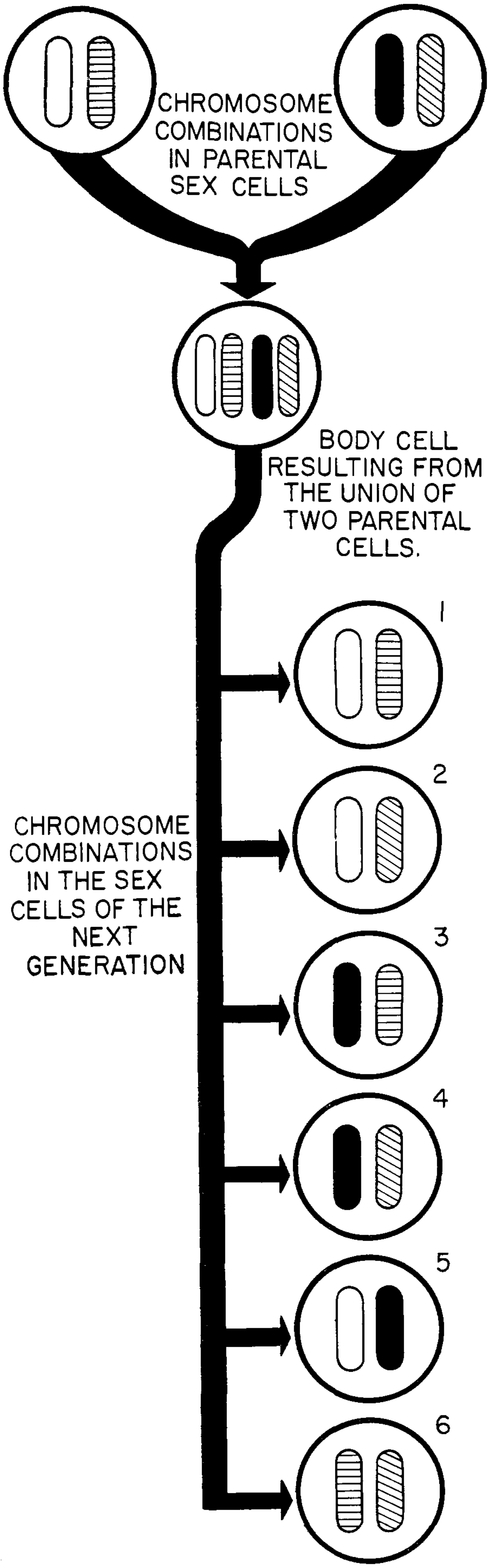

Plant Improvement Through Breeding

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PRODUCTION OF NEW VARIETIES of plants through breeding has been greatly improved since 1900 through the science of genetics—the science concerned with those small entities called genes, which are located in linear fashion on the chromosomes of living cells and which determine the hereditary characteristic of plants and animals, including man. The plant breeder evaluates and aids in the rearrangement of countless combinations of genes in a search for combinations of characters that will result in superior new varieties. Such varieties must be high-yielding, of high quality for the use intended, well adapted to their environment, and preferably easy to propagate.

The physical organization of living material through which these genes are transmitted from generation to generation is popularly called the germ plasm. Germ plasm is the hereditary core of living things. Diversity of germ plasm is both the key to survival of species and to the origin of new forms. Without diversity few of our present species could persist for long; many would be lost over large areas each year from ravages of diseases, insects, or bad weather. With the outbreak of a new menace to plant life or the occurrence of a natural disaster, only those divergent individuals can survive that resist the adverse condition, the disease, or pest. This is the law of the survival of the fittest. And without diversity, obviously no new combinations could occur and, therefore, no improvements could be made in our present species.

Collecting Diverse Germ Plasm

If the plant breeder wants to improve an existing variety but cannot find near at hand the desired character, such as hardiness to cold, resistance to a specific disease, tolerance to drought, or some particular growth habit, he must look to other regions and even other continents for suitable germ plasm. Interregional exchange of crops antedates recorded history, and exchange between the Old World and the New World began with the discovery of America. Thus, "foreign plant introduction" is not new.

