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Source: *Annual Review of Ecology and Systematics*, 1970, Vol. 1 (1970), pp. 1-18

Published by: Annual Reviews

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THE UNITS OF SELECTION

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The principle of natural selection as the motive force for evolution was framed by Darwin in terms of a "struggle for existence" on the part of organisms living in a finite and risky environment. The logical skeleton of his argument, however, turns out to be a powerful predictive system for changes at all levels of biological organization. As seen by present-day evolutionists, Darwin's scheme embodies three principles (Lewontin 1):

1. Different individuals in a population have different morphologies, physiologies, and behaviors (phenotypic variation).
2. Different phenotypes have different rates of survival and reproduction in different environments (differential fitness).
3. There is a correlation between parents and offspring in the contribution of each to future generations (fitness is heritable).

These three principles embody the principle of evolution by natural selection. While they hold, a population will undergo evolutionary change.

It is important to note a certain generality in the principles. No particular mechanism of inheritance is specified, but only a correlation in fitness between parent and offspring. The population would evolve whether the correlation between parent and offspring arose from Mendelian, cytoplasmic, or cultural inheritance. Conversely, when a population is at equilibrium under selection (for example, a stable polymorphism due to heterozygous superiority), there is *no* correlation in fitness between parent and offspring, no matter what the mechanism of inheritance. Nor does Principle 2 specify the reason for the differential rate of contribution to future generations of the different phenotypes. It is not necessary, for example, that resources be in short supply for organisms to struggle for existence. Darwin himself pointed out that "a plant at the edge of a desert is said to struggle for life against the drought." Thus, although Darwin came to the idea of natural selection from consideration of Malthus' essay on overpopulation, the element of competition between organisms for a resource in short supply is not integral to the argument. Natural selection occurs even when two bacterial strains are growing logarithmically in an excess of nutrient broth if they have different division times.

The generality of the principles of natural selection means that any entities in nature that have variation, reproduction, and heritability may evolve. For example, if we replace the term *individual* with the term *population* and

interpret *phenotype* to mean the distribution of phenotype in a population, then Principles 1, 2, and 3 describe a process by which one population may increase its proportional representation in the species relative to other populations. Similar reinterpretations of these principles could be made for species rather than populations and even communities rather than species. A completely general axiomatization of these principles has been made by Williams (2), who includes the Malthusian principle of limited population size in order to get a more complete evolutionary theory. This axiomatization makes clear that the principles can be applied equally to genes, organisms, populations, species, and at opposite ends of the scale, prebiotic molecules and ecosystems.

While rigorous formalization of the principles of natural selection is recent, it has been obvious in a general way that other units beside the individual could be the unit of selection, and a great deal of theory-making has gone on for natural selection at other levels. While there is a superabundance of such theory, both rigorous and heuristic, and while many natural-historical observations are interpreted as arising through the agency of natural selection of molecules, cells, populations, species, and communities, there is virtually a complete absence of direct experimental or natural-historical verification of these interpretations. In view of the strong antitheoretical stance of most of biology, it is remarkable that, in the absence of much evidence, the concept of natural selection of units other than the individual is so widely accepted.

SELECTION OF MOLECULES

Current views of the origin of life follow, in broad outline, the scheme of Oparin (3). At the earliest stage there would be abiogenic synthesis of a variety of complex organic molecules. These molecules would be in dilute solution in the aqueous environment and the energy for their formation would come from various electromagnetic radiations and electrical discharges (Miller 4). Although it has occasionally been suggested that some such molecules may have been autocatalytic by being the templates for their own production (Calvin 5), the present view is that all were formed by condensation reactions in which no information was provided by the already formed macromolecules. Since there was no autocatalysis, there was no reproduction or heredity and so no possibility of natural selection. At a later stage macromolecules entered into complex associations called *coacervates*, which in Oparin's view were open thermodynamic systems. These systems had membrane-like boundaries and took in small molecules from the surrounding medium for synthesis, thereby growing in mass. At the same time coacervates were not completely stable thermodynamically and broke down. Since the rate of growth and of breakdown of different coacervates was a function of their composition, certain compositions would be perpetuated, would grow, divide, and replace others with a lower stability or smaller growth rate. In Oparin's view, then, coacervates were the first units upon

which natural selection could be said to operate.

