Wheat

The grass that bears our daily bread is synonymous with European civilization. What is the basis of its usefulness, and what is the origin of modern wheat?

by Paul C. Mangelsdorf

WHEAT is the world's most widely cultivated plant. The wheat plants growing on the earth may even outnumber those of any other seed-bearing land species, wild or domesticated. Every month of the year a crop of wheat is maturing somewhere in the world. It is the major crop of the U. S. and Canada and is grown on substantial acreages in almost every country of Latin America, Europe and Asia.

Apparently this grain was one of the earliest plants cultivated by man. Carbonized kernels of wheat were found recently by the University of Chicago archaeologist Robert Braidwood at the 6,700-year-old site of Jarmo in eastern Iraq, the oldest village yet discovered—a village which may have been one of the birthplaces of man's agriculture. Through the courtesy of Dr. Braidwood I have had an opportunity to study some of these ancient kernels and compare them with modern kernels, carbonized to simulate the archaeological specimens. The resemblance between the ancient and modern grains is remarkable. There were two types of kernels in the Jarmo site; one turned out to be almost identical with a wild wheat still growing in the Near East, and the other almost exactly like present-day cultivated wheat of the type called einkorn. Evidently there has been no appreciable change in these wheats in the 7,000 years since Jarmo.

When he domesticated wheat, man laid the foundations of western civilization. No civilization worthy of the name has ever been founded on any agricultural basis other than the cereals. The ancient cultures of Babylonia and Egypt, of Rome and Greece, and later those of northern and western Europe, were all based upon the growing of wheat, barley, rye and oats. Those of India, China and Japan had rice for their basic crop. The pre-Columbian peoples of America—Inca, Maya and Aztec—looked to corn for their daily bread.

What are the reasons for this intimate relation between the cereals and civilization? It may be primarily a question of nutrition. The grain of cereal grasses, a nutlike structure with a thin shell covering the seed, contains not only the embryo of a new plant but also a food supply to nourish it. Cereal grains, like eggs and milk, are foodstuffs designed by nature for the nutrition of the young of the species. They represent a five-in-one food supply which contains carbohydrate, proteins, fats, minerals and vitamins. A whole-grain cereal, if its food values are not destroyed by the over-refinement of modern processing methods, comes closer than any other plant product to providing an adequate diet. Man long ago discovered this fact and learned to exploit it. Guatemalan Indians manage to subsist fairly well on a diet which is 85 per cent corn. In India people sometimes live on almost nothing but rice. Such diets do not meet the approval of modern nutritionists, but they are better than those made up too largely of starchy root crops such as potatoes, sweet potatoes or cassava, or of proteinaceous legumes such as beans, peas and lentils.

Perhaps the relationship between cereals and civilization is also a product of the discipline which cereals impose upon their growers. The cereals are grown only from seed and must be planted and harvested in their proper season. In this respect they differ from the root crops, which in mild climates can be planted and harvested at almost any time of the year. Root-crop agriculture can be practiced by semi-nomadic peoples who visit their plantations only periodically. The growing of cereals has always been accompanied by a stable mode of life. Moreover, it forced men to become more conscious of the seasons and the movements of the sun, moon and stars. In both the Old World and the New the science of astronomy was invented by cereal growers, and with it a calendar and a system of arithmetic. Cereal agriculture in providing a stable food supply created leisure, and leisure in turn fostered the arts, crafts and sciences. It has been said that "cereal agriculture, alone among the forms of food production, taxes, recompenses and stimulates labor and ingenuity in an equal degree."

From Grain-chewing to Bread

Today wheat is the cereal *par excellence* for breadmaking, and it is used almost exclusively for that purpose. But it is quite unlikely that breadmaking, a complex and sophisticated art, came suddenly into full flower with the domestication of wheat. Man may have begun by merely parching or popping the grain to make it edible. Primitive wheats, like other cereals, were firmly enclosed in husks, called glumes. Heating makes the glumes easy to rub off and allows the kernel itself to be more easily chewed or ground into meal. The scorching and parching of grains is still practiced on unripened cereals in parts of the Near East. In Scotland until recently barley glumes were sometimes removed by setting fire to the unthreshed heads. The Chippewa Indians still prepare wild rice by heating the unhusked kernels and tramping on them in a hollow log.

Hard-textured cereal grains with a certain moisture content explode and escape from their glumes when heated. In America the first use of corn was undoubtedly by popping. The earliest known corn had small vitreous kernels, and archaeological remains of popped corn have been found in early sites in both North and South America. In India certain varieties of rice are popped by stirring the kernels in hot sand. Many villages in India have a village popper who performs this service for his neighbors and provides himself with food by taking his toll of the product.

The botanical as well as archaeological evidence, though meager, indicates that wheat was first used as a parched cereal. The dwellings at Jarmo contain ovens which prove that this primitive economy knew the controlled use of heat. All the very ancient prehistoric kernels so far found are carbonized as if they had been over-parched. In itself this evidence is not telling, since only carbonized grains would be preserved indefinitely, but it is in harmony with other evidence. Finally, the most ancient wheats are species whose kernels would not be removed from the husks merely by threshing. The simplest method of husking them to make them edible would have been parching.

Probably the second stage in progress was to grind the parched grains and soak the coarse meal in water to make a gruel. For the toothless, both old and young, this must have been a life-saving invention. Gruel or porridge is well known as a primitive form of food. A gruel prepared from parched barley was the principal food of the common people of ancient Greece. American Indians prepared a kind of porridge from corn, which has its modern counterpart in "mush" and "polenta."