It was not until some 25 years or more after the birth of the science of genetics (1900), however, that the importance of germ plasm collection on a methodical basis was appreciated. The Russian scientist Vavilov and his colleagues were among the first to develop systematic plant introductions on an extensive scale. They scoured the world for forms of plants of possible value to their own country. Vavilov's classic researches on the diversity of species in relation to their geographic centers of origin and development have served as a guide to the most prolific sources of germ plasm of possible value in breeding better varieties all over the world.

The first introductions of plants from one country or continent into another were made for the purpose of using the introduced plants in the form in which they were found. A considerable amount of such introduction is in progress today, especially introduction of American varieties into numerous countries participating in the Point Four program. In the United States standards of excellence required in new varieties have gradually increased along with intensification of properties that make a variety suitable for a specific purpose or mode of production. At the same time pressure on the plantsman has been increased by the need for resistance to specific diseases and adaptability to hot,

Figure 1. Onion flowers as seen by the plant geneticist. Magnified 25×, on the left a normal flower, right, a sterile male with abortive anthers

cold, or dry climates. All these desired qualities are rarely if ever found in any single introduction from abroad. The interest in foreign introductions has, therefore, shifted to include varieties or wild plants that may be utterly worthless commercially in their present form but which may contain genes for only one or a few additional characters needed in the development of a superior new sort. Collections now are not limited to varieties of the same species as the one to be improved but include closely related cultivated and wild species which might possess one or more genes that can be incorporated into a superior new variety.

Unfortunately, some of the world's best sources of plant materials are now closed to outsiders. The Sino-Japanese war closed much of the Far East in the early 1930's and since the late 1930's international tensions have closed much of the Near East and western Asia to our explorers. Many valuable introductions from those areas were obtained, however, before they became inaccessible.

Germ Plasm Bank

The importance of germ plasm banks for preservation of germ plasm was not appreciated fully until recently. Formerly thousands of introductions of numerous crop species were given preliminary evaluation, were found to be of no use at the time, and were discarded. Others were lost when the seeds lost viability through lack of care as a result of shortage of personnel or adequate research funds to maintain them. As the hard-pressed plant breeder searches diligently through available stocks for that one gene which may mean the difference between optimum production and disaster to countless growers, he often wishes he had available the materials which were lost or discarded before a present menace was even known.

Regional maintenance and distribution stations for germ plasm recently have been established cooperatively by State Agricultural Experiment Stations of the respective regions. These are located at Ames, Iowa; Experiment, Ga.; Pullman, Wash.; and Geneva, N. Y. Each station gives special attention to those crops of importance in its region. Dry, cool, storage facilities for seed have been provided in order to prolong the life of the seed and reduce the frequency with which it becomes necessary to produce a new generation of seed at considerable expense. Facilities for growing seed are also provided. A State-Federal potato germ plasm bank has been established at Sturgeon Bay, Wis. Many state and other research groups maintain less extensive but highly important banks of breeding materials and foreign introductions.

