

SCIENCE AND COMMONSENSE

Jon Ogborn

Institute of Physics, London

For imagination is different from either perceiving or discursive thinking, though it is not found without sensation, or judgment without it. That this activity is not the same kind of thinking as judgment is obvious. For imagining lies within our power whenever we wish, ... but in forming opinions we are not free: we cannot escape the alternative of falsehood or truth.

Aristotle: *De Anima*

INTRODUCTION AND OVERVIEW

It is widely accepted that students bring to science lessons their everyday commonsense knowledge, and use this as part of understanding the science they are taught. However, the relationship of scientific and commonsense knowledge is too often trivialized, for example treating scientific knowledge as abstract and common knowledge as concrete. This article attempts to discuss each, and their relationship to one another, more deeply.

The discussion is organised under four main themes:

- The nature of scientific knowledge and reasoning;
- The importance of science and of its role in the development of rationality;
- The nature of commonsense knowledge and reasoning;
- Differences and similarities between science and commonsense;

Finally, I discuss some implications for the teaching of science.

SCIENTIFIC KNOWLEDGE

Science is reality re-imagined. It populates the Universe with an ontological zoo of entities, some mundane and at one with commonsense, some exotic and beyond but not disjoint from common experience; but some almost beyond belief, and some which seem to be purely theoretical fancies. What distinguishes this zoo from certain others is that its denizens are taken to be real. That is, once imagined, they are taken seriously as actual constituents of the physical world, existing and able to act or be acted on in their own proper ways without regard to what we may wish or expect. The scientific imagination, in Aristotle's words, is not free. The imaginings which do not survive this attribution of reality to them are in the end discarded. And because reality is no respecter of persons and their imaginings or opinions, this test makes science in some degree impersonal.

The organisation of scientific thought can be thought of as a dialogue between the transactional world of thought and imagination, which is free, and the intransigent world of brute reality, which is just as it is.

Figure 1 suggests what is involved in the attempt to construct things in the imagination which can, without known contradiction of fact or incoherence of concept, be supposed to exist independently of the imagination.

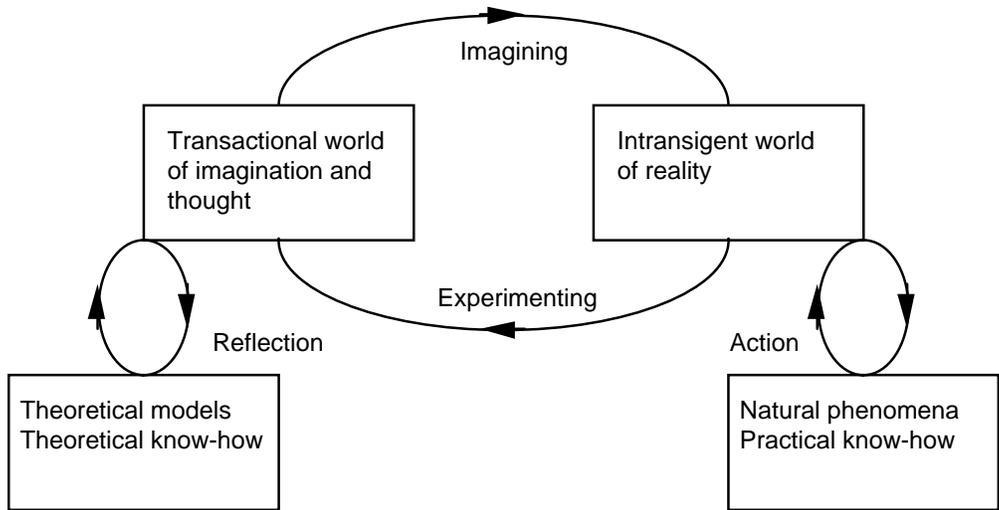


Figure 1 Organisation of scientific thought

The need for imagination

Everyday experience teaches us that the world is not always just what it seems: fish lurk in the depths of the sea, disease hides in left-over food, traits pass from parent to child, the seasons recur without obvious cause. To understand how things are we have to imagine, or hear imaginative tales, about how they are 'inside' or 'behind' the surface. Not everything can be read straight off the face of reality. The upshot of a few centuries of development of scientific knowledge is that the imagination turns out to be a great deal more important in understanding reality than might have been supposed. Surprisingly *little* can be taken to be just what it seems to be: the hardness of a stone turns out to depend on the strength of certain chemical bonds, and the colour of a flower to be both a quantum phenomenon within certain molecules *and* whatever is needed to attract insects to do part of the job of making a new plant with those flowers.

The need to constrain imagination

Wishing, or imagining, does not make it so. In envisaging how things may turn out, or in giving ourselves explanatory stories about why they turned out as they did, we are all-too-prone to wish-fulfillment. We are prone to false satisfaction as soon as a story first gives a good account, and then to invent excuses for it when it fails. The scientific mode of thought is to deny this temporary satisfaction and to try to imagine the world in such a way that the stories told about it *can not be faulted*. Doing so is not so much an obsession with consistency or absolute truth, as an acceptance that reality is independent of our fancies and does what it does without regard to what we would like or imagine.

The need to experiment

Reality is complex: its ontological zoo of entities can combine or annul each others' behaviour in many ways. It is a matter of common experience that things rather rarely turn out the same way twice (which makes the rather regular behaviour of the heavens especially astonishing, attractive and seemingly transcendent). For this reason, our imaginings cannot be tested merely by looking around us. If we want to try to see some imagined entity acting alone, we have to limit and control the actions of entities which may disturb or conceal the behaviour of the first. Thus we are

driven, in Bacon's words, to vex Nature, deforming natural states of affairs so as to simplify them and to disclose more clearly the behaviour of a given entity.

Knowledge is needed to experiment

It is, however, not possible to experiment 'blindly'. Since the need is to limit the interference of other entities on the one of interest, we need to know a good deal about those we want to control. We need not know everything, however. If we know that microbes are killed by heating or that they cannot get through glass, we can lock them out of an experiment without knowing exactly what they are or how they work. We need not know the source of a magnetic field to shield against it. In this way, experimental work can gradually get off the ground, bit by bit. But it cannot get off the ground with *nothing* to go on, which is why experimental investigation of some phenomena (e.g. consciousness) has barely yet been able to get started.

The need for practical know-how

A great deal of what we know is practical know-how rather than science. Lighting fires, making pots and glass, smelting metals, cooking, and looking after crops and animals are all mainly activities of this kind. Besides its everyday practical value, this practical know-how is an essential input into the doing of science. We use it to find out what some of the entities in the world can or cannot do or have done to them, so that experimenting can get started. But above all we use it as a source of imagination: is there fire hidden in wood? is there metal hidden in stone? And these imaginings get their meaning, not from definitions but from action; from the practical active know-how which underlies them.

