THE OBSTINATE REDUCTIONIST'S POINT OF VIEW ON THE LAWS OF PHYSICS*

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Abstract

The successes of the scientific method appear to imply that all phenomena in this universe, with all their variability and complexity, can be seen to follow from just a handful of fundamental Laws of Physics. This is called 'reduction'. If these Laws are all-embracing and unique, we may also have 'determinism'. These ideas have been uttered many times in the past. Paradoxically, modern science appears to deny the possibility to carry them to the extreme. This must be due to our present limited understanding.

1. Introduction.

With this lecture, I plan to concentrate on two basic philosophies of science, being *reductionism* and *determinism*. The two are closely related but they are not at all the same. Both are greeted with a fair amount of scepticism. One may believe in one more than in the other, but today one tends to regard determinism as a more extreme extrapolation of reductionism, and as such it is met with considerably more resistance, not only from

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the public[†], but also from many scientists themselves. The reductionist point of view, however, is also regularly under attack.

In the next 45 minutes, I shall explain as well as I can what these various notions imply, and how they developed in the past into what they are now. Our scientific views made a very profound change early in the 20th century. As for the future, I have reasons to speculate that changes in opposite directions may take place somewhere in this new century, but when and how is impossible to tell. Today, one must be very obstinate to carry reductionism and determinism to the extreme.

2. Reduction.

Let me first illustrate the notion of reductionism. When Isaac Newton discovered the general Law of Gravity, it was intended to explain in a concise way the motion of the planets in their orbits around the Sun: there is a simple force of attraction between any pair of masses, oriented in the direction of their separation. The planets simply accelerate exactly as dictated by these forces, which results in beautiful elliptical shapes for the orbits. It turned out, however, that the same law also prescribes the motion of moons around planets. The actual orbits are just slightly irregular, but this too can be explained using the same Law. If you assume that the motion of a celestial object is mainly controlled by just one other dominating object in its vicinity, then you find that its orbit is exactly an ellipse. Planets move in ellipses around the Sun, and a Moon moves in an ellipse around the parent planet. But if you take account of the influences of other bodies then the orbits are more complex. Jupiter and Saturn cause wobbles in the orbit of the Earth; the Sun causes the orbit of our Moon around the Earth to topple, and so on. All this is now understood in the most minute details. If you want to calculate how our Solar System evolves, then all you need to know is the masses of the planets and their moons, and what their positions and velocities were at one single moment, from where you start the calculation.

All these data, the masses of the planets and their initial positions, need to be registered at one particular moment. This is an elaborate list of numbers, but it is a much *smaller* list than what you would need to register if you did not know Newton's law. In that case, you would have to repeat the measurements of the positions of planets and moons at all times, and you would never be able to predict their positions in the future. This then is what we mean by reduction: the number of required measurements is greatly reduced, and not only does our knowledge of the Law of Gravity allow us to interrelate most of the measurements, but it also allows us to predict the positions in the future with great accuracy.

And then there is a bonus on top of that: Newton realized that the Law of Gravity, first intended to describe planets in the Heavens, also applies to apples falling from trees. Gravity is a dominating force on Earth as well as in the sky.

[†] 'public' here stands for all those interested lay persons who did not have a sound education either in physics or in philosophy.

Newton's Law of Gravity is a prototype of a result from Theoretical Physics. Since Newton, physicists have discovered numerous other such Laws, and each and every one of these gave rise to reduction, which is a way of saying that, *in addition* to measuring properties of physical objects, we could interrelate and foresee them. Maxwell's discovery of the complete set of laws controlling electric and magnetic fields is one other example. As soon as he found that, he realized that the same laws also explain many of the properties of visible light.

As for explaining the behaviour of inanimate objects, the art of reduction has reached a high degree of perfection in the hands of the physicists. For practically everything that we see happening in this universe of ours, we have Laws, and all that remains to be done, if we want to understand this behaviour and to foresee what will happen in the future, is to apply these Laws. In their most basic form, the Laws are known with great (though certainly not with infinite) accuracy.

These statements may sound surprising to some of you, or stupid and naïve to others, so I must elaborate a bit more what I intended to say.

Most of the known laws of physics actually form a hierarchy. For example, many processes that take place both in inanimate substances and in living organisms can be reduced to the *laws of chemistry*[‡]. All chemically pure substances obey laws that are characteristic and universal just for them. In turn, however, the laws of chemistry can be reduced further. There are numerous, practically infinite numbers of different substances, but their chemical properties can all be explained in terms of the laws by which electrons move around atomic nuclei. So we call this a *second step in reduction.* In turn, the laws by which electrons move in the vicinity of atomic nuclei can be further explained in terms of Quantum Field Theory, a universal description of fundamental particles. This chain of reducing steps ends at present with what we call *the Standard Model*. The Standard Model can be seen as a collection of fundamental equations describing quantized fields, and in principle they are not fundamentally different from Newton's laws, but they are much more universally valid. They together cover everything that we have ever seen or learned about.

