Disease and evolution

J. B. S. Haldane

RIASSUNTO.–Negli esempi addotti dai biologi per mostrare come la selezione naturale agisce, la struttura o la funzione presa in esame è per lo più collegata con la protezione contro forze naturali avverse, contro predatori, oppure con la conquista di alimento o dell'altro sesso. L'A. mostra che la lotta contro le malattie, e in particolare contro le malattie infettive, ha rappresentato un fattore evolutivo molto importante e che alcuni dei suoi risultati sono diversi da quelli raggiunti attraverso le forme consuete della lotta per l'esistenza.

RÉSUMÈ.–Les exemples portès par les biologistes pour montrer comment la sèlèction naturelle opère tiennent compte d'ordinaire de structures ou de fonctions liées à la protection contre des forces naturelles hostiles, centre des prèdateurs, ou bien liées à la conquête de la nourriture ou du sexe opposè. L' A. Montre que la lutte contre les maladies, et en particulier contre les maladies infectieuses, a représenté un facteur évolutif très important et que qualques-uns parmi ses résultats diffèrent bien de ceux qui ont été atteints par les formes ordinaires de la lutte pour la vie.

SUMMARY.–Examples quoted by biologists, in order to show how natural selection is working, almost present structures or functions concerned either with protection against natural forces or against predators, or with purchase of food or mates. The Author suggests that the struggle against diseases, and especially infectious diseases, has been a very important evolutionary agent and that some of its results have been rather unlike those of the struggle for life in its common meaning.

It is generally beheved by biologists that natural selection has played an important part in evolution. When however an attempt is made to show how natural selection acts, the structure or function considered is almost always one concerned either with protection against natural ((forces)) such as a cold or against predators, or one which helps the organism to obtain food or mates. I want to suggest that the struggle against disease, and particularly infectious disease, has been a very important evolutionary agent, and that some of its results have been rather unlike those of the struggle against natural forces, hunger, and predators, or with members of the same species.

Under the heading infectious disease I shall include, when considering animals, all attacks by smaller organisms, including bacteria, viruses, fungi, protozoa, and metazoan parasites. In the case of plants it is not so clear whether we should regard aphids or caterpillars as a disease. Similarly there is every gradation between diseases due to a deficiency of some particular food constituent and general starvation.

The first question which we should ask is this. How important is disease as a killing agent in nature? On the one hand what fraction of members of a species die of disease before reaching maturity? On the other, how far does disease reduce the fertility of those members which reach maturity? Clearly the answer will be very different in different cases. A marine species producing millions of small eggs with planktonic larvae will mainly be eaten by predators. One which is protected against predators will lose a larger proportion from disease.

There is however a general fact which shows how important infectious disease must be. In every species at least one of the factors which kills it or lowers its fertility must increase in efficiency as the species becomes denser. Otherwise the species, if it increased at all, would increase without limit. A predator cannot in general be such a factor, since predators are usually larger than their prey, and breed more slowly. Thus if the numbers of mice increase, those of their large enemies, such as owls, will increase more slowly. Of course the density-dependent check may be lack of food or space. Lack of space is certainly effective on dominant species such as forest trees or animals like *Mytilus*. Competition for food by the same species is a limiting factor in a few phytophagous animals such as defoliating caterpillars, and in very stenophagous animals such as many parasitoids. I believe however that the density-dependent limiting factor is more often a parasite whose incidence is disproportionately raised by overcrowding.

As an example of the kind of analysis which we need, I take Varley's (1947) remarkable study on *Urophora jaceana*, which forms galls on the composite *Centaurea nigra*. In the year considered 0.5% of the eggs survived to produce a mature female. How were the numbers reduced to $\frac{1}{200}$ of the initial value?

If we put $200 = e^k$, we can compare the different killing powers of various environmental agents, writing $K = k_1 + k_2 + k_3 + \cdots$, where k_r is a measure of the killing power of each of them. The result is given in Table 1. Surprisingly, the main killers appear to be mice and voles (*Mus*, *Microtus*, etc.) which eat the fallen galls and account for at least 22%, and perhaps 43% of k. Parasitoids âccount for 31% of the total kill, and the effect of *Eurytoma curta* was shown to be strongly dependent on host density, and probably to be the main factor in controlling the numbers of the species, since the food plants were never fully occupied.

