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What's All This About Genetics?

RONA HURST

A companion series to the Thinker's Library

What this book is about

What is it that determines the colour of a person's eyes and hair, the shape of a nose or chin? How are the characters which go to make up the many different kinds of plants and animals, and Man himself, handed on from one generation to another, so that each new individual grows up so very like its parents? What is "Variation," and how and why does it occur? How have the immense number of different forms of life on this planet arisen? What, to get down to the most fundamental of all such questions, is "Life"?

These are some of the matters which fall within the province of Genetics, one of the newest and yet most important and promising of the sciences; and in this little volume they are discussed with a clear conciseness and a refreshing absence of technical jargon by one who has spent many years in practical experiment.

Not all the questions that may be asked have been answered yet, but Mrs. Hurst says sufficient to show that some knowledge of the basic principles of Genetics is of vital interest to parents and to all who are concerned in any way with the raising and care of plants and animals, whether in the laboratory or on the farm, in the chicken-run or the garden.

WHAT'S ALL THIS ABOUT GENETICS?

Mrs. Rona Hurst has been connected with Genetics all her life. As a small child she watched the experiments carried on at Burbage, in Leicestershire, by her cousin, C. C. Hurst, one of the pioneer workers in the new science. After her marriage to him in 1922 she worked beside him in the biological laboratories at Cambridge for the next twelve years. The outbreak of war in 1939 found them at Horsham, in Sussex, where they were experimenting with orchids. During the War Mrs. Hurst joined the teaching staff of Christ's Hospital (Blue Coat School), and she still holds an appointment there. In her spare time she maintains her interest in Genetics, collaborating with the staff of the John Innes Horticultural Institution, and she is also a member of the Genetical Society.

WHAT'S ALL THIS ABOUT GENETICS?

Rona Hurst

AN EXPLANATION OF
INHERITANCE
IN PLANTS AND ANIMALS
(INCLUDING MAN HIMSELF)
FOR THE ORDINARY READER

Thrift Books

THRIFT BOOKS
No. 3

FIRST PUBLISHED 1951

Printed in Great Britain by Richard Clay and Co. Ltd.,
Bungay, Suffolk, and published by C. A. Watts and Co. Ltd.,
5 & 6 Johnson's Court, Fleet Street, London, E.C.4

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PREFACE

JUST fifty years have elapsed since the discovery of Mendel's Principles of Heredity gave such an impetus to scientific breeding and made 1900 the birth year of Genetics. Up to that time the breeding of domesticated animals and plants had been carried on slowly by what may be termed "common-sense" methods. From the earliest beginnings of farming, herdsmen and agriculturists had been saving their best animals and plants for breeding. They were always quick to notice any favourable change or combination of characters, and to utilize it for the general progress of their farming economy. As these variations piled up, the animals and plants improved out of all recognition, until today it is difficult to trace the original ancestry.

The great difficulty, however, was to "fix" or make permanent the most desirable characters; they were all too apt to disappear in later generations, or at any rate to be unpredictable in their appearance. At the end of the last century biological science was arriving at a position in which it was realized that if only the variations which occur in animals and plants, and their inheritance, could be intensively studied, it should be possible to do away with this uncertainty and to bring breeding into the condition of an exact science. Various people in this country and in Europe were groping their way towards a solution, unconscious of the fact that the clue had already been found but lay hidden in an obscure publication of the local natural history society of Brünn, in what is now Czechoslovakia.

In the mid-nineteenth century an Austrian monk, Gregor Mendel, had been experimenting with peas, and had discovered the way in which inheritance works in these plants. His results were published in 1866, but remained unnoticed until 1900, when they were discovered simultaneously by three Continental workers. The facts were at once made known, and those who had been working in other countries, particularly in England, quickly set to work to test whether the new theory of heredity was common to all plants, and whether it applied to animals as well. This proved to be the fact, and breeding came to be regarded no longer as a hit-and-miss affair but as a definite science, under the name of Genetics, by which the improvement of animals and plants can be carried on under strictly controlled conditions.

England took a very prominent place in this pioneer work. Under the able and enthusiastic leadership of William Bateson, of Cambridge University, various workers accumulated a mass of evidence confirming and extending Mendel's original work, while under the auspices of the Royal Horticultural Society important international conferences were held in London which stimulated interest and fostered research.

At the beginning of the second decade of this century, Genetics took another important step forward, when T. H. Morgan and his colleagues in America located what has been termed, for want of a better word, the "mechanism" of heredity. Within the cells of all animals and plants are minute thread-like bodies known as *chromosomes*, which securely harness the essential units of inheritance within themselves. These units, which were termed *genes*, are now known to be complex protein molecules, with the power to grow and to reproduce themselves as well as to perform all the intricate functions of building up the bodies of animals or plants according to their kind. This is an extremely complex story, and it has been possible to give here only the barest outline of the magnitude and scope of the researches into inheritance and its bearing upon Evolution which have been carried on all over the world during the last fifty years. It is hoped, however, that enough has been said to stimulate an interest in the broader aspects of the subject.

Genetics itself has been dealt with historically so far as possible, since it is easier for the layman to follow the intricate working of scientific discoveries if he can see them as the scientists themselves saw them, developing from year to year in their researches. Contemporary thought is usually some half-century behind scientific knowledge; so it is that most people are only just waking to the fact that there are such things as genes and heritable characters, and but few have caught up with all the ramifications of modern Genetics.

Every new discovery demands the jettison of a great accumulation of old ideas which have sunk deeply into the mass consciousness by education and training. The scientists themselves suffer in the same manner, and every new idea has to fight its way against the old. Controversy after controversy arises as new truths constantly emerge. As the following pages will show, this has happened repeatedly during the progress of Genetics. But controversy properly carried on is good; it prevents stagnation, and it makes each side work so hard to disprove the other that ultimate truths are brought to light more rapidly than would otherwise be the case, with the usual result that the two opposing sides join hands and proceed together.

The science of Genetics has been particularly enriched by these fusions, and it can only be hoped that the most recent controversy with the Soviet biologists will result in the same happy ending. The danger in this case is political, however—the subordination of Science, which can thrive only in complete freedom, to the direction of a dictatorship and a creed. Barriers of language as well as different political conceptions have made it difficult to understand the exact position. Translations of the works of Michurin and Lysenko are now available, and it is obvious that they, too, are suffering from the time lag, since their idea of "Western Genetics" is of the "Mendel-Morganism" of the beginning of the century.

Modern Genetics, like modern physics, is a very new science. Every year brings new extensions of the knowledge of evolution and heredity, especially in the extremely complex systems of the higher animals and plants, including Man. The early work has been proved again and again, but it is now enriched by an infinite variety of new work. There is still much to do before we can understand the ultimate workings of the genes, the cells, and the organism, but the main facts are known. Thousands of workers in great laboratories and research stations all over the world, including Russia, have traced the development and inheritance in organisms to the genes. By the use of modern techniques it is now possible to reach down to their level, so that the next few years should bring forth some of the greatest biological discoveries which have ever been made.

My most sincere thanks are due to Dr. C. D. Darlington for reading the proof sheets, and to my son and other "men in the street" who have by their conversation and questions given me some idea of the problems raised in the lay mind regarding the behaviour of inheritance.

RONA HURST

September, 1950

CHAPTER I

THE FOUNDATIONS OF GENETICS

FROM the time of Man's earliest development, Nature has always been his prime study. In the hard school of life he was forced by his daily needs to learn the ways of the creatures upon which he preyed, to discover which plants might be eaten with safety, and to track out the supplies of water, which was an even greater essential than food.

Nature had not been particularly kind to him physically. He lacked many of the defensive or offensive adjuncts of other animals. But he had two supreme gifts which in the end were to outweigh all the others: a larger and more agile brain, and a thumb and four fingers which eventually enabled him not only to fashion and use tools and weapons but also to make innumerable things for his greater comfort.

The other animals learnt to respect this queer creature which was able to wield stones and pieces of wood and also, as time went on, to make them dangerously sharp. Man learnt to control fire, and to make it for himself. He covered his nakedness with the skins of other animals, and later on made containers of various materials in which he could carry and store nuts, seeds, and other foods as well as water.

Finally, some seven thousand years ago, Man took a vital step in his development. He began to tame animals to his use and to sow seeds to produce his food-plants, with the result that he no longer had to spend most of his time hunting for his bare requirements;

he had leisure in which to carry on other occupations. Instead of searching for food, he could settle down to permanent husbandry and build homes of ever-increasing comfort and strength which it became his pride to make more decorative. He made pots and invented weaving. His standards of refinement and beauty were improved, and he collected or made beautiful things. He discovered the use of metals, and how to communicate by means of pictures and symbols; he evolved new ideas of religion, morals, and law. Modern Man had arrived, by long and tortuous ways, and at least a part of Nature's forces were now under his control.

But the study of Nature was an even greater need. Under the influence of his rapidly improving social conditions, Man's numbers were constantly increasing. He knew now how to produce food, but it was needed in ever larger quantities. He began to take much interest in breeding from the best animals of his herds and flocks and in sowing the best seeds of his food-plants, so that he gradually improved them out of all knowledge. Deeply interesting are the little models of domestic animals that have been recovered from the ancient Egyptian tombs and the animal mosaics and carvings of the Babylonians, since they make extremely interesting comparison with types in use today. Man's methods were very haphazard and took a long time. But they worked, and gradually domestic animals and plants evolved under Man's selection which were altogether different from those with which he had started, and infinitely more profitable in their production of food.

Exactly how this improvement was effected the majority probably did not worry about very much, or about how the multiplicity of life-forms on the earth had arisen, though we know from ancient writings that the more philosophically-minded were much intrigued by these things. Dating from the sixth century B.C. we find discussions on evolution by Greek authors which were sometimes surprisingly modern in their ideas, but, like many other things, this was largely forgotten during the later upheavals in European life. The spread of Christianity carried with it the old Babylonian legend of creation, which was accepted in its literal and not its figurative sense by all but the most inquiring minds.

It was not until the eighteenth century that the rapid extension of modern science gave rise to new interest in the questions of evolution and heredity. The great Swedish systematist Linnæus, who first brought animals and plants into definite classifications, believed that genera were specially created but that species and varieties arose from hybrids. Several other scientific writers put forward their views on the subject in this country and in that, but Erasmus Darwin (grandfather of Charles Darwin) was the first to make really clear the idea that life had persisted for millions of years, gradually evolving from primordial protoplasm.

Then Charles Darwin himself brought all these theories to a head when he published his famous *Origin of Species* in 1859, and later in his *Variation in Plants and Animals under Domestication* (1867), based on his own multitudinous observations and experiments. Darwin's theory of the origin of species by natural selection was backed up by such a weight of evidence that, in spite of strong opposition in some quarters, it carried the day; and although many attempts have been made to upset it, later work has given ever-increasing evidence of its fundamental truth.

Stated briefly, Darwin postulated that individuals of a species may vary in any direction, and that these variations will be inherited by their offspring. Those individuals whose variations best adapt them to the always changing conditions of life will tend to survive, while those less well adapted will be eliminated, thus giving rise to an orderly sequence of evolution through the periods of geological time, old species constantly giving place to new ones better fitted to survive in the altering environments.

For the most part, scientists and philosophers recognized the fundamental truths underlying the new ideas of evolution (though even here there were some " die-hards "), but since these ideas cut right across the current religious teaching, the Churches were immediately up in arms. Any believer in the new doctrines was branded as a heretic or an atheist, and it took a long time for it to be realized that the doctrine of creation by evolution from primeval simplicity to an ever-increasing complexity is far more inspiring than the idea of special creation, and is likely to evoke a deeper religious feeling in those who accept and understand it.

Biologists themselves found Darwin's evidence so overwhelming that they devoted little attention to the question of the *origin* of variation, and it was not until the end of the last century that it was realized that although there had been much glib talk about " variation " and " selection," no one had any idea how these variations arose or how they were inherited. Other evolutionary problems had been tackled wholeheartedly with much success, especially the study of comparative anatomy and embryology, with a view to tracing the relationships of animal groups and thereby their evolution, and the conclusions had been checked by comparison with fossil remains. But the question of the fundamental causes and working of evolution had not formed the basis of any inquiry.

In the 1890s there were several people in various countries who began to work on the problems of heredity, either by investigating some definite subject experimentally, or by collecting data which might throw light on the inheritance of variations. At this time it was believed that there was complete fusion of paternal and maternal elements in an individual, in much the same way as if one took a bottle of ink and a bottle of water and mixed their contents. In each subsequent generation (so it was thought) this fusion was automatically divided by half, so that one inherited (as it were) a half of one's parents, a quarter of one's grandparents, an eighth of one's great-grandparents, and so on in ever increasing dilution. It was also believed that variation is always proceeding by imperceptible changes in all possible directions. All this was being tackled statistically by Sir Francis Galton, W. F. R. Weldon, Karl Pearson, and other biometricians (as those scientists are called who specialize in the application of statistical methods to biological facts), working on an immense quantity of numerical data from various sources.

At Cambridge William Bateson was working up a great accumulation of facts on variation, the first batch of which he published in 1894 as *Materials for the Study of Variation.* In this book he showed that variation is not always continuous but may proceed by definite steps. At Burbage, in Leicestershire, C. C. Hurst was experimenting with orchid hybrids, and collecting data concerning those made by the numerous orchid hybridists of the time, which brought out the fact, proved also by Bateson, that variations behave as distinct entities and are not merged in the offspring, but appear again unchanged in later generations. This was a very important point, since one of the chief arguments against Darwin's theory had been that variations would be swamped on being crossed.

In 1894 the Royal Society had formed a committee, on the suggestion of Sir Francis Galton, for collecting statistics on the measurable characters of animals and plants, and in 1897 this was replaced by a committee formed to consider the more general aspects of evolution, with Bateson as its enthusiastic secretary. The next year Bateson invited the Royal Horticultural Society to co-operate, since he knew that the practical breeders had the greatest knowledge and experience of variation. The Royal Horticultural Society (R.H.S. for short) took up the idea with enthusiasm, and it is safe to say that it was largely due to this Society that England played such a leading part in the foundation of what was to be the new science of Genetics. Hurst had been a keen member of the R.H.S. for some years, and the publication of the results of his work in its *Journal* had aroused much interest, especially in the Society's brilliant secretary, the Rev. W. Wilks, who had himself become famed by raising the very popular Shirley Poppies, named after the parish of which he was the vicar. From now on Wilks worked tirelessly to further the knowledge that was being accumulated and to help those making the experiments. All practical horticulturists were asked to co-operate by making accurate observations on the quantities of material always passing through their hands, taking note of variations and their mode of inheritance and selection value. It was also emphasized that in all cases of hybridizing the failures were as important as the successes in solving the problems of evolution. Towards the end of the year, Wilks formulated a wonderful new scheme—a great international hybridization conference to be held the next summer by the R.H.S.; and invitations were sent out to well-known botanists and horticulturists all over the world.

The Conference—which, all unsuspected by its promoters, was to be the first of a series of great international genetical conferences—was held on July 11, 1899, and was a complete success. The greatest interest was aroused everywhere. Though it was held during a heat-wave, the enthusiasm never flagged; everyone seemed to feel that they were on the threshold of a great future of discovery in the new century just arriving, an expectation which was most amply fulfilled.

Bateson, Miss E. R. Saunders (who was working with Bateson at Cambridge), and Hurst put on various exhibits demonstrating their discoveries that variations were behaving as distinct entities which persist unchanged in crossings with the type, instead of becoming fused with it, as had previously been thought. They read papers on their experiments; and the famous Dutch botanist, Hugo de Vries, also stressed the same idea, since he had come to similar conclusions from his own numerous experiments. These papers showed the first comprehension of the facts which were to amaze the biological world in the following year—the Mendelian Principles of Heredity; and this conference of the R.H.S. was to prove a prime factor in preparing people for the reception of the new discoveries.

Bateson stressed the fact that it is only by crossing the varieties, or " sports," which arise from time to time, with the original types that a true understanding of how variation behaves can be attained. He regularly visited all the great nurseries and the famous animal-breeders, asking questions, seeing the new forms, and generally trying to get to the bottom of the processes of heredity and evolution. Under domestication all sorts of animals and plants have arisen which are quite distinct from the wild species. Very many of them could not have persisted under natural conditions, and their survival is due only to their protection by Man; but that does not alter the fact that these varieties have arisen. The many breeds of dogs, each specialized for some particular human requirement; the colours and patterns of fanciers' rabbits; the many different kinds of fruits and roses, and hundreds of other things, all were seen to bear witness to the fact that variation occurs very widely indeed. But how does it happen, and how does it avoid being swamped in later generations? How, in fact, does inheritance work at all in any organism, always giving progeny resembling the parents? That was the burning question.

Hybridization, it was clear, was responsible in considerable measure, and it was this realization that brought together all the great hybridists to discuss their work. Moreover, many of the orchid hybrids with which Hurst was working had shown that several orchids which had previously been regarded as pure species were really natural hybrids between other species, so it was seen that new species could apparently arise by hybridization—though this could not be true of all, for no amount of re-shuffling of parental characters could give rise to all the multitudinous species in existence.

Old ideas die hard, and before new discoveries can be made a lot of preconceived theories must be thrown overboard. The whole idea of the evolution of all the varied modern forms from a few ancient primitive types, which in turn stretch still farther back to "primordial protoplasm," was so completely different from the previous idea, deeply ingrained from centuries of teaching, of special creation of each individual species, that even the early evolutionists found it difficult to realize the constant changes which must have been taking place through the ages. Once the idea was grasped, however, the question of the origin of variations and their subsequent survival and mode of inheritance became of prime importance, and it was on this basis that the new work was planned.

CHAPTER II

THE BIRTH OF GENETICS

Now it is necessary to go back again, this time to the year 1857, and to travel across Europe to Brünn, in what is now Czechoslovakia, where, in the abbey garden, an Austrian monk, Gregor Johann Mendel, was just starting a wonderful series of experiments which (long after he was dead) was to make his name famous throughout the world. Mendel had developed an interest in the inheritance of variations; and, fortunately for the future of Genetics, he had hit on a plant which is unusually well suited for this study—the ordinary culinary pea. This is an annual, so that one can get a whole generation each year; it does not take up much room, so that comparatively large numbers can be raised in a small garden; most of its races breed true to type; and it possesses many characters which are so distinct that they can be spotted at once by even the most casual observer.

In races of peas there are normally two very different types of seed-colour: green or yellow. Mendel realized that the only way to test the behaviour of variations was to tackle one character at a time, so he crossed a pure-breeding yellow-seeded pea with the pollen of a pure-breeding green one, and in the resulting first generation he obtained all yellow seeds. He then reversed the process, pollinating a green-seeded pea with a yellow one, but the result was still the same—all yellows. Although he repeated this again and again he always obtained the same result—nothing but pure yellow colour in the first generation and no trace of the green of the father or mother parent, whichever way the cross had been made.

Satisfied on this point, Mendel now took the first-generation crossbreds and allowed them to self-fertilize. Each of the plants in the second generation produced peas of two colours, yellow or green, thus proving that the first crossbred yellow peas carried the green colour without showing it; in other words, the yellow colour was *dominant* over the green, which was termed *recessive*. Going on to the next generation, Mendel found that the green-seeded peas bred absolutely true, in spite of the fact that their parents had appeared to be yellow. No matter how many generations were sown, the yellow never appeared again; it had been completely thrown out.