A gruel allowed to stand for a few days in a warm dwelling would become infected with wild yeasts. Fermenting the small amounts of sugar in cereal, the yeasts would have produced a mild alcoholic beverage. This would have pointed the way to leavened bread. It is questionable which art developed first—brewing or breadmaking. Some students believe that brewing is older even than agriculture, but there is no supporting archaeological or historical evidence. On the contrary, the earliest Egyptian recipes for beer described a process in which the grain was first made into half-baked loaves, which then became the raw material for beer-making. There is no doubt that brewing and the making of leavened bread are closely related arts, both depending upon fermentation by yeasts.

Modern breadmaking, however, had to await the appearance of new types of wheat. It is as much a product of the evolution of wheat as it is one of human ingenuity.

From Wild Grass to Wheat

Wheat differs from most cultivated plants in the complexity of its variations. True, the other major cereals, rice and corn, are each differentiated into thousands of varieties, but these form a continuous spectrum of variation and hence are classed as a single botanical species. Wheat is separated into distinct groups which differ from one another in many ways and are therefore classified as separate species under the single Old World genus *Triticum*. The domesticated wheats and their wild relatives have been studied more intensively than any other group of plants, cultivated or wild, and from these studies, truly international in scope, a picture is beginning to emerge of the evolution of wheat under domestication.

Authorities differ on the number of distinct species of wheat. This article follows the classification of Nikolai Vavilov, the Russian geneticist and botanist who, with his colleagues, brought together for study more than 31,000 samples of wheat from all parts of the world. Vavilov recognized 14 species; other botanists have recognized fewer or more. All authorities agree, however, that the wheat species, whatever their number, fall into three distinct groups, determined by the number of chromosomes in their cells. The chromosome numbers (in the reproductive cells) of the three types are, respectively, 7, 14 and 21. They were discovered by T. Sakamura in Japan in 1918 and slightly later, but independently, by Karl Sax in the U. S. The numbers are closely associated with differences in anatomy, morphology, resistance to disease, productiveness and milling and baking qualities. It is interesting to note that August Schulz, a German botanist, had arranged the wheats into these three groups in 1913, well before their chromosome numbers were known.

The 14- and 21-chromosome wheats have all arisen from 7-chromosome wheat and related grasses, through hybridization followed by chromosome doubling. The cultivated wheats are the most conspicuous example of this "cataclysmic evolution," described by G. Ledyard Stebbins, Jr., in his article in Scientific American of April, 1951. It is the only known mechanism by which new true-breeding species can be created almost overnight.

Since different wild grasses have been involved in wheat's evolution, the species differ not only in the number but also in the nature of their chromosomes. Relationships of different sets of chromosomes are determined by studying the degree of chromosome pairing in the reproductive cells of hybrids. If the pairing is complete, or almost so, the chromosome sets (genoms) of the parents are regarded as identical or closely related. If there is no pairing, the parental genoms are considered to be distinct. Four different genoms, each comprising seven chromosomes, designated A, B, D

Wheat field and farm buildings

FOURTEEN SPECIES OF WHEAT are shown actual size. From left to right they are *Triticum aegilopoides* (wild einkorn), *T. monococcum* (einkorn), *T. dicoccoides* (wild emmer), *T. dicoccum* (emmer), *T. durum* (macaroni wheat), *T. persicum* (Persian wheat), *T. turgidum* (rivet wheat), *T. polonicum* (Polish wheat), *T.*

and G, are recognized in wild and cultivated wheats.

Another important difference in wheats is in their heads. Primitive cereals and many wild grasses have heads whose central stem is brittle and fragile, breaking apart when mature and providing a natural mechanism for seed dispersal. When such cereals are threshed, the heads break up into individual spikelets (clusters of one or more individual grass flowers) in which the kernels remain firmly enclosed in their husks. Under domestication this characteristic, so essential to perpetuation of the species in the wild, has been lost. New forms have evolved, not only in wheat but in other cereals, in which the stems are tough and the heads remain intact when mature. In such cereals threshing alone removes the kernels from their glumes. The cereals with free-threshing, naked grains are much more useful to man, especially for milling and baking, than those that cling stubbornly to their husks. In wheats, therefore, the naked varieties have almost completely superseded the primitive forms.

Ancestors

The 7-chromosome wheats, probably the most ancient, consist of two species: *T. aegilopoides* and *T. monococcum*, known as wild einkorn and einkorn. Carbonized kernels of both were found at Jarmo, but whether they are the only wheats occurring in this ancient village site remains to be seen. Both species of einkorn have fragile stems and firm-hulled seeds. Their spikelets contain but a single seed, hence their name. Each has the same set of chromosomes, genom A, and they hybridize easily together to produce highly fertile offspring. Cultivated einkorn has slightly larger kernels than the wild form and a slightly tougher stem. Its heads do not fall apart quite so easily when ripe. Except for these slight differences the two species are essentially identical, and einkorn is

timopheevi (which has no common name), *T. aestivum* (common wheat), *T. sphaerococcum* (shot wheat), *T. compactum* (club wheat), *T. spelta* (spelt) and *T. macha* (macha wheat). The first two species have 7 chromosomes; the following seven, 14 chromosomes; the last five, 21 chromosomes (*see table on next two pages*).

undoubtedly the domesticated counterpart of the wild species. Apparently little significant change has been wrought in them over the centuries.