The need for imagination to discipline itself

Not only is the scientific imagination disciplined by projecting imagined entities onto reality and living with the consequences; it is also disciplined by its own inner necessary consequences. The imagination is free to construct whatever entities it likes and to attribute them with whatever nature and behaviour it wishes, but having done so, definite consequences follow. If one imagines organisms breeding at a constant rate, then it follows that their populations will increase exponentially; if one imagines an interlocking set of chemical reactions then it follows that there may be regimes of stability or instability; if one imagines fields carrying energy then it turned out after a time to follow that they must also possess inertia and gravitate.

These facts have bred a whole autonomous activity, namely the investigation of the consequences of imagining various kinds of theoretical entity or structure, and the precise imaginative sources of the various necessities which are uncovered in them. Thus science acquires a stock of theoretical models which can be put to use, but which can also be played with and investigated for their own sake, sometimes in the process generating new ones (e.g. non-Euclidean geometry and chaos theory).

The need for theoretical know-how

Work on the consequences of and relationships between various theoretical imaginings has built up a body of theoretical know-how. It is to the imaginative choice as practical know-how is to practical choice. As theoretical knowledge builds up, theoretical know-how (such as how to solve a given kind of equation, how to make a good approximation), has come into being, together with a large number of theoretical concepts which help to organise and codify this knowledge and know-how. The scientific imagination is fed by this supply of models and of knowledge of

their behaviour, acquiring new resources and new language for thinking about how things might be. Scientific imagining thus becomes more flexible and more efficient, able to go down more adventurous paths and sometimes better able to avoid going down ultimately hopeless paths. And again, the meanings of imagined ideas and concepts derive from action, this time mental, from trying ideas out and seeing how they work.

Models as controlled thought experiments

The real world being as complex and messy as it is, one can never be sure of being in control of any experiment, however carefully thought out it is. The only way to have a world about which one knows *everything* is to make it oneself. Thus the great virtue of models is that we know that when they go wrong, the fault is entirely ours and is not some hidden accidental natural complication. The certainty they give has not to do with some magic of deductive logic, but with the fact that nothing is hidden. This is of course not to say that there are no surprises: that simple quadratic equations had the Mandelbrot set hidden amongst their consequences is one such startling example.

Models also provide a kind of scientific play, which experiments with ideas and representations. Because they are in a simplified, 'stripped down' form, one can sometimes see through to certain essentials: that some kinds of consequence cannot be avoided in a given kind of model, whilst others could never be achieved in that way (for example, decay with rate proportional to the amount left *must* be exponential).

Scientific explanation and 'the obvious'

A scientific explanation is a story. It is a story about how some imagined entities, taken as real, would by their nature have acted together to produce the phenomenon to be explained. If - as is often the case - the receiver of the explanation does not know about the relevant entities, much of the explanation will consist of describing them: what they are, what they can do and what can be done to them.

Many explanations contain little or no formalised deduction. Examples include the action of the HIV virus, the reasons why ripe fruit decays, and the mechanism of muscular contraction. Other examples include the mechanism of setting of cement and the formation of polymers. Only in some cases is a substantial fraction of an explanation taken up by a theoretical deduction, as when we explain the formation of the tides or the energy levels of hydrogen. More often there is something akin to deduction, when we account for a pattern of behaviour (e.g. a pattern of growth or oscillation) by showing that any imagined idealised model of the kind we have in mind would necessarily have such behaviour.

It seems better to say, not with Hempel that a scientific explanation is the deduction of a phenomenon, but that it is a story which attempts to make the reason for the occurrence of the phenomenon *obvious*. That is to say, it seeks to make the phenomenon become the natural working out of the presumed imagined nature of things. It deploys arguments of natural necessity, not mainly of logical necessity. It rests in the end on the virtuous circle of saying, "That happens because that is what those things do". The circle is virtuous, not vicious, because of the attribution of reality to the entities involved, so that they participate with the same behaviour in an unlimited range of other phenomena, being part of the explanation of those phenomena also, so that the behaviour is not tailored just for accounting for the one case.

'Obviousness' is where the explaining stops. That a certain quantum number cannot change is just what that quantum number does (or doesn't) do. There is no more to be said. The explaining may stop even if a further explanation would be possible; for example treating a gene as a locus on a chromosome, without being concerned about its DNA sequence.

'Obviousness' is to natural necessity as axioms are to logical necessity. Both represent the (current) bottom line. But logical necessity lives wholly in the transactional world, where sometimes deduction can show us how our imaginings necessarily relate to one another. 'Obviousness' derives from what we attribute as essential features of entities as we suppose them to be in reality.

Science as socially produced

Scientific knowledge is generated in a social process, directed to eliminating alternative explanations. The social structures of science have evolved over time, and are historical contingent products, reflecting both the nature of the work involved in doing science, and the needs, possibilities and structures of the larger society in which they have evolved. Over the last century, the general move has been towards a greater and greater 'industrialisation' of science, with organised infrastructures (funding agencies, institutes dedicated to specialised areas of science, and the deployment of scientific research in support of defence and industry) growing and developing. Much thinking about science, however, still reflects its social organisation at an earlier time, when scientific work was more individualised and less professionalised.

The social structures of science are not to be thought of as ideal, or inevitable. They are just what they happen to have become, and will doubtless evolve further. They may not always work consistently in appropriate directions: they can require secrecy (especially in defence or industry) which militates against the exposure of weaknesses in arguments or leads to the neglect of alternative explanations. They may operate in regimes which tempt, or even require, claims to be made of greater certainty than has been achieved.

Science as contingent achievement

Nothing about the process of science guarantees success. Such areas as there are where we have a measure of practical certainty, are simply historical contingent achievements. They did not have to happen, nor was their success underwritten in advance by any fixed 'scientific method'. The wish to solve a problem does not provide the means to solve it. Newton (we may well suppose) would have liked to understand gravitation and Faraday (we know) sought a unified field theory: neither could do it and any start on an answer had to wait for a long time. We in our time would like to understand many things which we cannot understand, including for example the workings of the mind.

There are however, some areas of knowledge where we may properly speak of practical certainty, that is, of knowledge on which it is appropriate to rely without hesitation until further notice. Doubt vanishes because no serious alternatives remain unexamined and uneliminated. It is probably best to think of these areas of secure knowledge as partial islands in an ocean of unknowing or of partial and insecure knowledge, though the value of their achieved existence is such that we are always liable to overestimate their magnitude.