But the tale of the yellow-seeded peas in the third generation was very different. While a part of the yellow peas bred absolutely true, in the same way as the green peas, the rest of the yellows always behaved in the same manner as the original crossbreds, throwing pure yellows, pure greens, and the impure yellows, which would repeat the mixture again. There was no means of telling the pure yellows from the impure yellows except by breeding, but the greens could always be relied on to give nothing but green. The purity of the extracted yellows and greens was a startling discovery in face of the current belief in the complete fusion of maternal and paternal characters, and formed the basis of what was to become known as the Mendelian Principles of Heredity.

Having got so far, Mendel began to add up his numbers, which disclosed another surprising fact. The two colours were segregating out in a perfectly regular way, in the ratio of one pure yellow and two impure yellows to one pure green, or three (apparent) yellows to one green. It was already known that seeds are formed by the union of a pollen grain from the male parent with the egg-cell of the female parent, and Mendel

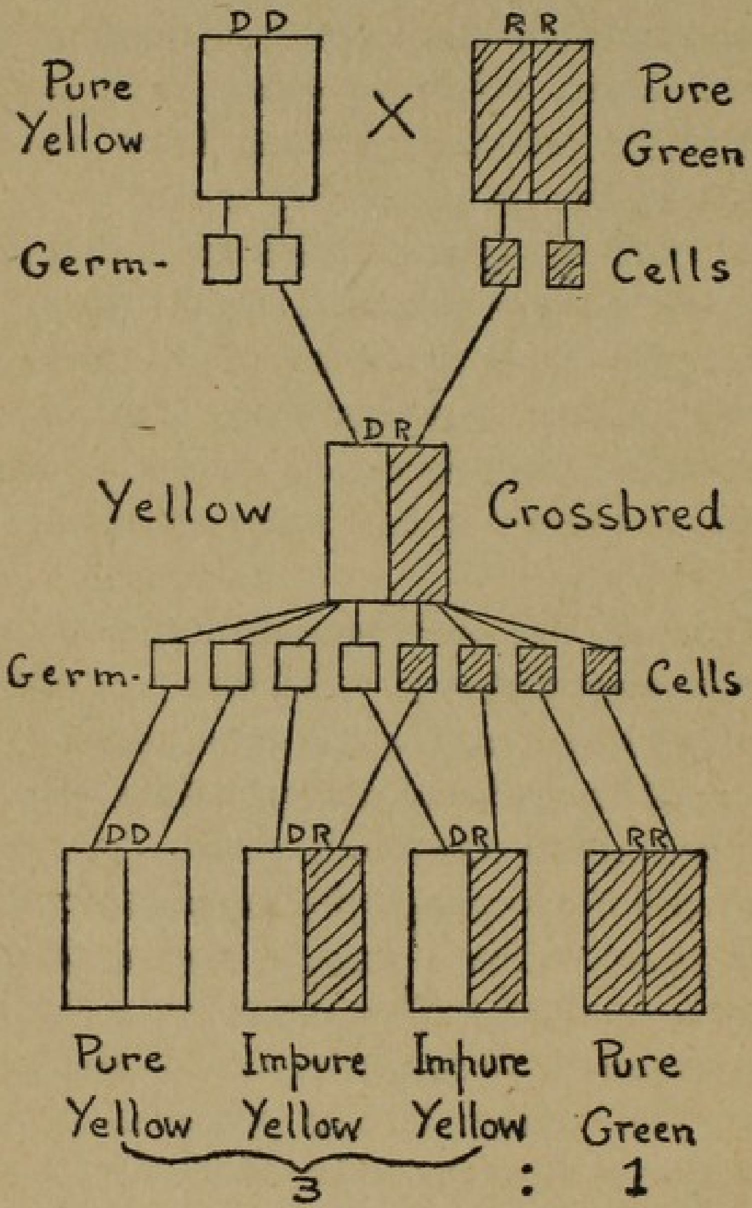

FIG. 1.—Diagram showing the segregation of yellow and green seed colour in peas, yellow being dominant (D) and green recessive (R).

realized that these must each carry one factor for seed colour—either the yellow or the green. When, by crossing, a yellow factor meets a green factor, it does not fuse with it but conceals or masks it, the two remaining side by side until the next germ-cell formation, when they once again separate, half the germ-cells automatically carrying the yellow factor, the other half the green. By the laws of chance, in the next generation yellow should meet green, green should meet yellow, yellow should meet yellow, and green should meet green, an equal number of times, thus giving 50 per cent impure yellows and 25 per cent pure yellows to 25 per cent pure greens, or the 3 : 1 ratio (Fig. 1).

This basic fact—that the body-cells are double for any given character while the germ-cells are single, and that each character retains its unity and purity—was Mendel's great discovery, and on it has been built up the vast edifice of genetical research of the past fifty years.

Mendel then went on to examine other pea characters, and found that they behave in the same way. He wrote an account of his results which was printed in 1866, but unfortunately only in the publication of the local natural history society. Hence, after arousing some local interest, it lapsed into oblivion, and the outside world heard nothing of Mendel's discoveries. Mendel himself had the ill fortune to extend his experiments to one of those few genera which, since they produce seed without sexual fertilization (a fact not known at the time), cannot conform to the normal laws of inheritance; and so he lost faith in his own discovery as a universal law. He died in 1884, almost unknown to the world of science, sixteen years before the unearthing of his paper showed him to be one of the greatest pioneer scientists of all time.

At the very beginning of this century, De Vries in Holland, and Correns and Tschermak in Germany, were searching through all available literature which might throw light on their own researches into variation, when they suddenly discovered Mendel's paper. They grasped its importance immediately, and saw in it much that was in line with their own researches. De Vries, remembering what he had seen and heard at the R.H.S. Conference, wrote off to Hurst: "You have had at Chiswick the kindness of telling me some figures you had won in crossing your *Berberis* species . . . and I should like very much to know in how far your experiments would confirm the law of Mendel. I think they do, and this would be a great success." He enclosed a reprint of a paper he had written on the subject, and sent another copy to Bateson; the English workers realized at once that Mendel had provided the clue to their own experiments.

When Bateson first read De Vries' paper he was in the train on the way to give another lecture to the R.H.S. on "The Problems of Heredity as a Subject for Horticultural Investigation" (May 8, 1900). He recognized immediately the magnitude of Mendel's discovery and incorporated an account of it in his lecture, so that it was the fellows of the R.H.S. who were the first in England to be informed of Mendel's principles. Wilks leapt at the opportunity. He got hold of Mendel's paper and had a full translation made, which appeared (its first printing in England) at the beginning of the *R.H.S. Journal* for the new year of 1901.

Now the whole aspect of things was changed. The old muddled ideas of the fusion and diffusion of parental characters were all swept away by the new knowledge that the body carried a double set of characters and the germ-cells a single set, and that from any pair of characters in an individual there can arise at most only two distinct types in the germ-cells, the dominant and the recessive, each retaining its individuality and purity. New work was at once begun to test whether Mendel's laws held good in other plants, and also whether they were true for animals as well.

Both Bateson and Hurst had been breeding poultry, and they quickly reorganized their experiments to see how far the same principles applied here. Again they were fortunate in their material, for in poultry there are quick generations, and a large number of progeny can be raised from good laying hens. It was soon found that characters in poultry were behaving in just the same way as in the peas. Hurst was working with rabbits as well, which are also quick-breeding animals producing big families, and large numbers are always important to test the ratios.

Many important facts came to light in this work with animals. Thus it was quickly discovered that most characters are controlled by more than one factor and that, so far as breeding is concerned, things are certainly not always what they seem. In rabbits, for instance, it was soon apparent that albinos (rabbits which are quite colourless themselves) may be carrying factors for colour which they can and do hand on to their offspring, so that it was never safe to breed experimentally with any animal until it had been thoroughly tested by previous breeding to find out what factors its germ-cells really contained, as the recessives were always concealed until extracted by breeding. Rabbit colours proved to be unexpectedly complex, but extremely illuminating.

The colour of the wild rabbit (Agouti) is really a complex mixture, as one can see on examination. The hairs are black with a yellow band. Along the back, loins, ears, and forehead are a few long black hairs, while below the body and tail the colour is greyish-white. Using the first letters of the alphabet as symbols for the factors involved, this colouring may be said to be due to dominant factor A, since no rabbit can have the agouti colour without it, but there are also many others involved. If we take just four of these, we may say that a wild rabbit's coat-colour is AABBCCDD, each pair of capital letters standing for a pair of dominant factors in its body-cells. When variations occur and AA becomes a recessive factor expressed by the small letters *aa*, we get an entirely black rabbit *aa*BBCCDD. If the BB change to *bb*, the resulting rabbit, AA*bb*CCDD, is a self-coloured yellow. Similarly, a rabbit AABB*cc*DD is an albino with pink eyes, while a rabbit with the formula AABBCC*dd* will have a white coat and blue or grey eyes.

Very many other factors are involved in all the different types of colour known in the fancy breeds of rabbits. There is one pair that will change agouti into cinnamon, and black into chocolate, when recessive, while another causes a dilution of colour, and so changes agouti to blue-grey, black to blue, chocolate to " lilac," and yellow to creamy brown.

Obviously this can be only an extremely simplified account, but it may give some inkling of the way all the numerous colour-forms of tame rabbits have arisen under domestication, thus making possible the analysis of the factors which go to make up the composite colour, agouti, which is common to rabbits, rats, mice, guinea-pigs, and other rodents and provides a very protective colouring in their natural habitats. In a wild state these colour variations, while they do occur, cannot normally survive, since the animals become too conspicuous and fall an easy prey to their enemies. If by any change in environment such a variation becomes useful, then, of course, it will persist; for example, the white colour of the polar bear or other creatures living in snow areas.

Much work was also done by the early Mendelians on flower colours in the sweet pea, and these proved to be just as complex as animal colours and to work in a similar way. Here another of the old ideas was disproved—that evolution has occurred only by imperceptible changes. In the many experiments carried out with sweet peas the main colour varieties appeared first, and it was only later that all the numerous intermediate shades arose which would now make it possible to arrange them in an apparently continuous series of minute variations. But that would not be the correct story of their origin, and so it was seen that what was true for a garden plant was most probably also true for the wild ones, and that evolution can proceed by large or small variations.

All this experimenting and working out took many years, and the first geneticists had to learn to walk before they could run. We may smile now at the apparent simplicity of some of their work and ideas, but it must be remembered that they were starting from scratch in an entirely uncharted country. They had all the breath-taking excitement of explorers in hitherto undiscovered territory, one which covered the whole field of living things; it was deeply puzzling, often baffling, but full of the thrill of virgin discovery. Every fresh piece of work was a new entry on the map, and their experiences can be compared only with those of the physicists whose great discoveries were made in much the same period of time. They, too, started very simply—first the atom, then electrons and protons (which Lord Rutherford demonstrated so delightfully with his billiard-ball models —now also smiled at); and it is only in recent years that all the later complications of neutrons, positrons, mesons, and so on have been added to make the picture more complete to the scientist but infinitely more confusing to the layman.

The new Mendelian researches attracted considerable attention, but unfortunately not always of the kind to be desired. The biometricians were quite unprepared to accept this simple explanation of the workings of inheritance after all their elaborate statistical inquiries, and a violent quarrel arose, which did a good deal of harm in some ways but in others cleared the ground for the eventual fusion of the two sciences which was to take place in later years, to their great mutual benefit.

The Mendelians' chief difficulty was to get enough land on which to carry out their experiments and the money to carry them through. There was as yet no corner for them in any of the academic faculties; their subject was linked with botany, zoology, agriculture, physiology, and chemistry but belonged to none, and all the experimenters were able to devote only their spare time to their research. No one as yet recognized the importance of their work except the Royal Horticultural Society, which backed them through thick and thin.

In 1902 the American horticulturists, immensely impressed by the R.H.S. Conference of 1899, organized another in New York. Bateson attended it and received a most enthusiastic welcome. For some time there had existed various large institutions in the U.S.A. for the study of agriculture, and these were just beginning to realize the value of the new work. Bateson came back greatly impressed and also much refreshed by his escape for a time from the turmoil of controversy in England. A book he had written in defence of Mendelism and containing some criticism of the biometricians had certainly not improved relations between the two bodies of research scientists, and in 1905 things came to a head when Hurst, always interested in horses as a keen rider to hounds, tackled the biometricians on the coat-colour of horses, which they had dealt with previously. By reference to volumes of the Stud Book of racing horses, he demonstrated that chestnut colour was working as a pure recessive, just like the green seed-colour in peas.

Bateson communicated this result to the Royal Society; and at an extremely stormy meeting, at which the biometricians hurled facts and figures at Hurst which he was unable to refute without recourse to the Stud Book, the paper was withdrawn pending further investigation. It was now a question of everyone getting down to it. Mendelians and biometricians alike pored over the Stud Books, and in a few weeks the vastly extended work completely confirmed the original, and Hurst's paper was triumphantly published.

So ended the worst of the opposition, and from then on the two rival lines of research gradually drew together, until now it is impossible to think of one without the other.

In 1906 the R.H.S. organized a third great hybridization conference, and it was at this meeting that Bateson coined the word "Genetics" as the name of the new science, "which sufficiently indicates that our labours are devoted to the elucidation of the phenomena of heredity and variation; in other words, the physiology of Descent, with the implied bearing on the theoretical problems of the evolutionist and the systematists, and application to the practical problems of breeders, whether of animals or plants."

CHAPTER III

THE ESTABLISHMENT OF GENETICS

As THE years passed, the original workers were gradually adding to their numbers. In 1903 R. C. Punnett joined Bateson and Miss Saunders at Cambridge, and from this strong team, together with the students who helped them, came a steady stream of work on various plants and animals, particularly sweet peas and poultry, and the exhaustive study of stocks which Miss Saunders maintained for something like forty years. Still the utmost difficulty was experienced in getting land and money for their experiments. Large numbers of progeny were needed to test out Mendelian ratios. Everyone knows that in tossing for heads and tails, they will not come down alternately: one must toss many times to get the half-and-half assortment to be expected. In the same way one cannot expect the factors in the germ-cells to sort themselves out 3 : 1 with unfailing regularity, and it is only by raising large numbers that this ratio becomes obvious.

When it comes to dealing with more than one character the ratios quickly become simply enormous, and this of course is where the work of the biometricians is so essential to Genetics, as well as for following the behaviour of characters under natural uncontrolled conditions. If we take the normal segregation of only two distinct pairs of characters—say of yellow or green colour in peas with wrinkled or round seed-coats—we get in the second generation 9RY : 3RG : 3WY : 1WG, yellow (Y) being dominant to green (G) and round (R) to wrinkled (W). In other words, only one out of sixteen individuals can be expected to carry the two desirable recessive characters for which one may be

Pollen-cells of the Round Yellow Crossbred	Egg-cells of the Round Yellow Crossbred: RY	WY	RG	WG
RY	RY RY round yellow (pure)	WY RY round yellow	RG RY round yellow	WG RY round yellow
WY	RY WY round yellow	WY WY wrinkled yellow (pure)	RG WY round yellow	WG WY wrinkled yellow
RG	RY RG round yellow	WY RG round yellow	RG RG round green (pure)	WG RG round green
WG	RY WG round yellow	WY WG wrinkled yellow	RG WG round green	WG WG wrinkled green (pure)

FIG. 2.—Table showing the segregation of two characters in peas—yellow, dominant to green, and round, dominant to wrinkled, giving 9 RY : 3 RG : 3 WY : 1 WG.

breeding. A glance at Fig. 2 will show this more clearly than any amount of written explanation. In working with three characters one can expect only one in sixty-four to show the three recessives in a pure state, and so on. Obviously in practice one may achieve this result within a few individuals if one is lucky; or by ill fortune (as any gambler knows) it may take many more than the expected number.

It will be realized that a good deal of room was needed for the experiments, and the pioneers, in their anxiety to test as many animals and plants as possible, were always short of accommodation. Bateson had bought Merton House, on the road to Grantchester, which had a certain amount of land attached—but not nearly enough for his needs. The famous allotment in the Cambridge Botanic Garden, where the first experiments had been carried out on the foundation of the Royal Society Evolution Committee in 1897, was always in use; while on the land of the Cambridge School of Agriculture R. H. Biffen started his classic experiments with wheats. Hurst fortunately had plenty of land at Burbage, and was consequently able to undertake many things which were difficult for the others, and he was aided by a keen body of his own workmen possessing all the craft and knowledge of breeding of the born countryman, which was very necessary in the production of healthy and successful progeny. All these experimental workers were carrying on their researches quite independently, but a constant flow of letters on their work and visits to each other kept them alive to all that was happening and to any new discoveries that might arise. They were also always in touch with the workers in Europe and America, and much knowledge concerning the working of heredity was soon accumulated.

In America the great experimental stations for agriculture were taking up Genetics with much energy, and very many workers soon became involved—far too many to mention individually here. At Harvard

University, W. E. Castle was carrying out researches with rabbits, the publication of his results often coinciding with that of Hurst; the fact that two independent workers on opposite sides of the Atlantic, using different stocks, should obtain the same results, provided one of the most convincing proofs of the truth of the Mendelian principles in the early days of controversy.

The practical aspect of the new knowledge was now becoming evident. Although the old breeders had had great success, it had all been " hit or miss ", and most of their best breeding had been done more by intuition than by direct knowledge. Before the analysis of characters by the Mendelian researches the idea of the fusion of parental characters had never given breeders any sure hope of getting what they wanted, or, having got it, of preserving it. But under the new system they could confidently breed for any given character or combination of characters that they desired.

Some of the best of the early work was done on wheats, the staple food-plant of many nations. The early colonists in the Dominions and the U.S.A. had made wheat their main crop in the areas where the climate was suitable to its growth, but there were vast tracts where it was too dry, others where it was too cold, and there were many pests of all kinds causing havoc in the crops. With the discovery of the purity of the germinal characters, however, it was realized that it was possible to bring together within one variety desirable characters which had hitherto been scattered through several varieties, and in so doing to eliminate undesirable characters. For instance, early ripening is a very necessary character in those areas with a short summer, and new varieties were soon bred which matured much more rapidly, with the result that it was possible to raise excellent crops over large areas where hitherto it had been impossible. It was also soon discovered that resistance to rust and some other disastrous diseases of wheats is inherited and disease-resistant varieties were produced which could be sown with the full assurance of reaping a normal crop.

The actual weight of wheat produced is obviously a prime factor. In Britain the average yield had been from 8 to 10 cwt. per acre, but the fine work of Biffen, F. L. Engledow, and others in breeding new genetical varieties with ever-increasing size and number of grains has now raised the yield to an average of 20 cwt. per acre, while a good farmer working on the best soils can get as much as 30 to 40 cwt. per acre. The world average, however, is still only 7 cwt. per acre, and it is obvious that there is enormous room for improvement in many countries. But it all needs to be very adequately controlled, if one is to avoid the ridiculous situation where one country will have to burn a bumper crop while another country is starving for lack of food. This actually did happen in some countries in the 1930s, when, by using the new methods of breeding and cultivation, the acreage was so rapidly expanded that more wheat was produced than could be dealt with in uncontrolled markets. The plant-breeders and scientific agriculturists can " produce the goods ", but it needs much foresight and organization to make the best use of what is produced without waste on the one hand or want on the other.

The rapid improvement of the larger domesticated animals is not so easy, because of the longer time they take to mature and their limited progeny on the female side. In the case of milk production it is extremely difficult to prove the value of a cow as a breeder, since she normally produces only one calf a year, which may be male, and so not milk-producing in itself. In consequence, milk-producing factors must normally depend on the bulls, since each bull has an extensive progeny of daughters which have acquired through him the milk-producing factors of previous female forebears, and can be tested. Now that artificial insemination is so widely practised, a bull may have thousands of daughters, and it is by testing these and his granddaughters that his own value can be assessed. This takes about nine years, and it is only then that he can be used with complete confidence; once proved, however, he can be an invaluable source of improvement for future herds. By this means even inferior herds can be up-graded quite rapidly, and our own pedigree bulls are always in great demand by the overseas milk- or beef-producing countries, such huge prices being given for them that they form one of our most profitable exports. Fat-content in milk is a prime factor in butter-making, and it is said that in Denmark a large part of the best butter-producing herds owe their superiority to two highly-bred bulls.