Even though individual molecules in solution may not have been autocatalytic, there may have been selection among variants of a given molecular species when incorporated within a coacervate, so that the coacervate itself would evolve. This is a likely possibility for nucleic acids. Recently, exciting experiments by Spiegelman and his colleagues (6-9) have shown that a simple in vitro system of RNA replication will evolve. A mixture of oligonucleotides ATP, CTP, GTP, and UTP, with a replication enzyme $Q\beta$ -replicase, will produce quantities of RNA if a single molecule of RNA is added as an initial template. Occasional mistakes in replication produce mutant RNA molecules and under certain selective conditions these mutant RNAs will replicate faster than the original type. As a result the mixture becomes enriched for the new RNA and "subcultures" can be formed that are pure for the new RNA "species." Among the types selected for was an RNA that could replicate faster than wild-type when the reaction mixture contained suboptimal concentrations of any of the four oligonucleotides. This *nutritional* mutant is postulated to alter the configuration of the replicase enzyme by an allosteric effect, making it more efficient. A second mutant RNA was resistant to the effects of a competitive analog inhibitor of RNA synthesis. In the presence of the analog the doubling time of wild-type RNA was 4.1 minutes as compared with 2.0 minutes for the resistant mutant. In the absence of the selective agent, both molecular species doubled every 1.0 minutes.

These experiments show clearly that natural selection among self-replicating molecular variants can occur in very simple reaction mixtures and that selection coefficients in the presence of a selective environment can be very high. Thus, considerable preorganismic selection of nucleic acids, perhaps in coacervates, could have occurred.

A similar phenomenon might occur in vivo in multiple infection of a cell by different viruses if one variety of virus nucleic acid could replicate faster than the other. Most bacteriophage completely exclude each other but this problem has not been studied, even for those cases like doubly lysogenic bacteria, in which both phage nucleic acids do replicate.

CELL ORGANELLES

There has been an increasing body of evidence showing that chromosomes are not the only organelles containing nucleic acids. Both plastids and mitochondria have DNA (Gibor & Granick 10) and, of course, ribosomes contain RNA. In ciliated protozoa the basal granules or kinetosomes of the cilia are nucleoprotein and have genetic continuity (11). At the moment, however, there is no evidence that ribosomes replicate under the control of their own RNA rather than under the control of nuclear genes. While kinetosomes clearly do replicate and clearly control cell morphology, there is no evidence for differential rates of replication within a cell of different basal granules as a result of genetic variation from granule to granule. Thus, any

selective effect of variation in kinetosomes will be at the level of the whole organisms of which they are a part.

There has long been evidence that individual plant cells may contain a mixture of normal and abnormal chloroplasts, the abnormal areas being colorless. Mixed cells occur in variegated plants in which some cells and patches of tissue are wholly without chlorophyll. Such patches are segregated out, for example in *Primula*, when meristematic cells containing both chloroplast types segregate (see review by Jinks 12). No evidence of differential rate of plastid replication has yet been found. In *Epilobium*, Michaelis (13) has shown that normal and abnormal plastids have about equal probabilities of segregation into daughter cells.

Much more evidence is in hand for variation in mitochondrial variants, or variants which are suspected to be associated with mitochondria but which may, in fact, have some other particulate basis for their inheritance. In fungi there is a variety of cytoplasmic respiratory and morphological variants like the *poky* mutant of *Neurospora* or the *red* mutant of *Aspergillus* which show differential reproduction. If a wild-type is crossed to the mutant, a heteroplasmon is formed. This heteroplasmon will segregate pure wild-type and pure mutant forms as well as replicating the heteroplasmonic state. However, there is a strong bias in the segregation so that eventually only one form of cytoplasmic determinant remains. In the *poky* mutant it is the abnormal mitochondria that take over, apparently by suppressing the replication of the normal mitochondria (12). In the *red* mutant, however, there is stabilization of the heteroplasmon because the increase in the abnormal plasmagene that results in its suppression of the wild-type particle is balanced by the lethality of homoplasmons for the mutant (14). In this interesting case the selection at two levels is in opposition. The interparticle selection favors the mutant but the interorganism selection favors the wild-type.