Certainties achieved through extended work

Certainty, of the kind which can (sometimes) be achieved in science is not built in, Cartesian fashion, from the bottom up. Rather it is slowly and patiently achieved by a process of extended work, examining and eliminating alternatives until only one remains. Plainly, a social process devoted to eliminating all but one alternative is not at all bound to succeed. That it could ever succeed may even seem surprising. And one needs to be continually on the watch for premature closure, induced by other social needs and ambitions.

But the essential point is the *work* involved. It is to be accounted for in terms of years of effort by many people both collaborating and competing, even to establish a single fact. After the event, individuals and moments of 'discovery' may be singled out, but such tales are no more accurate reflections of the real process than are the tales of generals winning battles single-handed.

There is a myth that theories are under-determined by data, that is, that a given finite set of data is compatible with an indefinitely large number of possible theories. The fact is that in the actuality of doing science it is extraordinarily difficult to think of even one theory which is compatible with the known data and other currently accepted ideas. To have two is an unaccustomed luxury and leads to a flurry of effort to eliminate one - the competition between 'big bang' and 'continual creation' theories of the Universe is an example.

Depersonalisation and decontextualisation

The social process of science is directed towards achieving explanations to which no reasonable objection appears to remain. Such accounts of the world, if they can be achieved, then do not then depend on the probity or authority of persons for their support. To that extent they become impersonal. They also progressively lose a sense of context. What was once an experiment which worked in a particular place and at a particular time, becomes (after much more work and sharing of tacit know-how than is often recognised), something which may be supposed to work anywhere. If it does not (as was the case with cold fusion) there is either more work to do or there is an illusion to be abandoned.

The decontextualisation of scientific knowledge must not be overstated. It exists within particular ways of looking at the world, each with its own way of carving up reality and of posing problems about it. For example, at one level of biological thought, bodies contain organs with their own functions, and the relevant problems concern the structure and functioning of those organs. At another level, organisms are seen as wholes, inhabiting ecological niches. At yet another level, they are seen as assemblies of cells all relying on the same DNA for their development and behaviour. These different levels do not necessarily fully connect or articulate with one another (and examples can also be given from other sciences). Thus scientific knowledge remains contextualised with particular ways of understanding the world, though new ideas which help erase a contextual boundary are always welcome.

Thus we have what sounds at first paradoxical: a kind of knowledge which is historical, contingent and contextualised but which seeks not to be (so that some say 'pretends not to be'). But there is no real paradox. The social process of science is just such as to continually test and attempt to cross contextual boundaries; to provide grounds for ignoring at least some contextual differences. That this can be done at all is not necessary; that it has been done to some extent is an historical fact.

THE IMPORTANCE OF SCIENCE

The importance of the natural sciences does not lie in a 'scientific method' which assures secure knowledge. Especially, the label 'science' attached to an area of knowledge guarantees nothing. Its importance lies in its particular concrete achievements, in what it has to say about reality on which we may securely rely for understanding and action until further notice. Thus Biology, Chemistry and Physics have merit, not as 'Science', but in what they tell us and in what they enable us to do. The value of the sciences lies (to adapt Edward Albee, author of "Who's afraid of Virginia Woolf?") not in their promise but in their performance.

Thus a great part of what is worth learning of the sciences is the world-pictures which they draw, the contents of their ontological zoos, the explanations they give of phenomena, and the technical devices they offer for manipulating the world. Not all of the knowledge they offer is of equal importance to everybody. Since scientific knowledge is just that knowledge for which, contingently, a certain measure of certainty happens to have been achieved, there is no necessary connection between the importance to human beings of a question, and the existence of any scientific answer to it.

That said, a good proportion of scientific knowledge *does* address questions of inherent human interest and value. The nature and origin of life, the nature and origin of the universe, the basic structure of matter, are all matters of fundamental human concern. So too are practical means of managing the world so as to stay healthy, warm, well fed and well provided for. And so too is an understanding of how pattern is organised, transmitted and reproduced; that is to say an understanding of information. Such an analysis could perhaps be the basis of a master plan for the school science curriculum.

Science And The Development Of Rationality

It has often been supposed that human rationality is fixed, and that science rests for its security on that fixed rationality. The image evoked is of humans with great powers of thought, gradually acquiring things to think through exercising those powers with due regard for correctness of method. On the contrary, science has gradually built up in concert areas of knowledge and ways of thinking, slowly but continually augmenting forms of human rationality through inventing tools for thinking about the world.

One crucial strand in the development of scientific rationality was the idea of using mathematical relationships to model reality. Starting from Descartes' invention of the link between algebraic and geometric relations (the graph) a first step was to represent relations, so requiring the new idea of *variables* as a way of imagining how the world is. Newton did more, creating *things* out of mathematical variables, notably the gravitational field. Far from forbidding the attribution of reality to theoretical entities as the positivists recommended, the developing scientific rationality adopted it as a policy. This encouraged the development of colonies of theoreticians. Rationality had to develop to deal with the essentially transactional character of mathematical theorising. The idea that theories should be constrained by symmetries and invariances are one result.

Rational ways of dealing with things like atoms which are too small to see, like stars which are too distant to touch, or like fossils which are from far back the past, all had to be evolved. Rational attitudes to other living beings when they were to be made objects of study as material entities had to be worked out: for example, determining if it was proper to attribute intentions to an animal.

Sometimes this developing rationality spawns whole new subjects. One such example is statistics, developing ways of conceptualising and dealing consistently with inherent variability. The very concept of *randomness*, problematic even today, is an outgrowth of this work. Every clarification of the idea (e.g. the algorithmic complexity approach of Kolmogorov) augmented rationality. But the construction of rationality is by no means smooth or automatic. Amongst current difficult areas are how to think about the affective behaviour of animals, including ourselves, from an evolutionary point of view; and about how to regard causation in quantum mechanics.

As with scientific knowledge, the ways of being rational which have evolved through scientific activity, are those which happen to have evolved. They are a contingent achievement, not given *a priori*. We may hope for more of the same. Rationality, then, develops, changes and has to be learned. The contributions science has made to rationality are just that: *contributions*. They are not the unique and only ways to be rational. But they *are* ways to be rational.

