WHAT IS LIFE?

The Physical Aspect of the Living Cell

with

MIND AND MATTER

&

AUTOBIOGRAPHICAL SKETCHES

ERWIN SCHRÖDINGER

The Classical Physicist's Approach to the Subject

Cogito ergo sum. DESCARTES

THE GENERAL CHARACTER AND THE PURPOSE OF THE INVESTIGATION

This little book arose from a course of public lectures, delivered by a theoretical physicist to an audience of about four hundred which did not substantially dwindle, though warned at the outset that the subject-matter was a difficult one and that the lectures could not be termed popular, even though the physicist's most dreaded weapon, mathematical deduction, would hardly be utilized. The reason for this was not that the subject was simple enough to be explained without mathematics, but rather that it was much too involved to be fully accessible to mathematics. Another feature which at least induced a semblance of popularity was the lecturer's intention to make clear the fundamental idea, which hovers between biology and physics, to both the physicist and the biologist.

For actually, in spite of the variety of topics involved, the whole enterprise is intended to convey one idea only – one small comment on a large and important question. In order not to lose our way, it may be useful to outline the plan very briefly in advance.

The large and important and very much discussed question is:

How can the events *in space and time* which take place within the spatial boundary of a living organism be accounted for by physics and chemistry?

The preliminary answer which this little book will endeavour to expound and establish can be summarized as follows:

The obvious inability of present-day physics and chemistry to account for such events is no reason at all for doubting that they can be accounted for by those sciences.

STATISTICAL PHYSICS. THE FUNDAMENTAL DIFFERENCE IN STRUCTURE

That would be a very trivial remark if it were meant only to stimulate the hope of achieving in the future what has not been achieved in the past. But the meaning is very much more positive, viz. that the inability, up to the present moment, is amply accounted for.

Today, thanks to the ingenious work of biologists, mainly of geneticists, during the last thirty or forty years, enough is known about the actual material structure of organisms and about their functioning to state that, and to tell precisely why, present-day physics and chemistry could not possibly account for what happens in space and time within a living organism.

The arrangements of the atoms in the most vital parts of an organism and the interplay of these arrangements differ in a fundamental way from all those arrangements of atoms which physicists and chemists have hitherto made the object of their experimental and theoretical research. Yet the difference which I have just termed fundamental is of such a kind that it might easily appear slight to anyone except a physicist who is thoroughly imbued with the knowledge that the laws of physics and chemistry are statistical throughout.[1] For it is in relation to the statistical point of view that the structure of the vital parts of living organisms differs so entirely from that of any piece of matter that we physicists and chemists have ever handled physically in our laboratories or mentally at our

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[1]This contention may appear a little too general. The discussion must be deferred to the end of this book, pp. 82–4.

writing desks.[1] It is well-nigh unthinkable that the laws and regularities thus discovered should happen to apply immediately to the behaviour of systems which do not exhibit the structure on which those laws and regularities are based.

The non-physicist cannot be expected even to grasp – let alone to appreciate the relevance of – the difference in 'statistical structure' stated in terms so abstract as I have just used. To give the statement life and colour, let me anticipate what will be explained in much more detail later, namely, that the most essential part of a living cell – the chromosome fibre – may suitably be called *an aperiodic crystal*. In physics we have dealt hitherto only with *periodic crystals*. To a humble physicist's mind, these are very interesting and complicated objects; they constitute one of the most fascinating and complex material structures by which inanimate nature puzzles his wits. Yet, compared with the aperiodic crystal, they are rather plain and dull. The difference in structure is of the same kind as that between an ordinary wallpaper in which the same pattern is repeated again and again in regular periodicity and a masterpiece of embroidery, say a Raphael tapestry, which shows no dull repetition, but an elaborate, coherent, meaningful design traced by the great master.

In calling the periodic crystal one of the most complex objects of his research, I had in mind the physicist proper. Organic chemistry, indeed, in investigating more and more complicated molecules, has come very much nearer to that 'aperiodic crystal' which, in my opinion, is the material carrier of life. And therefore it is small wonder that the organic chemist has already made large and important contributions to the problem of life, whereas the physicist has made next to none.

