SCIENTIFIC KNOWLEDGE

SOME USEFUL

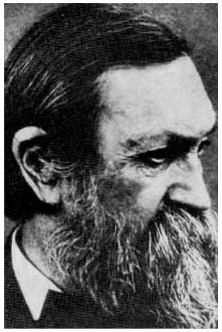
HISTORY 2

(Modern Era)

POSITIVISM, VERIFICATION, FALSIFICATION

The accelerating rise of science in the 19th century (including mechanics, electromagnetic fields, thermodynamics & the industrial revolution; palaeontology, The theory of evolution, genetics; rise of chemistry), led to even more empiricist ideas about what constituted truth, or knowledge, and what were "meaningful statements".

POSITIVISM: This philosophical movement began in the 19th century. Its foremost exponents was Ernst Mach in Vienna, who followed the empiricist line that experience/sense impressions were "primitive" (ie., could not be reduced to anything more basic), remarking that "*the world consists only of our sensations*"). Scientific Laws, according to Mach, simply linked sensations, & the only purpose of a theory was to provide quantitative links between measurements. Scientific explanation was then merely descriptive – in terms of measurements & data. Mach was actually an experimental physicist, which helped him spread his ideas.



Ernst Mach (1838-1916)

This movement then evolved under the influence of enormous advances in logic, made by, eg., Frege, and Russell & Whitehead. The result was

LOGICAL POSITIVISM: This began in the "Vienna circle, centred around M. Schlick – it also included R Carnap. Others who were members for a time were K Popper, L Wittgenstein, and K Godel. This philosophy argued that the meaning of any statement in language was found in the means used to empirically verify it – without such means, the statement was held to be literally meaningless. Hence all of metaphysics was held to be meaningless!

Obvious problems with this were (i) Is the criterion of verifiability itself meaningful (how is it be verified), and (ii) how is a scientific law verifiable, since experiments can only confirm it , not guarantee it.

M Schlick (1882-1936)

R Carnap (1891-1970)

FALSIFICATION: The remarkable philosopher Karl Popper advocated a somewhat different approach, which has enormously influenced practising scientists (most of all in biology). Popper argued that scientific statements were defined by a criterion of 'falsifiability' - scientists invent hypotheses about Nature which can't be conclusively verified by experiment (verification is merely inductive & cannot prove hypotheses), but can be falsified by a single experiment. This means that all scientific laws are provisional – we can never be sure of them.

K Popper
(1902-1994)

The most important laws have maximum simplicity, generality, & also extensive confirmation. Popper's ideas have been criticized, mainly because in practice falsification does not always kill theories, because the formulation & interpretation of experiments itself involves a lot of theory (so that one can question the theory on which the experiments is based, rather than the theory it is testing). In fact, it is impossible to test a hypothesis or theory on its own, since it always comes as part of a whole interconnected set of theories – so one cannot easily see what must be replaced or modified.

> Note the assumption here – almost unquestioned - that there is some sort of special "*scientific method*" which scientists are somehow using to do what they do, and which we are trying to somehow discover.

Later discussions of these all philosophical approaches have gone very far in different directions. Thus P Feyerabend argued that there was no such thing as a "scientific method"; that in reality scientists are opportunists who use whichever method works best; and that a rigorous "method" would simply prevent scientists from doing good work (and he gives lots of examples). The problem of course with this view is that it explains nothing – we then don't know how science works, or how it is different from non-scientific enquiry.

T Kuhn argued that science proceeds in many different ways – apart from "normal science" there were occasional "revolutionary" periods, in which all the rules changed, and after which everything looked different.

20^{TH} CENTURY SCIENTIFIC REVOLUTIONS

As the philosophers bickered over how science worked, 4 different revolutions, in science itself, proceeded to change many of the rules completely. Curiously, many working scientists seemed unaware of this – this is true even now.

1. CURVED SPACETIME: For over 25 centuries philosophers and scientists had tried to understand the nature of space and time. The Greeks had invented axiomatic geometry (now called "*Euclidean geometry*"), and had created logic & the axiomatic method in logic & mathematics. Newton had created a theory which we now "classical mechanics" involving absolute space & absolute time, and gravitational action at a distance through empty space. But in the 19th century Gauss, Riemann, & others showed that one could have curved geometries, and in 1915 A Einstein created the *"General Theory of Relativity"* ("GR") a single-handed feat which irrevocably changed our notions of space & time.

