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The Potato

What is the botanical origin of this important crop plant, and how did it first become domesticated?

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Among the most primitive potato fields in the world are those clustered about the high, cool rim of the Lake Titicaca basin in southern Peru and northern Bolivia, as well as along the steep valley walls flanking the ancient Inca capital of Cuzco, Peru. In both places the potato forms the chief subsistence crop of the local Aymara and Quechua Indians, who continue to cultivate their land in a manner essentially unchanged from that of their pre-Columbian ancestors (Fig. 1).

In its Andean homeland the potato figures prominently in the folklore and recorded postconquest histories of the Aymara and Quechua Indians as well as in the more than 2000-year-old archeological record of potato cultivation left by earlier cultures (*1*). The earliest preserved remains of the potato come from archeological sites at Chiripa, on the shores of Lake Titicaca (the present gene center in the sense of Vavilov); the ruins of Tiahuanaco in northern Bolivia and Pachacamac near Lima; and burial grounds at Arica, on the coast of northern Chile (*2, 3*). These remains date from about 400 B.C. to A.D. 1000, and consist of dried potato tubers or chuño, appearing no different in form from that processed today. Many clay phytomorphic representations of the potato have been found in pre-Inca ruins, especially on the northern and central coasts of Peru (*4, 5*). These consist of pottery vessels of many types, each characteristic of a different period, and often quite accurate in detail (Fig. 2). However interesting as these artifacts may be to anthropologists and archeologists, they give us little clue as to the origin of the cultivated potato from a botanical viewpoint. They do show, however, that the potato was in a highly developed stage of domestication at the time when these ceramics were manufactured; in fact, these clay representations of the potato are extremely similar in form and "eye" portrayal to present-day tubers as seen in native Peruvian markets (Fig. 3).

The potato, therefore, was probably in cultivation and in the process of development long before its initial appearance in the archeological record. Unfortunately, no phytomorphic representations or actual dried tuber remains of the potato have been recovered from the preagricultural campsites and kitchen middens of early South American man at Huaca Prieta and at San Nicolas, Peru. Both sites were once inhabited by a seminomadic culture that had an economy based largely upon fishing, hunting, and plant gathering (*6*). Consequently, we know very little about the history of the potato during its most critical period of evolution, that is, from the time of the initial appearance of the first nomadic hunters and plant gatherers in the Central Andes to the onset of the great civilizations founded by the Mochican, Chavin, Nazca, and Tiahuanacan cultures.

However, much insight into the evolution of the potato under domestication may be gathered from other lines of scientific evidence. Foremost among these are comparative studies of the cultivation of the potato by modern-day primitive agriculturalists, as well as cytological, genetic, taxonomic, and biosystematic studies of the crop itself.

The Andean farmer, like the modern Mexican cultivator of the potato (*7, 8*), often devotes far more time and effort to the initial preparation and planting of his field than to its subsequent care. His fields, therefore, are commonly invaded by large populations of wild or semiwild (that is, weedy) potato species, which tend to become firmly established in and between the rows of potato plants, as well as along marginal thickets of the fields. Although of little direct value to man, these plants are rarely removed or disturbed by the Indian farmer, who generally sees little harm in their presence. As a result, the wild or weedy species of potato are given ample opportunities not only to flourish, but also to hybridize with the crop.

The intimate relationship which exists between wild potatoes and cultivars has been generally overlooked by specialists seeking to explain the origin of the extreme variability of the cultivated potato. It is thus no surprise that the source of this variability has often been attributed solely to gene exchange between the diploid and tetraploid cultivars of the cultivated potato (*9*). The evidence now on hand, however, indicates that much wild germ plasm has been, and probably continues to be, introduced into both diploid and tetraploid populations of *Solanum tuberosum* through hybridization and introgression, and that hybridization has also played an important role in the origin of potato-field weed species as well as in the origin of the cultivated potato itself.

Classification of the Potato

The cultivated potato is a member of the nightshade family, or Solanaceae. Botanically, the potato is treated in the section Tuberarium of the genus

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Solanum. In addition to the cultivated potato, this section includes about 160 wild tuber-bearing species of *Solanum* that range in distribution from southwestern Nebraska (latitude 42°N) to south central Chile (47°S) (*10–12*). However, the cradle of potato variability in the New World lies in the Andes of Peru and Bolivia. Within this region are found over 90 species of wild potato as well as over 400 indigenously named cultivars (or varieties) of the common potato.