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[1]This point of view has been emphasized in two most inspiring papers by F. G. Donnan, *Scientia*, xxiv, no. 78 (1918), 10 ('La science physico-chimique décrit-elle d'une façon adéquate les phénomènes biologiques?'); *Smithsonian Report for 1929*, p. 309 ('The mystery of life').

THE NAÏVE PHYSICIST'S APPROACH
TO THE SUBJECT

After having thus indicated very briefly the general idea – or rather the ultimate scope – of our investigation, let me describe the line of attack.

I propose to develop first what you might call 'a naïve physicist's ideas about organisms', that is, the ideas which might arise in the mind of a physicist who, after having learnt his physics and, more especially, the statistical foundation of his science, begins to think about organisms and about the way they behave and function and who comes to ask himself conscientiously whether he, from what he has learnt, from the point of view of his comparatively simple and clear and humble science, can make any relevant contributions to the question.

It will turn out that he can. The next step must be to compare his theoretical anticipations with the biological facts. It will then turn out that – though on the whole his ideas seem quite sensible – they need to be appreciably amended. In this way we shall gradually approach the correct view – or, to put it more modestly, the one that I propose as the correct one.

Even if I should be right in this, I do not know whether my way of approach is really the best and simplest. But, in short, it was mine. The 'naïve physicist' was myself. And I could not find any better or clearer way towards the goal than my own crooked one.

WHY ARE THE ATOMS SO SMALL?

A good method of developing 'the naïve physicist's ideas' is to start from the odd, almost ludicrous, question: Why are atoms so small? To begin with, they are very small indeed. Every little piece of matter handled in everyday life contains an enormous number of them. Many examples have been devised to bring this fact home to an audience, none of them more impressive than the one used by Lord Kelvin: Suppose that

you could mark the molecules in a glass of water; then pour the
contents of the glass into the ocean and stir the latter thor-
oughly so as to distribute the marked molecules uniformly
throughout the seven seas; if then you took a glass of water
anywhere out of the ocean, you would find in it about a hundred
of your marked molecules.[1]

The actual sizes of atoms[2] lie between about $\frac{1}{5000}$ and $\frac{1}{2000}$ of
the wave-length of yellow light. The comparison is significant,
because the wave-length roughly indicates the dimensions of
the smallest grain still recognizable in the microscope. Thus it
will be seen that such a grain still contains thousands of
millions of atoms.

Now, why are atoms so small?

Clearly, the question is an evasion. For it is not really aimed
at the size of the atoms. It is concerned with the size of
organisms, more particularly with the size of our own corporeal
selves. Indeed, the atom is small, when referred to our civic unit
of length, say the yard or the metre. In atomic physics one is
accustomed to use the so-called Ångström (abbr. Å), which is
the 10^{10}th part of a metre, or in decimal notation 0.0000000001
metre. Atomic diameters range between 1 and 2Å. Now those
civic units (in relation to which the atoms are so small) are
closely related to the size of our bodies. There is a story tracing
the yard back to the humour of an English king whom his
councillors asked what unit to adopt – and he stretched out his
arm sideways and said: 'Take the distance from the middle of
my chest to my fingertips, that will do all right.' True or not, the
story is significant for our purpose. The king would naturally
indicate a length comparable with that of his own body,

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[1] You would not, of course, find exactly 100 (even if that were the exact result of the
computation). You might find 88 or 95 or 107 or 112, but very improbably as few as
50 or as many as 150. A 'deviation' or 'fluctuation' is to be expected of the order of
the square root of 100, i.e. 10. The statistician expresses this by stating that you
would find 100±10. This remark can be ignored for the moment, but will be referred
to later, affording an example of the statistical $\sqrt{n}$ law.

[2] According to present-day views an atom has no sharp boundary, so that 'size' of an
atom is not a very well-defined conception. But we may identify it (or, if you please,
replace it) by the distance between their centres in a solid or in a liquid – not, of
course, in the gaseous state, where that distance is, under normal pressure and
temperature, roughly ten times as great.

knowing that anything else would be very inconvenient. With all his predilection for the Ångström unit, the physicist prefers to be told that his new suit will require six and a half yards of tweed – rather than sixty-five thousand millions of Ångströms of tweed.