COMMONSENSE KNOWLEDGE AND REASONING

Everyday unreflective commonsense reasoning is concrete; appropriate to a context; pragmatic and often directed towards efficacious action; deriving its meaning from action; obtaining certainty by appeal to the 'obvious'; often prototypical in form; relying on images, metaphors and metonyms as much as on propositions; and is inherently creative. It seems to rely on a small number of dimensions of thought, which can however be freely combined and recombined.

Commonsense is concrete

The material of commonsense thought is imagined entities and events. We do not so much think *about* them as *with and through* them. Imagined entities and events come as whole packages of behaviours proper to them, so that using them to think with is efficient and speedy. At the same time, commonsense is in a different sense abstract. 'Concrete' does not contrast with 'abstract', but with 'formalised'. Imagined entities and events are abstracted from real ones, and new kinds never experienced (e.g. bird-men) are not hard to create in the mind. But the thinking is semantic, not syntactic, reasoning from imagined actions and responses to actions.

Commonsense is pragmatic

Commonsense thinking is generally directed towards immediate pragmatic goals. Its aim is generally to understand *here and now* in order to act efficaciously in the given context. No contradiction arises if in a different context we construct a different understanding and different actions are effective. The world as we know it does not behave very regularly, so that we are very properly rather cautious about generalising across contexts. Indeed, proverbs, which seem to offer to cross contexts, are often paired with their opposites to remind us to doubt general recipes for action.

Meaning derives from action

Commonsense language and thought derives its meaning from action, from our embodied presence in the world. The significance of an entity or event is a package of what it can do, what can be done to it, and what it is made of. It is in this way that concrete thinking gains its efficiency and power; the very nature of an imagined entity or event tells you what it could do or have done to it, from which possible actions with it or on it follow at once. It works through such immediate entailments, not through chains of logical inference.

Necessity, in commonsense reasoning, has to do with inaccessibility to action. That which cannot be changed, or cannot be prevented from doing what it will do, is necessary. And we project it onto the nature of things, onto *how things are*.

Commonsense certainty derives from the 'obvious'

Commonsense explaining stops at what is obvious, at 'how things just are'. And because the reasoning is concrete, thinking with (not about) how things are, some aspects of things are built into their very (imagined) nature. If they were not like that, they would not be what they are. So we reach certainty when we reach the level of the 'obvious nature of things'.

Commonsense reasoning is prototypical

Commonsense reasons not so much with particular imagined real entities and events as with middle level prototypes, neither too particular to apply widely nor so general that they lack immediate specific behaviours and properties. Fire, storm and flood are examples; disasters are too general to think with whilst a bonfire or an overflowing tank are too local. Prototypes derive from the process of empirical abstraction, that is, of trying to think about what is going on through imagining the behaviour of things. And of course language reinforces their use through making extensive use of them in images and metaphors.

Commonsense reasoning uses metaphor and metonymy

Commonsense reasoning makes extensive use of metaphor and metonymy. It tries seeing one thing as another, so as to form new ways of imagining things which could not have been experienced before. Many such metaphors find their way into language and become invisible. Metonymy, the use of a particular to stand for the general, is also fundamental. It retains the grip of thought on the concrete, bringing it back to the particular case as an example of the general.

Of course commonsense is also propositional. We use language (amongst other things) to remind us, to bring ideas to consciousness, and to persuade others to see things as we do. But in a sense the propositional is secondary. We know that we can think impossible things, and that we can be persuaded wrongly by a phrase. So we tend to suspect propositions, testing them against imagined examples. If the example fails, so much the worse for the proposition.

Commonsense is creative

Like language, commonsense reasoning is inherently creative. Because it works with imagined entities and events, it can always try combining and recombining them, or modifying them in various ways, to make new entities and events which might serve to understand something. But these new entities and events, be they dragons or demons, retain enough of their origins to serve as a vehicle of thought. We can still tell ourselves something about what they can do and what can be done to them. Even our fancies are imbued with natural necessities. Commonsense creative transactional thinking is not arbitrary, is natural for both children and adults, and uses metaphor, analogy and metonymy to develop and to guide its flight.

Commonsense is constrained

Although inherently creative, commonsense reasoning is constrained by - or rather works fundamentally within - a small set of basic dimensions which characterise how things could possibly be. Two fundamental dimensions appear to be:

place-like versus localised;

static versus dynamic

Combinations give us space, containers and states of affairs (place-like and static), time and events which surround us (place like and dynamic), objects (localised and static) and actions and particular events (localised and dynamic), which seem to be the main ways in which we characterise imagined entities and events. Besides distinguishing as above

entity versus event,

a further dimension,

discrete versus continuous

may arise from re-applying the dimension place-like versus localised to objects, to generate the basic object versus substance distinction. For events, it re-emphasises the difference between those which continue and those which begin and end.

Actions are the prototype of causes, and the dimensions

cause versus effect

external versus internal

distinguish actions as causes from the events they cause, and further distinguish changes as due to outside action (prototypically of a person on an object) from action proper to an entity as affecting that entity (prototypically persons moving themselves).

It is not claimed that we think consciously or analytically in these terms. Rather, we think in terms of prototypical packages, such as a flying stone, which we *know* must have been set moving by something which acted on it, is local in time and place, and may itself cause an effect. Entities and events are unmysterious to us when they fit well established combinations of dimensions. They are mysterious to us when they do not - for example in the non-local behaviour of quantum particles, even though we know that quantum particles have had built into them both localised (particle) and space-like (field) properties. No less mysterious would be imagined faëry agents who cause events without doing anything, or passive objects which act of their own volition. Such mysteries do not prevent us thinking of such things, and even in science taking them to be real - for example, active curved space making gravity.

COMMONSENSE AND SCIENCE

Commonsense and science are, if the above accounts are anything like right, both very different and very alike.

Differences between science and commonsense

The goals of science and commonsense are different. Commonsense is mainly concerned with immediate action in context; science is mainly concerned with achieving some understanding which - to some extent - is independent of persons and context, and in this interest may eschew the need for guiding immediate action.

Science has developed an extensive tool-kit of theoretical models, investigated in great detail, so that its imaginative resources are very finely structured and elaborated. It has generated a variety of new (and some not widely shared) ways of being rational. 'Logic' has a special role in science here, in the transactional domain where consequences of imaginings are followed through. Commonsense relies more

on the broad brush of basic dimensions of how things can possibly be. Its rationality boils down to *what makes sense*.

Science relies more on extensive collaborative and competitive *work* towards unarguable agreement. Commonsense is certainly collaborative (even collusive), but when differences arise, agreements to differ are common. In the commonsense world, *persons* think as they do; in the scientific world, *knowledge* is what it currently is.