The chromosome itself may in some cases have a differential rate of reproduction during cell division despite the usual great regularity of mitosis and meiosis. There are many cases of segregation distortion in which variant chromosomes are preferentially included in the sperm or egg nucleus (15). These include the sex-ratio inversions in *Drosophila pseudoobscura* and *D. persimilis* (16), segregation distorter in *D. melanogaster* (17), and supernumerary chromosomes in coccids (18) and in *Clarkia* (19). Such differential reproductive rates of individual chromosomes are very powerful forces in changing gene frequency, but they are stabilized in populations by the opposing force of selection at the organismic level, as in the case of the *red* cytoplasmic factor in *Aspergillus*. The sex-ratio inversions in *D. pseudoobscura* and *D. persimilis* are opposed by lower reproductive fitness of females homozygous for them (20), while the segregation distorter is linked to a developmental lethal. Fitness relations are not known for the supernumerary chromosome in *Clarkia*, but Nur (21) has estimated fit-

nesses in coccids and shown that fitness decreases with increased number of chromosomes.

A similar phenomenon, but with a different basic mechanism, is the segregation distortion of lethal sterile genes in *Mus musculus* found by Dunn (22). While no chromosomal segregation mechanism is known and the effect appears to be one of differential sperm survival, this case must be classified together with other segregation distorters rather than with gametic selection, because the dynamics of the selection process are the same as for true segregation distortion (23-25). The difference from gametic selection arises from the fact that it is only in the gametic pool of heterozygotes that there is any differential rate of production. The gametes produced by the homozygotes never compete with each other or with those from heterozygotes. Perhaps the most fascinating element of the segregation distortion in *Mus* is that three levels of selection are operating simultaneously: organelle selection because of segregation distortion, organismic selection because of lethality or sterility of homozygotes, and population selection in the case of sterile alleles since a small population may become homozygous and thus become extinct (26). (See, below, the section on population selection.)

Finally, organelle selection takes place for whole nuclei in fungi that are syncytial with many nuclei in a common cytoplasm. Because of hyphal fusion between separate colonies, such a fungus may carry nuclei of different genetic composition. The rate of replication of each nuclear type in such a heterokaryon depends, not only upon its own genes, but upon the genes in the other nuclei since it is in the cytoplasm that actual synthesis of the nuclear components occurs, and the cytoplasm is under the joint control of all the nuclei. This may lead to a symbiotic stabilization of nuclear ratios at an intermediate mixture. An example is the case of adenine-requiring mutants of *Neurospora* (27). A nucleus with such a mutant could not ordinarily replicate in the absence of an exogenous source of adenine. If a colony is a heterokaryon for two nonallelic adenine-requiring mutants, both nuclei can replicate, since each causes the cytoplasm to make the enzyme for which the other is deficient. In general, a characteristic stable ratio of nuclear types is attained in a heterokaryon; its value depends upon the initial frequencies and the environment (28).

CELLULAR SELECTION

In the development of a higher organism, different cell types have different division rates so that, in the broadest sense, the morphology of these organisms is a result of selection at the cellular level. A model of such a view of development is contained in the clonal selection theory of immunity developed by Burnet (29). Originally, Jerne (30) postulated that an organism might contain thousands of different antibody molecules with different specificities. When a particular antigen was introduced, it came into reactive contact with the matched antibody and this stimulated the production of

large amounts of that particular antibody molecule. Burnet changed the focus of this molecular selection theory to the cell level. He postulated the existence of a great variety of mesenchymal cell types, each making a specific antibody. A complementary antigen would react with the surface of the appropriate cell type, stimulating that cell to proliferate preferentially and to liberate large quantities of antibody. The requirement that on the order of 10,000 stem cell types preexist raises the question of where the genetic information for all these types resides. There may be 10,000 different genes, each specifying one cell type, or there may be only a few genes with some form of hypermutation, as suggested by Lederberg (31), but it appears certain that a single cell makes a single antibody type (32).

It is clear that both normal tissue repair and neoplastic growths are forms of natural selection at the cellular level. In the former case, tissue destruction results in a stimulation of certain cell types to reproduce faster than usual, but their reproductive rate returns to normal when repair is complete. In neoplastic growth, this normal feedback control is destroyed and certain cell types reproduce very rapidly, competing with normal cells and finally crowding them out. Radiation treatment and chemotherapy are means of reducing the relative fitness of these cell lines by introducing an environmental factor that selects specifically against dividing cells.

The likelihood that clonal selection is a good model for normal development is increased by findings on the importance of cell surfaces in growth and differentiation (33). The amount of information on cell selection in higher organisms is not great, but this appears to be an important line for future work.