Authorities differ on the number of distinct species of cultivated potato. This article follows the 1962 classification of K. S. Dodds, who recognizes one cultivated species, *S. tuberosum* (plus five horticultural groups), and two hybrid cultivars, *S.* × *juzepczukii* and *S.* × *curtilobum* (*13*). Other botanists recognize as many as 20 species of cultivated potato. However, Dodds' system of classification (Table 1) is unique as it is the only one which currently follows the *International Code of Nomenclature for Cultivated Plants*, rather than the *International Code of Botanical Nomenclature* which was set up primarily for the naming of wild species. Moreover, his classification appears to conform closely with the known genetic and evolutionary facts. All authorities agree, however, that the cultivated potatoes, whatever their specific number, fall into the four following distinct categories, as determined by the number of complete sets of chromosomes in their somatic cells: two sets (diploid, $2n = 24$); three sets (triploid, $2n = 36$); four sets (tetraploid, $2n = 48$); and five sets (pentaploid, $2n = 60$). Only the botanical origins of the Andean tetraploid and diploid potatoes (*S. tuberosum* groups Andigena and Stenotomum) will be extensively dealt with in this article since the others are fairly well known by comparison (*1, 13*).

Evolution of the Tetraploid Potatoes

According to the English potato specialist Hawkes (*1, 14*) the tetraploid *S. tuberosum* group Andigena potatoes arose in the Andes of Peru and Bolivia from one wild and one cultivated potato species by the process of amphidiploidy (that is, through the spontaneous doubling of the chromosomes of a diploid hybrid). Of the two putative ancestral diploid species considered by Hawkes, the first (*S. stenotomum;* = *S. tuberosum* group Stenotomum) is a primitive cultigen restricted to the Andes of South America, whereas the second (*S. sparsipilum*) is an aggressive weed that occurs naturally in the cultivated potato fields of Peru and Bolivia. Although the two putative ancestral species put forth by Hawkes do appear to be reasonable choices, and, in fact, are very likely to have been involved in the production of allotetraploids, it is difficult to believe that other diploid taxa, as well as other mechanisms of speciation other than that of amphidiploidy, were not indirectly (if not directly) very much a part of the overall cycle of potato evolution which led ultimately to the appearance of the cultivated tetraploids.

Fig. 1. Quechua Indians using the footplow, or "taclla," an instrument used to turn the soil in preparation for planting potatoes. Ceramic models of the footplow are known from the Chimu period (about A.D. 800).

The origin of the diploid species *S. sparsipilum* is a case in point. The results of the writer's own biosystematic studies on this group suggest that the various forms of this highly polymorphic species have arisen independently of each other in different localities throughout Peru and Bolivia (*15*). They probably owe their origin to the direct stabilization of a large number of diploid hybrid variants formed in natural crosses of the diploid cultivars of *S. tuberosum* (groups Stenotomum and Phureja) with either one or more (depending upon the locality where the hybridizations have taken place) of the following three closely related wild species: *S. canasense, S. brevicaule*, or *S. raphanifolium*. Due to their partly common ancestry from diploid *S. tuberosum* as well as their wide range of variability, it is probably best to maintain these stabilized hybrid derivatives under the single species, *S. sparsipilum*, rather than accord them specific or subspecific rank, as has been attempted in the past (*16*).

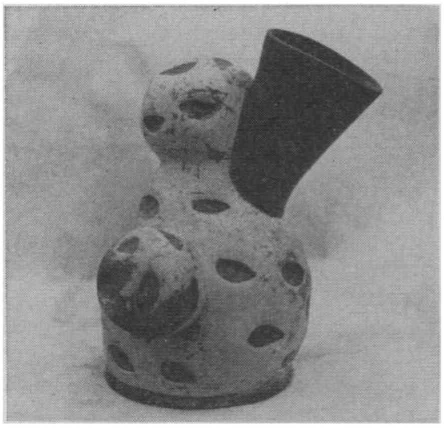

Fig. 2. Mochica vessel (about A.D. 400) portraying a special brand of dehydrated potato known as tunta, a product that is still manufactured in the Peruvian highlands today. Tunta is a stream-washed, or more purified version of another dehydrated form of the potato known as chuño. Both tunta and the darker colored chuño may be kept in storage almost indefinitely.

