Writing Science: Part Two

What follows is an essay on complementarity written by the particle physicist Goronwy Tudor Jones of the School of Physics and Astronomy at the University of Birmingham and Alan Wall. It is offered as an example of writing which makes every attempt to be scientifically literate while remaining at all times available to the non-scientific reader.

A version of this paper was given jointly by the authors at the Description and Creativity Conference held at King's College, Cambridge, in 2005.

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Writing Science: Part Two

The Most Beautiful Experiment

Goronwy Tudor Jones and Alan Wall

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The Two-Slit Experiment with Electrons

Ask nature one kind of question, you get one kind of answer. Ask it a different type of question, you get a different type of answer.

Here we have the essence of what is sometimes called wave/particle duality, which is in fact an aspect of complementarity. And the experiment which exemplifies this doubleness at the heart of nature is the double-slit experiment with electrons, originally a thought-experiment dreamt up by the great physicist Richard Feynman, which was later performed. Its original purpose was to provide a conceptual non-mathematical introduction to quantum mechanics. Its ultimate performance gave exactly the results Feynman had predicted, and it was recently voted the most beautiful experiment in history. So what is it?

We fire electrons at a screen which has two slits in it. We know that the electrons are tiny subatomic particles, so they should form little piles in front of the wall behind the screen with the slits in, just as they would if they were bullets. That's what they'd do if they were behaving as we expect particles to behave (*Fig. 1*).

But what we actually get is something quite different, something so extraordinary that we must rearrange our notion of reality to acknowledge it. What we see shows us that the electrons are not obeying Newton's laws of motion, as bullets and cricket balls do (*Fig. 2*).

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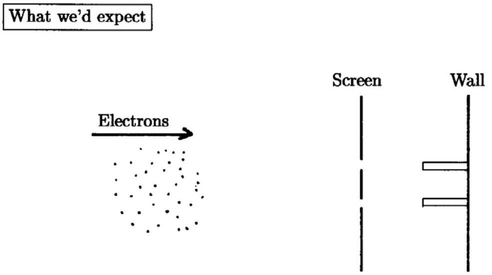

Fig. 1: Result expected if electrons behaved like Newtonian particles

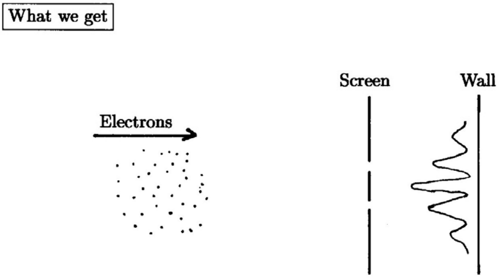

Fig. 2: Result obtained is totally different from Newtonian expectation

What we are seeing here is that the subatomic world is curiously different from our everyday, macroscopic Newtonian world, and the clue to understanding it is to study the undulating pattern of arrival points of the electrons at the wall. What we are seeing is something we know from elsewhere, namely the interference patterns observed in water if we drop two pebbles on to the surface at the same time.

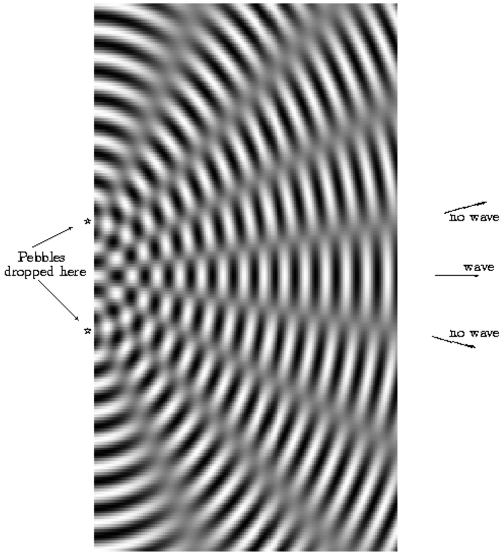

Fig. 3: Wave pattern caused by 'interference' of the waves from the two pebbles

In *Fig. 3* we see the recurrent patterns: first a strong wave going to the right, then a weak one on either side at about 15 degrees, then another strong one… If two equal waves meet, crest with crest and trough with trough ('in phase' to use the physicist's jargon), they double their size; but if, where they meet, the crest of one wave arrives with the trough of the other, and vice versa ('out of phase'), then they cancel each other out. This is classic wave behaviour. So what we see is this: in the two-slit experiment the individual electrons arrive like particles in particular places – you can count them in one by one on a detector - but by the time that they have all arrived at the wall they will have distributed themselves in a two-slit wave interference pattern. How can this possibly be?