Remarkably, no experimental input was involved at all – Einstein pursued his vision and created the theory by means of thought experiments designed to elucidate the nature of mass, inertia, energy, spacetime, & accelerated motion. At the same time he employed the newly invented mathematics of curved geometries to create a formal theory in which spacetime was a field, just like the electromagnetic field, in which gravitation was a manifestation of the *curvature* of spacetime, and where the curvature was created by mass-energy, and then acted back on this mass-energy to accelerate it.

GR is now one of the 2 pillars on which modern physics rests. It has predicted everything from the Big Bang to black holes; our modern understanding of astrophysical phenomena would be impossible without it.

Einstein was strongly influenced by his reading of Hume and Kant; & yet his theory removed the foundations from all previous work. Space & time were unified into one dynamical object, the *"spacetime field"*, which carried energy, waves, etc., which could "curl up on itself" or collapse, and was as "real" as any other field.

2. <u>FOUNDATIONS of LOGIC</u>: Another extraordinary genius, again working on his own, did work which undermined what had been for 22 centuries the foundation of all rational thinking. In 1931 the Viennese mathematician K Godel proved that no sufficiently complex logical or mathematical system could be both consistent & complete ("sufficiently complex" was in fact very simple – his proof applied even to the system of arithmetic). Here "consistent" means that there are no contradictions in it; & "complete" means that all statements that can be made in the system are either "true" (ie., provable) or false (ie., their converse is provable).

It is hard initially to grasp the overwhelming consequences of this result. If wants to keep the idea of "proving" statements to be true or false – logically – one has to give up the idea that all statements *are* true or false! There will be statements for which the question is meaningless. On the other hand of all statements are meaningful, then Some may be both true and false! Apart from anything else, this completely undermines any completely rational view of the world and objects in it (including ourselves) <u>insofar as they are knowable to us.</u> Godel's reaction was to argue that the objects of mathematics are discovered, not invented (a Platonic view).

A Einstein with K Godel
in Princeton (c 1950)

One feels that Kant might have simply laughed at this and said "well, I told you that the real world is IN PRINCIPLE unknowable!" In any case we see that the work of Einstein and Godel had undermined the deepest foundations of physics & mathematics.

In their later years Godel & Einstein ended up in Princeton. On Einstein's 70th birthday Godel presented him with a new solution to his gravitational equations, which showed that one could travel along "closed time curves" in spacetime (ie., travel back in time). Einstein was baffled by this. We now know there are many such solutions – and we are still baffled.

3. QUANTUM MECHANICS:

Even more unnerving was the discovery of Quantum Mechanics (QM). In contrast to GR, this was the work of many people, & had a large experimental input. Its genesis was in the theoretical work of Planck in 1900 – he argued that to fix paradoxes in the theory of radiation, one needed to postulate that energy came in discrete packets, or 'quanta'. Later Einstein & Bohr elaborated these ideas – Bohr showing that this could explain the discrete spectra lines of atoms – and finally Heisenberg, Schrodinger, & Dirac gave the theory a complete form.

However the result was very strange. Physical systems were not necessarily in one state – they could be in *"superpositions of states",* ie., several at the same time. What was worse, quantum mechanics forbade us from having complete knowledge of these states – we could only calculate the *probability* that a system was in some state, & this probability was intrinsic – it was not possible to talk of the real physical state of a system, but only of the probabilities. As Bohr wrote,

> "***an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation"*** ***(Bohr, 1928)***

Thus quantum mechanics apparently rejects the idea of an underlying objective reality – many argue that quantum mechanics can only refer to our *knowledge* of reality, attained by observations & measurements. However many others (notably Einstein) have strongly opposed this dogma. QM is full of surprises – here are some:

Einstein-Podolsky-Rosen (EPR) states

Two widely separated QM systems can be put in a state $|\alpha\beta>$ (where the 1st system is in state α and the 2nd in state β). They can also be in $|\beta\alpha>$; and in a superposition of states like $(|\alpha\beta> + |\alpha\beta>)$. However in this last state all we can say is that they are in "opposite states". Neither of them has an individual state on its own.