Several other possible modes of origin for the tetraploid Andean potatoes are suggested here. If one considers the low degree of genomic differentiation which exists among the weedy species of *Solanum*, section Tuberarium, the tendency toward polyploidy, the high incidence of natural interspecific hybridizations, and the tremendous diversity of the tetraploid cultivars, then it becomes difficult to escape the conclusion that there were probably a number of independently acting, but genetically interconnected, lines of evolution that were simultaneously involved. These could have given rise to an assemblage of primitive tetraploid cultivars which, through hybridization, have now become merged into the single cultigen, *S. tuberosum* group Andigena.

Thus, the view formerly entertained by Hawkes (*14*) that tetraploid *S. tuberosum* arose directly from the diploid group Stenotomum cultivars by autopolyploidy deserves reconsideration, at least as a partial explanation of the enormous variability of the tetraploid cultivars. However, the opinions of Brücher and Cardenas (*17*) regarding the possible ancestral role of the diploid northern Argentine wild potato species, *S. vernei*, would, if considered in the light of possible crosses and subsequent amphidiploid formation with diploid cultivars, be equally tenable. No doubt other wild diploid species of potato may have been also indirectly involved (see below).

The diploid *S. tuberosum* group Phureja cultivars are still another possible source of the variation to be seen in the tetraploid Andean cultivars of *S. tuberosum*. These may have given rise to broad segments of the tetraploid complex through either autopolyploidy or amphidiploidy, or possibly a combination of both. Like the *S. tuberosum* group Stenotomum cultivars from which they are obviously derived, the group Phureja cultivars are known to cross readily with the wild diploid *Solanum* species of section Tuberarium (and particularly the ubiquitous species of series Tuberosa and series Megistacroloba) and thus it would not appear unlikely that this group has given rise to certain forms of tetraploid *S. tuberosum* by interspecific hybridization, followed by chromosome doubling.

The introgression of wild germ plasm into *S. tuberosum* group Andigena through the semiwild *S.* × *curtilobum* appears to have contributed greatly to the variability of the cultivars of *S. tuberosum* grown in the vicinity of Lake Titicaca in southern Peru and northern Bolivia (*7*). Although pentaploid and often sterile, some clones of *S.* × *curtilobum* are as highly fertile as some indigenously grown cultivars of *S. tuberosum* group Andigena. The more fertile clones of this hybrid (Table 1) could serve as a genetic bridge for the natural introgression of genes from *S. acaule* into *S. tuberosum*. Certainly the extreme morphological variability and unusually high frost tolerances of the Lake Titicaca populations of *S. tuberosum* would suggest that gene exchanges with such hardy species as *S. acaule* have indeed played a major role in their evolution.

Evolution of the Diploid Potatoes

Ancestral to all the modern cultivars of the potato, the primitive *S. tuberosum* group Stenotomum cultivars have regularly occupied the attention of potato specialists from the time of their announced discovery by Russian cytologist V. A. Rybin in the mid 1920's [the report of which was officially published in 1929 (*18*)]. After Rybin's announcement, cytological and taxonomic studies of the diploid cultivars were taken up or continued in many different regions of the globe, and from these investigations, truly international in scope, a picture is beginning to emerge of the evolution of the potato under domestication.

Fig. 3. A market vendor in Puno, Peru. Potatoes of many different sizes, shapes, skin colors, textures, cooking properties, and flavors are sold in the native market places of southern Peru. All three chromosomal groups of *S. tuberosum* may be represented within a single market pile of Andean potatoes. However, cytological study is frequently the only means by which these may be told apart.

Thanks largely to the efforts of these scientists, the distribution and various horticultural characteristics of the cultivated diploid potatoes have now been fairly well worked out. The botanical origins of the cultivated diploids, however, have not been as thoroughly investigated. Considering the difficulties faced by everyone who has attempted to untangle the relationships of the species of this section, it may come as no surprise that two of the leading authorities on the evolution of the potato, Hawkes of England and Bukasov of the U.S.S.R., concur with each other only partially as to the exact numbers and kinds of wild species from which the diploid cultivars might have been derived. Hawkes (*1*), for example, contends that these may have arisen from *S. leptophyes*, *S. canasense*, and *S. soukupii*, three wild diploid potato species native to the Lake Titicaca region of southern Peru and northern Bolivia. Bukasov (*19*), on the other hand, although agreeing to the last two species proposed by Hawkes, adds two others, *S. multiinterruptum* of Peru and *S. sparsipilum* of Peru and Bolivia.