The double-slit experiment informs us that the electron is apparently behaving as both a wave and a particle (and light particles, photons, behave in the same way). This contradicts what had for centuries been a fundamental tenet of science.

Waves and Particles

It had always been believed that energy could arrive in two forms, either as wave or particle, but never as both simultaneously, since they were exclusive states. A particle goes from A to B, and having left A it must either now have arrived at B, or at some intermediate point between. I cannot say of any particle that it is both at A and at B. This would contradict our perception of reality. But a wave is an oscillating disturbance moving either through space or some other medium. It does not need to transpose matter from A to B; it can move energy from A to B while leaving the original matter at either place. A wave might have begun its motion a hundred miles away across the ocean, but the present disturbance I am witnessing before me is constituted entirely by local water. So the wave can be at A and B at the same time. One sees why the two states were thought to be mutually exclusive.

We know for certain that the electrons arriving for the double-slit experiment are particles. We can even count them if we choose, but we have also seen how they finally form patterns of diffraction and interference. In other words they are making wave patterns. Depending on what measurement we make, we might be observing the electron as a particle or as a wave.

The double-slit experiment appears to be informing us that the electron is behaving both as a wave and as a particle.

2

For centuries scientists had argued about the nature of light – was it a particle (or a corpuscle, as Newton would have said) or was it a wave? Newton thought it was probably a particle, Huygens and Euler a wave. Thomas Young in the early nineteenth century created a very primitive double-slit experiment and established that it was a wave. Later on, waves became more and more important in analysing the rudiments of matter; in Clerk Maxwell's electromagnetic world, waves are at the root of everything. Then, in the early part of the twentieth century, it was discovered, to everyone's astonishment, that light is in fact both wave and particle.

It was in 1900 that Planck postulated that light energy is granular, which is to say that it arrives, not in a continuous stream, but in quanta (small packets) known as photons. These tiny units are what give us the name and identity of quantum physics, and there were many more implications to his discovery than Planck realized at the time. Electromagnetic radiation, for example, could only be received or emitted in certain fixed quantities. What we perceive as a continuous stream of light is in fact discontinuous; it is made up of photons. In which case we now knew for certain that light was made up of particles. So surely that meant it couldn't very well be a wave as well, could it? But the answer to that question is in fact a decided 'Yes'. Nature responds to alternative modes of questioning with different answers. It is reported that on her deathbed, Gertrude Stein was asked by her long-time companion Alice B. Toklas, 'What's the answer, Gertrude?'

To which Gertrude sensibly replied, ‘Well, what’s the question, Alice?’ She was exemplifying complementarity.

3

Let us return to the two-slit experiment with electrons and see how it has profound philosophical implications for us all. We can never predict the individual behaviour of any of the particles; where they will actually end up against that wall. Imagine two physicists, A and B, setting up the experiment identically in different parts of the world, letting electrons through one by one, and recording their arrival points. There would be absolutely no correlation between the arrival point of the first electron in A’s experiment and that of the first electron in B’s; nor the second, nor the third. However, the final patterns of arrival – see *Fig. 2* above – would be the same for both.

Now here is the key to understanding one crucial aspect of complementarity: we can forecast the overall behaviour of particles in massive numbers (what we might call the **statistical model**), but we can never know where an individual particle will arrive (the **dynamic model**). Or, to put the matter differently, we can foretell the patterns of probability, but never the arrival points of an individual particle. Such unresolvability at the heart of matter has come to alter the way we think of reality. It has put a question mark over the whole issue of causality and determinism. We must look back a little into scientific history to see if we can situate this dilemma in a longer perspective.