Wild einkorn has its center of distribution in Armenia and Georgia of the Soviet Union, and in Turkey. It also occurs in the eastern Caucasus and in western Iran. Westward from Asia Minor it is a common grass on the sides of low hills in Greece and Bulgaria and a weed in the well-drained vineyards of southern Yugoslavia. Cultivated einkorn originated, according to Vavilov, in the mountains of northeastern Turkey and the southwestern Caucasus. However, if my identification of the kernels at Jarmo is correct, and if Jarmo represents the beginnings of agriculture, einkorn may have been domesticated first slightly farther south in eastern Iraq. Certainly it is an ancient cereal. Carbonized grains of it have been found in neolithic deposits of the lake-dwellers and in many other sites in central and northeastern Europe. Impressions of einkorn have been identified in neolithic pottery in Britain and Ireland. There are no records of its prehistoric occurrence in India, China or Africa.

Einkorn is still grown in some parts of Europe and the Middle East, usually in hilly regions with thin soils. Its yields are low, usually not more than 8 to 15 bushels per acre. A bread, dark brown in color but of good flavor, can be made from it if it is husked, but it is more commonly used as a whole grain, like barley, for feeding cattle and horses. Einkorn's importance lies not in its present use but in its progeny. It is the ancestor of all other cultivated wheats, with the possible exception of the type called emmer. Einkorn's descendants all have in common the set of seven chromosomes called genom A.

Second Stage

In the next stage of evolution are the 14-chromosome species, of which Vavilov recognized seven. All these have come from the hybridization and chromosome doubling of a 7-chromosome wheat with a 7-chromosome related wild grass. The wheat parent in each case was undoubtedly einkorn, or possibly in one instance its wild relative, since all the species possess the genom A. But the wild-grass parent remains to this day unidentified and is the chief botanical mystery in the origin of cultivated wheats. This parent contributed a genom B to all in the group except one species. Edgar McFadden and Ernest Sears of the U. S. Department of Agriculture have suggested that genom B may have been derived from a species of *Agropyron*, a genus of weedy grasses which includes the pernicious couch grass of the northeastern U. S. Only one of the 14-chromosome wheats is found wild. This species, which is called wild emmer, is indigenous to southern Armenia, northeastern Turkey, western Iran, Syria and northern Palestine.

Closely resembling wild emmer, and possibly derived directly from it by domestication, is emmer, the oldest of 14-chromosome cultivated wheats and once the most widely grown wheat of all. An alternative possibility, however, is that emmer is the product of hybridization between einkorn and a 7-chromosome wild relative. The fact that crosses of wild and cultivated emmer are sometimes partly sterile indicates that the two forms may not be closely related and that one may be the product of an ancient hybridization and the other of a more recent one. There is at least no doubt about the antiquity of emmer. Well-preserved spikelets scarcely different from those of modern emmer have been found in Egyptian tombs of the Fifth Dynasty. Emmer may well have been the chief cereal of the Near East from very early times to the Greco-Roman period, for until the Jarmo find it was the only wheat found archaeologically in early sites of that region. Remains or impressions of it have also been common in neolithic sites in continental Europe, Britain and Ireland.

Emmer, like einkorn, has a fragile stem and clinging hull. Good bread and fine cake and pastry can be made from it, but most emmer today is fed to livestock. Some varieties are quite resistant to stem and leaf rust, the principal diseases of wheat, and have been useful in plant breeding.

The 14-chromosome wheats were the first to produce species with tough stems and with kernels that thresh free from their glumes. Four such species are known: *durum* (macaroni), *persicum* (Persian), *turgidum* (rivet) and *polonicum* (Polish). All have a more recent history than einkorn or emmer. The oldest, durum, first appeared in the Greco-Roman period about the first century B.C. One of the most recent, Polish wheat, unique for its massive heads and long, hard kernels, did not appear until the 17th century. None of these wheats except durum is of great commercial importance today. Durum wheat, the best variety for the manufacture of macaroni, spaghetti and other edible paste products, is grown fairly extensively in Italy, Spain and parts of the U. S. Rivet wheat is of some interest because it is the tallest-growing (four to six feet high) and under ideal conditions one of the most productive. However, its grains are soft, yielding a weak flour unsuitable for breadmaking unless mixed with stronger wheats. One variety of rivet called "miracle" or "mummy" wheat, with massive branched heads, has been persistently exploited as a rare and valuable wheat claimed to have been propagated from prehistoric grains discovered in ancient Egyptian tombs, usually in the wrappings of a mummy. The story in all of its versions is a complete fabrication. Wheat kernels, like seeds of other plants, are living metabolic systems with a maximum life expectancy of about 10 years. Furthermore, there is no evidence that rivet wheat was ever known in ancient Egypt.

One additional 14-chromosomewheat, *T. timopheevi*, which has no common name, deserves mention. This species was discovered in this century by Russian botanists and is known only in western Georgia, where it is grown on a few thousand acres. The species is of botanical interest because its second set of seven chromosomes, designated genom G, is different from that of any of the other 14-chromosome wheats. It is also of great practical interest because it is resistant to virtually all diseases attacking other cultivated wheats, including rusts, smuts and mildews. In the hands of skilled wheat breeders it may become the ancestor of improved wheats for the next century.

Third Stage

The 21-chromosome wheats, of which there are five, are as a group the most recently evolved and the most useful today. All are cultivated; none has ever been known in the wild. All are products of the hybridization of 14-chromosome wheats containing the genoms A and B with a wild 7-chromosome relative of wheat (almost certainly a grass species of the genus *Aegilops*) containing the genom D. All are believed to have arisen from such hybridization after man, spreading the revolutionary art of agriculture, exposed his earlier cultivated wheats to hybridization with native grasses.