Walking that ladder backwards should allow us to calculate everything under the Sun, but of course there are problems with this: the effects of the laws are difficult to calculate. What I said earlier about Newton's Laws, the fact that the presence of many planets and moons all exerting forces onto another makes computation of the orbits complicated, also applies here: we can calculate the behaviour of *one* electron near *one* atomic nucleus quite accurately, and also the case of two electrons and two nuclei can be controlled quite well, but in the real world there are uncountably many electrons and nuclei. In principle, we know exactly what the mathematical equations are that would have to be solved, we know how to solve these approximately, and we also know how to derive *exact* properties of more complex systems, such as the conservation laws of energy, momentum, and a couple

[‡] Indeed, biologists have made impressive progress in understanding the laws of life processes in terms of much more basic physical laws, in particular the ways inheritable properties are transmitted by genes.

of others. But our computers are slow and our ingenuity to identify simple patterns in complicated structures is limited, and this is why physicists cannot at all 'predict the future' even though they can write down the exact Laws, and we do know how to make statements about the total energy, momentum and some other features in the future.

The Standard Model is not known with infinite accuracy; in fact, we know that it can't be *exactly* right, because there are internal inconsistencies. These limitations[§], however, are known to be insignificant compared to two more basic obstacles. One of these was just mentioned, the fact that we cannot do our calculations with the precision that would be needed to explain everything we see in as much detail as we would like. The other fundamental obstacle is what we call *chaos*. With chaos we mean something that is very precisely defined: even if you know the masses and the initial positions of planets with enormous accuracy, and if you could do the calculations extremely precisely, you would still find that you would not be able to predict their positions at all times. This is because even the tiniest errors at one given stage of the calculation, might have huge effects at later stages. A well-known example of this is the impossibility to make long-time weather forecasts. Even though the equations that control the weather patterns on Earth are precisely known, the instabilities of the weather systems can give rise to sudden and totally unpredictable deviations on the time scale of days.

Before dwelling further upon the notion of reduction, and the question as to how far reduction can go, whether one will end up with God, as Stephen Hawking once speculated, let me first say a few things about *determinism*.

3. Determinism.

The notion of determinism is older. The Persian scientist, astronomer, mathematician and poet, Omar Khayyam (1048-1131), wrote in his *robā'īyāt*:

"And the first Morning of creation wrote /
What the Last Dawn of Reckoning shall read."

So, according to him, the initial conditions of the Universe were set at the moment of creation, and they were decisive for the entire history of the universe, including its very end.

But there would be other powerful thinkers in the early days. Benedict de Spinoza (1632-1677) was a Dutch theologian and philosopher, whose parents were refugees from Portugal. In his masterpiece, the *Ethica*, he wrote about the 'free will'. Can one reconcile such a notion with the idea that everything happening in the Universe is determined by how things were set at the moment of creation? His answer was 'yes!'! The fact that our

[§] For instance, the Standard Model contains quite a few 'adjustable parameters', or 'constants of Nature', but the effects that adjusting these parameters would have on daily life processes is generally so minute that trying to do the calculations more accurately in most cases does not help; only dedicated experiments could help us to identify as accurately as possible these unknown constants.

actions are determined by laws of physics has nothing to do with the fact that we can be held responsible for these same actions. We use our rational minds to decide what we do, and these minds do make use of knowledge of the laws of physics. I still find it amazing that someone of that time period can view this issue so sharply, whereas still many of today's thinkers continue to be fuzzy. Khayyam and Spinoza were among the earliest determinists, obstinately defending their views in a hostile world.

Also the famous French scientist Pierre-Simon, marquis de Laplace (1749-1827) concluded that, once the settings of all objects in the universe would be given at any fixed moment in time, both the entire future and the entire past of this Universe would be uniquely determined. Why not? This, at least, was the spirit of Newton's equations. In fact, you could even go one step further. Laplace realized that laws such as Newton's laws of the gravitational force, can be formulated as a *local law*. This means that the rules for the transmission of the forces can be phrased in such a way that they become *field equations*; formulating the law of gravity as a law for the gravitational field, one may deduce that the Laws of Nature only relate phenomena that take place at one single spot in space as well as time.