Classical Determinism

Let us think about Laplace.

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Laplace once boasted that, given the 'initial conditions' – the position and velocity of every particle in the universe at one instant – he could, in principle, predict the future with absolute certainty. This was based on Newton's Second Law of Motion: if at some instant we know (1) the position of an object, and (2) its speed and direction of motion, then, using Newton's Second Law, which tells us how the motion of an object is changed by a force, we can predict its future motion with inevitability and exactitude.

Modern physics has shown this to be untrue. It has demonstrated that at the very heart of matter, and therefore at the centre of any physical system at all, there is a dynamic which is unpredictable. The unfolding of reality can never be foretold in the manner Laplace once imagined it could. Determinism in his sense, based upon a strict, predictable causality, is quite simply impossible, and the reason why this is so is one aspect of complementarity. The mystery that constitutes the essence of modern physics displays itself for us here in the double-slit experiment.

Let us examine two logical terms: causality and contingency. Causality is the kingdom of necessity; what must happen happens. So what is contingency? Contingency is the realm in which it might happen, but doesn't have to. It might not happen, but it could. When an accountant sets up a 'contingency fund', he is allowing for possibilities as yet unforeseen. Now what Laplace was saying about systems and their predictability was that he could translate all contingency into causality, given sufficient information. Some even transposed this unlimited causality to human behaviour, concluding that all of our actions are therefore predetermined. This is classical determinism, and it held sway for a long time; but no longer. Unpredictability in the movements of elementary particles, shown in the double-slit experiment, enshrines contingency at the very heart of reality.

And there is a further caveat. This is in relation to the observer and the observing machinery. Niels Bohr (who first formulated the Principle of Complementarity) said that the apparatus must be seen as part of the phenomenon. What does this mean? Heisenberg's famous Uncertainty Principle (another aspect of complementarity) establishes a simple law in regard to the atomic world: we can observe the velocity of a particle or its position, but not both simultaneously. The reason is that the energy we bring to bear on the observed object changes the state of that object. The energy contained in the light I shine to see where a particle is alters its state (defined by its position and velocity) by injecting new energy into it.

All energy has its effect. If I go out into my garden and shine a torch at the moon, I have directed a certain amount of energy into the cosmos, even though the cosmos contained that energy in the first place. But my torch shone at the moon does not represent enough energy to alter the celestial body I wish to observe; nor would a high energy cosmic ray photon (or gamma ray). But such a gamma ray hitting an electron would knock it clean out of the atom.

A spiralling track such as the one shown in *Fig. 4* (approximately life-size) is a common feature of bubble chamber pictures. They are produced when an electron is knocked out of a hydrogen atom in a tank of liquid hydrogen. As the electron forces its way through the liquid it heats it, making it boil, and leaving a trail of bubbles in its wake. (The curving is produced by a magnetic field.)

In the atomic and subatomic worlds, the seeing alters the seen.