With the exception of *S. sparsipilum* (which appears to have had a distinct origin), the remaining species proposed by Bukasov and Hawkes are all very closely allied, forming a closely knit circle of relationships that extends to other wild potato species of series Tuberosa as well. These could probably all be regarded as representing individual facets of local variation arising within the boundaries of a single superspecies, or "Artenkreis." To this extent, the differences of opinion between Bukasov and Hawkes do not appear as great as they might at first glance. Other members of this diploid chain in series Tuberosa include *S. brevicaule*, *S. bukasovii*, *S. abbottianum*, *S. liriunianum*, *S. ochoae*, *S. multidissectum*, *S. spegazzinii*, and *S. vidaurrei*. Concerning these, Correll (*10*), the latest monographer of *Solanum* section Tuberarium, states that "If all of these were placed together as one highly variable species it would probably be to the best interest of science." Notwithstanding his initial reluctance to depart from the more traditional typological concepts of potato species (Correll suggests in passing that these entities might have ". . . possible genetical [sic], if not taxonomic

Table 1. Classification and origin of the cultivated potatoes.

Species	Distribution	Origin
S. tuberosum		
1. Group Tuberosum, $2n = 48$	Cosmopolitan	By artificial selection in Europe, North America, and Chile from introduced clones of group 2
2. Group Andigena, $2n = 48$	Venezuela to northern Argentina; also sporadically in Central America and Mexico	From groups 4 and 5 by spontaneous doubling of the chromosome number
3. Group Chaucha, $2n = 36$	Central Peru to northern Bolivia	By hybridization between groups 2 and 4, or 2 and 5
4. Group Phureja, $2n = 24$	Venezuela to northern Bolivia	By selection for short tuber dormancy from group 5
5. Group Stenotomum, $2n = 24$	Southern Peru to northern Bolivia	By natural hybridization between wild species followed by artificial selection
S. × *juzepczukii*, $2n = 36$	Central Peru to southern Bolivia	From crosses of *S. acaule* with group 4 or 5
S. × *curtilobum*, $2n = 60$	Central Peru to southern Bolivia	Crosses of *S.* × *juzepczukii* (unreduced) with group 2

value"), it is clear that if a biologically realistic classification of these plants is to be attained, the oldest species name within this complex, *S. brevicaule* Bitter (1912), automatically should be designated as the one for adoption.

Taken together, the various "microspecies" of what may be termed here the "*S. brevicaule* complex" would appear at first glance to fulfill the role of a single putative wild ancestor of diploid *S. tuberosum*, but after further examination of their characteristics some questions remain. Thus, while the various "microspecies" of this complex approach *S. tuberosum* quite closely in certain major leaf and leaflet proportions (*15*), variations in other leaf characters and in flowers appear discordant by comparison. This suggests that some other species or perhaps still another group or series of species had been involved. Which species these were, if indeed they still exist today, can only be surmised. Considering the weedy tendencies of the species in section Tuberarium and the near panmixis of the group, it is likely that many diverse species may have provided chromosomes which enriched the gene pool of diploid *S. tuberosum*. Probably the ubiquitous species of series Megistacroloba (and particularly the ancestral forms of *S. raphanifolium* and *S. megistacrolobum*) were on hand from the very beginning to provide at least a small portion of the dissimilar germ plasm which led ultimately to extreme heterozygosity and allopolyploidy.

Owing to its stabilized hybrid origin from wild species and diploid *S. tuberosum*, it is obvious that the weedy *S. sparsipilum* could not have been involved in the initial origins of the cultivated diploid potatoes. Nevertheless, this plant may have played an active role in the early development of the primitive diploid cultivars, especially in the sense that it acts as a genetic bridge. The flow of genes from wild species into already established cultivars by way of *S. sparsipilum* may have increased their variability, allowing man to make wider selections.

No doubt a certain amount of introgression in the opposite direction (that is, from *S. tuberosum* to wild species) has also occurred by way of *S. sparsipilum*. A slight shifting in the physiological tolerances of the wild diploid members of this group might enable some of these to invade agricultural land. Here, because of close spatial proximity to diploid clones of *S. tuberosum*, the cycle of natural hybridization would be repeated. Viewed in this light, the weedy *S. sparsipilum* evidently stands out in this group as a major adaptive peak in a broad and continuous series of wild and hybrid forms that ultimately lead to the cultivated potato (Fig. 4).