4. Quantum Mechanics.

All this appeared to be an inescapable conclusion from the deductive principles of science, but this picture was nevertheless blown to pieces by a monumental discovery in the early 20^{th} century. Investigations in the intestines of the atom revealed that, there, an electron appears to move *indeterministically*. In spite of the existence of laws of physics that are quite accurately formulated, they seem not to be of the type that, given positions and velocities of particles at any given time, one may compute their positions and velocities at other times. The only thing one *can* calculate is the *probability* that a particular measurement will give a particular result. Computation of these probabilities requires the knowledge of the so-called *probability amplitude*, which is more than just a probability. Apart from this very strange aspect, the dynamics of electrons is controlled by equations that are as restrictive and compelling as Newton's equations for the motion of planets in a gravitational field. We call this dynamical framework *Quantum Mechanics*.

The phenomena that ensue from this theory are astounding. They defy common sense. Albert Einstein was among the first - and by far not the only - to raise objections against the theoretical picture that emerged. He too was an obstinate determinist. Quantum Mechanics cannot be a correct description of what really goes on inside atoms; all it does, and this we must admit, is to give an accurate prediction for the outcome of any conceivable experiment on atoms, molecules and other tiny objects in Nature. The question that must be asked is what the *ontological* interpretation ought to be of this theory.

Many theoreticians however are cherishing the view that the questions concerning ontology are irrelevant. All one can do is experiments, and if the theory correctly predicts the outcome of any conceivable experiment, what else can one want?

This was a blow for the deterministic world view. And by the turn of the 20^{th} century into the 21^{st}, the picture became even less transparent. The latest theories for the elementary constituents of matter are the so-called superstring theories. These theories began by assuming that the most basic building material of Nature is a string, but gradually a more complex picture emerged, called *M-theory*: there are different ways to formulate what happens; all these pictures appear to be totally unrelated at first sight, but arguments are put forward that they must be "mathematically equivalent". If this is really so, we will never be able to decide whether there are strings, superparticles, membranes or other strange building blocks - they all would give exactly the same predictions for the outcome of experiments. It should be added, however, that these theories are extremely ill-understood. We do not know for sure whether these mathematical equivalence principles hold rigorously, or only approximately (that is, only in a specific 'corner' of all possible events). In fact, we do not even know how to give any rigorous definition at all of the underlying laws of physics.

These problems are so severe that another unanswered question is obscured: *How did the Universe start*, and: *Is the Universe infinite or finite?* Or, if the Universe is finite, what are its edges like? Are they fold together into some delicate shape? In the language of Quantum Mechanics, one asks: *What was the initial probability amplitude?* But then, one is not allowed to ask: "What does this mean, if for instance an 'improbable' event takes place? Was the amplitude for that improbable event small or large?"

5. Will Reductionism survive the new century?

Leaving the unanswered questions of the previous section aside, we might first want to ask: What does Quantum Mechanics imply for the reductionist world view? Can all regularities that we see in the physical world be reduced to a single handful of equations? Or is there only one equation? This question is usually answered in the affirmative by string theoreticians. They foresee an ultimate equation. We note that there is a fundamental distance scale in physics, the so-called Planck scale, which is the size unit of 10^{-33} cm. Structure smaller than that cannot exist. So, one argues, these may well exist a unique equation for structures at that scale, describing their motion and evolution. There are no sub-structures. It is our scientific experience that laws of physics may be absolute. If this equation, or these equations, have absolute validity then this is the end of the road for reductionism, the ultimate reduction. String theory strongly supports the idea of the ultimate reduction, but rejects determinism.

Theoretical physicists working on string theory however are ready to admit that they have not at all achieved this goal. Their equations are ill-understood. We do not know how to compute features of the Standard Model using these theories. The program of reduction has proceeded a long way but it is far from finished. And indeed there is a lot of opposition. How could this universe have become such a special and such a beautiful place if all its features were just the outflows of one or two simple equations? A fundamental technical problem is: *How could the universe have grown so large?* How do we explain the extremely coincidental conspiracy between various physical features that led to the complexity of chemical forces, which in turn must be responsible for the emergence of biological life? Can all these be natural consequences of just so few equations?

The obstinate reductionist now points towards the Standard Model. Admittedly, it is not just one or two equations but a handful. Also, the Standard Model contains adjustable parameters, called *constants of Nature*, and we do not know how these could be 'reduced'. We observe that the Standard Model *is* a handful equations from which the rest of the Universe can be deduced. We observe that the Standard Model is not perfect. The degree of 'imperfection' depends on the values chosen for the constants of Nature. The values deduced from experiments imply that the imperfection would only show up under circumstances that we are unable to realize in the laboratory. If we were, we would probably not only realize an improved version of the Standard Model, but also we would be able to reduce the constants of Nature further. The fact that we are unable to do this now, simply confirms our human ignorance, but does not imply the impossibility of a complete reduction.