In the interests of knowledge, science tries to go behind things as they seem. To detect, control and understand the behaviour of entities, it creates artificial events (experiments) so as to isolate the effects of various entities. For this reason, experiments are, from the everyday point of view, thoroughly impractical. They work only in contrived circumstances. Commonsense is more concerned with *coping* with things as they are, in all their awkward combinations.

Out of all this, science has created a large ontological zoo of entities, many as real as any stone, but never before thought of, and quite beyond the ken of everyday commonsense. Science, unlike commonsense, is in a way never satisfied. New entities, once made real and serving in an imaginative world to create histories which explain certain phenomena, become themselves phenomena to be explained by going one layer deeper.

Similarities Between Science And Commonsense

Both science and commonsense rely on fundamentally concrete modes of thought. Reasoning is done with imagined entities and events. That the imagined entities of science are different from those of commonsense is not now the point; the point is that they are used in thinking in fundamentally the same kind of way. Explanations, both in science and in commonsense accounts of physical reality, are stories about what entities in a world would have done in order to bring about what is to be explained.

Both science and commonsense stop explaining at the level of what is (for the time being) made to seem obvious. Explaining stops when we understand events as working out according to the currently imagined and understood nature of how things are.

Both science and commonsense share, or at least so I suppose, the same common ontology of space, time, object, and action (that is, the same basic dimensions of thought). But they use them differently, and attribute entities and events differently to them. Thus, with Copernicus, the Earth ceased to be a place in which to live, against which spatial and therefore un-moving background change and movement occurred, and became a moving object, localised and dynamic, not place-like and static. With Faraday (and then Maxwell) static space became filled with dynamic fields, with untold and still unresolved later ontological consequences in both quantum physics and general relativity. With Darwin, natural behaviours and natures became subject to change, so that that level of what was 'obvious' was taken away. With the molecular theory, static matter became filled with ceaseless motion - the problem with molecules is not so much that matter is made of pieces, as that the pieces move all the time without being moved.

If the last point is right, then there may be a very profound point of similarity. Things seem unmysterious to us when we can see them as fitting the most fundamental ontological categories. And no matter how strange the entities it imagines, scientific thought retains some connection with those categories. When

there were to be molecules, they were still kept as little moving objects. When molecules, then atoms, were re-imagined, they were still assemblies of moving objects. Even when finally 'object-hood' was taken away, the essential static, localised and conserved character of objects was passed on to quantum numbers. But this point remains wholly speculative, needing much more reflection and evidence to sustain it. The idea is that, at the very bottom, scientific thought stops with obviousness understood in fundamentally the same way as in commonsense, at where things do what they do because of what they are.

IMPLICATIONS FOR THE TEACHING OF SCIENCE

There are implications for the teaching of science from the analysis of the nature and importance of scientific knowledge, and from the nature of commonsense thought and its relation to scientific thought.

Implications From The Nature And Importance Of Scientific Knowledge

The picture of scientific knowledge presented here is very different from both of two rather dominant pictures that often underlie the science curriculum.

A traditional view of the learning of science is to see scientific knowledge as a clear-cut, explicit and 'logical' account of how things are, so that teaching science is essentially a matter of laying out definitions, facts and their consequences with the greatest possible clarity. Failures to learn are, from this point of view, usually attributed to some lack of clarity on the part of the teacher or to inattentiveness to a crucial detail on the part of the student. The theories of for example Ausubel and Gagné, requiring scientific knowledge to be carefully analysed prior to any teaching into hierarchies of logically interdependent categories, and then to be taught in such a logically pre-planned sequence, fall into essentially this same mode. Learning is understood as a process of the learner becoming rationally convinced, by the power of a logical system of thought.

This leads to a curriculum planned around “central concepts” and the logical relations between them.

I argue that it would be better to construct the science curriculum around “stories that science has to tell about how things are”. This would introduce the many denizens of the ontological zoo, with students coming to know them through what they can do, what you can do to them, and what they are made of. Another way to put the point is to say that the building blocks of the curriculum – of what goes on in the classroom – ought to be *scientific explanations*.

The second dominant picture of scientific knowledge is empiricist. Understanding scientific knowledge as something like “reading the book of Nature”, learning is seen as essentially giving students experiences from which they can directly see “how things are”. Some constructivist ideas about teaching have come dangerously close to this naïve picture, and much common teaching practice in at least some countries turns science lessons into purely “hands-on” experience, with no “minds-on” activity to match.

Both accounts fail to take adequate account of the gulf between *doing* science and *learning* science. The key aspect of learning is finding out and understanding what others have thought, not finding out or thinking out for oneself. And, as I have stressed, the important part of what is known is the set of explanations on offer – the stories of how things are and come to be.

At the same time, the science curriculum has a duty to show where the stability and solidity of scientific explanations comes from, which is the hard, lengthy, cooperative work of testing and eliminating alternatives. To imagine that this can be shown in every case is manifestly absurd. But to do without it altogether is to fail to communicate how science actually works. So the curriculum needs to contain a few examples to highlight the point. Some of these can be historical accounts of the twists and turns of scientific thinking. Some need to be imitations, in the classroom, of the process itself. That is, there need to be some investigations, done by groups (science is a social activity), in which alternatives are proposed, tests devised, conclusions reached or overturned. Neither can happen very often, but both need to happen *sometimes*. Lacking them, and lulled by the Cartesian myth of certainty built in from the bottom by 'correct' use of 'scientific method', scientific work is presented as a simple and short path from hypothesis through test to conclusion.

Another aspect is the need for practical *know-how*. Too often, with the curriculum organized around concepts, practical know how is ignored or discounted. Yet it is one of the things most likely to be of use to a student in the future. So there should be a place for domestic wiring and plumbing in physics, for gardening and animal welfare in biology, and for cooking and cleaning in chemistry.

At the same time, one needs to think about *theoretical* know-how. As I have stressed, it is this which provides the scientific thinking tool-kit; the rational resources one can bring to bear on solving a problem or thinking about a phenomenon. Theory needs to be seen as the imagination at play, finding out the consequences of various imaginative moves.

A key issue is that of formalisation; of creating a finite set of formal objects and rules, which dance to tunes we decide for them. That science uses such resources is a part of its rationality, and as much effort needs to go into making them accessible, attractive and easy to understand as needs to go into doing the same for other scientific ideas.

The advent of the computer makes it much easier to play with theory, and the computer itself - a machine which obeys rules we ourselves provide for it - makes an excellent concrete representation of the idea of formalisation. If a mathematical system exists wholly on pencil and paper, it is very hard for students to distinguish between the work needed to implement or work out the consequences of a set of rules, and the work needed to choose or create a formalism. The effort of calculating obscures the effort of formalising or modelling. With the computer, the two are separated, and much of the effort of calculating is taken over by the machine. But the effort of telling it what and how to calculate is not.