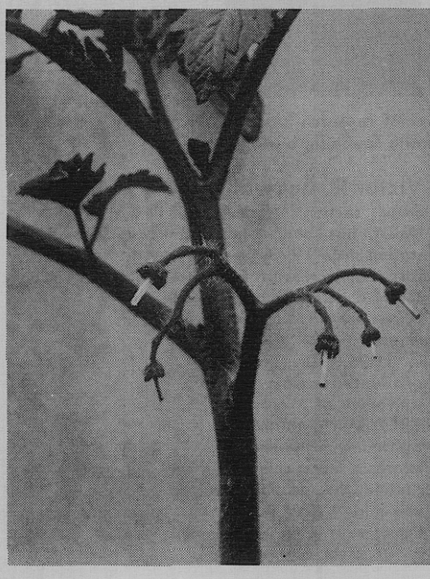
Evaluating Germ Plasm

The evaluation of germ plasm is a never-ending task, always time-consuming and expensive, often difficult, and sometimes unreliable because of factors beyond the investigator's control. Evaluation of each foreign introduction and newly produced variety for its agronomic or horticultural value requires trial plantings in each kind of environment in which its culture might be desired. Determining relative resistance to diseases to insects, to heat, to cold, to drought, or to adverse soil conditions involves repeated tests against each factor. Experience has shown that exposure to uncontrolled natural conditions is, in most instances, too slow and unreliable and, therefore, too expensive to be an acceptable method of evaluation under current conditions. To a rapidly increasing extent artificially controlled test conditions are being devised and used. With mechanical control of temperature, humidity, light, nutrients, and culture medium and with the suitable application of pure cultures of fungi, bacteria, viruses, or populations of nematodes or insects, highly reliable evaluations are rapidly obtained.

Many workers now test tens of thousands of plants against specific diseases in a period of weeks in a controlled greenhouse, obtaining more dependable results at lower cost than could be obtained on many acres of land in a year or more in the field. Certain diseases or pests, however, occur consistently enough in the field to permit satisfactory testing under field conditions.

Diseases are known in other lands which are not yet present in our country but which very probably will spread into the United States by natural or other means. Plant breeders and plant pathologists, in cooperation with those of other lands, sometimes test our collections of germ plasm in those lands where the disease already is present instead of waiting for it to attack us here. For example, over 11,000 kinds of wheat have been tested for reaction to race 15B of stem rust in Mexico where that race of rust is consistently prevalent. Also, workers in

Figure 2. Tomato flowers which have been emasculated for cross pollination experiments by removing anthers



Mexico aid us by testing some of our potato germ plasm collections for reaction to strains of the dread potato blight that are not yet found in our fields. By this kind of forehanded international evaluation of germ plasm, this country can be prepared to some degree in advance of serious plant scourges; and we may also help the cooperating country deal with problems already present within its borders.

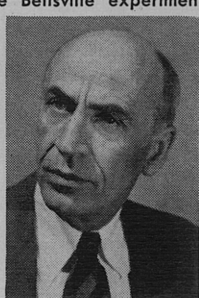
Altering Germ Plasm Artificially

When the breeder finds that none of the germ plasm available to him possess the particular character or characters he needs there are two possible ways of finding such characters. New explorations to collect additional materials may be sent abroad in the hope that the missing characters may be found somewhere, or attempts can be made to alter the available germ plasm in the direction desired. Of these alternatives, experience indicates that the former is more likely to be fruitful, but too often the costs or other factors make it prohibitive.

Nature produces alterations in germ plasm—introduces additional diversity into existing forms—through mutations. Mutations are changes in hereditary factors or genes which in turn cause changes in the characters that are controlled by those genes. Under natural conditions mutations are rare but they occur often enough to have been an important source of plant improvements and also a cause of varietal deterioration in some plants.

Martin G. Weiss, chief of the Field Crops Research Branch, USDA Agricultural Research Service, took his B.S., M.S., and Ph.D. at Iowa State. From 1936 until 1941, he was at the USDA's experiment station at Iowa State, returning to Iowa State as research professor of farm crops in 1945 after three years in the Army field artillery as a lieutenant colonel. He came to USDA's Beltsville, Md., experiment station in 1950 as project leader in charge of soybean investigations. His chief research has been in plant genetics work with soybean, barley, and forage crops.

Victor R. Boswell, head of the vegetable crops section, Agricultural Research Service, USDA, has been at the Beltsville experiment station since 1928. Before that he was professor of olericulture at the University of Maryland, where he took his Ph.D. in 1926. Dr. Boswell graduated from the University of Missouri in 1922 with a degree in agronomy. His research interests have centered around the production, physiology, and breeding of vegetable crops.