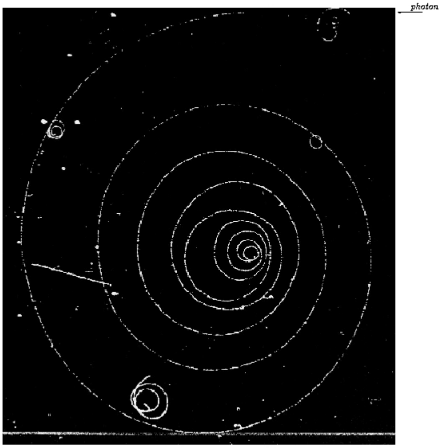

Fig. 4: Spiralling electron tracks in bubble chamber

4

'We are suspended in language,' Bohr often remarked. In trying to express scientific truths we employ language, and language is inherently metaphoric. It is important that we understand this before proceeding, because the problem – it might even be an opportunity – will recur. A crude form of scientific triumphalism once asserted that the language of science presented the literal truth, whereas art in its linguistic form was merely decorative. This was the essence of Thomas Sprat's mission to dispense with what he called 'this vicious abundance of phrase' – he was actually speaking of metaphor - when he wrote his *History of the Royal Society*. During the early part of the twentieth century, there was a movement in philosophy and linguistics which has since been dubbed 'the linguistic turn'. One aspect of this movement acknowledged that all language is inherently metaphorical; that there is no escape from 'metaphorical richness' to 'literal plainness'. Much of Wittgenstein's later philosophy is concerned to make us aware of the extent to which the inherent metaphors in the language we use prompt our thoughts in one direction or another, without our even being aware of the fact. Language itself is here foregrounded, not as the neutral medium through which truth might pass, but as a shaping and structuring world which the speaker, writer and thinker is forced to inhabit. If we are 'suspended in language', then the nature of that language dictates the circumstance of our suspension.

Much of what we call modernism in the arts asserted the supremacy of form. Once again the medium wasn't neutral, existing as a realist device for the unproblematical transmission of a truth content, but was in itself the bearer of form, the very manner of truth's transmission. Artistic form was no longer a matter of surface detail, or the mimicking procedures of illusionism, however exquisitely turned: it determined and structured the truth of the content within it.

This is curious, because at exactly the same time, in a scientific parallel, quantum mechanics was asserting the supremacy of form in reality. The quantum revolution discovered that the world is not one of infinite attenuation, as classical physics had supposed, but is a world of identifiable forms, even if those forms are statistical and probabilistic. An atom can take this form and this energy or that form with that energy, but nothing in-between. In fact there is no 'in-between'; 'in-between' here is an impossibility we play with, so as to try to understand what the real possibilities actually are. If a particle is in the ground state, then a fixed amount of energy is required for it to shift to one of the excited states above it. If the energy provided is less than that, it will not be accepted. There is this form and that one; things are either thus or thus; the nothing that lies between them is not truly expressible even as 'nothing'.

But we remember that our way of looking in the microcosmic world is also structuring the reality as it is perceived. Just as philosophy foregrounded language in the linguistic turn, and the modernist arts foregrounded form, so physics foregrounded its own method of observation in complementarity. The apparatus, said Bohr, must be regarded as part of the phenomenon. The observing/measuring process affects what is being examined.

A thought experiment. Let us make a hydrogen atom, by putting an electron near a proton. Wave-particle complementarity allows us to regard a hydrogen atom as a confined electron wave. We know about confined waves from music: only certain notes (frequencies) can be played on a string, and these are notes with wavelengths that match the length of the string. The string can only be in states that play certain frequencies, while others are not allowed: frequency, in other words, is quantized.

And it is the same in the hydrogen atom: the electron can only exist in certain quantum states which have characteristic shapes and well-defined energies (see *Fig. 5* below); nothing in-between is allowed. There is no in-between. Things are thus or thus.

And here we have another radical peculiarity. The quantum world is full of them. If, in our attempt to find out how these particles passing through our double-slit, one by one, end up as interference patterns, we set up some equipment so that we can monitor which hole each electron actually passes through – for example, we could scatter light from the electrons as they emerge from the slits - the interference patterns disappear. The mystical explanation for this is that the electrons choose not to be observed so closely; the unmystical explanation is that we are once again bringing energy to bear upon the situation and altering it. The apparatus is part of the phenomenon. Scattering light (photons) from the electrons disturbs them enough to smear out the interference pattern.

Now we return to metaphor, and see why it is so important to understand that we are 'suspended in language' and that language is never neutral. When Bohr and Rutherford first created their 'solar system' model of the inside of the atom, they were in effect creating a form of metaphoric perception. This is very common in science. The difference between the use of metaphor in literature and science is largely this: in literature the metaphor often decays into cliché; in science it is usually tested to destruction, then replaced. Let us try to be a little more exact about our use of metaphor here, since it is being asked to cover a large ground.

