V: Adaptive Polymorphism

TYPES AND POPULATIONS

PLATONIC PHILOSOPHY considers the elusively multiform, always changing natural phenomena to be mere shadows of the immutable ideas, of the eternally fixed essences of things. This philosophy has appealed to many scientists. Individual organisms and living populations are often supposed to represent imperfect incarnations of ideas, patterns, or types of their respective races, species, genera, etc. In 1896, the great anthropologist and pathologist Virchow defined human races as "acquired deviations from the original type" (see Count 1950). Acceptance of the biological evolution theory did not completely overcome the notion that the annoying variability of individuals is somehow a false front which conceals slowly changing racial or species types. The fiction of types is indeed helpful for the purpose of classification and of cataloguing of organisms (Chapter IX). It is also a great, though highly misleading, simplification for a physiologist or a medical man to believe that different individuals, or different patients, should react alike to similar treatments. The fictitiousness of the types has been shown by the Hardy-Weinberg's demonstration of the genetic equilibrium (Chapter III). The spatio-temporal entities in sexually reproducing and cross-fertilizing organisms are individuals and Mendelian populations. Every individual carries a constellation of genes, which is not likely to be found in other individuals. A population has a gene pool, from which the genes of individuals spring and to which they usually return. Gene frequencies and variances, rather than averages, characterize Mendelian populations. Superficially considered, natural populations of most species seem to consist of normal, or wild-type, individuals, among which are scattered aberrant specimens, which owe their origin to mutation. A closer study shows that the wild-type is also a fiction. "Normal" individuals are actually a heterogeneous collection of genotypes, the common property of which is that they possess a tolerable adapted-

ness to the prevailing environments. When the heterogeneity happens to be striking to the eye, or easily detectable by some method, it is referred to as polymorphism. Polymorphism is a loose descriptive term; all Mendelian populations are more or less polymorphic.

GAUSE'S PRINCIPLE

Gause (1934) has stated a simple principle, the significance of which has been pointed out by Lack (1947), Mayr (1947), Crombie (1947), Pittendrigh (1950), and others. Two or more forms with identical ecological requirements cannot coexist indefinitely in the same environment, because one of them will in all likelihood be more efficient than the others, and will eventually outbreed and supplant its competitors. Indeed, absolute equality of adaptive values of two biological forms is, like absolute equality of any two continuously varying characteristics, highly improbable. Now, if the adaptive value of one form is unity, and of the other $1 - s$, then, no matter how small is s, the less well adapted form will be, given enough time, eliminated.

Theoretically, an absolutely uniform and absolutely constant environment could be inhabited by only a single species. So stated, Gause's principle becomes unrealistic, because the very presence of inhabitants in an originally uniform environment makes the latter heterogeneous. The inhabitants may, for example, serve as food for a predator or a parasite, and thus the environment may support at least two ecologically complementary organisms (see Allee et al. 1949). But Gause's principle remains useful, because it emphasizes an important and often overlooked fact. Different living beings with ecological requirements of the same kind (i.e., different herbivores, different predators, etc.) can be sympatric only provided that the environment in a territory which they inhabit is heterogeneous. The heterogeneity may be spatial or it may be temporal. Two species, A and B, can be sympatric if A is more efficient than B in utilization of some food, while B is superior to A in exploitation of another food source in the same territory. Or, A may be better adapted than B in summer, while B is superior to A during the winter season. In reality, environments are always heterogeneous, although some are much more so than others. The heterogeneity permits the development of sympatric diversity of organisms.

Looked at from another angle, polymorphism within a species, or any other kind of diversity of sympatric forms, increase the efficiency of the exploitation of the resources of the environment by the living matter. A single genotype, no matter how versatile, could hardly function with maximal efficiency in all environments. Hence, natural selection has preserved a variety of genotypes, more or less specialized to render the organism efficient in a certain range of the existing environments. As pointed out almost a century ago by Herbert Spencer, division of labor is at least as important on the biological as it is on the sociological level.

CHROMOSOMAL POLYMORPHISM IN DROSOPHILA

Although polymorphism is nearly universal in sexual species, it happens that the most thorough, although by no means complete, understanding of this phenomenon has been secured for a rather covert trait, namely for inverted sections in chromosomes of *Drosophila* flies (cf. Chapter II). The first inversions were detected in *Drosophila melanogaster* through the suppression of crossing over in inversion heterozygotes (Sturtevant 1926, 1931). A less laborious and more exact method of study of inversions is observation of the giant chromosomes in the salivary gland cells of fly larvae (Heitz and Bauer 1933, Painter 1934). These chromosomes appear as cross-striped cylinders or ribbons. The stainable discs which form the striations may or may not correspond each to a single gene, but they form a constant pattern which reflects the gene arrangement in the chromosomes.

Suppose an inversion heterozygote has two chromosomes ABCDEF and AEDCBF. These chromosomes pair by forming a loop, shown schematically in Fig. 3 in the upper right corner. Suppose further that the original, ancestral gene arrangement in a chromosome is ABCDEFGHI. An inversion of the section from B to E gives rise to an arrangement AEDCBFGHI (Fig. 3). A second inversion may take place in this chromosome. The location of the second inversion may be outside the limits of the first: AEDCBFGHI → AEDCBFHGI. Such inversions may be described as independent. An individual heterozygous for ABCDEFGHI and AEDCBFHGI will have a double loop shown second from the top in Fig. 3. The second inversion may occur inside the first, forming included inversions:

ABCDEFGHI → AEDCBFGHI → AECDBFGHI (second from the bottom in Fig. 3). Finally, the second inversion may have one end inside and the other end outside the limits of the first. Such inversions are termed overlapping: ABCDEFGHI → AEDCBFGHI → AEHGFBCDI (the lower right corner in Fig. 3).

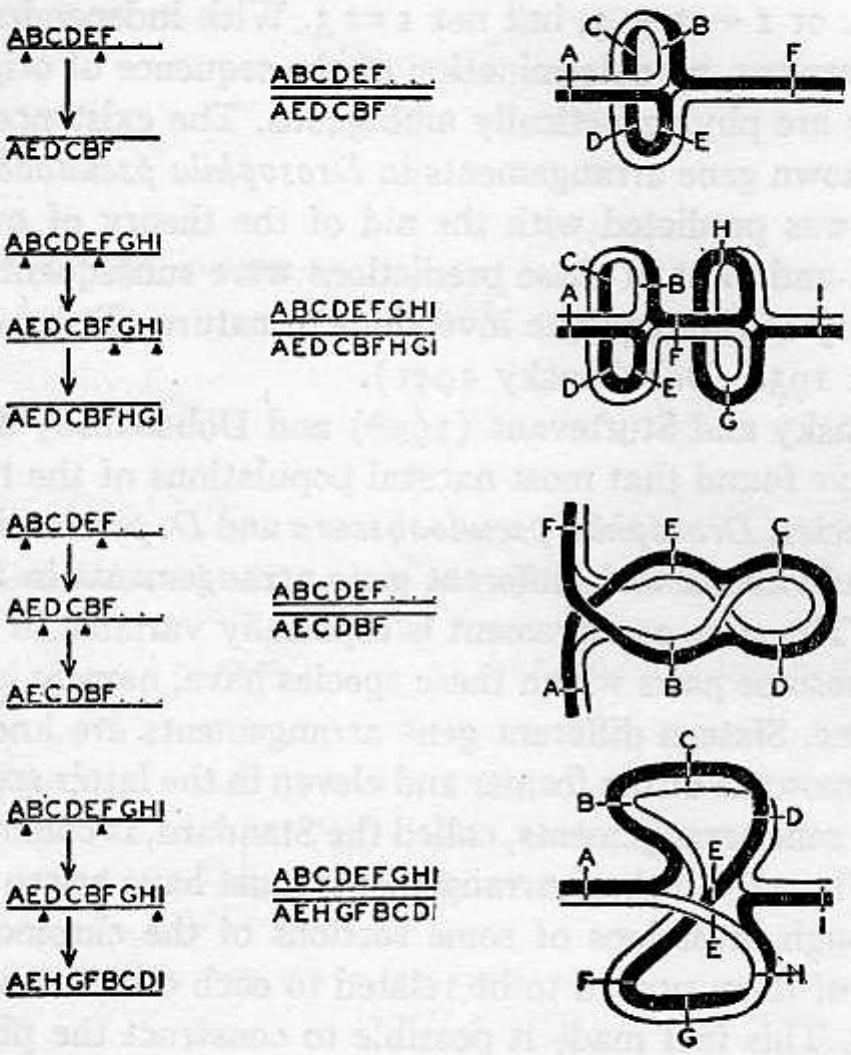

FIG. 3. Chromosome pairing in the salivary gland cells of individuals heterozygous for inversions. Upper row, a single inversion; second from the top, two independent inversions; third from the top, two included inversions; lower row, overlapping inversions.