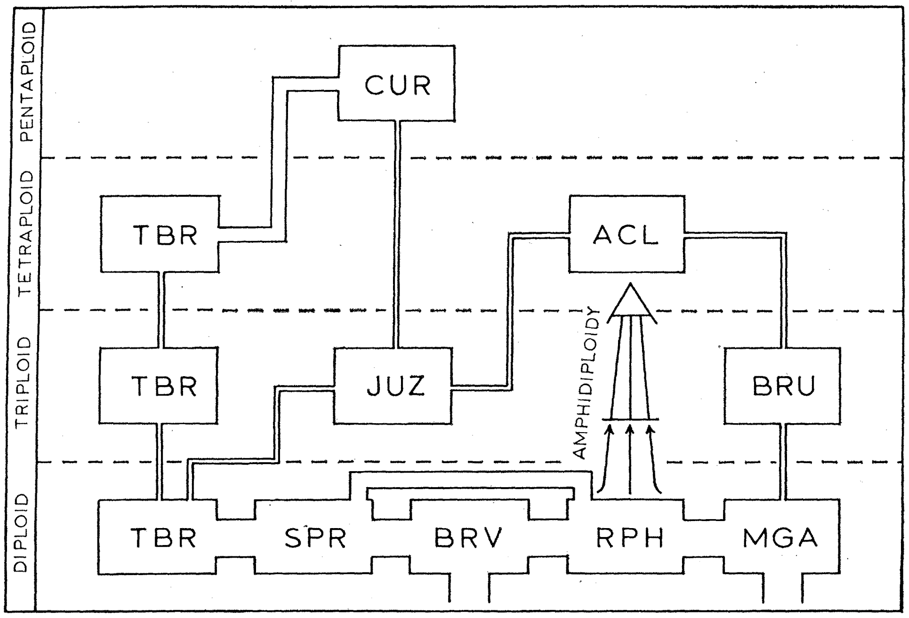

Fig. 4. Species relationships. Gene flow between hybridizing taxa is represented by channels drawn in varying widths. Wide channels indicate proportionately greater gene flow (and consequently greater morphological intergradation between taxa) than narrow ones. Two diploids, *S. sparsipilum* and *S. raphanifolium*, are stabilized hybrids. Key to symbols: *Solanum acaule* (ACL); *S.* × *brucheri* (BRU); *S. brevicaule* (BRV); *S.* × *curtilobum* (CUR); *S.* × *juzepczukii* (JUZ); *S. megistacrolobum* (MGA); *S. raphanifolium* (RPH); *S. sparsipilum* (SPR); and *S. tuberosum* (TBR).

Domestication of the Potato

Like the bread wheats, corn, and many other crops, the common potato did not come into existence until well after man's initial arrival upon the scene. The latter event, according to archeologists, began by immigration out of northeastern Asia by route of the Bering Strait (*20*). The crossing from Asia into Alaska probably occurred in early Pleistocene times, when a gradual lowering of the sea level exposed a narrow land connection across the Bering Sea. Migrating southward, man is believed to have reached the Andean mountains of Peru by no later than 10,000 B.C. He brought with him an economy based solely upon hunting, fishing, and plant gathering (*2*). The tubers of the various wild potato species, as well as of the other common tuber-bearing Andean plants (*Oxalis, Tropaeolum, Ullucus*, and so forth), might very well have been included among the very first plant species that were gathered and utilized by early man. The tubers of the wild potato species probably supplemented a meat diet, or, in time of need, may have become a major means of subsistence.

The nomadic wanderings of man probably brought him into contact with a number of different wild potato species, many or all of which could have been at one time or another gathered and used. The accidental or deliberate introduction of the tubers of two or more wild species of potato to the campsites of early man may have been the first step toward the development of a primitive cultigen. Since the South American potato species are kept apart in nature largely by altitude and differences in habitat, opportunities for natural hybridizations within this group are limited mainly to those areas where man has been influential in bringing together two or more formerly isolated species. The kitchen middens, or trash heaps, that surrounded the semipermanent campsites of early South American man, for example, may have served not only as a place where badly sprouted or imperfect (but still viable) potato tubers and other refuse was deposited, but also as a staging ground for the evolution of weedy hybrid forms that spread to surrounding areas. Mongrel as well as completely wild potato types may have been gathered and taken from one campsite to another, acquiring new genes by hybridization, or the various kinds may have migrated naturally along disturbed pathways that connected different campsites.

