendents of the ancient line that evolved seed hairs with the characteristics that enabled humans to spin them into yarn. Our best evidence suggests that

Figure 2. *G. mustelinum,* NE Brazil (J. McD. Stewart)

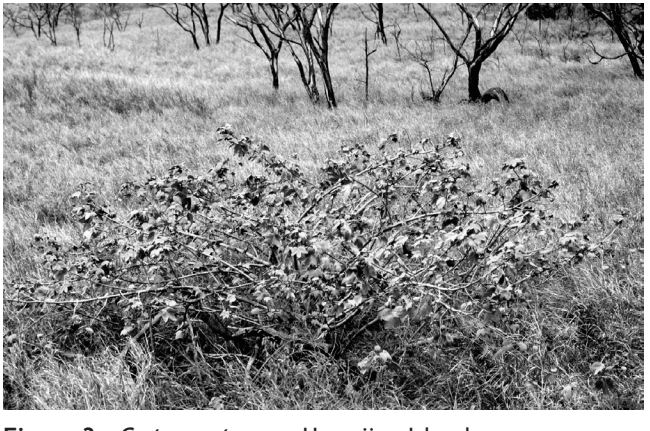


Figure 3. *G. tomentosum,* Hawaiian Islands (J. F. Wendel)

Figure 4.
G. arboreum
(J. McD. Stewart)

G. herbaceum was first cultivated in southern Africa while *G. arboreum* (Figure 4) probably was domesticated on the Indian subcontinent. These two species were the cottons of early human civilization in Asia and Egypt. One of the first archeological discoveries of cotton usage was in the Moenjo Daro ruins (Figure 5) of present-day Pakistan. This city was a thriving commerce center 5,000 years ago. Without doubt, the woven cotton materials found in the ruins were one of the Asiatic species.

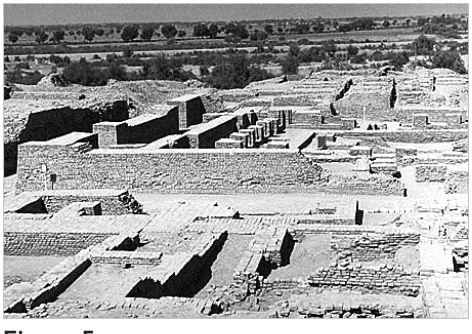


Figure 5.
Moenjo Daro ruins

On the other side of the world two other *Gossypium* species were being domesticated at about the same time. These species were derived from the "polyploid" hybrid of the New World. The earliest archeological evidence found, thus far, of cotton domestication in the Western Hemisphere is its use in fishing net cordage by indigenous peoples along the coast of Peru. These sites were dated to about 3,000 years ago. The species *G. barbadense* is native to Peru and probably is the species of cotton used by the fishermen. Studies on the migration of this species out of Peru suggest that humans carried it over the Andes, across the Amazon Basin, and into the Caribbean Islands, long before Europeans arrived.

At various periods in the last 300 years, and especially the last 200 years, this species was carried to various parts of the world and grown as a commercial crop. Breeding and selection in this species resulted in varieties known for their superior fiber quality. Included among these are the Sea Island cottons of the southeast coastal islands of the USA and the Caribbean Islands, the Pima cottons of the American southwest, and the Egyptian-American cottons. Collectively, these are called the long-staple cottons and are known for their long, fine fibers with exceptional tensile strength.

The second species that was domesticated in the Western Hemisphere was *G. hirsutum,* native to the northern coast of the Yucatan Peninsula

Figure 6. Wild *G. hirsutum* on north coast of Yucatan Peninsula (J. McD. Stewart)

(Figure 6). There is little archeological evidence of domestication, but this species was destined to become cultivated throughout the world and today comprises 90% of the world cotton production. By the time Europeans arrived in the Western Hemisphere, this cotton had been carried into present day central Mexico, southward through Guatemala and northward as far as the southwest USA. Regionally adapted landraces of *G. hirsutum* evolved in several of these regions (Figure 7).

Two of the landraces became especially important to the development of modern varieties of this species. One landrace known as "punctatum" was carried to Asia, probably by the British, and became known as Cambodian cotton. Until introductions from the USA in the second half of the 1900's, most of the *G. hirsutum* grown in Asia, including India and Pakistan, were derived from this landrace. The landrace that has contributed most to USA varieties is "latifolium". This material was brought to the USA in the 1700-1800's. Breeding and selection within this material resulted in the general class of cotton known as "upland" or "short staple" cotton.

One of the most important discoveries and introductions was cotton types that were day-neutral. Part of the problem of cotton production in the early history of the USA was the perennial and photoperiodic nature of *G. hirsutum* landraces of Central America. This means they only bloomed when the daylength was less than 12 hours. The cottons bloomed very late in the growing season in the temperate areas of the southern USA, so they did not have time to develop more than a few mature bolls before cold weather killed the plants. Discovery of day-neutral types allowed perennial cotton native to tropical regions to be grown as an annual

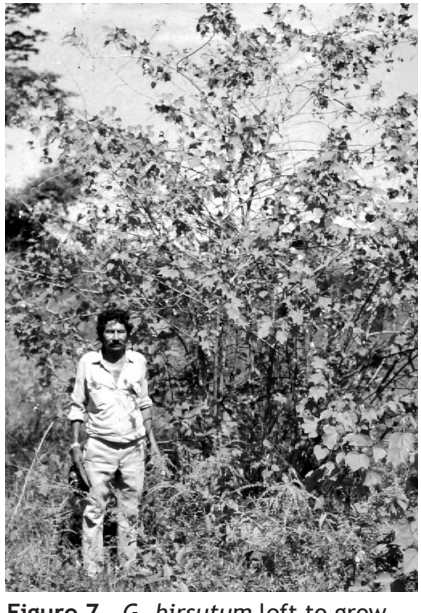


Figure 7. *G. hirsutum* left to grow as a tree. (J. McD. Stewart)

crop with good yields in the southern temperate areas of the USA.

Breeding and selection can be considered as a continuation of the domestication process. A wild genetic source has been selected and genetically manipulated over the centuries to give rise to modern cotton varieties with economy of yield and fiber characteristics that are unsurpassed by any other textile, natural or synthetic. These characteristics and the industry that has grown up around them are the subject of this book.

DEVELOPMENT OF A COTTON PLANT

DERRICK M. OOSTERHUIS, Ph.D.

To optimize fiber production, one must optimize reproductive growth and development in the cotton plant. Cotton plant development occurs in a very specific sequence of events. Each developmental stage of the plant impinges on fiber development. Better understanding of cotton plant growth and development and of the biological mechanisms that control flower production, fruit set and boll retention is essential for the continued profitablility of the cotton industry. This section summarizes the growth and development of the cotton plant as it relates to fiber production.

SEASONAL PATTERNS OF PLANT DEVELOPMENT

Cotton is a perennial plant, capable of growing year after year, producing flowers and fruit each year. Being a perennial, the cotton plant evolved indeterminate growth—the ability to continuously develop and grow new organs as long as the plant lives. This means that throughout its life the cotton plant will continuously produce flowers and fruit (bolls). Agriculturally, cotton is grown as an annual, being planted and harvested on a yearly basis. This combination of a perennial growth pattern and agricultural management as an annual, results in tremendous variability in boll maturity at the time of harvest.

Plant development in cotton proceeds through five main growth stages: germination and emergence, seedling establishment, leaf area-canopy development, flowering and boll development, and maturation (Figure 8). The transitions between these successive stages are not clearly distinguishable. Furthermore, each stage may have different growth processes operating with specific environmental and nutritional requirements.

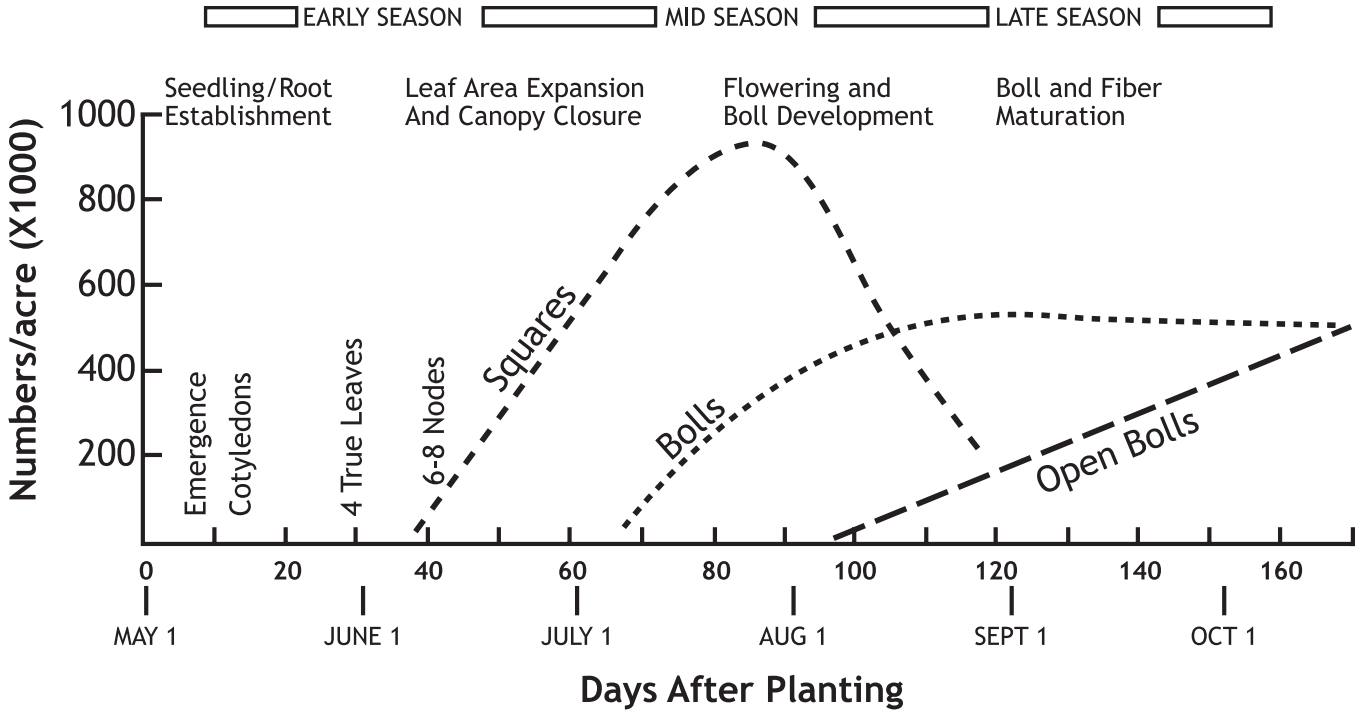


Figure 8. The seasonal development of cotton in the southern Mississippi River area, showing the production pattern of squares, bolls and open bolls. (D. Oosterhuis, 1990)

SEED GERMINATION AND EMERGENCE

A seed with all fibers removed is an ovoid, somewhat pointed, dark brown structure. The seed consists of a seed coat surrounding an embryo with two well-developed cotyledons (Figure 9). The embryo axis consists of a radicle (embryonic root), a hypocotyl, two cotyledons, and a poorly developed epicotyl (embryonic stem). The cotyledons, or seed leaves, form the first green leaves after emergence. Initially cotyledons contain stored food that supplies the energy for germination and early development. There are usually about 3,500-4,000 delinted seed per pound.

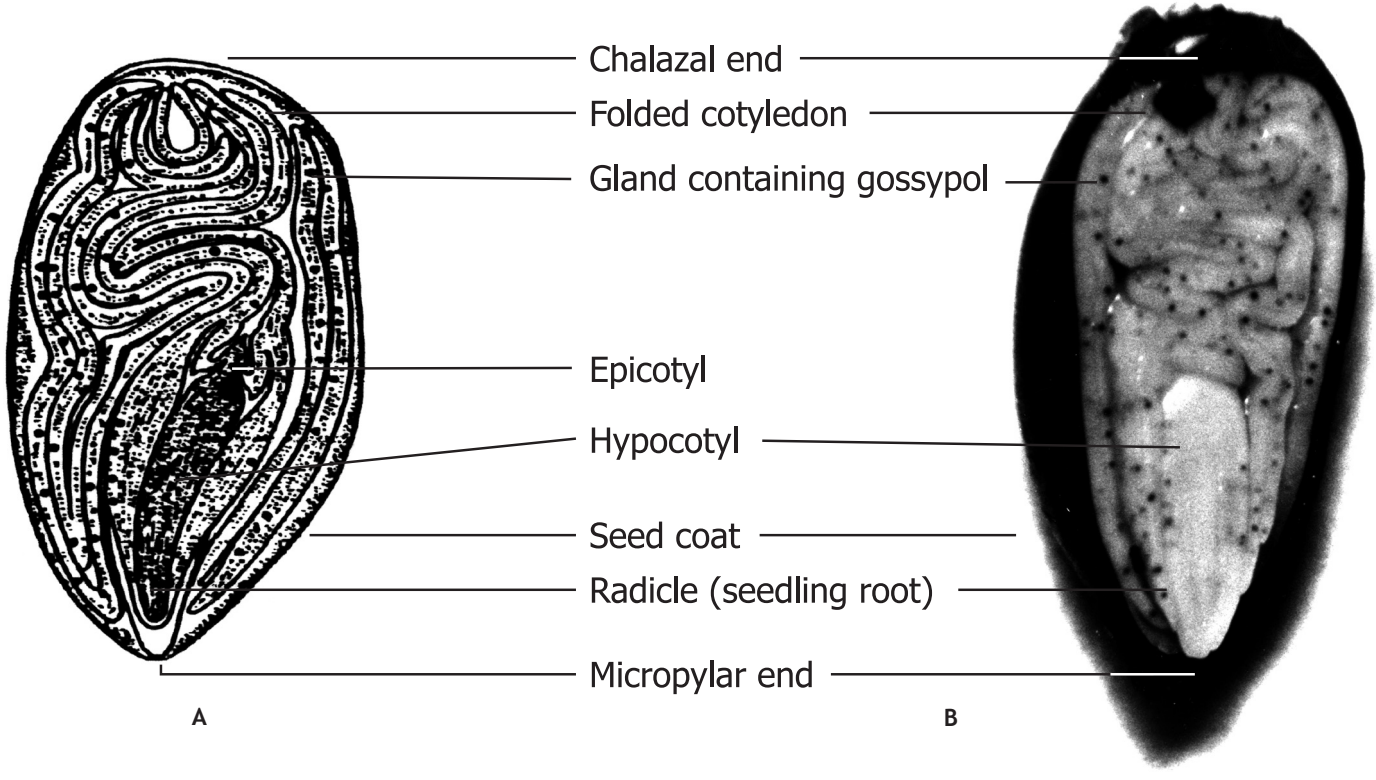


Figure 9. A diagram (A) and photo-micrograph (B) of a longitudinal section through a mature seed showing the seed coat and young embryo with folded cotyledons. (A, D. Oosterhuis; B, R.W. Seagull)

Germination begins within the first few hours of the entry of moisture into the seed. This results in increased oxygen uptake and the utilization of stored energy reserves to build new cells and tissues during embryonic growth. The seed/embryo swells as water is absorbed causing the seed coat to split. Under favorable conditions for germination, the radicle emerges through the pointed micropylar end of the seed in two to three days (Figure 10). The radicle becomes the primary root that grows downward into the soil. The tissues between the radicle and cotyledons (i.e. the hypocotyl) grow rapidly, arching near the cotyledons. With continued elongation of the hypocotyl, the cotyledons and embryonic shoot are pulled up through the soil surface (Figure 10). This is called emergence. Typically, the seed coat is shed and remains in the soil. Soil crusting due to surface compaction or high clay content may hinder the emergence of the cotyledons and embryonic shoot. When the cotyledons are free of the soil, they unfold and expand. After emergence and exposure to the light, the cotyledons develop chlorophyll and are capable of synthesizing food via photosynthesis.

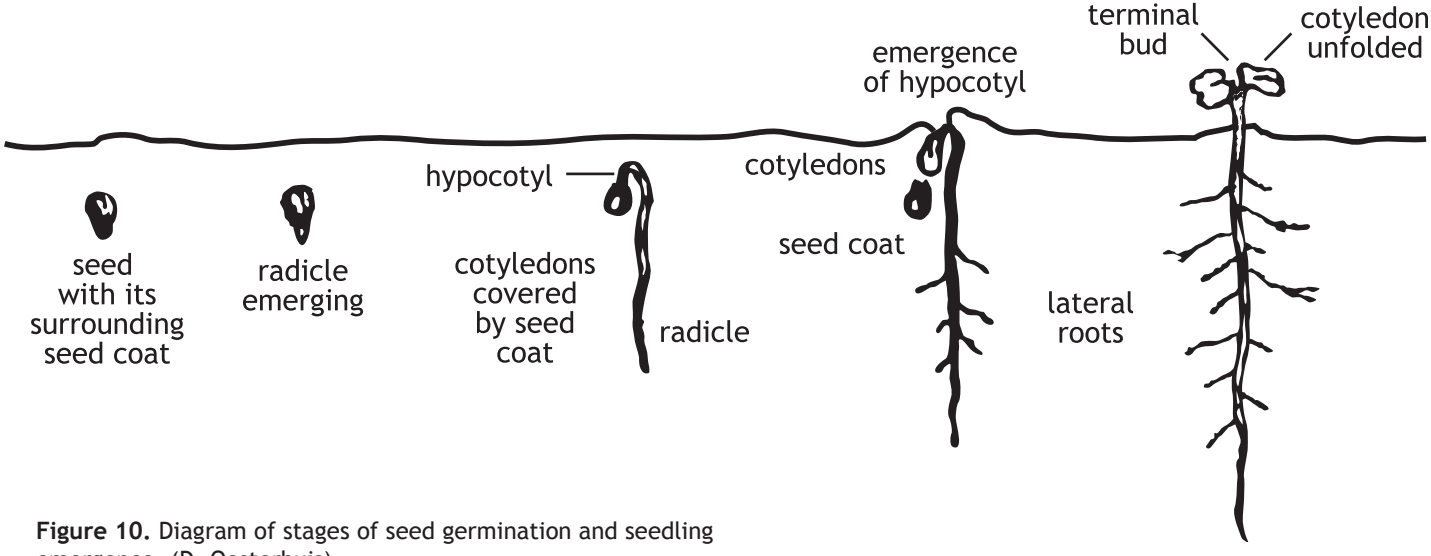


Figure 10. Diagram of stages of seed germination and seedling emergence. (D. Oosterhuis)

ROOT DEVELOPMENT

The function of roots is to absorb nutrients and water from the surrounding environment and transport these materials to the above ground portions of the plant. Much of the early development of the cotton plant is focused on growing a substantial root system. Growth of the above ground portion is relatively slow prior to canopy development. The primary root, or taproot, penetrates the soil rapidly and may reach a depth of up to 10 inches or more by the time the cotyledons unfold. Root development may proceed at the rate of 0.5 to 2.0 inches per day, depending on conditions, such that the roots may be 3 feet deep when the above ground portion of the plant is only about 1 foot (Figure 11). Numerous

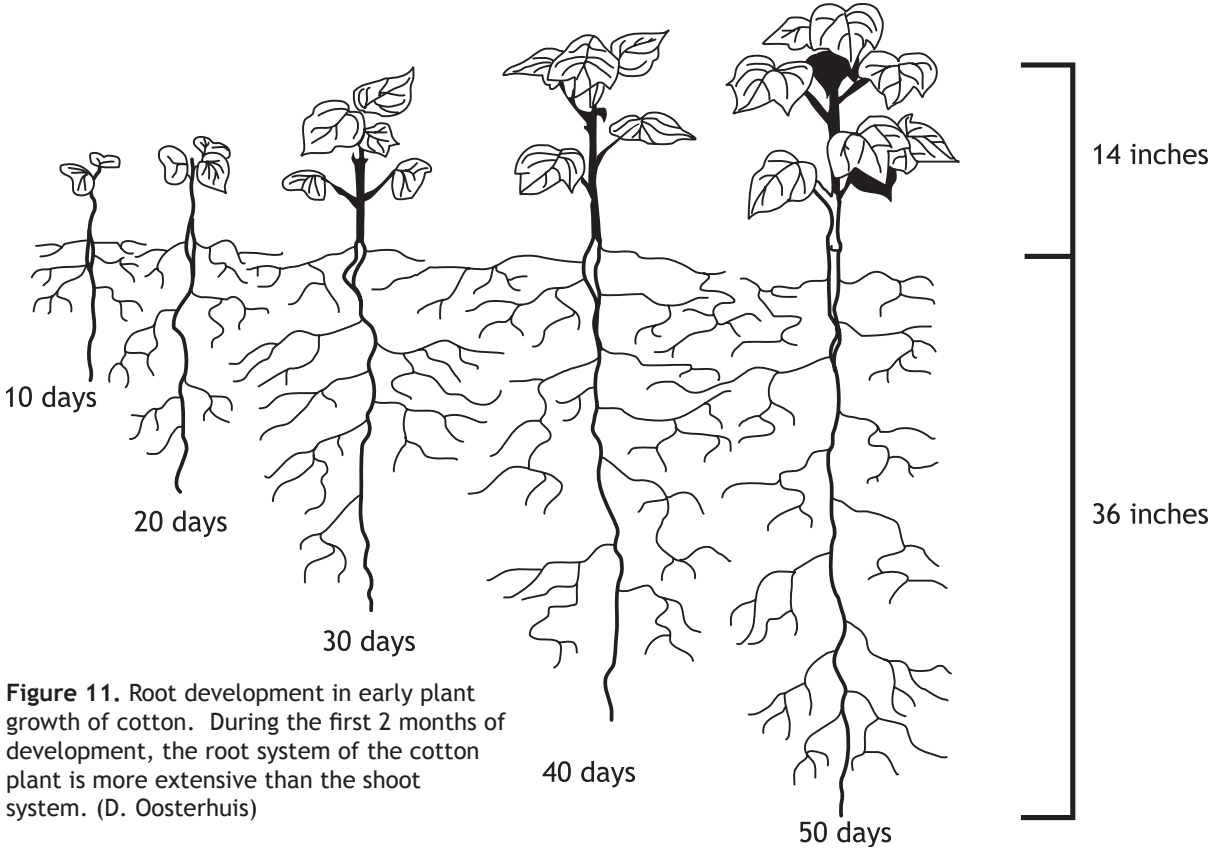


Figure 11. Root development in early plant growth of cotton. During the first 2 months of development, the root system of the cotton plant is more extensive than the shoot system. (D. Oosterhuis)

lateral roots spread outward from the taproot, forming a mat of roots extending several feet. The largest portion of the root system is located within three feet of the soil surface. Root distribution within the soil (root length density) is usually about 24 inches of root per cubic inch of soil but can vary considerably with soil and plant conditions. The total root weight comprises approximately 20% of the total dry weight produced by the plant during the growing season. However, the total root length produced during the same time may be several hundred yards. The total root length continues to increase as the plant develops until the maximum plant height is reached and fruit begins to form. Root length then begins to decline as older roots die.

SHOOT DEVELOPMENT

Main stem and branches

The cotton plant has a very prominent main stem that consists of a series of nodes (points of leaf and bud development) and internodes (length of stem between nodes). The main stem will continue to grow, producing new nodes and internodes indefinitely, consistent with an indeterminate growth habit. The main stem is erect and supports a spiral arrangement of leaves and branches. Branches develop from a bud located at a node in a location immediately above where the leaf joins to the main stem. Two types of branches are produced — vegetative and fruiting. Vegetative branches are structurally similar to the main stem. They normally arise from the main stem near the ground and grow in an upright position. The number of vegetative branches produced depends primarily on environment and plant spacing.

Fruiting branches develop from buds on the main stem or from vegetative branches (Figure 12) and are defined by the presence of floral buds (squares), flowers and fruit (Figure 13). Once fruiting has begun, fruiting branches tend to be produced at each successive main-stem node. The first fruiting branch is normally produced at the sixth or seventh node above the location of the cotyledons on the main stem.

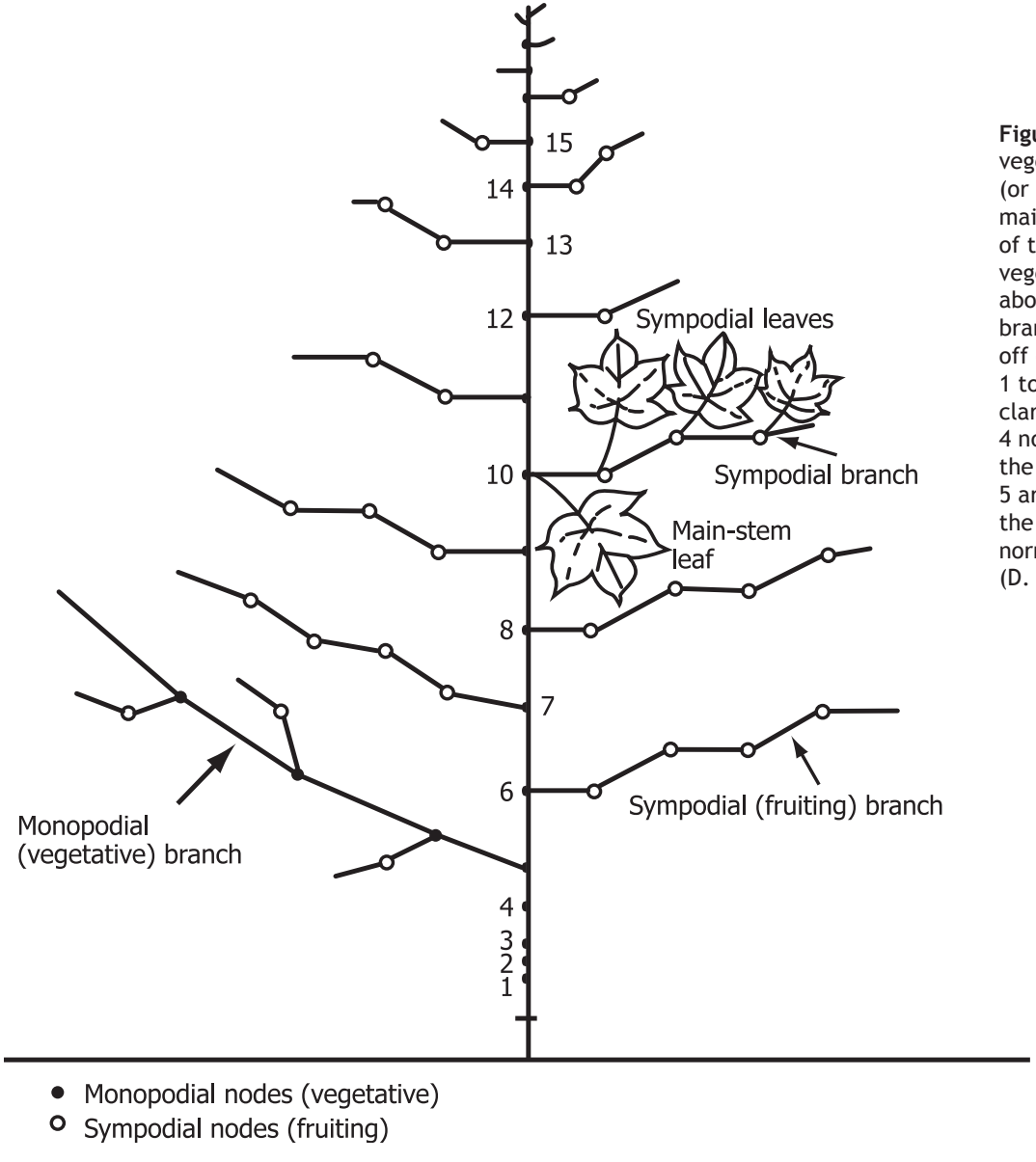


Figure 12. Development of vegetative and reproductive (or fruiting) branches from the main stem. The first 5 nodes of the main stem all produce vegetative branches. Nodes 6 and above all produce reproductive branches. Branches that form off of vegetative branches (nodes 1 to 5) are reproductive. For clarity, branches from the first 4 nodes have been omitted and the vegetative branch and node 5 are drawn extending away from the main stem rather than in its normal upright orientation. (D. Oosterhuis)

Leaves

There are three main types of leaves: cotyledons, prophylls, and true leaves (Figure 14). The kidney-shaped cotyledons from the original planted seed are usually about two inches wide. The prophylls are the first leaves that develop on a branch and are inconspicuous, usually about 0.2 inches long. The true leaves vary in shape from entire to deeply lobed, depending on the developmental stage and variety. The first true leaves formed on the cotton seedling are usually heart-shaped, whereas subsequently formed leaves are

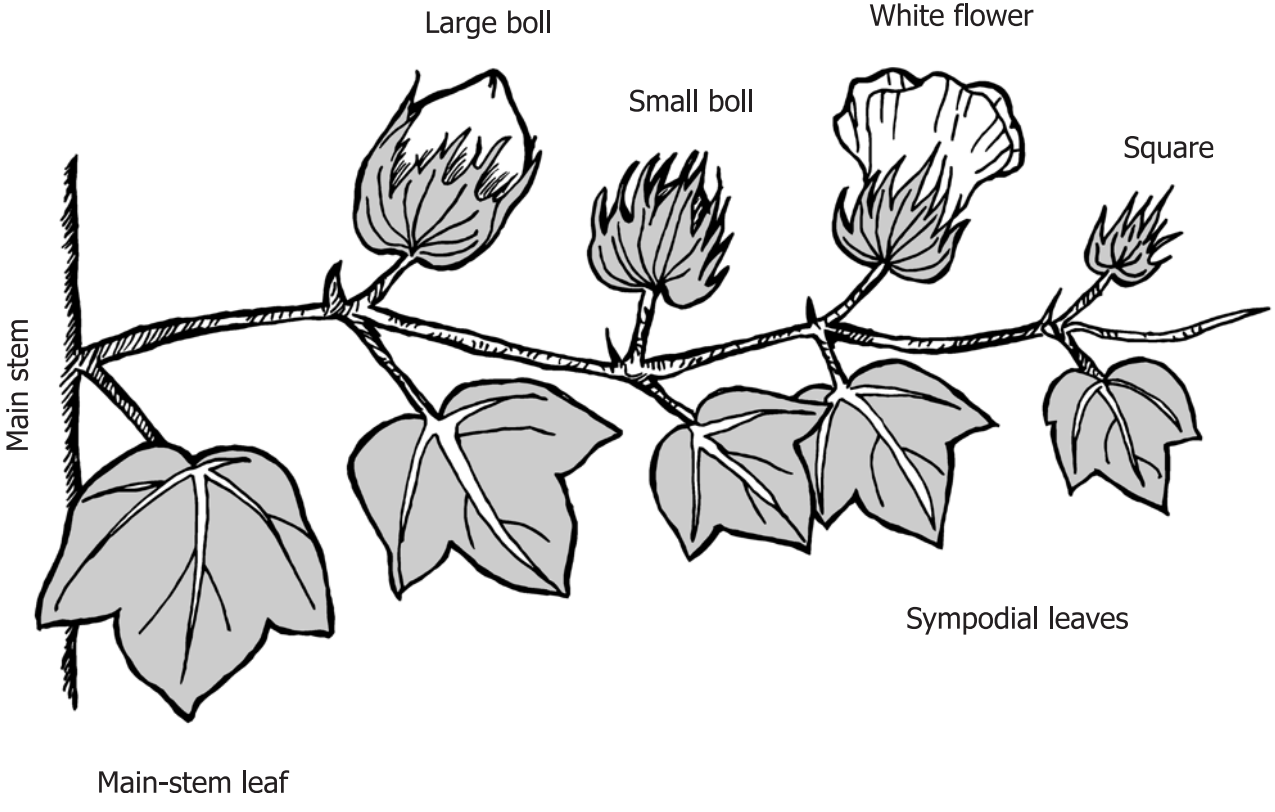


Figure 13. Diagram of reproductive fruiting branch illustrating various stages of square, flower and fruit development. (D. Oosterhuis)

lobed. The leaves of U.S. cotton cultivars are usually three- to five-lobed and about four to six inches wide. Cotton leaves generally have a thick waxy outer covering for protection. This layer contains numerous small pores (stomates) for the entry of carbon dioxide for photosynthesis as well as the exit of water vapor for evaporative cooling. Epidermal and glandular hairs are also located on the surface of the leaf.