GAMETIC SELECTION

By gametic selection we mean specifically the differential motility, viability, and probability of fertilization of gametes that arises from their own haploid genotype, independent of the genotype of the parents which formed them. Thus, differences in germination of seeds or hatching of eggs arising from different amounts of nutritive material are not gametic selection since they depend in part or in whole on the maternal genotype. Segregation distortion is excluded because the differential production or viability of gametes occurs only in heterozygous parents and does not apply to the gamete pool as a whole (23–25). Self-sterility alleles, such as occur in *Nicotiana* (34), are also an exception to simple gametic selection since the relative competitive ability of two pollen grains depends upon the genotype of the style on which they fall. So (35–37) the selection is a function of the relative frequencies of diploid genotypes in the population. The population dynamics of self-sterility alleles—which always leads to a stable equilibrium at equal frequencies of all alleles—as well as the dynamics of segregation distortion (23–25), can be regarded as a case of frequency-dependent gametic selection, but the qualitative consequences are quite different. In ordinary

gametic selection, as in the selection between haploids, if there is no frequency dependence, there can be no stable equilibrium, and one gene will disappear. Classical examples are certation of *R* gene pollen in *Oenothera*, discovered by Heribert-Nilsson (38), and Brink's work on the waxy gene in maize (39). In both cases, pollen carrying the two alternative alleles is produced in equal frequency by heterozygotes, but one of the two pollen types grows more slowly after germinating on the recipient style. For example, waxy pollen fertilize only 62% as many ovules as nonwaxy pollen, and in *Oenothera* the advantage of *R*-bearing pollens over *r* pollen is 2.7 to 1. If unopposed by selection at the individual diploid level, such gametic selection leads to very rapid loss of the inferior gene such that

$$p_t = p_0 m^{-t}$$

where p_0 and p_t are the gene frequencies in the initial and the t th generation and m is the ratio of superior to inferior pollen fertilization. In the case of *Oenothera* $m = 2.7$ as it would take only 2.3 generations to decrease the frequency of the *r* gene by a factor of 10. We should then expect to find such genes very rarely. Thus, pure gametic selection, like segregation distortion, should be absent in nature except when selection at this level is opposed by selection at the individual or some higher level. Otherwise, the superior genotype would be established in 100% of the population (barring an occasional mutant).

Gametic selection, as opposed to segregation distortion, is virtually unknown in animals. It ought to be looked for in those plankton organisms where gametic motility is of primary importance. Again, it will be discovered only in those cases where selection at the diploid level opposes it or where the gametic selection is frequency dependent in such a way as to lead to stable equilibria of gene frequencies.

INDIVIDUAL SELECTION

The primary focus of evolution by natural selection is the individual. The purpose of this review is not to delve into the excessively abundant literature on natural and artificial selection, theoretical, experimental, and natural-historical. That has recently been done to some extent by Lewontin (40) and Spiess (41). Rather, the emphasis of the present review is to contrast the levels of selection, especially as regards their efficacy as causes of evolutionary change.

By individual selection I mean the force on the genetic composition of a population that arises directly from differences in the age-specific mortality and fertility schedules of different genotypes, independent of the genotypes of their ancestors, their descendents, or their contemporaneous relatives. This does not mean that the fitness of a genotype need be independent of the genetic composition of the population in which it finds itself. Indeed,

selection dependent upon the population composition is common and may even be the rule (42-44). Rather, in individual selection, it is sufficient to know the genotype of the individual and all the relevant environmental variables, without inquiring how he came by that genotype or what the genotypes of his offspring will be. This definition is made in order to group together phenomena with the same form of evolutionary dynamics. It excludes such cases as the *grandchildless* gene in *D. subobscura* (45), in which all offspring of a given genotype are sterile, irrespective of their own genotype, and it excludes all forms of maternal-fetal incompatibility in which a given genotype is selected against only when born to a particular maternal genotype—as for example *Rh* incompatibility in man (46) or the self-incompatibility reported in the mouse by Hull (47). The theory of individual selection was worked out for single loci by Fisher (36), Haldane (48), and Wright (49) and was later modified for frequency-dependent selection by Wright (50) and for many loci by several workers (51). For our present purposes the chief result of this theory is Fisher's Fundamental Theorem of Natural Selection (36), which states that the rate of change of population fitness with time is equal to the genetic variance in fitness. This theorem is less fundamental than Fisher thought it to be since it does not apply for frequency-dependent selection (52), nor to multiple loci (53), nor to continuously breeding populations with age-distributed mortality or fecundity (54), but its essential qualitative conclusion is correct. The rate of evolution is limited by the variation in fitness of the units being selected. This has two consequences from the point of view of comparison between levels of selection. First, the rapidity of response to selection depends upon the heritability of differences in fitness between units. The heritability is highest in units where no internal adjustment or reassortment is possible since such units will pass on to their descendent units an unchanged set of information. Thus, cell organelles, haploid organisms, and gametes are levels of selection with a higher heritability than diploid sexual genotypes, since the latter do not perfectly reproduce themselves, but undergo segregation and recombination in the course of their reproduction. In the same way, individuals have a greater heritability than populations and assemblages of species.

