The science of genetics is concerned with differences between organisms belonging to the same species, or to species which can be crossed. It is not concerned with all such differences. If we have two dogs, one with straight legs, the other with bent legs, the difference may be due to the fact that the bent-legged dog had a diet insufficient in vitamin D, or that his father was a dachshund. The geneticist is concerned with the latter case. The difference may also turn out to be inexplicable in terms of our present knowledge.

Now if an observed quantity or quality varies as the result of a number of conditions, we shall try to analyse the variation by keeping all but one of these conditions constant, and varying the remaining one. Thus if we wish to analyse the variation in the volume of a gas we shall first keep its temperature constant, and obtain Boyle’s law; then keep its pressure constant, and obtain Charles’s law.

It is obvious that if we are studying the genetics of a character which varies appreciably in response to environment we shall try to keep the environment constant. We shall see that all our dogs receive the same amount of vitamins, sunlight, and so on, so far as possible. This is an ideal which we cannot even approach asymptotically. For it turns out that high frequency radiation and particles of high velocity are very important components of the environment, causing heritable changes by a process called mutation. Even if we could conduct our experiments behind 30 metres of lead the fact that mutation has a temperature coefficient is enough to show that it depends in part on energy fluctuations which are uncontrollable.

Secondly we do not know a priori how long our constant environment must operate. In mammals it is no use to stabilise it after birth. For example in the guinea-pig the children of young mothers are more likely than those of old mothers to have extra toes. The question as to how long the environment must remain uniform to eliminate variation due to its diversity is an empirical question. The affirmation or denial of Lamarckism depends on how it is answered.

In a sufficiently constant environment variation still occurs, and it is found that the children of different parents differ. The difference may or may not be an example of heredity in the ordinary sense of that word, namely resemblance between parents and offspring. Thus in *Matthiola* a yellow flowered plant will give all yellow offspring, and a red plant will give all, or at any rate many, red offspring. Also some parents will give all normal flowered offspring, others a majority with double flowers, in which the presumptive reproductive organs are represented by petals. We cannot however say that doubleness is inherited (I discuss later the meaning of this distressingly vague word), because double-flowered plants are always completely sterile.

How are we to minimise the difference between the progeny of different parents? In other words, how are we to approximate to a genetically homogeneous population? The answer to this question is given by experiment, and rests on well-veriﬁed theory. There are three main methods. We may obtain a clone, that is to say a group of individuals related only by mitotic, and not meiotic, nuclear divisions. Such are a group of tulips of a named variety derived by vegetative reproduction from a single individual, or a pair of human monozygotic twins. We may obtain a pure line by prolonged inbreeding or by brother sister mating (though here of course we really have a pure line of females and another of males in bisexual organisms). Such are the named varieties of wheat, and a few lines of mice and rats. Finally we may use the first generation of hybrids between two pure lines. It can be shown theoretically that the variance in a population is reduced to a millionth after 10 generations of self-fertilisation or 30 of brother-sister mating.

1 Haldane, JBS. Some Principles of Causal Analysis in Genetics. *Erkenntnis* 1936; 6: 346-357. Reprinted with the kind permission of Mrs Lois Godfrey.
A nearly genetically homogeneous population in a nearly constant environment is often very uniform. And most of the differences which occur are not inherited, as Johannsen first showed. If the environment is variable more differences may occur. And in general these are not inherited. This important negative fact is the basis for the denial by most geneticists of Lamarck’s theory that acquired characters are inherited, or more accurately that differences in one generation due to diversity of environment give rise to differences in another generation due to diversity of ancestry. The denial of Lamarckism also rests on the positive fact that most genetically determined differences are due to differences in genes, distributed according to Mendel’s laws, and inconsistently with Lamarck’s hypothesis.

Some pure lines however are not uniform, either in a variable environment, or in an environment as constant as we can make it. Thus Timofeff-Ressowsky (1927) obtained a line of Drosophila funebris in which 89.6% of all individuals have an incomplete radial vein. The difference is not inherited within the line, though lines with 0% or 100% incomplete veins can readily be obtained. He was unable to notice any difference in the percentage of abnormalities as the result of environmental conditions such as temperature and humidity. Most geneticists would without hesitation ascribe non-heritable variations within a pure line to differences of environment. This is a reasonable working hypothesis, as it stimulates them to discover such differences. Nevertheless it may turn out that such variations are due to causes which are in principle beyond our control, for example to details of cell-division which are at the mercy of molecular fluctuation. It is at least important to realise that the question remains open. It is interesting that such unstable forms rarely occur in nature.