Growth of true leaves is relatively slow at first compared to root growth, such that at one month after planting only about four or five true leaves may be unfolded and visible. During the later vegetative period, the emphasis changes to square and flower development. The average life span of a leaf is about 70 days. The large petiole (stalk joining leaf to stem) at the base of the leaf is often analyzed to estimate plant nutrient status. Total leaf area development continues to increase, reaching approximately three to four square yards of leaf per square yard of soil surface in a mature crop.

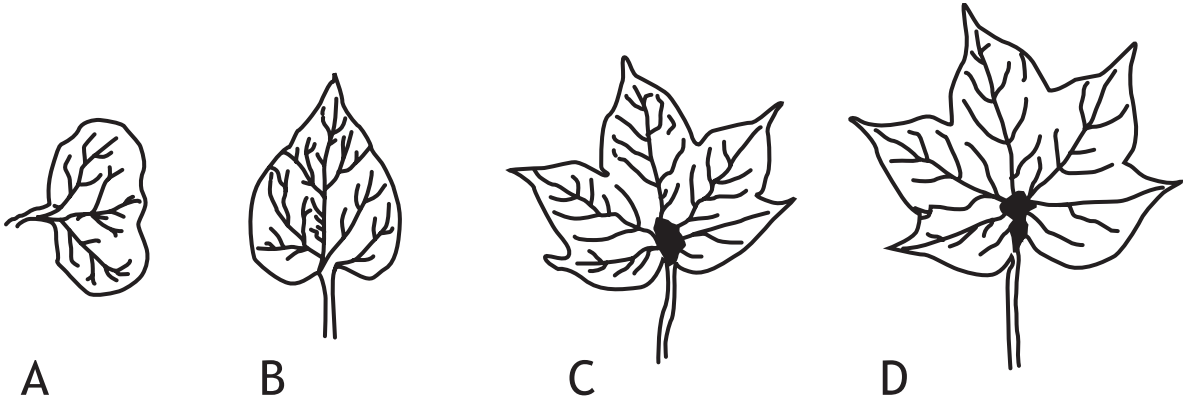


Figure 14. Variation in leaf morphology in cotton. (A) cotyledons, (B) small first leaves on main stem, (C) larger leaves on vegetative branches, (D) largest leaves that develop on nodes of main stem. (D. Oosterhuis)

REPRODUCTIVE DEVELOPMENT

The cotton plant, due to its indeterminate growth habit, continues both vegetative and reproductive development throughout the remainder of the season. Reproductive growth commences with the formation of the floral buds in the apical part of the plant which give rise to the flowers (Figure 15) and subsequent bolls (Figure 13).

Cotton has a distinctive and predictable flowering pattern. The first flowers to open are low on the plant, usually on main-stem nodes six or seven and on the first position along a fruiting branch. About three days elapse between the

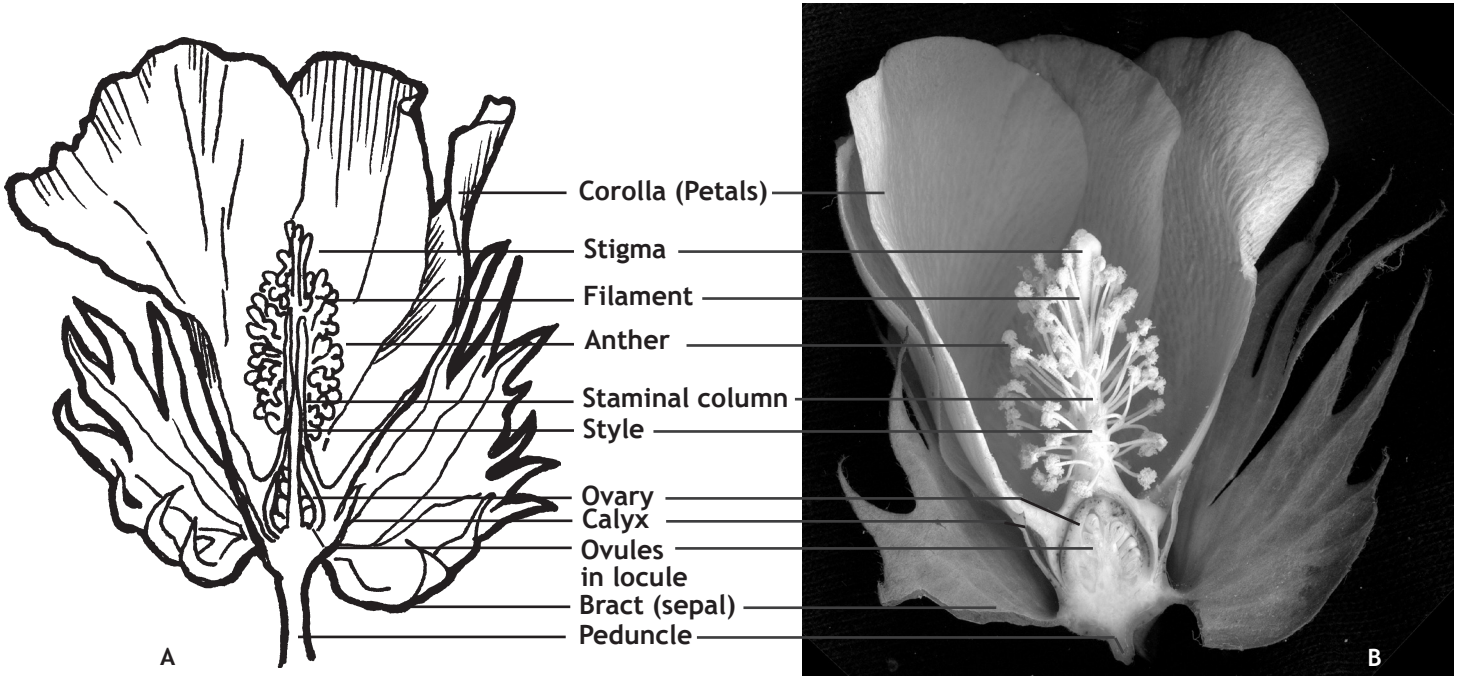


Figure 15. Diagram (A) and photograph (B) of a cotton flower on the day of anthesis. Petals and bracts are prominent. The male reproductive organs (stamens) encircle the female organ (pistil consisting of stigma, style and ovary). (A, D. Oosterhuis; B, R.W. Seagull)

opening of a flower on a given fruiting branch and the opening of a flower at the same relative position on the next higher fruiting branch. On the other hand, the time interval for the development of two successive flowers on the same branch is about six days. The order is thus spirally outward and upward. Flowers continue to be produced (indeterminant growth) as long as the plant is actively growing. In an agricultural setting, active plant growth is stopped by defoliation or frost.

Cotton is genetically programmed to produce seed for sexual reproduction. For the plant, the fibers that coat the seed evolved to facilitate seed dispersal, probably functioning to entangle in fur and feathers so that seeds were carried away. Wild cotton plants produce much smaller seeds with far fewer and shorter fibers. Humans dramatically influenced the evolution of domestic cotton by selecting plants that produce large quantities of fiber (Figure 16). Thus the original function of the fiber on the seed coat, to ensure propagation of the species by spreading the seed to new locations, has been superceded by a new function. Humans select seed for propagation based on fiber production. The end result is the same —

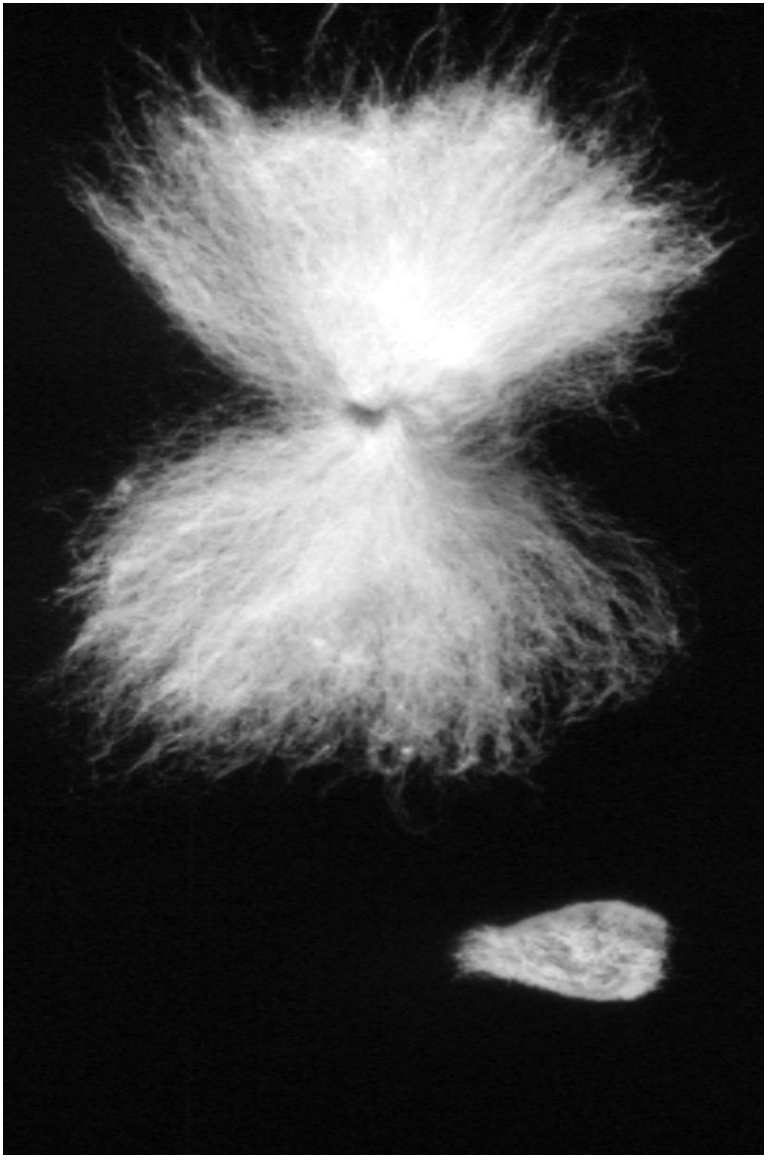


Figure 16. A mature cotton seed with fibers splayed out. Below; a ginned seed. (C.H. Haigler)

continuation of the species. The seed contains the embryonic plant for the next generation, composed of cotyledons, a root, a stem and leaves (Figure 9).

Squares

The buds appear first as small, green, triangular structures known as squares. The first squares (pinhead squares) are usually visible about five weeks after planting and the first flowers about three weeks later. New squares will appear in the top of the plant every three days and will appear on each fruiting branch at approximately six-day intervals. The total time for a flower bud to develop (from pinhead square until flower opening) is approximately six to seven weeks.

Flowers

The cotton flower is large and showy (Figure 15). On the outside of the flower are three large green bracts that enclose and protect the growing flower parts. The bracts are all that is visible of the square. Immediately inside the bracts are the reduced sepals which tightly enclose the five conspicuous white petals. The staminal column, composed of numerous stamens (male reproductive organ) each with a two-lobed anther (Figure 17) surrounds the style. The female reproductive organ consists of the stigma (pollen receiving structure), style (structure that supports the stigma) and ovary (container for the developing ovules). The ovary is composed of three to five compartments (carpels) each with ovules attached to the central column in the locule (Figure 18).

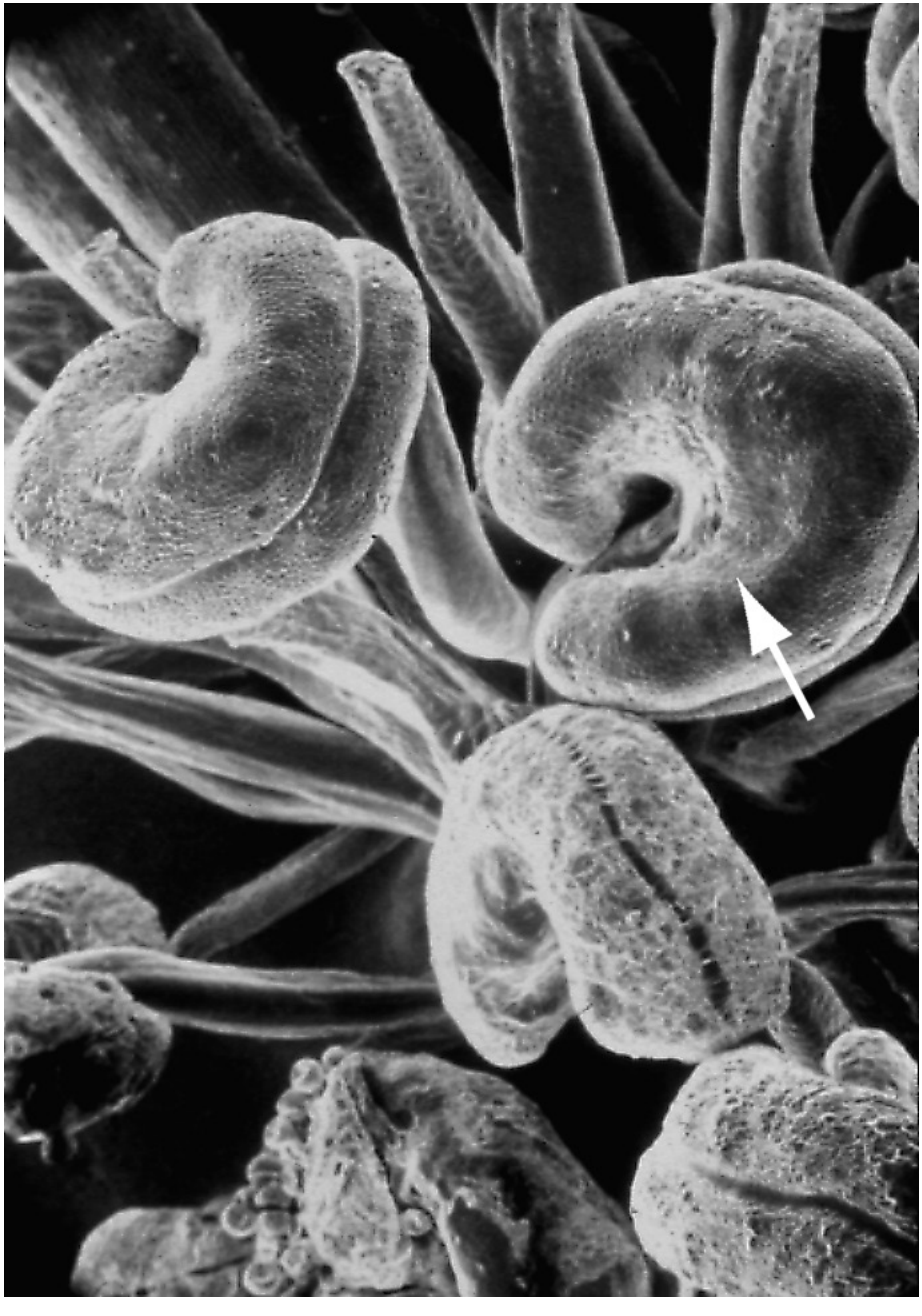


Figure 17. A scanning electron microscopic (SEM) image of anthers (pollen producing organ) (arrow) from a mature cotton flower ready to shed pollen (J. McD. Stewart).

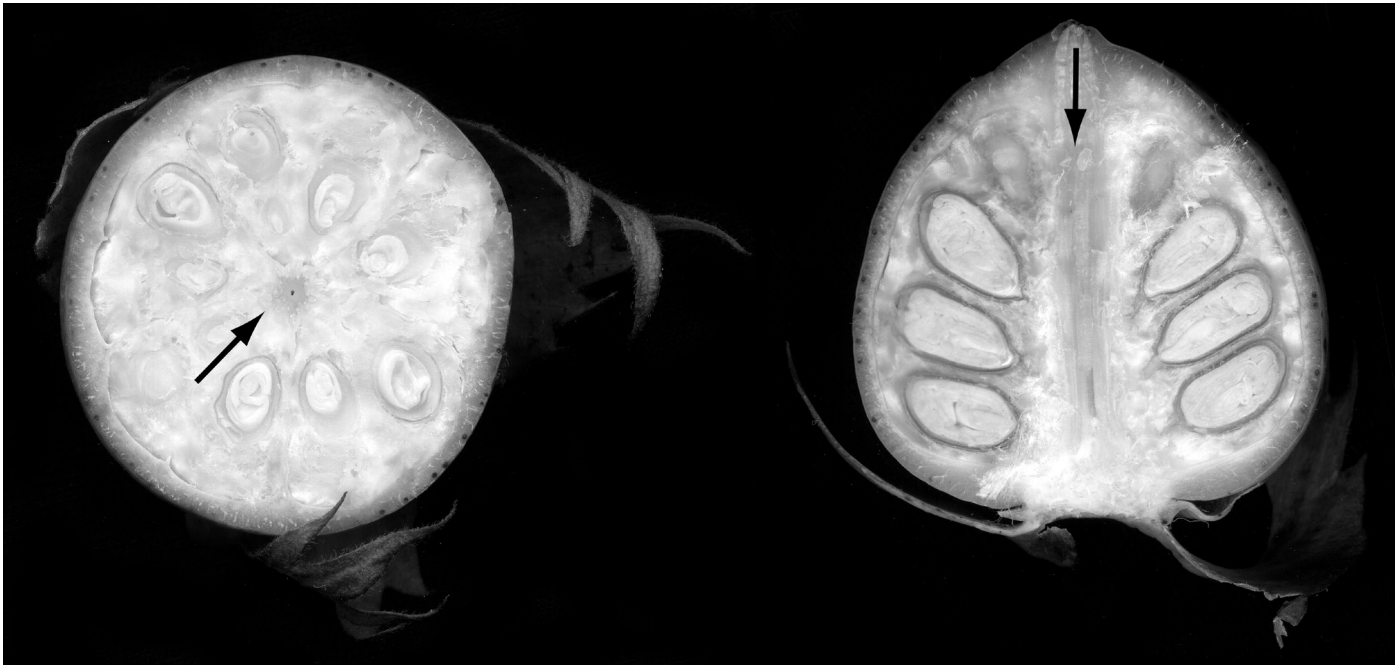


Figure 18. A photograph of a boll showing the seeds attached to the central placenta. On the left is a boll in cross section showing the seeds surrounding the central placenta (arrow). On the right is a longitudinal section showing seeds on either side of the central placenta (arrow). (R.W. Seagull)

Within the ovary, each ovule is somewhat "tear-drop" shaped and attached to the ovary near its "pointed end" by a short stalk-like structure (the funiculus) that transports nutrients from the parent plant to the growing ovule (Figure 19).

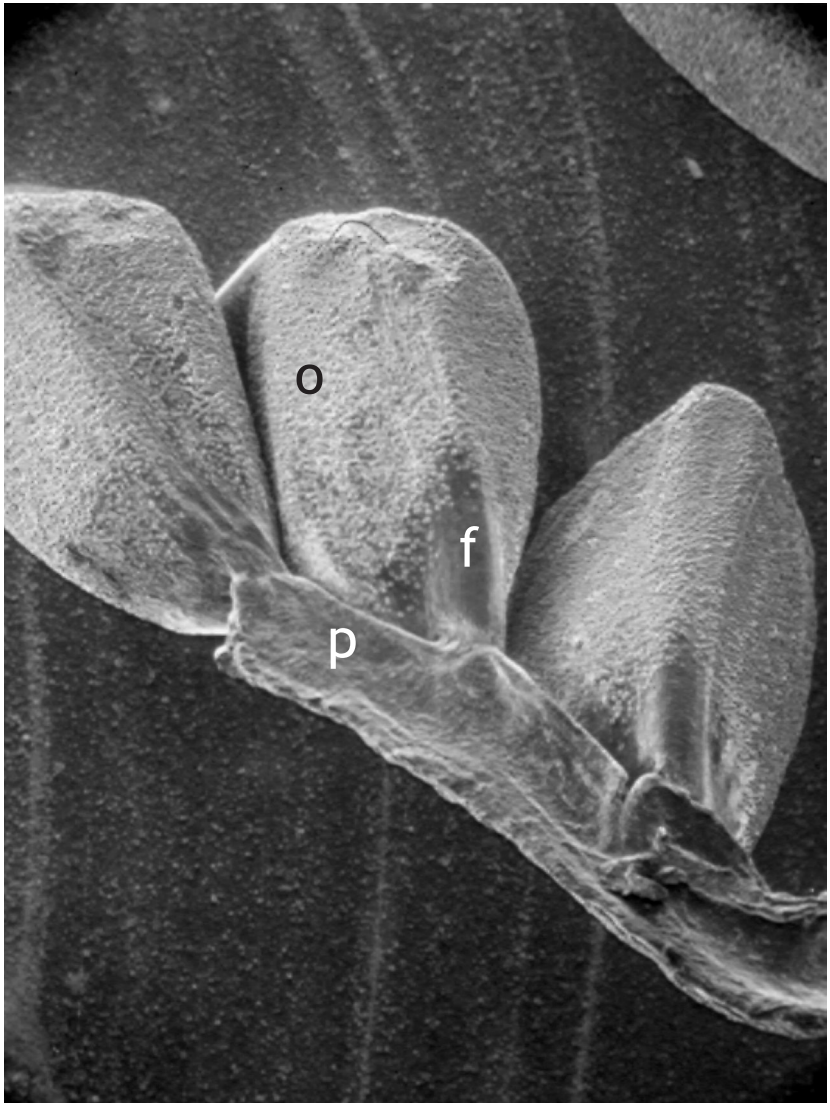


Figure 19. A SEM view of ovules dissected from the boll and receiving nourishment from the plant through the funiculus (a short stalk-like attachment) (f) between the ovule (o) and placenta (p) of the boll. (J. McD. Stewart)

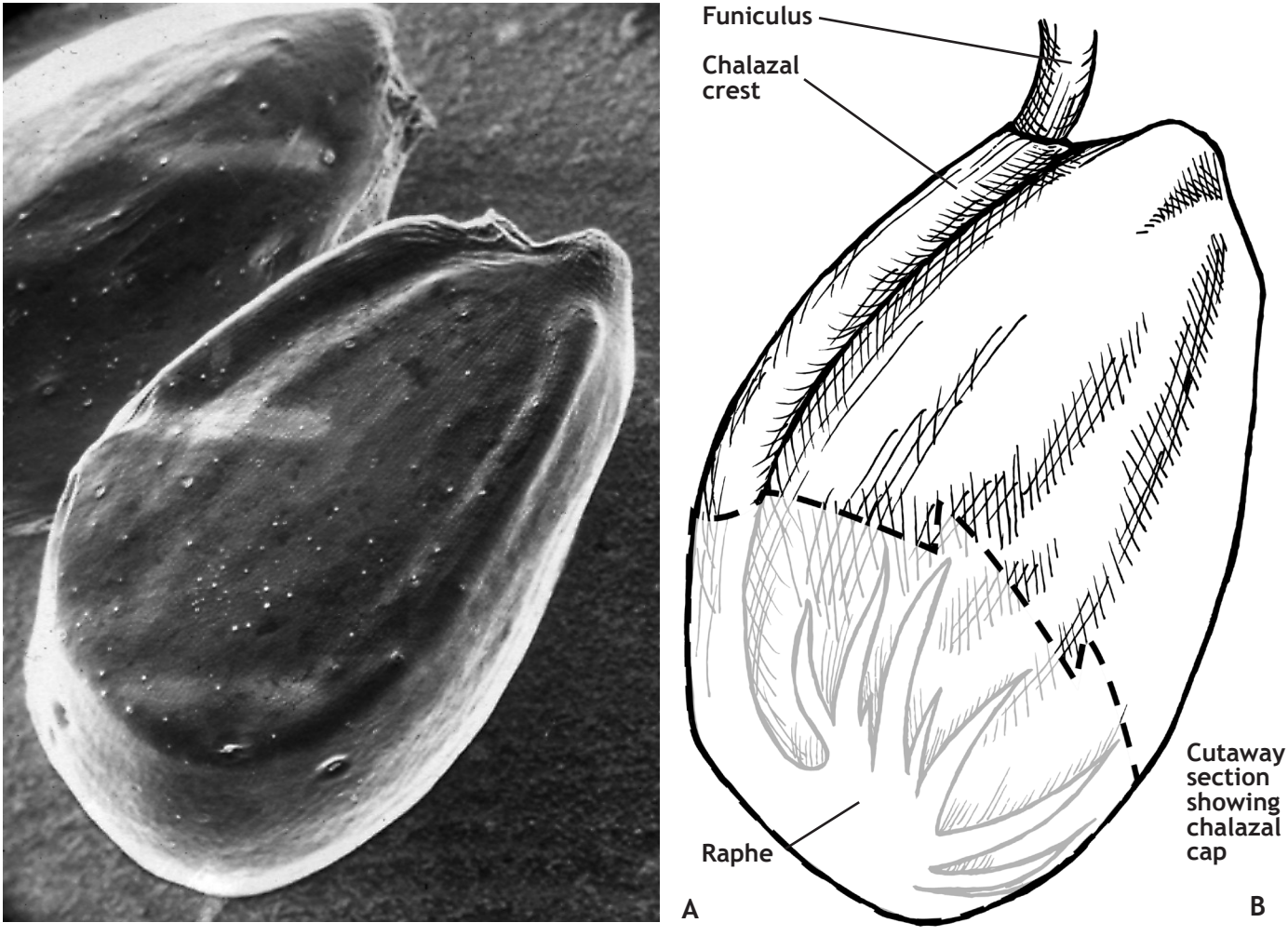


Figure 20. An SEM image (A) and diagram (B) of an ovule illustrating the point of attachment of the funiculus and the raphe of the ovule. The diagram shows the nutrient supply system of the ovule. The funiculus attaches the seed to the parent plant. The raphe extends along the side of the seed forming a crest. The raphe contains vascular tissue which branches when it reaches the blunt end of the seed (chalazal). The vascular tissue branches from an internal handlike structure within the chalazal cap that distributes nutrients to the tissue of the ovule.
(A, J. McD. Stewart; B, K. Charlton)

The raphe extends along the side of the ovule forming the "crest" and terminates internally in a large, "hand-like" structure at the chalazal end (wide end) of the ovule (Figure 20). As nutrients enter the ovule, the embryo sac and surrounding integuments expand. The integuments and other tissues encase the embryo sac and where the integuments come together at the "pointed end" of the ovule, a small opening (micropyle) is created (Figure 21).

Figure 21. A SEM view of the micropyle, a small hole (arrow) for entry into the embryo sac (egg chamber) at the base (pointed end) of the ovule.
(J. McD. Stewart)

Pollination and fertilization

On the day of anthesis, the flower opens its white petals at dawn and anthers shed pollen within a few hours. The pollen often adheres to the stigma of the same flower (self-pollinated) (Figure 22), although some insect pollination can occur between different flowers on different plants (cross-pollination).