IMPLICATIONS FROM THE NATURE OF COMMONSENSE THOUGHT AND ITS RELATION TO SCIENTIFIC THOUGHT

For at least the last twenty years, science teachers and educators have been greatly concerned with the ideas that students bring to the classroom – their “alternative conceptions”. There is abundant proof of their existence and influence, but much less convincing evidence of ways to deal with them.

One response must be to face very squarely the real difficulties of learning science. One is that many of its explanations necessarily run counter to, or even undermine, commonsense everyday knowledge, particularly when what to commonsense knowledge are basic facts are turned into that which is to be explained. Equally if not

more important are the huge imaginative leaps that learning science sometimes involves.

To tell any of the scientific stories successfully is necessarily to try to excite the imagination. The inhabitants of the ontological zoo have to have life breathed into them. Their strange goings on have to come to seem a natural part of how they are. Attempting to do this obliges the teacher to do something of the first importance, often largely neglected. This is to talk about the fundamental qualitative nature of scientific entities; that a gene is a tiny localised packet of information; that molecules move forever without reason; that fields fill empty space without blocking the path of anything, and so on.

Science offers opportunities to stretch the imagination in very specific and important ways. And that these *are* the special ways in which it stretches the imagination, is an important lesson to learn about what science has turned out to be like. One way is to dive down inside matter to smaller and smaller scales, from the body to cells and microbes, to shapely protein molecules which lock and unlock doors, to molecules and atoms, to electrons and protons, to quarks and leptons. The first stretch of the imagination is simply one of scale; to have some idea of how big and so of how numerous things are at each level. The second is to find that the inhabitants at a lower level are not miniatures of those at a larger level, but are quite different from them in their very nature. Where they explain what is going on higher up, they do so indirectly. This imaginative stretching to smaller scales can begin in the primary school, looking at dirty pond water with a hand lens, and the primary teacher should know that she is preparing important imaginative ground for later on.

A second way in which science stretches the imagination is by going up in scale, both in time and space. Stories of evolutionary history are one way to begin, as are stories of the stars and planets. And here the essential lesson is the development of scientific rationality through the progressive removal of anthropo-centrism from scientific thinking. Yet another essential imaginative leap of science is to have made space active, filling it with invisible fields. Television is less mundane than people imagine, as indeed 'seeing at a distance' ought to be!

The imagination needs exercise on a more modest scale too. To watch snow crystals melt with a hand lens and to ask whether the water is to be thought of as *coming out* of the ice, or as *forming on* the ice, or whether the ice is *turning into* water, is such an exercise in imaginative thinking. So are watching a dye diffusing in water, watching water droplets condense on a glass of cold water, watching wax melt, and watching wood burn. And so is observing animal behaviour and noticing our tendency to project our own desires and purposes onto them. One of the best is to watch the Sun set, and to try to imagine the horizon coming up to cover the Sun instead of seeing the Sun going down behind the horizon.

Children often suppose that imagining the world really to be radically different from the way commonsense imagines it is simply a species of madness. For the same reason, they find history difficult, thinking of past modes of thought as simply absurd. This does not at all mean that they find imagining things difficult. Concrete modes of thought give plenty of access to new imaginative worlds, through metaphor, analogy and metonymy. What they have to understand is that science tries to make tight connections between transactional imagination and intransigent reality; that the game is to suppose that what has been imagined *really is so*. This suggests a role in science teaching for fantasy, asking children to imagine things in

as whatever ways they can, and then to see what happens if those imaginings are taken seriously as suggesting how things really are.

IDEAS CONFRONTING REALITY

Throughout, I have argued that science makes a special kind of link between what we can imagine and what we take to be real. Science emerges from taking seriously and systematically developing the simple and obvious thought that although we can think whatever we like, we cannot do whatever we like. The task for science education is to communicate both the startling imaginative range of what science draws from the first, and the toughness and security of the knowledge it has gained by the slow hard work of systematically confronting the one with the other.

The sciences we have are just what, contingently and historically, we happen to have. The main reason for learning about them, which should determine how they are taught and learned, is to enable people to form judgments of their worth. A few will join the future process of making more scientific knowledge; if we are successful most will be in a better position to evaluate for themselves the very special addition to culture and rationality which the sciences happen to have provided. And they may taste the pleasures of the startling insights into reality which they offer.

FURTHER READING

Philosophical and sociological accounts

- Abelson R, Lalljee M (1988) 'Knowledge structures and causal explanation' in Hilton D J (Ed) *Contemporary Science and Natural Explanation* Harvester Press: Sussex
- Achinstein P (1983) *The Nature of Explanation* Clarendon Press: Oxford
- Aronson J R (1984) *A Realist Philosophy of Science* Macmillan: London
- Berger P, Luckmann T (1967) *The Social Construction of Reality* Penguin: London
- Bhaskar R (1978) *A Realist Theory of Science* Harvester Wheatsheaf: London
- Bhaskar R (1986) *Scientific Realism and Human Emancipation* Verso: London
- Bhaskar R (1989) *Reclaiming Reality* Verso: London
- Bunge M (1959) *Causality: the Place of the Causal Principle in Modern Science* Harvard University Press: Cambridge Mass.
- Collins H (1992) *Changing Order: Replication and Induction in Scientific Practice* Chicago University Press: Chicago
- Craik K (1943) *The Nature of Explanation* Cambridge University Press: Cambridge
- Davidson D (1980) *Essay on Actions and Events* Clarendon Press: Oxford
- Davidson D (1984) *Inquiries into Truth and Interpretation* Clarendon Press: Oxford
- Davidson D (1986) 'A coherence theory of truth and knowledge' in LePore E (Ed) *Truth and Interpretation: Perspectives on the Philosophy of Donald Davidson* Blackwell: Oxford
- Dennett D C (1992) *Consciousness Explained* Penguin Allen Lane: London
- Feyerabend P (1975) *Against Method* Verso: London
- Feyerabend P (1987) *Farewell to Reason* Verso: London and New York
- Goodman N (1978) *Ways of Worldmaking* Hackett: New York
- Gregory R L (1974) *Concepts and Mechanisms of Perception* Scribner: New York
- Gregory R L (1981) *Mind in Science* Weidenfeld and Nicholson: London
- Grice P (1975) 'Logic and conversation' in Cole P, Morgan J L (Eds) *Studies in Syntax: Vol 3 Speech Acts* Academic Press: New York