When we have similar tables for a dozen species we shall know something about the intensity of possible selective agencies. Of course in the case of *Urophora jaceana* analysis is greatly simplified by the fact that the imaginal period is about 2% of the whole life cycle, so that mortality during it is unimportant.

A disease may be an advantage or a disadvantage to a species in competition with others. It is obvious that it can be a disadvantage. Let us consider an ecological niche which has recently been opened, that of laboratories where the genetics of small insects are studied. A

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Table 1.

Month	Density per square metre	Cause of death	k.
July	203.0	–	–
"	184.7	Infertile eggs.	0.095
"	147.6	Failure to form gall.	0.224
"	144.6	? Disease.	0.021
"	78.8	*Eurytoma curta*	0.607
Aug., Sept.		Other parasitoids	0.222
"	50.2	Caterpillars.	0.234
Winter	19.2	Disappearance, probably mice.	0.957
"	7.0	Mice.	1.009
"	5.2	Unknown	0.297
May-June		Birds.	0.090
"	3.6	Parasitoids	0.270
July	2.03	Floods.	0.581
			4.606

Mortality of *Urophora jaceana* in 1935–1946, after Varley.

number of species of *Drosophila* are well adapted for this situation. Stalker attempted to breed the related genus *Scaplonyza* under similar conditions, and found that his cultures died of bacterial disease. Clearly the immunity of *Drosophila* to such diseases must be of value to it in nature also.

Now let us take an example where disease is an advantage. Most, if not all, of the South African artiodactyls are infested by trypanosomes such as *T. rhodesiense* which are transmitted by species of *Glossina* to other mammals and, sometimes at least, to men. It is impossible to introduce a species such as *Bos taurus* into an area where this infection is prevalent. Clearly these ungulates have a very powerful defence against invaders. The latter may ultimately acquire immunity by natural selection, but this is a very slow process, as is shown by the fact that the races of cattle belonging to the native African peoples have not yet acquired it after some centuries of sporadic exposure to the infection. Probably some of the wild ungulates die of, or have their health lowered by the trypanosomes, but this is a small price to pay for protection from other species.

A non-specific parasite to which partial immunity has been acquired, is a powerful competitive weapon. Europeans have used their genetic resistance to such viruses as that of measles (rubeola) as a weapon against primitive peoples as effective as fire-arms. The latter have responded with a variety of diseases to which they are resistant. It is entirely possible that great and, if I may say so, tragic episodes in evolutionary history such as the extinction of the Noto-ungulata and Litopterna may have been due to infectious diseases carried by invaders such as the ungulates, rather than to superior skeletal or visceral developments of the latter.

A suitable helminth parasite may also prove a more efficient protection against predators than horns or eryptic coloration, though until much more is known as to the power of helminths in killing vertebrates or reducing their fertility, this must remain speculative.

However it may be said that the capacity for harbouring a non-specific parasite without grave disadvantage will often aid a species in the struggle for existence. An ungulate species which is not completely immune to *Trypanosoma rhodesiense* has probably (or had until men discovered the life history of this parasite) a greater chance of survival than one which does not harbour it, even though it causes some mortality directly or indirectly.

The winter disappearance was probably due to galls carried off by mice. The mortality attributed to mice is based on counts of galls bitten open. The k due to *Eurytoma curta* in the preceding year was 0,069, in the subsequent year 0,137. This cause of death depends very strongly on host and parasitoid densities. The caterpillars killed the larvae by eating the galls.

I now pass to the probably much larger group of cases where the presence of a disease is disadvantageous to the host. And here a very elementary fact must be stressed. In all species investigated the genetical diversity as regards resistance to disease is vastly greater than that as regards resistance to predators.

Within a species of plant we can generally find individuals resistant to any particular race of rust (Uredineae) or any particular bacterial disease. Quite often this resistance is determined by a single pair, or a very few pairs, of genes. In the same way there are large differences between different breeds of mice and poultry in resistance to a variety of bacterial and virus diseases. To put the matter rather figuratively, it is much easier for a mouse to get a set of genes which enable it to resist *Bacillus typhi murium* than a set which enable it to resist cats. The genes commonly segregating in plants have much more effect on their resistance to small animals which may be regarded as parasites, than to larger ones. Thus a semiglabrous mutant of *Primula sinensis* was constantly infested by aphids, which however are never found on the normal plant. I suppose thornless mutants of *Rubus* are less resistant to browsing mammals than the normal type, but such variations are rarer.