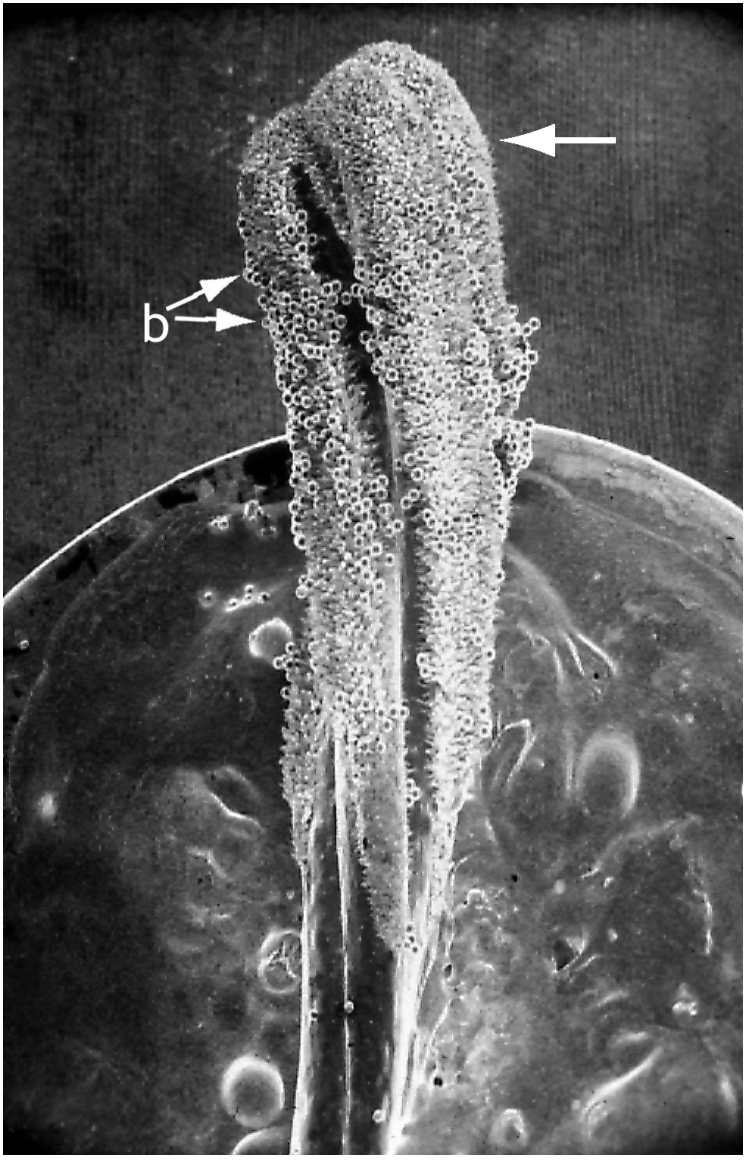
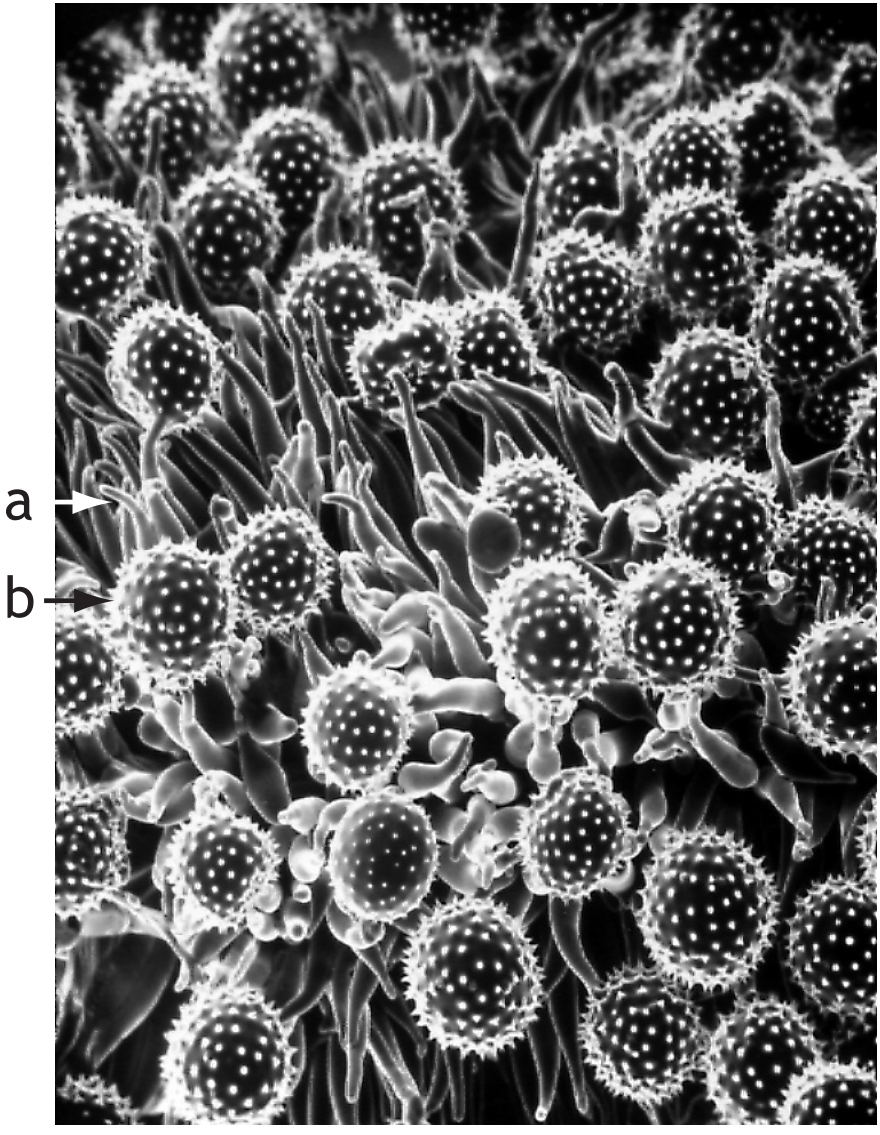


Figure 22. A scanning electron microscopy (SEM) view of the stigma (pollen receiving organ) (arrow) of a mature cotton flower. The numerous small spheres (b) are pollen grains attached to the stigma. Figure 23 is an enlargement of the grains. (J. McD. Stewart)



Long hairs on the stigma entrap the sticky pollen grains (Figure 23).

Figure 23. A SEM of mature pollen grains after landing on the stigma. Elongated cells (a) on the stigma help hold the pollen grains (b). (J. McD. Stewart)

Pollen grains germinate to produce a pollen tube (Figure 24) that grows down the style.

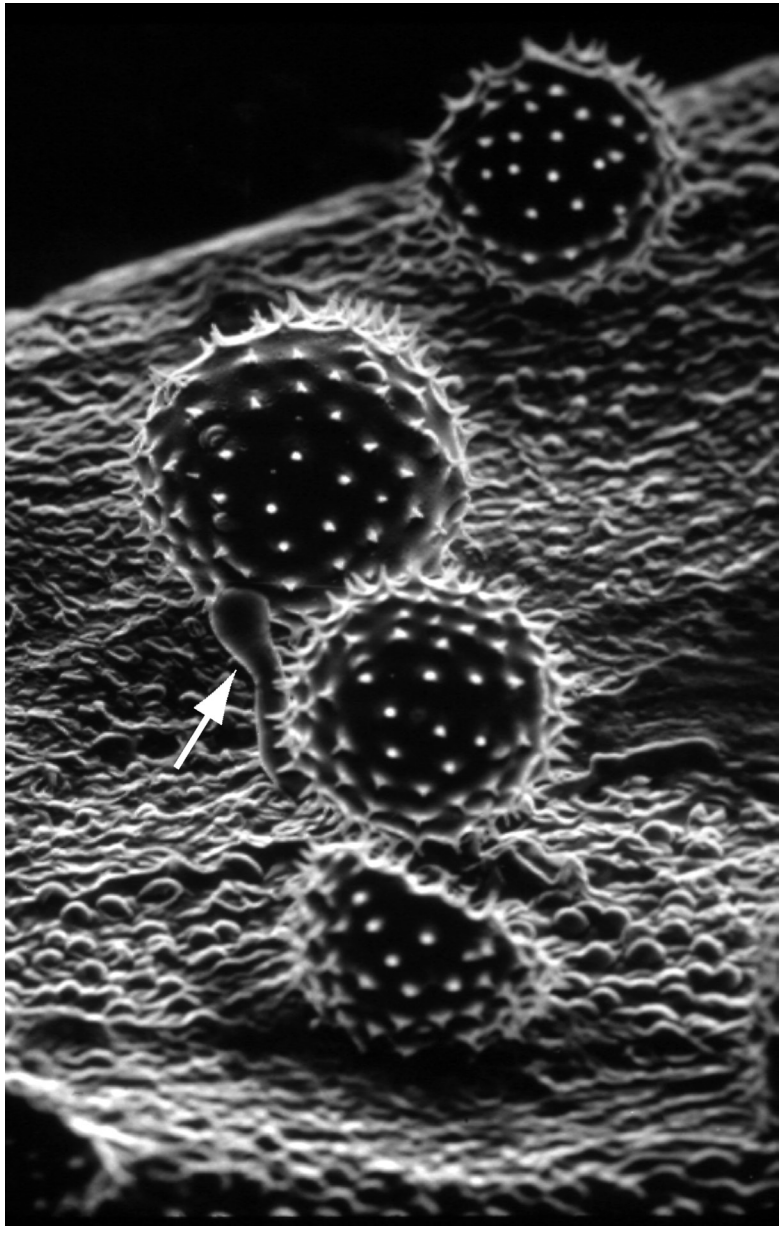
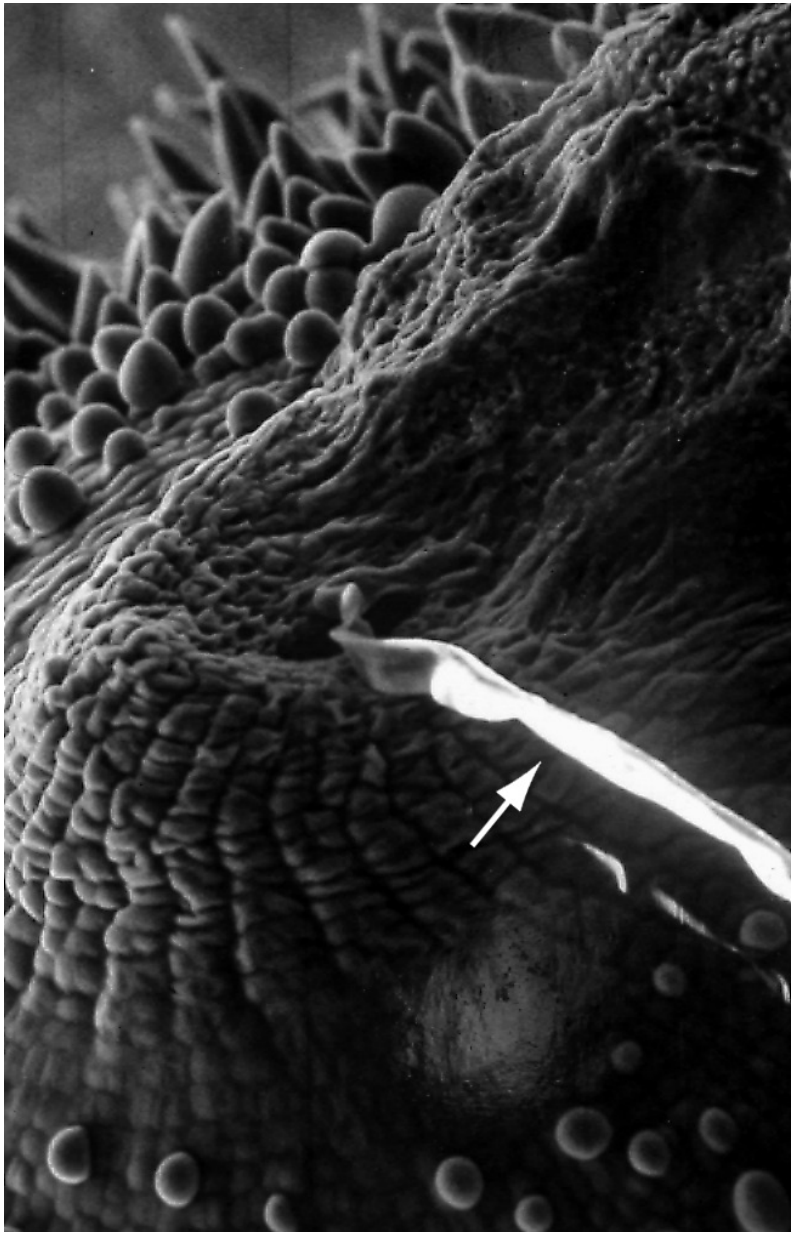


Figure 24. A SEM of germinating pollen grain that produces a pollen tube (arrow) which carries sperm cells to the developing egg cell in the ovule. (J. McD. Stewart)



The pollen tube enters the micropyle (Figure 25) to fertilize the egg cell inside the ovule (immature seeds), usually between 12 and 24 hours after pollination. The petals of the cotton flower are creamy yellow on the day of anthesis, but turn a pink-red color the following day and wither and usually fall off within three days.

Figure 25. Using SEM, a pollen tube (arrow) is seen entering the micropyle to reach the embryo sac containing the egg cell. (J. McD. Stewart)

SEED AND BOLL DEVELOPMENT

Initially the embryo is very small and the endosperm comprises most of the embryo sac (Figure 26). The endosperm swells as it fills with nutrients from the parent plant. As the ovule matures into the seed, the stored nutrients are transferred from the endosperm to the developing cotyledons of the embryo. During seed germination and early seedling growth, these nutrients are used to support the plant until it can photosynthesize and make its own food. By the time the seed is ready to germinate, the endosperm is not detectable and the embryo consists of two large cotyledons and the embryonic axis, including radicle, hypocotyl and epicotyl (Figure 9).

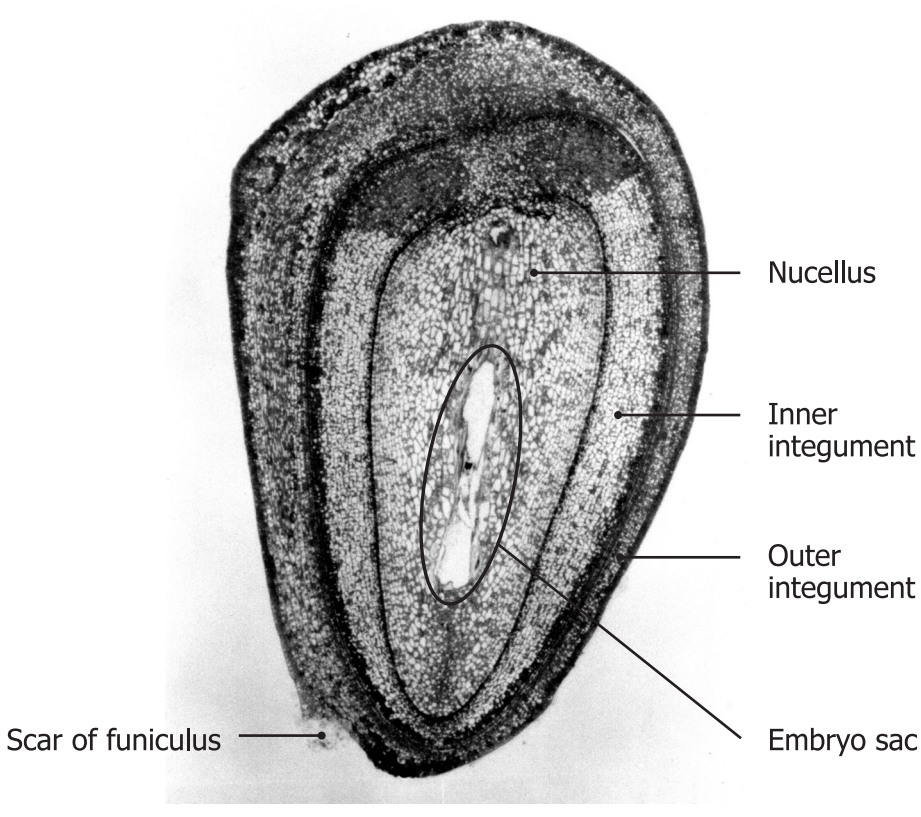


Figure 26. A light micrograph (LM) of a longitudinal section of ovule on day of anthesis illustrating a portion of the embryo sac, nucellus, inner and outer integuments, and scar of funiculus. (K.R. Jacobsen and J. Jernstedt).

Seeds attain their full size about three weeks after fertilization, but do not reach maturity until the boll opens. Only ovules that are fertilized and develop an embryo reach maturity. Immature or aborted ovules, called motes, are often found in mature bolls. Fertilization and fiber production are linked processes, in that fertilization is required for optimum fiber growth and development on the plant. Unfertilized ovules will develop fibers; however, the extent of fiber development is severely limited and is one of the causes of textile motes (undeveloped seeds with immature fibers) (Figure 27).

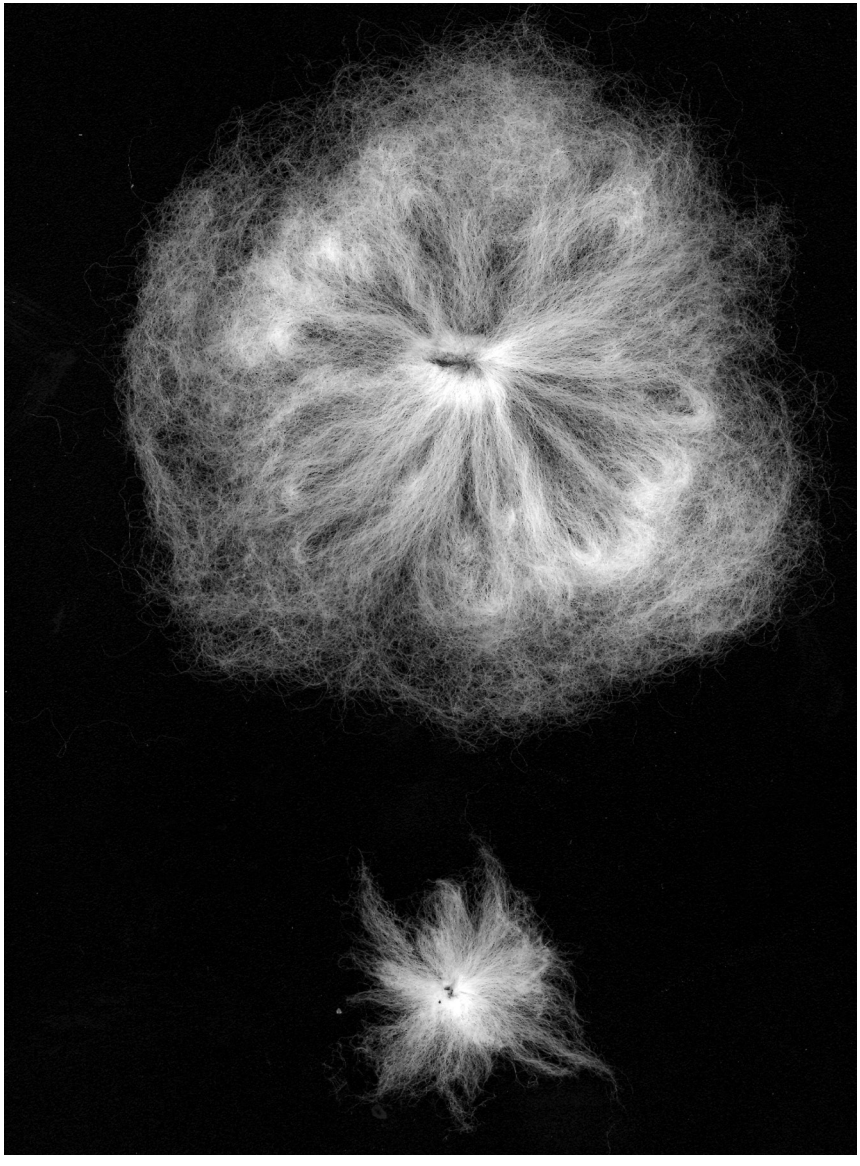


Figure 27. If the egg in the ovule is not fertilized by sperm from the pollen, then the seed and fibers do not develop properly. Motes are immature seeds and bare abnormal fibers. Ovule and fibers on top exhibit normal growth and development. The mote on the bottom has a much smaller seed and shorter fibers.
(P. Gould)

The boll, or fruit, of the cotton plant varies in form and size but is generally a spherical or ovoid leathery capsule, light green in color, and with a few pigment glands (Figure 28). The boll grows rapidly after fertilization, especially between 7-18 days, and full size is reached in about 20 to 25 days. Maturation of the boll, from anthesis to the time of boll opening, usually takes about 50 days but this varies with genotype and environmental conditions. The boll is composed of three to five locules (compartments of the ovary) each with eight or nine seeds attached to the central column (Figures 18, 28). At maturity the boll splits along suture lines in the ovary wall.

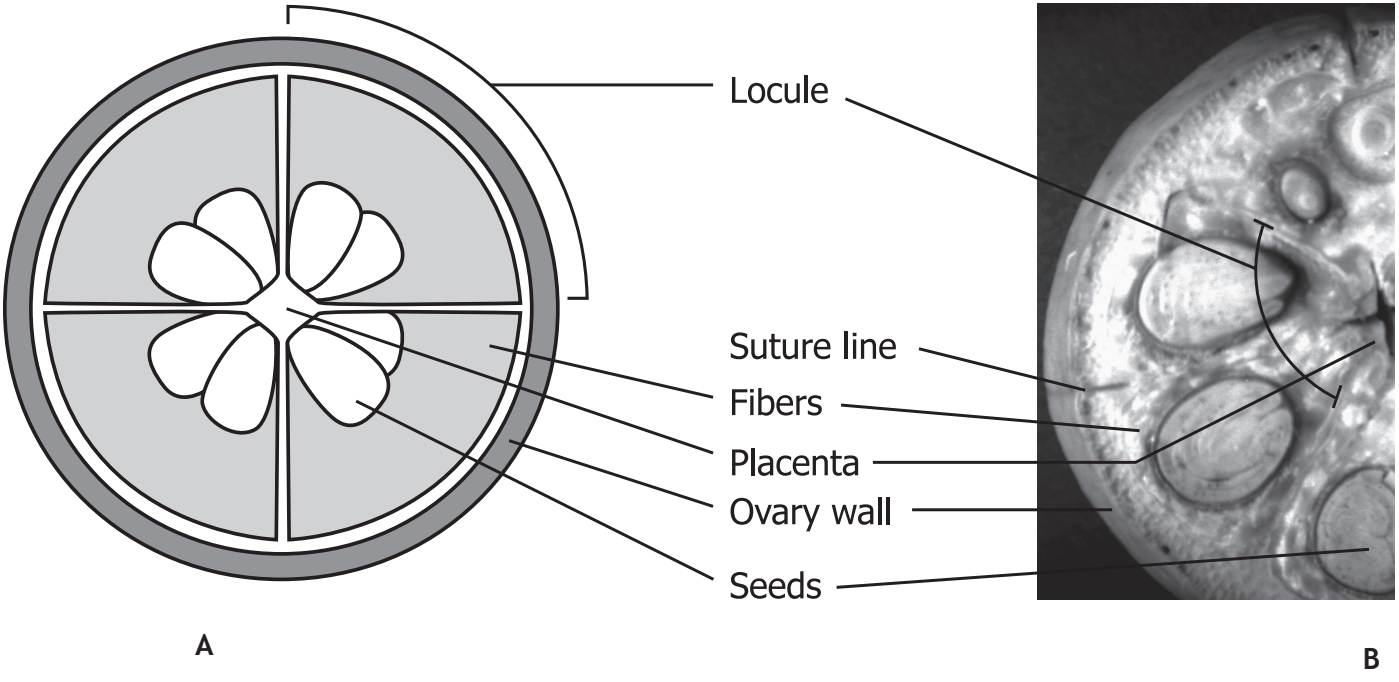


Figure 28. A cross section through a developing boll. The boll is divided into compartments or locules. Ovules appear near the center of the boll and between the ovules and boll wall one finds the mass of developing fibers. (A, K. Charlton; B, R.W. Seagull)

The mature white seed-cotton within expands greatly, pushing out beyond the capsule, forming a white fluffy mass divided into locs (Figure 29). About 300 bolls are required to produce a pound of lint and there are about 145,000 bolls per bale of lint.

The fertilized ovule develops into a seed if the young boll is not shed. Shedding occurs either before anthesis (squares) or after fertilization (developing bolls). Flowers are not shed. The shedding of squares and young bolls is a natural occurrence in cotton that is accentuated by adverse environmental conditions including extended overcast weather, extreme high temperatures, water stress, and insect damage. A cotton plant in a typical field commonly sheds about 60% of its squares and young bolls, mostly in the younger regions of the plant (i.e., ends of branches and main stem).

Figure 29. Mature open cotton boll with five locs. (R.W. Seagull)

FIBER DEVELOPMENT & MATURATION

ROBERT W. SEAGULL, Ph.D.

The mature dried fiber is the most economically relevant part of the cotton plant. The production of fiber with appropriate physical properties requires a very specific sequence of developmental steps, each controlled by a number of as yet poorly defined biological processes. Fiber development requires fertilization of the ovule and growth of the embryo within. Each of the three stages of fiber development (initiation, elongation and secondary wall synthesis) directly impacts the final physical properties of the mature fiber. Fiber maturation refers to the natural drying and collapse of the fiber that occurs when the boll opens. Exposure of the mature fibers to air results in the drying of the fibers. The physical and chemical processes involved in maturation are closely related to the structure and chemical composition of the fiber. This section describes the growth and development of cotton fibers, emphasizing the biological processes required for each stage of development and the changes that occur in the fiber once the boll opens and the living fiber cell dies.

Fiber growth and development is rather unique among plant cells. Only a few plant cells in nature (fiber cells from flax and ramie) can reach the final length and volume of a cotton fiber. From its inception as an immature epidermal cell on the ovule to its death upon the opening of the boll, fiber cells increase in length some 4,000 – 5,000 times. The fiber increases in diameter by two to three times and volume some 10,000 – 15,000 fold. From epidermal cell to mature fiber, the cell undergoes a three step developmental sequence (initiation, elongation and secondary wall synthesis) followed by maturation. These first three steps occur in the living fiber and are controlled by the biological processes that regulate cell growth and development. The final step occurs upon opening of the boll and includes the death of the fiber cell. In addition to the long fibers, most commercial cultivars (excluding Pima or *Gossypium barbadense)* have very short white or colored fibers on the seed called linters or fuzz fibers. Fuzz fibers are of less commercial value. Cotton fiber quality,

as defined by length, maturity, strength, and micronaire, is primarily determined by the genetic makeup of the plant, but is also influenced by climatic conditions experienced by the crop.

FIBER INITIATION

Fiber development begins when the flower is about to open. As the ovule grows, immature epidermal (protoderm) cells of the future seed coat divide to accommodate the increase in volume of the ovule. Non-fiber epidermal cells divide and expand in a manner so as to increase the surface area of the seed. By a process that is still not understood, some epidermal cells dramatically change their pattern of growth to become fiber cells. Surface cells destined to become fibers stop dividing and dramatically change their growth direction, producing extremely long, single cells that extend perpendicularly above the surface of the ovule (Figure 30, 31).

Figure 30. On the day of anthesis numerous fiber initials develop primarily at the chalazal end of the ovule. (J. McD. Stewart)

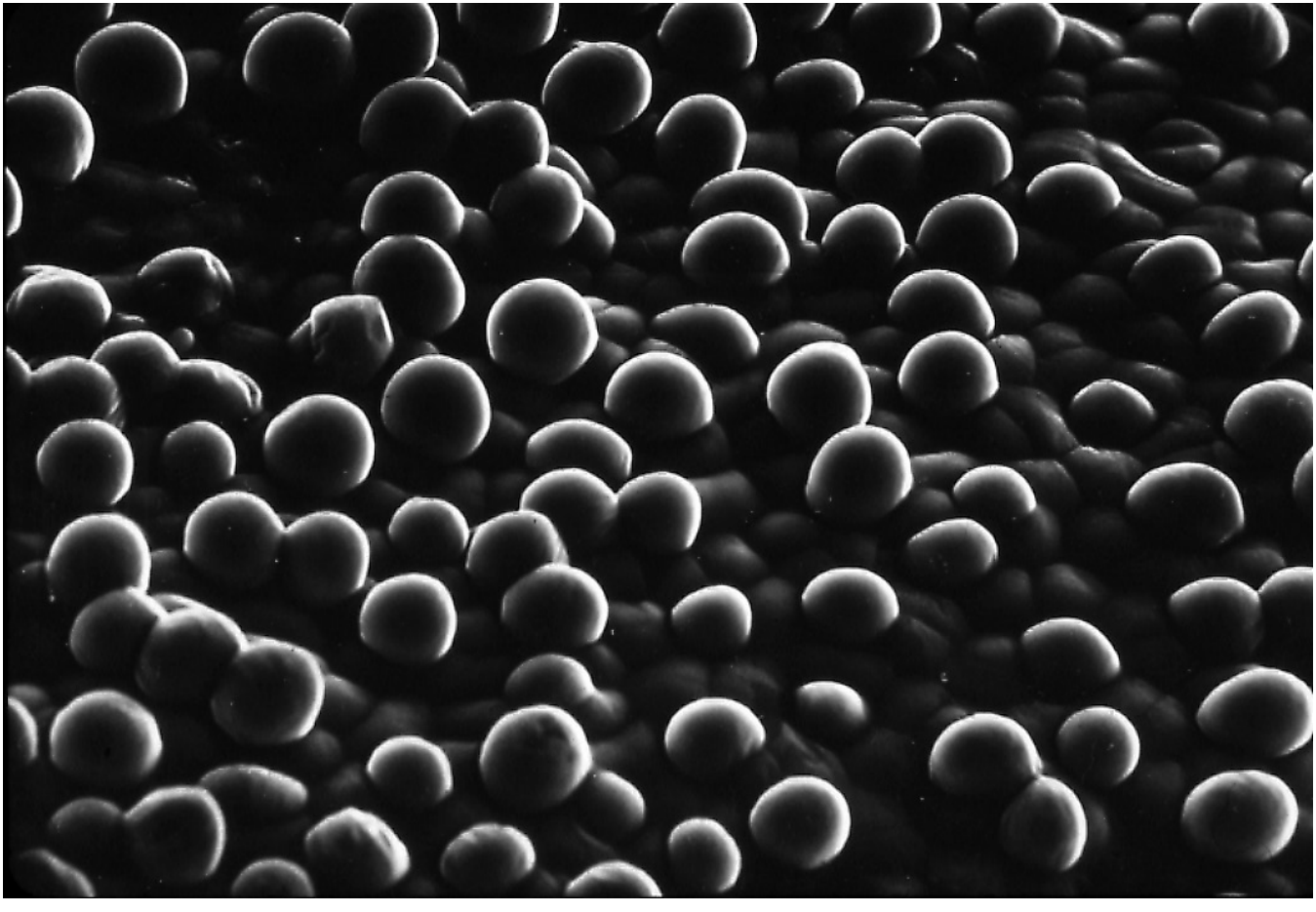


Figure 31. Using SEM, fiber initials first appear as hemispherical swellings or bumps on the surface of the ovule. (J. McD. Stewart)

The change in growth direction occurs near the day of anthesis. Depending on the cotton species and environmental conditions, fiber initials are first observed between –1 and 0 DPA (days post anthesis). While originally believed to be signaled by ovule fertilization, fiber initiation before fertilization clearly indicates that the two processes (fertilization and fiber initiation) are not mutually dependent on each other.

Estimates vary, but between 10 and 25% of immature protodermal (immature epidermal) cells develop into cotton fibers. Fiber initiation is first detected by a swelling of the protodermal cell above the surface of the ovule (Figure 32). The

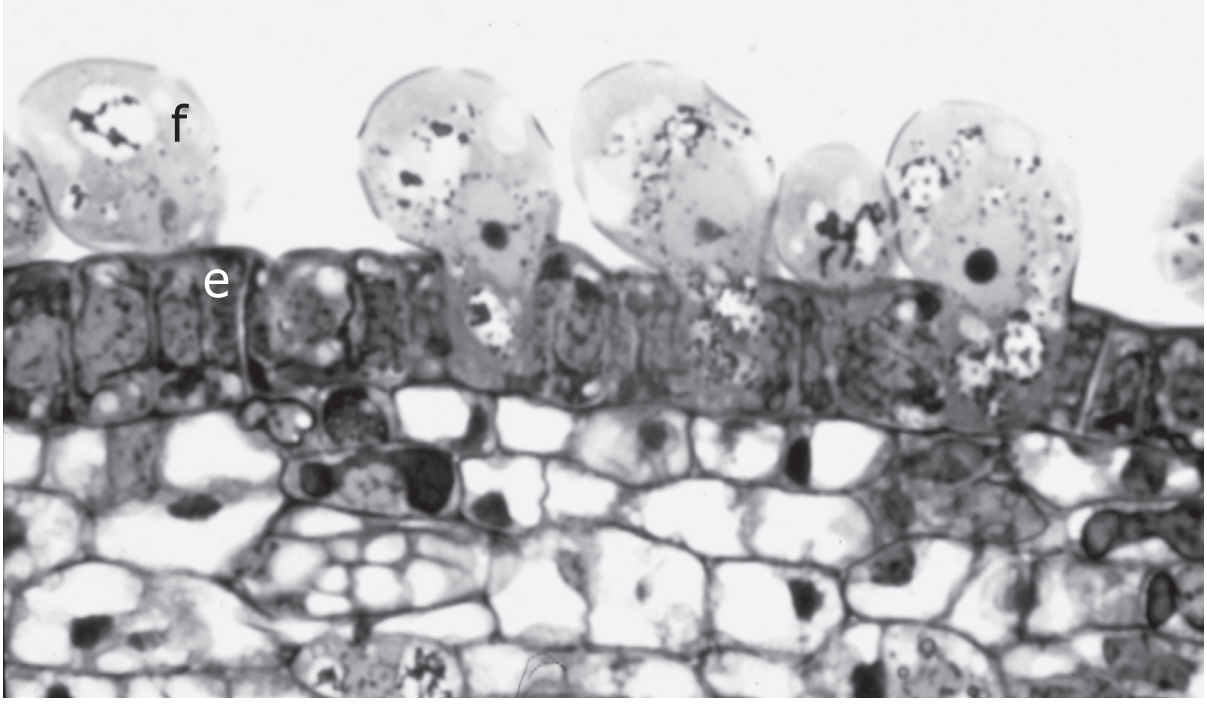


Figure 32. Using LM, sections of the ovule and developing fibers reveal that as fiber initials swell above the surface of the ovule, cell diameter increases so that fiber cells (f) are much wider than neighboring protodermal cells (e) and over-spread them. (P. Lu and J. Jernstedt)

initial swelling of the protodermal cell is isodiametric (equal in all directions). However, within a day or two, the swelling is specifically directed toward cell elongation.