Second, the rate of evolution per unit time is dependent upon the rate of reproduction and mortality per unit time. It is not always realized that fitness, defined for the individual, has the units of (time)⁻¹. This is seen clearly in Fisher's Fundamental Theorem:

$$\frac{d\bar{W}}{dt} = \text{Var}(W)$$

so that

$$dt \sim d\bar{W}/\bar{W}^2$$

and

$$t \sim 1/\bar{W}$$

where \bar{W} is mean fitness and $\text{Var}(\bar{W})$ is the variance in fitness.

This means not only that a species with a much longer life cycle cannot evolve as fast as one with a short life cycle, but that the force of natural selection resulting from selection at different levels depends upon the *cycle* time at each level. For example, gametes have the same cycle time as the individuals that produce them since they alternate in the life cycle. But, as I shall argue below, population selection must be weaker than individual selection in nearly every case since the birth and death of populations usually encompasses many individual life times.

Individual selection does not necessarily lead to replacement of one type by another. In sexually reproducing diploids, there will be a stable intermediate equilibrium if heterozygotes are superior. The more intense the selection, the more resistant the equilibrium will be to perturbations. Even when heterozygotes are not superior or when selection is acting on asexual forms, there may be stable equilibrium, provided that fitness of genotypes is a function of their frequency so that the rarer genotypes are the more fit (55).

THE POPULATION CONSEQUENCES OF INDIVIDUAL SELECTION

There has been a widespread confusion among geneticists about the effect on a population of natural selection among individuals. This confusion arises from the erroneous equation of relative fitness of two genotypes and their absolute rates of reproduction. The confusion is manifested in two ways. First, it can be demonstrated in a wide variety of circumstances that evolution in a population changes the population's genotypic composition so as to maximize average fitness (56). This leads to the conclusion that a population will somehow make better uses of its resources or have a higher rate of increase or a larger size at genetic equilibrium than it would if it were not at that equilibrium. Indeed, some experiments show that a population with a stable genetic polymorphism may be superior in these respects to monomorphic populations. An example is inversion polymorphisms in *Drosophila* (57, 58). But this is only empirically, not logically, true (59), as shown by experiments in which the opposite is the case (60). If absolute fitnesses are a function of the frequency of different genotypes in the population, then absolute reproductive rates may decrease while the population is evolving to maximize relative fitnesses. This was recognized theoretically by Wright (61), who considered, among other cases, the important and common one where the total population size is fixed by some nonelastic resource like space so that all the genotypes must be constantly changing their relative and absolute fitnesses, keeping \bar{W} constant. There is no information at all about how often genetic changes in a population resulting from individual selection cause changes in population size or rate of increase, al-

though such changes have occasionally been hypothesized (62).

The second manifestation of the error of confusing relative with absolute fitness is in the notion of the *cost of selection* (63) and the closely related concept of *genetic load* (64–66). If a population varies in fitness, either because the population is at a polymorphic equilibrium with inferior homozygotes segregating every generation or because the population is in the course of replacing one gene by another, then the population is not as fit as it would be if only a single, most fit, genotype made up the entire population. This deviation of the mean fitness from the fitness of the optimum genotype is the genetic load. The error is to suppose that this load is actually manifest as a loss in the reproductive capacity or size of the population. This would be true if the selection were causing inelastic losses in numbers, that is, if one were dealing with pure mortality independent of density. In many real populations, however, mortality is density dependent at some stages so that death from genetic causes results in lower death rates from nongenetic causes. A particularly absurd example is the genetic load that can be calculated when a gene arises in a population causing its carrier to have a higher fecundity. Such a population has a large genetic load until the new gene is fixed, yet obviously there is no cost to the population in acquiring such a gene. As more realistic ecological considerations enter the thinking of population geneticists, the error of supposing that genetic load is necessarily a real reproductive load is being corrected (67–69). The most interesting and fruitful area of empirical research on the borderline between genetics and ecology concerns precisely the changes in demographic properties of populations as a result of natural selection of individuals. While a start has been made on the theory (54, 70, 71), we know virtually nothing about the facts.