The question of the quantity, fat-content, etc., of milk was one of the earliest subjects for investigation, especially in the great American experimental stations, where room and money were available for such large-scale work. Our own investigators could not hope to cope with such things in the early days, for they were much too short of money as well as of space; only the smallest grants occasionally came their way to help them with their work. The amazing thing is the amount of work that they did do, keeping England in the forefront for many years by utilizing smaller creatures, and more often than not covering expenses out of their own private incomes.

The noisy controversy with the biometricians certainly aroused considerable interest in Genetics, and was also a spur to further attempts to prove or disprove Mendel. A war is the surest means to whip up invention and production, and in this instance many who came to scoff became converted and ranged themselves on the side of the geneticists. As the years of the century's first decade passed, many important biologists, both professional and amateur, joined in the work, if only as a hobby—for genetical research has the great advantage that anyone who has the space to grow things can test for himself the truth of the Mendelian principles, provided he has also the necessary patience and breeding technique. Of these new researches, the work of R. N. Salaman on the potato has probably been the most far-reaching, since it has continued up to the present day and has proved particularly important with regard to the study of virus diseases (page 65).

With all this extension of the work many different facets of inheritance were discovered and studied, but they all went to prove and extend the original work of Mendel. Furthermore, what was discovered in one particular plant or animal always corroborated what was found in others, thus making all work on any form of life of equal importance since the same laws apply to all.

In France, L. Cuénot was one of the first to experiment with animals; he used mice, in which he found several new aspects of the Mendelian law, one of the principal being that in some cases a character can be lethal (death-dealing) to the individual who is carrying it in a pure state. Cuénot found on crossing yellow mice that they were not really pure yellow but were also carrying the wild agouti colour in a recessive condition. In the crossbreds, however, instead of getting three yellows to one agouti, as he expected, he got only two yellows to one agouti; and on the yellows being bred from again they were all found to be impure and carrying the agouti factor. In other words, there were no pure yellows, all the individuals carrying the two yellow factors having failed to develop; and what had looked like a contradiction of the Mendelian 3 : 1 ratio proved to be an added confirmation.

These characters which prove to be lethal in a pure state are quite widely spread throughout the plant and animal populations, and, as we shall see later (see page 84), they have a very important bearing on evolution. The actions of these " lethals " are many and varied, and much work has been done on them. In rats, for instance, one was discovered which gave rise to an abnormal cartilage formation which caused upheaval all over the body—deformity of the bones and the consequent restriction of the arteries and of breathing and feeding capacity, which resulted in suffocation, bleeding, starvation, and ultimately death.

In their experiments with sweet peas Bateson and Punnett found that some characters went together into the same germ-cells so that they were " coupled " so far as their inheritance was concerned. This was later to prove one of the most important facts of Genetics, but, as with many new discoveries, this was not realized at the time.

In the early poultry experiments of Bateson and Hurst, and later in other animals, including Man, a strange type of inheritance was discovered which was linked with sex. This is best known today in the form of the cross between a Rhode Island Red cock and a Light Sussex hen, in which all the female chicks are red like the father and all the male chicks white like the mother—an extremely useful occurrence to poultry-keepers, since they use it to discover at birth the sex of the chicks, when they retain the pullets and get rid of the cockerels. This was extremely puzzling when it was first discovered; in fact the whole question of sex-inheritance was one of the greatest of the enigmas, but it was easily explained in the light of future work (page 47).

In 1907 Hurst brought out the first paper on Genetics in Man, showing the recessive character of pure blue eyes. In humans, eye-colour is very complex and due to many factors, even the blue having many complications, as an apparently blue eye may show traces of pigment if examined carefully with a lens. Obviously one cannot breed for human characters, so Hurst tabulated a large number of people living in his district, and worked out the facts from them. The British Association met at Leicester in that year, and a number of parents and children were taken there to give visual proof of the facts, and learned members of the Royal Society carefully examined them with hand lenses. The examination proved to be entirely convincing, and this work became the standard example of Mendelian inheritance, appealing to the popular imagination as nothing else could have done. The Press took it up, printing popular articles on Mendelism under such captions as "Blue-eyed Babies for Blue-eyed Parents", which certainly awakened the man in the street to a realization that something was going on. All the same, this cheap advertisement had many unfortunate repercussions which were not relished by the geneticists.

And now, so much having been definitely established, things began to look infinitely brighter for the new science. A professorship of Genetics was founded at Cambridge in 1909, with Bateson as the first professor. Scarcely had he settled in, however, than he was offered the directorship of the newly-established John Innes

Horticultural Institute at Merton, and as this carried with it far greater opportunities in money and land for experiment, he relinquished the professorship to Punnett and left Cambridge to build up what was to become one of the greatest genetical experimental stations in the world. Hurst, too, was now getting various good grants—for egg-production in poultry and for the breeding of new types of horses, among many other things—and it was necessary to regularize his position. So the Burbage Experiment Station for Genetics was founded in 1910.

For a few years the science went merrily ahead in England, but the small cloud was appearing on the horizon, and in 1914 the terrible impact of war fell, with devastating effects. Bateson and Punnett struggled on as well as they could with ever-dwindling staffs and constant war work. Hurst, one of the chief Territorial leaders of his county, was immediately swept into the Forces for the duration of the war—with fatal results to his new station, rapidly depleted of its staff. All the other workers were affected in greater or lesser degree, and when the war ended, Genetics in England had been dealt such a blow, so far as research facilities were concerned, that it took years to get the experiments back again to pre-1914 standard.

CHAPTER IV

CHROMOSOMES AND GENES

By the commencement of the Great War of 1914–18 the science of Genetics had been firmly established by a large number of workers all over the world, and numerous laboratories and stations were being erected for further research. Thousands of carefully checked and tabulated breeding experiments in many different types of animals and plants had entirely corroborated the results of Mendel's original experiments with peas. It was proved beyond doubt that characters in an animal or plant are controlled by particular factors which are present in pairs in any given individual but only singly in its germ-cells. By tracking out the behaviour of these factors through crossing variations with the type (as in the cross of the yellow and green peas), it was found that although one of the two factors for a given character in an individual may be concealed in the first generation, it will reappear quite unaltered in later generations when it can meet its like. In short, these factors are definite entities which may normally persist unaltered from one generation to another, though the fact that variations do occur showed that they can change at times, and that the alteration is usually by a definite step which gives a visible change. These variations, or *mutations* (Latin, *mutare*, change) as they are termed, become permanent entities themselves and are again inherited, thus providing the basis for genetical experiments, since (as Bateson had surmised) it was only by the study of variations from the type that a fuller knowledge of heredity could be obtained.

Here it is hoped to avoid professional jargon as much as possible, but there are a few terms which it is difficult to dispense with, since they provide a convenient shorthand which simplifies explanations once their meaning is grasped. In biological language, then, an individual is termed a *zygote*, implying its double nature, and two new words have been coined to show the distinction between individuals which are pure for any given character and those which are hybrid, like the yellow–green cross-bred peas. Those which are carrying two identical factors are called *homo*zygotes, those carrying two unlike ones are termed *hetero*zygotes. The variations of any particular factor are called *allelomorphs*; there may be only two—the type and its mutation (or " sport " as it is usually termed by gardeners)—or there may be more than one mutation from the type, so giving a series of allelomorphs for the character involved. The factors themselves have become known as *genes*, for it was realized more and more that they must be very definite physical entities, and not the rather shadowy conceptions of the early days.

What are these genes? This became the all-important question for every investigator. They had again and again proved that there was something quite definitely in control of each character in any individual, which normally carried on with unfailing precision from one generation to another, providing that sureness of inheritance that from sheer repetition one quite unconsciously expects without thought or question. If we plant a packet of Savoy cabbage seed we quite confidently expect a crop of Savoy cabbages, and not Drumheads or Brussel Sprouts—providing, of course, that we have dealt with a reliable seedsman.

The answer to the question was soon forthcoming, but to understand it fully it is necessary to return once more to the biological work of the last century. With the ever-increasing power of microscopes it was becoming possible to delve deeper and deeper into the inner constitution of animals and plants. It was found first of all that they were both built up on a structure of cells rather like a cross-section of a honeycomb. As the limits of vision were extended by the invention of better lenses, it was found that these cells were continually increasing in size and then dividing into two, so extending the bulk of the tissue they were forming—in fact, it was discovered how bodies grow in size. As microscopical powers increased, it became possible to examine the cells individually, and strange and wonderful things were observed in them beyond anything that had been conceived.

Many investigators in this work covered numerous species of animals and plants, as the geneticists were doing for the study of inheritance. Within each cell, whether animal or plant, could be seen a central body, which they called the *nucleus* of the cell. As the cell grew in size, this nucleus was seen to resolve itself into a number of small, worm-like bodies, which were termed *chromosomes*, since at this time they took up the dyes (introduced in the microscopical preparations in order to make them visible) very heavily, and were indeed highly "coloured bodies", so that their actions could easily be traced. It was observed that they then disentangled themselves, came to lie in a more or less flat figure (when they could be easily counted), and then each one split in half lengthways, one half of each chromosome passing to opposite sides of the cell. A new cell wall grew up between the two bodies of halved chromosomes, and so two new cells stood in place in the old one, each containing exactly the same number of chromosomes as the parent cell.

Millions of cells were examined in all sorts of creatures, and the story was always the same: each new cell arose from the exact division of a previous cell and its chromosomes into two equal parts.

Following up this discovery, the investigators began to find that though the number of chromosomes in the cells is constant for any given individual, and usually for all other individuals of the same species, different species and, particularly, different genera may have a different number of chromosomes, though this is again constant for each individual of that particular species. The number may vary from two up to a very large number of chromosomes, and the chromosomes themselves may differ considerably in size and length.

Moreover, it was found that in animals, or in plants in which there are two sexes, the males and females rarely have identical chromosome complexes, but one of the sexes carries two unlike chromosomes, which were designated the X and Y chromosomes. In animals, including Man (who, incidentally, was found to have forty-eight chromosomes in his body-cells), it was observed that the females carry two X chromosomes, while the males have the two unlike X and Y chromosomes. In birds, however, it was the other way round: it is the females who carry the unlike XY complex, while the males are pure XX.

Carrying this work still farther, it was discovered that when the germ-cells are formed the chromosomes behave very differently. They come together in pairs and, instead of each chromosome dividing, as in the body-cells, one chromosome from each pair goes to opposite sides of the cell, thus halving the normal number of chromosomes. By this means the germ-cells, whether male or female, are formed with only half the number of chromosomes found in the body-cells. At the fertilization of the maternal egg-cells, either by the sperm-cells in the case of animals or by the pollen in plants, the two halved numbers coming together make up the whole number

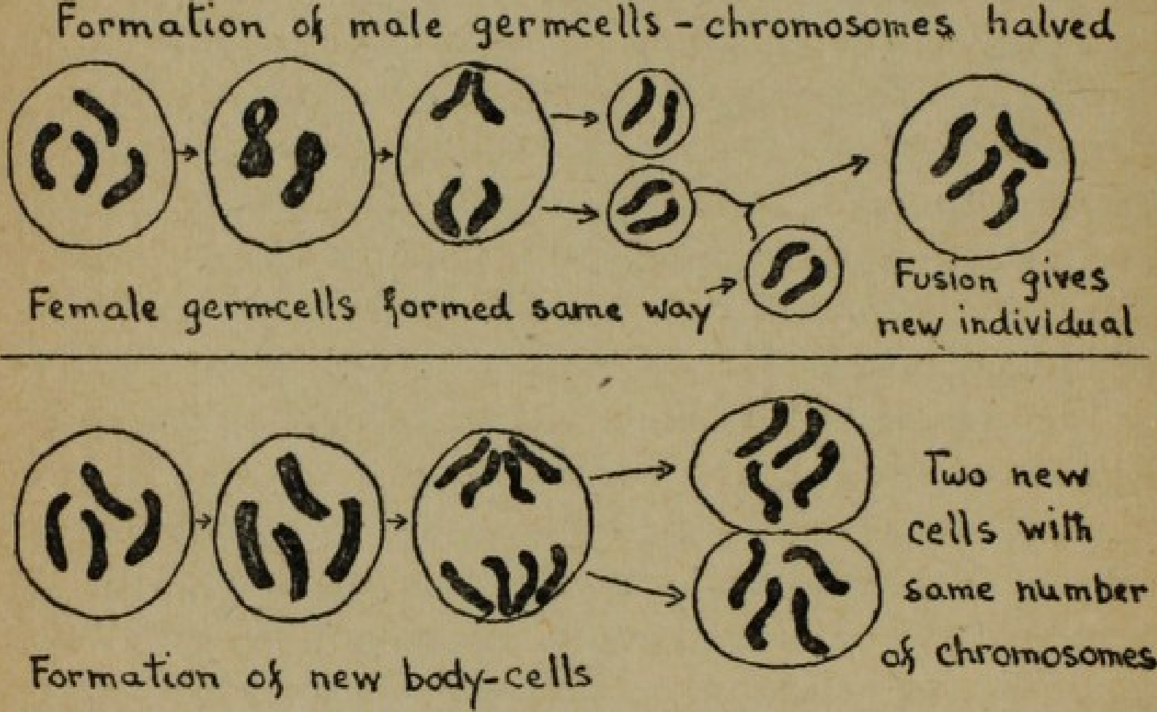

FIG. 3.—Diagram comparing chromosome behaviour in germ-cells and body-cells. In the germ-cells they pair and only one chromosome of each pair is included in a mature germ-cell, thus halving the number. In the body-cells each chromosome divides lengthways, thus preserving the full number attained by the fusion of male and female germ-cells. (For the actual process of division, see Fig. 5.)

once more, and the new individual arising has the same number of chromosomes as its parents (Fig. 3).

Here, indeed, was a perfect mechanism for heredity, and as such it was pointed out by A. Weismann in his famous book on the Germ-plasm, published in 1893. But the time was not yet ripe; other biologists were still immersed in the idea of the fusion of parental characters, and so could see no implications in this work of the cytologists (as the workers on cell behaviour were called) beyond the fact that they had discovered the mechanism of cell division and of structural growth. Hurst in his early work with orchids was very struck with the possibilities of this cell mechanism as the explanation of the workings of heredity, and in his paper on Orchids published in the *R.H.S. Journal* in 1899 he gave it as the probable clue to his finding of the orchid characters behaving as distinct entities. Bateson and many others, however—still befogged apparently by earlier ideas—could see no point in it at all; so for the time being the matter dropped. After all, how could it be true? Chromosomes were comparatively few, and obviously there were hundreds of characters in the make-up of an individual.

The cytologists had almost as big a fight as the early Mendelians in getting their work accepted. It all sounded so incredibly far-fetched. The fact that their material was killed, and subjected to all sorts of chemical treatment in the preparation of the slides, led people to suppose that what they could see were merely post-mortem effects. The cytologists' question as to why, if this were so, the results should be so constant—the same number of chromosomes in the cells, the same behaviour in animals and plants—fell on deaf ears, and it was not until they had devised methods for keeping embryonic tissue in a living condition, so that the behaviour of the cells could be watched in their living state under the microscope, that their work was finally accepted.

There is nothing more exciting than to watch a cell about to divide. It becomes intensely active, its contents seem to boil and bubble; the chromosomes appear, twisting and turning in their divisions before journeying to opposite ends of the cell. The new cell wall appears, and two cells stand where there was only one before, the whole process (in chick embryos) having taken about an hour. In relation to observations on the living cell, fixed preparations can only be what a still photograph is to a cine-film, though in both cases they are extremely useful and of course necessary for any intensive study.

When, later, genetical experiments began to show that characters did not always segregate alone when the germ-cells were formed, but might be linked or coupled together, the original ideas of the cytologists began to take form again. In America, T. H. Morgan, working on the cytology of insects, was particularly struck by the behaviour of the sex chromosomes. He was using the small fruit-fly, *Drosophila*. It was an easy subject, since it has only four pairs of chromosomes, each pair extremely distinct, and in the male the X differs from the Y. Now, if the *genes*, as the factors controlling the characters were now called, have any connexion with the chromosomes, there must be four groups of linked genes in Drosophila. Much of the genetical work had been on animals and plants bearing a rather high chromosome number, but if one could use a creature with only a few chromosomes it should be comparatively easy to trace out if there were any linkage of genes.

So argued Morgan; and the results of his researches, so brilliantly planned and carried out, soon began to show the truth of his ideas. Like Mendel's work, his results came from the utilization of simplicity; as a cytologist he carefully selected his material, and then began his genetical experiments. More and more workers joined him, fascinated by the opportunities of the research, and the apparently insignificant Drosophila became the keystone of modern Genetics.

Drosophila has, too, some very useful variants, notably a white-eyed mutant from the normal red eye. This was particularly good, as it was behaving in a similar way to the gold and silver plumage in fowls (page 37), and Morgan saw that if the genes were connected with the chromosomes this character must be located in the sex chromosome. Since red eye is dominant to white eye, which is recessive, the white eye can appear only when in a pure state, like the green pea.

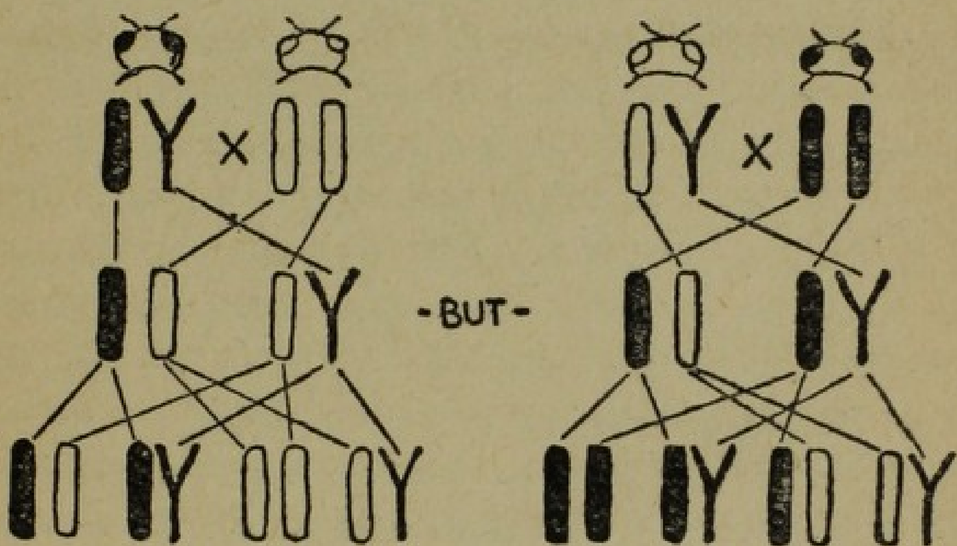

FIG. 4.—Sex-linked inheritance, comparing the different results from reverse crosses of red and white eye in Drosophila (red being dominant to white). A red-eyed male throws red-eyed daughters and white-eyed sons, but a white-eyed male has only red-eyed progeny. The red-eyed male has white-eyed grandsons and granddaughters, but the white-eyed male has only white-eyed grandsons. (Y individuals are male, black bars = red, white bars = white.)