Gene mutations involve random changes and although those changes sometimes represent improvements, they are usually harmful rather than helpful, from man's point of view. As a rough illustration, a variety of crop plants that has evolved through countless generations of natural selection followed by purposeful selection by man may be likened to a watch—the product of many generations of human skill. If we drop a watch on a floor one or more random changes may occur. There is a possibility—very remote of course—that some random change in the dropped watch will improve its appearance or its operation above that possessed before it was dropped. Obviously, most random changes of this kind leave us with a less desirable rather than more desirable organization of materials.

Some mutations are beneficial in some circumstances, harmful in others. What if adaptation to a new or changing environment is sought? A mutation to white coat in the cottontail rabbit would doubtless be deleterious in Florida, because the rabbit's protective coloration would be gone; but in the far north it might permit survival of the species. A mutation to high carotene content in a pale-fleshed variety of sweet potato is seized upon as a valuable find in this country but in some other lands it would be discarded as unattractive and, therefore, undesirable.

Induced Mutations

In a specific plant improvement program it is hardly sufficient to await the random chance of a naturally occurring mutation to obtain the desired change. Mutations, however, can be stimulated artificially at frequencies far greater than they occur naturally. X-rays and, more recently, radioactive materials from thermonuclear processes have been used to increase the frequency of mutations. Mutations induced by such means have contributed substantially to basic knowledge of genetics and plant breeding. It appears that the diversity induced in plants by x-rays is similar to that which occurs naturally; that is, most of the changes that can be noted are of no value to man.

No noteworthy improvement in plants has been produced through irradiation in this country, but Swedish scientists have reported marked success in improving small grains through x-radiation. Work in the United States with oats indicates that disease resistance, plant height, and other characters can be modified in the desired direction, as well as in undesired directions, by radiation from thermonuclear products. It should be emphasized that irradiation, as yet, does not offer any quick, sure, and easy method of modifying germ plasm in just the way that man would like to have it

Figure 3. Operator is removing anthers from onion flowers which will then be placed in the transparent film bags with blow flies. The blow flies will carry pollen from male to female flowers inside the bag

modified to serve his immediate purposes. As by other methods of plant improvement, hundreds of thousands of plants must be grown from irradiated material and carefully evaluated individually in order to find any improved properties. Nevertheless, irradiation may hold important potentialities of hastening the occurrence of desired variations, such as increased resistance to disease, in plants.

Rearranging Genes in Germ Plasm

Up to this point we have dealt almost entirely with the raw stuff with which the plant breeder works—what it is, where and how he gets it, how he stockpiles it and classifies it for use, and for what purposes. From this point are outlined some of the ways the plant breeder works with his raw materials to produce new and, he always hopes, better varieties of crop plants.

The plant breeder has not yet created a new gene but he is rapidly discovering new ones and determining how they control the characteristics of plants. In the first paragraph we referred to the plant breeder's rearrangement of genes in his efforts to produce new and more useful kinds of plants. His "creations" consist only of new arrangements of genes and groups of genes, much as the synthetic chemist's "creations" consist of new arrangements of atoms and groups of atoms. For the most part the plant breeder only rearranges plant characters, but occasionally he rearranges genes in such a manner as to "create" a specific plant character not known to exist previously. Many new combinations of characters are constantly being produced by purposefully improving the chances for them to occur.

A plant breeder must find or establish a population of plants with adequate diversity of germ plasm to afford good chance for the desired combination to occur before he can hope to develop a variety that has that desired combination of traits. Such combinations, if not already present in a mixed population, often may be brought about through hybridization of parent types which together contain the characters the breeder strives to combine in one type.