Overlapping inversions have interesting properties. Suppose we observe in different strains the arrangements ABCDEFGHI, AEDCBFGHI, and AEHGFBCDI. The first can arise from the second or give rise to the second through a single inversion. The same is true for the second and the third. But the third can arise from the first, or vice versa, only through the second arrangement as the probable intermediate step in the line of descent. If we find in natural popula-

tions of some species only the first and the third arrangements, it is probable that the second remains to be discovered, or at least that it existed in the past. If all three are actually observed, the probability of the first and the third being related through the second becomes almost a certainty. To recapitulate, the phylogenetic relationship of the three gene arrangements indicated above is $1 \rightarrow 2 \rightarrow 3$, or $3 \rightarrow 2 \rightarrow 1$, or $1 \leftarrow 2 \rightarrow 3$, but not $1 \rightleftarrows 3$. With independent and included inversions, no determination of the sequence of origin is possible; they are phylogenetically ambiguous. The existence of previously unknown gene arrangements in *Drosophila pseudoobscura* and *D. azteca* was predicted with the aid of the theory of overlapping inversions, and most of these predictions were subsequently verified by discovery of the requisite inversions in nature (Dobzhansky and Sturtevant 1938, Dobzhansky 1941).

Dobzhansky and Sturtevant (1938) and Dobzhansky and Epling (1944) have found that most natural populations of the two closely related species, *Drosophila pseudoobscura* and *D. persimilis*, are mixtures of individuals with different gene arrangements in their chromosomes. The gene arrangement is especially variable in one of the five chromosome pairs which these species have, namely in the third chromosome. Sixteen different gene arrangements are known in the third chromosome of the former and eleven in the latter species. Only one of the gene arrangements, called the Standard, is common to both species (Fig. 4). All these arrangements must have arisen from each other through inversions of some sections of the chromosome, and nearly all of them proved to be related to each other as overlapping inversions. This fact made it possible to construct the phylogenetic chart of the gene arrangements in the third chromosome shown in Fig. 4. Each arrangement is designated by the name of the geographical locality in which it was first encountered. Any two arrangements connected in Fig. 4 by an arrow give a single inversion loop in the heterozygotes. Some of the arrangements (Santa Cruz, Tree Line) had been postulated theoretically as the necessary "missing links" between the other arrangements, and subsequently found when more strains were examined. One of the arrangements (see Fig. 4) remains hypothetical as far as the species *D. pseudoobscura* and *D. persimilis* are concerned, but an arrangement possessing the essential properties

of this hypothetical one has been met with in a related species, *D. miranda*.

None of the gene arrangements shown in Fig. 4 occur over the entire distribution areas of their species; and in no natural population is the complete collection of the arrangements found. The geographic

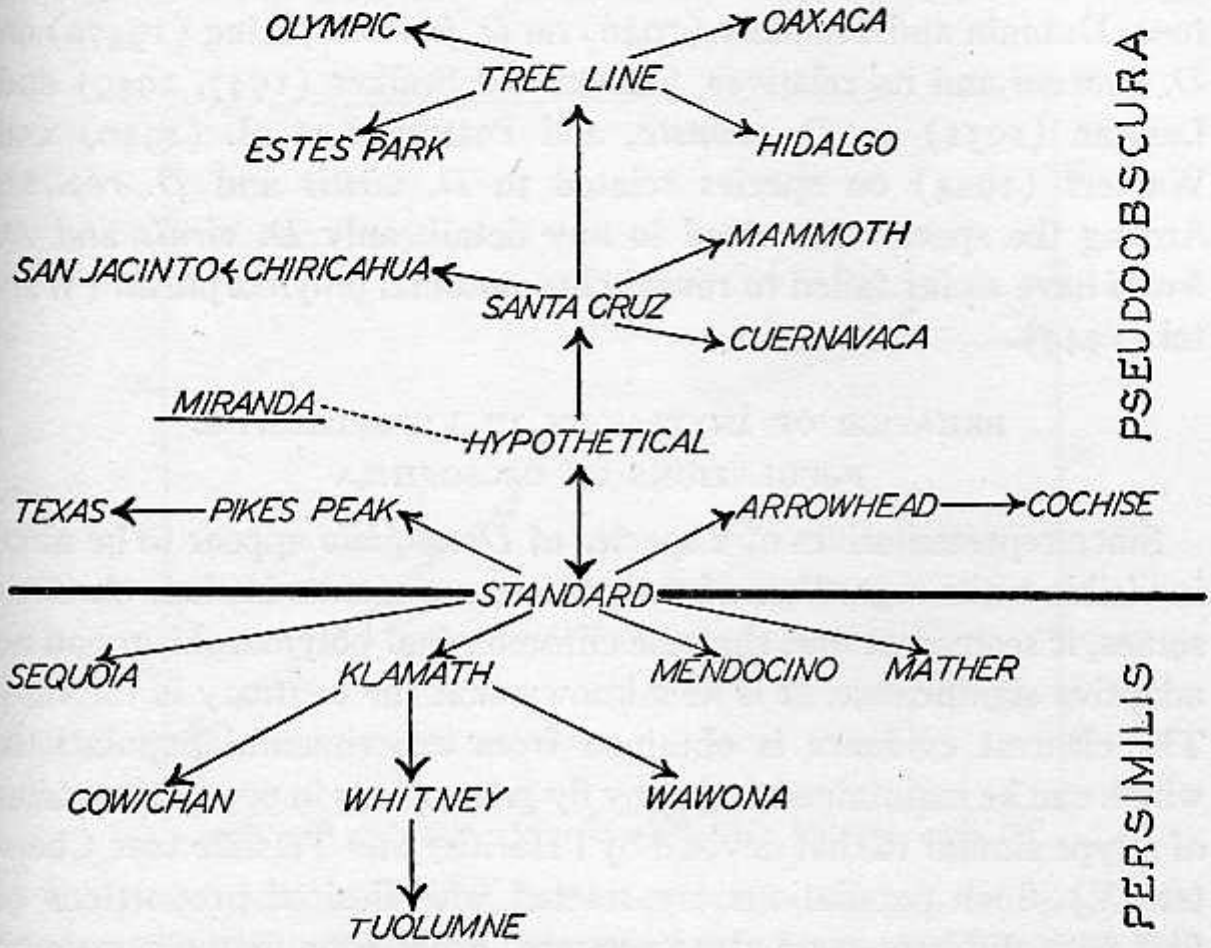

FIG. 4. A phylogenetic chart of the gene arrangements encountered in the third chromosome of *Drosophila pseudoobscura* and *Drosophila persimilis*.

distribution of the gene arrangements will be discussed in Chapter VI. It is sufficient to state here that in some localities up to eight arrangements occur together, and that both inversion homozygotes (flies having two chromosomes with the same gene arrangements) and inversion heterozygotes (flies with two chromosomes of a pair having different gene arrangements) are encountered in nature. The chromosomal inversions thus give rise to a remarkable polymorphism in fly populations.

Chromosomal polymorphism due to inversions is known in natural populations of about 30 species of *Drosophila*. The principal works

in this field are those of Sturtevant (1931), Dubinin et al. (1937), and Ives (1947) on *D. melanogaster,* Kikkawa (1938) on *D. ananassae,* da Cunha et al. (1950) and Dobzhansky et al. (1950) on *D. willistoni* and its relatives, Pavan (1946b) on *D. nebulosa,* Dobzhansky and Sokolov (1939) on *D. azteca,* Miller (1939) on *D. algonquin,* Novitski (1946) on *D. athabasca,* Cavalcanti (1948) on *D. prosaltans,* Dubinin and Tiniakov (1946) on *D. funebris,* King (1947a) on *D. guarani* and its relatives, Carson and Stalker (1947, 1949) and Levitan (1951) on *D. robusta,* and Patterson et al. (1940) and Warters (1944) on species related to *D. virilis* and *D. repleta.* Among the species examined in any detail, only *D. virilis* and *D. hydei* have so far failed to reveal chromosomal polymorphism (Warters 1944).