Now, if the gene for colour is carried by the X but not by the Y chromosomes, that would account for the appearance of red-eyed females and white-eyed males in a cross between red-eyed males, XY, and white-eyed females, XX. The white-eyed females, obviously being pure for the recessive colour, produce all white eye-genes in their germ-cells; the red-eyed male carries the gene for red in his X chromosome but neither red nor white in the Y. Therefore in the first crossbred generation we get red X from the male meeting a white X from the female, which will give red XX females, while the empty Y meeting the white X from the female will give white XY males, since there is no dominant to mask the recessive (Fig. 4).

There are many variants of this sex-linked inheritance, according to whether the male or female is carrying the dominant gene or which is the heterozygous (XY) sex, but it has been one of the prime factors in probing into the behaviour of the genes, as it is obviously much easier to follow their course than when they are in the normal condition, where the dominant always masks the recessive in a cross, as in the yellow-green peas. The Y, too, can vary considerably. Sometimes it contains normal genes; at others it appears to be partly without genes, or at all events inactive; while in yet other cases it is absent altogether, or is very minute. One of the most significant aberrations of the sex chromosomes is when one of the X chromosomes gets lost during the first division of the fertilized egg-cell, giving rise to a body which is female on one side and male on the other. In a bird like the pheasant, with quite different plumage in male and female birds, this is very compelling evidence for the connexion between genes and chromosomes, since one-half of the creature is decked in the gay feathers of the cock and the other in the more sober garb of the hen.

By innumerable experiments the Drosophila workers proved that there are indeed four linkage groups which can definitely be associated with individual chromosome pairs. In addition to the unlike XY chromosomes, there is also a pair of extremely small chromosomes, which can obviously contain only a few genes, and a correspondingly small linkage group was found to exist.

It was fairly clear that if the genes were located in the chromosomes, then they must be strung out lengthways like a chain of beads, otherwise the longitudinal split of the chromosomes, and also presumably of the genes, during the formation of the new cells could have no connection. It was soon found that it was possible to prove this, and even to map out the relative position of genes in the different chromosomes. It was discovered that although the genes were normally linked together, in a certain percentage of cases they became separated and

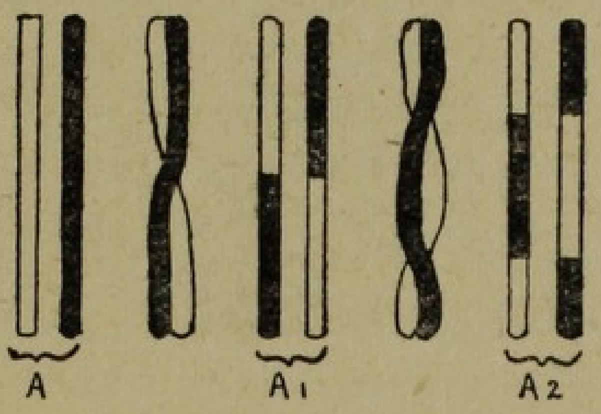

FIG. 5.—Two examples of the extra segregation of characters caused by the occasional crossing over of parts of chromosomes during pairing. The number of crossovers possible depends largely on the length of the chromosomes involved. A = the normal chromosome pair; A_1 = the result of a single crossover; A_2 = the result of a double crossover.

linked up with characters in the opposing chromosome of the pair. It had been observed cytologically that when the chromosomes come together in pairs at the formation of the germ-cells they coil round one another, sometimes so tightly that a break occurs, and though it mends up afterwards in the process the pieces may change partners. Obviously genes lying far apart are likely to become separated more frequently than those lying near together, since there is more chance of a break (which might happen anywhere along the chromosome) occurring between them. By an enormous number of experiments and calculations it has been possible to map out more and more of the gene locations or "maps" of the chromosomes of Drosophila in this manner (Fig. 5).

To crown this great achievement, of linking up the genes with the chromosomes, another fortunate circumstance in Drosophila (and also in other flies) has given ocular demonstration of the position of the genes. Normally, chromosomes are extremely small; and during the phases in which they can best be seen, and are usually pictured for illustration, their contents are coiled up like a spring and enveloped in a darkly-staining mass of nucleic acid, giving them the appearance of comparatively short, thick, solid bodies. Sceptics of the truth of Morgan's work could not believe in the physical possibility of the genes lying, as was claimed, in linear position within the chromosomes. Then, by a lucky accident, during the 1930s, while some microscopical investigations were being made on the internal structure of the larvæ of the flies, it was found that (for some at present undiscovered reason) the chromosomes of the salivary glands and some other parts of the body string themselves out to their fullest extent and go on dividing without contracting or separating, giving the appearance of giant chromosomes variously banded and striated.

A close examination showed that these markings corresponded closely in their variations to the estimated positions of the genes in the chromosome maps, and although it could not be claimed that the actual genes themselves could be seen, the chromosomes showed definite pattern structures which corresponded closely with the previously calculated positions of the genes. By this means it has been possible to get ocular proof of many things which had previously been calculated mathematically, or surmised from breeding experiments.

C. D. Darlington, working during the 1930s with material having favourably large chromosomes in the germ-cells, was able to work out the actual complicated mechanism of crossing-over between chromosome parts—an extremely important occurrence, since it is by this means that chromosome maps can be constructed in any organism. It also has considerable bearings on evolution, as it gives the opportunity for a greater segregation of characters than could otherwise occur.

The present development in microscopical technique, either in the electron microscope or in other types of instrument, enables knowledge to be gained each year of the actual physical behaviour of the chromosomes and the genes. Certain workers were able to see in the latter part of 1949 what they believe to be the actual genes. We are once again on the threshold of far-reaching discoveries.

CHAPTER V

CHROMOSOMES AS THE MECHANISM OF EVOLUTION

THERE has been much adverse criticism by uninformed people of the Drosophila work. Why should whole laboratories and hundreds of workers have spent some forty years on the minute study of this quite insignificant and useless fly? The answer is, that in no other way could the knowledge of inheritance behaviour have advanced at such a rapid rate.

Although each individual plant, animal, or human being, by reason of the complexity of its make-up, must always be more or less a law to itself, yet the main laws hold good for all living creatures, and what happens in one can also happen in another. It is only by the intensive and controlled study of everything that can occur in *one* species, in the same way that Mendel had his great success by dealing with only one character at a time, that it is possible to follow what is happening in others.

We have already seen that there are certain essentials which go to the make-up of the ideal experimental animal or plant. It must produce enough progeny to provide the necessary ratios; it must breed rapidly so that new generations can be quickly achieved; it must not take up too much room or eat too much food, or its upkeep will prove too great a problem; above all, it must have well-defined characters on which to work, and the fewer chromosomes it has the better.

Drosophila answers to all these requirements. A large number of progeny result from each mating; it matures so rapidly that there is, on the average, a new generation every ten days; it is so small that large numbers can be reared quite happily in milk-bottles which can be easily stored, tabulated, and kept under constant observation in a controlled environment; its only food requirement is a small quantity of fruit-pulp; its characters are well defined and easy to follow. Over and above all this, *Drosophila melanogaster*, the species most worked with, has only four pairs of very distinct chromosomes, one pair being the distinctive XY sex chromosomes that give rise to the sex-linked inheritance of certain characters, while in certain cases, as we have seen, the chromosomes are so large as to be very useful in tracing visually the positions of the genes. One could not imagine anything more ideal for experimental work.

The various nearly allied species of Drosophila are equally easy to follow, and by a study of their character and chromosome differences it has been possible to explain most problems concerning the evolution of these different species. It is estimated that one year in a Drosophila population is roughly equivalent to two thousand years of our own reckoning, so that it is obvious that in all the long period given over to Drosophila research there has been time to witness considerable evolutionary processes at work and to obtain controlled experimental knowledge of how these have given rise to the infinite complexity of life on this planet.

One of the first necessities was to try out the new work in other animals and in plants, just as Mendel's principles had been tested. All over the world people began counting chromosomes and planning new breeding experiments to find out how far the action of the characters and genes could be correlated with the action of the chromosomes. The first part of the Drosophila work took place just before and during the 1914–18 War, so it was not until the War was over that it was possible to do much in Europe.

Soon after the War, Bateson started some cytologists working at the John Innes Horticultural Institute, and various other people began to deal with the chromosomes of whatever animal or plant they were working with. There was neither money nor labour available to re-establish the Burbage Experiment Station as it had been before the War, so Hurst, following up his old interest in chromosomes, went up to Cambridge to work out the chromosomes and characters of *Rosa*, one of the genera on which he had been working when war broke out.

This new linkage of Genetics with Cytology was no more popular with the majority of biologists than the original Mendelian work had been. Research soon showed that not only was it the clue to the progress of evolution but also to the adequate classification of species. The older biologists were frankly aghast at being told it was no longer possible to be dogmatic about a species until they had studied its chromosomes. Were they all to turn cytologists? Surely a preposterous suggestion—just think of the work involved! The fight was on; and although it was not conducted with the personal rancour of the Mendelian–Biometrician dispute, it was nevertheless tiresome and dispiriting to the cyto-geneticists, and Hurst found himself in much the same position, as he ardently preached the new crusade for chromosome study, as he had been in during the early days of Mendelism. However, the work proceeded in the usual snowball manner of scientific discovery. Every new experiment confirmed and expanded the

Drosophila work. The genes were indeed within the chromosomes, but more and more complex reactions were discovered as more complicated systems were examined.

Very occasionally in the Drosophila cultures a chromosome was observed to go the wrong way during the formation of the germ-cells—accompanying its partner instead of separating from it, so that one of the resulting germ-cells had one more chromosome and the other one less than the normal number. Usually the depleted one dies, since it cannot form a complete chromosome complex; but the other can form an individual with an extra chromosome, which will enhance the effect on the characters of all the genes contained in it. One of the most profitable lines of study in plants proved to be in the *Datura* or Thornapple, which was used by A. F. Blakeslee and J. Belling in America to locate gene linkages. This plant is more than usually prone to this mishap, and it was used as a most profitable means of discovering linkage groups. All the characters controlled by the genes in the errant chromosome would show the effect of their being present in triplicate instead of in duplicate, when a normal germ-cell was fertilized by an abnormal one. One by one, varieties were bred with different chromosomes in triplicate, and the genes could be traced by this means. In later generations it is possible to stabilize these extra chromosomes so that they form an extra pair, and this has been an important evolutionary step, judging from the number of related genera or species which vary by one or a few extra pairs of chromosomes. This may also arise from a fusion or a break among the chromosomes, but in this case considerable variation in size will provide a pointer as to what has happened.

It was also found that many plant or animal varieties had, in comparison with the type, parts of their chromosomes reversed or attached to other chromosomes—abnormalities which were found to occur in Drosophila during the complicated business of crossing over, when breaks might not always join up again in the right sequence. A piece of one chromosome could become entangled in the coils of another pair, get nipped off, and then attach itself to the wrong chromosome, or in their coilings the detached ends of parts of the same pair might turn round completely, and on rejoining become reversed in relation to the normal " map " of that chromosome. It is interesting to note that when the salivary gland chromosomes were examined, this inversion of pieces of chromosome could be observed.

It does not appear that this could make a very great difference—the same genes are present, although in a different position. Actually it is one of the most important types of mutation or variation. To begin with, the Drosophila work has shown that although each gene controls its own particular character, it also works in conjunction with the other genes; in other words, the individual or zygote is the end result of the working together of its entire gene complex and not to the sum of the individual action of separate genes. Consequently, when a group of genes is displaced in any way, it comes into contact with genes not normally associated with it and loses touch with its usual companions, thus giving a somewhat different end reaction. In those cases where a piece of chromosome becomes attached to another pair it will cause a duplication of that particular section of the chromosome if it meets normal germ-cells in later generations, and a consequent enlargement of characters controlled by this section will usually result.

More important, however, is the fact that an alteration of this kind will give rise to a chromosome which is no longer identical with its normal partner, and if the deviation is a large one it will make them no longer adequate partners. It is probable that in later generations the chromosomes resulting from these mutations will come together, as the pure yellows or pure greens will segregate out in the yellow-green pea crosses; when this happens a new chromosome complex is established, differing from the old one by reason of this changed chromosome. If more of these chromosome mutations occur in the other chromosomes, or in other parts of the same chromosome, the subsequent progeny become farther and farther removed from the parent type, until they are no longer fertile together, and a new species is born, isolated from the parent species and evolving its own new types by chromosome or gene mutation.

Side by side with chromosome mutations are mutations in the genes themselves. All the mass of work on the genes points to the fact that they are extremely complex protein molecules, linked together in the chromosome, each made up of groups of atoms arranged in a long chain. Proteins are most complicated molecules peculiar to living organisms, and there may be thousands, often millions, of atoms in each one. Before the cell divides the proteins of the gene become associated with a substance known as nucleic acid (causing the dark staining of the chromosomes at this time), which seems to give them the power to grow and to reproduce themselves. In such enormous molecules the possibilities for the varying arrangement and rearrangement of the atoms are almost infinite, providing the basis for all the variation between the different genes and their reactions.

The amazing thing is that in *normal* chromosome and gene divisions each of the individual genes reproduces itself identically, the new cells being the exact replica of the old so far as gene and chromosome content are concerned. Millions of gene divisions are always taking place, one after another, without the slightest hitch, reproducing the same character generation after generation.

Occasionally, however, there is a " slip up." One of the genes does not exactly reproduce itself; there is a slight rearrangement, loss or gain of some of its atoms, and so the action of the new gene will not be quite the same. It may be very different, it may be only a little different, but a new variety arises, a new allelomorph. These gene mutations are a great source of evolutionary progress, for since all the numerous genes in a normal chromosome complex are subject to these occasional aberrations, their sum total throughout all living creatures is enormous.

Often in plants (more rarely in animals) there is a duplication of the entire set of chromosomes. This also duplicates all the genes and their reactions, and normally has the effect of producing plants with all their parts larger than in the normal type. The duplication may take place by an uncompleted division in the body-cells giving rise to tissue and finally germ-cells with twice the number of chromosomes, or it may arise from germ-cells in which the chromosomes failed to reduce their number by half. In the latter case, mutant germ-cells meeting the normal ones of the type will produce progeny with three sets of chromosomes, and so three doses of each gene.

Another more important type of duplication arises in sterile hybrids. It is often possible to produce a desired hybrid which, proving to be sterile, is useless for further work. Some of these, however, have duplicated their chromosomes, and so achieved two sets of paired chromosomes, which makes them fertile. Probably the best known of these is the loganberry, a hybrid between a blackberry and a raspberry. Many wild-growing species show that this type of change has been occurring fairly frequently in Nature and is obviously an important factor in evolution, for it combines within itself the genes and characters of two species, thus giving the new species a wide range of variability to fit it for changing conditions, while the greater gene and chromosome content provides wider scope for mutation.

These types with duplicated chromosomes are known as *polyploids*, since the term *diploid* had been given to the normal double set of chromosomes in an individual and *haploid* to the single set in the germ-cells. In these polyploids we find triploids with three sets of chromosomes, tetraploids with four sets, pentaploids with five sets, hexaploids with six, and so on—a truly complicated story which cannot be followed up fully here.

One of the most interesting aspects of these polyploid plants from a practical point of view is their importance in horticulture, since a great many of the magnificent new forms of garden flowers are the result of their possessing more than the one set of paired chromosomes. The discovery just before the Second World War that one could induce this condition by treating normal diploids with a chemical known as colchicine, prepared from the autumn crocus, has proved a source of great excitement in the horticultural world, but usually this duplication is useful only for producing better flowers and not fruits. Since there are four of each chromosome present instead of the normal pair, all sorts of complications arise in the formation of the germ-cells, which causes a good deal of sterility, and a consequent falling off in the number of seeds set, and so in the size of the fruit. But in the production of vegetatively-propagated flowers such as the daffodil and the narcissus (in which all the wonderful new forms are polyploid) the chemical treatment is certainly ideal for producing bigger and better varieties.

The greatest possibility, however, lies in the duplicating of the chromosomes of desirable sterile hybrids, usually between distinct species. Since in this case the maternal and paternal chromosomes are not like enough to pair, their duplication actually only produces once more two complete sets of paired chromosomes which carry through normal reductions when forming their germ-cells, and so a new and fertile species results with twice the number of chromosomes and genes contained in the two parent species. In this case there is often no increase in size of any of the parts, as, carrying different genes, there is rarely any question of characters being increased by the action of more than one pair of identical genes. Indeed, in the polyploid species of *Rosa* it would almost seem that the presence of more than one full complex of genes has an inhibiting effect, since most of the wild polyploid species are smaller than the diploids. In any case, it causes some highly intricate controls of characters by the different genes, and a great deal of work has yet to be done on this extremely complex type of inheritance.

It will be seen from this short account of the main chromosome and gene mutations which occur in animals and plants that there is plenty of scope for evolution in the variations which can occur. These changes range from the mutation of a single gene, through changes in the chromosome due to inversions, duplications, and the transference of sections of one chromosome to another, to the addition of extra chromosomes, as in Datura, and the even more complicated change of polyploidy. In this lies the explanation of the enormous range in size, shape, and number of the chromosomes and their gene content to be found throughout the animal and plant kingdoms, and one can see how the accumulation of small and large mutations throughout the ages has given rise to all the complexity and variation of life on this planet today.

In fact, anything can happen; and although one may term it the mechanism of evolution, it is very far from the idea of mechanism as we know it. Although each genus seems to have its own favoured method of variation, it is also quite as likely to change by other ways as well, and the more one examines the species and individuals of any genus the more one realizes the enormous complexity and possibilities of the means of variation.

A study of the *Chromosome Atlas*, compiled by C. D. Darlington and E. K. Janaki Ammal, giving the chromosome numbers of cultivated plants, is a most interesting form of detective work. In the large Rose Family, for instance, which includes most of our fruits as well as roses and other well-known garden plants, the basic number of chromosomes is 7. Roses, strawberries, blackberries, and raspberries, as well as various garden plants belonging to this family, all carry this number, though many polyploids occur, all multiples of 7, running up in the blackberries to 84 (7 × 12) and in Potentilla to 112 (7 × 16). In the Prunus branch of the family, including the almonds, peaches, plums, and cherries, the basic number is 8—probably 7 + 1—running up to 176 (8 × 22) in the cherry laurel. When we come to the Pomoidae, which includes the hawthorn, quince, medlar, service, crab, apple, pear, white beam, mountain ash, etc., we find the curious number 17. Work by Darlington and Moffett showed, however, that this has arisen from the ancestral 7-chromosome type, since in their cytological preparations they found four of the chromosomes represented four times and three represented six times, so the number 17 appears to have arisen by polyploidy accompanied by the duplication of three more of the chromosomes. It is probable that the exaggeration of the fruit and the woody habit compared with the rest of the family is due to the duplicate action of the genes in the extra chromosomes.

The whole question of evolution takes on an entirely new aspect in the light of these researches. It is no longer a question of wild surmises, but the methods of its progression can be followed and checked by controlled experiment.

CHAPTER VI

MICROSCOPIC LIFE

CHARLES DARWIN'S work aroused an enormous enthusiasm for the study of evolution. Comparative anatomy, whereby animal relationships were discovered by careful study of their relative structures, soon provided a mass of evidence of the progress of evolution, accompanied and linked as it was with equally intensive studies of fossil remains. These remains are often very fragmentary and scattered, but in some cases, such as the horse and the elephant, a strikingly complete record exists, stretching back into remote ages and giving striking proof of the gradual evolution of the particular creature in question.