Anyone with any experience of plant diseases will of course point out that the resistance of which I have spoken is rarely very general. When a variety of wheat has been selected which is immune to all the strains of *Puccinia graminis* in its neighbourhood, a new strain to which it is susceptible usually appears within a few years, whether by mutation, gene recombination, or migration. Doubtless the same is true for bacterial and virus diseases. The microscopic and submicroscopic parasites can evolve so much more rapidly than their hosts that the latter have little chance of evolving complete immunity to them. It is very remarkable that *Drosophila* is as generally immune as it is. I venture to fear that some bacillus or virus may yet find a suitable niche in the highly overcrowded *Drosophila* populations of our laboratories, and that if so this genus will lose its proud position as a laboratory animal. The most that the average species can achieve is to do dodge its minute enemies by constantly producing new genotypes, as the agronomists are constantly producing new rust-resistant wheat varieties.

Probably a very small biochemical change will give a host species a substantial degree of resistance to a highly adapted microorganism. This has

an important evolutionary effect. It means that it is an advantage to the individual to possess a rare biochemical phenotype. For just because of its rarity it will be resistant to diseases which attack the majority of its fellows. And it means that it is an advantage to a species to be biochemically diverse, and even to be mutable as regards genes concerned in disease resistance. For the biochemically diverse species will contain at least some members capable of resisting any particular pestilence. And the biochemically mutable species will not remain in a condition where it is resistant to all the diseases so far encountered, but an easy prey to the next one. A beautiful example of the danger of homogeneity is the case of the cultivated banana clone ((Gros Michel)) which is well adapted for export and has been widely planted in the West Indies. However it is susceptible to a root infection by the fungus *Fusarium cubense* to which many varieties are immune, and its exclusive cultivation in many areas has therefore had serious economic effects.

Now every species of mammal and bird so far investigated has shown a quite surprising biochemical diversity revealed by serological tests. The antigens concerned seem to be proteins to which polysaccharide groups are attached. We do not know their functions in the organism, though some of them seem to be part of the structure of cell membranes. I wish to suggest that they may play a part in disease resistance, a particular race of bacteria or virus being adapted to individuals of a certain range of biochemical constitution, while those of other constitutions are relatively resistant. I am quite aware that attempts to show that persons of a particular blood group are specially susceptible to a particular disease have so far failed. This is perhaps to be expected, as a disease such as diphtheria or tuberculosis is caused by a number of biochemically different races of pathogens. The kind of investigation needed is this. In a particular epidemic, say of diphtheria, are those who are infected (or perhaps those who are worst affected) predominantly drawn from one serological type (for example *AB*, *MM*, or *BMM*)? In a different epidemic a different type would be affected.

In addition, if my hypothesis is correct, it would be advantageous for a species if the genes for such biochemical diversity were particularly mutable, provided that this could be achieved without increasing the mutability of other genes whose mutation would give lethal or sublethal genotypes. Dr P. A. Gorer informs me that there is reason to think that genes of this type are particularly mutable in mice. Many pure lines of mice have split up into sublines which differ in their resistance to tumour implantation. This can only be due to mutation. The number of loci concerned is comparable, it would seem, with the number concerned with coat colour. But if so their mutation frequency must be markedly greater.

We have here, then, a mechanism which favours polymorphism, because it gives a selective value to a genotype so long as it is rare. Such mechanisms are not very common. Among others which do so are a system of self-sterility genes of the *Nicotiana* type. Here a new and rare gene will always be favoured because pollen tubes carrying it will be able to grow in the styles of all plants in which it is absent, while common genes will more frequently meet their like. However this selection will only act on genes at one locus, or more rarely at two or three. A more generally important mechanism is that where a heterozygote is fitter than either homozygote, as in *Paralettix texanus* (Fisher 1939) and *Drosophila pseudoobscura* (Dobzhansky 1947). This does not, however, give an advantage to rarity as such. It need hardly be pointed out that, in the majority of cases where it has been studied, natural selection reduces variance.