Two of the 21-chromosome wheats, *T. spelta* (spelt) and *T. macha*, are, like einkorn and emmer, hard-threshing species. *T. macha*, like *T. timopheevi*, is confined to western Georgia, where it is grown on not more than a few thousand acres. Spelt was once the principal wheat of central Europe. No archaeological remains of it have been found in the Near East or any part of Asia. There is no doubt about the hybrid origin of spelt, for it has now been synthesized by McFadden and Sears and independ-

LATIN NAME	COMMON NAME	CHROMOSOMES NUMBER	CHROMOSOMES GENOMS	GROWTH	GRAINS
T. AEGILOPOIDES	WILD EINKORN	7	A	WILD	HULLED
T. MONOCOCCUM	EINKORN	7	A	CULTIVATED	HULLED
T. DICOCCOIDES	WILD EMMER	14	AB	WILD	HULLED
T. DICOCCUM	EMMER	14	AB	CULTIVATED	HULLED
T. DURUM	MACARONI WHEAT	14	AB	CULTIVATED	NAKED
T. PERSICUM	PERSIAN WHEAT	14	AB	CULTIVATED	NAKED
T. TURGIDUM	RIVET WHEAT	14	AB	CULTIVATED	NAKED
T. POLONICUM	POLISH WHEAT	14	AB	CULTIVATED	NAKED
T. TIMOPHEEVI		14	AG	CULTIVATED	HULLED
T. AESTIVUM	COMMON WHEAT	21	ABD	CULTIVATED	NAKED
T. SPHAEROCOCCUM	SHOT WHEAT	21	ABD	CULTIVATED	NAKED
T. COMPACTUM	CLUB WHEAT	21	ABD	CULTIVATED	NAKED
T. SPELTA	SPELT	21	ABD	CULTIVATED	HULLED
T. MACHA	MACHA WHEAT	21	ABD	CULTIVATED	HULLED

SOME CHARACTERISTICS of the 14 species, as well as their distribution and antiquity, are given in this table. The genoms are sets of inherited characently by H. Kihara in Japan. In both cases the researchers concluded that the botanical characteristics to be sought in the unknown 7-chromosome parent of spelt were possessed by *Aegilops squarrosa*, a completely useless wild grass which grows as a weed in wheat fields from the Balkans to Afghanistan. Both researchers hybridized this wild grass with wild emmer. McFadden and Sears doubled the chromosome number by treatment with colchicine; Kihara was fortunate in discovering a case of natural doubling. The hybrid was highly fertile and similar in characteristics to cultivated spelt. As a final step in a brilliant piece of inductive reasoning and genetic experimentation, McFadden and Sears crossed their synthesized spelt with natural spelt and obtained fully fertile hybrids. The results leave no doubt that the wild grass used in this experiment is one of the parents of cultivated spelt, and they suggest strongly that the other four 21-chromosome wheats are likewise hybrids in which the genom D has been derived from the same grass or a species close to it.

These experiments suggest that cultivated spelt originated in the region where the species of wild grass and wild emmer overlap. But the primitive hulled form of spelt has not been found there. An alternate possibility is that the wild grass hybridized not with wild emmer but with the cultivated species, which has had a much wider distribution. Vavilov concluded that hulled spelt originated in southern Germany. Earlier Elisabeth Schiemann, Germany's leading student of cereals, had placed it in Switzerland and southwest Germany. Both centers are not far from the northeastern limits of the area in which cultivated emmer and the wild grass are known to have occurred together. Thus the botanical and historical evidence are not far apart in indicating a central European origin.

The remaining three species of 21-chromosome wheats are *T. aestivum* (common), *sphaerococcum* (shot) and *compactum* (club). They are the true bread wheats, accounting for about 90 per cent of all the wheat grown in the world today. The three are closely related and easily intercrossed. Whether they are the product of three different hybridizations between 14-chromosome wheats and wild grasses, or of three diverging lines of descent from a single hybridization, is not known. Club and shot wheat differ from common wheat in a number of details whose inheritance is governed by a relatively small number of genes. It is possible, therefore, that the three species are descended from a single hybrid ancestor. Common wheat or something very like it has recently been produced by Kihara by crossing 14-chromosome Persian wheat with the wild grass used to synthesize spelt. Its chromosome number has not yet been doubled, but its botanical characteristics are those of common wheat.

Where and when the modern bread wheat first occurred are still matters for conjecture. Since Persian wheat is known only in a limited area in northeastern Turkey and the adjoining states of the Soviet Union, common wheat very probably originated there. Kernels of shot wheat have been found at the most ancient site in India, Mohenjo-Daro, dated about 2500 B.C. A wheat found in neolithic store-chambers in Hungary has been identified as club wheat. Impressions of grains of bread wheat, either common or club, have been found in the neolithic Dolmen period, dated between 300 and 2300 B.C. The earliest archaeological wheat in Japan, dated in the third century, is regarded by Kihara as a bread wheat. And since the 14-chromosome wheats evidently are recent introductions in China, it is possible that the wheat described in the Chinese classics for the Chou period (about 1000 B.C.) is a 21-chromosome bread wheat. All these items, none in itself conclusive, indicate that the bread wheats originated before the time of Christ but later than einkorn or emmer. A conservative guess would put their origin at approximately 2500 B.C.