In a population that has been brought to approximate genetical homogeneity, two types of heritable variation may occur. A gene, that is to say a self-perpetuating unit in the nucleus, may mutate. That is to say it becomes a self-perpetuating unit of a different nature. In this way another pure line may arise. Or, particularly as the result of temperature changes, variants may arise which, as females only, transmit their novel character to some of their offspring. These changes, which Jollos calls Dauermodifikationen, always disappear in a few generations. They seem to be due to substances in the cytoplasm with a limited capacity for self-perpetuation.

In an ordinary population we have both a variety of environments and a variety of individuals. Each individual belongs to a certain genotype, and it is always theoretically possible, and in some plants practically possible, to produce a number of individuals of approximately the same genotype, and to place them in different environments. The distinction between an organism and its environment in this case turns out to be a practically and theoretically valuable abstraction. It is however important to remember that it is an abstraction. The physiologist finds his main difficulty in making it spatially. Thus he sometimes finds it convenient to regard the blood plasma as part of the organism, sometimes as part of the environment. The geneticist is a little unsure where to make it in time.

Thus, in practice, abnormalities found in human beings at birth are classed as congenital. Yet some, such as ichthyosis, are due to abnormal genotypes, others, such as mongolian idiocy, largely at least to abnormal prenatal environment. Fortunately the geneticist can classify his results with success in most cases if he draws the line at the moment of fertilisation. It is rare to find that the character of the new organism produced by the fusion of two gametes is affected by the environment to which the parents have been exposed, except in so far as the female parent provides an environment for the embryo. Nevertheless exceptions undoubtedly occur, as in the case of Dauermodifikationen.

With these slight reservations we can say that all the differences in a population are due to the existence of different genotypes in different environments. Some differences are wholly due to genotypic diversity. Thus in man the colour of the iris is almost entirely determined genetically. On the other hand the language first learned as a child is determined wholly by environment. But most characters depend both on genotype and on environment. Size is a character of this kind. So are economically important characters such as milk-yield, and socially important characters such as criminality or mathematical performance. No one doubts the importance of environment. Some criminals are well-behaved if they have no access to alcohol. Mathematicians must learn mathematics. No one who has read such works as Lange’s “Verbrechen als Schicksal” can doubt the importance of genotypic differences in the determination of criminality.

But to admit the importance of genotypic differences is not to say that an individual of genotype \( A \) has a greater tendency than an individual of genotype \( B \) to height, milk-yield, criminality or mathematical achievement. This is only so if the effect of substituting \( B \) for \( A \) on the character considered is in the same direction in all environments. Where differences in a character depend very little on environment we can sometimes speak of a character as inherited. But this is a special case, and is probably not typical for most of the characters which interest the animal breeder, let alone the eugenist.

Let us suppose we are dealing with a character which can be measured, or at least ordered. For example health can be measured in terms of longevity, time lost through
sickness etc. Students can be classed according to their performance in a given examination at a given age. We can, at least in theory, measure or order enough members of each genotype to make the difference between genotype, and environments significant.

Now suppose we have \( m \) genotypes and \( n \) environments. In certain cases we can arrange them in such a way that in each environment the genotypes occur in the same order, and with each genotype the environments occur in the same order. E.g. if we have three genotypes \( A, B, C \) and three environments \( X, Y, Z \) the nine characters can be placed in an order and given numbers from 1 to 9. The following cases would obey our criterion:

\[
\begin{array}{ccc}
X & Y & Z \\
A & 1 & 3 & 5 \\
B & 2 & 6 & 8 \\
C & 4 & 7 & 9 \\
\end{array}
\]

\[
\begin{array}{ccc}
X & Y & Z \\
A & 1 & 2 & 4 \\
B & 3 & 5 & 7 \\
C & 6 & 8 & 9 \\
\end{array}
\]

In such cases we can say that genotype \( A \) has, in any of the environments where it has been tested, a higher milk-yield, intelligence, or whatever we are studying, than \( B \). We also say that the environment \( X \), in the case of all genotypes studied, is more favourable than environment \( Y \). Almost all schemes, either for improvement of the human race, or for political and economic reform, are based on the ridiculous fallacy that this state of affairs is typical, that we can speak of a healthy environment, or an innate tendency to crime, without further qualification.