It thus being settled that our question really aims at the ratio of two lengths – that of our body and that of the atom – with an incontestable priority of independent existence on the side of the atom, the question truly reads: Why must our bodies be so large compared with the atom?

I can imagine that many a keen student of physics or chemistry may have deplored the fact that every one of our sense organs, forming a more or less substantial part of our body and hence (in view of the magnitude of the said ratio) being itself composed of innumerable atoms, is much too coarse to be affected by the impact of a single atom. We cannot see or feel or hear the single atoms. Our hypotheses with regard to them differ widely from the immediate findings of our gross sense organs and cannot be put to the test of direct inspection.

Must that be so? Is there an intrinsic reason for it? Can we trace back this state of affairs to some kind of first principle, in order to ascertain and to understand why nothing else is compatible with the very laws of Nature?

Now this, for once, is a problem which the physicist is able to clear up completely. The answer to all the queries is in the affirmative.

THE WORKING OF AN ORGANISM REQUIRES EXACT PHYSICAL LAWS

If it were not so, if we were organisms so sensitive that a single atom, or even a few atoms, could make a perceptible impression on our senses – Heavens, what would life be like! To stress one point: an organism of that kind would most certainly not be capable of developing the kind of orderly thought which, after passing through a long sequence of

earlier stages, ultimately results in forming, among many other ideas, the idea of an atom.

Even though we select this one point, the following considerations would essentially apply also to the functioning of organs other than the brain and the sensorial system. Nevertheless, the one and only thing of paramount interest to us in ourselves is, that we feel and think and perceive. To the physiological process which is responsible for thought and sense all the others play an auxiliary part, at least from the human point of view, if not from that of purely objective biology. Moreover, it will greatly facilitate our task to choose for investigation the process which is closely accompanied by subjective events, even though we are ignorant of the true nature of this close parallelism. Indeed, in my view, it lies outside the range of natural science and very probably of human understanding altogether.

We are thus faced with the following question: Why should an organ like our brain, with the sensorial system attached to it, of necessity consist of an enormous number of atoms, in order that its physically changing state should be in close and intimate correspondence with a highly developed thought? On what grounds is the latter task of the said organ incompatible with being, as a whole or in some of its peripheral parts which interact directly with the environment, a mechanism sufficiently refined and sensitive to respond to and register the impact of a single atom from outside?

The reason for this is, that what we call thought (1) is itself an orderly thing, and (2) can only be applied to material, i.e. to perceptions or experiences, which have a certain degree of orderliness. This has two consequences. First, a physical organization, to be in close correspondence with thought (as my brain is with my thought) must be a very well-ordered organization, and that means that the events that happen within it must obey strict physical laws, at least to a very high degree of accuracy. Secondly, the physical impressions made upon that physically well-organized system by other bodies from outside, obviously correspond to the perception and experience of the corresponding thought, forming its material,

as I have called it. Therefore, the physical interactions between our system and others must, as a rule, themselves possess a certain degree of physical orderliness, that is to say, they too must obey strict physical laws to a certain degree of accuracy.

PHYSICAL LAWS REST ON ATOMIC STATISTICS AND ARE THEREFORE ONLY APPROXIMATE

And why could all this not be fulfilled in the case of an organism composed of a moderate number of atoms only and sensitive already to the impact of one or a few atoms only?

Because we know all atoms to perform all the time a completely disorderly heat motion, which, so to speak, opposes itself to their orderly behaviour and does not allow the events that happen between a small number of atoms to enrol themselves according to any recognizable laws. Only in the co-operation of an enormously large number of atoms do statistical laws begin to operate and control the behaviour of these *assemblées* with an accuracy increasing as the number of atoms involved increases. It is in that way that the events acquire truly orderly features. All the physical and chemical laws that are known to play an important part in the life of organisms are of this statistical kind; any other kind of lawfulness and orderliness that one might think of is being perpetually disturbed and made inoperative by the unceasing heat motion of the atoms.