A Historic Explosion

Whether the bread wheats originated earlier than this or later, and whether they had one hybrid origin or three, they represent today the most rapid increase in geographical range and numbers of any species of seed-plant in history. They are now grown in all parts of the world from the Equator to the Arctic Circle. Originating probably not more than 5,000 years ago in the general region of Asia Minor, the new species have increased at an average rate of

GEOGRAPHICAL DISTRIBUTION	EARLIEST EVIDENCE
VESTERN IRAN, ASIA MINOR, GREECE, SOUTHERN YUGOSLAVIA	PRE-AGRICULTURAL
ASTERN CAUCASUS, ASIA MINOR, GREECE, CENTRAL EUROPE	4750 B. C.
VESTERN IRAN, SYRIA, NORTHERN PALESTINE, NORTHEASTERN TURKEY, ARMENIA	PRE-AGRICULTURAL
NDIA, CENTRAL ASIA, NORTHERN IRAN, GEORGIA, ARMENIA, EUROPE, MEDITERRANEAN AREA, ABYSSINIA	4000 B. C.
ENTRAL ASIA, IRAN, MESOPOTAMIA, TURKEY, ABYSSINIA, SOUTHEASTERN EUROPE, U.S.	100 B. C.
AGESTAN, GEORGIA, ARMENIA, NORTHEASTERN TURKEY	NO PREHISTORIC REMAINS
.BYSSINIA, SOUTHERN EUROPE	NO PREHISTORIC REMAINS
BYSSINIA, MEDITERRANEAN AREA	17TH CENTURY
VESTERN GEORGIA	20TH CENTURY
VORLD WIDE	NEOLITHIC PERIOD
ENTRAL AND NORTHWESTERN INDIA	2500 B. C.
OUTHWESTERN ASIA, SOUTHEASTERN EUROPE, U.S.	NEOLITHIC PERIOD
ENTRAL EUROPE	BRONZE AGE
VESTERN GEORGIA	20TH CENTURY

teristics, or combinations of sets. The chromosome number is a clue to the evolution of wheat. The species with larger chromosome numbers descended from those with smaller by hybridization and chromosome doubling.

HEAD of common wheat is dissected to show the rachis (*lower right*) which bears the spikelets. Enclosing each kernel is a bearded glume. In some varieties the beard is absent. At lower left is a single spikelet of spelt, which during threshing remains intact and attached to a joint of the rachis.

about 75,000 acres per year until they now occupy almost 400 million acres. Their evolution and dispersal have been explosive phenomena in which man's principal part has been to recognize their usefulness and to open up new agricultural areas for their culture.

The particular value of the bread wheats lies not only in their productiveness and in their free-threshing, naked kernels, but in the peculiar quality of their gluten, the protein component. Of all the cereals only the bread wheats are capable of producing the light, fluffy, leavened breads we know today.

All known species of cultivated wheat, except einkorn and possibly emmer, came into existence spontaneously. Man played no part in their origin except as he spread their culture and their opportunities for natural hybridization over the earth. There is no evidence that ancient man gave much attention to selection of superior forms, or if he did, no evidence that he succeeded. The cultivated einkorn of today is scarcely different from the einkorn of millennia ago, and it, in turn, is no great improvement over wild einkorn. Essentially the same can be said about emmer. Consequently, to speak of primitive man as a plant breeder is to attribute more purposefulness to his activities than the evidence warrants.

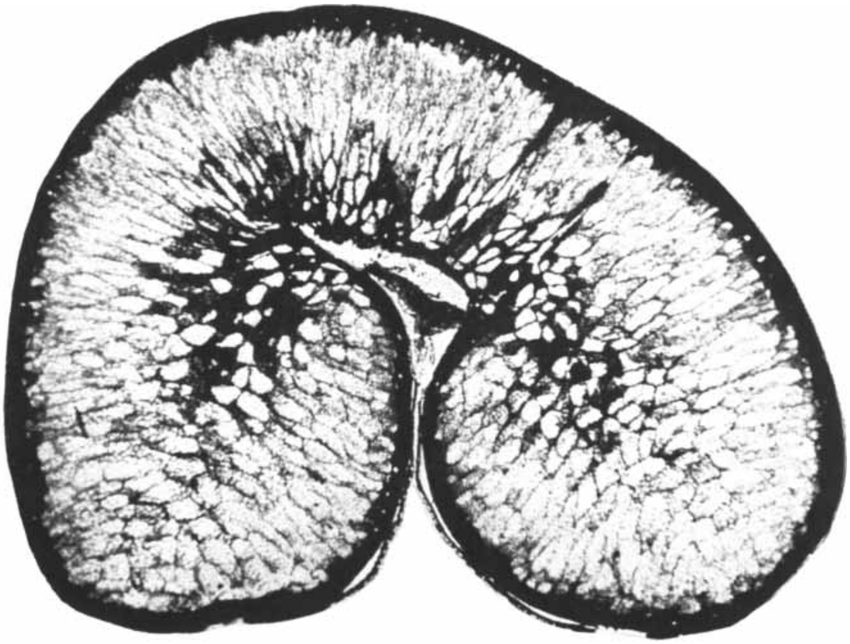
Within the past century, especially since the rediscovery of Mendel's laws of inheritance in 1900, vast programs of wheat improvement have been undertaken in almost all the wheat-growing regions of the world. These have been especially successful in the U. S. and Canada, where a constant succession of new varieties has been introduced. Scarcely any state of the Union today grows extensively the principal varieties of wheat grown 50 years ago.