Quantum Computing

One can use states like EPR states to do "quantum computing", exponentially more powerful than classical computing

Macroscopic Quantum States

In some systems, like superfliuids, one can have superpositions at our own scale, involving ~ 10^{20} particles.

4. The GENETIC CODE: The 4th great revolution began in 1953, with the elucidation of the structure of the DNA molecule in work by R Franklin, and J Watson & F Crick. The importance of this molecule for the inheritance of biological properties was clear from work that had been done by Avery et al. in 1944; biologists had been on the track of some sort of mechanism since de Vries had rediscovered Mendel's 1865 work on inherited traits.

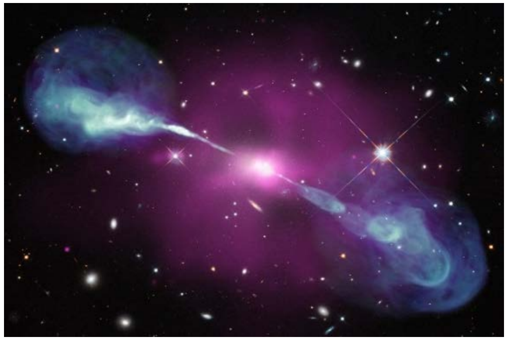
The genetic revolution unrolled in multiple steps. Key developments were

(i) Structure of DNA: this was the famous double helix, in which the nucleotides in each chain (these being adenine, cytosine, guanine, and thymine) pair off in the double chain, with adenine-thymine and cytosine-guanine pairs. Each chain is C-bonded, and so each chain stays together; but the H bonds between the nucleotide pairs are weak, so the molecule is easily "unzipped". This unzipping happens as part of the reproductive process.

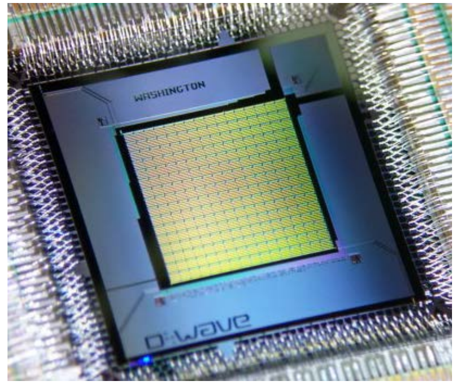
(ii) Genetic Code: As Crick realized, one could use the sequence of nucleotides as a code for the construction of proteins in the cell; by this means the inherited information is used in the construction of a new organism. In essence the DNA carries the blueprint of a new factory (the new organism), in which the construction materials are the proteins. The DNA unzips and then, via an RNA intermediary, the sequence of amino acids in the protein is "expressed" directly from the DNA chain sequence. The process is regulated by "transcription factors", and so not all sections of the DNA are expressed – indeed large sections can remain dormant for many millions of years as "junk DNA" (to be used when the need might arise, often under stress, when evolution can proceed extremely rapidly). The information flow from DNA to protein was called the "central dogma" of genetics by Crick.

Attitudes have changed over the years. Many changes can be inherited without going through the DNA, but simply by modifying the expression mechanisms ("epigenetics"). This is necessary anyway for *cell differentiation*. The role of inter-related metabolic cycles, which may even involve other organisms (eg., the bacteria in our gut & elsewhere in the body, and even further beyond), has also become of central interest.