A metaphor brings together two elements of dissimilarity which nevertheless can be perceived to share elements of similarity. In the dissonance between the dissimilarity and the similarity we generate an intellectual energy which is provocative of thought. 'The moon is a balloon' the singer tells us, and we accept what is in one sense an inherently ludicrous comparison because of a number of striking points of similarity. Both objects are round(ish), and the balloon is trying to rise into the sky. The fact that we know the moon is not 'floating away', but is held in its orbit by the pull of gravity, does not invalidate the momentary perception of the singer, particularly if he is informing us that he is in love and therefore, in an age-old tradition, sees all celestial bodies as shining upon him, and winking at his good fortune, which appears to be ballooning by the minute.

The metaphor is neither the moon nor the balloon; it is the compounding of the two into a single phrase or image. Science uses metaphor in a similar way: it says, let us say that ‘this’ is ‘that’, and see what happens. To say that ‘this’ is ‘that’ makes us think very closely about what we mean by ‘that’ and to see to what extent ‘this’ really corresponds to it. We can only pursue the model, only examine the metaphoric connections and interactions, for as long as they retain some credibility. Science is provisional, in that it always puts itself to the test by checking hypotheses against experiments. If it ceases to do so, it ceases to be science. And this is precisely what happened with the Rutherford-Bohr model. Let us say that ‘this’ is ‘that’. Let us say that the inside of the atom is a miniature version of the solar system. The nucleus was seen as the sun, since it was a massive entity at the heart of the atom. Except for one thing: the more the metaphor was looked into, the more ragged the model it presupposed became. In science the rapid exhaustion of a metaphor means that great progress is being made.

Why did the metaphoric interactions wear out so quickly? Well, if electrons were really orbiting the nucleus as planets orbit the sun, then they would be losing energy constantly in the process – this is what Maxwell’s electromagnetism tells us. But if they were constantly losing energy, then the electrons would spiral into the nucleus and the atom would not form. So how is it then that the electrons don’t make it down as far as the nucleus? The answer to that question lies in wave-particle complementarity and the quantum states. These images (*Fig. 5*) are not photographs but pictorial representations of the results of quantum mechanical calculations. They show

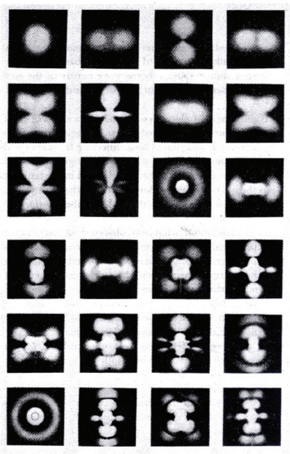

Fig. 5: Images of the quantum states – the fundamental shapes of nature

the shapes that atomic quantum states can take. The molecules that are made when atoms combine – for example, when two hydrogen atoms and an oxygen atom combine to make a water molecule – must reflect these shapes. Every water molecule is the same because of this – the lines joining the centres of the hydrogen atoms to the centre of the oxygen atom make an angle of about 105 degrees with each other. So these quantum states are the fundamental forms that determine what kind of matter can be produced in nature. That scientists can meaningfully talk about how the Universe has evolved, or can 'create' new materials not yet discovered in nature, is a consequence of the immutable nature of these quantum states. (Not one of these states allows the electron to reside on the nucleus.)

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Contraria sunt complementa: this was the legend that Bohr incorporated into his own device when he was awarded the Danish Order of the Elephant.

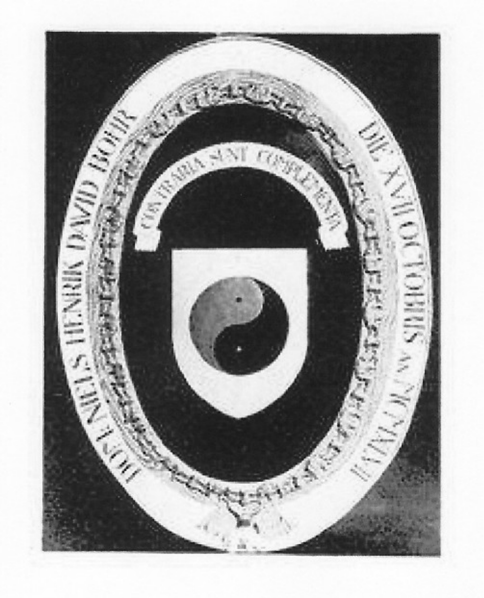

Fig. 6: Niels Bohr's Coat of Arms

Contraria sunt complementa: contraries complement one another. What can this mean? It connects with another statement of Bohr's: that all great truths are equally true the other way around; that the contradiction of any great truth is also valid. This only applies to great truths though, not superficial ones. We must look for a moment at the notion of contradiction.