BEHAVIOR OF INVERSIONS IN EXPERIMENTAL POPULATIONS OF DROSOPHILA

Since representatives of a species of *Drosophila* appear to be alike in visible traits regardless of the gene arrangements in their chromosomes, it seemed at first that the chromosomal polymorphism had no adaptive significance. It is now known that the contrary is the case. The clearest evidence is obtained from experimental populations, which can be maintained for many fly generations in population cages of a type similar to that devised by l'Héritier and Teissier (see Chapter IV). Such populations are started with desired proportions of flies with different gene arrangements. From time to time, samples of larvae in the population are taken, and the incidence of the chromosomal types among them determined by cytological examination.

Figure 5 presents an example of results obtained in an experimental population of *Drosophila pseudoobscura,* which at the start of the experiment contained about 11 percent of Standard (ST) and 89 percent of Chiricahua (CH) chromosomes derived from a natural population of a locality in California. It can be seen that, within approximately 4 months, the frequency of ST chromosomes in the population about quadrupled, then rose more slowly to about 70 percent, after which no further changes occurred. It is clear, that the carriers of ST chromosomes had some adaptive advantages under the conditions of the experiment over the carriers of CH chromosomes, and that the rapid increase of the incidence of the former was

caused by natural selection. But if so, why has selection failed to eliminate CH chromosomes altogether, and to make the population uniformly ST? As explained below, the establishment of the equilibrium, at which both ST and CH chromosomes are present in the gene pool with definite frequencies, is due to the chromosomal polymorphism being balanced, because the heterozygotes (individuals

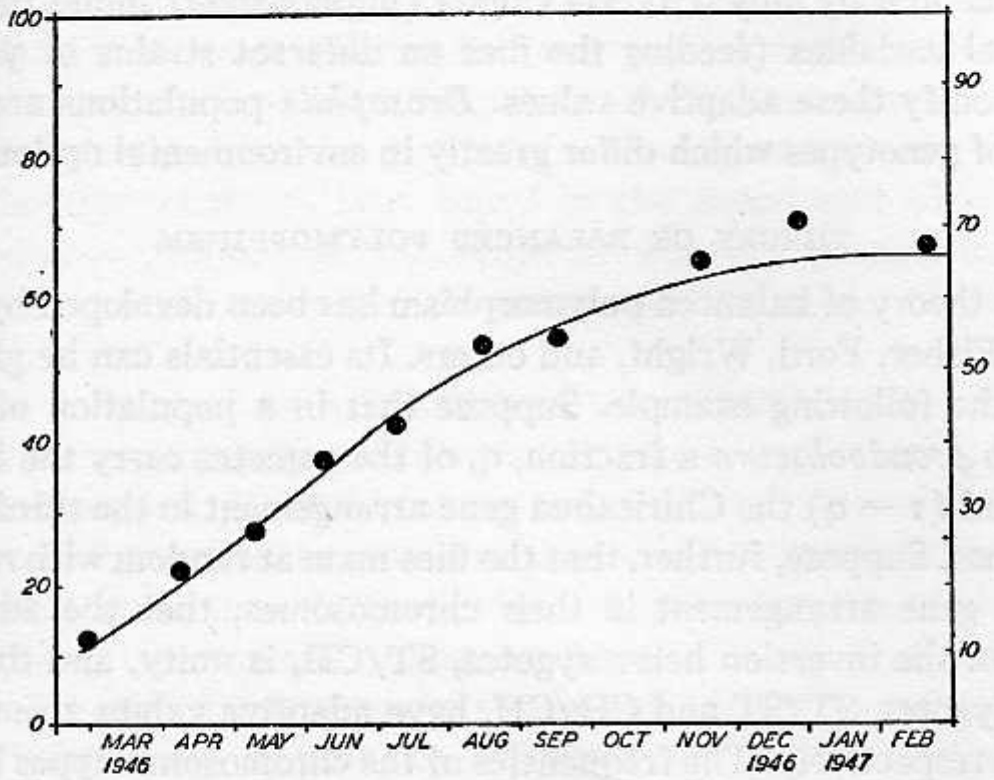

FIG. 5. The frequency of chromosomes with the Standard gene arrangement in an experimental population of *Drosophila pseudoobscura*. At the start of the experiment, this population contained about 11 percent of chromosomes with the Standard, and about 89 percent with the Chiricahua gene arrangement.

having one ST and one CH third chromosome) are superior in adaptive value to both chromosomal homozygotes (ST/ST and CH/CH).

In *Drosophila pseudoobscura,* the establishment of stable equilibria in experimental populations is the rule whenever the competing chromosomal forms are derived from flies collected in the same geographical locality (Dobzhansky 1947a and b, 1949, Wallace 1948). A similar situation has been discovered by Spiess (1950) in *D. persimilis* and by Levitan (1951) in *D. robusta*. It is probable that the chromosomal polymorphism in other species is also balanced. A further interesting fact is an extraordinary sensitivity of the adaptive values of the chromosomal forms to environmental conditions. The experiment

reported in Fig. 5 was carried out at a temperature of 25°C. Populations which contain ST and CH chromosomes show, however, no changes in the relative proportions of the two types if kept at 16°C. In *D. persimilis*, Spiess has, on the contrary, observed changes at 16°C. but in some cases not at 25°C. This means that the chromosomal types are greatly different in adaptive value at one temperature but are nearly or completely equal at another temperature, differing from the first by only 9°C. Da Cunha (unpublished) found that nutritional variables (feeding the flies on different strains of yeasts) also modify these adaptive values. *Drosophila* populations are mixtures of genotypes which differ greatly in environmental optima.

THEORY OF BALANCED POLYMORPHISM

The theory of balanced polymorphism has been developed by Haldane, Fisher, Ford, Wright, and others. Its essentials can be gleaned from the following example. Suppose that in a population of *Drosophila pseudoobscura* a fraction, q, of the gametes carry the Standard, and $(1 - q)$ the Chiricahua gene arrangement in the third chromosomes. Suppose, further, that the flies mate at random with respect to the gene arrangement in their chromosomes, that the adaptive value of the inversion heterozygotes, ST/CH, is unity, and that the homozygotes, ST/ST and CH/CH, have adaptive values $1 - s_1$ and $1 - s_2$ respectively. The frequencies of the chromosomal types before and after selection will, according to the binomial square rule (Chapter III) be as follows:

GENOTYPE	ST/ST	ST/CH	CH/CH	TOTAL POPULATION
Adaptive value (W)	$1 - s_1$	1	$1 - s_2$	$\overline{W}$
Initial frequency	q^2	$2q(1 - q)$	$(1 - q)^2$	1
Frequency after the selection	$q^2(1 - s_1)$	$2q(1 - q)$	$(1 - q)^2(1 - s_2)$	$1 - s_1q^2 - s_2(1 - q)^2$

The rate of change, Δq, of the frequency of standard chromosomes in the population in one generation will be:

$$\Delta q = \frac{q(1 - q)\,[s_2(1 - q) - s_1 q]}{1 - s_1q^2 - s_2(1 - q)^2}$$

Making $\Delta q = 0$, and solving the equation for q, we obtain: $q = s_2/(s_1 + s_2)$. This means that natural selection will not eliminate

either ST or CH chromosomes from the population, but will establish an equilibrium at which the population will be polymorphic and will contain the two kinds of chromosomes in the gene pool, with frequencies dependent upon the selection coefficients, s_1 and s_2. From the speed of the changes in the frequencies of ST and CH chromosomes observed in the population which is represented in Fig. 5, the adaptive values of the chromosomal types can be calculated. If that of the heterozygotes, ST/CH, is 1, that of the ST/ST homozygotes turns out to be approximately 0.7 ($s_1 = 0.3$), and that of the CH/CH about 0.4 ($s_2 = 0.6$). The frequency of ST chromosomes at equilibrium should, then, be $q = 0.6/(0.6 + 0.3) = 0.67$, which is approximately what has been found in the experiment (Fig. 5). As stated above, these selection coefficients are very strongly influenced by temperature and other environmental variations (Wright and Dobzhansky 1946).