THEIR PRECISION IS BASED ON THE LARGE NUMBER OF ATOMS INTERVENING. FIRST EXAMPLE (PARAMAGNETISM)

Let me try to illustrate this by a few examples, picked somewhat at random out of thousands, and possibly not just the best ones to appeal to a reader who is learning for the first time about this condition of things – a condition which in modern physics and chemistry is as fundamental as, say, the fact that organisms are composed of cells is in biology, or as
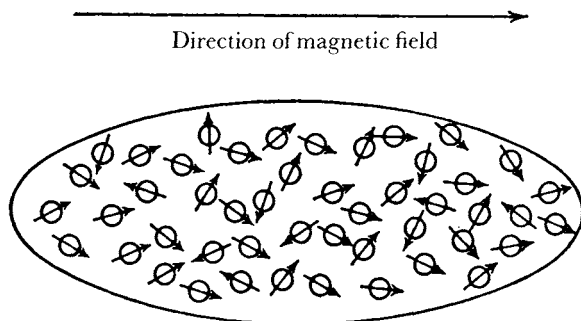
Fig. 1. Paramagnetism.

Newton's Law in astronomy, or even as the series of integers, 1, 2, 3, 4, 5, . . . in mathematics. An entire newcomer should not expect to obtain from the following few pages a full understanding and appreciation of the subject, which is associated with the illustrious names of Ludwig Boltzmann and Willard Gibbs and treated in textbooks under the name of 'statistical thermodynamics'.

If you fill an oblong quartz tube with oxygen gas and put it into a magnetic field, you find that the gas is magnetized.[1] The magnetization is due to the fact that the oxygen molecules are little magnets and tend to orientate themselves parallel to the field, like a compass needle. But you must not think that they actually all turn parallel. For if you double the field, you get double the magnetization in your oxygen body, and that proportionality goes on to extremely high field strengths, the magnetization increasing at the rate of the field you apply.

This is a particularly clear example of a purely statistical law. The orientation the field tends to produce is continually counteracted by the heat motion, which works for random orientation. The effect of this striving is, actually, only a small preference for acute over obtuse angles between the dipole axes and the field. Though the single atoms change their

[1] A gas is chosen, because it is simpler than a solid or a liquid; the fact that the magnetization is in this case extremely weak, will not impair the theoretical considerations.

orientation incessantly, they produce on the average (owing to their enormous number) a constant small preponderance of orientation in the direction of the field and proportional to it. This ingenious explanation is due to the French physicist P. Langevin. It can be checked in the following way. If the observed weak magnetization is really the outcome of rival tendencies, namely, the magnetic field, which aims at combing all the molecules parallel, and the heat motion, which makes for random orientation, then it ought to be possible to increase the magnetization by weakening the heat motion, that is to say, by lowering the temperature, instead of reinforcing the field. That is confirmed by experiment, which gives the magnetization inversely proportional to the absolute temperature, in quantitative agreement with theory (Curie's law). Modern equipment even enables us, by lowering the temperature, to reduce the heat motion to such insignificance that the orientating tendency of the magnetic field can assert itself, if not completely, at least sufficiently to produce a substantial fraction of 'complete magnetization'. In this case we no longer expect that double the field strength will double the magnetization, but that the latter will increase less and less with increasing field, approaching what is called 'saturation'. This expectation too is quantitatively confirmed by experiment.

Notice that this behaviour entirely depends on the large numbers of molecules which co-operate in producing the observable magnetization. Otherwise, the latter would not be constant at all, but would, by fluctuating quite irregularly from one second to the next, bear witness to the vicissitudes of the contest between heat motion and field.