I wish to suggest that the selection of rare biochemical genotypes has been an important agent not only in keeping species variable, but also in speciation. We know, from the example of the *Rh* locus in man, that biochemical differentiation of this type may lower the effective fertility of matings between different genotypes in mammals. Wherever a father can induce immunity reactions in a mother the same is likely to be the case. If I am right, under the pressure of disease, every species will pursue a more or less random path of biochemical evolution. Antigens originally universal will disappear because a pathogen had become adapted to hosts carrying them, and be replaced by a new set, not intrinsically more valuable, but favouring resistance to that particular pathogen. Once a pair of races is geographically separated they will be exposed to different pathogens. Such races will tend to diverge antigenically, and some of this divergence may lower the fertility of crosses. It is very striking that Irwin (1947) finds that related, and still crossable, species of *Columba*, *Streptopelia*, and allied genera differ in respect of large numbers of antigens. I am quite aware that random mutation would ultimately have the same effect. But once we have a mechanism which gives a mutant gene as such an advantage, even if it be only an advantage of one per thousand, the process will be enormously accelerated, particularly in large populations.

There is still another way in which parasitism may favour speciation. Consider an insect in which a parasitoid, say an içhneumon fly, lays its eggs. And let us suppose both host and parasite to have an annual cycle, the parasite being specific to that particular host. To simplify matters still further, we shall suppose that the parasite is the only density-dependent factor limiting the growth of the host population, whilst the density-dependent factor limiting the growth of the parasite population is the difficulty of finding hosts. It is further assumed that the parasitoid only lays one egg in each host, or that only one develops if several are laid. Varley showed that all these assumptions are roughly true for *Urophora jaceana* and *Eurytoma curta*.

Let e^k be the effective fertility of the host, that is to say let k be the mean value of the natural logarithm of the number of female-producing eggs laid per female. Let k_1 be the killing power of agents killing during the part of the life cycle before the host is not infested. Let k_2 be the killing power of agents other than the parasite killing during that part of the life cycle when it is infested, and therefore killing the same fraction $1-e^{-k_2}$ of parasites as of hosts. Let k_2 be the killing power of agents killing after the parasites have emerged as imagines.

Let x be the equilibrium density of adult hosts, y that of parasitoids, and a the mean area of search of the parasitoid.

Then the fraction of hosts which are not parasitized must be e^{-k_4}, where $k_1+k_2+k_3+k_4=K$. Nicholson and Bailey (1933) showed that $k_4=ay$. But

the host density available for parasitism is e^{K-k_1}. Of these $(1-e^{-k_2})\,e^{K-k_1}$ are parasitized. And $e^{K-k_1-k_2}\,(1-e^{-k_3})$ of the parasites live to emerge. This is diminished by a factor e^{-k_3}. The equilibrium densities are given by

$$x=\frac{e^{k_1-k_3}y}{e^{K-k_1-k_2-k_3}-1},$$

$$y=\frac{K^{k_1-k_2-k_3}}{a},$$

though there is perpetual oscillation round this equilibrium. Now consider the effect of changes in these parameters. Any gene in the host which increases $K-k_1-k_2-k_3$ will give its carriers a selective advantage over their fellows, and will therefore spread through the population. This will cause an increase in the density of parasitoids. If it acts before or during parasitisation, thus diminishing k_1 or k_2, it will diminish the equilibrium value of x. If it acts after parasitisation is over, thus diminishing k_3, it will increase the equilibrium value of x, though not very much. But since we have supposed that the parasitoids only emerge shortly before the end of the hosts life cycle, every increase in its adaptation to environmental factors other than the specific parasite will diminish the numbers of adult hosts, though it may increase the number of their larvae at an early stage. This is a striking example of the way in which the survival of the fittest can make a species less fit.

A concrete case would be a gene which, by improving cryptic or aposematic coloration of the larvae, enabled more of them to escape predators, and therefore more parasites to do so. Since the host population is denser they will parasitise a larger fraction of the hosts and thus reduce their number. Since a larger fraction of parasites escape, equilibrium will be reached with a lower host density. Fewer of the caterpillars ((nati a far l'angelica farfalla)) will achieve this end. More of them will give rise to ichneumons or chalçids.

Natural selection will also favour genes which enable the host to resist the parasitoid, but the latter will also increase its efficiency by natural selection. As Nicholson and Bailey showed, every increase in the area searched by it will diminish the density of both hosts and parasites.

The best that can be said for this tendency, from the host's point of view, is that it makes it less likely to become extinct as the result of other agencies. For the parasitoid being dependent on the density of the host population, will allow its numbers to increase rapidly after any temporary fall.