Mechanics of Hybridization

Controlled crosses in plants are made through use of diverse and ingenious methods. The task is usually easy in crops which bear male and female flowers separately, such as corn, hemp, cucumbers, and melons. For example, pollen from the male flower or tassel of one corn plant can be collected and transferred to the stigma of the protected female flower—silk of the ear—of another plant. In most plants which have complete flowers—female and male parts in the same flower (Figure 1), some provision must be made to prevent self-pollination, and in all cases unwanted foreign pollen must be excluded, usually by bagging or caging the female parent flowers.

In some crops the pollen-bearing anthers must be removed manually prior to shedding of pollen (Figure 2). In others, such as sorghum, the flower may be submerged in hot water or dilute alcohol solutions to kill the pollen. Conditions must be controlled carefully so that pollen in the anthers is killed without injury to the female portion of the flowers. In flowers like those of lettuce no method of emasculation or inactivation of the pollen has been developed. The hybridizer cannot work with the flower until after pollen has been discharged upon the stigma, then, before it germinates, he must wash this self pollen from the stigma with a tiny jet of water and replace it with the desired pollen.

With certain flower structures it is impossible to isolate the female from the male portion without removing either from the flower. In the cotton flower a piece of soda straw slipped over the female part effectively isolates it from undesired pollen. With the lima bean the stigma and part of the pistil may be extruded from the unopened petals of the bud leaving the immature anthers enclosed, thus preventing contamination of the stigma by self pollen. The naked stigma, however, must be protected from other unwanted pollen by doing this work in an insect-free enclosure. This is best done in a screened greenhouse equipped with fine mist nozzles for maintaining high humidity to prevent drying-out of the pistils. Regardless of method of isolation, pollen from the male parent must be applied to the isolated female portion of the female parent plant, often by the tedious manual application with a camel's-hair brush.

In certain crops such as onion, sugar beet, barley, and others having complete flowers, a male sterile gene may be introduced into prospective female lines to prevent formation of functional pollen (Figure 1, right). Such lines, having no pollen, cannot be self-pollinated; all seed formed must be of hybrid origin. When male sterility is present in the female or the female parent flowers have been emasculated insects may be used to effect the cross pollination. Introduction of appropriate numbers of artificially reared blowflies into bags or cages containing the male and female parent flowers of onion has been highly successful in relieving the breeder of a time-consuming task. The pupae of these flies are held in cold storage in containers of sand until a few days before the flies are needed. The flies soon emerge from pupae placed at room temperature in small screen containers from which they are introduced to the bags or cages enclosing the flowers (Figure 3). Hives of bees may be used in large cages containing male-sterile and pollinating lines. Many forage legumes may be cross pollinated successfully by enclosing them in a screen cage with honey bees or bumble bees.

Special Problems

As though the mechanics of controlled pollen transfer do not introduce enough problems, prospective parent varieties sometimes are relatively incompatible. For instance, pollen tubes from one plant may be prohibited from growing in female tissue of another plant because of the presence of genes promoting incompatibility. In such a case fertilization of the egg cell does not occur. Or, after fertilization, the new plant or embryo may be crowded out by abnormal growth and development of cells from the female flower. Some parent varieties or species do not flower at the same time. Sometimes that difference in time of development can be overcome by manipulation of planting dates. In instances of parents that respond differently to daylength, however, it may be necessary to alter artificially the photoperiod under which one or the other is grown in order to induce simultaneous flowering. In breeding plants commonly propagated asexually many otherwise highly desirable potential parents remain useless because of their lack of flowers or of functional egg or pollen cells. Sometimes it is possible by altering light, temperature, or other environ-