The validity of the application of the natural selection theory to the chromosomal polymorphism in *Drosophila* can be tested by other methods as well. If the differences in the adaptive values of the chromosomal forms lead to a differential mortality between the egg and the adult stage, then the proportions of those types should be different among the eggs and among adult flies. (To be sure, differential mortality need not necessarily be present, since differences in adaptive values may as well be expressed in different fecundity, or longevity, or different sexual activity of the carriers of the chromosomal types.) With experimental populations, the test can be arranged as follows. Samples of eggs deposited by the flies in the population cages are taken, and the larvae from these eggs are raised under optimal conditions, to enable all of them to survive. Examination of the chromosomes in such larvae reveals the chromosomal types to be present in proportions demanded by the binomial square rule, q^2ST/ST : $2q(1 - q)$ ST/CH : $(1 - q)^2$CH/CH. This shows that flies mate at random with respect to the chromosomal type. Now, samples of the adult flies developed in the population cages, under stringent competition of larvae for a limited food supply, are taken, and the chromosomal constitution of these flies is determined. Among the adult flies, the heterozygotes are more, and the homozygotes are less, common than they should be according to the binomial square rule. The differential mortality of the chromosomal types is thus demon-

strated (Dobzhansky 1947b). Wallace (1948) and Heuts (1948) have found some physiological differences between the carriers of certain chromosomal types in *Drosophila pseudoobscura* which may be responsible, in part, for the observed differences in the adaptive values of these types. More information of this kind is, however, needed to correlate the genetical and the physiological pictures.

Dobzhansky and Levene (1948) have adduced evidence of selection pressure on the balanced chromosomal polymorphism also in natural populations of *D. pseudoobscura*. Females, which had mated with males in their natural habitats, were collected, and allowed to produce offspring in the laboratory, under optimal conditions. In these offspring, the inversion homozygotes and heterozygotes were present with frequencies conforming to the binomial square rule. A small but significant excess of heterozygotes, and a corresponding deficiency of homozygotes, were however found among the adult flies (males) captured outdoors. Thus, in natural, like in the experimental, populations the mating is at random with respect to the chromosome structure; but a differential mortality favoring the heterozygotes relative to the homozygotes takes place during the development of the flies.

BIOLOGICAL FUNCTIONS OF THE CHROMOSOMAL POLYMORPHISM IN DROSOPHILA

The experiments just described throw light on certain very remarkable phenomena observed in natural populations of *Drosophila pseudoobscura* and other species. If samples of populations are taken repeatedly in the same localities, the relative frequencies of chromosomal types can be shown to undergo cyclic seasonal changes. A summary of observations in a locality on Mount San Jacinto, in California, conducted from 1939 to 1946 is presented in Fig. 6. The three commonest gene arrangements in this population are Standard (ST), Arrowhead (AR), and Chiricahua (CH). The frequency of ST decreases, and that of CH increases, from March to June; the opposite change takes place during the hot season, from June to August.

Now, since the gene arrangement in a chromosome is a hereditary trait, we are dealing here with genetic changes in the constitution of a population. These are evolutionary changes by definition. Further-

more, these changes are brought about by natural selection. With balanced polymorphism, the equilibrium point depends upon the relative adaptive values of the homozygotes, $(1 - s_1)$ and $(1 - s_2)$. During the hot season, selection evidently favors ST homozygotes relatively more than it does in spring, when CH homozygotes have a relatively higher adaptive value. In fact, the speed of the changes observed in nature during the hot season can be accounted for if the

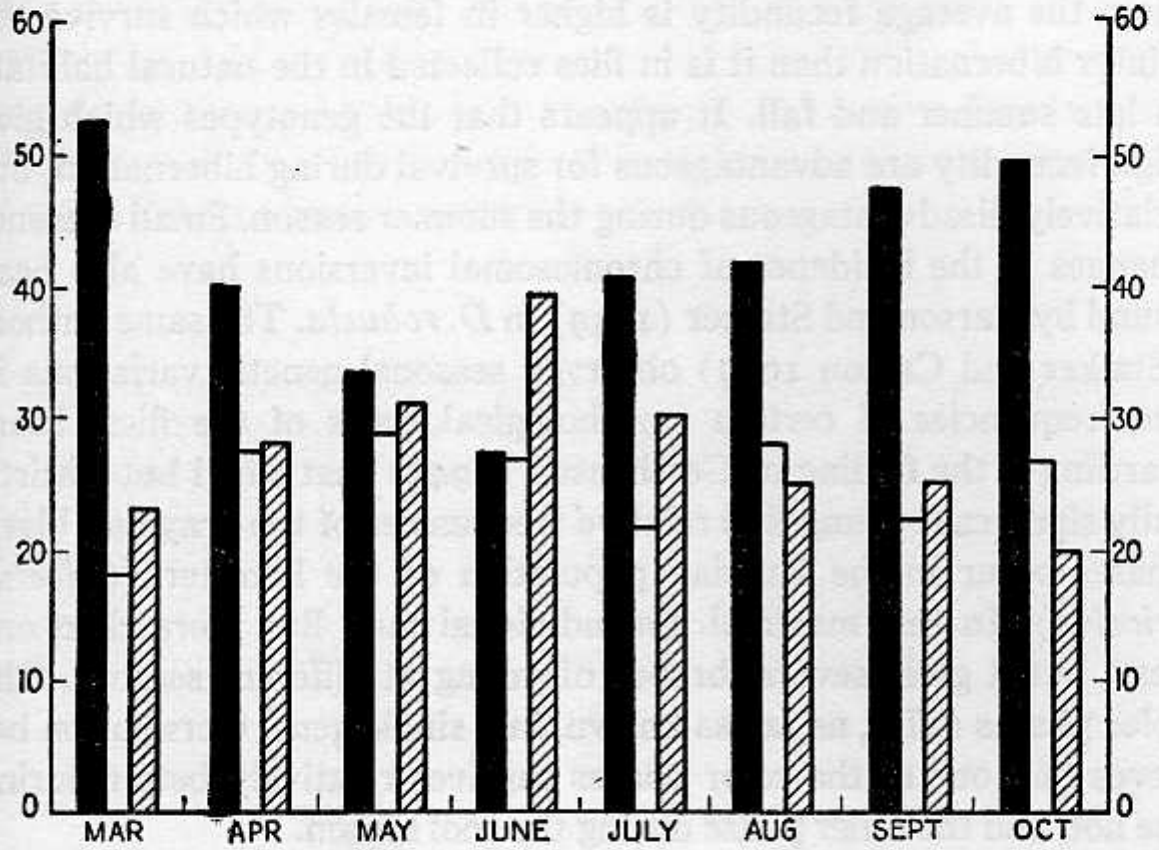

FIG. 6. Seasonal changes in the relative frequencies of the third chromosomes with the Standard (black), Arrowhead (white), and Chiricahua (cross-hatched columns) gene arrangements in a natural population of *Drosophila pseudoobscura*. The ordinates indicate percentages.

chromosomal types have adaptive values which they are observed to have in experimental laboratory populations at 25°C. (see above). At a lower temperature, 16°C., no changes occur in experimental populations, and none seem to occur in nature from September to March. The system operates in such a way that the average adaptive value of the population as a whole remains high in different seasonal environments.

Dubinin and Tiniakov (1945, 1946b and c) observed cyclic seasonal changes in the incidence of chromosomal types in *Drosophila*

funebris. They have also shown that in this species some chromosomal types survive more often than others when known mixtures of flies are exposed to low temperatures in artificial "hibernation" tests. In another experiment they released 100,000 flies homozygous for a certain inversion in a locality near Moscow, and observed a gradual decline of the frequency of this inversion towards the equilibrium value which it has naturally in the population of this locality. Another seasonal genetic change involves the fecundity of the female flies: the average fecundity is higher in females which survive the winter hibernation than it is in flies collected in the natural habitats in late summer and fall. It appears that the genotypes which give high fecundity are advantageous for survival during hibernation, but relatively disadvantageous during the summer season. Small seasonal changes in the incidence of chromosomal inversions have also been found by Carson and Stalker (1949) in *D. robusta*. The same authors (Stalker and Carson 1949) observed seasonal genetic variations in the frequencies of certain morphological traits of the flies. More startling is the finding of Gershenson (1945) that small but statistically significant changes in relative frequencies of the gray and black phases occur in the Russian population of the hamster (*Cricetus cricetus*). In this mammal, an individual may live more than one year, but it gives several broods of young at different seasons. The color phases differ, as far as known, in a single gene. Gershenson believes that one of the color phases survives relatively better during the hot, and the other phase during the cool season.