The host can hardly hope to throw off the parasite permanently by changing its life cycle, developing immunity (if this is possible) or otherwise. But it can reduce its numbers by speciating. For suppose that the pair of species is replaced by two host-parasitoid pairs, the population will be doubled, in so far as the parasitoid is the regulator. It is unlikely that a species can divide sympatrically, but the reduction in numbers caused by parasitoidism will leave food available for other immigrant species of similar habits, even if they are equally parasitised.

Thus certain types of parasitism will tend to encourage speciation, as others encourage polymorphism. This will specially be the case where the parasite is very highly adapted to its host, the most striking cases of adaptation being probably those of the parasitoid insects.

We see then that in certain circumstances, parasitism will be a factor promoting polymorphism and the formation of new species. And this evolution will in a sense be random. Thus any sufficiently large difference in the times of emergence or oviposition of two similar insect species will make it very difficult for the same parasitoid to attack both of them efficiently. So will any sufficiently large difference in their odours. We may have here a cause for some of the apparently unadaptive differences between related species.

Besides these random effects, disease will of course have others. It is clear that natural selection will favour the development of all kinds of mechanisms of resistance, including tough cuticles, phagocytes, the production of immune bodies, and so on. It will have other less obvious effects. It will be on the whole an antisocial agency. Disease will be less of a menace to animals living singly or in family groups than to those which live in large communities. Thus it is doubtful if all birds could survive amid the faecal contamination which characterises the colonies of many sea birds. A factor favouring dispersion will favour the development of all kinds of mechanisms of recognition at great distances such as are found in some Lepidoptera.

Again, disease will set a premium on the finding of radically new habitats. When our ancestors left the water, they must have left many of their parasites behind them. A predator which ceases to feed on a particular prey, either through migration or changed habits, may shake off a cestode which depends on this feeding habit. When cerebral development has gone far enough to make this possible, it will favour a negative reaction to faecal odours and an objection to cannibalism, and will so far be of social value. A vast variety of apparently irrelevant habits and instincts may prove to have selective value as a means of avoiding disease.

A few words may be said on non-infectious diseases. These include congenital diseases due to lethal and sub-lethal genes. Since mutation seems to be non-specific as between harmful and neutral or beneficial genes, and mutation rate is to some extent inherited, it follows that natural selection will tend to lower the mutation rate, and this tendency may perhaps go so far as to slow down evolution. It will also tend to select other genes which neutralise the effect of mutants and thus to make them recessive or even ineffective, as Fisher has pointed out. Whether the advantage thus given to polyploids is ever important, we do not know. But the evolution of dominance must tend to make the normal genes act more intensely and thus probably earlier in ontogeny, so that a character originally appearing late in the life cycle will tend to develop earlier as time goes on.

Deaths from old age are due to the breakdown of one organ or another, in fact to disease, and the study of the mouse has shown that senile diseases such as cancer and nephrosis are often congenital. In animals with a limited reproductive period senile disease does not lower the fitness of the individual, and increases that of the species. A small human community where every woman died of cancer at 55, would be more prosperous and fertile than one where this did not occur. Senile disease may be an advantage wherever the reproductive period is limited; and even where it is not, a genotype which leads to disease in the 10% or so of individuals which live longest may be selected if it confers vigour on the majority. As

Simpson (1944) has emphasized, some of the alleged cases of hypertely can be explained in this way.

Deficiency diseases are due to the lack of a particular food constituent which an organism or its symbionts cannot synthesize or make from larger molecules. They must act as a selective agent against the loss of synthetic capacity which is a very common type of mutation in simple organisms at least, and in favour of genotypes with a varied symbiotic flora. They might thus have speeded up the evolution of the ruminants, whose symbionts probably make vitamins as well as simple nutrients like acetic acid. To be precise it might be an advantage to have a small rumen where symbionts made B vitamins before it got large enough to add appreciably to the available calories.

On the other hand Rudkin and Schulz (1948) have shown that deficiency diseases can select mutants which utilize the nutrilite in question less than does the normal type. In particular the vermilion mutant of *Drosophila melanogaster* does not form the brown eye pigment ommatin from tryptophane. It is more viable than the wild type on a diet seriously deficient in tryptophane. Thus deficiency diseases may cause a regressive type of evolution characterized by the loss of capacity to utilise rare nutrilites for synthesis.

In this brief communication I have no more than attempted to suggest some lines of thought. Many or all of them may prove to be sterile. Few of them can be followed profitably except on the basis of much field work.