In fact, one could use a 'religious' argument *in favor* of complete reductionism: if our experience has shown that a large majority of all phenomena in this universe can be reduced to some simple laws of physics, why should God Almighty not have succeeded in carrying this aspect of our world to an extreme perfection? If our present theories have not reached that extreme perfection, what else is there to blame than our own limited intellectual resources?

Considering the pace at which progress was made in the 20^{th} century, some physicists have predicted that the ultimate theory is just around the corner. To my mind this is a severe underestimation of the difficulties still lying ahead. Already we see a slowing down. The danger of a deadlock is looming in front of us. Particle accelerator machines may be approaching their theoretical limits within a couple of decades. Past history teaches us that human inventivity is nearly limitless, but the obstacles to be surmounted do seem to get higher and higher. As certain as I am on the possibility of the extreme reduction, I am considerably less certain as to whether humans will discover the ultimate laws in the foreseeable future.

6. Is there hope for determinism?

The case for determinism is even bleaker. Suppose we had a deterministic theory. If it were of a kind like Newton's equations for gravity, we still would have the problem of 'chaos' to cope with: the positions of the 'planets' would have to be described with exact, infinite precision — a hopeless task. The only way out of *that* difficulty would be to opt for a deterministic world where only integer numbers appear, like the positions of pieces on a checker board. No 'real' numbers such as positions or velocities in a continuous space are allowed. This we can imagine, though it already requires a drastic departure from our conventional views about the world we are in. The much more daunting problem is Quantum Mechanics.

According to Quantum Mechanics, particles have 'incommensurable' properties. The probability amplitude of a particle allows one to measure either its position or its velocity, but not both (at least not both with unlimited precision). But more importantly, the theory implies that a particle does not *have two properties* such as velocity and position, but only one. Only after it passed a measuring device, we may tell either its velocity or its position, but before measuring it, it did not have velocity *and* position.

Be this as it is, why should one 'want' to revert to a deterministic world view at all? Why not accept the facts that have been so clearly revealed to us by countless experiments as well as theoretical underpinnings?

As we already saw in Newtonian mechanics, there are two sides of the Laws of Physics: one is the 'local law', the law that tells us how a system evolves, given all required data at one prespecified time. The other side is the determination of the 'initial conditions'. Our 'ultimate reduction' would be unfinished if we had nothing to say about the initial state of the Universe. Sooner or later, one has to ask the question, how did it all get started? More to the point, we need to phrase the Laws in such a way that the question concerning the initial conditions is a meaningful one. This is where Quantum Mechanics has its fundamental shortcomings. The theory says: if you start out this way, you have such-and-such probabilities that you end up with that. Or: if you find this situation now, the odds that it was such-and-such in the past, are given by these calculable numbers. The theory cannot describe the initial state uniquely. Quantum Mechanics is an obstacle standing in the way of a completely reduced picture. You can't understand a physical law if you do not understand its boundary conditions. This is a difficulty that, in fact, emerged in a very technical manner when we tried to understand how quantum mechanics can be reconciled with the existence of black holes. Thus, the desire for a complete reduction leads us to seek for a theory that will supplant quantum mechanics by a deterministic underlying theory. In principle, it is only too natural to suspect that what we call Quantum Mechanics today is nothing more than a prescription, found empirically, for making the best possible prediction for the outcome of an experiment, and the fact that this prediction gives you 'probabilities' instead of answers with absolute certainty, could just be a reflection of our limited intelligence.

Neither position, nor velocity can be 'ontological' properties of an electron. If we want a deterministic theory, we need to introduce quite different notions. This has been attempted by many researchers. They always were confronted with questions of the following kind: What *is* the property of the electron that one measures in a detector? I have the 'free will' to measure either velocity or position. How does the electron 'know' in advance what I decide to do at that moment?

The problem turns out to be a technical one, and the answer to the question is difficult to discuss here. but the bottom line is clear: the 'free will' of the experimenter to measure either one or another property of a subatomic particle is Spinoza's free will: the experimenter himself, or herself, must be seen as being controlled by deterministic laws of physics just as much as the phenomenon that is being studied. The amazing conclusion that one has to draw is that the properties of a subatomic particle that one is about to measure are directly 'linked' to those laws of physics by which the experimenter is driven to do one thing rather than another. This is not an easy way out of our dilemma, and it will surely spark a formidable amount of discussion, but I believe that such conclusions will not only be tenible, they are also inevitable.