Plant remains, too, showed the same orderly sequence of change; and as older and older rocks were examined for fossils, it was found that the types of animals and plants became more and more primitive and smaller and smaller, until finally the only representatives of living things are so small that only the most elementary remains can be observed. Obviously, more minute creatures still could leave no fossil remains at all, as there must be some fairly solid type of structure to leave any impression behind. But arguing from the analogy of life today, it is evident that the earliest living creatures on this planet were microscopic uni-cellular and pre-cellular organisms.

As microscopes improved, cytologists studied not only the cells of the higher animals and plants but also the vast world of creatures which consist of only one cell or a very few cells, or even less than a cell, which are quite beyond our normal perception and, being out of sight, are usually quite out of mind unless we unfortunately encounter them in the shape of some germ causing disease.

It is a rather startling thought that all around us is another vast world of beings which carry on their lives in the soil, in water, and in the air without our normally being conscious of their existence. But take a drop of pond-water and put it under the microscope, and we enter into a new and enthralling world. These microscopical creatures may be very complex; and in spite of the fact that they may consist of only a single cell, they often show the most surprising structural complexities, forming the most beautiful shapes, sometimes with rays and filaments, which add still further to their loveliness.

From these more elaborate one-celled creatures, as complex internally as the cells of many animals and plants, with nucleus and chromosomes complete (and some with an enormous number of chromosomes), there is every grade down to minute types in which there is no nucleus and very little differentiation, but various staining bodies within them point to the probability that there are genes present existing in a free state without the linking mechanism of the chromosome. Some of these unicellular creatures behave as animals, preying on other creatures, while others behave as plants, being able to synthesize food for themselves from their surroundings. In between are others which are claimed now by zoologists and now by botanists, and about which there have been quite heated discussions; indeed, it is said that some behave as plants by day and as animals by night.

But this is quite high up in the microscopic world. Below them is all the vast world of the bacteria which are always present everywhere, some causing us much discomfort by producing diseases, others making life possible for us by their beneficent action—such as those in the soil which fit it for the growth of higher plants and, through them, of the higher animals, including ourselves.

More minute still are all the viruses, or "filter-passers" as they were originally called, since they are so small that they pass through the finest filters and are quite beyond the range of ordinary microscopes. Consequently they long defied the efforts of biologists to study them. Only by their actions could they be followed, and these were certainly serious enough, since they produce many of the most obstinate and dangerous diseases in animals and plants. Small-pox, typhus, yellow fever, measles, and influenza in Man; foot-and-mouth disease in cattle and pigs; mosaic and other diseases in potatoes, tomatoes, tobacco, and other plants are a few of the better-known diseases caused by these viruses. The "breaking" of colour in tulips is also due to virus infection, as are many other cases of variegation of different plants.

In 1935–36 F. P. Bawden and N. W. Pirie in England and W. M. Stanley in America showed plant viruses upon which they were working to be nucleo-protein molecules, so bringing them very near to the genes in their make-up; as such they may be regarded as the link on the borderland between life and what is normally termed "matter." These complex virus protein molecules, like the genes, have the power to grow and reproduce themselves and to mutate. Taking the gene as the origin and basis of heredity and evolution in living organisms, one can only surmise that they, too, at the beginning, were free living entities which gradually, by congregating together and achieving food storage and protective coverings, gave rise to the most primitive types of cell life, which in their turn formed colonies, and finally the complex bodies of animals and plants, always attaining greater complexity and variation by mutations and recombinations.

That this evolutionary process actually occurred is demonstrated in the story of the rocks. Sometimes evolution proceeded along the wrong track, as when, in the great dinosaurs, body size was increased beyond all bounds of comfortable transport and adequate nutrition, while the brains remained so small that the creatures fell an easy prey in the end to the superior brains and greater agility of the small mammals which were just starting out on their eventual conquest of the world. Even in Man, the prehistoric type known as Neanderthal Man also succumbed from an over-specialization which rendered him less fitted to survive than the type which evolved into *Homo sapiens*—Modern Man.

Quite apart from their evolutionary significance, the study of these borderland forms of life is of immense importance in the understanding of heredity. Since the viruses are of the nature of free genes, their behaviour must be similar to that of the genes, and it is obviously much easier to deal with the reactions and to diagnose the structure of an unattached gene than to work with the genes which are strung up in a chromosome and subject to the interactions, not only of the other genes, but also of the other cell contents. In the viruses we arrive on the dim boundary between the " living " and the " non-living ". The capacity for growth and reproduction in these borderland entities is usually considered as the distinction between living molecules and molecules of matter, which (although proving themselves to be composed of extremely lively atomic contents according to the latest discoveries in physics) have not this power of perpetually increasing themselves. But here, too, there seems to be every intermediate condition, in this case between growth and non-growth.

Until the recent invention of the electron microscope (which has enormously enlarged our range of vision down to molecular levels very much as the construction of the giant telescopes has extended our knowledge of the stars and nebulæ), it was not possible to see the viruses, but now some excellent photographs have been taken of them showing the crystalline structures formed by them with the component virus molecules. In 1949 D. C. Pease and R. F. Baker were able to see within the chromosome small bodies of about the same size as virus molecules, which they believe to be the actual genes themselves—a great triumph after fifty years of experiment on their behaviour without the power to observe them physically.

The more complex viruses have other additions, such as fats and carbohydrates. While the genes are permanently attached to their particular organism, and are indeed an integral and essential part of its composition, the viruses are free-living in the bodies of their hosts. They are not part of the normal make-up of a creature, and gain admittance by means of the air, water, or quite frequently by the bite of an insect. Once inside, they behave as do the genes, growing and reproducing themselves, but increasing with a far greater rapidity than the genes, harnessed as these are to the general cell and chromosome metabolism. Obviously, the presence of these foreign proteins or viruses is extremely upsetting to the normal working of the cells, and all sorts of complications arise. If the virus is of a really dangerous type and the attack is severe, the host dies. If the attack is less severe, *antibodies* are produced by the cells which fight against or neutralize the virus and, by their presence, produce a greater or lesser immunity for the future. In some cases a state of equilibrium exists in which a virus can persist in a plant for generation after generation without any real physical harm, but producing certain abnormalities, such as the streaking in the lovely Dutch tulips in the famous flower-paintings of the seventeenth century which still persists in the tulips of today, carried on from bulb to bulb.

Quite frequently a host may be infected by more than one virus, in which case they either live in neutral harmony together, or they may interact with one another as do the genes, producing a combined result. More useful for us, however, is the condition where, if they are related, a milder type may starve out the more dangerous one by exhausting the common food supply, or it may stimulate the host cells to produce antibodies to protect itself. It is on this principle that most vaccinations can be worked.

One of the most interesting things about the viruses, however, is that they mutate or change just in the same way as the genes do, which obviously provides the opportunity to study mutation at its lowest level. In those viruses which have been intensively studied, many fully tested strains have arisen—fifty have occurred in the tobacco mosaic alone—in the same way as the numerous gene mutations have arisen in the Drosophila cultures, each giving a different reaction in the host.

Between the viruses and the one-celled organisms lie the bacteria, which, although much more complex than the viruses and obviously aggregations of genes, have still not achieved definite cellular structure, though they are able to associate together in chains. They also show variation by mutation, and since they are within the range of an ordinary microscope, it has been possible to follow these variations visually as well as by their reactions. Actually this capacity for mutation in the lower organisms can be extremely disconcerting. Not only do comparatively harmless types suddenly assume an alarming virulence, as in the *Verticillium* of the Kentish hop-gardens, which, after being comparatively innocuous, suddenly produced a danger type some twenty years ago, but when a cure has at last been found, a mutation will arise which cares nothing for it, and so one has to begin all over again to find another cure.

Only the fringe has been touched as yet in the study of these multitudinous organisms and their reactions to each other, the higher organisms, and their environments. Since they are the cause of most of our diseases, upsetting in various ways the normal metabolism of our bodies, and so bringing about dangerous stoppages in essential reactions which may cause death, it is necessary that they should be more and more intensively studied. Perhaps the study of those which are helpful and necessary is even more important. Our soils are teeming with microscopical life of all kinds; thus it has been estimated that there may be as much as four tons of bacteria in one acre, together with enormous quantities of other types, all competing with and reacting on each other in the most intricate manner—indeed, one may regard the soil as a vast living system in which all the parts are free but interacting. By means of enzymes (ferments) which they secrete they are able to break down dead organic material and complex molecules in or on the soil, primarily for their own food, but ultimately fitting it again for the use of the higher plants which are unable to make use of it themselves. And so the cycle goes on; nothing is wasted, everything is brought back into life again. An enormous amount of work has been done on these organisms, since they are so all-important to agricultural science, but the whole thing is so vast it takes a long time to work out even one small problem. During these utilitarian researches much is bound to come to light concerning the behaviour of these lowest forms of life which may solve many problems in more complex forms, and it may also be possible to track some of the causes of mutation.

A considerable number of experiments have been made during the last twenty-five years on inducing mutations both in the smaller organisms and also in the higher animals and plants, and especially in Drosophila. One of the most frequent experiments has been the bombardment of the germ-cells with X and other rays, but various poisonous substances have also been tried and extremes of heat or cold. So far it is a very hit-and-miss affair in the higher organisms, since there are as yet no facilities whereby a particular gene or even a particular chromosome can be made the target, so that the whole gene complex is subjected to an equal dose. The rate of gene mutation is very much increased by this means, which also causes considerable havoc among the chromosomes, resulting in breakages and reassortment of parts as well as delayed cell divisions which give rise to polyploid cells. In fact, the same variations occur which arise naturally, but much more frequently, and there has been considerable speculation as to whether mutations, either genic or chromosomal, may arise in Nature from the bombardment of cosmic rays upon the earth, by the sudden onset of extremes of temperature, or even by an accidental meeting with some poisonous substance.

Methods have still to be perfected whereby biologists can penetrate to these fundamental units of life. Each year new techniques are devised giving greater powers to the experimenters, but it will be a long time before really positive knowledge can be gained, since one has to get down to molecular levels to make an adequate examination and answer the question how some molecules are able to reproduce, and so build up through the ages the great superstructure of life upon this planet. Much will be done as quickly as possible, for not until the viruses and bacteria which cause our diseases have been fully studied can they be held in check. That they can be entirely eradicated is doubtful, since by their mutations they are able to get round our precautions and reinstate themselves with all their old virulence.

None the less, there are ways of setting a thief to catch a thief which have scarcely been tried yet. Certain of the smallest types of living things are known as *bacteriophages*, since they feed on bacteria. If these could be regulated so that they could be put on to the task of eliminating harmful bacteria, it should prove the best cure yet, though up to the present experiments have not proved very successful. Going higher up the scale, bacteria have been found in some tropical soils which produce a substance that kills fungi, and many fungoid diseases in the soil might be got rid of in this way. Other bacteria produce other substances which will destroy or neutralize various organisms. We already have our selective weed-killers, and if this principle could be extended down the scale we might be able to get rid of a great part of the diseases and pests which devastate our crops, without running the risk of destroying the good things also—as when, by using certain sprays, we kill some destructive pests but at the same time make our flowers poisonous to bees which should be fertilizing them to produce a good crop.

CHAPTER VII

COMPLEXITIES OF THE CELL

JUST as the unicellular creatures show all sorts of complexities in their make-up, so the cells which form the bodies of animals and plants contain many different elements. The study of the contents of individual cells is extremely difficult and needs refinements of technique which have not yet been fully developed, but it probably holds the best hope for the future progress of biology.

There are many vital questions regarding a cell. The primary one is, What are its actual contents? And then, How do the contents react within the cell, with neighbouring cells, and with regard to the whole organism?

To understand something more of the functions of cells we must think of their evolution. There are all degrees of cellular complexity and cellular co-operation. Just as there appears to be every stage from free genes up to the most complicated gene-arrangements in large chromosome complexes, so there are all degrees of cell organization, from the most primitive unicellular organisms up to the extreme cell specialization present in the organs of the higher animals.

The organization of the chromosome, which one may regard as a kind of super-molecule, was a great step. It enabled genes to work together, and provided them with a mechanism of accurate division without loss. By mutations, duplications, inversions, and all the other changes that took place from time to time, ever more and more complex forms evolved, and their coverings became also more elaborate.

Presumably the primitive unicellular organisms went on perpetually growing and dividing, mutating, and then growing and dividing again, until many different strains arose. Eventually as they became more complex a new factor entered into their behaviour—the evolution of sex. At any rate, this appears to be so today. Sometimes two cells actually fuse, sometimes they merely lie side by side with an exchange of material. In either case there has been a redistribution of the genes they contain, and also of any mutations which may be present. The mechanism of sex has been one of the most potent factors in evolution, for only by the bringing together of two cells in this way can all the mutations occurring in scattered organisms be united and continually shuffled and re-shuffled, so building up more and more complex forms with greater capacity for varied reactions. In fact, the evolution of sex has gone hand-in-hand with the evolution of all living creatures throughout the ages, and without this co-operation there could not have been such a diversity of life.

As great a step as the evolution of the chromosome was the evolution of cell colonies. How this came about in the beginning is an open question, since various different types of elementary cell colonies exist in the world today. In some cases they are apparently formed by the unicellular organisms failing to separate after divisions; in others one enormous cell, showing considerable structural characters, may contain several nuclei with no cell walls between them. At first these colonies are merely a collection of free cells, each cell living for itself; but as we move up the scale the necessity of getting food and of getting rid of waste products as the colonies become bigger causes the gradual specialization of groups of cells to cope with the various functions, until in the higher animals we see it in its greatest degree, with all the different organs of the body—the heart, the liver, the kidney, the eye, the brain, and so on—each with its entirely specialized function, each entirely dependent on the healthy co-operation of the others, so that if one defaults they all suffer and probably die.

As the organisms become more advanced, so also the gene and chromosome complexes and the sexual behaviour become more complicated. From the fusion of like cells in the lower unicellular creatures we gradually get a differentiation of the sexes, male and female, depending (as we have seen) on their possessing different gene complexes. But although many sex-inherited genes depend on the XY chromosome mechanism, it is the balance of all the chromosomes and genes together which goes to make up the complete animal, male or female; and if this balance is upset in any way we may get intersexes, or reversals to the opposite sex, or supersexes, as has been shown in the Drosophila and other experiments, especially with poultry. The whole question is extremely complex, and indeed it would take volumes to give an outline of all the deviations which occur throughout the animal and plant kingdoms.

Normally the higher plants are what are termed *hermaphrodites*—that is to say, both sexes are in one plant, the pollen and egg-cells each being produced in the same flower. In other plants, like the hazel with its male catkins and little red female flowers, or like maize with its cobs and tassels, there are distinct male and female flowers on the same plant; while in plants like the sallow or pussy-willow they are on entirely different individuals. Examination of the chromosomes shows that in plants the same mechanism is working as in animals where the sexes are separate.

There are, however, some cases in plants and a few in the lower animals where there is no sexual reproduction. The egg-cells arise without a reduction of their chromosomes, and are not fertilized, but form seeds or embryos which grow into replicas of the mother. In such cases the offspring are identical and are no more than buds of the mother, such as one gets in budding roses, growing potatoes from tubers, or planting the offset of bulbs. This means of reproduction, however, is likely to lead to a dead end, as there can be none of the recombinations of genes, so advantageous from the evolutionary point of view, which arise from the segregation of the genes when the chromosomes reduce in the parental germ-cells, and their re-shuffling by the coming together of the male and female cells at fertilization.

And the two cells having come together—what then? How does the new individual, with all its specialized characters, arise from that one minute cell? That is the great question, and it is taking all the resources of the cytologists, the embryologists, and, above all, the biochemists to solve it.

The formation of a new individual may be likened to the swarming of bees, each of which will have its own particular job to do, when they go out to build up a new hive to encircle their queen, whose work it will be to carry on the race. Only in this case the "bees" will meet another "swarm", probably carrying some variations in the art of building up a fitter body to shelter and feed the all-important germ-cells. But bees are large enough to watch in an observation hive; the observation of the genes is a very different matter. The geneticists are discovering how characters are inherited through the genes, and the physical location of the genes in the chromosomes; but how the genes actually work to bring about all the complex reactions that build up the bodies of animals and plants is a problem that requires for its solution techniques so intricate that it is only by utilizing the most recent discoveries in physics and chemistry that they can be devised. Gradually, however, a mass of evidence is being accumulated, and by correlation of results achieved by the different sciences involved there should eventually emerge more and more understanding of the problems of development.

The cytologists have been making for some time an extended study of the contents of cells, as viewed through the microscope, and each improvement of microscopical technique brings further knowledge. First and foremost of the cell contents is the nucleus, which, as we have seen, is made up of the chromosomes and their contained genes. Surrounding the nucleus is a mass of material, mostly composed of proteins, to which is given the general term *cytoplasm*; but contained within it are various entities of which little is known definitely, though many of them are the products of the normal metabolism of the cell. Much work is being done on these cell inclusions, but their microscopic proportions makes it a difficult task even with the most modern appliances.

The most striking inclusions in plant cells are the *plastids*—i.e., rounded bodies which have the power to synthesize starch under the influence of the sun's rays and provide the chlorophyll and other pigments. These are also self-multiplying, and contain a certain amount of nucleic acid, which plays such an important part within the nucleus. For some time the maternal inheritance of leaf-colour in some normally sexual plants has led to the belief that this must be due to plastids in the maternal cytoplasm of the egg-cells, and that they are therefore carrying heritable characters themselves—though other experiments prove that they are also controlled by normal chromosomal genes. Later work seems to point to the fact that plastid inheritance is under dual control—partly from normal genes, and partly from entities within themselves which have been termed *plastogenes*, since they appear to have the same power to mutate as normal genes.

Similar bodies are also believed to be present in the cytoplasm itself, and these have been termed *plasmagenes*. They, too, are inherited, but in direct proportion to the amount of cytoplasm contributed by either parent; and since in the majority of cases the male cells carry little or no cytoplasm, all cytoplasmic inheritance is bound to be largely maternal. These plasmagenes appear to be created by a nuclear gene in the first instance, but once released they can go on indefinitely reproducing as free entities and can be inherited through the cytoplasm, though if anything occurs to upset their equilibrium or to destroy them they cannot make a fresh start without the intervention of the nuclear gene. In this way they differ from the virus particles, which are not dependent on hereditary transmission but can wander from host to host by infection. Furthermore, the plastogenes and plasmagenes, like the nuclear genes, are part and parcel of the hereditary make-up of the organism, and therefore must conform to its requirements, or they and it will come to grief; whereas the viruses are able to travel from organism to organism, and the downfall of a host does not mean their own end. On the other hand, some viruses, such as those which cause "breaking" in tulips, are very near to the plasmagenes in their action, persisting in the cells of the tulips without any detrimental effect for hundreds of years, and giving rise, in the breaking up of the colours, to effects similar to those caused by some of the plastogene and plasmagene reactions.

To sum up, we find that there are various genic entities within the cell, but it is only those whose behaviour is entirely organized which are the truly fundamental units of normal development and inheritance. The genes in the chromosomes are safely carried through from generation to generation, performing their work of controlled growth and development, and on them depends the orderly procession of life. The free genes in the cytoplasm have no such orderly sequence. So long as they are hereditary or due to genic action they are not normally harmful to the health of the organism, since their own continuance depends on it, though they often cause various aberrations, such as variegation in colouring. But when they are free living, as in the case of the viruses, they do not conform to the laws of the organism they infect, and (so far as at present observed) their action is generally harmful.