The falsity of this assumption will appear from a few concrete cases. Consider two genotypes \( A, B \), in two environment [sic] \( X, Y \) and a character displayed by them which can be measured or ordered. In the simple case considered above we shall have such a condition as:

\[
\begin{array}{cc}
X & Y \\
A & 1 & 2 \\
B & 3 & 4 \\
\end{array}
\]

Further it is probable that this will almost always be the case where the genotypes or the environments only differ very slightly.

(2.) Next let us consider the very common case where one genotype is more modifiable than the other, though both are modified in the same direction. The order is:

\[
\begin{array}{cc}
X & Y \\
A & 1 & 4 \\
B & 2 & 3 \\
\end{array}
\]

This is the normal situation resulting from domestication in animals or plants. The primitive type \( B \) gives a slightly better yield in cultivation \( X \), than in the wild state \( Y \). A cow of a primitive type will give a little more milk in a Danish meadow than an[sic] a barren heath. The domesticated type \( A \) gives a very good yield on cultivated ground \( X \), but on very poor pastures it gives none at all, because it dies. Less extreme cases also occur, as where wheat \( A \) gives a better yield than \( B \) when the seeds are sown far apart \( X \) and worse when they are sown close together \( Y \).

(3.) The complementary case:

\[
\begin{array}{cc}
X & Y \\
A & 1 & 2 \\
B & 4 & 3 \\
\end{array}
\]

where \( A \) is a consistently better genotype than \( B \), but environment \( X \) is better in the case of \( A \), \( Y \) in that of \( B \), is less interesting. It is illustrated by the case where \( A \) is a normal man, \( B \) a so-called congenital idiot, \( X \) is the normal world, and \( Y \) an institution for mental defectives. The character ordered might be any of a number of human achievements.

(4) The last and most striking case is:

\[
\begin{array}{cc}
X & Y \\
A & 1 & 4 \\
B & 3 & 2 \\
\end{array}
\]

or

\[
\begin{array}{cc}
X & Y \\
A & 1 & 3 \\
B & 4 & 2 \\
\end{array}
\]

in which neither genotype, and neither environment, is consistently superior. This is the normal situation where \( A \) and \( B \) are local races, \( X \) and \( Y \) the environments to which they are adapted. Thus is [sic] \( A \) represents Englishmen, \( B \) West African negroes, \( X \) England, and \( Y \) West Africa, the order of expectation of life is probably:

2. Negroes in West Africa.
3. Negroes in England (tuberculosis!).
4. English in West Africa (Yellow fever!).

Even if all members of a race were genetically alike (which of course they are not) this elementary example would show that assertion that race \( A \) is superior to race \( B \) is in general meaningless, though perhaps for that reason all the more charged with emotional content.

I have chosen my examples from familiar cases where the genotypes are inexactly defined. I might have chosen them from rigorous experiments with pure lines of animals and plants. The results would have been the same.

In the cases so far considered the four combinations of genotype and environment gave different results. It is very common to find that several of the four are
indistinguishable. In the case of inherited resistance to disease, for example, we have:

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

where A represents a resistant [sic], B a susceptible type, X is an environment with no infection, Y one with infection, and resistance is complete. If we allow for the fact that two or more combinations of genotype and environment may be indistinguishable, we can enumerate 15 cases in all, every one of which occurs in practice.

It is generally possible to choose examples of the two genotypes A and B such that in all environments so far studied A possesses a character P which B does not. However it generally turns out that these are all chosen so as to favour A. Some types which we grade as mental defectives may be unadapted to social life, but better adapted than the normal to a solitary life on a desert island. Others might be mentally normal if their environment included daily injections of a particular hormone, and so on.

If in a population containing a number of genotypes A, B, C - in a number of environments X, Y, Z - we find that in every environment the genotypes are placed in the same order as regards a certain character, we may say that this character is an innate character, though influenced to a certain extent by the environment. But we have no assurance that if we introduce a new genotype or a new environment this will still be true.

The whole discussion is greatly complicated by two facts. We can only define our genotypes at present by their appearance and that of their offspring, in a certain environment, as we define chemical substances by their properties and reactions. But it is as unscientific to regard tallness or idiocy as an essential property of a certain genotype as to regard solidity as an essential property of iron, which can equally well exist as a liquid or a gas. Secondly, geneticists have naturally preferred to study those differences between genotypes which are stable in a large variety of environments, just as chemists have preferred to study substances like methane rather than highly unstable radicals like methyl.