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Discussion

MONTALENTI. Sottolinea l'importanza delle vedute espresse dal Prof. Haldane. Ricorda il caso della microcitemia o talassemia, studiato da Silvestroni, Bianco e Montalenti. Qui un gene, letale allo stato omozigote (morbo di Cooley) si trova, allo stato eterozigote, con tale frequenza in alcune popolazioni (più del 10%) che bisogna ammettere che esso rappresenti in questa condizione un vantaggio per gli individui che lo portano. Poiché da alcune ricerche, Lutt'altro che complete, sembra che il gene sia più frequente in zone malariche, il Prof. Haldane ha suggerito in comunicazione verbale che gli individui microcitemici, i quali fra l'altro hanno resistenza globulare aumentata, possano essere più resistenti all infezione malarica. Comunque è questo un caso interessante di eterosi, che si ricollega a quanto ha illustrato il Prof. Haldane.

JUCCI La relazione del Prof. Haldane ha sviluppato magistralmente, in modo quanto mai suggestivo, un argomento del più alto interesse. Desidero fare qualche commento su qualcuno dei tanti aspetti del problema. Non conoscevo le ricerche di Varley su *Urophora*. Certo gh insetti gallicoli offrono un materiale particolarmente adatto. Anni fa cominciai a raccogliere dati analoghi sul cecidomide *Mikiola fagi*. Ma la mia attenzione fu particolarmente assorbita dal fatto che nella zona da me esplorata —ogni singolo faggio lungo la strada che sale al Terminillo, nel tratto da 1000 a 1200 metri di altezza—si presentava una varietà di comportamento spiccatissima. Accanto a un faggio carico di galle spesso un altro ne era del tutto sprovvisto, come per una variabilità genetica di comportamento della pianta ospite. Le ricerche verranno riprese ed approfondite ora che stiamo per organizzare una Stazione montana di Genetica sul Terminillo, all'altezza di 1700 m. Suggestive le considerazioni del Prof. Haldane sul pericolo che per la specie presenta una eccessiva omogeneità e sul vantaggio di una capacità a presentare mutazioni biochimiche in rapporto alla possibilità di esprimere dalla costituzione genetica razze resistenti a parassiti Io ho avuto occasione di studiare a lungo le diverse recettività di due bombici serigeni, *Philosamia ricini* e *Ph. cynthia*, al virus del giallume. La *ricini*, forma domestica, è resistente: portatore sano; la *cynthia*, selvatica sull' ailanto, recettiva come il *Bombyx*. Forse è per questa ragione che in Italia la *cynthia* è diffusa largamente, ma ovunque poco abbondante. Una o poche mutazioni (nella F2 dell' incrocio si ha la disgiunzione dei fattori con ritorno a forme resistenti e recettive, come le parentali) possono aver determinato nella *ricini* la capacità ad essere allevate in massa. A proposito della tendenza antisociale che il periodo delle malattie infettive può imprimere a molte specie di organismi, noterò che per l'evoluzione degli insetti sociali deve certo avere avuto larga importanza l'acquisizione di forte resistenza alle infezioni. Sarebbe interessante paragonare a questo riguardo la recettività della forma domestica (*Apis mellifica*) e di forme affini selvatiche alla peste delle api e simili forme epidemiche. Una delle vie per le quali il fattore malattia da infestione o infezione deve avere profondamente influenzato il processo evolutivo è stata certo quella della simbiosi, che va considerata come uno stato di alleanza subentrato a un periodo piu o meno lungo di guerra fra due organismi. Caratteristico il caso dei batteri simbionti nel tessuto adiposo di Blattidi e di Termiti. La simbiosi risale ai Proto-blattoidi del Carbonifero, come lo dimostra l'identità dei processi di trasmissione dei batteri da una generazione all'altra nei Blattidi e nel *Mastotermes*. Gli Isotteri hanno lasciato cadere lungo la via filogenetica la simbiosi con i batteri forse perché hanno trovato assai più vantaggiosa la simbiosi con i flagellati dell'intestino che hanno loro permesso la conquista del mondo della cellulosa. Interessantissimo l'accenno del Prof. Haldane alle malattie di carenza: mutazioni in questo senso possono aver sollecitato lo stabilirsi di simbiosi nelle quali l'associato veniva ad offrire il fattore accessorio che l'ospite non era più capace di produrre e che non poteva trovare nell'am-biente.