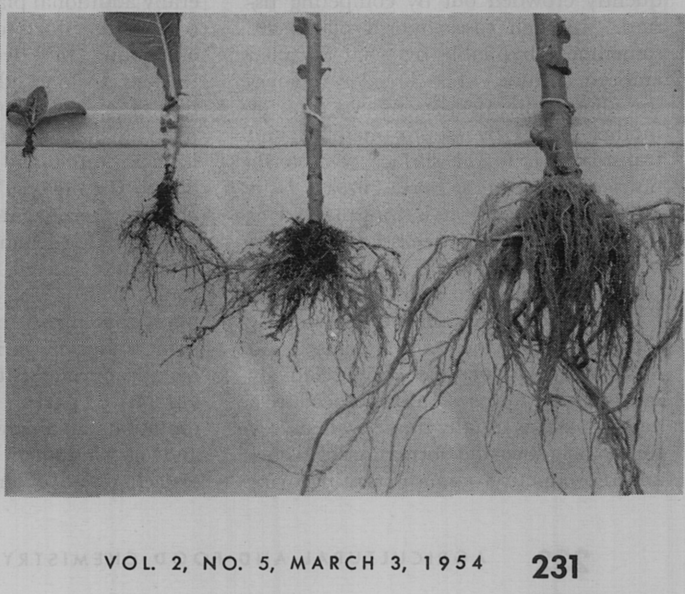
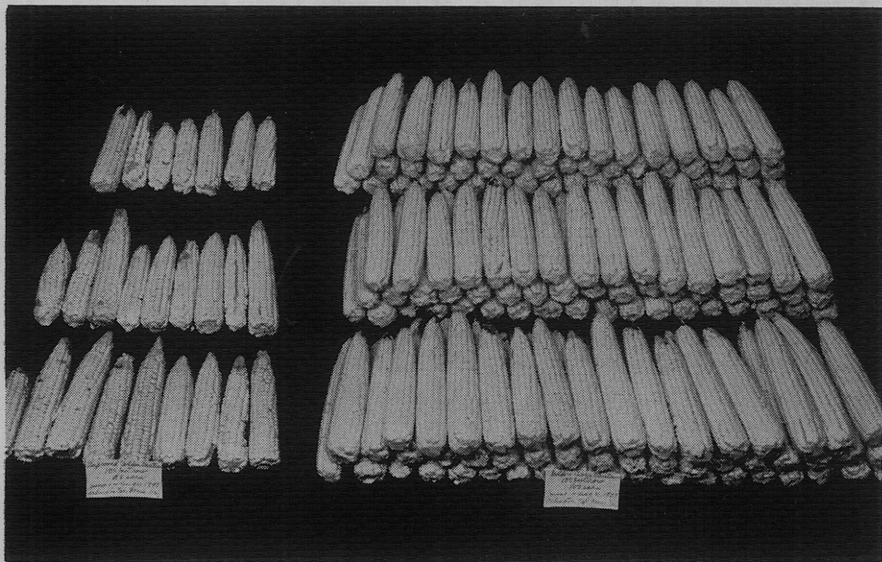



Figure 4 and Figure 5. Two experiments in plant breeding for disease resistance. On the right. A species of tobacco resistant to blue mold, left, was crossed with commercial variety, right, to produce hybrid plant, center. In picture on right, resistance to black root rot is illustrated: a susceptible variety, two resistant varieties, and resulting immune hybrids



Yields from disease resistant varieties of corn compared with normal susceptible strains. Left, improved Golden Bantam produced 25 marketable ears from a 130 ft. row. Right, Golden Cross Bantam, a disease resistant variety, produced 153 marketable ears from a row of the same length

mental conditions, or by physiological tricks such as ringing or girdling to induce production of functional reproductive organs. Breeders sometimes take or send their selected parents to a distant land of quite different environment in order to make crosses that cannot be made economically, or at all, at their home bases of operations. For example, breeders in Puerto Rico are making certain crosses of sweet potato varieties that cannot satisfactorily be accomplished in the United States.