The potato, therefore, probably became a "camp follower" of man in its initial stages of development during the preagricultural era. Significantly, the descendants of the "camp-follower" potatoes still exist today. These find their modern counterparts in the weedy *S. brevicaule–S. raphanifolium* diploid complexes of southern Peru and northern Bolivia.

Archeologists report that the era of incipient agriculture was marked by great social and material changes, especially by the replacement of nomadic cultures with dominant stable civilizations. These advances were made possible by a gradual shift in the food economy; that is, from a system based upon hunting and plant gathering, to one of animal and plant domestication. Since these changes probably occurred quite gradually, it is likely that the composition of the first agricultural fields corresponded very closely to the weedy floras of the earlier kitchen midden sites, which in reality, of course, were primitive gardens of a sort in their own right. However, as settled populations became larger, their economies became more and more dependent upon the efficient production of food crops. In time, therefore, man learned to exercise a higher degree of clonal selection upon his crop, planting those cultivars which showed favorable yield, desirable flavor, or other good qualities, and allowing the undesirable types to either become extinct or to persist as weeds along the borders of his fields.

A highly variable array of weedy and semidomesticated potato types was probably already in existence by the opening of the era of incipient agriculture. This probably contained all or most of the desirable genes associated with a cultivated species, but they were widely spread throughout a natural population.

If one assumes that the primitive agriculturalist did not practice clean cultivation methods (as is certainly true of indigenous agriculture today), his fields may have contained a large assortment of hybrid cultivars formed in crosses of the crop with the wild or weedy potato species of the field. Although the majority of these plants were probably undesirable types, a few probably had newly recombined and improved characteristics. As these desirable types were recognized and added to the list of favored cultivars, the older and less desirable clones were planted with decreasing frequency.

Plants showing desirable characteristics were probably never subjected to stabilization by means of artificial crosses or inbreeding. The older cultivars, as well as the newer recombinant types, were probably maintained strictly by clonal propagation, as they are today. Thus, a wide genetic base was never lost as the result of selective inbreeding; rather the base became wider through the process of recurrent cultivar–wild species crosses, introgression, and subsequent clonal selection. In this respect, a primitive potato field may be thought of as a population continually changing in composition with the addition of clones of ever-increasing heterozygosity.

However, this hybrid-clonal–heterozygosity cycle terminates or diminishes with the introduction of spontaneously formed tetraploids. Although these plants are formed from highly heterozygous cultivar stocks, they are genetically isolated from their wild diploid ancestors by differences in ploidy, and the only connection they have is through nearly sterile triploid hybrids. Thus, early or primitive tetraploid potatoes probably received a measure of isolation from wild species while retaining all the important gene combinations of the diploids.

Although our hypothetical early agriculturalist cannot be expected to have realized the genetic advantages of this new potato, he probably did perceive some real differences in yield and perhaps in hardiness. It is likely that the tetraploid potatoes were selected quite rapidly into their present Andean form after their new qualities became known. This rapid transformation into efficient, high-yielding clones became possible through the fortuitous combination of genetic isolation, heterozygosity, hybridization and recombination among tetraploids, and by careful selection, in many places and by many groups of primitive men.

The introgression of wild germ plasm into present-day native potato populations remains a strong directive force in their development, much as in their historical past. Since gene exchange between wild and cultivated potato populations frequently results in increased cultivar diversity, disease resistance, and adaptability to climatic changes, it is vital to the perpetuation of the Andean potato. Homogeneous, or uniform potato field populations are extremely vulnerable to destruction by disease and other natural causes. The disastrous crop failures of Ireland in 1845, for example, might have been entirely avoided if many different cultivars of varying degrees of resistance (or susceptibility) to any one particular strain of fungal pathogen had been planted. Instead, late blight disease of potato met with little resistance as it spread from one uniform field of genetically similar potatoes to another (*4*). Natural and human selection, however, has acted upon the Andean cultivated potatoes for many thousands of years without effecting their total extinction. Regarding these, conservationist H. H. Iltis has written that ". . . the great vigor of these populations speaks for real evolutionary strength in diversity. Heterogeneous potato fields are in effect a 'homeostatic system' in which the loss of one or several genotypes to natural selection affects but just a small proportion of the population" (*21*). It would appear, therefore, that we need to preserve these highly heterozygous native potato populations as a kind of natural "gene pool," or a source from which to work when our own limited numbers of cultivars fail.