That there is a constant interaction between the nucleus and the cytoplasm is evident: the one depends on the other. The cytoplasm must always provide the necessary food for the gene protein molecules to grow and reproduce themselves, while the genes must provide all the complicated interactions of development. Together they form that complex entity, the cell. For the past twenty years the biochemists have been making experiments on the ultimate chemistry of the cell, with ever-increasing success. Their discoveries of vitamins, enzymes, hormones, etc., have not only greatly benefited the health of the world, but have also given us an insight into how the genes may be exercising their extensive control throughout an organism. The hormones that are produced by the various glands have shown in particular the most far-reaching effects on development of various parts of the body. New techniques are constantly being evolved which give greater power of penetration into the behaviour and chemical constitution of the living cell. The new radioactive tracer elements, X-ray crystallography, ultra-violet and infra-red spectroscopy, and various micro-techniques, together with the electron microscope, are furnishing ever greater facilities for the exploration of the cell.

All experiments lead to one point, however—the complexity of the individual cell, and also what one may term the uniqueness of the cells of an individual, at least in the higher organisms, due to the immense range of variation possible in the presence of a large number of chromosomes and genes. A striking example of this arose during the Second World War, when it was found impossible to succeed with skin-grafts in the repair of skin burns, even if used from a near relative—which seems to show that just as each individual has a distinct fingerprint, so there is some unique protein combination in each individual skin.

The actual development of the organism as a whole has been much studied by the embryologists, who have done a good deal to unravel the mysteries of growth and the differentiation of the various parts of a body, but they, too, still have far to go. The subject is too complex to deal with here, but many experiments show that there are definite stages of organization giving a controlled and orderly development of the various specialized areas of the body. Many grafting experiments have been carried out which have thrown much light on the periods when the definite organization of embryonic tissue sets in, and the effect or non-effect of tissues from different parts of the body upon one another.

Grafting in plants has long been a subject of much interest from a commercial point of view, since the majority of our fruit trees, roses, and various other garden forms, are grafted or budded on to stocks which provide them with stronger roots, and therefore a better food supply, than they can get from their own. More important, however, is the fact that they are such complex hybrids that they cannot come true from seed, and the only way to preserve all these fine varieties is to propagate them vegetatively. The fact that one can graft a piece of one plant on to the stem of another and confidently expect it to remain the same, is perhaps one of the greatest proofs of the constancy of the gene and chromosome complex, since shoots coming from below the graft are true to the characters of the stock, while those above are true to the scion or grafted portion. Rate of development and general health are certainly influenced by the stock, since it is the main source of nutriment. But the actual characters of the scion remain the same, or the nurserymen's catalogues with all their named varieties would make no sense at all. If we order a Cox's Orange Pippin apple or an American Pillar rose we expect them to be true to their variety, or we should not ask for them.

Nurserymen are always experimenting with new stocks to increase the development value, or to produce greater resistance to adverse climatic conditions. One of the most famous of these experimenting nurserymen was the Russian, I. V. Michurin, upon whose work Soviet genetics is now largely based. Working to provide new types of fruits for the very diverse and often adverse conditions in Russia, he made a special study of different kinds of stocks. Among other things, he found that although development always depends on the suitability of the stock, the actual characters were not affected unless the union took place at an exceptionally early stage of development—which points to the fact that plants may have organization levels, such as have been found in animals, unless under these conditions they have formed true graft hybrids. In spite of repeated experiments, so far other workers have failed to achieve any alteration.

Later Russian work with tomatoes has given rise to the claim that real hybrids can be formed by grafting, in the same way that they can be formed by sexual fusion of the germ-cells, producing segregating progeny. It seems likely, however, that this may have been due to heterozygosity in the parents.

Many curious results of grafting have arisen from time to time, one of the most famous being the garden graft hybrid, *Laburnum Adami*, raised in France in 1825 by shield-grafting *Cytisus purpureus* on to the common laburnum, and kept going ever since by ordinary grafting on laburnum stock. In this case the tissue of the two parents has grown up together, and appears normally to persist side by side, giving a hybrid effect. But every now and then one will break free from the other, and varying areas of the same tree will reappear as pure Cytisus or pure Laburnum, which gives quite a startling effect in a garden, where it is known as the purple laburnum.

In these grafting experiments lies a wide field of research which may be expected to yield some strange results, and until more has been done on these lines with many kinds of plants one cannot say what may happen.

CHAPTER VIII

THE IMPORTANCE OF THE ENVIRONMENT

Now that we have seen that the genes, working within a complex internal environment, are the all-important units of heredity, we may proceed to discover what part is played by the external environment of animals and plants. That it has much influence is obvious to anyone who has had any contact with living creatures; and since the genes are living entities requiring many things to supply their needs, they must have suitable surroundings if they are to carry on their normal reactions.

Every gardener knows that to ensure the best crops he must buy only the finest varieties of seed from a reputable seed merchant. They may be expensive, but in the long run they pay for themselves over and over again in the extra quantity and quality of their produce. But, having bought the seeds, it is not enough to depend on the potentialities within them. It is sheer waste to plant them in poor soil without manures or an adequate water supply: the parable of the sower could not be more apt. The seed-grower has done his part in producing good seeds containing the genes which will produce the characters required; now the gardener must do his part in providing adequate living conditions to allow those good qualities to manifest themselves. Adverse conditions, however, will not turn one variety into another: they will only affect development.

Furthermore, certain varieties are much more suited to one type of soil than others, which will prove much better on another soil, since they require different conditions for their full development. The wise seedsman stocks those varieties which he knows will do best in the area he is serving. Trial grounds are laid out all over the country to test the reactions of new varieties to the various types of soil, which may vary considerably within a quite small area; and breeders are always working to produce more suitable types for difficult soils. This can often be achieved by bringing in genes present in wild species which may be found growing under similar adverse conditions. The Russian geneticist, N. I. Vavilov, collected species and varieties from all over the world to produce types fitted to the very varied conditions of his own country. Michurin, too, worked on the same lines.

Temperature also has a great effect on development, each organism being most delicately adjusted in this respect. If plants are used to warmer climates than our own they are dubbed "half-hardy" for the less extreme forms, or "greenhouse plants" for tropical plants, and no one would expect them to survive our chilly and damp winters out of doors, though we know they thrive exceedingly in their own countries. In other words, Darwin's "Natural Selection" is always at work, eliminating all those forms which are not fitted for the environment in which they find themselves.

Side by side with Darwinism grew up a rival theory known as Lamarckism, after the French naturalist Lamarck, whose views were similar to those of his contemporary Erasmus Darwin, Charles Darwin's grandfather. Charles Darwin himself postulated what we now know to be true from genetical experiments, that organisms are continually varying in all directions and the new varieties have persisted or otherwise according to whether they were fitted or not fitted to their environment. Lamarck, on the other hand, believed that things worked in the opposite direction, that variations arose in response to the environment. When a change in living conditions arose, the organism was able to adapt itself to the new conditions by acquiring new characters, which would then be inherited by its offspring.

The earlier geneticists were much opposed to the then still numerous Lamarckians, for all their work on inheritance showed that only gene mutations could reappear in the offspring. It is true that one can put plants into different environments, thus causing them to become larger or smaller or to show physiological difference. But the change is not inherited. Return the progeny to the normal habitat, and they develop in the same way as the originals. Many experiments were tried, but always with the same result, that the genes controlled the characters and that they could mutate in any way, either within themselves or in blocks within the chromosome.

However, these gene mutations do give rise to a condition which can be regarded as almost Lamarckian. In a great number of cases the mutations which occur are definitely harmful, and when, by segregation, they come together in a pure state they cause the death of the individual either in the initial stages, as in the pure yellow mice (page 36), or in later stages. This is easily understandable, for the gene–character–environment complex is a very stable unit absolutely adapted to work as a whole. If any change occurs, especially in a gene controlling some far-reaching physiological character, then the whole balance is upset, between the genes themselves, in the working of the organism, and in its adaptation to the environment.

But there are many recessive mutations which can persist indefinitely in a heterozygous condition—that is, in individuals carrying the normal gene plus the mutation —since the normal dominant gene is strong enough to outweigh the disadvantages of the recessive mutation. Since the same gene will often mutate periodically in the same way, a large number of these concealed mutants can accumulate over a period of time in any population, spreading quite widely by outbreeding and segregation. So long as conditions remain unchanged these permanent heterozygotes will continue, but if for any reason the environment should alter or the species wander into another environment, it often happens that the mutant, instead of being a dead weight, becomes an asset, fitting the organism better for the new conditions. The hitherto lethal homozygotes of the mutant now become the best fitted for the new environment, while the normal type is less fitted, and so likely to die out itself, and is replaced by the mutant form which was lethal under the old conditions.

In a large population of any plant or animal, mutations are often occurring—only rarely in any individual gene, but throughout the whole gene complex a considerable number will occur, taking all the genes together. In this way large numbers of individuals arise which are heterozygous for various characters, and so carry, within the species, quite a wide potentiality to fit themselves to changing conditions. Since through the long ages that living creatures have inhabited the earth conditions have always been slowly changing, this flexibility of the various species, through the carrying of mutant genes in a heterozygous condition, has been a very important factor in evolution.

It was largely due to this permanently heterozygous condition that the old breeders were able to improve their stocks and to raise so many different varieties of animals and plants. It has already been seen (page 26) that all the colours and patterns of fancy rabbits are due to mutant genes occurring from the wild type, and that in a state of nature these would not persist (although they occur, as anyone conversant with rabbit burrows can observe) unless conditions change, so as to make the variety advantageous, as is the case with Arctic and Mountain hares, in which white fur is the safer colour.

It was for a long time held against the early geneticists that they were working with characters which have no survival value, and the same may be said of the breeders of fancy strains of dogs and birds. When wild animals came to be observed more closely, however, it was realized that there is an enormous range of survival values, and the larger the number of mutant genes existing in an apparently useless heterozygous state within a species, the greater its ability to spread and to survive in a number of situations. Many cases have been worked out in wild species with most interesting results.

A striking example of the difference in the value of a character under different conditions may be observed in the frizzle fowl. This is a breed showing a mutation in which the feathers are turned up, and so no longer fulfil their normal function of keeping the animal warm. It is almost impossible to keep these birds alive in our climate, since they die from cold, but in hot countries they flourish and are quite a common breed. Presumably the frizzle character is much more comfortable in the heat than the normal close feathering, and what is lethal here is a distinct advantage under other conditions.

Under domestication many mutations which could not persist under natural conditions are preserved and increased because they are of use to Man, and since Man's control over Nature is ever increasing, Man's selection is becoming as potent a factor as natural selection over wide areas. To take another poultry example as an extreme case: the breeders have now raised pedigree stocks which, by the genetical combination of desirable factors, are capable of laying an enormous number of high-grade eggs without becoming broody. In a wild state this would certainly be a lethal condition, since no eggs would be hatched out to carry on the breed, unless they could come to some cuckoo type of arrangement with other birds. But with modern incubators and rearers this is of no importance, and the breeds increase under Man's control.

So in all populations, wild or domestic, we find this condition of underlying heterozygosity with many concealed mutant genes giving immense possibilities of variation in times of necessity. It also explains the popular idea that inbreeding is dangerous, for if a stock is carrying several disadvantageous genes, they will be brought together, with disastrous results, whereas so long as they are outbred there is not so much danger of their meeting. On the other hand, if a stock has none of these deleterious genes there is no danger, and in some cases it may be a positive advantage. Humans are no exception to the rule, and most populations carry a number of these heterozygous genes. Since Man has forty-eight chromosomes containing a very complex assemblage of genes, there is the possibility of a very wide range of variation, providing him with remarkable and unique powers of adaptation to every kind of terrestrial conditions. This is in some measure due to his ability to protect himself against the external environment by clothes, shelter, etc., but even so he shows a surprising facility for withstanding every condition, from arctic cold to tropical heat, sometimes passing from one to the other in a matter of a few hours in these days of quick air travel. His power to change his environment, and his very varied feeding habits, also further the protection and spread of mutations.

Not only do gene mutations give rise to this facility for adaptation, but chromosome mutations also have the same effect. Where duplications of sections of chromosomes and other aberrations occur, there are further opportunities for a breadth of variation if need arises. The greatest possibility of variation, however, exists within the polyploids—those individuals or species which possess more than the normal two sets of chromosomes in their body-cells. Many wild species appear to have arisen from the sterile hybrids between two original species which have become fertile by a duplication of their chromosomes (page 58). These species are obviously in a very different condition from an ordinary diploid. They have two or more complete chromosome complexes containing all the various genes of the original species. Since each of the original species had its complete set of genes controlling its development, there are now several more genes in control of each character. Sometimes these genes have a cumulative effect, as in certain characters in wheats (which have six sets of chromosomes instead of the normal two) where the Mendelian ratios depended on the relative combinations of the dominant and recessive genes. In a cross between red-grained and white-grained varieties one can get all combinations in later generations between six red genes and six white genes, the intermediates being lighter in colour in relation to the number of white genes present.

Most cases are not nearly so simple, however, the genes not being so similar; in which case the gene of one complex may dominate that of another. But very little work has been done as yet to disentangle the exact relationships of these multiple effects, not only of the genes themselves, but of all the complex inter-reactions which must take place under such conditions. Studies of individual plants of polyploid roses seem to show that they can react to differing conditions from year to year within the same individual, but years of careful observation would be needed to substantiate this. In Hurst's polyploid rose species hybrids, now growing in the R.H.S. gardens at Wisley, one may in some cases observe different gene manifestations in the same character scattered through the plant.

It is perhaps interesting to point out here that Michurin's work in Russia, upon which the new Soviet genetics—a form of Lamarckism—is based, was largely with complex fruit hybrids, principally apples, which are also polyploid (page 62). He, too, found that they gave varied reactions under differing conditions. Both he and Lysenko, who has worked much with polyploid wheats, stress the importance of hybridizing and crossing to make the organism as unstable as possible towards its environment, so that it can vary in any direction required. As Michurin points out in his papers, since the parentage of most of his varieties was unknown and it would take too long to test such slow-growing trees, Mendelism could not be applied. Without genetic control one can only revert to the methods of the old breeders.

Michurin also elaborated the "mentor" method, in which he grafted cuttings from an old, heavily fruiting variety on to a new poorly fruiting one, thereby causing it to become extremely fruitful. He claimed that fruiting was hastened by this means, and other deviations were winter-keeping qualities, improved colouring, and sugar content. He believed this to be due to the production of hormones in the grafted shoots affecting growth and development in the main tree, which would be akin to our own treatment of plants with auxin, the hormone controlling growth which is produced by the growing tips of plants. It is now possible to synthesize auxin in the laboratories from various sources such as yeasts, certain fungi and bacteria, and from the wheat-germ. It forms a very useful treatment for hastening the growth of cuttings and seeds and preventing the dropping of fruits. In America orchards are now regularly sprayed with auxin preparations for the latter reason. More spectacular is the production of seedless fruits by substituting auxin for pollen, which contains a large amount of this hormone normally stimulating the fruit to grow round the fertilized seeds.

Whatever their reactions may be at any given time, the potentialities of polyploids in evolutionary time are infinitely greater than those of the diploids, for, in addition to the wide range of reactions possible in the multiple gene complex, the possibility of mutation is also increased in proportion to the number of genes present. It is probably significant that many of the polyploid plant species tend to be located in the less favourable environments where extremes of temperature or humidity occur which might be expected to eliminate less adaptable species. In the wild-rose species, for instance, in which one finds diploids, tetraploids, pentaploids, hexaploids, and octoploids (page 61), the majority of the diploid species are found in the south temperate localities, while the polyploids tend to have a northerly or mountain distribution, especially the octoploids, which are for the most part found in the far north.

A great number of the higher plant genera have numerous polyploid species, and it seems as if these proved themselves more capable of populating the more difficult localities which occur from time to time. During the retreat of the ice after the great Ice Ages an ever-increasing habitation space became available, but it was a very exacting environment, which could be filled only by species of an extreme flexibility. Such were the polyploids, and they took their chance, resulting in some of the large polyploid plant populations of today. Climatic conditions probably contributed to their formation in the first place by retarding cell divisions and so giving rise to polyploid germ-cells.

In animals polyploidy is rare, owing to the very great difficulties of propagation. In a plant, polyploid tissue will provide male and female germ-cells which can self-fertilize, but in the normal animal in which the sexes are separate there is little chance of two polyploid germ-cells meeting, and the condition usually disappears rapidly —though in controlled Drosophila cultures they have arisen from time to time.

In some cases, species have become so adapted to a settled environment and have accumulated so few gene variations that when a change does come they are not flexible enough to respond to it, and become extinct. In this way many dead ends have occurred in the evolutionary sequence—blind alleys from which the unfortunates involved have had no escape. This is particularly true of isolated communities where continual inbreeding must occur, for in this case the mutations which persist and make for variability in an outbreeding system get lost by their continual meeting in related individuals, since in a pure state they are so often lethal until conditions make them advantageous. That life as we know it exists in other parts of the universe is more than likely, given similar conditions. That it should be identical is not very probable; indeed, widely differing forms of "life" might evolve to fit the extremely divergent environments of planets in this or other solar systems. Even on our own globe it is now known that there are various organisms which can exist under temperatures and conditions previously believed to be completely inimical to all life.

As Man spreads his influence farther and farther over the face of the earth, the environment becomes increasingly under his control. Vast tracts of land have been brought under cultivation, some profitably, others wastefully, creating man-made deserts. The whole trend of modern agriculture is to study the production of ideal environments for crops and animals, and, conversely, to produce plants and animals capable of withstanding the uncontrollable difficulties of latitude and weather. Barren lands have been made profitable by starting with crops which will enrich the soil, either alone or in conjunction with animal-rearing which will, by good husbandry, gradually produce optimum "living soil" conditions for the major food-producing plants and animals.

By careful genetical research, involving the discovery of valuable genes in wild populations and incorporating them in domesticated types, it is now possible to go a long way towards producing disease-proof races capable of giving a maximum crop under conditions previously considered impossible. The chief difficulty now lies in securing sufficient political unity to ensure that the surplus of one country may supply the need of another. Science can produce the food, but the problems of efficient control of production, transport, and distribution, still remain.

CHAPTER IX

HUMAN GENETICS

MAN, being an animal, conforms to the same laws as the other living creatures on this planet. One of the most surprising results of the study of Genetics is the discovery that the same mechanism of inheritance holds good throughout all life, whether plant or animal. Obviously it is extremely efficient, providing an absolutely sound reproduction system from one generation to another, coupled with the variation produced by the occasional gene or chromosome mutations to give the necessary flexibility to react favourably to the changing environments of geological time.

Starting with the free genes we can recognize an ever-increasing complexity; the evolution of the single cell, the increasing specialization of cell colonies, up to the production of the very highly developed animal and plant types of today until we come to its highest expression in Man himself.

Not only do we find all these variations from the simple to the complex in the world today but, going backwards in time through the rocks, we find fossil proof of the extremely primitive condition of the earliest forms of life upon which has gradually been built up the imposing variation of today. The very earliest forms of life it is not possible to see, since no creatures of the order of the free genes or viruses could leave any trace behind. But perhaps some of the newer microscopical techniques may be able to discover some of the results of their actions on the ancient rocks.

Traces of the earliest life so far found are in rocks dating back some six hundred million years, but these are already relatively complex, minute animal and plant remains which must have had a considerable evolutionary history behind them. The first really abundant remains are in the rocks dating from some five hundred million years ago—remains of algae, worms, and trilobites.

Complexities of organization gradually increase as one moves upwards through the rock layers. Animal structure becomes based on the backbone, which gives a far greater possibility of free growth and development, providing not only a necessary rigidity but also, with its accessory bones, protection for the internal organs, as well as flexibility of movement. Primitive fishes occur in considerable numbers as time goes on, always increasing in development and organization. During the long ages of the Carboniferous Period, when the coal measures were laid down, some three to four hundred million years ago, reptiles begin to appear, from which were to branch off the varied land animals of the vast future—the birds, the mammals, and finally Man.