Early in the century the most common method of wheat breeding was "pure-line" selection as invented by Wilhelm Johannsen, a Danish botanist and geneticist. Johannsen had concluded from experiments on garden beans that self-fertilized plants such as beans, peas and cereals are racial mixtures of many pure lines, differing from one another in many characteristics but each genetically uniform. Continuous selection can have no effect in changing the characters of a genetically pure line, but a mixture of lines can be separated into its component parts and improvements effected by propagating the superior lines.

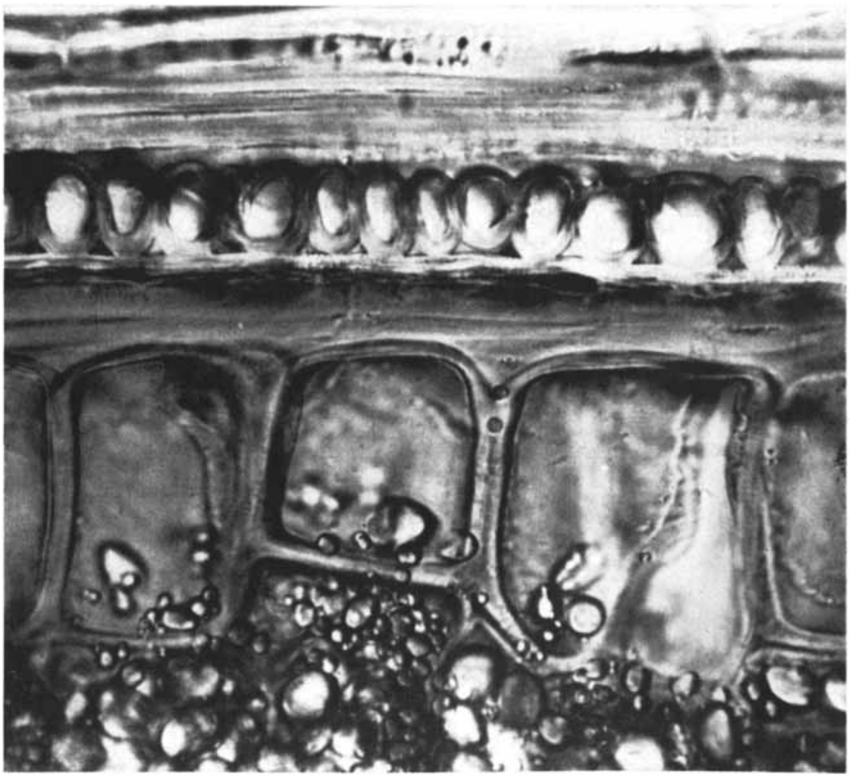
In practice the wheat breeder selects hundreds of individual heads from a variety, threshes each one separately and grows the progeny of each in a short row called a head row. In succeeding generations more and longer rows are grown, and the pure lines, each originating from a single head, are compared in productiveness and other characteristics. Among wheat breeders in the

U. S. it is standard procedure at this stage to use rows 16 feet long and one foot apart. Rows of this length and spacing simplify computation, since the yield of grain in grams can be converted to a bushel yield per acre by simply pointing off one decimal place. The more promising lines are increased still further in field plots and eventually one is chosen as the best, is named and is distributed to farmers.

The two outstanding U. S. varieties produced by pure-line selection are both Kansas products. The first, Kanred (Kansas Red), was selected by Herbert Roberts of the Kansas Agricultural Experiment Station from Crimean, a hard, red, winter-type wheat introduced from Russia by Mark Carleton. The first head selections were made in 1906, and the improved pure line first distributed for commercial growing in 1917. By 1925 Kanred wheat, the product of a single head only 19 years earlier, was grown on nearly five million acres in Kansas, Nebraska, Colorado, Oklahoma and Texas. The second Kansas wheat, Blackhull, is the product of a single head selection made in 1912 from a field of Turkey wheat by Earl Clark, a farmer and plant breeder. Blackhull, like Kanred, was first distributed in 1917. By 1929 it occupied almost six million acres, principally in Kansas and Oklahoma.



KERNEL of common wheat is photographed in cross section at the Northern Regional Research Laboratory of the U. S. Department of Agriculture. The interior of the kernel is the endosperm, from which flour is made.