Adaptation to seasonal changes in the environment is assuredly not the only biological function of the chromosomal polymorphism in *Drosophila*. Table 9 shows differences in the incidence of ST, AR, and CH chromosomes in populations of *D. pseudoobscura* at different elevations in the Sierra Nevada mountains of California. It can be seen that ST chromosomes are more frequent at low than at high elevations; conversely, AR chromosomes increase in frequency as one ascends to higher elevations; CH chromosomes are relatively more constant in frequency. Here, then, the chromosomal polymorphism serves the function of adaptation to altitudinal variations in the environment. But seasonal changes are observed in these populations as well: the incidence of ST increases, and that of AR chromosomes decreases, as the summer progresses, while the opposite

changes presumably occur during winter. In other words, during the warm season the populations of localities at higher elevations come to resemble in composition those of localities at lower elevations earlier in the season (Dobzhansky 1948). Changes in the frequencies of chromosomal types with elevation have also been found by Stalker and Carson (1948) in *D. robusta* in the Great Smoky Mountains of Tennessee. Dubinin and Tiniakov (1946a) found that in *D. funebris* the incidence of certain chromosomal types is much greater in urban than in rural populations. This species lives as a scavenger in human households, and is therefore common in cities; but it also occurs in undisturbed natural habitats, in the vicinity of Moscow, Russia. Some chromosomal types have considerably higher equilibrium frequencies in man-made environments than in natural ones.

TABLE 9

INCIDENCE OF THIRD CHROMOSOMES WITH DIFFERENT GENE ARRANGEMENTS IN POPULATIONS OF *Drosophila pseudoobscura* WHICH LIVE AT DIFFERENT ELEVATIONS IN THE SIERRA NEVADA OF CALIFORNIA

ELEVATION OF THE LOCALITY (FEET)	GENE ARRANGEMENT (%)			
	Standard	*Arrowhead*	*Chiricahua*	*Others*
850	46	25	16	13
3,000	41	35	14	10
4,600	32	37	19	12
6,200	26	44	16	14
8,000	14	45	27	14
8,600	11	55	22	12
10,000	10	50	20	20

BALANCED POLYMORPHISM AND HETEROSIS

It has been shown above that hybrid vigor or heterosis, in other words adaptive superiority of heterozygotes over homozygotes, is the essential condition for the establishment of balanced polymorphism in a Mendelian population. If a mutant produces a heterotic heterozygote, natural selection will retain this mutant in the population, regardless of how poorly adapted, or even lethal, may be the mutant homozygote. The fitness of the homozygotes influences only

the equilibrium frequencies, but not the preservation, of heterotic mutants. The origin of such mutants has been observed by Gustafsson (1946a) and Gustafsson et al. (1950) in barley. The chromosomal polymorphism in *Drosophila pseudoobscura* and other species is, however, due to heterotic effects produced not by single gene mutations but by heterozygosis for inverted sections of chromosomes. Now, an inverted section may modify the physiological characteristics of its carriers either through position effects (cf. Chapter II), or through possession of mutant genes different from those in chromosomes with the alternative gene arrangement, or through a combination of these causes.

Experimental data which shed some light on this problem have been obtained in *D. pseudoobscura*. In this species, any two gene arrangements found in the population of any one locality give, as a rule, a heterotic heterozygote. Some of the gene arrangements occur, however, in rather extensive geographical areas (see Chapter VI). Experiments have been arranged in artificial populations, in which chromosomes with one gene arrangement from a locality in California were made to compete with chromosomes with a different gene arrangement from localities several hundred miles away from the first, either in California or in Mexico. When the chromosomes are derived from geographically remote populations, the inversion heterozygotes show heterosis only in a minority of cases; in others the adaptive values of the heterozygotes are intermediate between those of the homozygotes; and in one case the heterozygote proved only as viable as the least viable homozygote. The adaptive value of a heterozygote is, accordingly, not always determined by the gene arrangements in the chromosomes which it carries. It must be determined at least in part by the genes in these chromosomes (Dobzhansky 1950c).

The most probable interpretation of these facts is as follows. The chromosomes with different gene arrangements carry different complexes of genes (arising ultimately through mutation). The gene complexes in the chromosomes found in the population of any one locality have been, through long continued natural selection, mutually adjusted, or "coadapted," so that the inversion heterozygotes possess high adaptive values. But the genes in chromosomes with the same or with different gene arrangements vary also from locality to locality. The gene complexes in different localities are not coadapted

by natural selection, since heterozygotes for such foreign gene complexes are seldom or never formed in nature. Heterosis is, therefore, an outcome of a historic process of adaptation to the environment. This adaptation is, however, increasing the fitness of the Mendelian population as a whole, and it is attained despite the production of relatively ill-adapted inversion homozygotes. Indeed, the adaptive value ($\overline{W}$) of the whole population under balanced polymorphism can be shown to reach the highest level when the equilibrium proportions of the competing variants, $q = s_2/(s_1 + s_2)$, are established (see above).

Balanced polymorphism has certain advantages as a method of adaptation over a polymorphism unconnected with heterosis. Imagine a population like *Drosophila pseudoobscura* in the California localities discussed above, in which carriers of ST chromosomes, whether heterozygous or homozygous, would be favored during the hot part of the year, while the carriers of AR chromosomes would be superior during the cool season. Now, an exceptionally hot or prolonged summer could, conceivably, result in elimination of all AR chromosomes. A population in which this would happen, would be placed at a disadvantage during the winter season, because in winter the carriers of AR are superior. No such "adaptive accident" can take place if the polymorphism is balanced. Here natural selection does not eliminate either ST or AR chromosomes, but conduces the population towards the equilibrium point which is adaptively most favorable in a given environment (Dobzhansky 1949, 1950c).

CHROMOSOMAL POLYMORPHISM IN ORGANISMS OTHER THAN DROSOPHILA

It is not difficult to see why balanced polymorphism is so often, at least in *Drosophila,* connected with inverted sections in the chromosomes. The principal genetic effect of inversions is suppression of recombination of genes located in the chromosomes involved in inversion heterozygosis. If the high fitness, the heterosis, of the inversion heterozygotes is due to interaction of gene complexes carried in the chromosomes, then the preservation of these gene complexes as units (Darlington and Mather's "supergenes," 1949) is advantageous. Crossing over and gene recombination would break up these gene complexes. Inversions acquire selective advantages if they arise in

chromosomes which carry adaptively valuable gene complexes (Dobzhansky 1950c).

The detection of chromosomal polymorphism is technically simplest in the representatives of the order Diptera (flies) which have giant chromosomes in the salivary glands. Inversion heterozygotes have been found in the natural populations of some, but not of all, species of midges (Chironomidae) studied by Bauer (1936, 1945), Hsu and Liu (1948), and other investigators. Carson (1944) and Rohm (1947) found inversions in some species of *Sciara,* Wolf (1941) in *Dicranomyia,* and Mainx (1949) in *Liriomyza.* Inversions are rare in natural populations, but occur in hybrids between species of mosquitoes (Frizzi 1950).

In organisms which do not have giant chromosomes, resort may be had to examination of the meiotic divisions. In inversion heterozygotes, the chromosomes undergo pairing by formation of loops represented schematically in Fig. 7. If a chiasma becomes established within the inversion loop, the result of meiosis is as represented diagramatically in Fig. 7. Two normal non-crossover chromatids, one dicentric chromatid, and an acentric chromosome fragment are formed. At the anaphase of the first meiotic division the dicentric chromatid becomes a "chromatid bridge" connecting the two poles of the spindle, as shown in Fig. 7. The chromatid bridge may be seen under the microscope; it is, however, evident that only those inversions which permit formation of chiasmata and crossing over within the inverted regions may be detected with the aid of this method. This is not always the case, and short inversions, which suppress the chiasma formation inside the inversion loops, produce no cytologically visible effects at the meiotic divisions. Negative evidence, absence of chromatid bridges and acentric fragments, does not exclude the possibility that inversions may be present.