Many times the breeder cannot find the desired trait in the crop species with which he is working and must look to exotic and wild relatives of the crop (Figure 4). Much difficulty is usually encountered in making interspecific crosses. At times growth-regulating substances applied to the female flower are effective in stimulating hybridization or preventing flower drop before slow-growing pollen tubes reach the egg cell. In other instances the hybrid embryo may become established but is subsequently crowded out by competing tissues. In such cases hybrid plants are sometimes obtainable by what is called embryo culture. The breeder removes the almost microscopic embryo from its mother tissues by aseptic methods and transplants it to the surface of a sterile nutrient jelly in a sterile flask. If it grows satisfactorily it is transplanted as a tiny plantlet some weeks later to a pot of soil and ultimately to the bed or field where it develops to a full-grown plant.

Chromosome doubling of parents by the use of colchicine is also used as an aid to effecting unions between relatively incompatible forms. In this procedure a parent plant is usually treated when very small to induce the formation of tissues and reproductive organs possessing twice the normal numbers of chromosomes. For reasons not understood such a "doubled" or tetraploid parent will sometimes cross more readily with a non-doubled or diploid plant than it would in its original form. Although such a procedure may yield an improved percentage of successful crosses the progeny, being triploid, is difficult to work with and leaves much to be desired. Chromosome doubling has been more useful as a device to obtain fertility in sterile progenies of hybrids.

Systems of Breeding

Hybridization, although it often involves great difficulties in itself, is only a single step, the first after finding suitable parents to use. The work of hybridization is usually the least part of the breeder's task. The choice of suitable parents may require years of search and testing before any hybridizing of even the easiest kind is in order. Then beyond the successful first hybridization must come generations of selection and generally additional planned recombinations (crosses) in efforts to improve the chances of finding the desired set of characteristics in one plant. Among plants that are normally propagated by vegetative (asexual) means, it is not necessary to carry out many generations of selection to "fix the type" as it is among plants normally propagated by seeds (sexual means). For example, once the breeder finds in a mixed population of sugar canes, fruit trees, or potatoes just one plant that meets the requirements, that plant is the new variety. It is multiplied by appropriate cuttings or divisions of vegetative parts. Aside from chance mutation, no further shuffling of genes and of characters occurs because the sex cells do not enter into the propagation process. In plants normally propagated by seeds, after one or a few satisfactory plants are found in a mixed population, there remains many generations of further selection to produce a supply of foundation seed that will in turn produce plants of reasonable uniformity and conformity to requirements.

The system to be followed after successful hybridization depends upon the plant characters the breeder is dealing with and the manner in which they are inherited. Sometimes simple selection suffices to turn up the new combination of characters sought, but more often repeated backcrossing (crossing of a hybrid or a selection following hybridization with one of the parents of the original hybrid) is necessary to build up the resemblance of the new sort to the more desirable parent. Often too, the characters of a third parent must be introduced (by outcrossing), or many more than three parents may contribute to a final result. The pedigrees of many of our modern crop varieties are highly involved and represent up to 25 years or more of painstaking work.

Some End Results

In the evaluation of potential new varieties the breeder joins hands with the manufacturer, the chemist, the shipper, the food processor, the end user. Baking laboratories are maintained as a part of the wheat breeding program; malting laboratories for barley; canning, freezing, and cooking laboratories for fruits and vegetables; processing laboratories for peanuts; chemical laboratories for oil seeds and sugar plants; and textile laboratories for fibers. Before a new variety is released to the public it should be subjected to every practicable test to ensure that it will be satisfactory for the use intended.

Our main purpose here has been to give some idea of how the modern plant breeder goes about his job and why. It is possible here to mention only a few examples of the scores of highly important successes of the past 30 years, but they are to be found over a very wide range of plant production and utilization problems. These successes are of direct interest to producers, manufacturers, and consumers alike and include: disease resistant and more productive varieties of wheat, corn (Figure 6), oats, barley, rice, potatoes, sugar cane, pasture and hay plants, cotton, tobacco (Figure 5), soybeans, castor beans, and other industrial raw stuffs, vegetables, fruits, and flowers.

Almost anyone can make intervarietal hybrids within species, or even interspecies hybrids after some one shows how it can be done, but to obtain an improved, and more useful variety following such a hybridization is quite another matter.