The word *contradict* comes to us from the Latin *contra* and *dictare:* to say against, to gainsay. In a logical system a contradiction signifies error. If a classical physicist made two statements, that firstly, **P** is a particle, and secondly, **P** is a wave, then assuming we are speaking of the same **P**,

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both statements cannot be true, since the condition of being a wave excludes the simultaneous possibility of being a particle. In the system of classical physics, **P** could either be described as wave or particle, but not both, not if wave and particle are defined (as they were) as mutually exclusive modes of travel for energy. And yet the double-slit experiment demonstrates over and over that electrons and photons behave as both particles and waves. How could we possibly come to terms with this? *Contraria sunt complementa*. We had to stop thinking either/or, and think instead both/and. It might be worth acknowledging that this has altered the notion of thinking itself. We have entered the new age of quantum enlightenment. Quantum mechanics has generated its own quantum logic. And we might also need to consider what we mean when we name something.

Parenthesis on Naming

For thousands of years we have tried to name the elementals: those rudimentary facts of nature beyond which we cannot go: earth, water, fire and air. They were thought for many centuries to be the ultimate ingredients of matter and energy – the elements. We don't think so now.

Water we say isn't an element; it's a molecular compound. Two atoms of hydrogen combine with one of oxygen and the molecular structure produced is what we call water. Even at the time of Lavoisier, scientists were still thinking of fieriness as a separable substance which permitted the flaming of certain entities. The name for this substance at this time was phlogiston. Now if there was something called phlogiston which burnt away during the fire, then presumably the substance after the burning should be lighter than the substance before. Measure it then: the clarion call of modern science. Take a small measurable aspect of reality; observe and quantify it: this is the key to experimental science since Galileo, and it is what set Galileo so firmly in opposition to Aristotle. In fact it was soon discovered that if you slow-burn tin in a sealed container, the ash at the end of the process weighs more than the tin you began with. Phlogiston evidently can't have departed then – something had been gained, not lost. So out went phlogiston. Fire is not one of the elements; it is rather an emanation from a chemical process involving a number of elements.

How elemental 'fire' is or isn't depends on our view of reality. Each type of naming involves a different conception of the world. And this is true of all naming processes; the names we assign to reality articulate our conception of the world we inhabit. For a long time we used the word atom (employing its Greek etymology) to mean the last indivisible unit of matter: you couldn't go any further than an atom. Atoms were as infinitesimal as the material world could get. In fact the last hundred years have shown that we can get considerably more infinitesimal than that. We now speak of electrons and quarks. In naming the particles we are assigning identities to the aspects of reality we have uncovered. We are saying that certain aspects of reality are characterized by a certain composition, and we can rediscover such identities over and over again. The perceivable structure has expanded.

Imagine that I say, 'I met Picasso once' and you reply, 'Really? Which one?' One of us is in the wrong language game. Because here 'Picasso' refers to a particular unmistakeable character, a diminutive Spanish genius of the visual arts. To name him is to conjure forth that particular identity; only ignorance could produce confusion. But now imagine I said, 'I met a Spanish painter once' and you replied, 'Really? Which one?' Your question is entirely valid, even though 'Spanish painter' is one accurate description of Picasso. Why the difference? Grammatically we could say the distinction lies between the realm of common nouns and that of proper nouns. A common noun provides us with a generic class; a proper noun with an individual. What does individual mean here? It means an object or being capable of the retention of specific identity. Picasso is identifiable by his work; his face; his lovers; his homes; his statements. But if I remain in the realm of generality, then I cannot attribute specific identity. All I know is that someone paints and is also Spanish. Beyond that I can only speculate.