Among species in which inversions are detected through observation of chromatid bridges and acentric fragments at meiosis, the Tyrolean populations of the plant *Paris quadrifolia* are most remarkable (Geitler 1938). Every individual studied proved heterozygous for one or more inversions, and it appears that inversions exist in every chromosome of the complement. Stebbins (1938) and Walters (1942) found inversion heterozygotes in every species of *Paeonia* studied by them. The list of plant species in which some inversions

have been recorded is a long one; rye (Lamm 1936), *Elymus* (Stebbins and Walters 1949), *Fritillaria* (Frankel 1937), *Tradescantia* (Swanson 1940), *Rumex* (A. Löve 1944), *Melandrium* (D. Löve 1944), *Polygonatum* (Suomalainen 1947), oats (Howard 1948), and *Clematis* (Meurman and Therman 1939) may serve as examples. Inversion heterozygotes in animal populations seem to be less common than in plants, if flies are excepted. Koller (1936) recorded them in

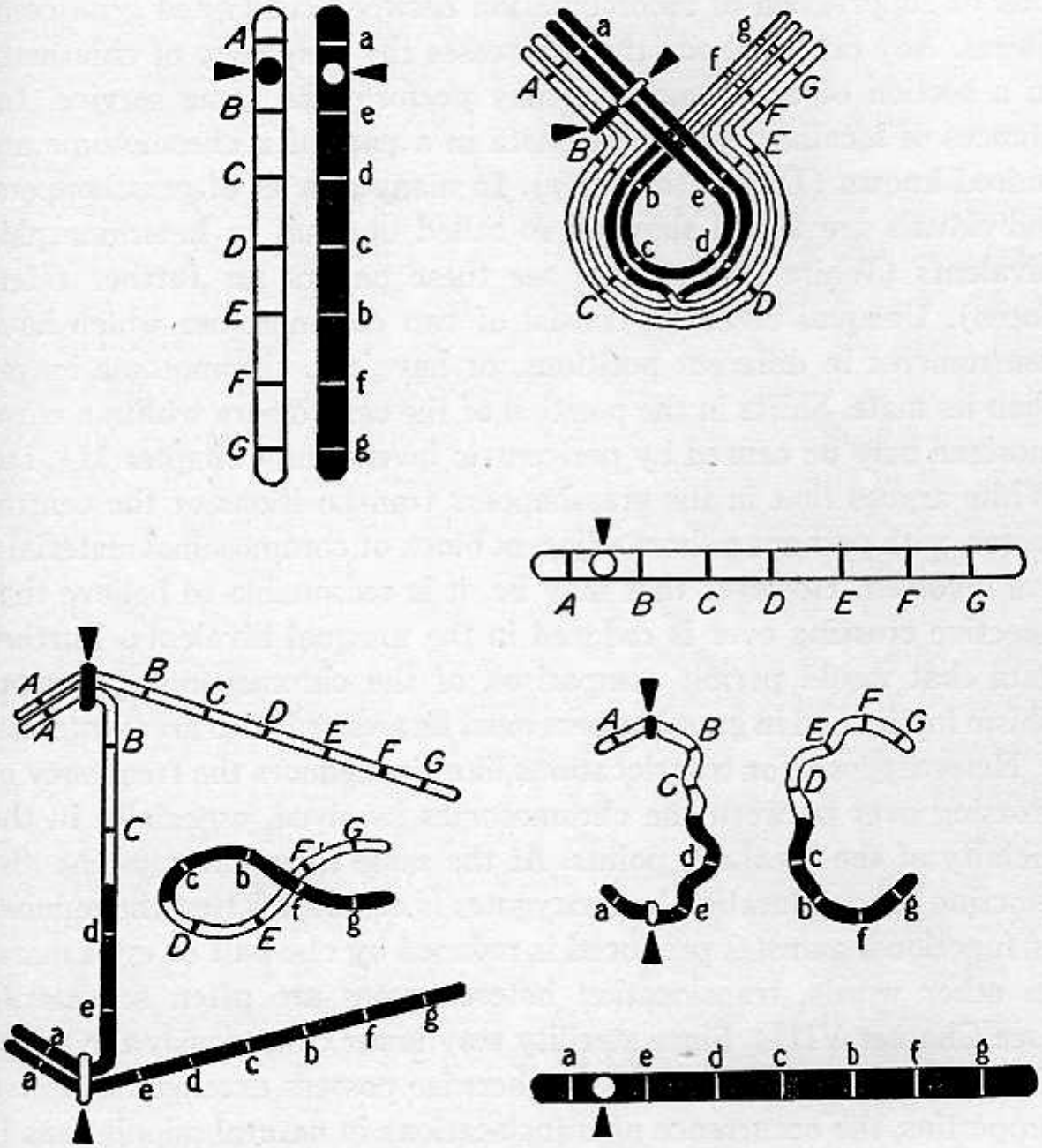

FIG. 7. Crossing over in an inversion heterozygote. Upper left, two chromosomes which differ in a paracentric inversion; upper right, chromosome pairing at the diplotene stage of meiosis; lower left, the "chromatid bridge" and the acentric fragment formed at the first meiotic division; lower right, the two viable and the two inviable chromosomes formed through crossing over. The black triangles indicate the centromeres.

the squirrel *Sciurus carolinensis,* and found a perhaps doubtful case in man (Koller 1937). Darlington (1936) and Coleman (1947) described isolated instances among grasshoppers, but White's (1949) far more extensive studies on many species show that in this cytologically unusually favorable group of insects inversions are decidedly rare in natural populations.

Here it must be emphasized that inversion heterozygosis is merely one of the genetic mechanisms which can serve the biological function of suppression of recombination between coadapted gene complexes. Any other agency that decreases the frequency of chiasmata in a section of a chromosome may perform the same service. Instances of localization of chiasmata in a part of a chromosome are indeed known (Darlington 1937). In many species of grasshoppers, individuals are found showing so-called unequal or heteromorphic bivalents (White 1945, 1949, see these papers for further references). Unequal bivalents consist of two chromosomes which have centromeres in different positions, or have one chromosome longer than its mate. Shifts in the position of the centromere within a chromosome may be caused by pericentric inversions (Chapter II), but White argues that in the grasshoppers transpositions of the centromeres, with perhaps a short adjacent block of chromosomal materials, are involved. However that may be, it is reasonable to believe that effective crossing over is reduced in the unequal bivalents. Further data that would permit comparison of the chromosomal polymorphism in flies and in grasshoppers must be awaited with great interest.

Heterozygosis for translocations likewise reduces the frequency of crossing over between the chromosomes involved, especially in the vicinity of the breakage points. At the same time, chromosome disjunction in translocation heterozygotes is often such that the number of functional gametes produced is reduced by one half or even more. In other words, translocation heterozygotes are often semisterile (see Chapter VIII). Since sterility may lower disastrously the adaptive values of genotypes which otherwise possess excellent adaptive properties, the occurrence of translocations in natural populations is possible only under exceptional circumstances (Wright 1941a). A translocation may, conceivably, produce position effects favorable enough to counterbalance the semisterility, or it may, through suppression of crossing over, tie together a highly adaptive gene system.

More important is the fact that the disjunction of chromosomes at meiosis in translocation heterozygotes may be modified by gene mutations in such a way that the sterility is reduced or even eliminated. Genes which regulate the meiotic disjunction of chromosomes have, indeed, been observed by Rhoades in maize (unpublished data). Finally, in plant species in which self-pollination is the predominant method of reproduction, translocations become fairly easily established in homozygous condition. In plants the semisterility of translocation heterozygotes is expressed in abortion of a part of the pollen grains and ovules; in animals it leads to abortion of a part of the fertilized eggs. It is probably for these reasons that translocation heterozygotes occur more often in some plant than in animal populations.

Extensive data on the occurrence of translocations in the Jimson weed (*Datura stramonium*) of different geographic origin have been reported by Blakeslee and his collaborators (Bergner et al. 1933, and Blakeslee et al. 1937 for further references). This plant possesses twelve pairs of chromosomes, which normally form twelve bivalents at meiosis. In crosses between certain strains, one or more circles of four or six chromosomes appear, the remainder of the chromosomes forming bivalents as usual. The circle formation at meiosis is due to translocations involving two or more chromosomes. The chromosomes of two strains are shown in Fig. 8 a and b respectively. The chromosome structure observed in one of these strains might arise from that in the other by means of a translocation; for instance, the chromosomes 1.2 and 3.4 (Fig. 8a) might exchange sections, giving rise to the chromosomes 1.3 and 2.4 (Fig. 8b). Since like parts of chromosomes come together and pair at meiosis, a cross-shaped configuration (Fig. 8d) will be formed in the hybrid between the two strains. At the metaphase of the first meiotic division, the cross-shaped figure will be transformed into a twisted circle shown in Fig. 8e. A translocation in which three different chromosomes have exchanged sections gives a circle of six chromosomes (Fig. 8j); two translocations between two different pairs of chromosomes produce two circles of four chromosomes each, etc.