I have not so far used the word heredity, or discussed what meaning, if any, can be attached to such statements as “Blue eyes are hereditary” or “Intelligence is inherited”. Inheritance may be taken to mean resemblance between parent and offspring, or between an ancestor and some more remote descendant, such resemblance being greater than that between members of the same population taken at random, and living in the same environments as the relatives who are compared. If a character is genetically determined in a given set of environments it may or may not be inherited in this sense, though it generally is so.

As an example of the extreme difficulty of accurate definition in such cases I will try to give a precise meaning to the statement “Intelligence is inherited in the population of Denmark”. Here is the best that I can do. It is of course only a member of an infinite class of possible meanings.

“If, by means of a test specified elsewhere, and presumed to measure intelligence, all persons in Denmark any of whose children have now reached the age of 16 years or over had, at the age of 16 years, been placed in classes according to the number of marks obtained, and further if their children had been distributed at random among the various environments in which they were actually placed, then it would have been found that the order of the mean marks obtained by the children of the members of any class was the same as the order of the parental classes, provided that the number in each class was so large that errors due to random sampling could be excluded with a very high degree of probability”.

Clearly unless the children could be distributed at random the result would prove little, since a test of religious opinions at the age of eight, which are almost wholly determined by environment, would show a very considerable agreement between parents and children unless the children were distributed at random. I may add that the random distribution should take place by cross-transplantation of embryos between women at the time of conception!

I should not like to class the statement “Intelligence is inherited in the population of Denmark” as nonsensical because it cannot be tested, as is e. g. the statement that triangular squares are blue. It may belong to the class of unverifiable statements which become more and more probable with time, e. g. that all fish in the North Sea in the year 1900 classifiable as herrings by their external appearance contained some haemoglobin. I do most emphatically deny that it can be regarded as at present almost certain, like the statement about the herrings. We do not for example know whether a group of genotypes characterised by high intelligence in a favourable environment may not be characterised by low intelligence in an unfavourable environment. The interaction of heredity and environment may be simpler in the case of the intelligence of man than of the milk-yield of cattle. But this is not a priori certain, nor perhaps even very probable.

The process by which the genotype of an individual is determined is pretty well understood. It is determined mainly by the set of genes carried in the nucleus. These genes are bodies of the dimensions of protein molecules, one of which almost always reproduces two similar genes when the nucleus divides. The statistical laws by which the
genes in a cell are distributed to the gametes which fuse to make a new individual are well understood. But the actual process of distribution at a particular division involves particles in Brownian movement. It is therefore in principle unpredictable by any observational methods which we can at present apply or even imagine.

The reproduction of genes also raises some fundamental problems. A gene may be altered by radiation or otherwise, and is then sometimes reproduced in an altered or mutated form. The substitution of one form for another may give rise (in the presence of a certain range of other genes and of environments) to a visible difference such as albinism, extra toes, altered tropisms, and so on. From a biological view we may say that the gene reproduces itself, and that the two new genes are heirs. But it is reasonably certain that a gene does not consist of a number of like parts. It does not therefore grow gradually and divide into two like a cell. From the chemical point of view its reproduction must be regarded as a copying; a new gene, or copy, being built upon an old gene, or model, by a process analogous to crystallisation. But modern physical concepts suggest that no series of observations could determine with complete certainty which of a pair of “sister” genes is the model and which the copy, though they could, I think, make a statement on the subject highly probable.

Here, then, where the mechanistic and biological points of view are obviously at variance, the uncertainty principle seems to show that both are at fault. It does not yet, so far as I can see, allow of any verifiable predictions. I do not think that the interchange energies concerned are large enough to give rise to effects at present observable. But they are not in principle unobservable, and it may well be that in this case the new physics may help to answer the fundamental question “What are the properties of non-living matter which render life possible?”

I have perhaps given the impression that genetics is a mere name for a series of unsolved problems. On the contrary, it is a highly developed and exact branch of biology, with its own laws and therefore its own mathematics. A geneticist, like a chemist, can do a lifetime of good work without examining his fundamental assumptions. It is essential that genetics should develop independently if the internal contradictions contained in these assumptions are to be laid bare. The geneticist must and will continue to use such expressions as “a gene for extra wing veins” even though the substitution of this gene for its normal allelomorph only produces extra veins in presence of certain other genes and a certain environment.

Nevertheless such expressions, appropriate as they are to laboratory experiments, are less so to agriculture and grossly inappropriate to eugenics. If genetics is to aid in the improvement of the human race, and in the investigation of the nature of life, its assumptions must be rigorously criticised. In this paper I have attempted to criticise a few of its assumptions.