<center>SECOND EXAMPLE</center>
<center>(BROWNIAN MOVEMENT, DIFFUSION)</center>

If you fill the lower part of a closed glass vessel with fog, consisting of minute droplets, you will find that the upper boundary of the fog gradually sinks, with a well-defined velocity, determined by the viscosity of the air and the size
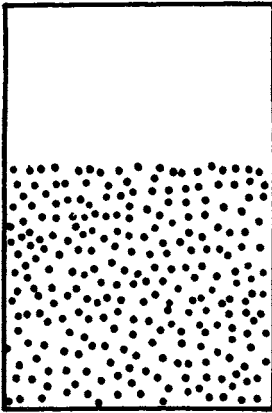
Fig. 2. Sinking fog.

Fig. 3. Brownian movement
of a sinking droplet.

and the specific gravity of the droplets. But if you look at one of the droplets under the microscope you find that it does not permanently sink with constant velocity, but performs a very irregular movement, the so-called Brownian movement, which corresponds to a regular sinking only on the average.

Now these droplets are not atoms, but they are sufficiently small and light to be not entirely insusceptible to the impact of one single molecule of those which hammer their surface in perpetual impacts. They are thus knocked about and can only on the average follow the influence of gravity.

This example shows what funny and disorderly experience we should have if our senses were susceptible to the impact of
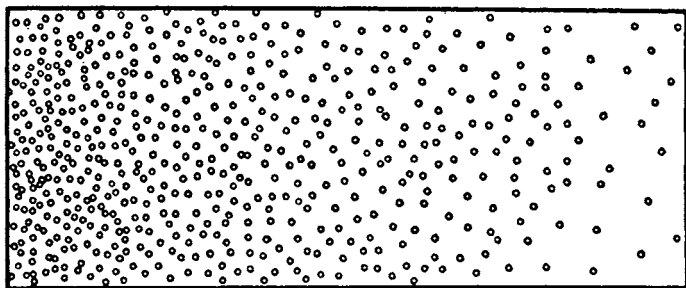
Fig. 4. Diffusion from left to right in a solution of varying concentration.

a few molecules only. There are bacteria and other organisms so small that they are strongly affected by this phenomenon. Their movements are determined by the thermic whims of the surrounding medium; they have no choice. If they had some locomotion of their own they might nevertheless succeed in getting from one place to another – but with some difficulty, since the heat motion tosses them like a small boat in a rough sea.

A phenomenon very much akin to Brownian movement is that of *diffusion*. Imagine a vessel filled with a fluid, say water, with a small amount of some coloured substance dissolved in it, say potassium permanganate, not in uniform concentration, but rather as in Fig. 4, where the dots indicate the molecules of the dissolved substance (permanganate) and the concentration diminishes from left to right. If you leave this system alone a very slow process of 'diffusion' sets in, the permanganate spreading in the direction from left to right, that is, from the places of higher concentration towards the places of lower concentration, until it is equally distributed through the water.

The remarkable thing about this rather simple and apparently not particularly interesting process is that it is in no way due, as one might think, to any tendency or force driving the permanganate molecules away from the crowded region to the less crowded one, like the population of a country spreading to those parts where there is more elbow-room. Nothing of the

sort happens with our permanganate molecules. Every one of them behaves quite independently of all the others, which it very seldom meets. Every one of them, whether in a crowded region or in an empty one, suffers the same fate of being continually knocked about by the impacts of the water molecules and thereby gradually moving on in an unpredictable direction – sometimes towards the higher, sometimes towards the lower, concentrations, sometimes obliquely. The kind of motion it performs has often been compared with that of a blindfolded person on a large surface imbued with a certain desire of 'walking', but without any preference for any particular direction, and so changing his line continuously.

That this random walk of the permanganate molecules, the same for all of them, should yet produce a regular flow towards the smaller concentration and ultimately make for uniformity of distribution, is at first sight perplexing – but only at first sight. If you contemplate in Fig. 4 thin slices of approximately constant concentration, the permanganate molecules which in a given moment are contained in a particular slice will, by their random walk, it is true, be carried with equal probability to the right or to the left. But precisely in consequence of this, a plane separating two neighbouring slices will be crossed by more molecules coming from the left than in the opposite direction, simply because to the left there are more molecules engaged in random walk than there are to the right. And as long as that is so the balance will show up as a regular flow from left to right, until a uniform distribution is reached.