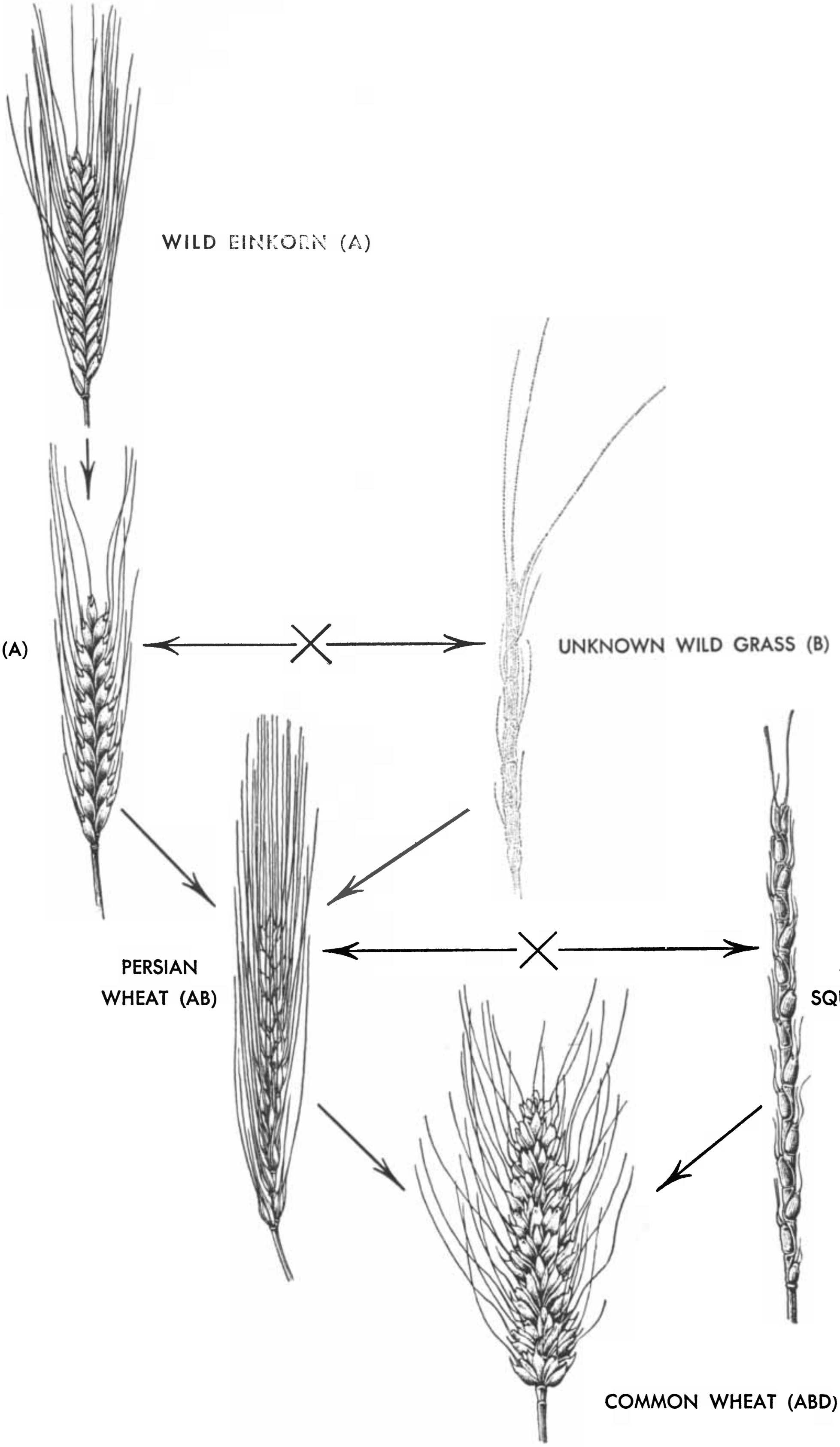
BRAN, or outer layer of the kernel, is shown in this photomicrograph made at the Northern Regional Research Laboratory. At the bottom of the photomicrograph, which enlarges these structures 600 times, is the endosperm.

The Hybrid Wheats

Pure-line selection merely sorts out from a variety the superior lines already there; it creates no new genetic combinations. To form a new variety the breeder employs hybridization. He selects as parents two varieties with the characteristics he seeks to combine. For example, one parent may be chosen for its superior milling and baking qualities, the other for its resistance to disease. To cross these two the breeder first emasculates one of them by removing the anthers, the male pollen-containing organs, with delicate forceps when these organs are full-grown but not yet ripe. Then he covers the emasculated head with a small glassine bag to prevent uncontrolled pollination. A few days later, when its female organs, the stigmas, have become receptive, the operator pollinates them with ripe anthers taken from the second parent.

Such pollinations produce seeds that grow into first-generation hybrid plants. These are quite uniform and nothing is accomplished by practicing selection among them. But in the second and subsequent generations genetic segregation creates new combinations as numerous and diverse as the hands in a shuffled deck of cards. The opportunities for creative selection are enormous. It is in the early generations following a cross that the plant breeder shows his skill, for at this stage he must select for propagation those combinations which approach most closely the ideal wheat he has in mind and discard those which do not meet his specifications. Eventually genetic segregation produces pure lines.

One of the earliest and greatest achievements in hybrid wheat was the development of the Marquis strain. This variety, a hybrid of early-growing Hard Red Calcutta from India and Red Fife from Poland, was produced in Canada by Charles Saunders, cerealist for the Dominion from 1903 to 1922. The cross from which Marquis wheat was derived



EVOLUTION of common wheat is outlined. Wild einkorn (7 chromosomes, genom A) evolved into einkorn, which, crossed with a wild grass (genom B), gave rise to Persian wheat (14 chromosomes, genom AB). When this wheat was crossed with another grass (genom D), common wheat (21 chromosomes, genom ABD) resulted.

had been made in 1892 by his brother Arthur under the direction of his father, William Saunders, who had been hybridizing wheats since 1888. The new hybrid was promising from the beginning. It was a few days earlier than the spring-planted varieties then commonly grown in Canada, thus often avoiding the first frosts. The grain yielded a cream-colored, strongly elastic dough with strong gluten and excellent baking qualities. Marquis wheat later set new standards for baking quality. By 1907, four years after the initial head selection, there were 23 pounds of seed. Distribution to farmers began in the spring of 1909. News of the new wheat spread swiftly from the prairie provinces down into our own spring-wheat belt. By 1913 Marquis seed was being imported into Minnesota and the Dakotas at the rate of 200,000 bushels per year. In 1918 more than 300 million bushels were produced, and the superiority of this variety over those previously grown was a factor in meeting the food shortage of World War I, just as 25 years later hybrid corn was a similar factor in World War II.