KIN SELECTION

It was early realized by Haldane (48) and Fisher (36) that some characters of organisms seemed to be contradictory to the principle of natural selection in that individuals appeared to lower their own fitness while benefiting other organisms. These were the so-called *altruistic* or *socially valuable* characters of Haldane.

One way in which such characters might be established is that, if the beneficiaries of the altruistic act were close relatives of the altruist, the gene for altruism might be increased by an indirect path. This type of case was considered by Haldane and by Wright (61). An obvious example is maternal care, in which the probability of the parent's survival is reduced by sharing resources with the offspring, but without such care there would be no offspring at all. Not only postnatal care is involved, of course, but the entire evolution of viviparity, which is of clear disadvantage to the mother but of advantage to the offspring. Hamilton (73, 75) attempted to generalize this theory for any degree of relationship and obtained the heuristic relationship that if K is the ratio of the advantage to the disadvantage and r is genetical

correlation between the altruist and the beneficiary, then the altruistic gene would increase if $K > 1/r$. This can be made more general still if we assume n individuals, with an advantage K_i conferred on the i th individual in the population whose relationship to the altruist is r_i . Then the condition for increase of the gene is $\text{cov } K_i r_i > (1/n) - \bar{K}\bar{r}$. This gives the remarkable result that, if the average advantage \bar{K} is sufficiently high, the gene may be fixed even if close relatives are favored less than distant relatives ($\text{cov } K_i r_i$ negative). A completely thorough treatment of this problem has not yet been made. Particular models have been examined by various workers. The evolution of alarm calls by kin selection, provided they began as a warning of the sibs or offspring, was shown to be possible by Maynard Smith (72). The problem of the division of labor in social insects, and especially the problem of sterile castes, is dealt with by Williams & Williams (74) and in very great detail by Hamilton (75). Again it is shown that kin selection is effective in such cases. It is sometimes stated (76) that sterile castes are simply parts of a large "individual," the colony, so there is no difference between evolution of social insects and the evolution of division of labor among the cells of a higher organism. The problem is a little more complicated than that because the sterile diploid workers are not genetically identical with the fertile queen or the fertile haploid males. Moreover, some colonies of social insects have more than one queen (some ants) or are the result of multiple insemination (*Apis mellifera*).

A great variety of social and cooperative behaviors are discussed by Williams (77) in his excellent book, whose thesis is that essentially all examples of adaptations of groups at the expense of individuals can be explained either by direct selection of individuals or by kin selection, so that selection at yet higher levels need not be invoked. Kin selection is an especially powerful argument since very general cooperative behavior can be regarded as a hypertrophy of maternal care, from which it originated.

The principle of kin selection was used by Fisher (36) and Kolman (78) to solve one of Darwin's puzzles, the evolution of the sex-ratio. Darwin could see no advantage or disadvantage in the "battle for life" from producing any particular ratio of males to females. Fisher stated, and Kolman proved, that if there is a fixed expenditure of energy in the production of offspring, then individuals who expend equal amounts of energy in producing the two sexes will have their genes represented more in future generations than those who expend their energies unequally. Like the case of the grandchildless genes, selection operates here by its effect on descendents rather than on the fitness of the individual directly. Such cases dramatize the fact that evolution occurs because different genotypes have different rates of propagation to future generations, no matter what devious and indirect paths they may take.

POPULATION SELECTION

One of the most controversial questions in evolutionary ecology is

whether selection operates on groups as units rather than on individuals. I have tried to avoid some of the confusion by separating out kin selection. It may be objected that if a female bird cares for her young, she is serving a group, but this is a false lead. The operation of kin selection does not depend upon the selection of a number of individuals *as a unit*. It works just the same when clutch size is one. I will distinguish from such kin selection the differential survival and reproduction of a population as a unit. Survival of such a unit means simply that the entire population has not become extinct, regardless of the numbers of individuals it contains. Reproduction of a population is more difficult to define, but since we are concerned with some property of the population, then reproduction must mean the budding off of new colonies with the same characteristic property whose evolution we are explaining. In addition to simple budding or extinction, populations may also genetically swamp or be swamped by other conspecific populations as a result of massive immigration of adults, propagules, or gametes.