- Gross P R, Levitt N (1994) *Higher Superstition: the Academic Left and its Quarrel with Science*. Baltimore: The John Hopkins University Press
- Hacking I (1983) *Representing and Intervening* Cambridge University Press: Cambridge
- Hanson N R (1958) *Patterns of Discovery* Cambridge University Press: Cambridge
- Hanson N R (1963) *The Discovery of the Positron* Cambridge University Press: Cambridge
- Hanson N R (1972) *Observation and Explanation* Allen and Unwin: London
- Harré R (1972) *The Philosophies of Science* Oxford University Press: Oxford
- Harré R (1981) *Great scientific experiments* Phaidon: London
- Harré R (1986) *Varieties of Realism* Blackwell: Oxford
- Harré R, Madden E H (1975) *Causal Powers* Blackwell: Oxford
- Hesse M (1961) *Forces and Fields* Nelson: London
- Hesse M (1963) *Models and Analogies in Science* Sheed and Ward: London
- Hesse M (1974) *The Structure of Scientific Inference* Macmillan: London
- Hilton D J (Ed) (1988) *Contemporary Science and Natural Explanation* Harvester Press: Sussex
- Körner S (Ed) (1975) *Explanation* Blackwell: Oxford
- Kuhn T (1962) *The Structure of Scientific Revolutions* International Encyclopedia of Unified Science, University of Chicago Press: Chicago.
- Latour B, Woolgar S (1986) *Laboratory Life: The Construction of Scientific Facts* Princeton University Press: Princeton
- Latour B (1993) (translated: Catherine Porter) *We Have Never Been Modern*. London: Harvester Wheatsheaf
- Mead G H (1962) *Mind, Self and Society* University of Chicago Press: Chicago
- Mead G H (1938) *The Philosophy of the Act* Open Court: Chicago
- Medawar P B (1967) *The Art of the Soluble* Methuen: London
- Merleau-Ponty M (1942) *La Structure du Comportement* Presses Universitaires de France: Paris, English translation (1965) Methuen, London
- Merton R K (1973) *The Sociology of Science* Chicago University Press: Chicago
- Oakeshott M (1962a) 'The tower of Babel' in Oakeshott M *Rationalism in Politics* Methuen: London
- Oakeshott M (1962b) 'Rational conduct' in Oakeshott M *Rationalism in Politics* Methuen: London
- Oakeshott M (1962c) 'Rationalism in politics' in Oakeshott M *Rationalism in Politics* Methuen: London
- Pitt J C (Ed) (1988) *Theories of Explanation* Clarendon Press: Oxford
- Polanyi M (1958) *Personal Knowledge* Routledge: London
- Popper K (1979) *Objective Knowledge* Clarendon Press: Oxford
- Putnam H (1975) *Philosophical Papers* Cambridge University Press: Cambridge
- Putnam H (1981) *Reason, Truth and History* Cambridge University Press: Cambridge
- Quine W V O (1960) *Word and Object* MIT Press: Cambridge Mass.
- Quine W V O (1981) *Theories and Things* Belknap Press: Harvard
- Rubén D-H (1990) *Explaining Explanation* Routledge: London
- Ruse M (Ed) (1989) *Philosophy of Biology* New York: Macmillan
- Salmon W (1990) *Four Decades of Scientific Explanation* University of Minnesota Press: Minneapolis
- Schutz A, Luckmann T (1973) *Structures of the Life-World* Heinemann: London
- Schutz A (1982) *Life Forms and Meaning Structure* translated H R Wagner, Routledge and Kegan Paul: London)

- Sober E (1993) *Philosophy of Biology* Oxford University Press: Oxford
- Wartofsky M W (1968) *Conceptual Foundations of Scientific Thought* Macmillan: New York
- Wittgenstein L (1922) *Tractatus Logico-Philosophicus* Routledge & Kegan Paul: London
- Wittgenstein L (1953) *Philosophical Investigations* Basil Blackwell: Oxford
- Ziman J (1967) *Public Knowledge* Cambridge University Press: Cambridge
- Ziman J (1978) *Reliable Knowledge* Cambridge University Press: Cambridge
- Ziman J (1994) *Prometheus Bound: Science in a Dynamic Steady State* Cambridge University Press: Cambridge

Language and communication

- Antaki C (Ed) (1988a) *Analysing Everyday Explanation* Sage: London
- Antaki C (1988b) 'Explanations, communication and social cognition' in Antaki C (Ed) *Analysing Everyday Explanation* Sage: London
- Black, M. (1962) 'Metaphor' in Black M (Ed) *Models and Metaphors* Cornell University Press: New York
- Black M (1979) 'More about metaphor' in Ortony A *Metaphor and Thought* Cambridge University Press: Cambridge
- Draper S (1988) 'What's going on in everyday explanation?' in Antaki C (Ed) *Analysing Everyday Explanation* Sage: London
- Fillmore C (1968) 'The case for case' in Bach E, Harms R (Eds) *Universals in Linguistic Theory* Holt, Rinehart and Winston: New York
- Fodor J (1990) 'Psychosemantics, or: Where do truth conditions come from?' in Lycan W G (Ed) *Mind and Cognition* Blackwell: Oxford
- Halliday M A K (1985) *An Introduction to Functional Grammar* Arnold: London
- Halliday M A K, Martin J R (1993) *Writing Science: Literary and discursive power* The Falmer Press: London
- Johnson M (1987) *The Body in the Mind: the bodily basis of meaning, imagination and reason* University of Chicago Press: Chicago
- Lakoff G, Johnson M (1980) 'The metaphorical structure of the human conceptual system' *Cognitive Science*, Vol 4, pp 195-208.
- Lakoff G, Johnson M (1981) *Metaphors We Live By* Chicago University Press: Chicago
- Lakoff G (1987) *Women, Fire and Dangerous Things* Chicago University Press: Chicago
- Miller A I (1987) *Imagery in Scientific Thought* MIT Press: Cambridge, Mass.
- Miller G (1979) 'Images and models, similes and metaphors' in Ortony A *Metaphor and Thought* Cambridge University Press: Cambridge
- Vygotsky L S (1969) *Thought and Language* MIT Press: Cambridge Mass.
- Vosniadou S, Ortony A (1989) *Similarity and Analogical Reasoning* Cambridge University Press: Cambridge
- Wattenmaker W D, Nakamura G V, Medin D L (1988) 'Relationships between similarity-based and explanation-based categorisation' in Hilton D J *Contemporary Science and Natural Explanation* The Harvester Press: Sussex