Several waves of fiber initiation occur on the ovule. Initiation is observed first at the crest and chalazal end of the ovule (Figure 33). Fiber initiation proceeds down the ovule such that by 24 to 48 hours, fiber initials are observed at the micropylar (pointed) end of the ovule (Figures 33 and 34).

Figure 33. The wave of fiber initiation is observed along the length of the ovule, using SEM. Longer (older) fibers are observed at the chalazal end of the ovule. As one proceeds towards the micropyle end of the ovule (arrow), shorter and shorter fibers are observed. (J. McD. Stewart)

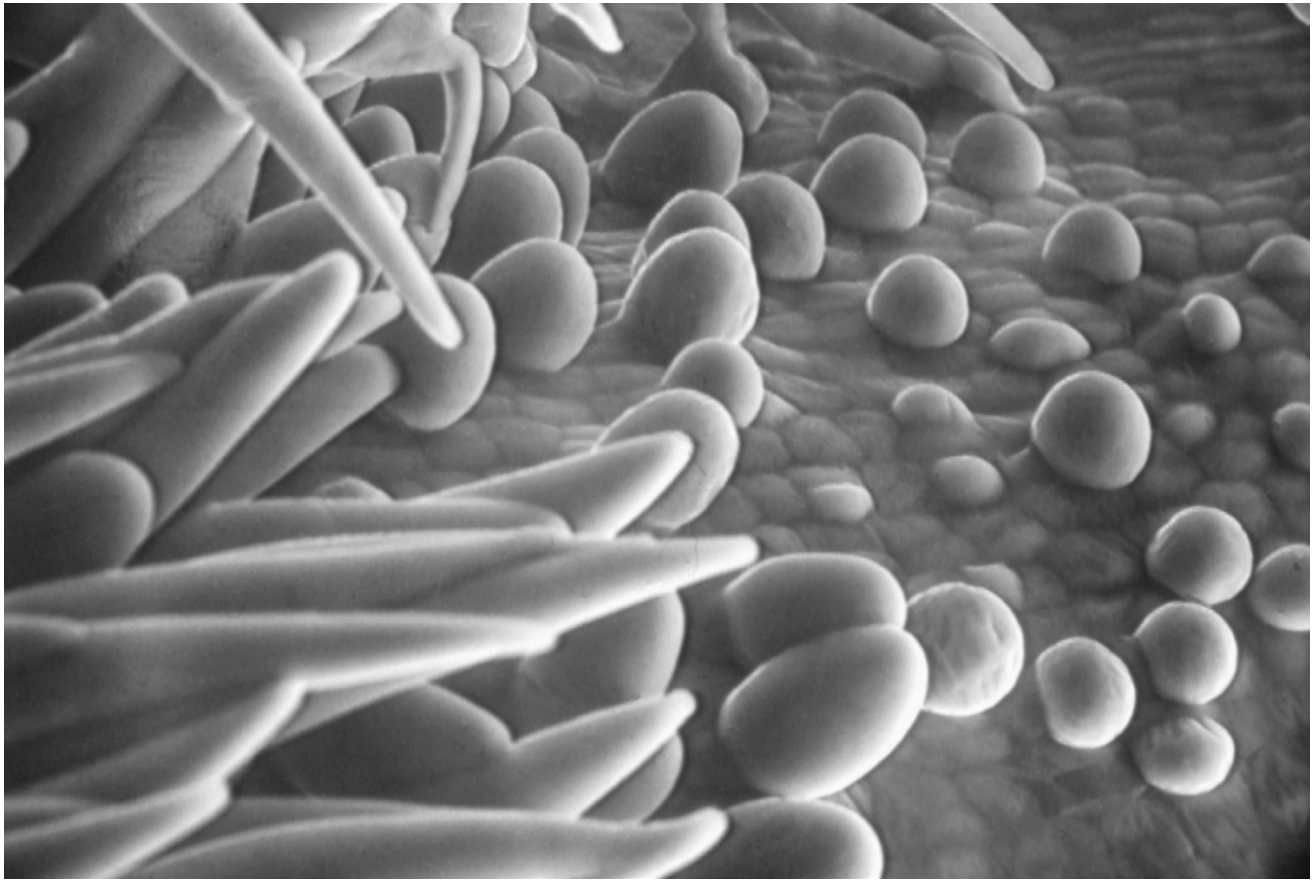


Figure 34. Using the SEM and looking from the chalazal end towards the micropyle (from left to right in the photograph), longer tapered fibers are followed by shorter fiber initials. (J. McD. Stewart)

Although reports vary, recent evidence indicates that fiber initials continue to be produced for four to five days. These initials develop into the lint fibers used for textiles. Subsequent waves of fiber initiation result in the production of fuzz fiber. Fuzz fiber appears to be initiated about 10 DPA.

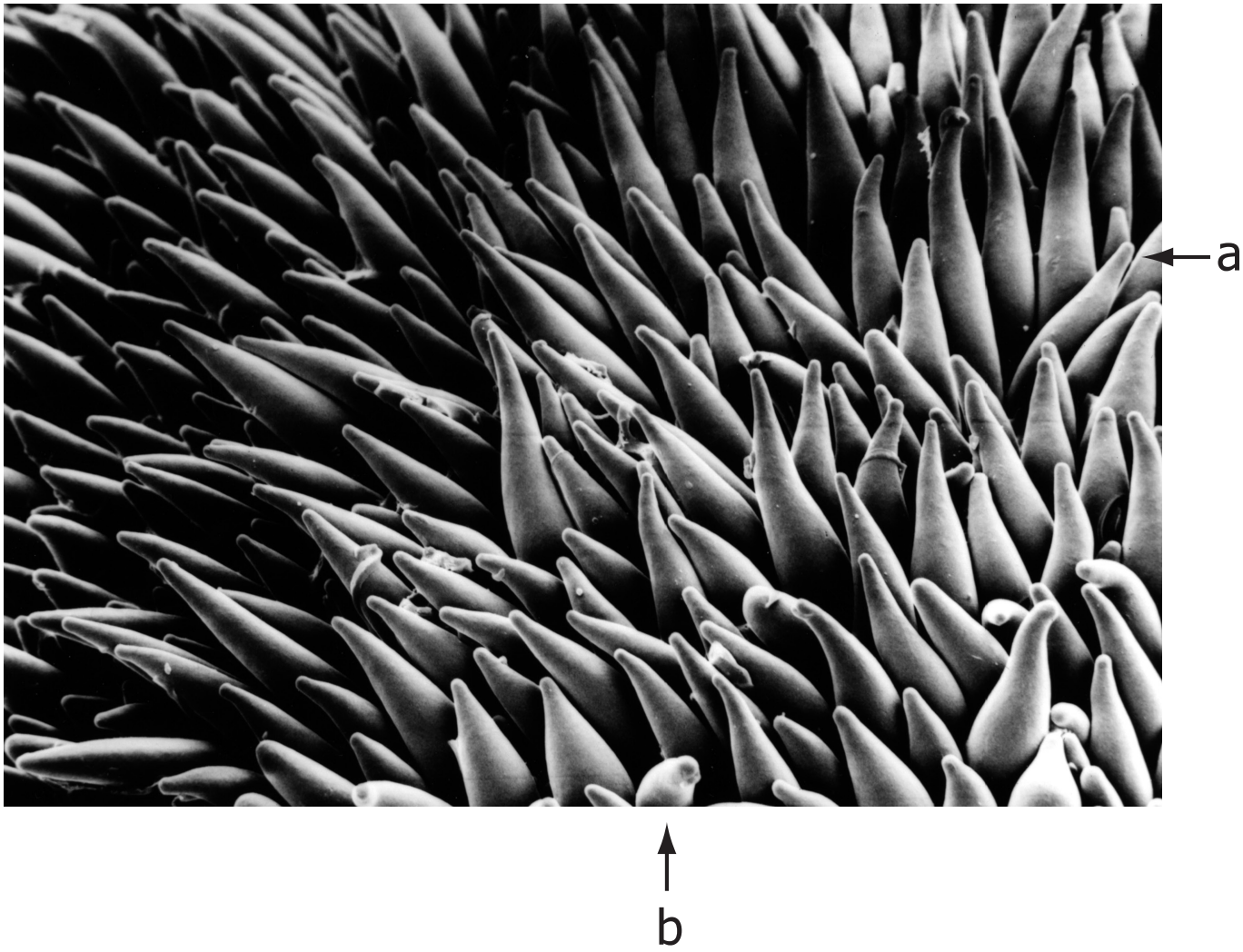


Figure 35. As fibers enter the phase of rapid elongation (3 DPA) variability in shape of fibers is observed. Using SEM, fibers form different shapes, with some exhibiting long narrow tips (a) while others have broader, more blunted tips (b). (P. Lu and J. Jernstedt)

FIBER ELONGATION

After one day of development, fiber initials take on a tapered appearance. Early in development fibers may exhibit a tapered or rounded tip shape (Figure 35). As fibers continue to elongate, they begin to twist together forming large clusters (Figure 36). The mechanism that regulates this process remains unknown. By ten DPA, the ovule is encased in a tight array of cotton fibers. Fibers from the ovule begin to entangle, giving the appearance of an ovule meshed in a dense mat (Figure 37).

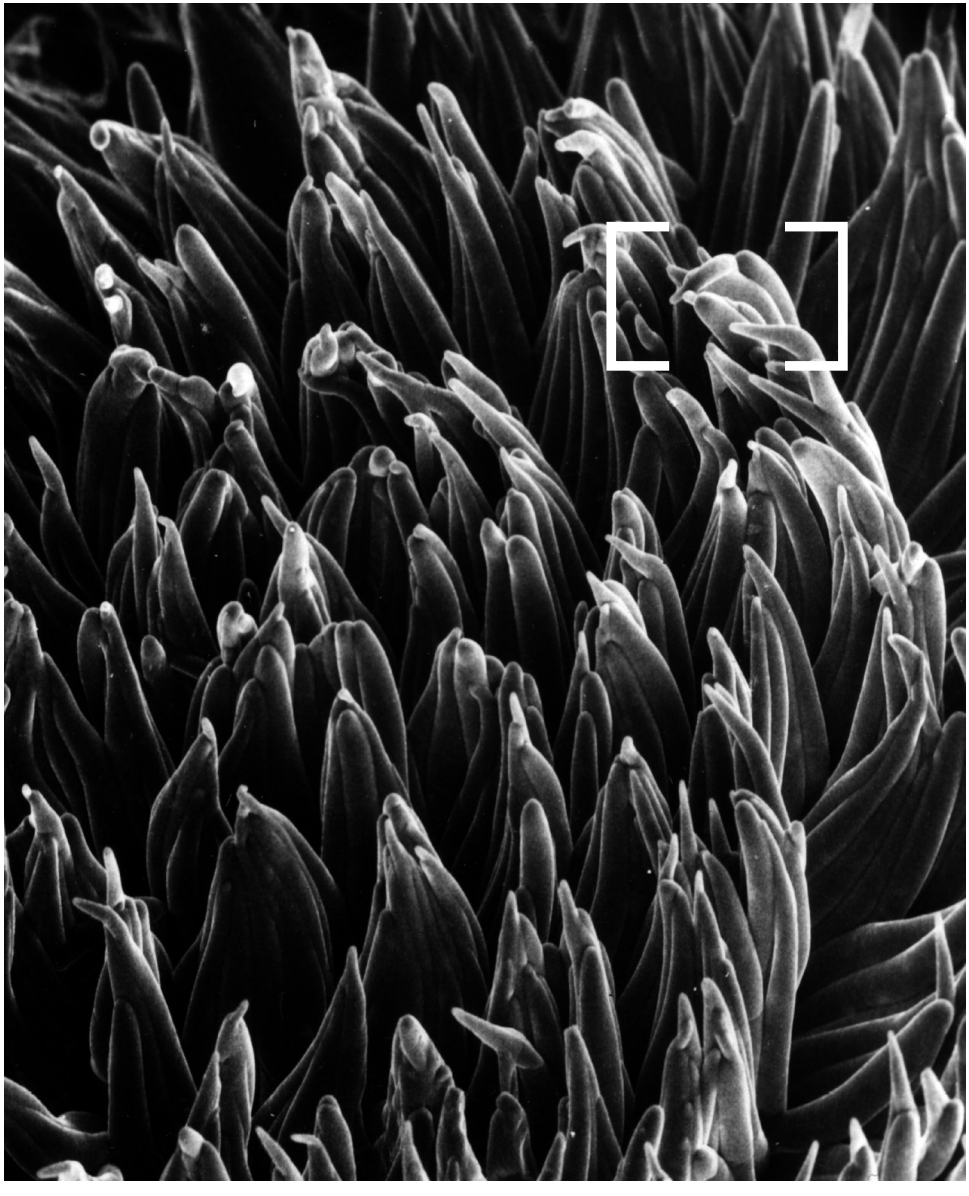


Figure 36. SEM images reveal that groups of fibers grow together. As fibers elongate they twist around each other forming clusters (brackets).
(J. McD. Stewart)

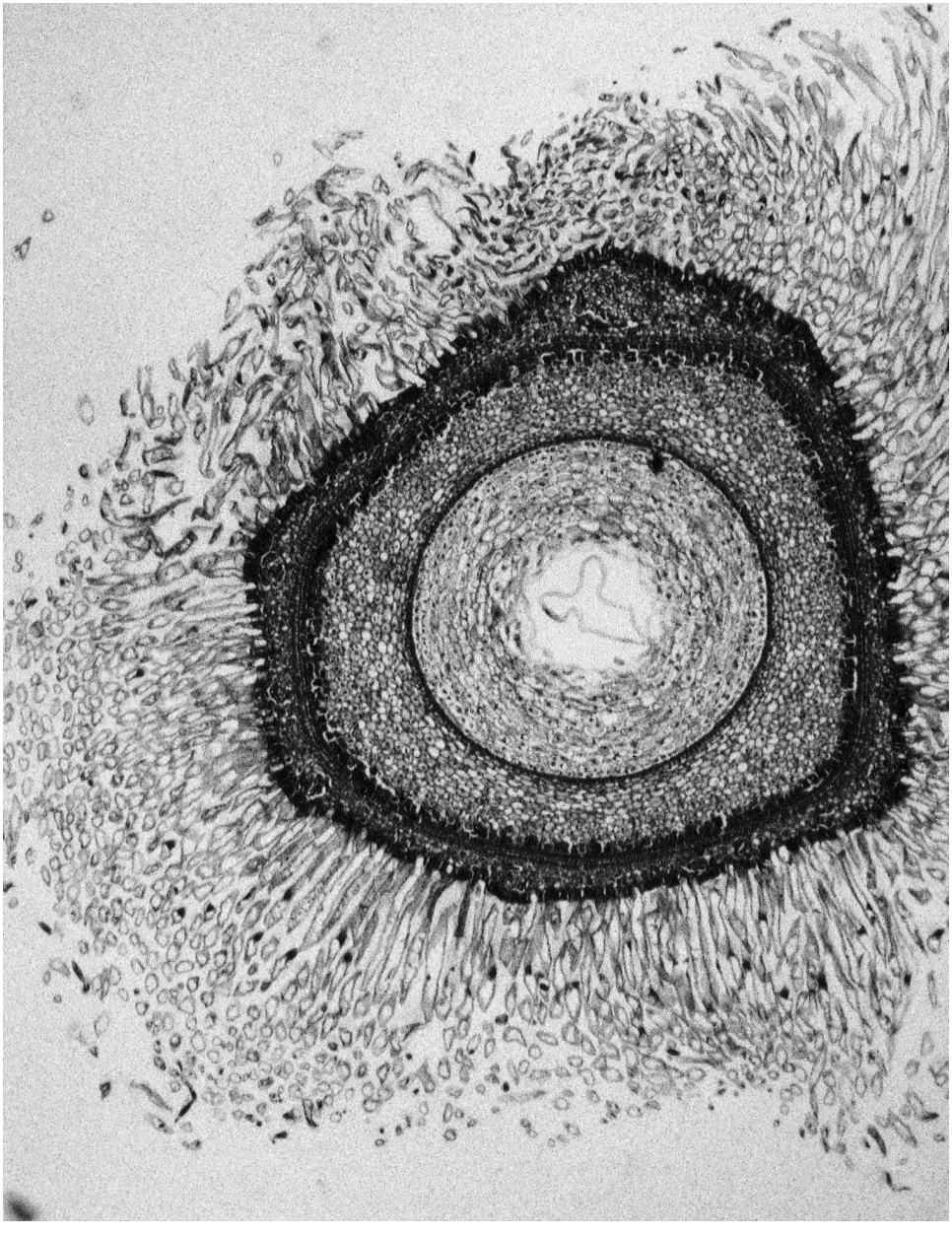


Figure 37. LM section through an ovule, showing array of fibers on the outside. (R.W. Seagull)

Fiber elongation occurs over a number of weeks. The most rapid rate of elongation occurs in the first three weeks after initiation (Figure 38). However, fibers continue to increase in length throughout most of their development. The extent of elongation and the exact rates of elongation vary among cotton genotypes and with environmental conditions. Accompanying changes in length are also changes in fiber diameter. Recent data indicate that fiber diameter continues to increase throughout the elongation phase (Figure 38). Thus the elongation phase includes not only increases in cell length, but also increases in cell diameter. Fiber diameter not only changes during development but also changes along the length of individual fibers. Lint fibers exhibit varying degrees of taper at their tip. Some fiber exhibit a relatively long tapered region (4 – 5 mm), while others have a short (> 1 mm) tapered region.

During the elongation phase the fiber produces a thin, flexible cell wall, capable of growing as the cell volume increases. This primary cell wall is similar in structure to the primary cell walls of most other expanding plant cells.

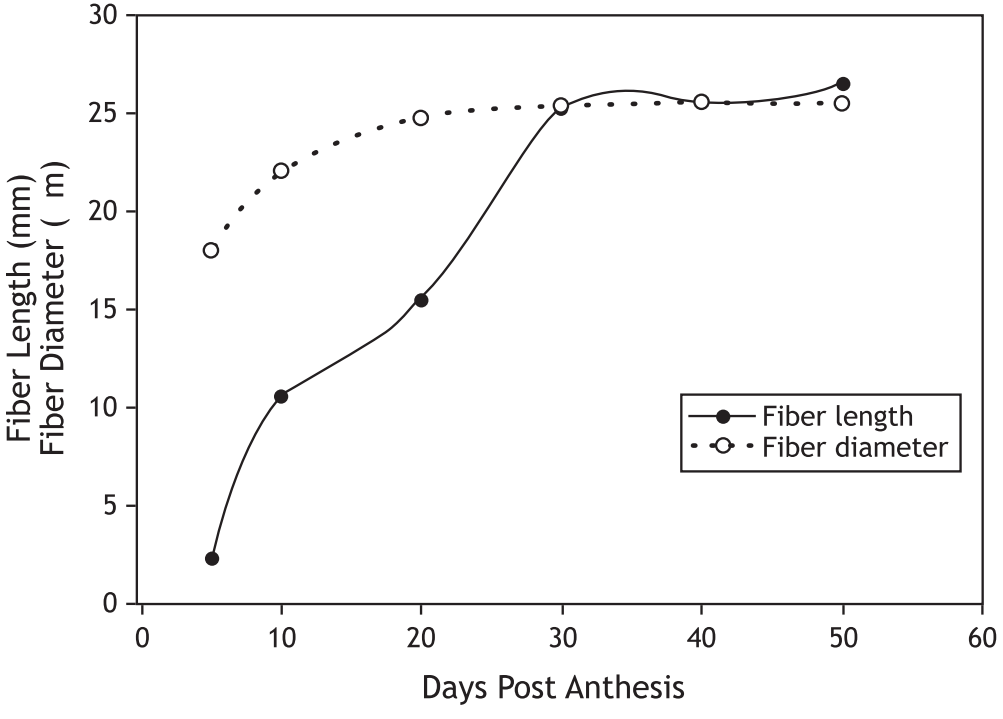
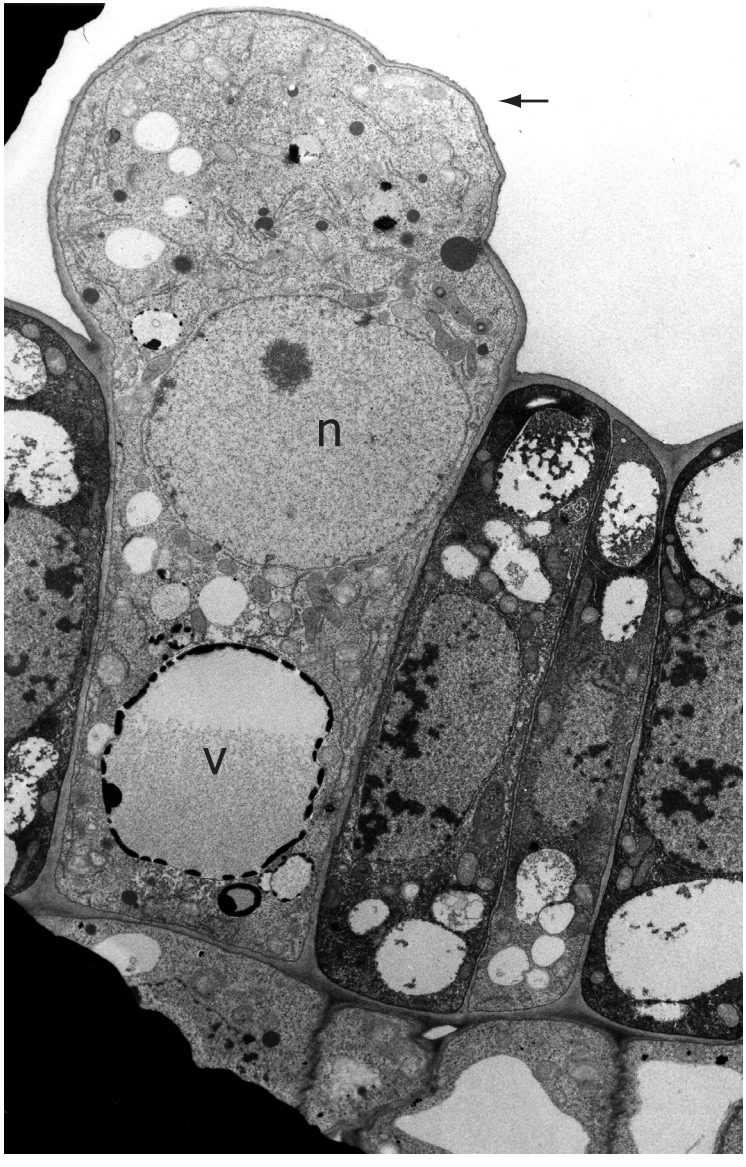


Figure 38. A graph of the changes in never dried fiber length and diameter during development of *G. hirsutum*, variety MD51Ne. Both length and diameter increase early in fiber development and exhibit a slowing rate of increase as the fiber enters into the secondary wall synthesis stage. Other varieties and species of cotton exhibit similar growth kinetics. (R.W. Seagull)

The wall is coated with a waxy cuticle and is composed of a gel-like matrix of polysaccharides in which are embedded relatively rigid cellulose microfibrils (Figure 39). The patterns of cellulose microfibrils in the wall control the direction of cell expansion and the ultimate morphology of the fiber.

Figure 39. Using transmission electron microscopy (TEM) one can observe the various components of the primary cell wall. During fiber elongation the outer surface of the primary wall is coated with a waxy cuticle (c). Throughout the thickness of the wall there are layers of cellulose microfibrils (m). (R.W. Seagull)



Within the cell is a collection of various cytoplasmic organelles (Figure 40). As the fiber grows, new components are inserted into the cell wall and membrane. Because this new material is deposited throughout the length of the fiber, this type of cell expansion is called diffuse growth.

Figure 40. Using TEM one can see that during fiber initiation and elongation the cell contains a densely packed cytoplasm that is responsible for the synthesis and distribution of the components required for fiber development. Most evident are the primary cell wall (arrow), the nucleus (n) and the vacuole (v). (J. Berlin)

SECONDARY WALL THICKENING

Accompanying the increases in fiber length and diameter are increases in cell wall thickness. Starting about 15 to 20 DPA (depending on genotype), the fiber begins the deposition of a thick, more rigid secondary cell wall. The secondary cell wall is composed almost exclusively of cellulose microfibrils. Deposition of the secondary cell wall results in a thickening of the wall and a gradual infilling of the cell lumen. The final cell wall can be up to 10 μm thick.

The transition from primary to secondary wall production is marked by the deposition of a thin layer of wall material called the winding layer. The winding layer is distinguished from both the primary and secondary wall layers by the microfibrils in this layer. The cellulose microfibrils in the winding layer are oriented in a steeply pitched helix, whereas the microfibrils in the primary wall are deposited in a shallow pitch helix (essentially oriented transversely to the long axis of the fiber). When compared to other secondary wall layers, the microfibrils of the winding layer are somewhat larger in diameter and are oriented with an opposite helical gyre.

The rest of the secondary cell wall is composed of successive layers of cellulose microfibrils, with each layer being deposited with a steeper helical gyre than the previous layer. The result is a wall with a poly-lamellate construction (Figure 41). See also Figure 50 for a cross section.

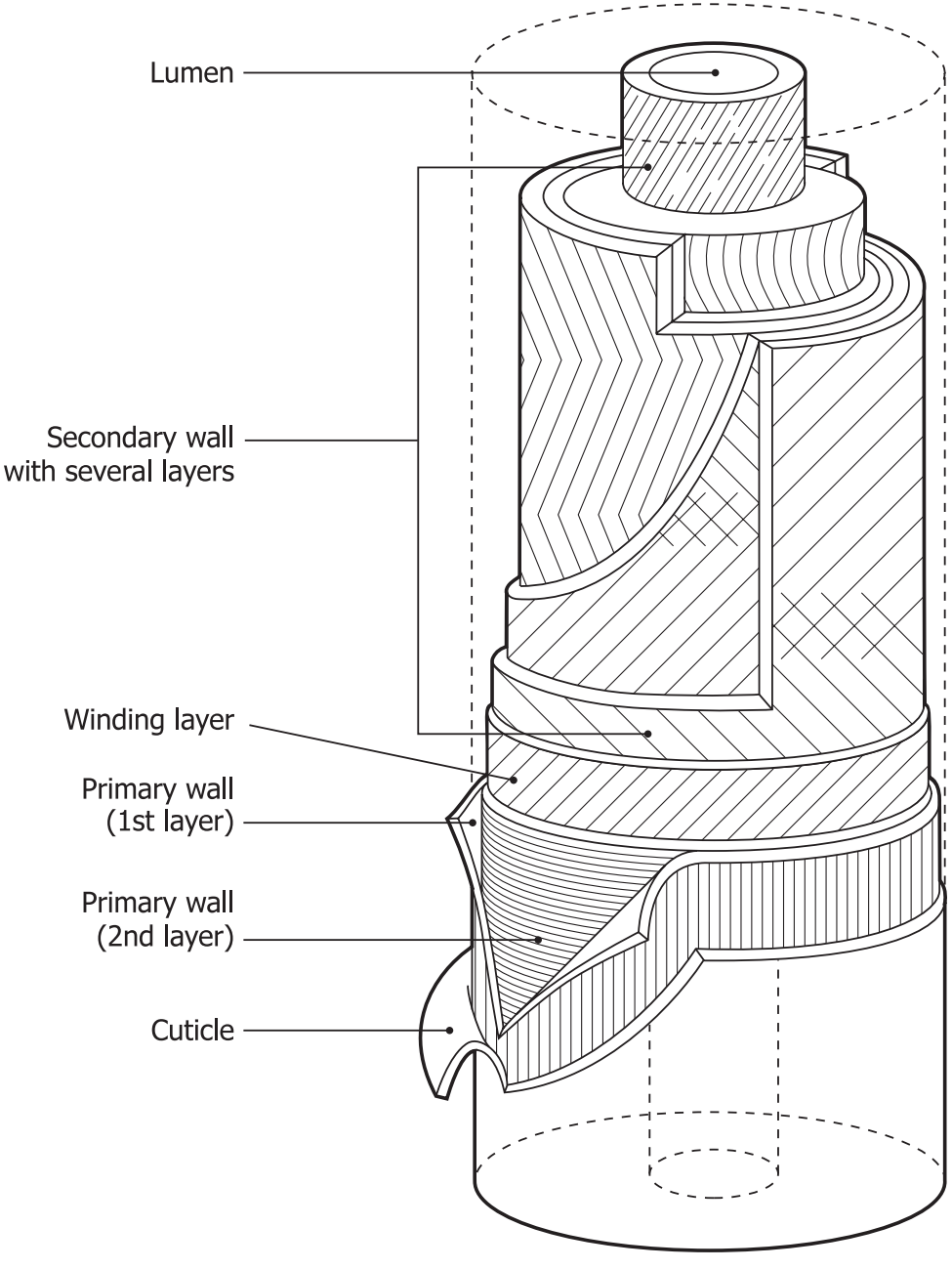


Figure 41. During secondary wall synthesis a multi-layered wall is deposited between the living cytoplasm (ultimately the lumen) and the primary cell wall, resulting in a poly-lamellate structure with microfibrils in each layer exhibiting different orientations. (K. Charlton)

Daily cycling of temperatures (from warm days to cool nights) during secondary wall synthesis can also generate layering in the fiber wall. Swelling of the mature fiber wall in caustic soda reveals a ring-like pattern (Figure 42) that is produced by the temperature dependent changes in cell wall synthesis. These layers are not detected unless the wall is swollen.