There are three questions to be asked about population selection: 1. Do we need to invoke it to explain evolutionary change? 2. At what rate can evolution go on by such a mechanism? 3. Does it happen?

Population selection is invoked by those like Wynne-Edwards (79), Emerson (76), and Brereton (80) who maintain that there are group characteristics essential to the survival of the population which are unstable to individual selection within the population or, at best, of no selective value between individuals within the group. There is a direct analogy drawn with certain forms of human cooperative behavior in which rational behavior for an individual becomes irrational if everyone does it. For example, if a bank is short of funds and in some danger of closing, it is clearly of advantage for an individual to rush to the bank and withdraw his money, but if everyone does it, the bank will surely close and everyone will lose his money.

The usual cases discussed in biology involve the regulation of population size (79, 80) and the cooperative behavior of various members of the population in altering the environment (76, 79). For example, if vegetation limits the growth of an herbivore population, any mechanism of more rapid and efficient food gathering, even if the food is not efficiently used, will be favored by individual selection. Yet, in the extreme the super herbivore would extinguish the population. In this connection the evolution of territoriality is regarded as a population regulation device which could have evolved by population selection. Yet another example is the supposed evolution of senescence (76). Death of senescent individuals is said to be advantageous to the population as a whole, since resources in short supply are saved, and to be of no conceivable selective advantage or disadvantage to the individual since he is postreproductive at death. Most of the claims for the operation of selection at the population level arise from what are perceived to be the self-regulating properties of population (79, 80). That is, it is said that quite generally the numbers in a population are regulated by

some internal adaptation of the population so that resources are not overexploited. Populations are not directly resource-limited because they have evolved to parcel out resources optimally, like the survivors of a shipwreck, so that the stability of the population is guaranteed. In such a regulated population it is clearly advantageous for a single individual to depart from this cooperative behavior, just as it is advantageous for the single depositor to run to the bank in the economic analogy. In the theory of games, the cooperative solution is not an equilibrium solution since it is always advantageous for a single individual to become uncooperative, no matter how the others act. Then natural selection within populations cannot lead to cooperative behavior and, it is said, we must invoke interpopulation selection.

The best contrary analysis is given by Williams (77), who meets these arguments in three ways. First, many adaptations turn out to be explicable by simple selection at the individual level. The elimination of senescent individuals, for example, can be explained as a direct consequence of selection for increases in reproductive rate at earlier ages, which, in continuously breeding populations, is of direct selective advantage. Second, other adaptations, as for example alarm calls and maternal care, can be explained by kin selection. Finally, self-regulation of numbers, on which most of the argument for group selection is built, simply does not occur. It is an aesthetic prejudice of ecologists that animals regulate their own numbers so as somehow to achieve "optimal" numbers. What are optimal numbers? They might be defined as the number that will minimize the probability of extinction of the population as a whole. But what is, indeed what can be, the evidence that any population or species regulates itself at that optimal number? It is only ecologists' impression that a species is not "overcrowded." The circularity of this argument is obvious. As Williams points out, the number of organisms in a population can be explained by density-independent variation in resources and controlling physical factors, as in the theory of Andrewartha & Birch (81), together with occasional density-dependent population reductions when resources are expended. That is, populations do occasionally crash in numbers and even sometimes become extinct, so we have no need of the concept of self-regulation and could not demonstrate it if it did occur. Williams is quite correct in calling especial attention to the serious epistemological difficulties that arise from any theory of self-regulation to an optimal number.

The second question raised is whether such a mechanism can in fact exist and at what rate it would cause evolution. I have already called attention to the importance of Fisher's not-so-fundamental theorem in this respect. The rate of evolution under population selection depends upon the rate at which entire populations become extinct or bud off new colonies. This rate must be compared with the rate of individual selection which, especially in the case of cooperative behavior, is acting in opposition to population selection. Moreover, the population composition is at an unstable point with re-

spect to intrapopulation fitness and depends upon being homozygous for the "cooperative" genes. Any mutation or introduction of alternate alleles for "selfish" behavior by immigration will cause a rapid evolution within the population in the wrong direction. We should then expect to find population selection most effective in colonizing species in which the lifetime of a population is of the same order of magnitude as the generation time and in which a small number of propagules may serve as founders. In this way a newly formed colony may deviate significantly from the genetic composition of the parent population and may chance to have characteristics that would not occur through natural selection operating within populations. Such a condition is described by Wright (61) as the optimum one for exploring the variety of adaptations open to a species. In general, however, unless colonization is frequent so that the time rate of selection is great and unless populations are either homozygous or asexually reproducing so that the heritability of population characteristics is high, interdeme selection will be at a much lower rate than selection on the individual and organelle level.