Compared with the great age of life as a whole on the planet, Man is an extremely recent production. Stretching along the wall of one of the galleries in the Haslemere museum is a lay-out, showing the relative ages of the rocks. A single white tape at one end depicts graphically the very short span of Man's existence in comparison with that of other creatures. The earliest remains approaching our own type date back only some seven hundred and fifty thousand years, but relics of the early ancestors of ourselves and the apes may be referred to between fifty and sixty million years ago. Comparatively few examples of our forebears have been found so far, for Man was a somewhat rare animal, just as are the great apes today. Moreover, fossils are preserved only under rather unusual combinations of accidents which will ensure their continuance, and so only those creatures which occur in very large numbers may be expected to leave behind any great accumulation of remains. Recent work, however, has discovered several of the " missing links ", the search for which caused so much excitement at the turn of the century, and our knowledge of the gradual ascent of Man is rapidly increasing.

Several fortunate possessions enabled him to gain an ascendancy over all the other creatures. First and foremost was the enlargement of the brain, coupled with his distinctive powers of vision and correlated with the thumb–finger ability to hold and to use other objects. By his greater powers for thought—for memory of the past and forethought for the future—he was able to outwit the other animals and, as this power gradually evolved to greater heights, he was able to take other forms of life for his own use by the domestication of animals and plants. More and more has he come into the control of his environment, and today we see him mastering one force of nature after another until the whole resources of the planet come under his control. Not content with this, his roving mind stretches out to the other planets and to the remotest recesses of the universe.

As an experimental animal, Man is a complete failure. The normal production of only one child at a birth, and the very long time which elapses between generations, are sufficient stumbling-blocks in themselves, but coupled with these is the impossibility of putting any direct control on his breeding. On the other hand, we have a long and accurate account of his history, stretching back for a considerable time, and of no other animal have we such reliable information covering such a length of time.

To take a trivial character, the famous Hapsburg Lip (a projection of the lower lip) can be traced by means of portraits through all the royal families of Europe, connected with the Hapsburgs, over a considerable period, and the familiar accounts of distinguished people will usually give a description of any peculiarities they may have possessed. The importance of disease, too, leads to compilations of information by medical people which has proved of great value and interest to geneticists investigating human inheritance.

Man's genetical structure is extremely complex, as one might well expect. Any creature which has so many chromosomes—forty-eight—must have accumulated a vast assemblage of genes, many of which will be in control of each character, providing all sorts of complications in their investigation. Only in a relatively simple organism like Drosophila, with its four pairs of chromosomes, is it possible to track out characters with any ease, but it is by comparison with these controlled experiments that one can fathom what is happening in the more complex organisms. In Man (as in rabbits, which have forty-four chromosomes) there are numerous genes in control of colour factors, of eyes, hair, and skin. This is apparent to all on looking at the variations which can occur in such a country as our own, with its very mixed population resulting from Celtic, Roman, Saxon, and Norman occupations and the constant influx of refugees through the centuries.

The only way to track the behaviour of inheritance in Man is by examining or making pedigree charts giving the occurrence of various characters through as many generations as possible. The first work on brown and blue eyes (page 38) was done in this manner by the close examination of the eyes of as many children, parents, and grandparents as possible in a village population. Here, owing to the intermarriage of local families, one can follow the tracks of the genes in a very useful manner, and in a rural population longevity and early marriages will often provide several living generations in one family. There is also the remembrance of dead ancestors which, although not absolutely reliable, can often give useful checks. At least an outstanding abnormality will be remembered and can be relied upon.

In Man, the two sexes being divided, the usual XY chromosome mechanism is present, the male being the heterozygous (XY) sex, which accounts for the fact that males show more infant and pre-natal mortality than females, since, if any recessive lethal mutation is present in the X chromosome, it cannot be covered by the normal dominant in the male, as the allelomorphic gene is not present in the Y. Such a character is the condition known as hæmophilia, in which the victims are lacking in the power of their blood to clot after an accident, so that without prompt medical aid, or even probably with it, they bleed to death even from a quite insignificant wound. This condition is carried by the female, and shows itself in half her sons but not in her daughters, unless she has made a very improbable marriage with a hæmophilous man. But half the daughters will be carrying it, and so can again pass it on to half their sons. In the case of the male, he hands on the gene to his daughters only, in a recessive condition, since his sons receive only the blameless Y from him.

Colour-blindness and various diseases and abnormalities also follow the same procedure, and since they arise again and again by mutation, it is impossible to get rid of them. In Man the study of the abnormal has been more prominent than that of the normal, for the simple reason that in many medical cases it is necessary to find out whether the disease is inherited, or whether it is due to infection or environment, before steps can be taken for its final cure or stamping out. Since the sex-linked genes are easier to locate and to follow by their unmasking in the X chromosome of the male, more complete knowledge of them was achieved in the beginning than of those genes situated in the other chromosomes which, through the normal outbreeding of Man, will only rarely come together and so show themselves, except in an isolated community where a certain amount of inbreeding must always occur. Compared with the inheritance of normal characters, that of abnormalities is surprisingly simple; they are usually due to the mutation of a single gene, and so one has only to deal with the normal or mutant condition occurring in the progeny instead of the complications arising from multi-gene control.

One of the most generally interesting facets of inheritance in Man has been the behaviour of the blood groups. The high incidence of loss of life from hæmorrhage in accidents or war led doctors to experiment on the transfusion of blood. The results were surprising. When they had developed their technique sufficiently to effect the transfusion successfully it was found that whereas in some cases it was a triumphant success, in others, for no apparent reason, it was a complete failure. The obvious answer was that the defect must lie within the blood itself: there must be some incompatibility between the blood of the donor and that of the recipient when the operation failed. As this was a matter of life and death, much work was done on it and is still being carried on. It was discovered that there are a number of different blood-groups which are inherited in the normal fashion. The most important may be termed A, B, and O (B and O being mutants of A and therefore allelomorphs to it), while two more allelomorphic genes, M and N, work independently, and a third, known as the rhesus factor, has proved to be very important indeed.

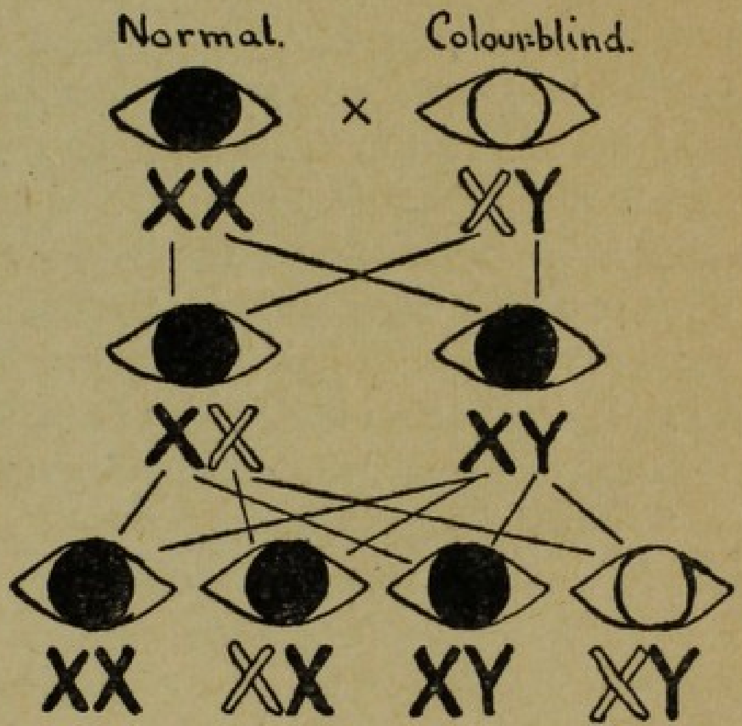

FIG. 6.—Colour-blindness in Man. A colour-blind man marrying a normal woman has normal sons and normal but heterozygous daughters. In the next generation normal males and females, heterozygous females and colour-blind males occur in equal numbers.

With so many genes involved there are numerous combinations, some of which work successfully together in a transfusion while others do not, causing the death of the recipient.

As soon as this was discovered, careful tests were taken of the blood of all donors and recipients, so that the right type could be administered, and this work certainly proved to be one of the greatest life-savers during the

Second World War. Many complications arise from this variation in blood-groups, especially in marriages between two different types, when the antagonism of the blood of the mother to the paternal element in the child may cause it to be stillborn or to suffer from severe anæmia if it survives birth. Now that the cause of this is known, it is possible to cure it by transfusions of a suitable blood.

The natural occurrence of blood-groups throughout the world throws many interesting lights on the evolution of human races. Since, so far, the factor B has not been found in the native American Indians, it is believed that it arose as a mutation in the Old World, where its incidence decreases towards the west, from 60 per cent of the population in India to only 10 per cent in Ireland. The occurrence of the different types can provide many clues as to human migrations and to the racial differences between men.

One of the most useful aspects of human genetics in elucidating the working of the genes lies in the study of identical twins, a peculiarity almost unique in sexual production. These occur by the accidental separation of the two cells arising from the first division of the fertilized egg-cell. Since they are what would normally produce the right and left sides of the body respectively, truly identical twins are usually the one right-handed, the other left-handed; for the rest they are alike in all other characteristics—barring any accidents during development. Here is the ideal material for testing out the relative importance of genic inheritance and the environment in development, since genetically they are identical, and any differences that they show must be due to environmental influences. In a number of cases identical twins have been separated at birth, so producing a different environment for each one; but in every case not only has the ordinary physical development corresponded, except for slight size deviations arising from differences in nutrition, but their mentality and also the development of heritable diseases have coincided. Unlike-twins, arising from the fertilization of two different egg-cells, are as different as ordinary brothers and sisters, since the normal gene segregation has occurred—in spite of the fact that they have been brought up constantly in the same environment from conception and throughout their life within the family.

In Man, however, a unique complication arises—the presence of another form of inheritance which is acquired but not inherited, though at times it is not easy to distinguish where this begins and normal heredity ends. Side by side with the evolution of mind and memory has gone the evolution of the means of communication between individuals, first of all by signs and sounds, and later by the symbols of writing. In this way a vast accumulation of knowledge of all kinds, practical and æsthetic, has been handed down through the ages, always gaining in quantity and quality. Although it may be regarded as Man's greatest inheritance, giving him the power to control all other inheritance if he so wills, it is not inherited in itself, but has to be more or less painfully acquired by each succeeding generation.

What *is* inherited, however, is the aptitude to acquire this superimposed inheritance. Babies, like all young animals, are born able to make a noise which, guided by their parents, gradually becomes articulate in a normal child. They are also born with or without other aptitudes, for mathematics, for science, for music, etc., which gives them the ability to profit by the accumulated knowledge of their forebears and to increase that knowledge themselves, passing it on to others in their turn, and so adding to the sum total of human achievement.

The study of mental heredity is extraordinarily difficult, entangled as it is with so many different considerations, but it would seem that many, if not most, of these aptitudes are recessive characters, as one would expect. Certain famous families have arisen from time to time, like the Darwin family in science and the Bach family in music, which by inbreeding, or outbreeding with families carrying the same aptitude, have given rise to many gifted individuals. But on the whole a genius is more likely to crop up suddenly in some comparatively mediocre family and to die leaving no progeny of his own magnitude. Again, the outbreeding of humans has brought together recessive genes, probably of a very complicated nature, which have been lost in the next generation by meeting the normal dominants.

Before the Second World War, Hurst formulated a theory, based on extended observations of a living population correlated with pedigrees of famous historical families, that there is a dominant gene for normality present in the average population, together with various cumulative genes giving, when freed from the dominant, various stages of ability corresponding roughly to the I.Q. (Intelligence Quotient) grades used in testing intelligence. These may be low, down to complete imbecility, or high, up to supreme brilliance, like the isolated cases of a Newton or a Leonardo da Vinci—in other words, "genius is akin to madness", and if the gene for the normal average is lost one may get a family producing the most varied grades of intelligence—as has frequently happened in various well-known families.

Obviously an enormous amount of work would have to be done in many different grades of society to substantiate this, since super-imposed on this general intelligence ability are all the specialized abilities which can run concurrently with it or isolated from it. We have all heard of the "village idiot" who yet has the power to compute numbers in the most amazing fashion, and the majority of people possess some special aptitude or interest, however mediocre their general intelligence. The greatest genius would then appear to be the one who possesses the greatest number of special aptitudes correlated with a very high overall general intelligence.

In any case, Man is particularly subject to his environment, culturally as well as physically, and although nothing can be done to improve an individual's gene complex, everything can be done to make the best of what he has. All modern ideas of feeding, clothing, housing, and education are based on this principle, to give everyone the facility for the fullest expression of his or her capabilities. It is not always easy to see what these are: some children are very late in developing or they may not have the opportunity to come into contact with their real bent. Many famous people have had a black school record and are notorious examples of this difficulty, which modern education is striving to rectify. Since each individual is unique by reason of the excessive complexity of the human gene-complex and the constant gene re-combinations by outbreeding, in many cases it is not easy to fathom what is the right course, and round pegs still often get pushed into square holes. But we are learning all the time, and by a closer study of the genetics of the human race much may be done in the future.

Whether controlled genetics should be applied to Man is a very debatable question. Who is to say what are the most desirable characters to breed for? Many of the most illustrious people in all walks of life have not been what one would regard as physically desirable; they have suffered from some abnormality or disease which would certainly have been avoided in breeding for physical excellence, but it has not deterred them from their work—indeed, in many cases it seems to have acted rather as a spur to their performances. Also it takes all sorts to make a world, and the present *laissez-faire* methods are probably infinitely more efficient in providing a st ady flow of very varied people suited for the multitudinous jobs necessary to preserve our very complicated structure of civilization. Indeed, in no other time has such variation been necessary, and one might be tempted to say that Man has been building and storing up all his inherent capacities for variation for just such a complex environment. It was only by reason of the great flexibility arising out of his numerous assortment of genes that he was able to rise to his present status, and in the future we may expect better types to arise by mutation and recombination, just as they have arisen in the past.

The fact that the speed of mutation is likely to be much accelerated by the indiscriminate use of atomic energy, just as it has been in controlled experiments with various types of radiation, has caused considerable alarm, for one has to remember that most mutations are harmful, upsetting the normal balance of the gene complex. On the other hand, the incidence of valuable mutations should also be stepped up, and by this means evolution might progress at a more rapid rate than heretofore in spite of the danger of an increased number of harmful genes lying dormant in a heterozygous condition. A secondary danger, in humans, lies, paradoxically, in the advance of medical science, which now has the power to keep alive individuals who in a natural condition would not survive, certainly not long enough to breed.

The whole idea of atomic energy is so new that no one has had time to fathom its implications. Like all epoch-making discoveries, it has spread fear, dissension, and unrest, and it is not until modern civilization has re-orientated its ideas of science, philosophy, and ethics in the light of this most recent development that we can expect it to become part of our normal outlook. Rightly used, like all scientific discovery, it can enrich man's life on this planet beyond all present conception; and that there is a strong will to see that this is done, and that its evil possibilities are overcome, is evident in all quarters. If pre-historic man could make fire his servant, it should not be beyond the power of modern man to chain atomic energy. Each new era has to face up to its own discoveries; the forces of nature are so mighty that their control must always present many problems.

CHAPTER X

MODERN GENETICS

AND so we come to Genetics today. It is not yet a hundred years since Darwin published his *Origin of Species*, and just over fifty years since the Mendelian principles came to light. It will be clear from what has been written above that although very much has been learnt there is still a mass of unexplored facts to be studied. The present is the most exciting time in the whole history of Science. The great strides made in physics and engineering are bringing new microscopes and techniques into use which reveal more and more of the worlds that lie beyond normal vision and confirm facts which previously could only be surmised through calculation and experiment. Ordinary language cannot even express the new concepts. The old ideas of " life " and " matter " have to be thrown overboard, and physical death is seen as the substitution of new forms of life. Everybody should be " microscopically educated " to a knowledge of the worlds within worlds, of the teeming life around and within us—passing down, through cells, chromosomes, genes, and molecules, to the whirling " life " of the atoms. Looking in the other direction through the new super-telescopes to the stars and nebulæ, all following the same laws, one must feel that there is a great unity throughout the universe—that there is no strict borderland between the stages from the infinitely small to the infinitely large, but that all are merged in one interlocking whole, whose workings are gradually unfolding before our startled eyes and senses and forcing upon us a new philosophy.

Genetics itself impinges upon all the sciences, since it deals with the fundamental units of life. As an evolutionist, the geneticist becomes involved with geology and geography. Only by a study of the rocks and their fossils in the past, and their deposition in the present in relation to mountains and seas, can he fathom the workings of evolution, the relation of the genes and their products to the environment, and the workings of natural selection. For the knowledge of how the genes work in development he must study the behaviour of the very lowest types of life and the chemistry of the cell and of the body as a whole, using the methods of the physicists when he gets down to the ultimate constituents of living matter. In his dealings with animals and plants he must have a good knowledge of zoology, botany, and agriculture. In human genetics he becomes interested in archæology and history, and his researches have a direct bearing upon medical science and psychology. He must be a good microscopist to enable him to study the workings of the chromosomes, and an expert breeder and husbandman in order to carry his living experiments to a successful fruition.

It will be clear that no one man can have more than a very general acquaintance with all these sciences; teamwork is necessary, and many great laboratories are given over to the study of the various aspects. All the same, the average geneticist has probably a broader outlook upon life than most other scientists, for he knows that all the sciences are, in the end, only branches of his own, and that it ill becomes him to disregard any of them.

Mathematics especially has become an essential part of his work. In dealing with the immense numbers involved recourse must be had to the most elaborate calculations in order to envisage the potentialities of inheritance and evolution. The science of Biometry under the brilliant leadership of R. A. Fisher and J. B. S. Haldane is now firmly linked with Genetics, and upon its followers devolves the onerous task of working out all those fine shades of inheritance that would be too irksome to prove by individual experiments—though these are carried on so far as is physically possible.

Especially in the study of the progress of evolution is biometry essential. It is obviously impossible to experiment with the creatures of bygone ages, but by biometrical calculations it can be estimated what rate of mutation would be necessary to produce the variation which built up all the diversity of living creatures and, by comparing this with the actual rate of mutation today, to get a picture of how evolution progressed.

Much of the disbelief of the early biometricians in Mendelism was due to the fact that they were dealing with characters which are now known to be controlled by a number of genes which, under the old idea of things, really did give the impression of a fusion of parental characters. We have seen (page 88) the effect of various doses of red and white in wheat; stature is a similar but much more difficult case—for the effect of environment will also give a bias to one side or another, resulting in an overlapping effect. Such "polygenic inheritance" frequently occurs, as we have seen, from various forms of gene duplication, and it is only by careful experiment correlated with mathematical analyses that such extremely complicated inheritance can be disentangled.

In some cases when working with a single pair of genes the dominance of one over the other is not complete; for instance, in the Four o'Clock, *Mirabilis jalapa*, if one crosses the red- with the white-flowered varieties the crossbreds are pink, but in the next generation they segregate out, one pure-breeding red to two impure-pink to one pure-breeding white, and so cannot be confused with the intermediate results one gets from the crossing of polygenic types.