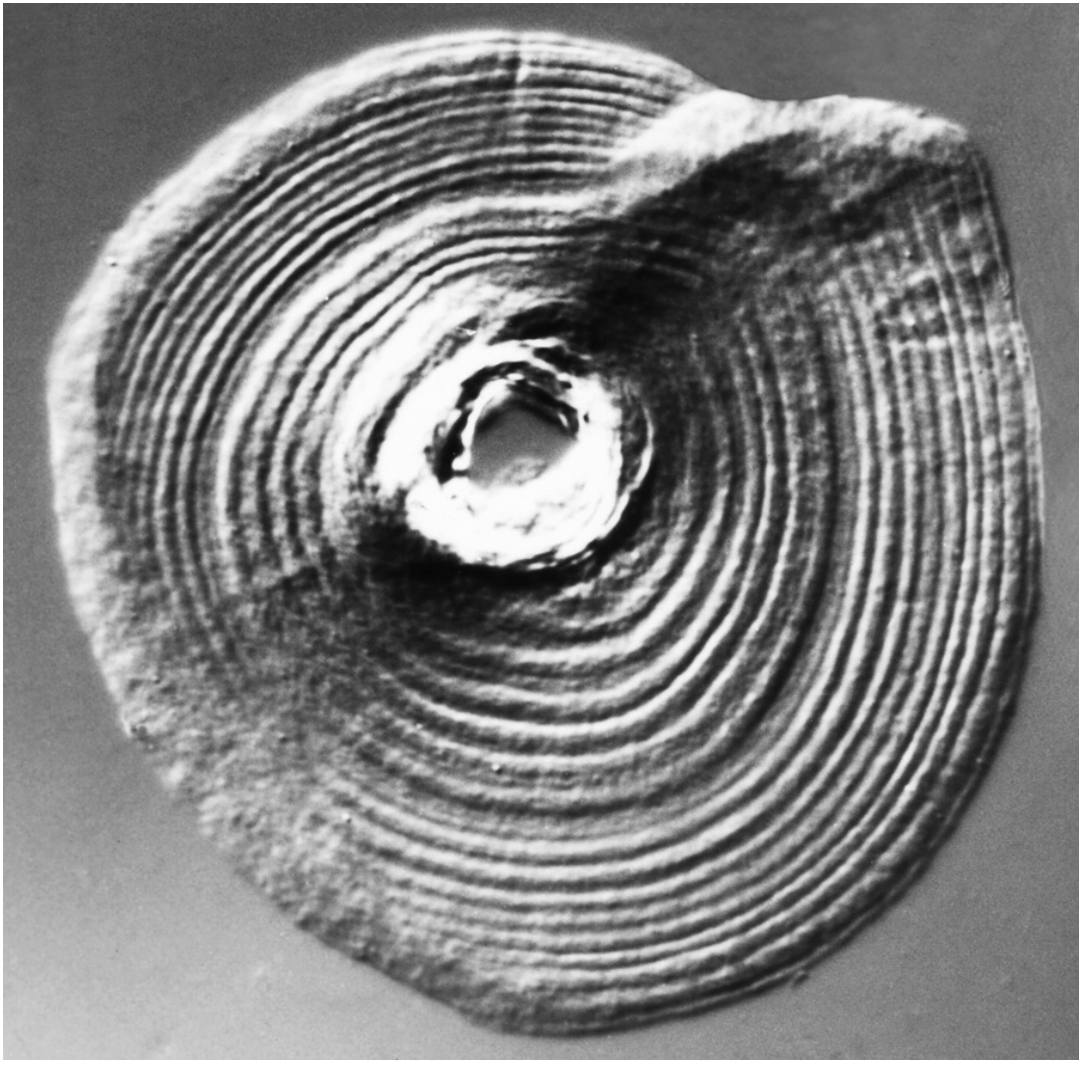


Figure 42. Secondary wall synthesis is affected by temperature; thus, daily fluctuations in temperature produce a ring-like appearance in the wall that can be viewed using DIC (light microscopy) when the wall is swollen. (C.H. Haigler)

Unique to cotton fibers is the production of reversals in the secondary cell wall. Reversals are regions in the wall where the helical gyre of the secondary wall microfibrils reverses direction (Figure 41, 43). All fibers have reversals but their frequency along the length of the fiber varies with genotype and developmental stage.

During secondary wall synthesis, the fiber cell is very metabolically active. The cytoplasm is responsible for providing the machinery needed for wall synthesis and contains many components, typical of an active, living cell (Figure 44).

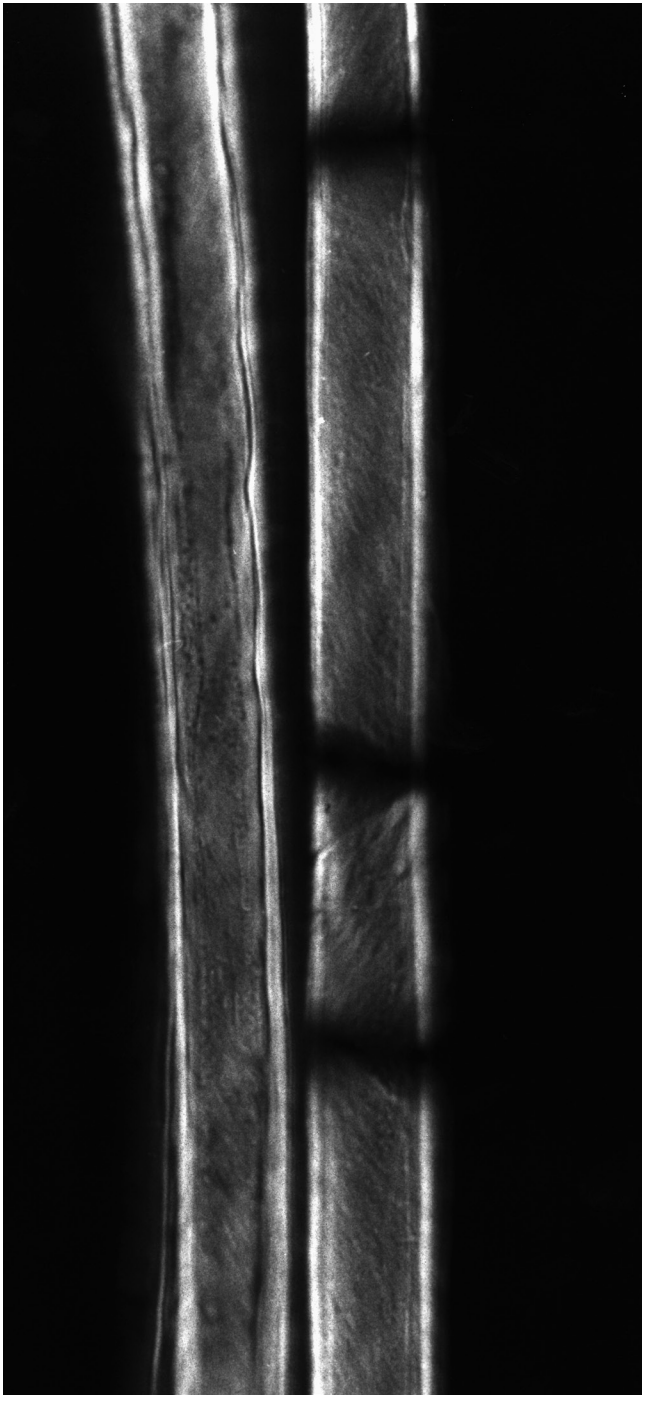


Figure 43. During secondary wall synthesis cellulose microfibrils are laid down in a helical pattern. Reversals are regions in the fiber where the helically oriented cellulose microfibrils reverse their gyre. Reversals are most easily observed using polarized light microscopy. The wall appears bright, with reversals appearing as dark bands. The distance between reversals and their frequency along the fiber varies with developmental stage, genotype and environment. (P. Gould)

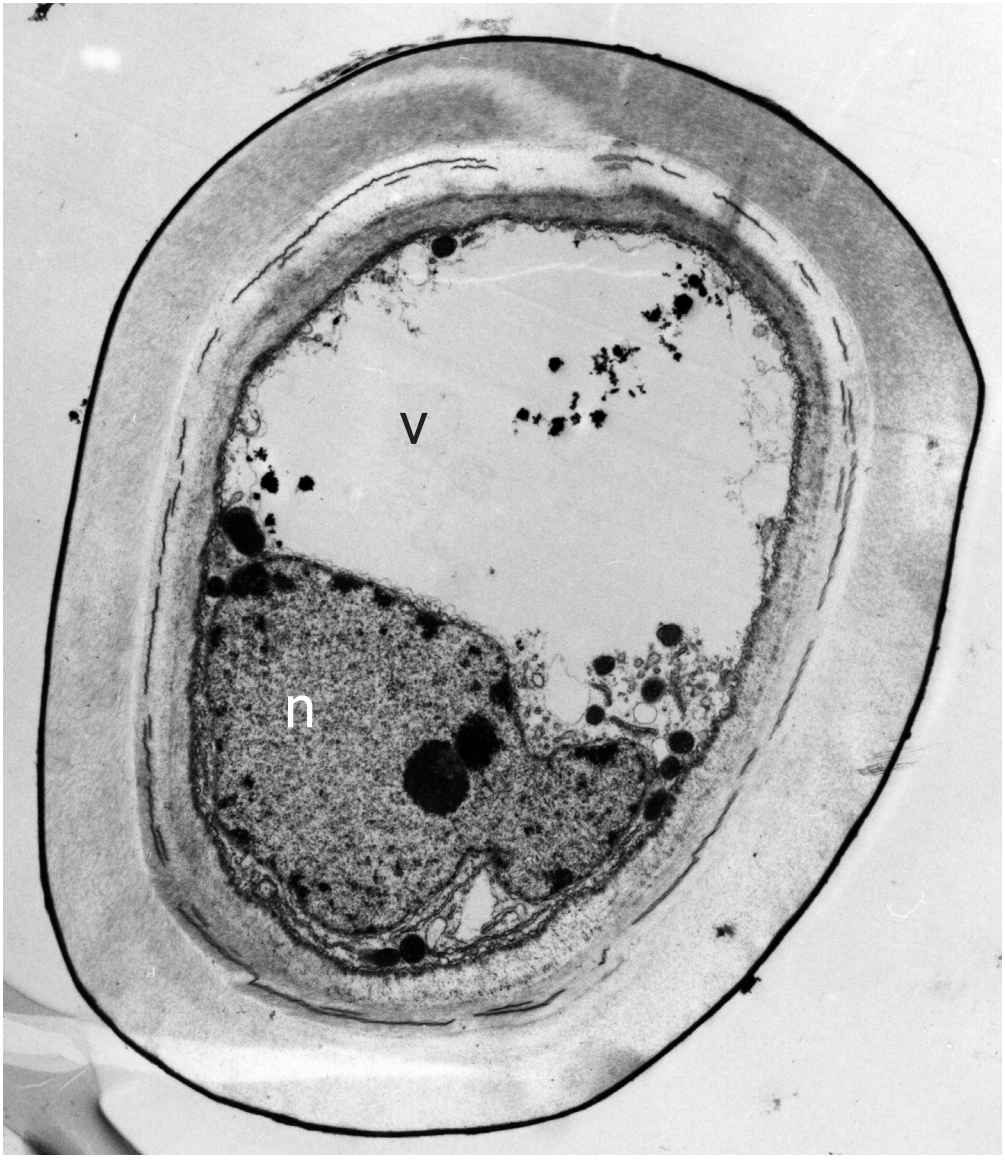
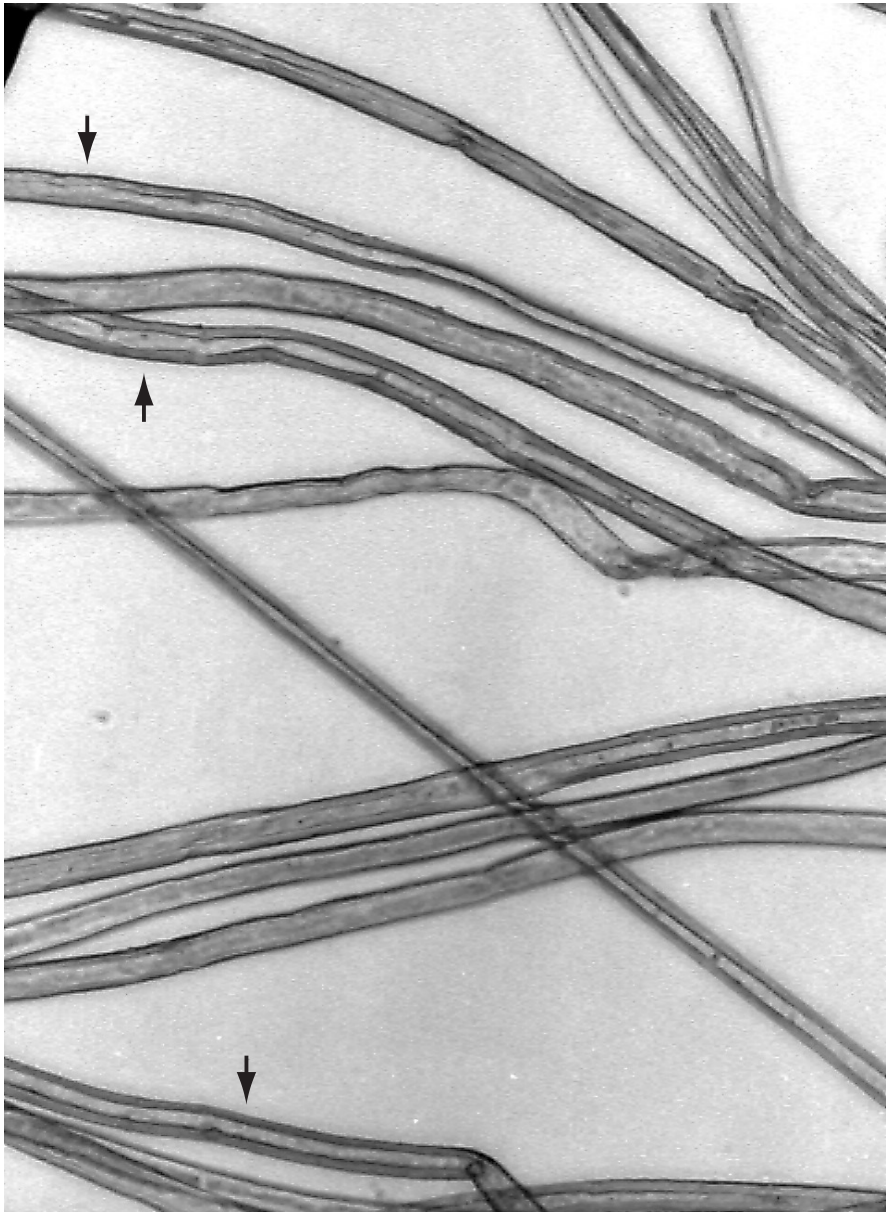


Figure 44. The fiber cell remains metabolically active during secondary wall synthesis and contains a similar complement of organelles as seen during primary wall synthesis. Using TEM, an assortment of cytoplasmic structures are observed, including the nucleus (n) and central vacuole (v).
(J. Berlin from C.H. Haigler)



FIBER MATURATION

The mature fiber, before it dries, appears as a long cylinder (Figure 45). The normally cylindrical fibers collapse, producing a flattened, twisted ribbon structure (Figure 46).

Figure 45. LM view of mature fibers from a closed boll (i.e., never dried fibers). These fibers exhibit a cylindrical morphology and thick cell walls (arrows). (R.W. Seagull)

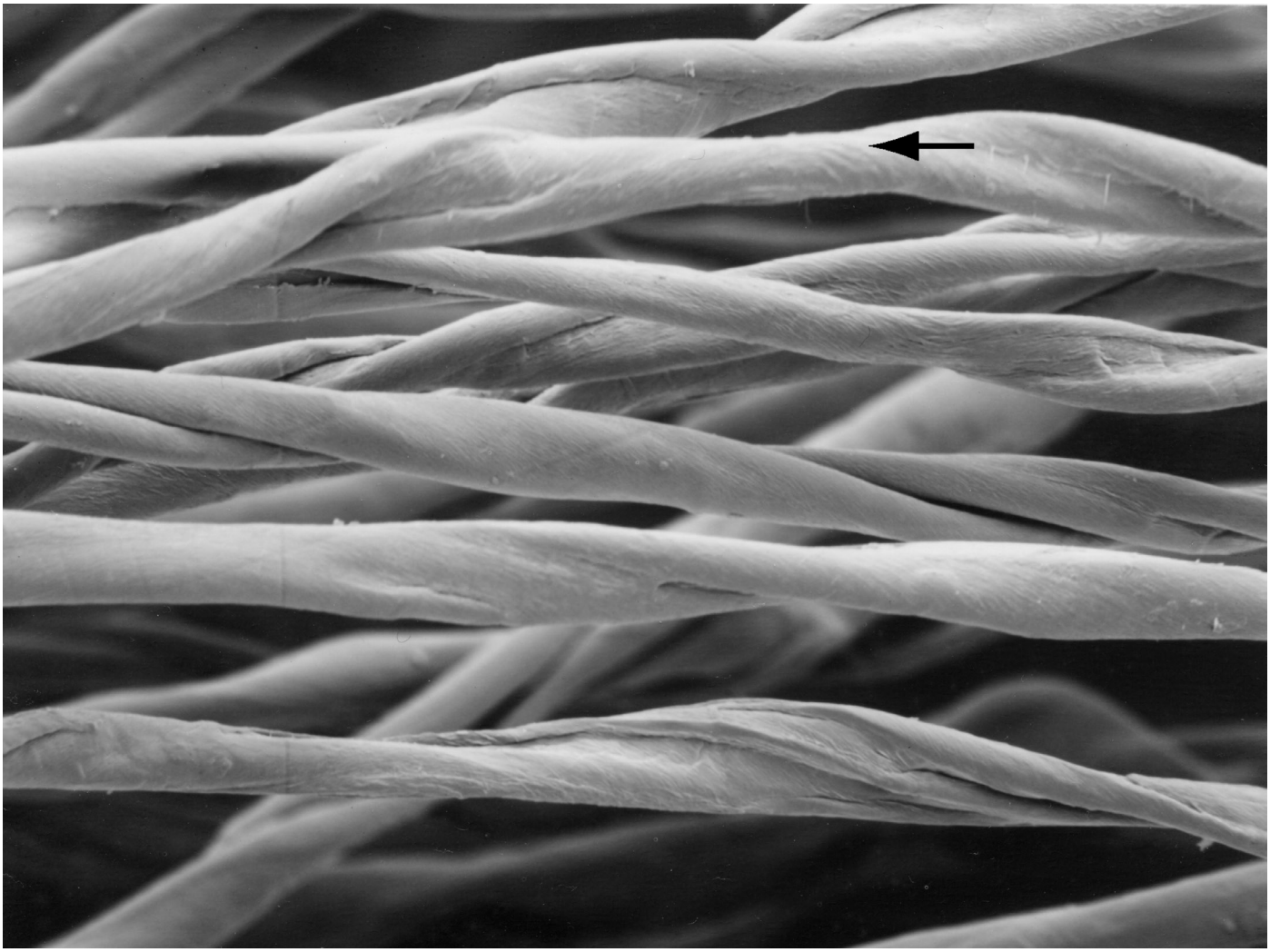


Figure 46. When mature fibers dry they twist and flatten slightly. Using SEM, the convolutions of the fiber are easily observed. Reversal patterns in the secondary wall are observed as impressions (arrow) in the thin primary wall. (Y.L. Hsieh)

If the fiber does not produce a thick secondary wall, the fiber is said to be immature. When such fibers are dried, they form thin, flattened ribbons with minimal twisting (Figure 47).

Figure 47. If fibers die before sufficient secondary wall is made, then fibers form flat ribbons. When viewed using SEM these immature fibers lack convolutions and exhibit abrupt bends and flat twists. (Y.L. Hsieh)

Because of the extreme length of the fiber it is impossible to photograph the entire fiber at a magnification that is suitable to see detailed ultrastructural elements. Low magnification views exhibit overall fiber structure whereas high magnification allows for the detailed analysis of fiber wall structure. When mature fibers dry, they bend and twist together to form an entangled, three-dimensional network (Figure 48). This natural twisting and entangling facilitates the spinning of fibers into yarn.

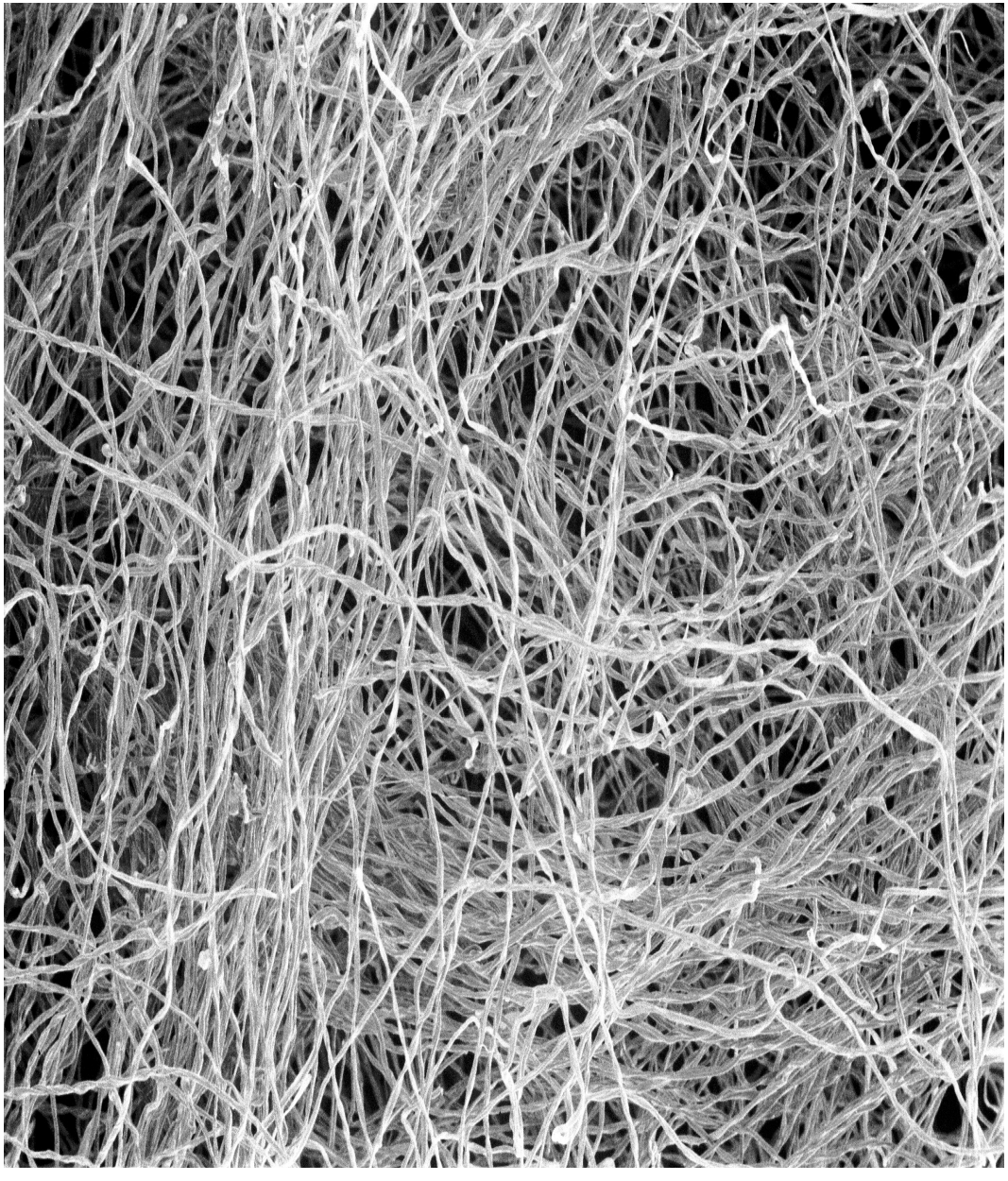
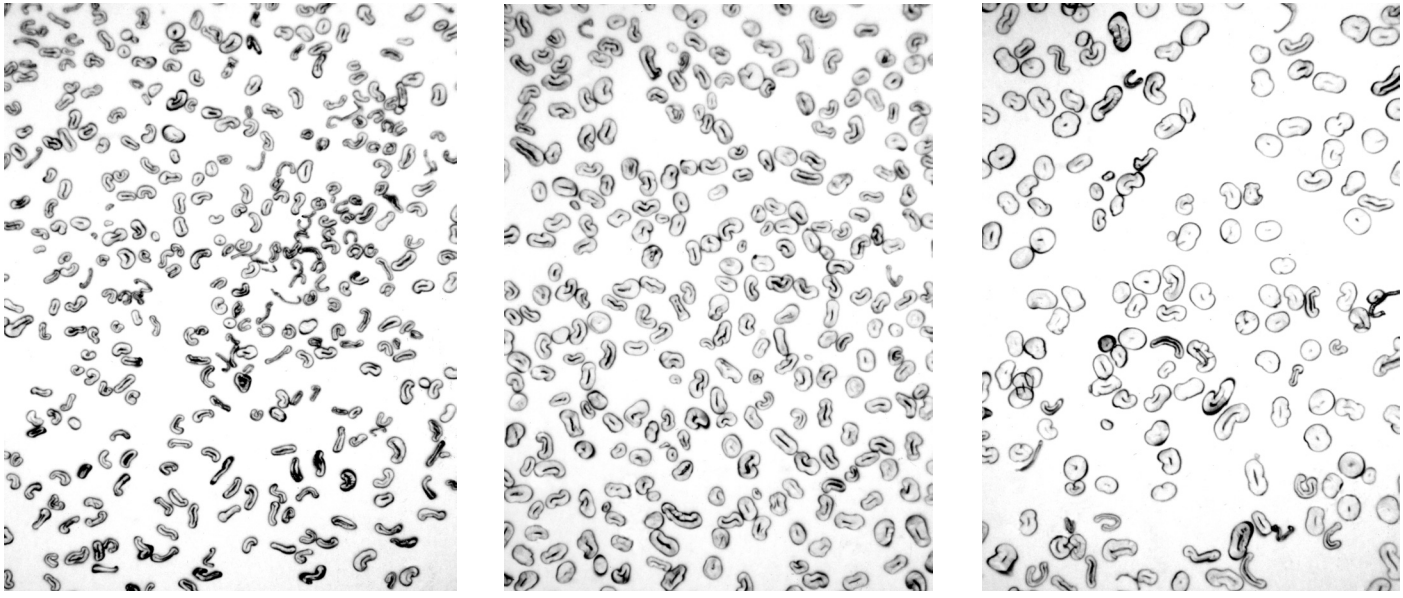


Figure 48. When viewed with LM, populations of dried fibers naturally exhibit twists and convolutions that facilitate the formation of yarns and fabrics. (M.J. Grimson)

Yarn and fabric quality is partially determined by the mechanical and physical properties of the fiber secondary cell wall. There is a direct correlation between the measurement of micronaire and wall thickness at maturity (Figure 49).



A. 3.1 micronaire **B. 4.6 micronaire** **C. 6.5 micronaire**

Figure 49. As fibers mature, the secondary walls thicken, thus increasing micronaire. Mature fibers can exhibit a range of micronaire values, depending on wall thickness. Panels A, B and C exhibit increasing micronaire values from 3.1 to 4.6 to 6.5, respectively. Note that fibers with thinner walls [panel A] have lower micronaire values. (E. Boyleston)

Because fibers begin development at different times (see section on initiation), on a mature seed there may be fibers with differing levels of maturity. If a population of fibers is examined for wall thickness, one often observes fibers with differing degrees of wall thickness (Figure 50).

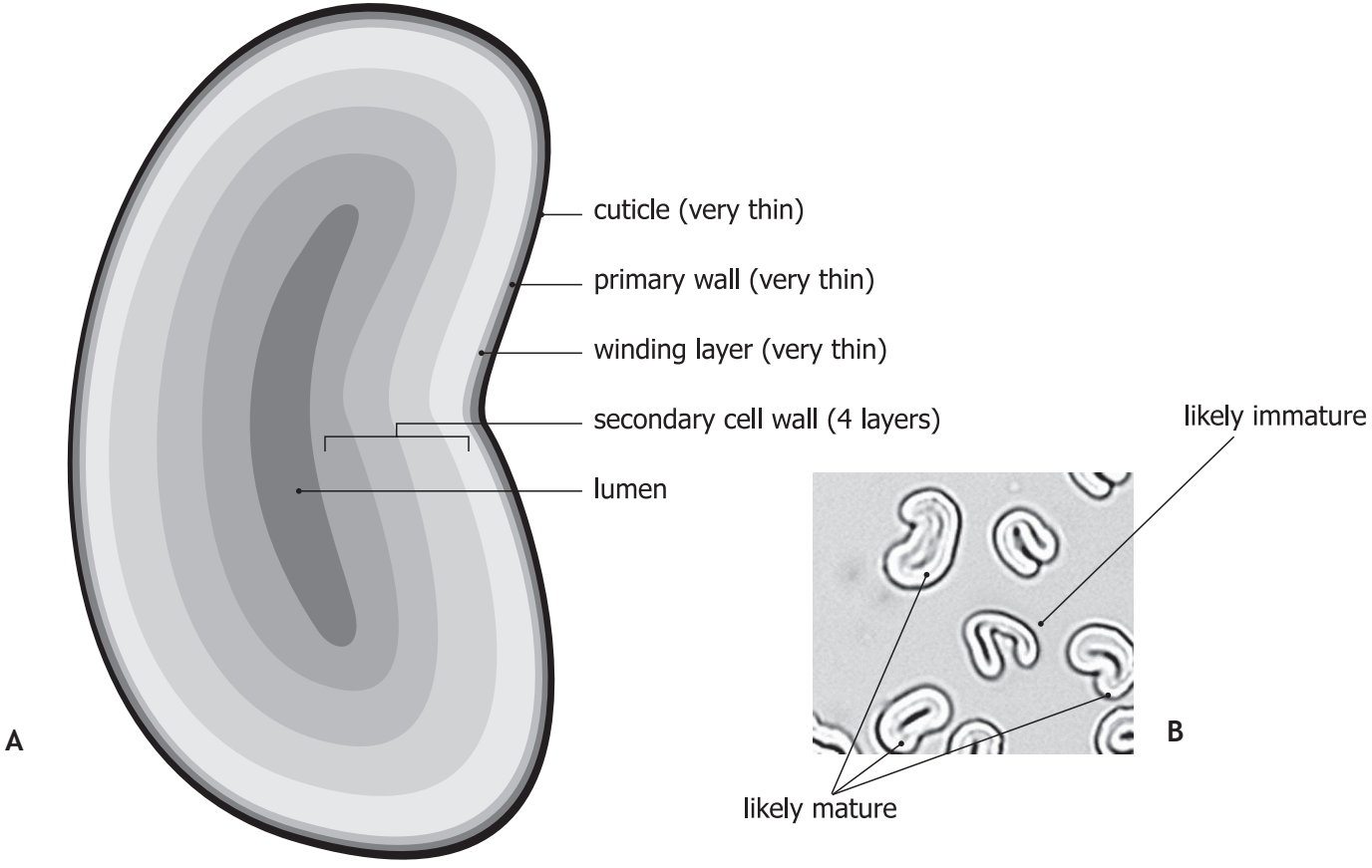


Figure 50. Within a population of fibers there is a natural variability in wall thickness (i.e., fiber maturity). This is easily observed when fiber cross sections are examined with light microscopy (B). Each fiber is composed of the multi-layered cell wall (A). (K. Charlton)

The mature dried cotton fiber represents the culmination of many biological processes. Reproductive branch development, flower production, ovule fertilization, embryo growth and epidermal cell differentiation all occur in specific sequence to produce fibers. The growth patterns of seed epidermal cells determine the quantity of fiber and the length characteristics. Wall development is the final biological process in the life of the fiber. Composition, organization and amount of wall material define fiber strength. Combined, these biological parameters determine the physical properties of cotton textile.