The introduction of modern potato varieties and clean cultivation methods to the Andean potato fields may someday have a deleterious effect upon the future development of our own varieties. If the primitive Andean potato stocks are lost, our modern, artificially produced varieties will become completely isolated from their ancestral base, and it may then require extraordinary efforts to keep our higher-yielding but more inbred clones free from extinction. Although it is inevitable perhaps that some native potato populations will be lost in future years, it is vital that we at least preserve the more critical or ancient centers of potato variability, and guard these against the encroachment of the modern varieties.

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20. E. P. Lanning, *Peru before the Incas* (Prentice-Hall, Englewood Cliffs, N.J., 1967); whereas there may have been sporadic, accidental contracts between Melanesia and America either before or after the arrival of the Mongolian immigrants, such meetings (if indeed they occurred) have had apparently little or no impact on the mainstream of Indian culture in Latin America (compare V. W. von Hagen, *Realm of the Incas* (Mentor, New York, 1961).
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22. A portion of this study was undertaken at the University of Wisconsin and was supported by NSF grants G-23677 and GB-4233, the Rockefeller Foundation, and the Inter-Regional Potato Introduction Project, IR-1. Appreciation is also expressed to Drs. A. J. Sharp (University of Tennessee) and H. H. Iltis (University of Wisconsin) for their helpful suggestions and critical review of the manuscript; to Dr. P. R. Rowe for the use of the facilities of the University of Wisconsin Experimental Farm at Sturgeon Bay; and to the Botany Department of Southern Illinois University, Carbondale, for their support.

Communication in the Physical and the Social Sciences

The processes of disseminating and assimilating information differ in these two groups of sciences.

William D. Garvey, Nan Lin, Carnot E. Nelson

In the last quarter of a century the scientific community has concerned itself increasingly with the flood of scientific information, initially emphasizing the need for improving the distribution, storage, and retrieval of scientific literature. About a decade ago, however, a number of scientists challenged this emphasis. One such scientist, Bentley Glass, called for a more eclectic approach to improving scientific communication (*1*): "In light of the very large sums of money—to say nothing of the time and the skilled labor—expended annually on the indexing and abstracting of the scientific literature and on the development of new methods of recording and retrieving information, it seemed desirable to examine the actual ways in which representative scientists in practice find out about the existence of scientific work that is crucial to the development of their own research."

Since Glass's remark, much research (*2*) has been done to explore scientific communication activities in several disciplines, and it is now generally recognized that the scientific literature, while a crucial medium, is only one facet of the overall process of disseminating and assimilating scientific information. Active researchers rely heavily upon informal media for information crucial to their continuing research.

These findings, greatly generalized in recent years, have left the impression that, regardless of the discipline, all scientists exhibit identical patterns of communication behavior and therefore have similar problems. The research conducted at Johns Hopkins and reported here provides, we believe, evidence on which to reevaluate that impression. This article focuses on differences between the physical and the social sciences regarding three major factors associated with the dissemination and assimilation of scientific information: (i) lags in the process of information flow; (ii) the organization and effectiveness of informal networks; and (iii) the transfer of information from the informal to the formal domain (*3*).

Lags in Information Flow

Time intervals associated with production of journal articles. Figure 1, part *A*, shows the average times at which critical stages associated with the production of articles eventually published in "core" journals (*4*) occurred. The graphs of Fig. 1, part *A*, illustrate the times when authors (*A-1*) began the work reported in the articles; (*A-2*) completed the work; (*A-3*) began first drafts of the manuscripts; and (*A-4*) submitted the manuscripts to the journals that published them. Each stage of this process—from the inception of work to its publication—occurred closer to the time of publication for the physical sciences than for the social sciences.

The graphs of Fig. 1, part *B*, illustrate the points where lags in the process occurred. The major lag (*B-1*) relates to the actual conduct of the work, each group requiring a year, on the average, to complete it. Graph *B-2* shows that little time is wasted between completion of the work and the initiation of first drafts of the manuscripts; the lag (2 months) is identical for the two groups. Graph *B-3* shows the interval between the time the authors started their manuscripts and the time they submitted them to the journals that published them; these intervals were longer for social science articles (7 months) than for physical science articles (4 months). Graph *B-4* shows that the lags between time of submission of the manuscript and time of publication are generally the second longest lags in the process. The physical scientists reported publication lags 4 months shorter than those reported by the social scientists.

Owing to these longer lags associated with publication of social science articles, the social scientists, it was found, started disseminating oral or written

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