When these considerations are translated into mathematical language the exact law of diffusion is reached in the form of a partial differential equation

$$\frac{\partial \rho}{\partial t} = D\nabla^2\rho,$$

which I shall not trouble the reader by explaining, though its

meaning in ordinary language is again simple enough.[1] The reason for mentioning the stern 'mathematically exact' law here, is to emphasize that its physical exactitude must nevertheless be challenged in every particular application. Being based on pure chance, its validity is only approximate. If it is, as a rule, a very good approximation, that is only due to the enormous number of molecules that co-operate in the phenomenon. The smaller their number, the larger the quite haphazard deviations we must expect – and they can be observed under favourable circumstances.

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THIRD EXAMPLE

(LIMITS OF ACCURACY OF MEASURING)

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The last example we shall give is closely akin to the second one, but has a particular interest. A light body, suspended by a long thin fibre in equilibrium orientation, is often used by physicists to measure weak forces which deflect it from that position of equilibrium, electric, magnetic or gravitational forces being applied so as to twist it around the vertical axis. (The light body must, of course, be chosen appropriately for the particular purpose.) The continued effort to improve the accuracy of this very commonly used device of a 'torsional balance', has encountered a curious limit, most interesting in itself. In choosing lighter and lighter bodies and thinner and longer fibres – to make the balance susceptible to weaker and weaker forces – the limit was reached when the suspended body became noticeably susceptible to the impacts of the heat motion of the surrounding molecules and began to perform an incessant, irregular 'dance' about its equilibrium position, much like the trembling of the droplet in the second example. Though this behaviour sets no absolute limit to the accuracy of measurements obtained with the balance, it sets a practical one. The uncontrollable effect of the heat motion competes

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[1]To wit: the concentration at any given point increases (or decreases) at a time rate proportional to the comparative surplus (or deficiency) of concentration in its infinitesimal environment. The law of heat conduction is, by the way, of exactly the same form, 'concentration' having to be replaced by 'temperature'.

with the effect of the force to be measured and makes the single deflection observed insignificant. You have to multiply observations, in order to eliminate the effect of the Brownian movement of your instrument. This example is, I think, particularly illuminating in our present investigation. For our organs of sense, after all, are a kind of instrument. We can see how useless they would be if they became too sensitive.

THE $\sqrt{n}$ RULE

So much for examples, for the present. I will merely add that there is not one law of physics or chemistry, of those that are relevant within an organism or in its interactions with its environment, that I might not choose as an example. The detailed explanation might be more complicated, but the salient point would always be the same and thus the description would become monotonous.

But I should like to add one very important quantitative statement concerning the degree of inaccuracy to be expected in any physical law, the so-called $\sqrt{n}$ law. I will first illustrate it by a simple example and then generalize it.

If I tell you that a certain gas under certain conditions of pressure and temperature has a certain density, and if I expressed this by saying that within a certain volume (of a size relevant for some experiment) there are under these conditions just n molecules of the gas, then you might be sure that if you could test my statement in a particular moment of time, you would find it inaccurate, the departure being of the order of $\sqrt{n}$. Hence if the number $n = 100$, you would find a departure of about 10, thus relative error $= 10\%$. But if $n = 1$ million, you would be likely to find a departure of about 1,000, thus relative error $= \frac{1}{10}\%$. Now, roughly speaking, this statistical law is quite general. The laws of physics and physical chemistry are inaccurate within a probable relative error of the order of $1/\sqrt{n}$, where n is the number of molecules that co-operate to bring about that law – to produce its validity within such regions of space or time (or both) that matter, for some considerations or for some particular experiment.

You see from this again that an organism must have a comparatively gross structure in order to enjoy the benefit of fairly accurate laws, both for its internal life and for its interplay with the external world. For otherwise the number of co-operating particles would be too small, the 'law' too inaccurate. The particularly exigent demand is the square root. For though a million is a reasonably large number, an accuracy of just 1 in 1,000 is not overwhelmingly good, if a thing claims the dignity of being a 'Law of Nature'.