COTTON PROCESSING: HARVESTING

ALAN BRASHEARS, Ph.D.

Cotton processing begins at harvest. This section describes the two mechanical harvesting methods and how they differ and the effects of those differences.

Once the cotton bolls have matured, they are mechanically removed from the plant by either of two harvest methods: cotton strippers or cotton pickers. A cotton harvester is self-propelled with special heads that harvest the cotton and a basket to hold the seed cotton. In some parts of the world, cotton is still harvested by hand.

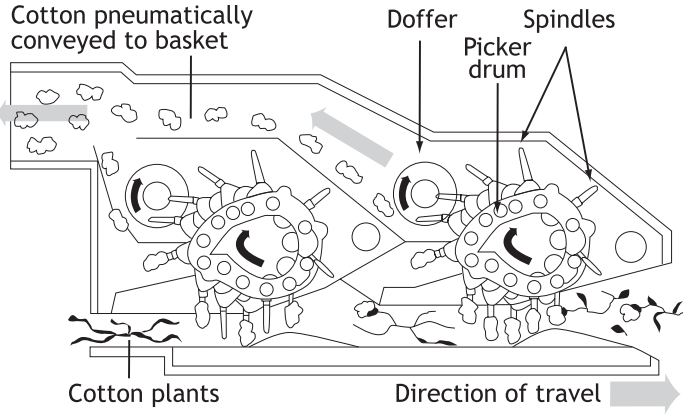
Pickers (Figure 51) remove only the seed cotton from the boll, leaving the burrs (dried locules) and the plant intact in the field. Cotton pickers utilize a series of spindles stacked on a spindle bar in the picker drum. The spindles, which rotate, are round, tapered and fluted with barbs. The entire spindle bar is rotating as it enters the row of cotton plants. As the rotating spindles come in contact with the seed cotton on the plant, the cotton is pulled out of the burr (locule). The bar continues to rotate and comes into contact with a spinning doffer that wipes the cotton off the spindle and into a pneumatic conveying system that moves it to the basket.

Strippers (Figure 52) are used in areas with storm proof cotton varieties (these varieties minimize field losses from weather). The seed cotton is held in the boll until the plant is killed by cold weather or chemical harvest aids. The cotton stripper removes the complete boll from the plant utilizing two counter-rotating stripper rolls consisting of nylon brushes and rubber bats. This method of harvest will result in a higher trash content of harvested seed cotton. Some strippers have field cleaners that can separate the burrs and sticks from the seed cotton that goes into the basket, leaving the trash in the field.

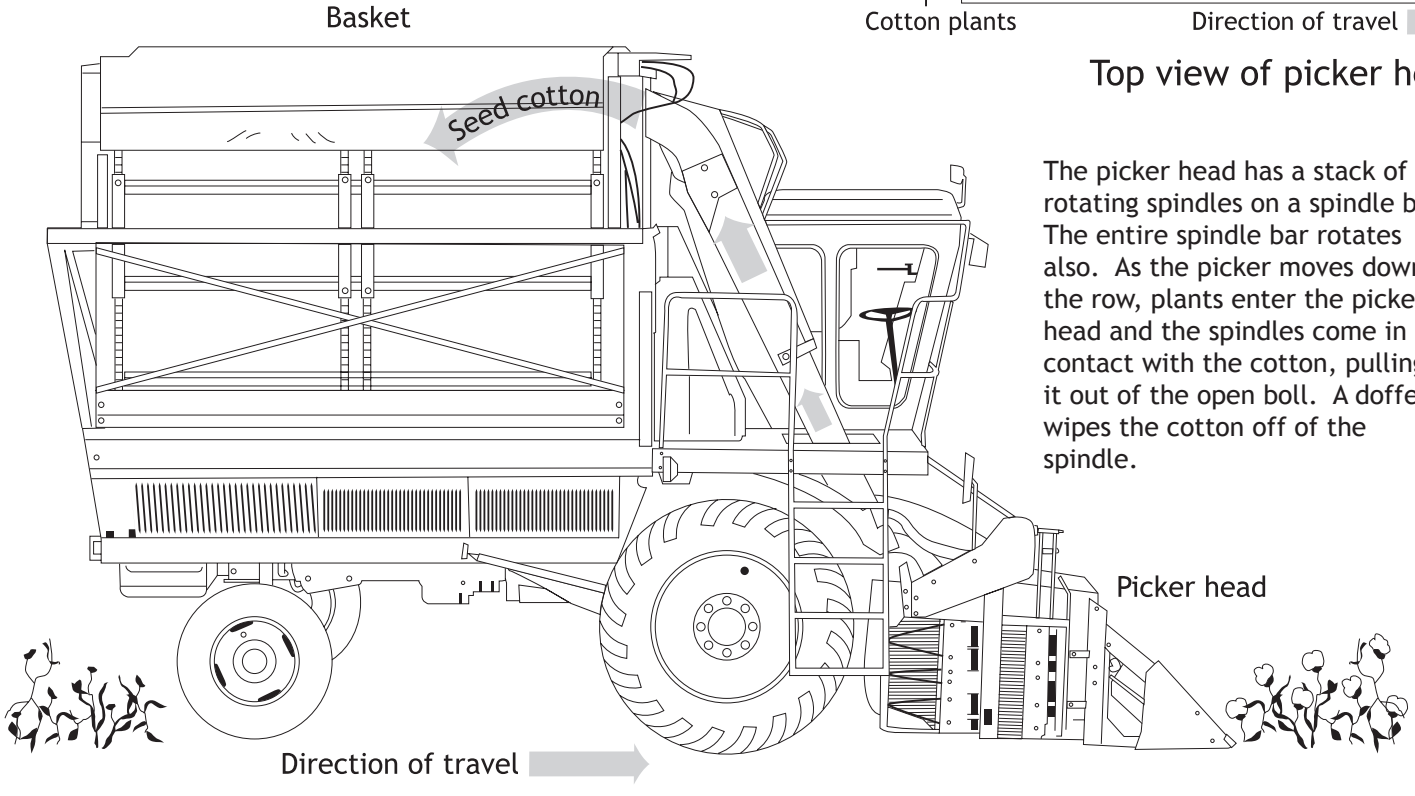
The harvester basket full of seed cotton is then dumped into a module builder. The module builder (Figure 53) can pack the cotton into an eight to twelve bale module. The module of cotton is left in the field to be picked up by a module truck and taken to the yard of the gin to wait for ginning.

Cotton Picker

Figure 51. Mechanical cotton picker. It removes only the seed cotton from the open boll, leaving plants in the field. The cotton picker moves down the rows of cotton plants, picking the cotton from the bolls. The cotton is conveyed to the cotton basket.
(T. Lee, K. Charlton)



Top view of picker head



The picker head has a stack of rotating spindles on a spindle bar. The entire spindle bar rotates also. As the picker moves down the row, plants enter the picker head and the spindles come in contact with the cotton, pulling it out of the open boll. A doffer wipes the cotton off of the spindle.

Cotton Stripper

The stripper head consists of two counter-rotating rolls with long brushes and rubber batts spaced close together and slanted towards the ground. As the stripper moves, plants enter the head and the whole boll is snapped off of the dried plant by the bats. The boll is conveyed up to the basket by augers and pneumatic conveyors.

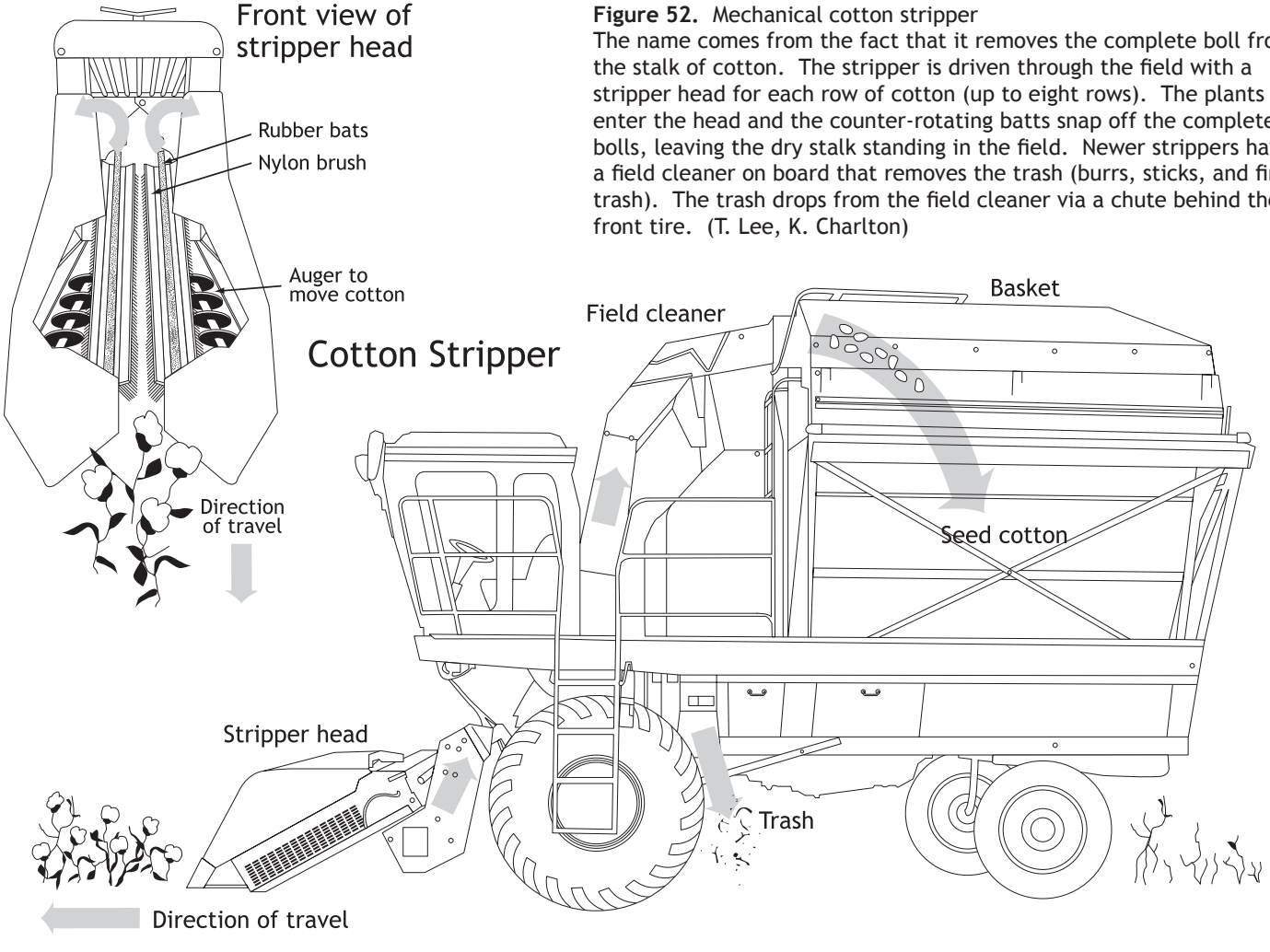


Figure 52. Mechanical cotton stripper
The name comes from the fact that it removes the complete boll from the stalk of cotton. The stripper is driven through the field with a stripper head for each row of cotton (up to eight rows). The plants enter the head and the counter-rotating batts snap off the complete bolls, leaving the dry stalk standing in the field. Newer strippers have a field cleaner on board that removes the trash (burrs, sticks, and fine trash). The trash drops from the field cleaner via a chute behind the front tire. (T. Lee, K. Charlton)

Cotton Module Builder

The harvester basket full of seed cotton is dumped into a module builder. A module builder is a metal box with no top or bottom and a moveable tramper that packs the cotton into an eight to twelve bale module, much like a trash compactor. When finished, the rear door opens, the builder is lifted by hydraulics and pulled away from the module by a tractor to another location where the next module can be compacted. The module of cotton usually has a tarp pulled over the top. It is left in the field to be picked up by a module truck and taken to the gin. The development of the module builder as a replacement for cotton trailers helped eliminate storage and handling problems between the field and the gin.

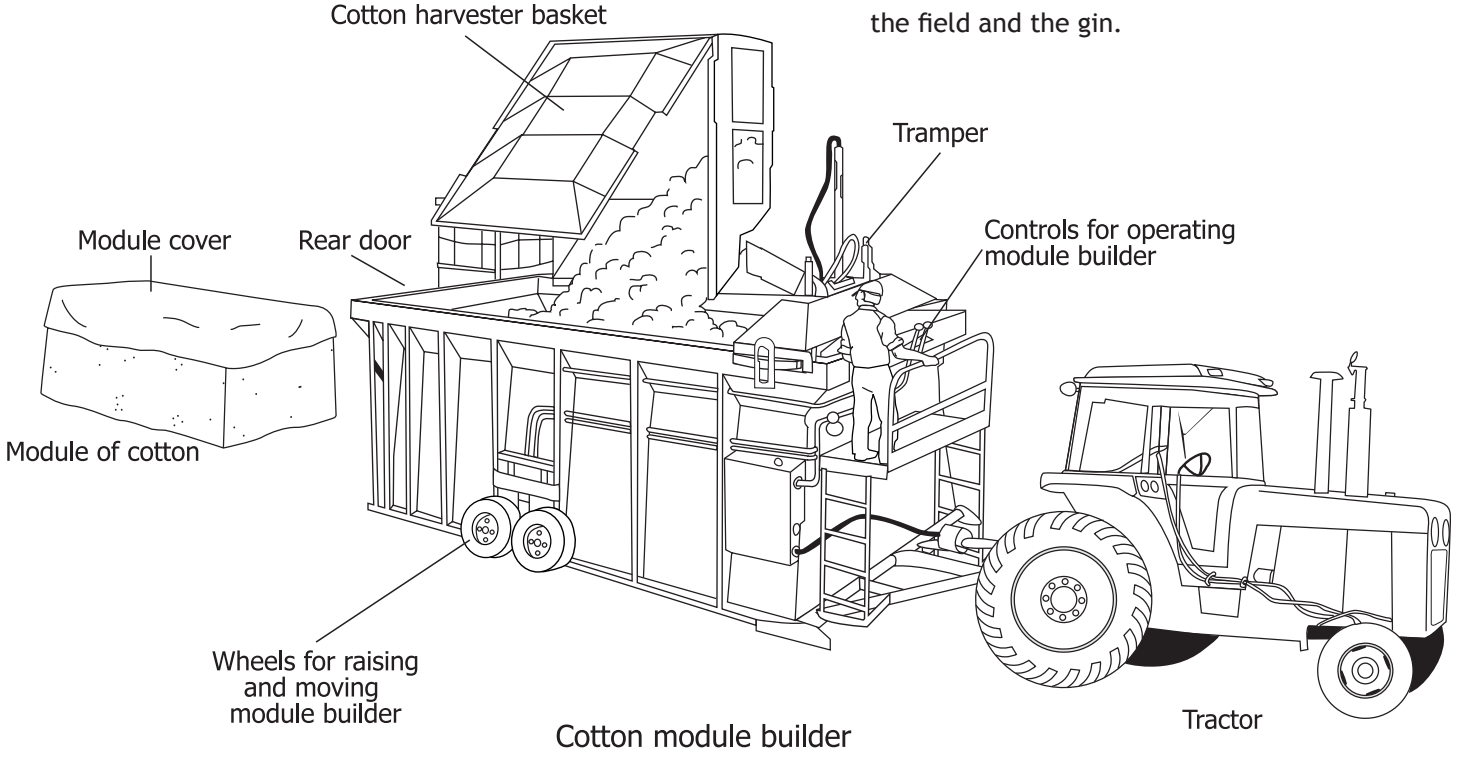


Figure 53. Module builder receiving a load of cotton from a harvester. When the module is completed, the builder is pulled away to the next site and filled again. A module truck from the gin will pick up the modules in the field. (L. Lalor)

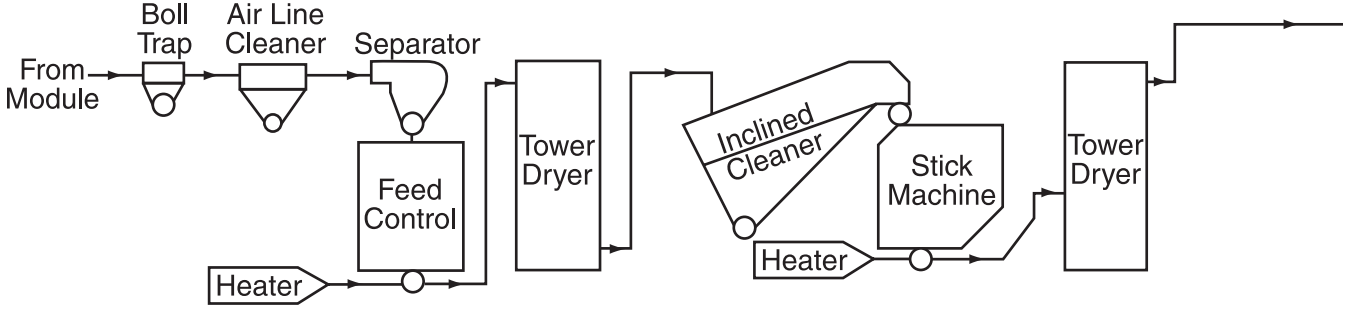
GINNING

ROY V. BAKER

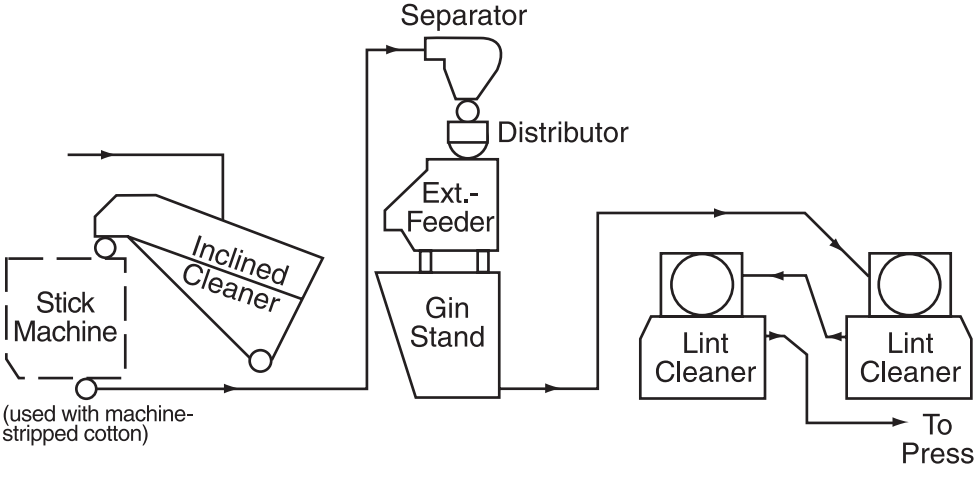
Harvested cotton is called seed cotton because the fibers are still attached to the seed. The ginning process removes the seeds and cleans the fiber. Clean cotton is important because a bit of trash incorporated into a spun yarn can cause the yarn to break. When the bale of fiber comes out of the bale press, a sample is taken for cotton classing (fiber evaluation).

The principal function of a cotton gin is to convert the farmers' harvested seed cotton into salable commodities, i.e., fiber and seed. Thus, ginning is the bridge between cotton production and cotton textile manufacturing. To satisfactorily convert today's mechanically harvested cotton into salable commodities, gins have to dry and clean the seed cotton, separate the fibers from the seed, further clean the fibers and place the fibers into an acceptable package for commerce. Cottonseed are sold to dairies for feed, to oil mills for production of many valuable products, or saved for planting next year's crop. The fibers are the more valuable product, however, and the design and operation of cotton gins are oriented toward fiber production. In essence, the modern cotton gin (Figure 54) enhances the value of the cotton by separating the fibers from the seed and by removing objectionable non-fiber matter, while preserving as nearly as possible the inherent qualities of the fiber.

Figure 54. Recommended gin machinery for machine-stripped and machine-picked cotton



The module of cotton is opened and cotton is moved with an air stream into the gin, first passing through a boll trap that removes green (unopened) bolls and rocks. The airline cleaner takes out fine trash and sand (for stripper harvested cotton). The separator removes the cotton from the air stream, dropping it into the feed control, which regulates the flow of cotton into the ginning stream. The tower dryers dry the cotton, if it is wet or harvested before the plant was completely dry. The inclined cleaners (or cylinder cleaners) are a type of cleaner that removes fine trash. The CBS (combination burr and stick) machine in a stripper cotton gin removes sticks and burrs. In a picker cotton gin, a stick machine, at this location, removes sticks and green leaf. The cotton then goes through a second dryer, another inclined cleaner, and a second stick machine (in a stripper gin). Another separator takes cotton out of the conveying air stream and drops it into a conveyor distributor. The distributor delivers cotton to each of several extractor-feeders, which feed the gin stands uniformly and at a controlled rate. The gin stand is the heart of the ginning process where the fibers are removed from the seed (Figure 55). Most gins are equipped with two lint cleaners that remove small trash that remains in the lint after ginning. These cleaners are equipped with bypasses to regulate the amount of cleaning required. The fiber then goes into a gin press where it is compressed into a 480-pound bale suitable for commerce.



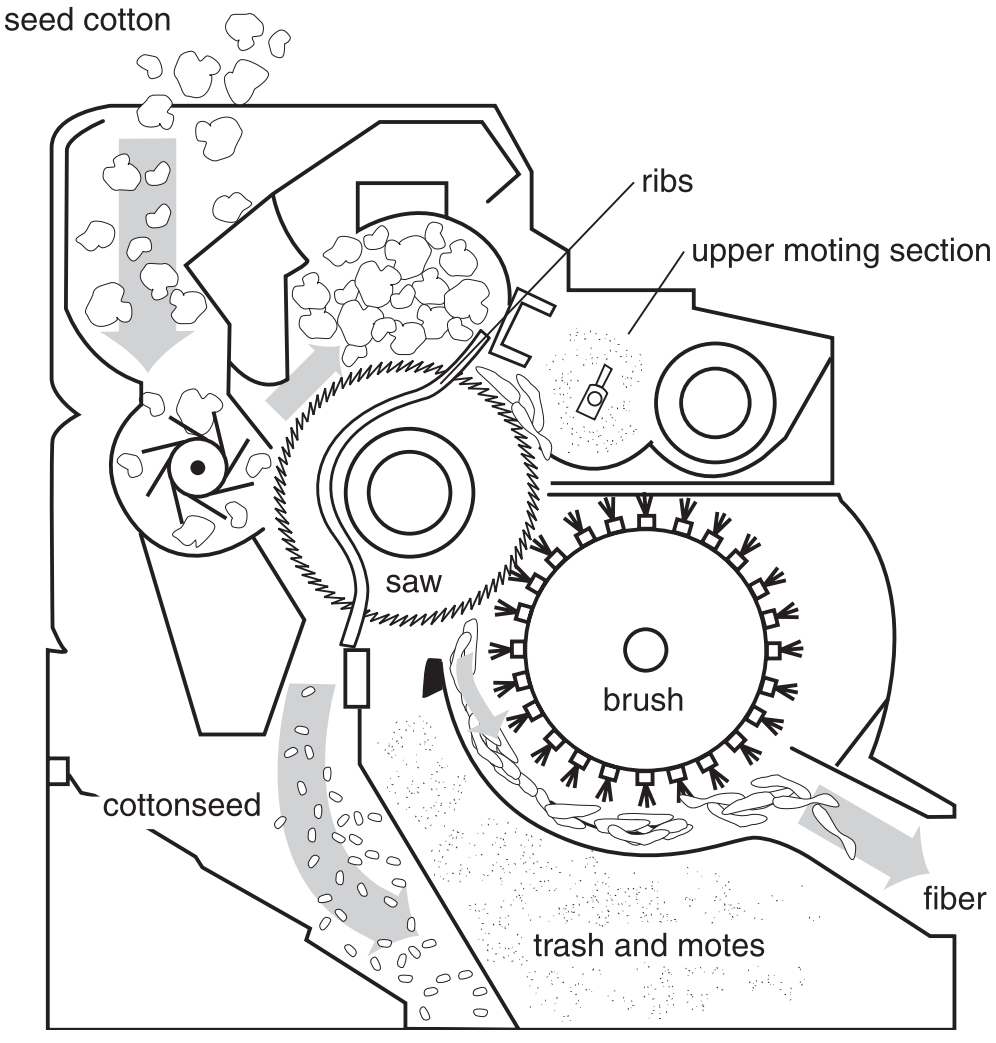


Figure 55. Gin stand cross section. A series of ribs are closely spaced (less than the size of the seed) with a saw blade between each rib. The seed cotton falls down on the turning saws and the fiber is pulled between the ribs by the saw teeth, doffed off by a brush, and carried away by an air stream. The seed, which cannot pass between the saw and the ribs, fall down another chute, and are conveyed away.

FIBER EVALUATION

The following section draws heavily from
The Classification of Cotton
USDA, Agricultural Marketing Service,
Cotton Division, Agricultural Handbook 566,

by Mike Watson, Cotton Incorporated

Every bale of cotton produced in the U.S. is uniquely identified by a Permanent Bale Identification (PBI) tag, since each bale has unique fiber properties. These fiber properties are determined through a combination of instrument evaluations using High Volume Instrument (HVI) technology and grading by a skilled cotton classer. The information gathered on each bale is utilized in marketing that bale and is also used by textile mills when they process that bale. This section describes the cotton fiber properties that are tested and how they are evaluated at a U.S. cotton classing office.

A. INSTRUMENT DETERMINATIONS

Measurements for the following quality factors are performed by high-volume, precision instruments, commonly referred to as "HVI" classification.

STAPLE LENGTH

The staple length of cotton fiber is a critical quality attribute since the length affects yarn strength and evenness as well as the efficiency of the spinning process. Traditionally, the staple length was estimated by the 'hand stapling' process performed by a cotton classer. Now, determination of the cotton staple length is one of the critical functions of the High Volume Instrument system. The staple length is calculated from the length fibrogram sensed by the HVI. The fibrogram is an arrangement of fibers from the shortest to the longest in terms of span lengths (the distances fibers extend from a random catching point) (Table 1).

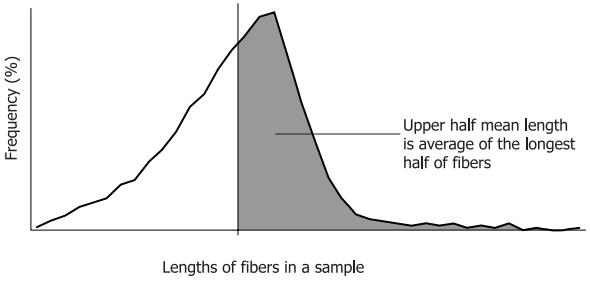


Table 1. Histogram illustrating fiber length distribution

Staple length is reported as the average length of the longer one-half of the fibers (normally called "upper-half-mean" length).

Fiber length is measured by clamping a sample of fibers, then combing and brushing to straighten and parallel those fibers. The resulting

"beard" of fibers is then passed through a sensing point in the HVI length instrument. Fiber length is reported in 100ths of an inch, which is often converted to 32's of an inch, the measurement unit used in traditional hand stapling (Table 2).

Upland Fiber Length Conversion Chart	
Inches	**32nds**
0.79 & shorter	24
0.80 - 0.85	26
0.86 - 0.89	28
0.90 - 0.92	29
0.93 - 0.95	30
0.96 - 0.98	31
0.99 - 1.01	32
1.02 - 1.04	33
1.05 - 1.07	34
1.08 - 1.10	35
1.11 - 1.13	36
1.14 - 1.17	37
1.18 - 1.20	38
1.21 - 1.23	39
1.24 - 1.26	40
1.27 - 1.29	41
1.30 - 1.32	42
1.33 - 1.35	43
1.36 & longer	44 & longer

Table 2.

Fiber length is determined by an interaction of cotton variety, growth environment and crop management. Extreme temperatures, water stress, insect pressure or nutrient deficiencies can all shorten the staple length. Excessive cleaning or drying of cotton fiber at any point in its processing can also reduce the length.

LENGTH UNIFORMITY INDEX

Length uniformity index is the ratio between the "mean length" of the fibers and the "upper half mean length". Both measurements are taken when the fiber beard described above is passed through the length sensor of the HVI system. There is a natural distribution in the length of cotton fibers. The lower the variation in this length distribution, the higher the length uniformity index.

Like staple length, length uniformity (Table 3) affects yarn strength and evenness as well as the efficiency of the spinning process. Cotton with a low length uniformity index (high variance in fiber length) is more likely to be difficult to process and result in lower quality yarn.

Length Uniformity	
Degree of Uniformity	**HVI Length Uniformity Index (%)**
Very High	Above 85
High	83 - 85
Intermediate	80 - 82
Low	77 - 79
Very Low	Below 77

Table 3.

STRENGTH

Fiber strength as measured on the High Volume Instrument is the force in grams required to break a bundle of fibers one tex unit in mass. A tex unit is the weight in grams of 1000 meters of fiber length. Strength measurements are made on the same beard of cotton used by the HVI to measure staple length. After the length measurement is made, the beard is clamped between two sets of jaws that are spaced 1/8th of an inch apart,

then broken. The result is reported in "grams per tex" (Table 4).

Fiber strength is largely determined by genetics, so cotton variety plays an important role in this fiber quality. However, the growing environment and crop management cannot be ignored since they do contribute toward determination of fiber strength.

Fiber Strength	
Degree of Strength	**HVI Strength (grams per tex)**
Very Strong	31 & above
Strong	29 - 30
Average	26 - 28
Intermediate	24 - 25
Weak	23 & below

Table 4.