For 20 years Marquis was the "king of wheats" in Canada and the U. S., and during this period it served as a standard both in the field and in the milling and baking laboratory. Marquis was also used extensively as a parent in new hybrids and is the ancestor of many improved wheats, including Tenmarq, developed in Kansas by John Parker; Ceres, produced in North Dakota by L. R. Waldron, and Thatcher and Newthatch, bred by Herbert K. Hayes and his associates in Minnesota.

Today most new wheat varieties are produced by controlled hybridization rather than by pure-line selection, which is little used. The modern wheat breeder has many objectives. Usually his principal one is productiveness, but involved in this are many factors, including resistance to diseases and tolerance of unfavorable environmental conditions. To test new wheats for these characteristics, breeders have invented devices and methods for subjecting wheat to artificial drought, cold and epidemics of disease.

Breeders *v.* Fungi

Breeding for disease resistance is especially important because wheat is a self-fertilized plant which, except for natural hybridization and occasional mutations, tends to remain genetically uniform. A field of wheat of a single variety, especially one originating from a single head, contains millions of plants which are genetically identical. If the variety happens to be susceptible to a disease, it serves as a gigantic culture medium for the propagation of the disease organism, usually a fungus. Thus the growing of new varieties over large acreages increases the hazards from those diseases to which they are susceptible. The result is a never-ending battle between the wheat breeders and the fungi.

The breeding of wheat for resistance to stem rust, a devastating disease, is a prime example. There are many kinds of stem rust. Pathologists, led by Elvin Stakman of the University of Minnesota, have devised ingenious methods of identifying them by inoculation of different hosts. The wheat breeder then develops a new variety which is resistant to the predominating races of stem rust. This is distributed to farmers and its acreage increases rapidly. But while the wheat breeder is hybridizing wheats, nature is hybridizing rusts. The reproductive stage of stem rusts occurs not on wheat but on an alternate host, the common barberry. On this plant new races of rust are constantly created. Although most of them probably die out, one that finds susceptible wheat varieties may multiply prodigiously and in a few years become the predominating race. The wheat breeder then searches the world for wheats resistant to the new hazard and again goes through all the stages of producing a new hybrid variety. The competition between man and the fungi for the wheat crop of the world is a biological "cold war" which never ends.

A wheat breeder must seek not only disease resistance and productiveness but also milling and baking quality. In modern mass-production bakeries with high-speed mixing machinery, dough undergoes stresses and strains which it was never called on to endure when kneaded by hand in the home. As a result wheat breeders have been compelled to subject their new productions to elaborate milling and baking tests which simulate the processes of commercial bakeries. A new wheat that proves superior in the field may be rejected in the laboratory.

In spite of the difficulties involved, the development of more productive varieties of wheat is one of the surest ways of increasing the food supply and raising living standards. When Mussolini drained the Pontine swamp in Italy, the Italian wheat breeder Alzareno Strampelli produced new varieties of wheat which flourished in the fertile soils newly opened to cultivation. An important part of the well-publicized Etawah Village Improvement Program in India is the growing of improved varieties of wheat developed by British and Indian geneticists. Mexico's agricultural program, sponsored by the Rockefeller Foundation in cooperation with the Mexican Government, owes much of its success to new rust-resistant varieties of wheat. Crossing the old varieties of Mexican wheat with rust-resistant wheats from the U. S., South America, Australia and New Zealand, the U. S. breeder Norman Borlaug and his associates, working closely with Mexican technologists, have bred new varieties so resistant to rust that they can be grown in Mexico's summer rainy season as well as in the winter dry season, heretofore its only season for growing wheat. The bulk of Mexico's wheat acreage is now devoted to new hybrids developed since 1943, while acreage and production have expanded substantially.

Hybridization among wheats is usually confined to varieties of one species, but interspecific hybrids also are employed and sometimes are successful. A notable example is the development of Hope wheat by McFadden from a cross of Marquis with Yaroslav emmer, a 14-chromosome wheat extremely resistant to stem rust, leaf rust and several other diseases. From this hybrid, which was partly sterile, McFadden succeeded in developing a 21-chromosome wheat which has a high degree of resistance to many races of stem and leaf rust. Unfortunately Hope wheat has a grain somewhat lacking in milling and baking qualities and the variety has never become important commercially. It has, however, been the parent of many modern varieties of wheat which are commercially grown, including Newthatch in Minnesota, Austin in Texas and several of the new varieties developed in Mexico.

New Cereals

A future possibility in wheat breeding is the creation of wholly new types of cereals by species hybridization followed by artificial chromosome doubling, a man-made counterpart of wheat's earlier evolution in nature. In the U.S.S.R. and the U. S. wheat has been crossed with rye to produce a fertile, true-breeding hybrid cereal which combines the chromosomes of both. The hybrid, neither a wheat nor a rye, is more resistant to cold than wheat is, but less useful as a bread-making cereal. It has not become popular. Wheat has been crossed with a perennial wild grass to produce a new perennial cereal for which Russian agronomists have made fantastic claims. A field of this wheat, once planted, will, according to the Russians, yield a crop of grain year after year with little or no further attention except to gather the annual harvest. It turns out that this perennial "wheat" may have some promise as a forage grass for livestock, but so far little bread has been made from it and few people have been fed by it.

The idea of producing new cereal species by hybridization and chromosome doubling is, however, quite sound, and the possibilities inherent in it are far from exhausted. Some day new wheat species consciously created by man may replace those which arose spontaneously in nature.