HADORN Bei Bakterien gibt es zahlreiche Beispiele, die zeigen dass biochemische Mutationen die zu synthetischen Defekten führen, gleichzeitig eine Resistenz gegen Infektionen (Phagen) bedingen. Vielleicht konnte dies als Modell dienen für den positiven Selektionswert im Falle von Thalassemia.

Wie kann man erklären, dass die Negerbevölkerung von Zentralafrika gegenuber der tropischen Schlafkrankheit weniger resistent ist als die eingewan-

derten Europäer? Es wäre vielmehr zu erwarten dass die Selektion bei der schwarzen Bevölkerung eine erhöhte Immunitat begünstigt hätte.

HALDANE, J. I agree with Dr. Montalenti's project. Another possibility is that (by analogy with the advantage possessed by vermilion *Drosophila* on media deficient in tryptophan) microcythemic heterozygotes may be at an advantage on diets deficient in iron or other substances, thus leading to anaemia.

2. Perhaps the theory that most diseases evolve into symbioses is somewhat panglossist. I doubt if it occurs as a general rule, though it may do so. The position for the original host is however best.

Animal communication and the origin of human language*

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If we accept the theory of evolution, we must face the problem of the evolution of human language. We cannot yet solve this problem, but we are nearer to solving it because a great deal has been learned about animal communication in the last twenty years. The greatest discovery in this field is von Frisch's analysis of bee communication, but bees' methods are so unlike our own that his work throws little direct light on the human problem.

I say that animal X communicates with animal Y if it produces a signal S describable in the language of physics or chemistry which alters Y's behaviour. "Telepathic" or "paranormal" co-ordination of the activities of X and Y, if it occurs, is not necessarily communication between X and Y. Bee Y might imitate the actions of X because both were controlled by the "spirit of the hive." In the case of bees at least, von Frisch's observations make any such hypothesis unnecessary. We cannot draw a sharp line between communication and other forms of intercourse, but we can say that the signal usually involves little expenditure of energy by X, and has a large positive or negative effect on Y's energy expenditure. We can classify these signals in many ways.

The most obvious is by their physical nature, or what comes to the same thing, the receptor organ by which Y receives the signal. A classification by X's effector organ yields a quite different and less useful picture. For example, a production of skin pigment, a contraction of chromatophores, and a muscular movement can all start visual signals. Our rough classification is: Chemical (olfactory), optical (visual), vibratory (acoustic), mechanical (tactile or kinaesthetic), and electrical (receptor not yet fully described). The type of reception is bracketed. There is some overlap between auditory and tactile reception.

We can also classify signals as transient or persistent (perhaps dynamical and statical). A peacock's feathers last for some months, his erection of them for a few seconds or minutes. Chemical signals are always somewhat persistent. An animal can sometimes turn an odour on suddenly. It can rarely turn it off suddenly. Only chemical and optical signals can be persistent.

When we consider the function of a communication our most obvious classification is into communication within a species and between members of different species. (We might also, of course, consider communication between cells in an organism, and even within a cell.) Communication within a species appears, usually at least, to be advantageous to the species, and quite often to both the individuals X and Y, though it is not a simple matter to define the word "advantageous." Communication between two species may be advantageous to both, but is often harmful to one. We shall see that it includes "negative communication" (Spurway, 1955b) or hiding, and the equivalent of human lying. Members of one species may "understand," that is to say react appropriately to, the signals of another. Thus many of our small song birds are alarmed by the alarm calls of other species.

Within a species we can distinguish (again with some uncertainty) between the signals repeated by the recipient, and those which are not. A signal by X, as we shall see, always predicts X's behaviour. If it evokes a quite different, but biologically complementary, behaviour by Y, it is not repeated by Y. Thus some adult birds X signal to their chicks Y with coloured patches on the beaks, and appropriate movements. The chick does not repeat these signals. It commonly emits quite different ones, such as a characteristic sound, and opening its beak to show coloured throat patches. When the signal results in Y performing a similar activity to X, it is commonly repeated. Thus when dog X growls at dog Y, Y commonly growls back, and they proceed to "threatening" gestures. When finch X emits the alarm call appropriate to a hawk, it takes cover. If finch Y hears it, it repeats the note, and takes cover too. Thus the alarm is rapidly spread through a flock.

*A summary of lectures given at the Royal Institution on November 30th, December 2nd, and December 7th, 1954. If any of the ideas here put forward are novel, they are as much due to my wife (Dr. H. Spurway) as to myself.

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