MICRONAIRE

Micronaire is a measurement of both fiber fineness and maturity. Micronaire is determined by measuring the air permeability of a constant mass of cotton fibers compressed to a fixed volume. Fine or immature fibers that are easily compressed have a lower air permeability and therefore low micronaire. Coarse or mature fibers that resist compression have high micronaire.

Micronaire is the cotton fiber property most influenced by the environmental conditions during the growing season. Various combinations of moisture, temperature, sunlight and length of season all contribute to micronaire level.

Micronaire gives important information about the dyeing characteristics of the cotton products produced from the fiber. Micronaire values are used to assess the market values of cotton (Table 5).Uneven distribution of micronaire within a fabric can result in poor color uniformity of that fabric and problems such as barré or streaks.

While micronaire is not a direct measurement of fiber fineness, it does give some indication of this property. Cotton fiber fineness affects processing performance and the quality of end products in several ways. Fine fibers require careful opening, cleaning and carding to prevent damage, which can result in uneven yarn. However, yarns produced from fine fibers will have more fibers in the yarn cross-section, resulting in improved yarn strength.

Table 5. Relationship of Micronaire Readings to Market Value

HVI COLOR GRADES FOR AMERICAN UPLAND COTTON

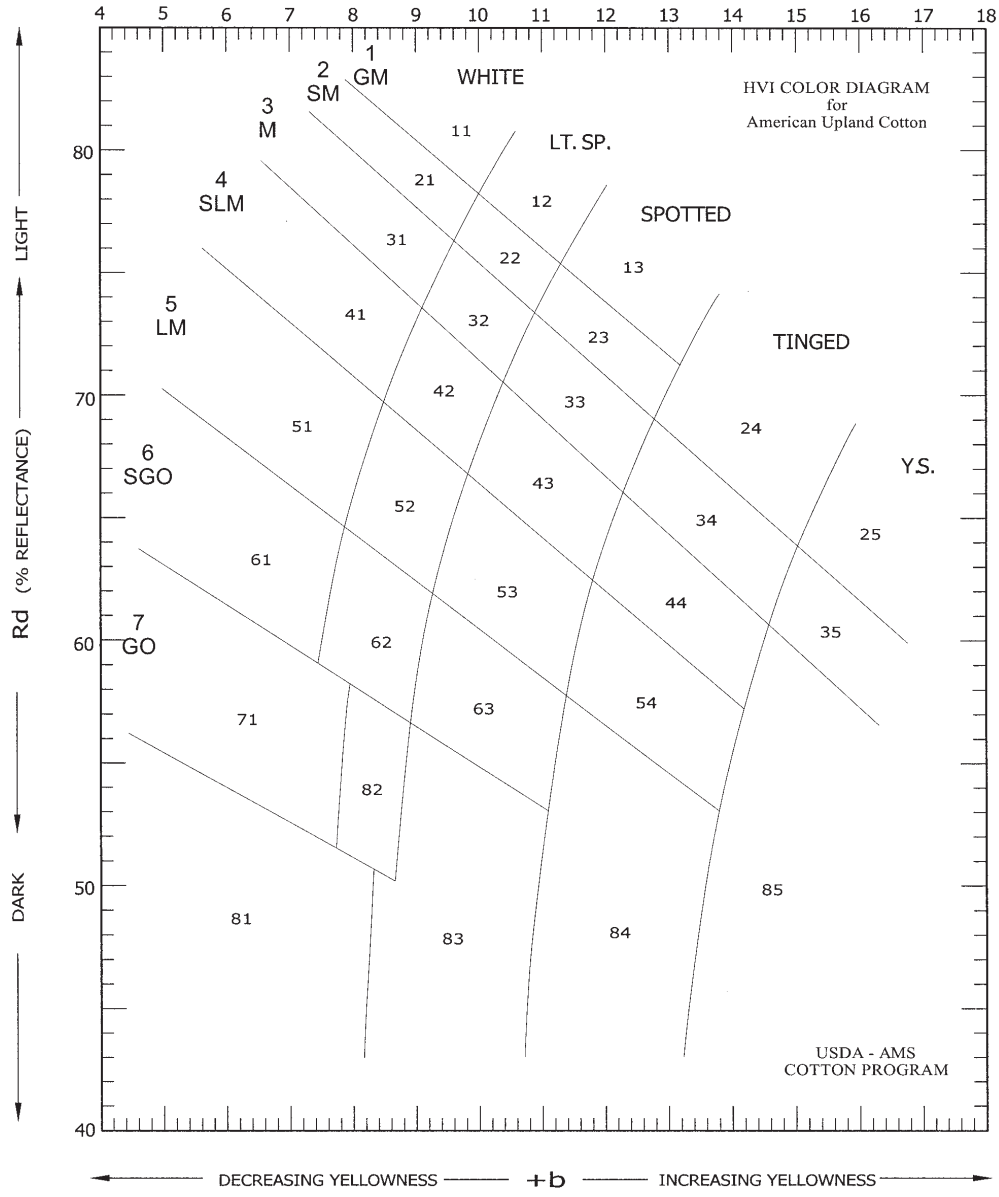


Table 6.

COLOR

The color of cotton is measured using a cotton colorimeter and is expressed by the degrees of reflectance (Rd) and yellowness (+b). Reflectance, which typically ranges between 50 and 85 units, indicates how white or gray a sample is. The higher the Rd value, the whiter the cotton.

In color measurement science, positive "b" values indicate yellowness, so cotton with higher +b measurements is more yellow. The most typical range of +b in upland cotton is from 6 to 12.

COLOR GRADE

Traditionally, cotton classers determined the color grade of cotton by comparing a sample to physical color standards. There are 25 official color grades for American upland cotton, plus five categories of below grade color. The USDA Cotton Program maintains physical standards for 15 of the color grades (Table 7). The instrument color readings of these physical standards have been plotted on a Nickerson-Hunter cotton colorimeter diagram. By utilizing the Rd and +b measurements described above and the colorimeter diagram, we can determine the traditional color grade of the cotton (Table 6).

The color of cotton fibers can be affected by environmental variables such as rainfall, freezes, insects and microorganisms. Sometimes, cotton fiber can be stained on the plant by contact with soil, grass or the leafy portions of the cotton plant. Color can also be affected by high levels of moisture and temperature during storage, both before and after ginning.

Color Grades of Upland Cotton - Effective 1993

	White	Light Spotted	Spotted	Tinged	Yellow Stained
Good Middling	11*	12	13	---	---
Strict Middling	21*	22	23*	24	25
Middling	31*	32	33*	34*	35
Strict Low Middling	41*	42	43*	44*	---
Low Middling	51*	52	53*	54*	---
Strict Good Ordinary	61*	62	63*	---	---
Good Ordinary	71*	---	---	---	---
Below Grade	81*	82	83	84	85

*Physical Standards. All other are descriptive

Table 7.

Relationship of Trash Measurement to Classer's Leaf Grade

Trash measurement (4-year average) (% area)	Classer's Leaf Grade
0.13	1
0.20	2
0.34	3
0.51	4
0.72	5
1.00	6
1.25	7
1.57	8

Table 8.

HVI TRASH

When cotton fiber is tested using HVI instruments, the surface of the sample is scanned by a video camera and the percentage of the surface area occupied by trash particles is determined by image processing software. Trash particles in cotton fiber come from parts of the cotton plant such as leaf and bark that are removed along with the fiber during harvesting. The HVI trash measurement is not part of the official USDA cotton classification, but is provided as additional information. Classer's Leaf Grade, described below is the official classification for trash content. However, there is a correlation between HVI trash measurement and classer's leaf grade as shown in Table 8.

B. CLASSER DETERMINATIONS

Although USDA provides a comparable HVI trash measurement, the traditional method of classer determination for leaf-grade and extraneous matter remains part of the official USDA classification.

LEAF GRADE

The classer's leaf grade is a visual estimate of the amount of cotton plant leaf particles in the cotton. There are seven leaf grades, designated as leaf grade "1" through "7", and all are represented by physical standards. In addition, there is a "below grade" designation which is descriptive.

Leaf content is affected by plant variety, harvesting methods, and harvesting conditions. The amount of leaf remaining in the lint after ginning depends on the amount present in the cotton prior to ginning, and on the type and amount of cleaning and drying equipment used. Even with the most careful harvesting and ginning methods, a small amount of leaf remains in the cotton lint.

From the manufacturing standpoint, leaf content is all waste, and there is a cost factor associated with its removal. Also, small particles cannot always be successfully removed, and these particles may detract from the quality of the finished fabric.

PREPARATION

Preparation is a term used to describe the degree of smoothness or roughness in the cotton fiber sample. Various methods of harvesting, handling, and ginning cotton produce differences in roughness or smoothness of preparation that can be seen in the cotton sample.

EXTRANEOUS MATTER

Extraneous matter is any substance in the cotton other than fiber or leaf. Examples of extraneous matter are bark, grass, spindle twist, seedcoat fragments, dust, and oil. The kind of extraneous matter and an indication of the amount (light or heavy), are noted by the classer on the classification document.

TEXTILE PROCESSING

DAVID M. CLAPP

The textile process begins with bales of cotton and continues through various processes for the purpose of creating yarns and fabrics for many end uses.

YARN FORMATION

Yarn formation is the process of converting loose cotton fiber into a yarn structure involving a progression of distinctly different and separate processes. The primary functions of these processes are:

- Fiber opening and blending
- Fiber cleaning
- Fiber straightening and paralleling
- Formation of a continuous fiberous strand
- Twist insertion

No matter the end result desired, proper fiber selection is the foundation of any successful spinning operation.

The requirements of the end product, or of the consumer of the yarn, will be the dictating forces in determining the fiber quality and properties that are best suited for the most economic situation. Using fiber that is of *better* quality than required will prove unprofitable. Likewise, using fiber that is of *poorer* quality than required will result in losses. Therefore, correct decisions regarding the most suitable fiber properties for a given operation are paramount for maintaining profitability.

Opening

Opening breaks down compressed layers or clumps of fiber into small tufts, facilitating transport and efficient cleaning (Figure 56).

Blending

Blending brings together fiber tufts from many bales to form a consistent, homogenous mix.

Cleaning

Cleaning removes extraneous matter from desirable fiber.

Basic principles of cleaning:

- beating action
- density differences
- centrifugal and inertial forces
- air flow

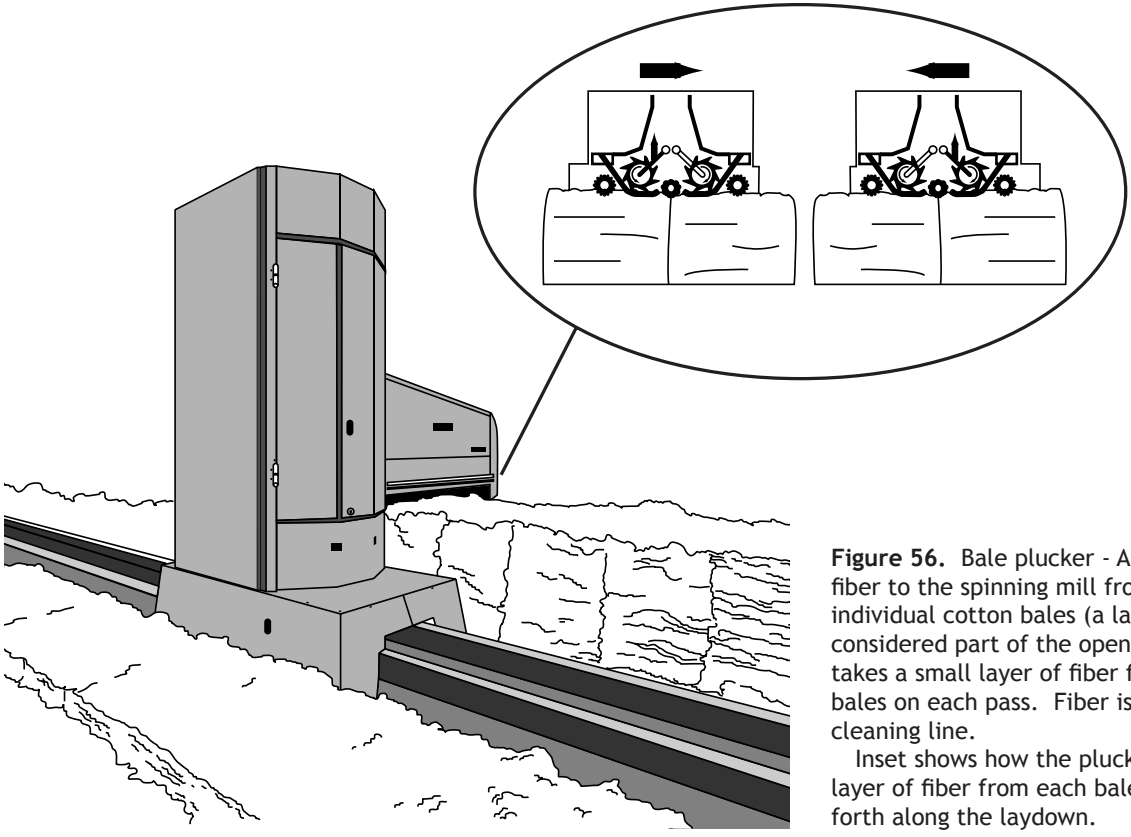


Figure 56. Bale plucker - A bale plucker feeds fiber to the spinning mill from an assemblage of individual cotton bales (a laydown). This step is considered part of the opening process. The plucker takes a small layer of fiber from the top of all the bales on each pass. Fiber is then transferred to the cleaning line.

Inset shows how the plucker head removes a small layer of fiber from each bale as it travels back and forth along the laydown.

Carding

Carding aligns, parallels, cleans, and condenses fiber into sliver (Figure 57).

Other important capabilities of carding:

- nep reduction
- short fiber reduction
- dust removal
- leveling

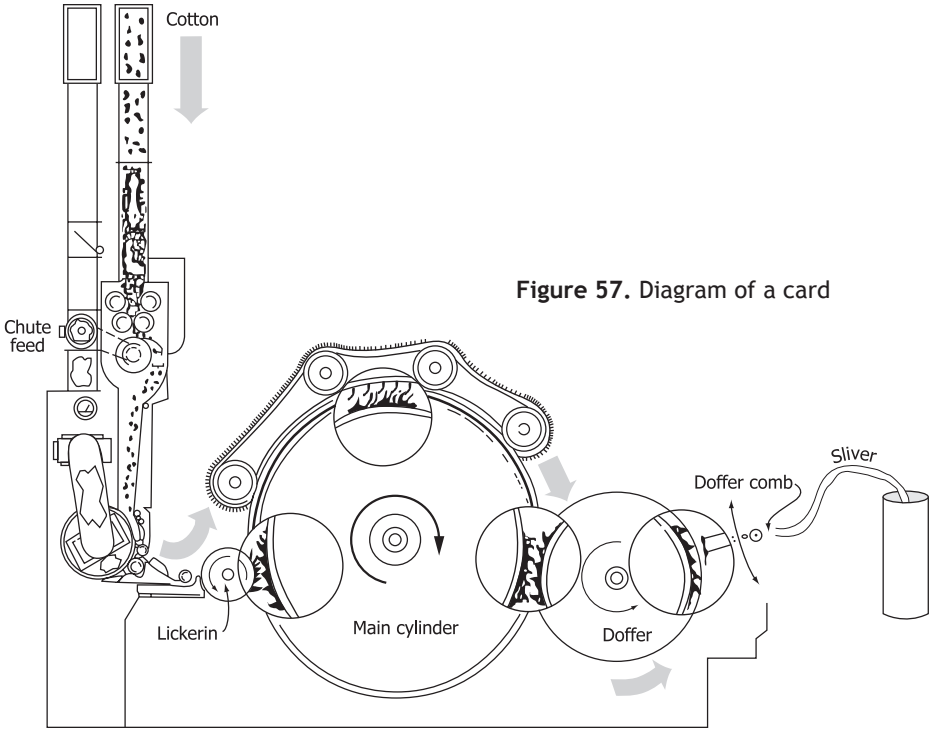


Figure 57. Diagram of a card

Drawing

Drawing blends, straightens, and levels (Figure 58).

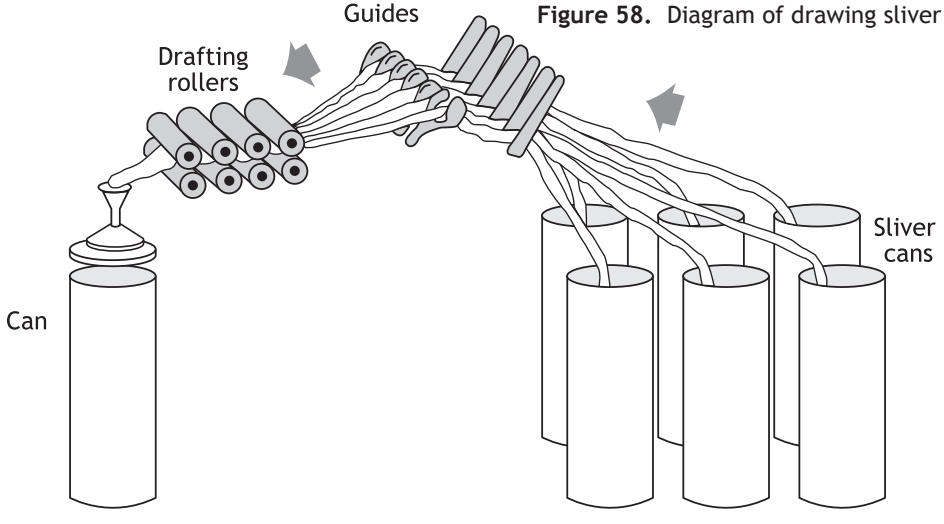


Figure 58. Diagram of drawing sliver

Lap preparation

Lap preparation combines a number of slivers into a wound, flat ribbon, (lap) necessary for combing.

Combing

Combing removes short fibers, straightens, and blends.

Roving

Roving is an intermediate drafting process required for ring spinning that also places sliver onto a bobbin (Figure 59).

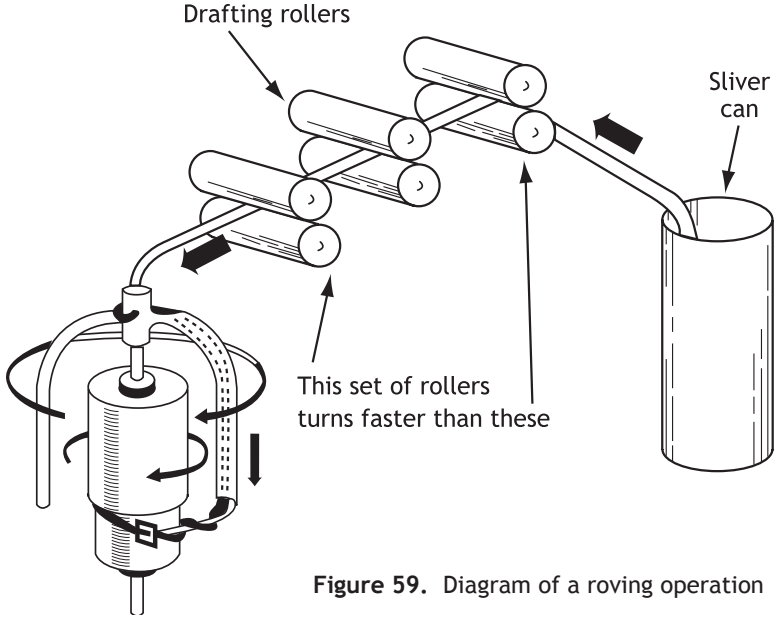


Figure 59. Diagram of a roving operation

Spinning

The insertion of twist into the fiber strand is necessary in order to give integrity and strength to the fiber bundle. The methods employed for inserting this twisting action are distinctly different depending on the spinning technology used. Because the methods for inserting twist are different, the resulting yarn structures also display their own unique forms.

There are three main technologies available for inserting this twist for the purpose of creating a yarn structure. These are ring spinning, open end (or rotor) spinning, and air jet (vortex) spinning.

RING SPINNING

Ring spinning inserts twist by means of a rotating spindle (Figure 60). Ring spinning is both the slowest spinning method and the most expensive spinning method due to the additional processes required (roving and winding).

Ring spinning produces the strongest, finest, and softest yarn (Figure 61). It is also the most mature spinning technology.

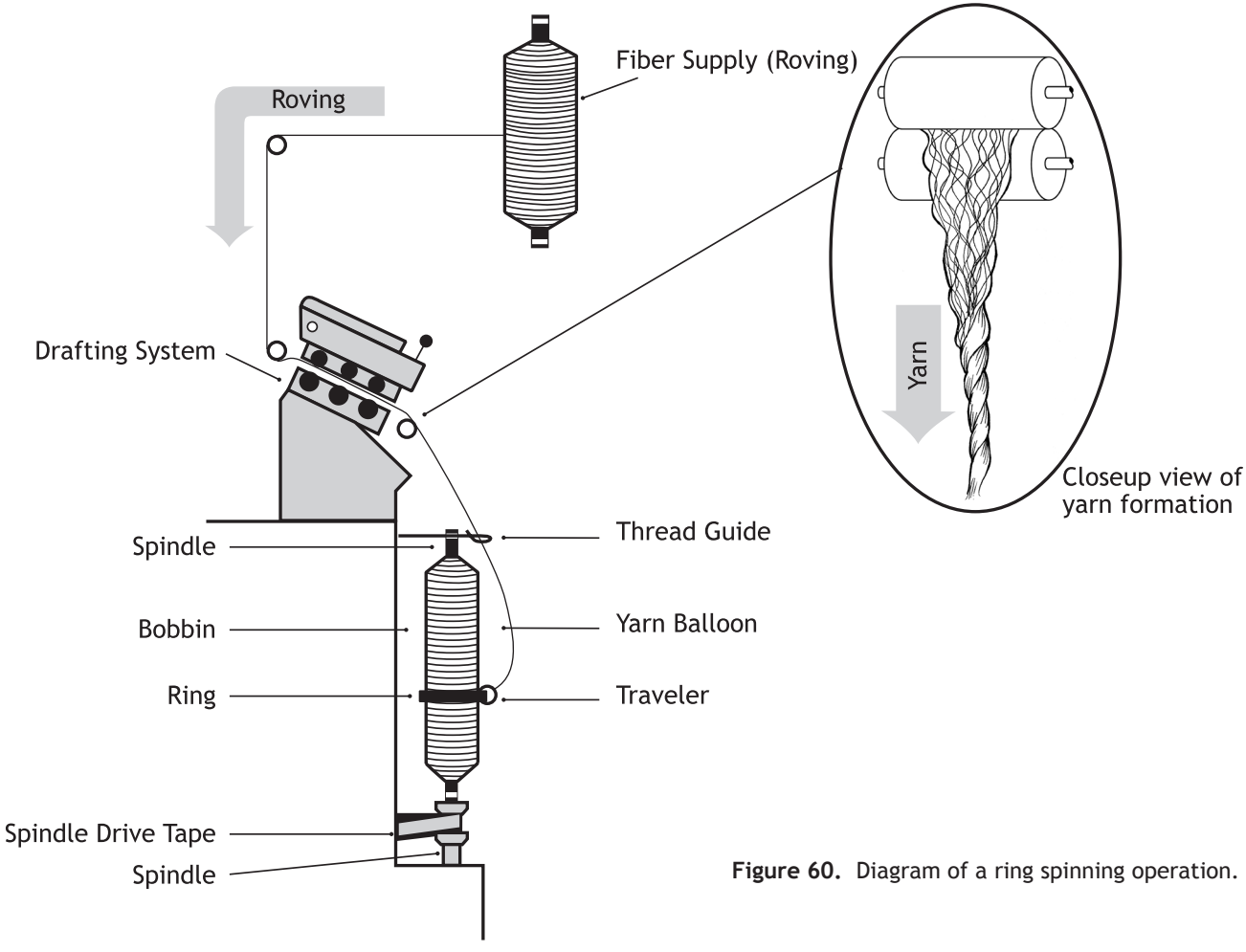


Figure 60. Diagram of a ring spinning operation.

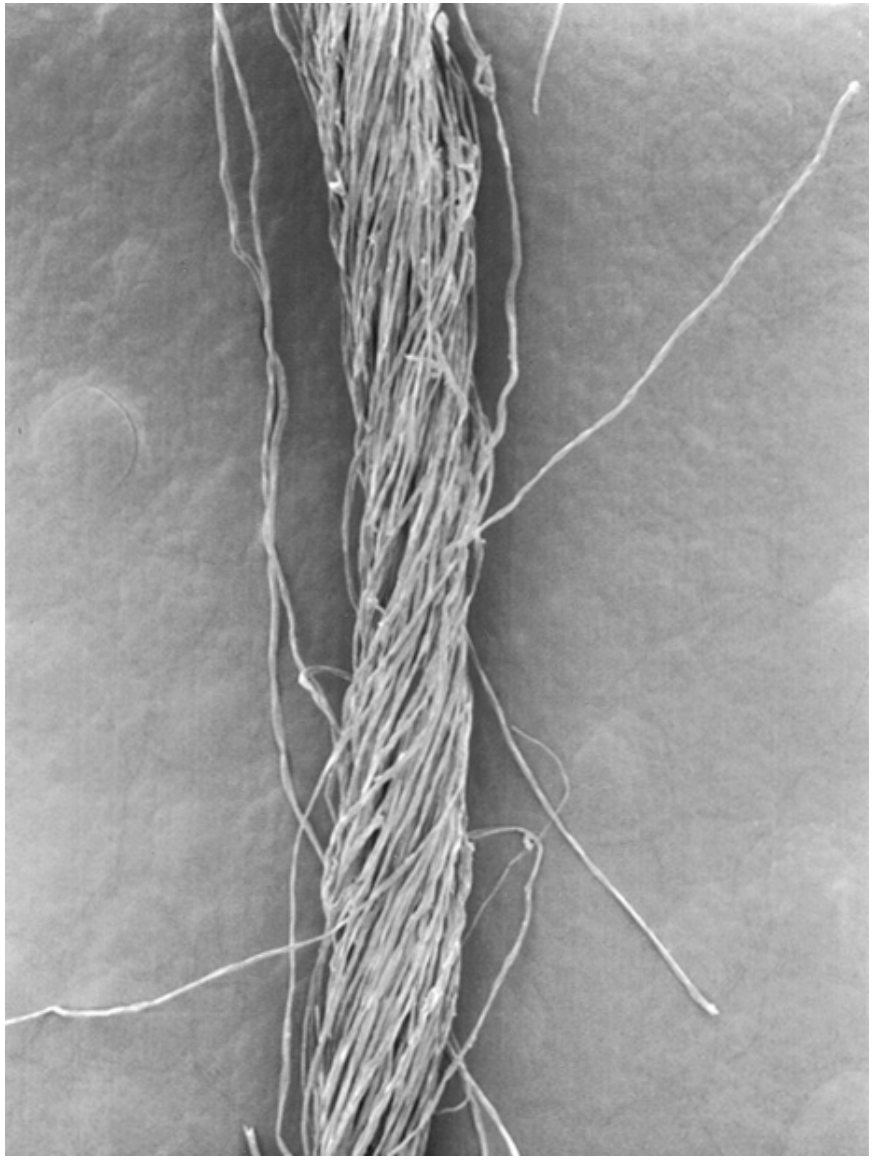


Figure 61. Ring spun yarn -This SEM image clearly shows the helix angle of twist which is responsible for holding the individual cotton fibers together. (M.J. Grimson)

OPEN END (ROTOR) SPINNING

Open end or rotor spinning inserts twist by means of a rotating rotor (Figure 62).

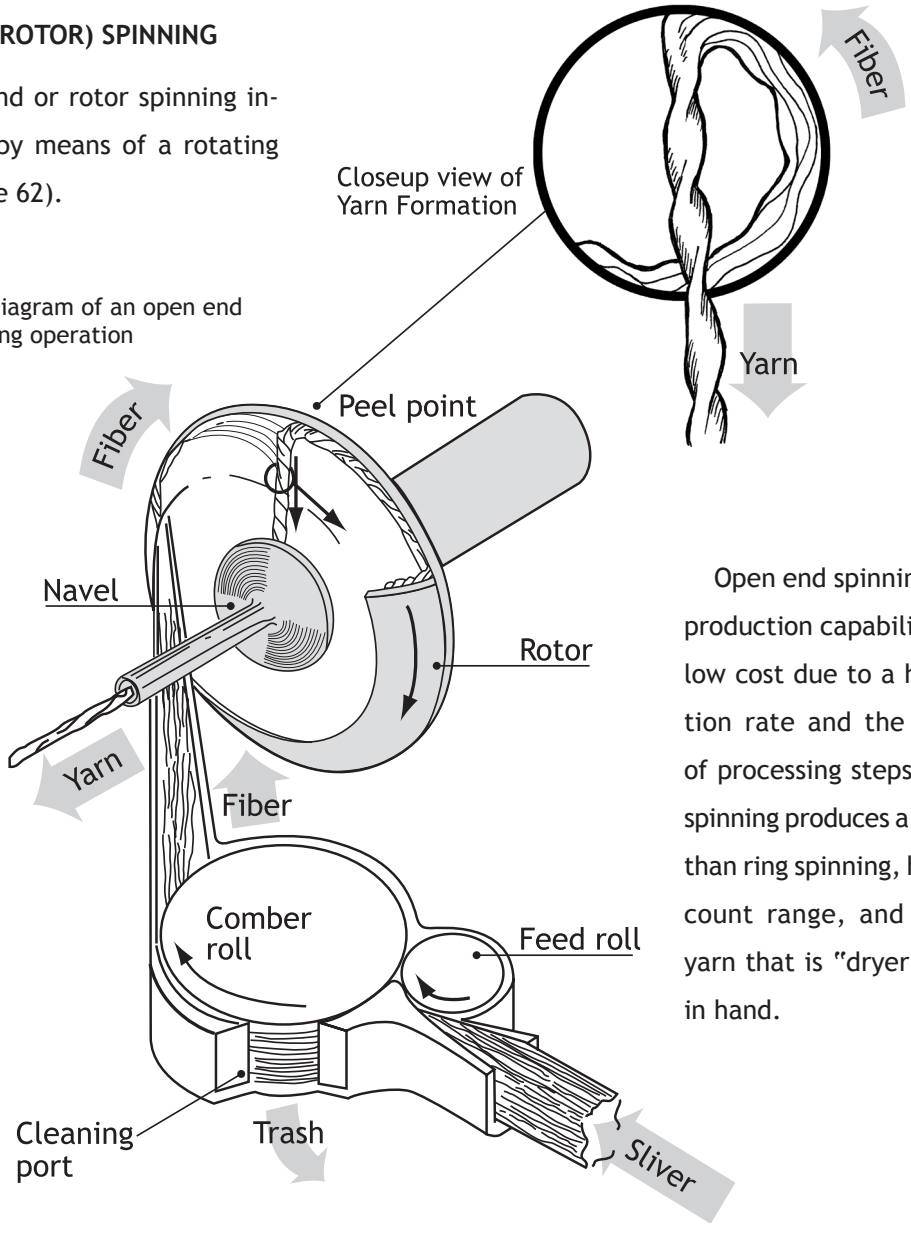


Figure 62. Diagram of an open end (rotor) spinning operation (K. Charlton)

Open end spinning has a high production capability and has a low cost due to a high production rate and the elimination of processing steps. Open end spinning produces a weaker yarn than ring spinning, has a limited count range, and produces a yarn that is "dryer" or harsher in hand.