Many economic characters are due to polygenic inheritance, which makes them much more difficult to analyse and control, and sometimes causes the practical farmer to look askance at the value of genetical breeding. It seems to be largely on these grounds that the new Soviet genetics has broken away from classical genetics, protesting that it takes too much time. However, once it is done it forms a sound basis for future work; and by reason of their high selection through a long period of time, most domesticated animals and plants are extremely complex in their genetical make-up. In horticulture, many of the plants now cultivated are comparatively recent introductions and, although they are rapidly achieving an alarming complexity, they are under Man's control, and it is by following the evolution of these new varieties, and even species, that he can understand what has happened in the past.

The sweet pea is one of the plants which has profited most by the copious experiments made on it by the earlier geneticists, in which they succeeded in analysing a surprising number of genes involved in the production of the wild colour. During their investigations many of the magnificent colours of today were fixed and handed on to the practical horticulturists. Above all, the famous Spencer mutation, which gives the elegant frilled edges to the petals, was quickly fixed in all varieties by genetical breeding immediately it arose, so that in the course of a few years the flower was completely transformed. But the sweet pea was comparatively simple, having only seven pairs of chromosomes. One can imagine what happens when such a plant has its chromosomes duplicated—an operation that is being performed in many garden plants today.

Hybridization has always been a prime factor in agriculture, and recent work has given it even more importance. It has long been observed that hybrids exceed their parents in size and vigour, and experiments with maize have shown that in this plant a certain amount of heterozygosity is necessary for the best results. If one keeps on inbreeding a certain strain, the genes become more and more homozygous and the vigour and fertility less as the heterozygosity decreases until, finally, the minimum is reached after some half-dozen generations, when the progeny will keep more or less to a certain level of development. By crossing them with a different strain, hybrid vigour results once more, since each strain will be pure for different allelomorphs, showing that outcrossing is necessary to maintain the best results. It is the practice now in many places to grow two strains of maize side by side, so that this desirable condition may be preserved. A great number of plants show this continual need for outbreeding, and in the majority this is performed naturally by insect fertilization or by wind pollination or other means by which pollen can be distributed, and there are often elaborate devices to ensure its taking place.

Most animals, by reason of their distinct sexes and their power to wander from one place to another, are definitely outbreeders, though for this very reason they often cannot achieve some of the complexities of plants, such as polyploidy, which can be attained only by a certain measure of inbreeding.

In many domesticated animals one is always up against the fact that only limited progeny can be obtained. As we have seen, under modern methods of artificial insemination it is now possible to improve the weaker herds of cattle by using a few superlative bulls over a wide area. Methods are now being devised to make more use of high-grade females. By the injection of a special hormone, cows can be made to produce a number of ova instead of the normal one. If these can be successfully transferred one at a time into cows which, after artificial insemination, will act as incubators, the progeny of pedigree cows can be enormously increased.

An immense amount of work still lies ahead in the study and experimental union of the ideal gene–climate–soil combinations. Climate is a thing one cannot improve, though tentative attempts have been made to control rainfall and redistribute cloud areas, but its effects can be mitigated by means of irrigation, drainage, and the planting of conservation areas. The study of soils results in their improvement and the fitting of suitable crops to the varying conditions. By careful genetic recombinations of characters, eliminating unwanted ones, and by the utilization of desirable new mutations, new varieties of food-plants can be evolved which will face up to difficult regions, and this has already been done in many cases. Gradually more and more areas are being brought under human control and into a useful productivity. It is evident from the mishaps of the past which have turned certain areas into "dust-bowls" that this can be only a slow and thoroughly controlled process, with efficient study and planning beforehand to forestall all the possible complications which are likely to arise when one starts tampering with natural conditions and so upsetting the normal balance of Nature.

Much further analysis is needed of the relationships of the various organisms, large and small, their inter-relations and their varied reactions to their surroundings. Pests, diseases, parasites, together with the creatures which prey upon them—all need the most profound study if the good results of the production of better types are not to be offset by the failure to provide them with adequate protection. One of the difficulties that confront investigators is the so much quicker life-cycle of the smaller organisms, which gives them a much greater mutation rate than their hosts, with the result that no sooner does a host achieve immunity by a mutation of its own or by human intervention, than a counter mutation will occur in the offending organism, giving it as great a virulence as before. Moreover, an organism which is quite innocuous in its normal surroundings will become a serious menace if transplanted to another area where it has no enemies to keep it in control; or the destruction of one pest will open the way for a new danger, arising from a pest upon which it preyed. Only the most intensive field work can reveal all these inter-relationships, and as Man replaces natural selection by his own selection it is imperative that he should know how to recreate the natural balance of things which he destroys in the taking over.

Conversely, the knowledge of good relationships is just as necessary. To give an example in our own country, the excellent fodder crop, lucerne, would not thrive in the north and west of England. This was thought to be due to the difference in climate, but direct experiment proved that it was due to the lack in the soil of the essential nitrogen-fixing bacteria which live in partnership on the roots of leguminous plants. When the lucerne seed was treated with cultures of the bacteria, all was well. Even here, however, care has to be taken, since there are different races of the bacteria, some of which produce much better growth than others.

We live and learn; only by actual experience can we gain real knowledge. Sufficient is it that we now have the main key to the complicated workings of life, which all depend on the complex reproducing molecules we call genes. One of the great steps of future knowledge will be the unravelling of how these genes actually produce their varied effects which go to build up the complete organism. The discovery of enzymes and vitamins is very important in this respect. Enzymes are proteins in the body which have the power to perform the numerous chemical reactions necessary to make the various constituents of food and other intakings available for development. These chemical changes are performed step by step by different enzymes—which, however, will work only in co-operation with what are known as co-enzymes; these are usually vitamins or those traces of various metals which have long been known to be essential in healthy dietary. The study of these enzymes in the most primitive organisms should supply many answers as to how they perform their work in the more complex ones. The extraordinary thing about them is that they are able speedily to bring about at ordinary body temperatures chemical changes which either cannot be performed at all in the laboratories or only by the use of great heat or powerful chemicals. Moreover, they themselves remain unchanged in the process. Hormones, too—the substances produced in definite areas of the bodies of animals and plants—show the most far-reaching effects on growth, development, and behaviour.

How the work of all these different proteins, including the genes, links up is the great problem. They are of immense complexity, often containing some thousands of atoms of varying kinds in their structure. Some have already been studied considerably, and the new aid of the electron microscope is rapidly advancing the study, since they can now be photographed. In the viruses lies the chance to study the combined functioning of the nucleoproteins with the nucleic acids (as in the genes), together with the cause and manner of the occasional mutations which arise in them. Here we get down to fundamentals, and a great field of work lies open before the biochemists in conjunction with the geneticists, and we may confidently expect as productive a collaboration as that with the biometricians.

And why all this elaboration—the complex bodies whose physical use is to act as protectors and guardians to the everlasting flow of the germ-cells ? What is the point of growth, since it must be counteracted by " death " ? Superimposed upon all this is the evolution of mind, with all its vast ramifications, whose intricacies, after centuries of questioning, no one can yet pretend to understand. " Robot brains " are being invented of tremendous ingenuity, far more infallible in some ways than the human brain, but they are the inventions of man's own brain, the latest offshoots of his acquired inheritance. The emergence of " life " from " matter ", of " mind " from " life ", always vexes the philosophers. We can only wonder what greater emergences may arise in the future. The ultimate questions still remain, even though they have been pushed farther back.

PIONEERS OF GENETICS

VOLUMES would be required to give details of the lives of the thousands of workers who have, by their patient and careful experiments, built up the science of Genetics. By its very nature it has depended on the teamwork of a great number of enthusiastic men and women in every country. But below are mentioned those who are more intimately connected with the story put forward in the preceding pages, and the brief outline of their lives may constitute a short history of the development of this fundamental branch of Biology. The arrangement is in order of birth.

Erasmus Darwin (1731–1802) was born in Nottinghamshire. He studied medicine, but devoted himself to science in his spare time and also wrote poems on botanical subjects. His ideas on evolution foreshadowed those of Lamarck and of Charles Darwin. He married twice, and Charles Darwin was a grandson by the first marriage and Francis Galton by the second.

Jean Baptiste Monnet, Chevalier de Lamarck (1744–1829) studied medicine and botany after ill-health forced him to abandon a military career, and after the publication of his *Flore Française* (1778) he was made Royal Botanist and later keeper of the Herbarium at the Royal Garden (now Jardin des Plantes) in Paris. After twenty years' intensive study of living creatures, he came to the conclusion that special creation was impossible and that the great variation in life is due to evolution, creatures changing by adapting themselves to their environment. These views were much in advance of his time, and little notice was taken of them until much later when they became a rival theory to Darwin's Natural Selection.

Charles Darwin (1809–1882) was born at Shrewsbury, and after taking his degree at Cambridge, set off as naturalist on the survey ship *Beagle* which was about to visit the Atlantic Islands, South America, and Australasia. The work he did on this voyage led to his new theories on the origin of species by natural selection of favourable variations, and in 1842 he settled at Down House at Downe in Kent, and devoted his life to studying and experimenting. He began to write up his observations, but was slow to publish. In 1858 he discovered that **A. R. Wallace** (1823–1913) had arrived at similar conclusions, so he and Wallace read a joint paper before the Linnean Society in London. The next year Darwin published his *Origin of Species by Natural Selection*, which aroused a controversy of extreme virulence. He continued his experiments at Downe until his death, accumulating a vast assemblage of facts and publishing many books. His house was presented to the British Association in 1929 as a permanent memorial of his work, and Darwin is now acknowledged throughout the world as one of the greatest pioneer scientists of all time.

Gregor Johann Mendel (1822–1884) was a monk in the Augustinian monastery at Brünn in what is now Czeckoslovakia. He was made Abbot in 1860, and was also lecturing in natural history. He was particularly interested, however, in the study of inheritance, and had the genius to see that the only way to solve its problems was to deal with only one very clearly defined character at a time. He chose the garden pea for his experiments, and after a series of brilliant and careful researches formulated his principles of the purity and orderly segregation of characters from one generation to another. The publication of his results in the journal of the local natural history society led to its neglect until its discovery in 1900, when, the time being now ripe for its understanding, it burst upon the world as one of the great fundamental discoveries of science. But Mendel died comparatively unknown, and unaware that his name was soon to become one of the most famous in the world of science.

Francis Galton (1822–1911) was a man of unusual versatility, but his primary interests were anthropological. He published works on *Hereditary Genius* (1869) and *Inquiries into Human Faculty* (1883) and was the founder of the science of Eugenics, for which he started a laboratory in 1904. His work was closely bound up with that of the early biometricians, and the Galton Laboratory, at University College, London, is world-famous for the work carried on there.

August Weismann (1834–1914) was born at Frankfort-on-Main. He was a physician, but gave this up for the study of zoology; in 1866 he became Professor of Zoology in Freiburg, where he remained until 1912. His greatest work was on evolution and variation, demonstrating that acquired characters cannot be inherited, and, most important of all, the continuity of the chromosomes from one generation to another—thus laying the foundation for the union of genetics with cytology. His famous book, *The Germ-plasm : A Theory of Heredity*, was translated into English in 1893, but its full importance was not appreciated until much later.

Hugo de Vries (1848–1935), one of the great pioneers and prophets of modern biological science, was born in Haarlem. He was Professor of Plant Physiology in the University of Amsterdam until 1918, when he retired to Lunteren, where he carried on his experiments until his death. In 1889 he published his theory of intracellular pangenesis, postulating that there must be hereditary particles in the cells of plants and animals—thus foreshadowing the discovery of the genes. He was one of the discoverers of Mendel's lost paper, and was intimately connected with all the early genetical work; but he is best known for his mutation theory published in 1901, in which he differentiated between fluctuating variations due to environmental changes and true variations caused by a change in the inherited material. In 1904 he urged the trial of X-rays on germ cells, but it was nearly a quarter of a century before his hopes were fulfilled. He was a great experimentalist, a keen observer, and an ardent collector of facts.

Karl Pearson (1857–1936) was called to the Bar but gave up law for the study of evolution and heredity from the statistical point of view. He was one of the keenest of the early biometricians, and later became Galton Professor of Eugenics in the University of London and director of the Francis Galton Laboratory. He also edited the two journals, *Biometrika* and the *Annals of Eugenics*.

William Bateson (1861–1926), the leader of the first English "Mendelians," had been working on the subject of variation in plants and animals, and its inheritance, for some ten years before the discovery of Mendel's paper provided the clue for later experiments. His first publication in 1894 of *Materials for the Study of Variation*, showing that it could be discontinuous, was followed by a series of books and articles on the study of inheritance. After a long struggle to get the new science established, a professorship and laboratory were founded at Cambridge for the study of genetics by Arthur Balfour, who had always taken a great interest in the work. Bateson was the first occupant (1908), but two years later he became director of the newly-formed John Innes Horticultural Institution at Merton where he remained for the rest of his life, building up there one of the most famous research stations in the world. His enthusiasm and experimental skill were a powerful stimulant to the early workers, not only in this country but all over the world.

Charles Benedict Davenport (1866–1941) was one of the early workers in America. In 1904 he was made director of the Carnegie Institution, where much valuable work was carried on in experimental evolution. He was particularly interested in human inheritance, and in 1910 was made head of the Eugenics Record Office. In 1918 he became head of the Genetics Department, and many books and papers came from his pen on varied aspects of heredity.

Thomas Hunt Morgan (1866–1945) was the great pioneer worker in the linking up of the genes within the chromosome with the inherited characters in animals and plants. Originally Professor of Biology at Bryn Mawr College, U.S.A., he was made Professor of Experimental Zoology in Columbia University in 1904. Here it was that he conceived and carried through the vast series of experiments on the fruit-fly *Drosophila* which proved beyond doubt that genes and chromosomes provided the "mechanism" for heredity. He gathered around him a brilliant school of workers which soon became world-famous. In 1928 this was moved to the Californian Institute of Technology at Pasadena. His genius in confining his main experiments to one comparatively simple species led to the most convincing evidence on the workings of heredity and evolution.

Charles Chamberlain Hurst (1870–1947), prevented from continuing his scholastic career by an attack of T.B., utilized his enforced open-air life by experimenting in breeding and collecting facts with regard to inheritance, based on the writings of Darwin. Working with pigeons, poultry, rabbits, and particularly orchids, he demonstrated (1898) that characters were behaving as units, reappearing intact in later generations. After the discovery of Mendel's paper in 1900 he carried through many experiments confirming and extending Mendel's laws, discovering the presence of colour and pattern factors in albino rabbits and orchids. In 1910 he founded the Burbage Experiment Station for applied genetics. After service in the 1914–18 war, he worked at Cambridge on the correlation of genetics, cytology, and the classification of animals and plants with regard to the origin of species and evolution. [His wife, Mrs. Rona Hurst, the author of this book, was closely associated with him in his work for many years.]

Reginald Crundall Punnett (b. 1875) was one of the earliest English workers, joining Bateson at Cambridge in 1903 and working with him in the important experiments then being carried on, particularly in poultry and sweet peas. It was during this time that they discovered that characters did not always work separately but might be linked, thus laying the foundation of the later work on the linkage of genes within the chromosome. In 1910 he succeeded Bateson as Professor of Genetics at Cambridge, where he carried on extensive experiments with poultry, especially in connexion with sex-linkage.

Calvin Blackman Bridges (1889–1938) was one of the earliest workers with Morgan on Drosophila, and until his death a leader of a famous group working under a grant from the Carnegie Institution of Washington. He was particularly responsible for the " mapping " of the position of the genes in the chromosomes, and for work on the determination of sex. His careful and brilliant work in keeping the chromosome maps received its reward in 1933 when the discovery of the giant salivary chromosomes made it possible to corroborate them visually. A vast amount of work has been carried through by the Carnegie Group in producing and maintaining Drosophila stocks for study, experiment, and teaching purposes, and large volumes known as the "Drosophila Information Service," bringing together the vast mass of data, have been published.

Ronald Aylmer Fisher (b. 1890), a brilliant statistician who early became interested in genetics and eugenics. He carried on scientific research in mathematics, and published various books on the subject. In 1933 he became Galton Professor of Eugenics in London University, and in 1943 he followed R. C. Punnett as Arthur Balfour Professor of Genetics at Cambridge, where he now leads an important school of genetical research on various plants and animals, but particularly mice—which by reason of their small size and rapid breeding are especially valuable for experimental purposes.

John Burdon Sanderson Haldane (b. 1892) is primarily a biochemist and mathematician, but has always taken an important part in genetical research. From 1922 he was Reader in Biochemistry at Cambridge, carrying on genetical research at his own home, and in 1927 he joined the staff at the John Innes Institute as part-time director of genetical investigations under Sir Daniel Hall, who had succeeded Bateson. In 1933 he became Professor of Genetics in London University, and in 1937 Professor of Biometry at University College. He has written many papers and books on genetics, evolution, and eugenics, and the philosophical implications of modern science, and has achieved a very high reputation for the brilliance and originality of his ideas.

Cyril Dean Darlington (b. 1903) joined the staff at John Innes in 1923, where Bateson put him on to work in cytology. He became head of the cytological department in 1927 under Sir Daniel Hall, and gained an international reputation for his brilliant discoveries on the behaviour of the chromosomes and methods for their investigation. He has travelled widely, visiting the great genetical institutions all over the world; and in 1939 succeeded Hall as Director of the John Innes Institution at Merton. Recently, under his leadership, this famous institution has been removed to Bayfordbury, near Hertford, where a large country house and extensive gardens and farmlands afford it a scope far beyond its original possibilities. Darlington is the author or co-author of several important books on modern genetics.

SOME BOOKS TO READ

THERE is an immense amount of literature on Genetics, mostly scattered through the hundreds of biological publications issued in every country to give detailed reports on the researches that are being carried out. From time to time, however, books appear synthesizing these results, and any of these will give a good bibliography of books and papers on the various aspects of the science. One of the latest of these publications is *The Elements of Genetics*, by C. D. Darlington and K. Mather, 1949, which deals very fully with modern genetics.

For the practical application of the science, *The Genetics of Garden Plants* (M. B. Crane and W. J. C. Lawrence), *Practical Plant Breeding* (W. J. C. Lawrence), and *Recent Advances in Genetics* (F. W. Sansome and J. Philp) deal with breeding in the garden.

Many books have been written from the standpoint of evolution, some of the more important being *The Evolution of Genetic Systems* (C. D. Darlington), *The Genetical Theory of Natural Selection* (R. A. Fisher), *The Causes of Evolution* (J. B. S. Haldane), and J. S. Huxley's *Evolution, The Modern Synthesis*, which contains a vast assemblage of facts.

For a study of the chromosomes *The Chromosome Atlas of Cultivated Plants* (C. D. Darlington and E. K. Janaki Ammal) gives an enormous quantity of chromosome numbers and their evolutionary significance. *The Mechanism of Creative Evolution* (C. C. Hurst) is a popular account with profuse illustrations of chromosomes and the characters linked with them, while *The Cell in Development and Heredity* (E. B. Wilson) is a standard work on the purely cytological side of Genetics.

For human heredity one may read *Genetics in Relation to Clinical Medicine* (F. A. E. Crew), *An Introduction to Medical Genetics* (J. A. Fraser-Roberts), and *Human Genetics* (R. R. Gates), while the biometrical angle is dealt with in *Biometrical Genetics* (K. Mather).

The earlier stages of Genetics may be followed in *Mendel's Principles of Heredity*, and *Problems of Genetics*, both by W. Bateson; *Experiments in Genetics*, a collection of C. C. Hurst's papers from 1896 to 1923; *The Physical Basis of Heredity* and *The Theory of the Gene* by T. H. Morgan, giving the early work on Drosophila; and the early text-book on *Mendelism* by R. C. Punnett.

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