In the atomic world there is no retention of specific identity, which is why we must try to be clear what we mean by 'naming' in this sphere. Since celestial systems were so often used as the basis of metaphoric models for atomic ones, let us return to this theme. We can identify the specific celestial body we call the Moon by various techniques. Photographic images of its surface, with all its craters and mountains, would make it familiar to the eye of a practised astronomer. So we should be able to distinguish this moon from others in the universe. We should be able to distinguish 'Moon' from 'moon'; this is only possible because of the retention of identity.

In the world of the atom this does not apply. There is no retention of identity for atoms or particles. And this means we cannot meaningfully speak of the history of a particle; only of its state, its position or its velocity. (Here we are being precise: in the quantum world, the state of a particle is given by its position or its velocity – the Heisenberg Uncertainty Principle.) It is meaningless to say this specific carbon atom came from Siberia; that one from North Wales. That is to employ the wrong language. In the atomic world there is no Moon; only moons. There are no proper nouns; only common nouns.

It is important to grasp this because the double-slit experiment provides us with a certain type of information which is only meaningful in the light of this non-retention of identity. If we release particles one by one at the slits, sooner or later diffraction and interference patterns will still appear on the screen. How can this be? Are the individual particles interfering with themselves? A pattern of probability is being built up, a pattern that forces us to think in terms of statistical realities, not dynamic ones. We mustn't carry our metaphoric relations from the macrocosm into the world of the microcosm; if we do we will confuse the issue and find the realities being observed even more baffling than they were to begin with. 'We are suspended in language' – Bohr was right, we are, and for that reason we must be aware of the potency of language, particularly in its metaphoric forms.

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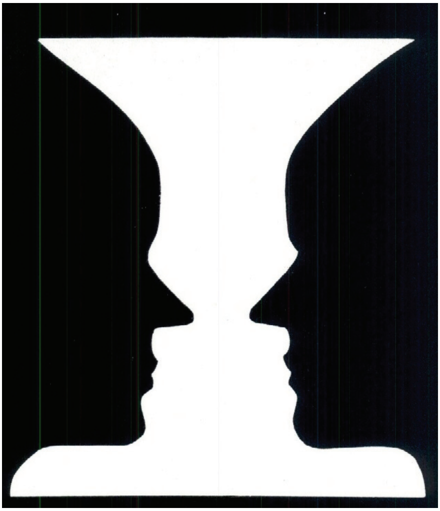

Fig. 7: Wine glass or two faces?

There are a number of images known as 'figure-ground images', one of the most famous being the 'faces and the wine glass' reproduced here. What characterizes the image is this: depending on what portion of the picture you focus as background, and what as foreground, you will see different things. You will see either two faces or a glass. Switch foreground and background and you will now see the alternative. But you can't see both at once. Either the black background is foregrounding the white glass or the white space is now a background to the black faces. This image operates as an emblem of complementarity. We elect planes of reality for observation; the foregrounded plane to some degree makes the background invisible in formal terms. We can see waves or particles; we can determine the velocity of a particle or its position, but not simultaneously.

What we are looking at here is a process of epistemological selection: the notion that we have to elect a form of knowing, and that it will not be all-inclusive in any of its individual modes. The mode of knowing also has its effect upon the identity of the known: the apparatus is a part of the phenomenon. Laplace never anticipated this. He thought truth could be all-comprehending, encyclopaedic and monocular. He thought that observation could be neutral. He believed that metaphors could ultimately be left out of the description, as fanciful. Reality has turned out to be far more baffling; it doesn't yield itself up for universal comprehension quite so easily. Modern physics has discovered mysteries as profound as anything ever imagined in the arts. It has also found itself in agreement with that most anti-scientific of poets, William Blake: 'the eye altering alters all.'

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Fig. 4, showing a bubble chamber picture of spiralling electron tracks, is reproduced by kind permission of the University of California, Berkeley.

Fig. 5 is reproduced from H. E. White, *Physical Review*, Vol. 37, 1416 (1931).

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