Datura stramonium is a weed which at present is nearly cosmopolitan in distribution, because of its involuntary transport by man with agricultural products. In organisms so deeply influenced by man

clearly defined geographical races are seldom found. Even more interesting, therefore, is the fact that populations of *D. stramonium* from different geographical regions proved to be unlike in their chromosomal constitution. Plants having chromosomes apparently identical with those of the standard line have been grown from seed collected in the United States, in the West Indies, Brazil, France, Portugal, Italy, Japan, Portuguese West Africa, and Australia. The

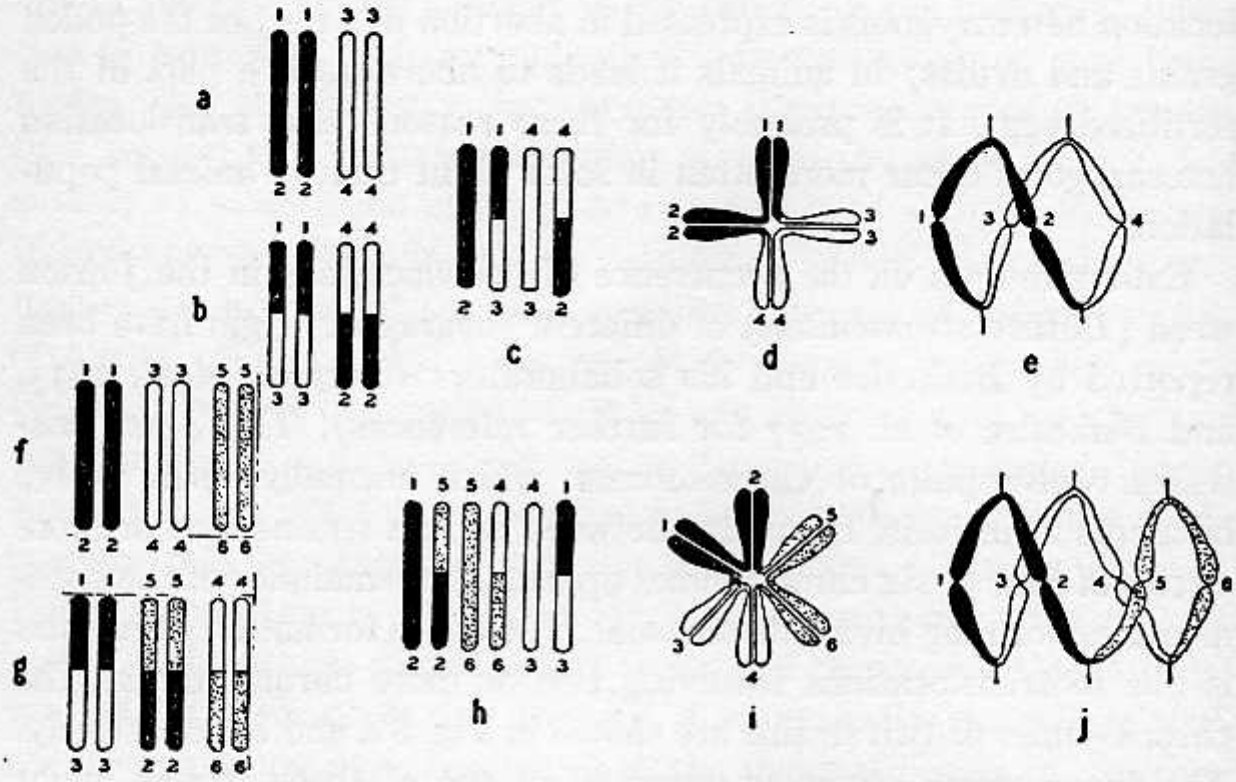

FIG. 8. Translocation between two (b-e) and between three (g-j) chromosomes. Normal chromosomes (a) and (f); (b) and (g) translocation homozygotes; (c) and (h) translocation heterozygotes; (d) and (i) chromosome arrangement at pairing stages; (e) and (j) arrangement of chromosomes at the metaphase of the meiotic division.

populations from Brazil and from the United States, except along the Atlantic seaboard, seem to have only standard chromosomes. The "translocation 2" has a wider distribution; it is very common in Central and South America (except in Brazil and Argentina), on the Atlantic seaboard in the United States, in Europe, in Asia (except Japan), and in Africa (except the eastern Portuguese colonies). The "translocation 3" is restricted to Peru, Chile, and Central America, but has been found once in Spain. The translocations 4 and 7 occur in the eastern United States, the West Indies, the Mediterranean countries of Europe, South Africa, and Australia.

The extraordinary behavior of many representatives of the plant genus *Oenothera* was for many years one of the outstanding puzzles in genetics. It is now known to be caused by many strains of *Oenothera* being balanced translocation heterozygotes, with the corresponding homozygotes eliminated by certain special mechanisms (see Cleland 1940, 1944, and Stebbins 1950 for reviews and references). The whole situation may be characterized as a genetical tour de force, which makes maintenance of heterosis compatible with prevalence of self-pollination in the plants concerned. A similar situation exists in a few other plants, such as *Rhoeo discolor*. In *Godetia whitneyi* and its relatives, many populations contain numerous translocation heterozygotes, suggesting that in these forms an *Oenothera*-like situation may be in the process of development (Håkansson 1942, Stebbins 1950). Translocation heterozygotes are known also in many other plants (see Darlington 1937, Müntzing 1939, Stebbins 1950, and Darlington and La Cour 1950 for references).

Probably for the reasons discussed above, translocation heterozygotes are decidedly rare in animals. In *Drosophila,* a single instance of the occurrence of a translocation in a population of *D. ananassae* is known (Dobzhansky and Dreyfus 1943). In grasshoppers, several instances have been recorded by White (1940, 1945) and other workers, the clearest being in *Metrioptera brachyptera*. A single heterozygote was found in a certain locality in England in 1934; in 1937 several more translocation individuals were encountered in the same locality. The translocation has evidently persisted in the population for at least three years. Suomalainen (1946) found a translocation heterozygote in the cockroach *Phyllodromia germanica.*

GENIC POLYMORPHISM

Up to now, our attention has been confined to consideration of instances of polymorphism in which chromosomal changes and blocks of genes, rather than single genes, were the units. In a great majority of polymorphic species known to systematists, the variable morphological traits are all that has been studied. In the relatively few cases in which the heredity of such traits has also been examined it is not possible to decide whether the genes which condition the polymorphism are or are not connected with chromosome aberrations. There

is, of course, no reason why single gene mutations could not cause heterosis and polymorphism, and in point of fact the work of Stubbe and Pirschle (1941), Gustafsson (1946a), and Gustafsson et al. (1950) already referred to above suggests that they sometimes do. Thus, the instances of polymorphism now to be discussed may or may not be due to single genes.

Timofeeff-Ressovsky (1940b) has described cyclic seasonal changes in the ladybird beetle *Adalia bipunctata*. This species produces at least two generations per year and hibernates as an adult insect. Several color phases, due to a series of multiple alleles, coexist in all European and American populations; these phases may be classified into light and darkly pigmented groups. In the vicinity of Berlin the relative frequencies of the dark individuals increase, and those of the light ones diminish, from spring to autumn. Among the hibernating beetles, the mortality is heavy. Timofeeff-Ressovsky has been able to show that the proportion of survival is greater among the light than among the dark phase. It appears, then, that the dark form is superior to the light one during the breeding season, but the opposite is the case in winter.

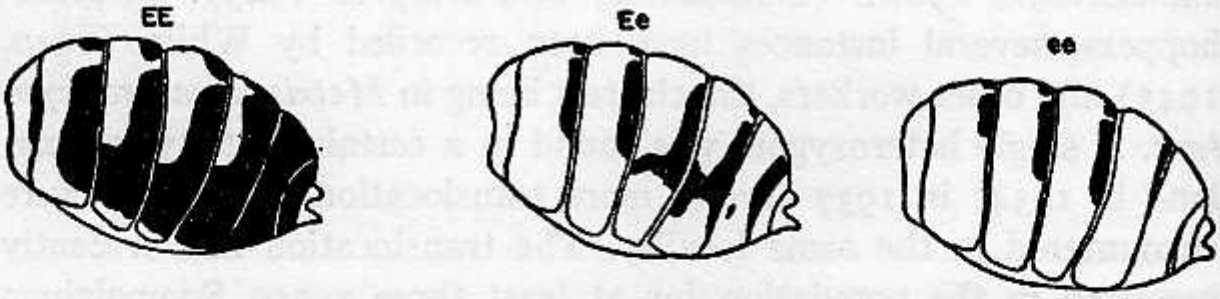

FIG. 9. The color patterns of the abdomen of *Drosophila polymorpha*. The heterozygote is shown in the middle, and the two homozygotes are on the right and on the left. (After da Cunha.)