Although Williams demonstrated that we do not need population selection to explain evolution and although I have demonstrated that in most instances it would be an inefficient process, there is still the possibility that population selection does occur. There are, in fact, two well-documented cases of interdeme selection, and both have the necessary features of small population size or frequent deme extinction discussed above. The first example is the evolution of the *t* gene in *Mus musculus* (22, 26, 82). In this case selection is going on at three levels. The effective sperm pool of heterozygous males contains about 85% *t*-bearing sperm and only 15% \pm sperm. Thus there is powerful organelle selection to increase the frequency of *t*. However, males homozygous for *t* are completely sterile so the frequency of *t* is reduced by powerful individual selection. These two forces lead to an intermediate equilibrium, but because of the very small size of mouse populations and the domination of a territory by one or two males, it often happens that a small deme will have only *t/t*, sterile males. That deme will then become extinct so that *t* genes are removed from the species by population selection. The cycle is regenerated by new mutations and occasional immigration from a heterozygous population into a wild-type deme. In this case the genetic composition of the species is a result of the more or less equal interaction of powerful selection at three levels.

The second case, which is much less idiosyncratic and must represent a fairly frequent class of events, is seen in the coevolution of the rabbit *Oryctolagus cuniculus* and a disease virus, myxoma, in Australia (83). Myxoma virus was introduced into Australia to control the rabbit. When first introduced, it killed more than 99% of the rabbits who became infected. In subsequent years, however, the severity of symptoms in rabbits and the proportion killed decreased progressively. When rabbits from the wild were tested against laboratory strains of virus, it was found that the rabbits had become

resistant, as would be expected from simple individual selection. However, when virus recovered from the wild was tested against laboratory rabbits, it was discovered that the virus had become less virulent, which cannot be explained by individual selection. The key is that myxoma virus is spread by mosquitoes, which mechanically transfer a few virus particles to the rabbits they bite (the virus is not in the mosquito but on its mouthparts). Each rabbit is a deme from the standpoint of the virus. When a rabbit dies, the deme becomes extinct since the virus cannot survive in a dead rabbit. Moreover, the virus cannot be spread from that deme because mosquitoes do not bite dead rabbits. Thus there is a tremendously high rate of deme extinction, with the result that those demes are left extant that are least virulent. This causes a general trend toward avirulence of the pathogen despite the complete lack of selective advantage of avirulence within demes. It is very likely that these observations are a model of the general evolution toward avirulence of parasites in which the death of the host causes death of the parasite. There is also a rabbit flea which could spread the virus even after the death of a rabbit. One would predict that the introduction of such a flea in Australia would prevent the evolution toward avirulence of the myxoma virus. It is now being tried.

Thus, we see that even if interdeme selection is not necessary to explain most facts of evolution, it does occur under a restricted, although not exceptionally rare, set of circumstances.

HIGHER LEVELS OF SELECTION

At yet higher levels, the species and the community, natural selection obviously must occur. Species evolve to survive in a certain environmental range, and if the environment should suddenly change, some species will become extinct but others will survive. The same is true of communities whose stability of composition depends upon the interaction among their constituent species. If the rate of environmental change is slow enough, natural selection operating within species will allow the phylogenetic line to survive even though the species may slowly transform. Yet more than 99% of all phyla that have ever existed are extinct. On the geological scale of time, then, there is selection between phyla for those best able to survive even the slowly changing environment. At times environments shift more rapidly, as in the Pleistocene, so that extinction rates are very high. More recently, environmental change has been very rapid so that species as units are being selected quite often. Pests, weeds, and commensals with man, like *Rattus* and *Mus*, are all examples of species that, formerly rare, were accidentally preadapted to human environments and especially to the monoculture of certain crop plants and animals. These preadapted species have undergone an explosive increase as compared to the extinction or near extinction of those wild relatives that were unable to escape from the old habitats. When the habitats were destroyed, so were the species. Thus man, by his rapid

transformation of habitats, creates the conditions for efficient natural selection of species and species relationships, on a scale never before existent in evolution.

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