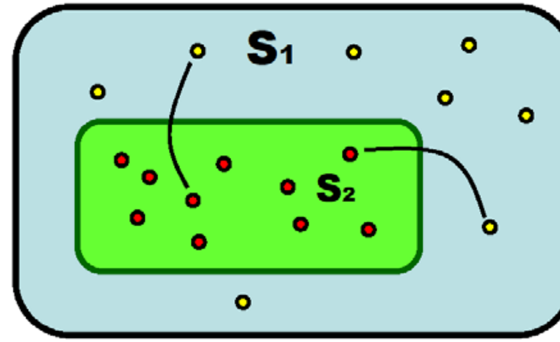
A PICTURE GALLERY of REVOLUTIONS



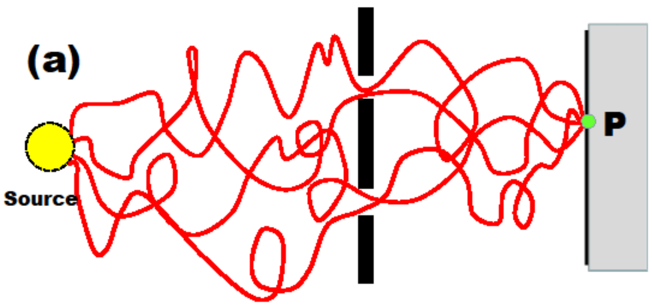
A supermassive black hole



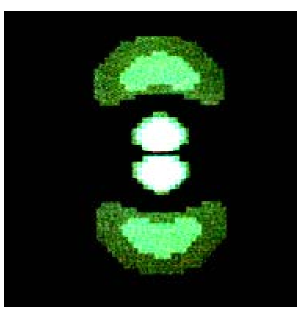
D-Wave processor (Quantum Computer)



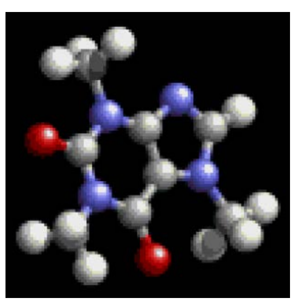
Godel numbering between system & metasystem



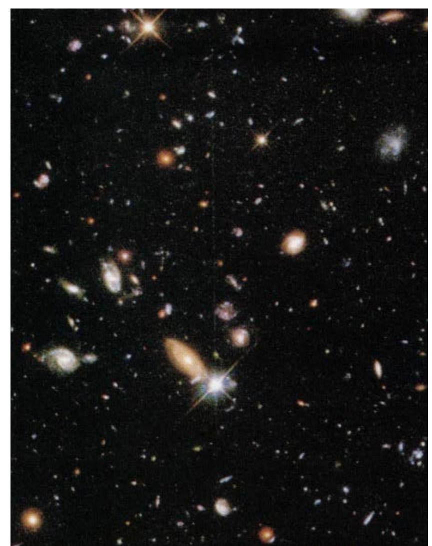
Sum over paths in quantum mechanics



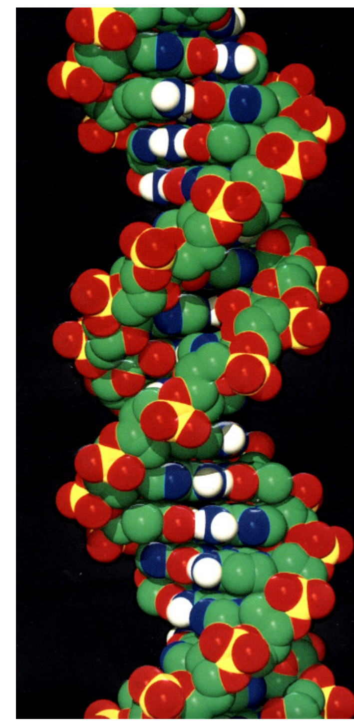
H atom – probability cloud



Caffeine molecule



Edge of the universe – Hubble deep space photo



DNA molecule

SOME KEY POINTS

These 4 revolutions seem independent from other but they were not. Thus, eg., the DNA revolution depended on (i) the understanding of chemistry at the atomic and molecular scale, including chemical bonds, which came entirely from QM; and (ii) X-ray crystallography, which was a discovery in physics which also needed QM to be understood.

The revolutions in Logic and GR were strongly & self-consciously driven by philosophical questions. Although the QM revolution was not, the eventual formulation of QM was very strongly influenced by certain philosophical doctrines, which many have been trying to strip away aver since. Philosophy played very little role in the genetic revolution.

All of these revolutions led to massive re-evaluation of the way science works, & the view of the world it gives. The revolutions in logic & physics showed that huge discoveries could be made at an entirely theoretical level, even as their observational (and eventually technological) consequences were overwhelming. But at the same time they made the world seem much stranger – nothing is what it seems, & the underlying reality is utterly different from what we experience. On the other hand the new vision of biology seemed to be completely materialistic.

Essentially everything in our lives, in the year 2020, is the result of these revolutions, along with one other – the "electromagnetic revolution" which sprang from the experimental work of Faraday and the theoretical work of Maxwell in the 19th century.