Drosophila polymorpha, a species native in tropical America, shows three types of coloration of the abdomen represented in Fig. 9. Da Cunha (1949) found that these types are inherited as if caused by two alleles of a single gene, *E* and *e*, the dark and the light types being the homozygotes, *EE* and *ee*, and the intermediate type the heterozygote, *Ee*. Among 8,070 flies of this species found in the state of Paraná, Brazil, 3,969 were dark, 3,174 intermediate, and 927 light. This corresponds to frequencies of 0.69 of *E* and 0.31 of *e* in the gene pool. Polymorphism is observed in populations of this

species from all parts of Brazil, although the frequencies of the gene *E* vary from 0.61 to 0.82 in different samples. An experimental demonstration of heterosis in *Ee* heterozygotes has been secured as follows. When dark and light flies are intercrossed in the laboratory, the offspring in the F_2 generation should segregate in the ratio 1*EE*: 2*Ee* : 1*ee*. In reality, the heterozygotes are more, and the homozygotes are less frequent than expected, as shown in the following table:

	DARK	INTERMEDIATE	LIGHT
Observed	1,605	3,767	1,310
Expected	1,670.5	3,341	1,670.5
Deviation	−65.5	+426	−359.5

If the viability of the heterozygote is taken to be 1, that of the dark homozygote turns out, on the basis of these data, to be 0.85, and that of light homozygotes 0.695. Da Cunha observed the competition of the three genotypes in an apparatus which resembled in principle the population cages mentioned in the present and in the preceding chapters. Natural selection in such experimental populations rapidly leads to establishment of equilibrium, at which the populations consist of 40–45 percent dark, 35–45 percent intermediate, and about 15 percent light flies. Taking the adaptive value of the heterozygote, *Ee*, to be 1, the observed speed of the selection process indicates the adaptive value 0.56 for the dark, *EE*, and 0.23 for the light, *ee*, homozygotes. These adaptive values differ from the viability quotients computed on the basis of the deviations from normal segregation ratios. This difference is not unexpected, since the competition in experimental populations is far more stringent than in ordinary culture bottles. The really unexpected result obtained by da Cunha is that in natural populations the heterozygotes, *Ee*, are actually less frequent among the adult flies than expected on the basis of the binomial square rule. The cause of this is not clear. It is possible that in the natural environments the heterozygotes are less viable than the homozygotes, but that the deficient viability is offset by some advantage in the adult stage, such as a greater fecundity. As shown in Chapter IV, the adaptive value of a genotype is not necessarily proportional to the viability of its carriers.

The color polymorphism in wild populations of the grasshopper

Paratettix texanus is due, according to Fisher's (1939) analysis of the hybridization experiments of Nabours, to the presence of a variety of dominant mutant alleles which are adaptively favorable when heterozygous but deleterious when homozygous. Alleles of this sort cause the polymorphism also in the bird *Poephila* (Southern 1945) and the moth *Ephestia* (Caspari 1950).

POLYMORPHISM AND MIMICRY

Balanced polymorphism, based on adaptive superiorities of heterozygotes, is not the only possible kind of adaptive polymorphism. A species will be polymorphic if it contains a variety of genotypes each of which is superior in adaptive value to the others in some habitats which occur regularly in the territory occupied by this species. Mutation pressure producing a variety of gene alleles which are close to adaptive neutrality may also make a species polymorphic (this nonadaptive polymorphism will be discussed in Chapter VI).

The appearance and spread of melanic variants of several species of moths in the vicinity of large industrial cities is one of the spectacular instances of the origin of polymorphism in natural populations (see Hasebroek 1934, Ford 1937, 1945, and Huxley 1942 for reviews and references). Variants more darkly pigmented than the norm appear in a population, and in the course of several decades become more frequent than the original form, finally supplanting the latter. In a number of instances the melanic forms have been shown experimentally to differ from the paler relatives in a single dominant gene. The first appearance of the melanic forms is always recorded in the vicinity of large industrial cities, and the spread of the dark variants goes hand in hand with the industrialization of the country. Thus, the black form of *Biston betularia* was observed near Manchester in 1850, and in the twentieth century it has superseded the normal form. In Germany the development of "industrial melanism" was observed somewhat later, beginning with the Rhine district and the environs of Hamburg. Still later, analogous phenomena appeared in France and elsewhere. Ford has discovered that, in at least some species, the melanic forms are superior to the light-colored ancestors in viability. According to Ford's ingenious hypothesis, the spread of melanic mutants was precluded before the advent

of industrial developments owing to the destruction of such mutants by predators, since dark individuals are not protectively colored. This disability is removed in industrial regions by the general darkening of the landscape. The superior viability of the melanics is able, then, to assert itself, and their rapid increase in frequency is the result.

Ford (1937, 1940a, 1940b, 1945) has reviewed and analyzed the data on several species of butterflies in which the polymorphism is restricted to one sex, usually the female, the other sex being uniform.

Systematists and collectors described and gave some two dozen varietal, and even specific, names to the color forms of the highly variable moth *Zygaena ephialtes*. Bovey (1941) showed that all these forms can be satisfactorily accounted for as due to recombinations of just three pairs of alleles. The gene *P* makes the hind wings of the moth red or yellow with a black margin, while the allele *p* makes them black except for some colored spots. The heterozygote, *Pp*, is intermediate in color. The dominant gene *R* makes the spots in the wings red, while the recessive makes them yellow. The dominant *B* makes the colored spots on the hind wings double, while the recessive *b* causes them to be single. Populations of different countries are characterized by different incidence of the dominant and recessive alleles of these genes.

ADAPTIVE POLYMORPHISM AND ECOLOGICAL OPPORTUNITY

It should now be evident that adaptive polymorphism is a widespread phenomenon in the living world. As pointed out at the beginning of the present chapter, adaptively polymorphic populations should, in general, be more efficient in the exploitation of ecological opportunities of an environment than genetically uniform ones. It can be further surmised that, other things being equal, populations which occupy many habitats in a given territory should be genetically more diversified than populations restricted or specialized for occupation of only few habitats.

This hypothesis has been submitted to a test by da Cunha et al. (1950) and Dobzhansky et al. (1950). Four very closely related species, *D. willistoni, D. paulistorum, D. equinoxialis,* and *D. tropicalis* occur in the American tropics. The first two of these species occur in the entire tropical zone, are among the commonest repre-

sentatives of the genus in most of their distribution areas, and live on a great variety of food substances. At least 40 and 34 inversions respectively have been recorded in the chromosomes of natural populations of these species. *D. tropicalis* and *D. equinoxialis* are restricted to the basin of the Amazon or a part of it. They are fairly rare in most localities, and appear to be ecologically specialized species. Only four inversions have been found in each of these species.

Even more suggestive are the data on frequencies of inversion heterozygotes in the populations of species related to *Drosophila willistoni*. A wild individual of *D. tropicalis* is heterozygous, on the average, for 0.14 ± 0.06 inversions, and *D. equinoxialis* for 0.11 ± 0.05 inversions. In *D. paulistorum* the numbers of heterozygous inversions per individual vary from 0.55 ± 0.20 to 1.77 ± 0.31 in different localities, while in *D. willistoni* the averages range from 0.81 ± 0.03 to 9.36 ± 0.26 inversions per individual in different parts of the distribution area. The most highly polymorphic populations of *D. willistoni* occur in the central part of the species area, and the polymorphism becomes more limited towards the margins of the area. Ecologically favorable areas with diversified food sources (tropical jungles) are inhabited by more highly polymorphic populations than are rigorous environments (deserts). Polymorphism is higher where the species is more abundant and widespread than its competitors, and less where the competitors exceed in abundance the species in question.

Vavilov (1926) advanced the generalization that the genetic variability in populations is greatest in the territory in which the species arose and from which it subsequently spread elsewhere. This "center of origin" hypothesis may at present be re-stated as follows. The evolutionary process which generates adaptive polymorphism, and thereby enables the species to conquer and control more and more habitats, requires time. Therefore, the longer a territory is occupied by a species the greater will tend to be the adaptive polymorphism and the variability in populations. Conversely, at the margins of its distribution area, unless the species is stopped by an insuperable geographic barrier, it is likely to have a toehold in only few ecological niches. A limited adaptive variability is likely to characterize marginal populations.