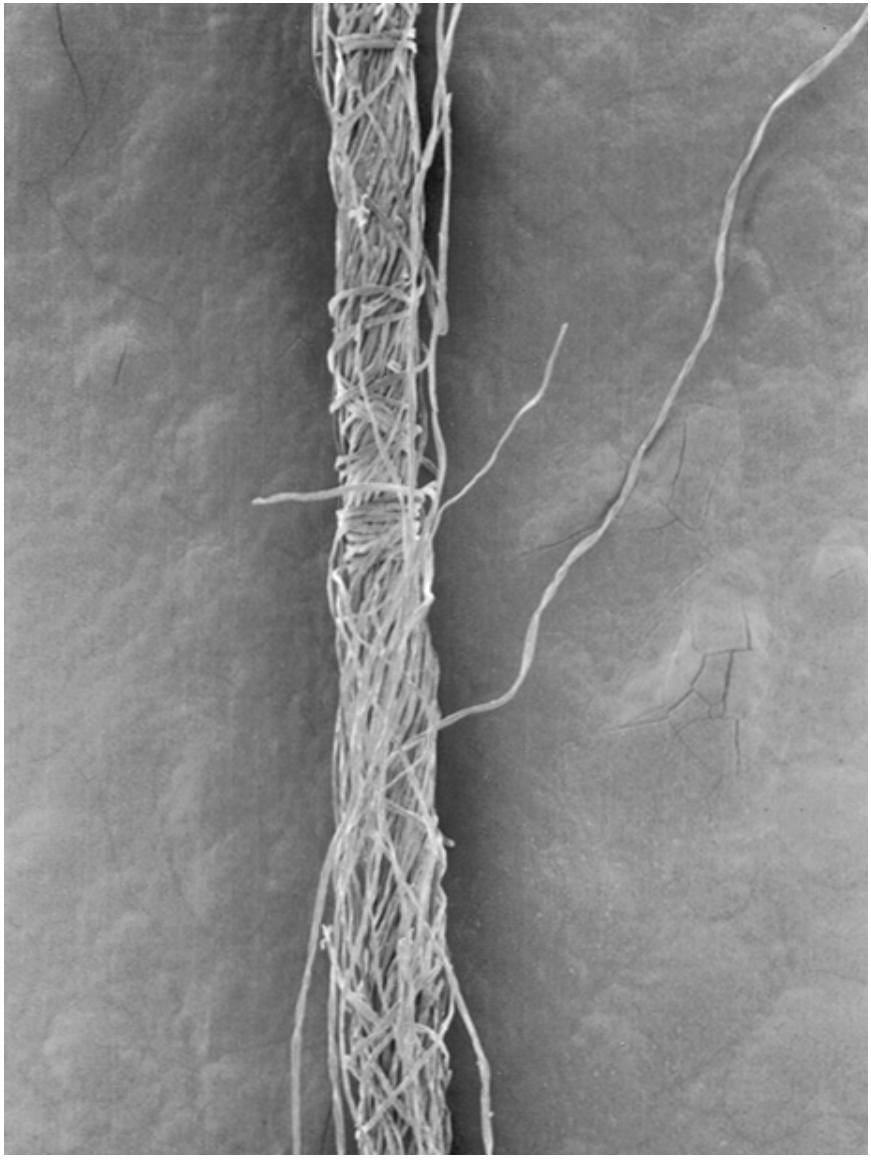


Figure 63. Open end (rotor) yarn - In comparison with the ring spun yarn (Figure 61), the difference in yarn structure is very evident in this SEM image of an open end yarn. Note particularly the wrapper fibers which are perpendicular to the yarn form. (M.J. Grimson)

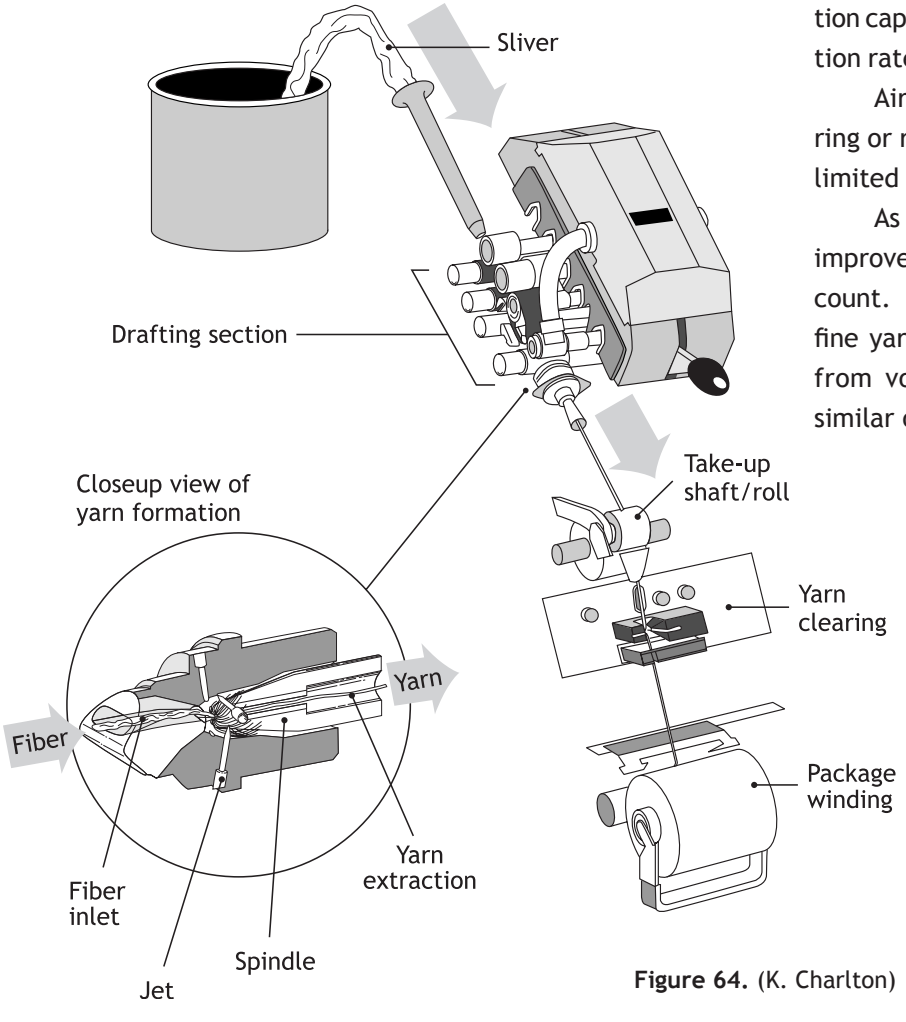


Figure 64. (K. Charlton)

AIR JET (VORTEX) SPINNING

Air jet (vortex) spinning (Figure 64) inserts twist (Figure 65) by means of a rotating vortex of compressed air. Air jet spinning has a high production capability and a low cost due to a high production rate and the elimination of processing steps.

Air jet spinning produces a weaker yarn than ring or rotor spinning (for 100% cotton) and has a limited range of yarn sizes (counts).

As the yarn count gets finer, the yarn strength improves over open end spun yarns of the same count. Vortex yarn is appropriate for medium to fine yarn counts. The softness of fabrics made from vortex spun yarns usually falls between similar open end and ring fabrics.

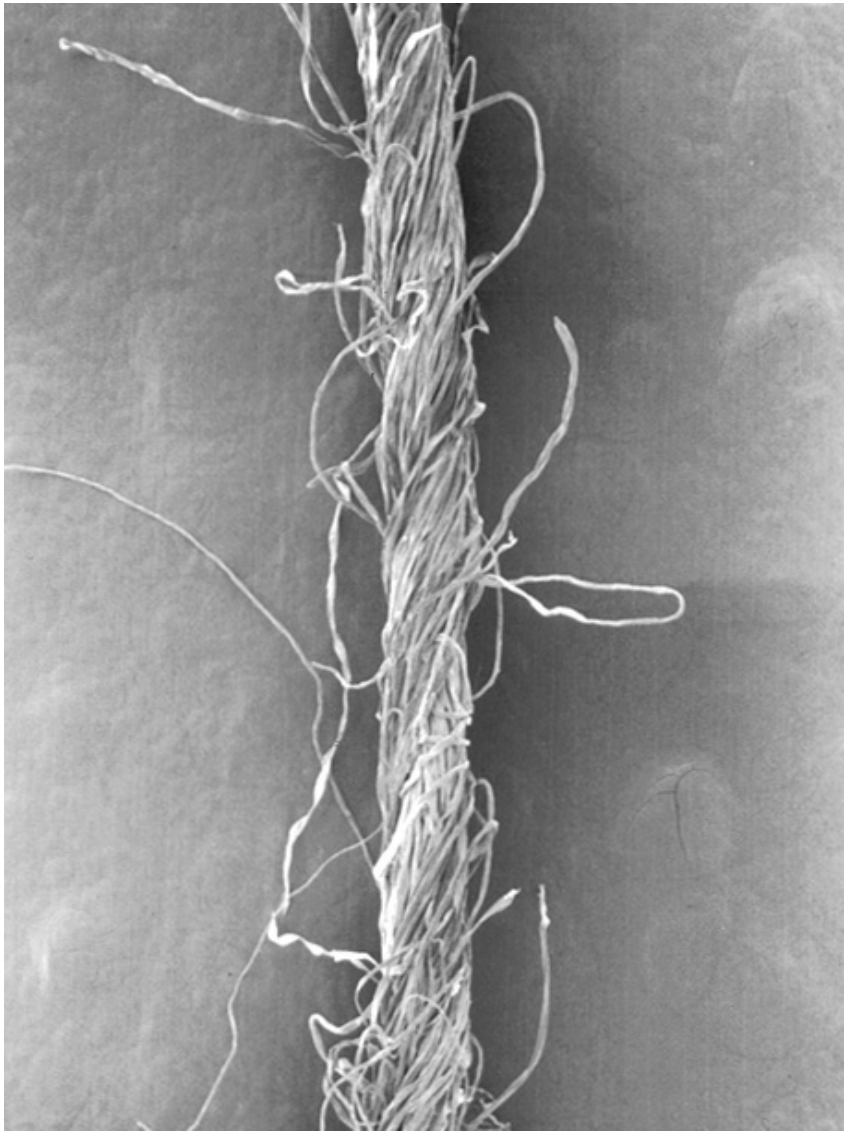


Figure 65. Air jet (vortex) spun yarn - This SEM image of a vortex yarn shows a high degree of similarity to the ring yarn structure.
(M.J. Grimson)

FABRIC FORMATION

Spun yarns can then be used in the formation and production of fabric. There are two main methods for creating fabric structures from yarn - weaving and knitting. Each structure has its own unique characteristics and end uses. For instance, denim is a woven fabric and T-shirts are usually knit fabrics.

WOVEN FABRIC

Weaving involves the interlacing of yarns at right angles, much like making a basket. Depending on the setup of the loom, many weave patterns and fabric constructions can be produced.

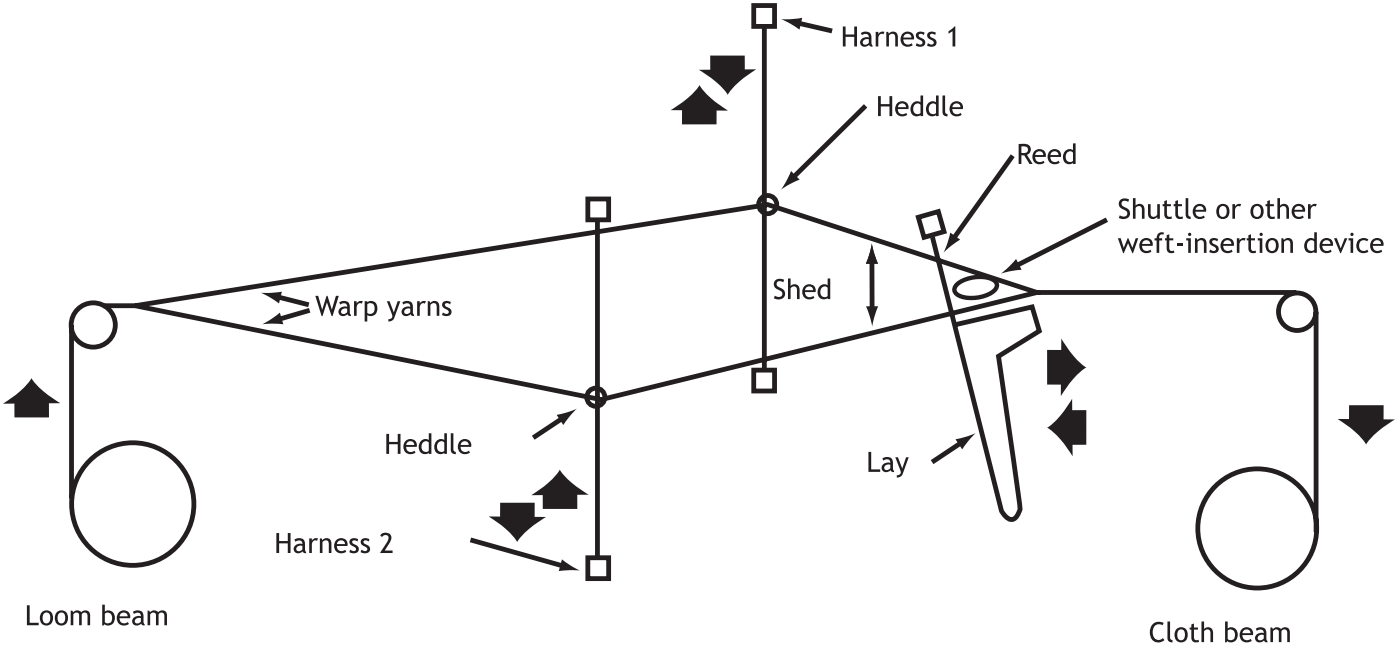


Figure 66. Diagram of a weaving loom - These elements of a loom show how a "sheet" of warp yarns on the loom beam are fed into the harness heddles where they are alternately separated by an up and down motion in order to feed the weft, or filling, yarns perpendicular to the warp yarns. This continuous cyclical action creates the woven fabric structure.

Figure 67. Woven fabric (plain weave pattern) - This SEM shows the interlacing/basket-type configuration of the yarns in a woven fabric. (M.J. Grimson)

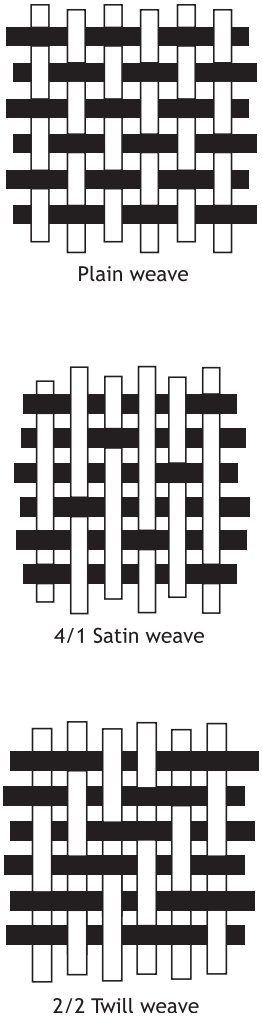


Figure 68. Basic weave patterns. These illustrations are examples of some basic fabric constructions.

KNITTED FABRIC

Knitting involves looping the yarn or yarns around and through one another, much like hand knitting or crocheting (Figures 69 and 70).

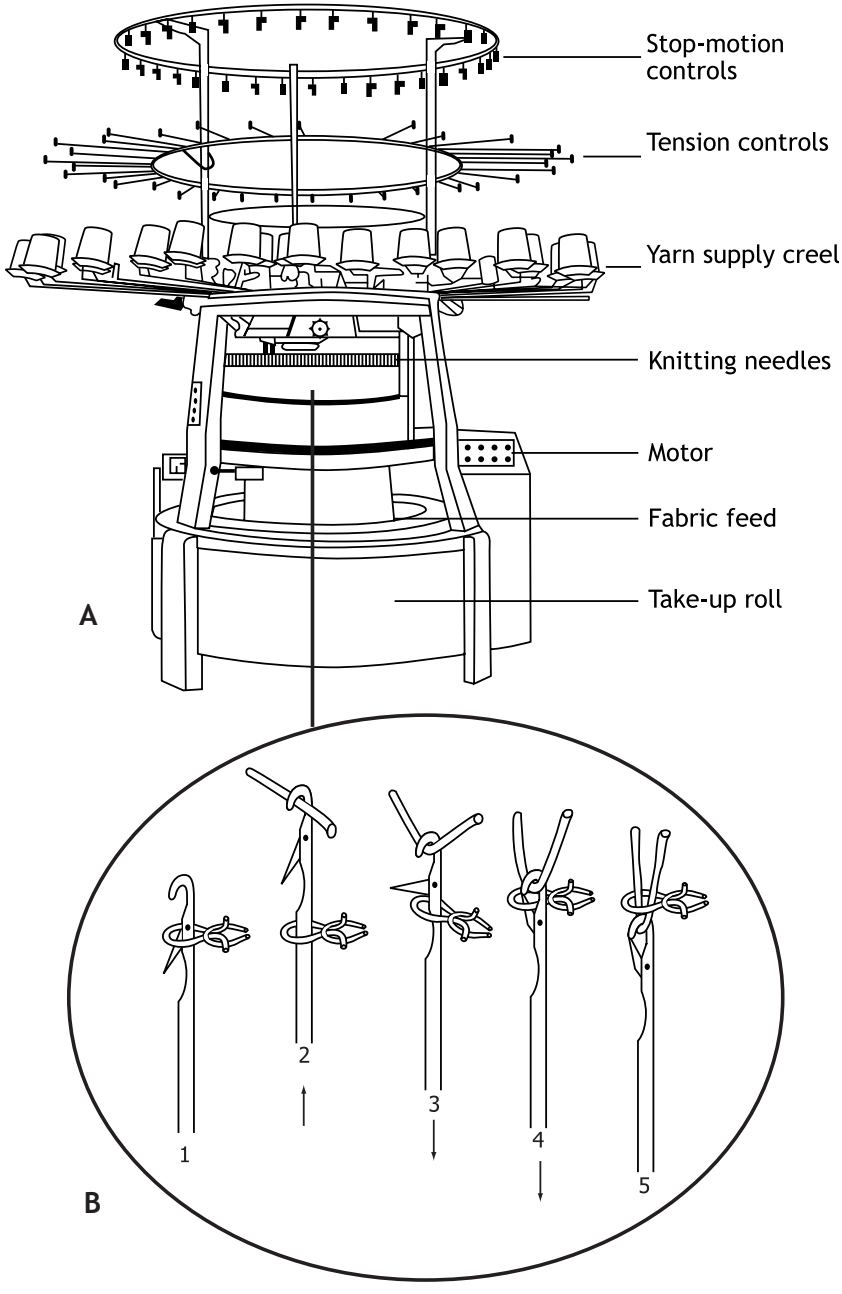
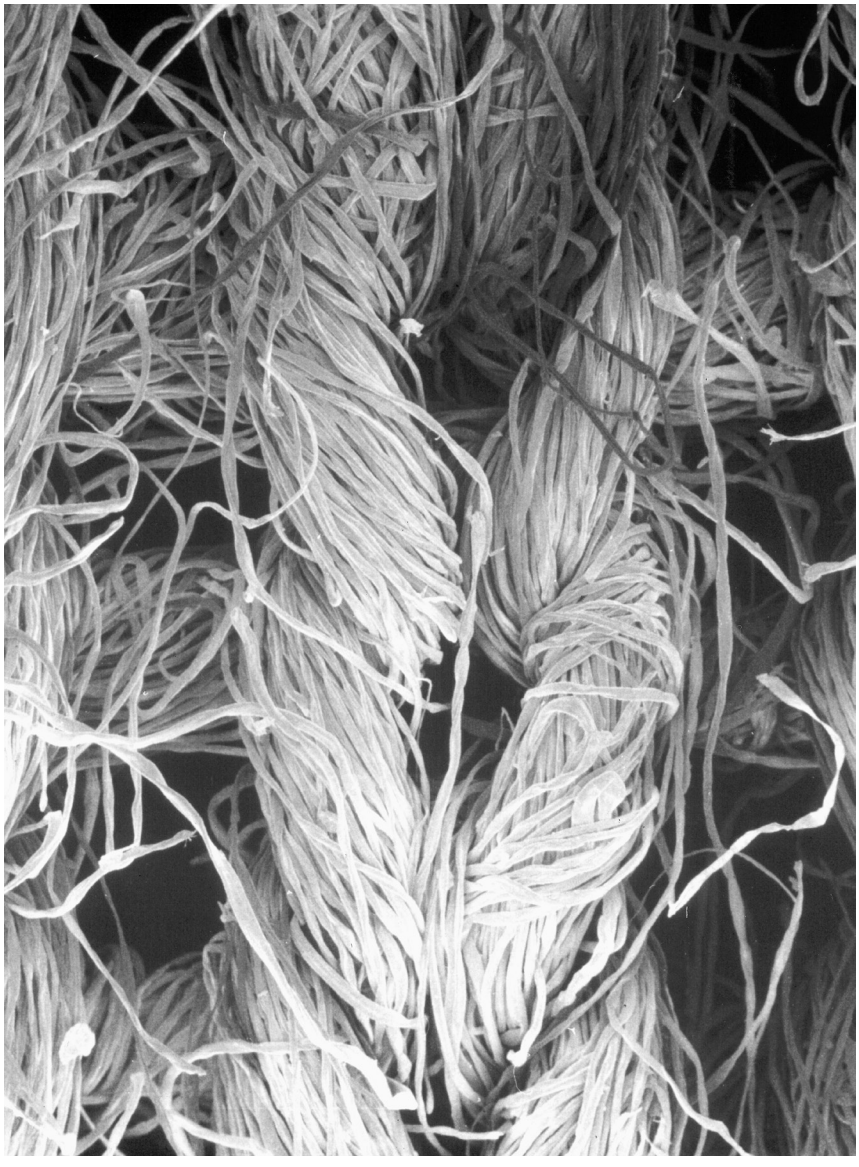


Figure 69. Circular weft knitting -
(A) Circular (weft) knitting produces fabric in a continuous spiral form from numerous yarn supply packages.
(B) Latch needle function and loop formation of knitting.



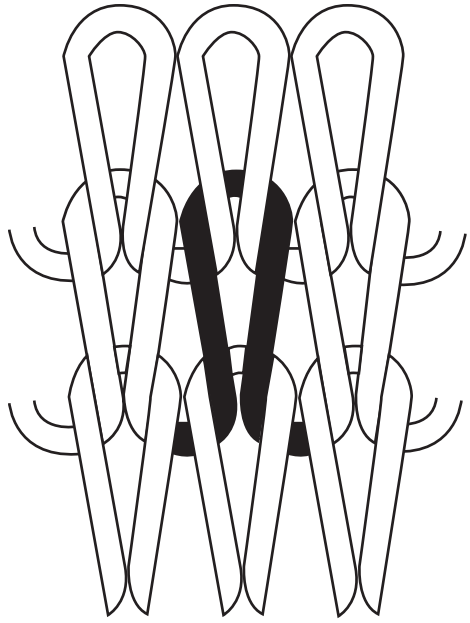


Figure 70. Diagram of knitted fabric

Figure 71. SEM of knitted fabric - This SEM of knitted fabric shows clearly the looping configuration of the yarns which is the basis of most knit structures.
(M.J. Grimson)

NONWOVENS

Nonwovens are fabric structures that are created directly from fiber, bypassing the necessity for yarn formation. These fabric structures depend on thermal bonding, chemical bonding, and /or mechanical entanglement for their integrity. Varied processes, chemistry, and machines are required, depending on the specific end product desired and the technology employed. Common uses of nonwoven fabrics include many products like diapers, disposable wipes, and feminine hygiene products. U.S. paper currency is a nonwoven product using some cotton fiber (Figures 72 - 74).

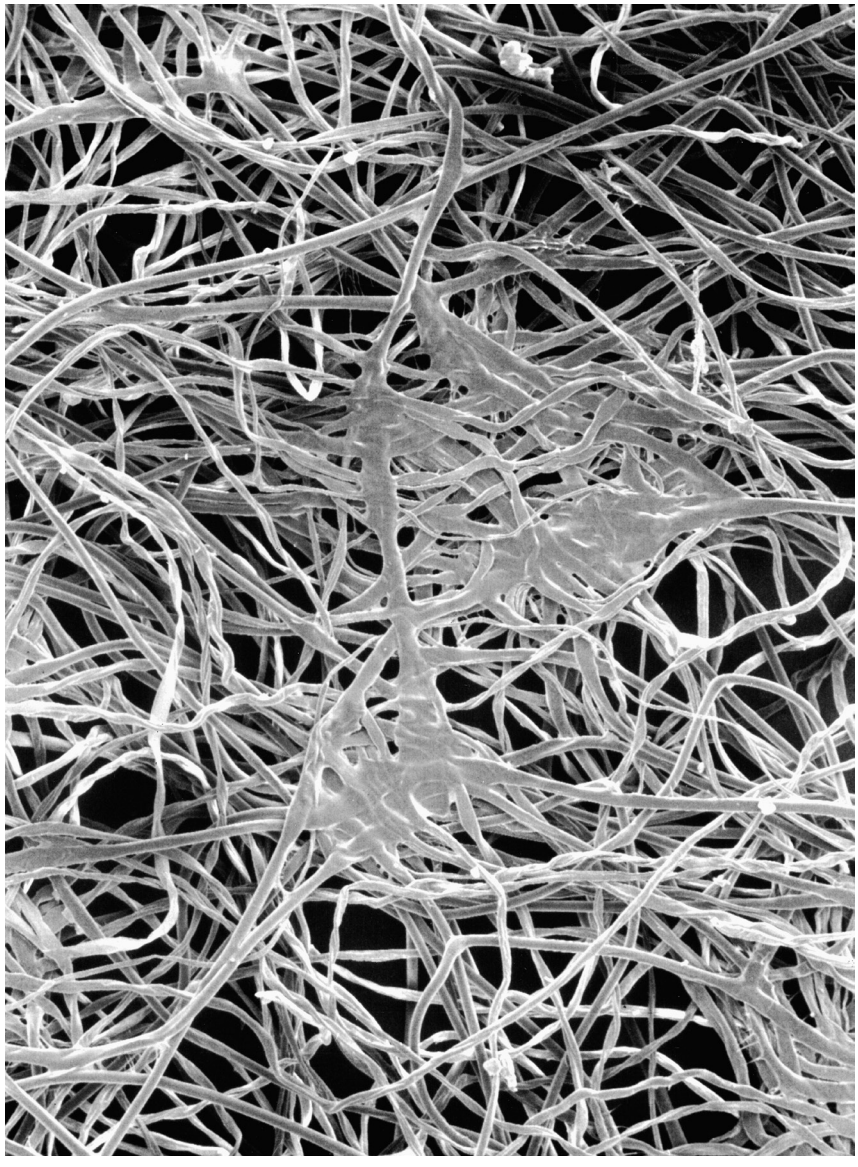


Figure 72. SEM of a thermal bonded nonwoven fabric (M.J. Grimson)

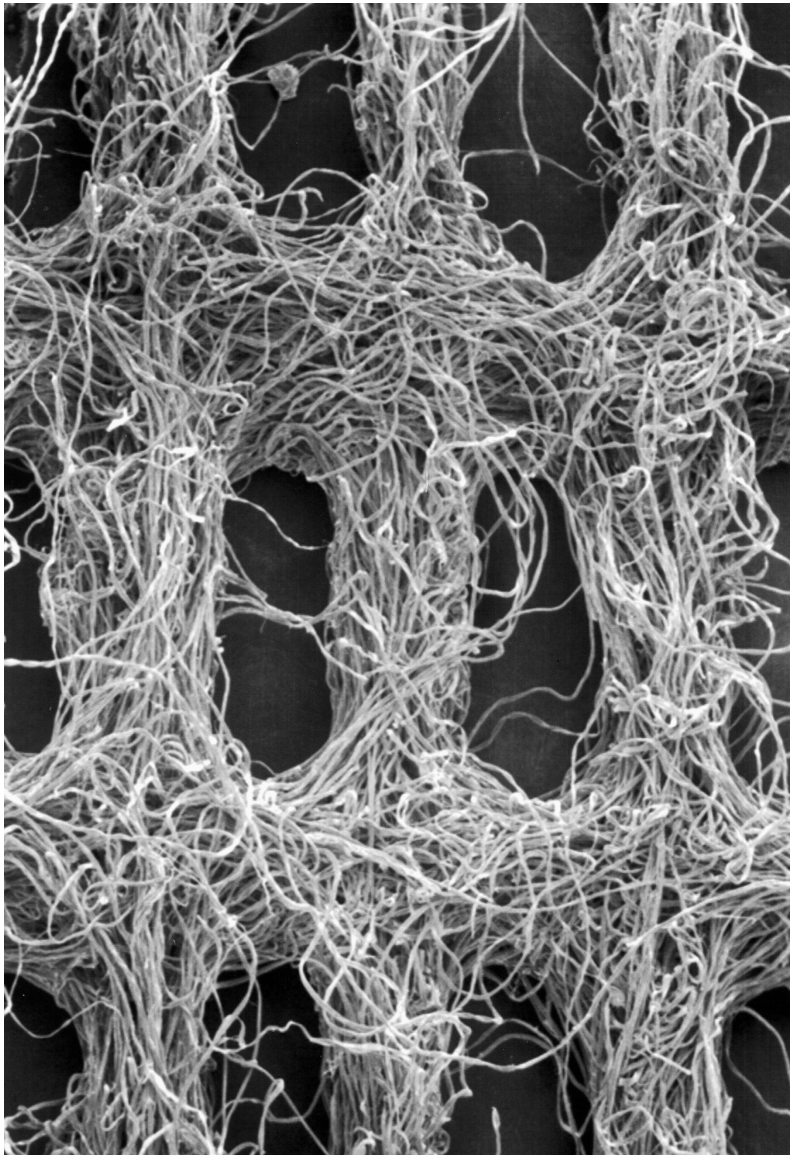


Figure 73. SEM of a hydroentangled nonwoven fabric (M.J. Grimson)

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