Science education research

- Andersson, B. (1986) 'The experiential gestalt of causation: a common core to pupil's preconceptions in science' *European Journal of Science Education* Vol. 8, No 2, pp 155-171

- Arcà M, Guidoni P, Mazzoli P (1983, 1984) 'Structures of understanding at the roots of science education, Part I: Experience, language and knowledge; Part II Meanings for formalisation, *European Journal of Science Education* Vol 5, No 4, pp 367-375; Vol 6, No 4, pp 312-319
- Bliss J, Ogborn J (1989) 'Tools for Exploratory Learning' *Journal of Computer Assisted Learning* Vol 5, pp 37-50
- Bliss J, Ogborn J, Whitelock D (1989) 'Secondary pupils' commonsense theories of motion *International Journal of Science Education* Vol 11, No 3
- Bliss J, Ogborn J (1992) 'Steps towards the formalisation of a psycho-logic of motion' in Tiberghien A, Mandl H (Eds) *Intelligent Learning Environments and Knowledge Acquisition in Physics* NATO ASI Series, Springer Verlag: Berlin
- Bliss J, Ogborn J (1993) 'Steps towards the formalisation of a psycho-logic of motion' *Journal of Intelligent Systems* Vol 3, No 1, pp 3-48
- Bliss J, Ogborn J (1994) 'Force and motion from the beginning' *Learning and Instruction* Vol 4, pp 7-25
- Chi M (1992) 'Conceptual change across ontological categories: examples from learning and discovery in science' in Giere F (Ed) *Cognitive Models of Science: Minnesota Studies in the Philosophy of Science* pp 129-160 University of Minnesota Press: Minneapolis
- Closset J L (1983) *Le raisonnement séquentiel en électrocinétique*. Doctoral thesis Université Paris VII. Paris.
- Closset J L (1984) 'Sequential reasoning in electricity' in Delacote G, Tiberghien A (Eds) *Research in Physics Education* La Londe les Maures pp 313-319 CNRS: Paris
- diSessa A (1988) 'Knowledge in pieces' in Forman G, Pufall P B (Eds) *Constructivism in the Computer Age* Lawrence Erlbaum: New Jersey
- diSessa A (1993) 'Towards an epistemology of physics' *Cognition and Instruction* Vol 10, No. 2 & 3, pp 105-225
- Driver R (1989) 'The construction of scientific knowledge in school classrooms' in Millar R (Ed) *Doing Science: Images of Science in Science Education* Falmer Press: Lewes
- Driver R, Oldham V (1986) 'A constructivist approach to curriculum development in science' *Studies in Science Education* Vol 13, pp 105-122
- Fauconnet S (1981) *Etude de résolution de problème: quelques problèmes de même structure en physique* Doctoral thesis, Université Paris VII, Paris
- Fauconnet S (1984) 'Etude de résolution de problèmes analogues' in Delacote G, Tiberghien A (Eds) *Research on Physics Education* La Londe les Maures CNRS: Paris
- Guidoni P (1985) 'On natural thinking' *European Journal of Science Education* Vol 7, No 2, pp 133-140
- Gutierrez R, Ogborn J (1991) 'A causal framework for analysing alternative conceptions' *International Journal of Science Education* Vol 14, No 2, pp 201-220
- Law N (1990) *Eliciting and understanding commonsense reasoning about motion* PhD Thesis, University of London
- Mariani M C, Ogborn J (1990) 'Commonsense reasoning about conservation: the role of action', *International Journal of Science Education* Vol 12, No 1, pp 55-66
- Mariani M C (1992) *Some dimensions of commonsense reasoning about the physical world* PhD thesis, University of London
- Mariani M C, Ogborn J (1991) 'Towards an ontology of commonsense reasoning' *International Journal of Science Education* Vol 13, No 1 pp 69-85

- Maurines L (1986) *Premières notions sur la propagation de signaux mécaniques: étude des difficultés des étudiants*. Doctoral thesis, Université Paris VII: Paris
- Mellar H, Bliss J, Boohan R, Ogborn J, Tompsett C (1994) *Learning with Artificial worlds* Falmer Press: London
- Millar R (Ed) (1989) *Doing Science: Images of Science in Science Education* Falmer Press: Lewes
- Millar R, Driver R (1987) 'Beyond processes' *Studies in Science Education* Vol 14, pp 33-62
- Nicholls G, Ogborn J (1993) 'Dimensions of children's conceptions of energy' *International Journal of Science Education* Vol 15, No 1, pp 73-81
- Ogborn J (1985) 'Understanding students' understandings: an example from dynamics' *European Journal of Science Education*, Vol 7, No 2, pp 141-150
- Ogborn J (1987) 'Prolog and models of reasoning in science' *Physics Education* Vol 22, No 4
- Ogborn J (1990) 'A future for modelling in Science Education' *Journal of Computer Assisted Learning* Vol 6 No 1 pp 103-112
- Ogborn J (1992) 'Fundamental dimensions of thought about reality: object, action, cause, movement, space and time' in *Teaching about Reference Frames: from Copernicus to Einstein* Proceedings of GIREP Conference, Torun, Poland, August 1991, Nicholas Copernicus University Press: Torun
- Rozier S (1988) *Le raisonnement linéaire causal en thermodynamique élémentaire*. Doctoral thesis, Université Paris VII: Paris
- Saltiel E (1978) *Concepts cinématiques et raisonnement naturels: étude de la compréhension des changements de référentiels galiléens par les étudiants en sciences* Doctoral thesis, Université Paris VII: Paris
- Solomon J (1983) 'Learning about energy: how pupils think in two domains' *European Journal of Science Education* Vol 5, No 1, pp 49-59
- Solomon J (1984) 'Prompts, cues and discriminations: the utilization of two separate knowledge systems' *European Journal of Science Education* Vol 6, No 3, pp 277-284
- Viennot L (1977) *Le raisonnement spontané in dynamique élémentaire* Doctoral thesis, Université Paris VII: Paris
- Viennot L (1979) *Le raisonnement spontané in dynamique élémentaire* Hermann: Paris
- Viennot L (1979) 'Spontaneous reasoning in elementary dynamics' *European Journal of Science Education*, Vol 1, No 2, pp 205-221.
- Viennot L (1996) *Reasoning in physics: the part of common sense*. Kluwer: Dordrecht
- Whitelock D M (1990) *Commonsense understanding of causes of motion* Phd Thesis, University of London
- Whitelock D M (1991) 'Investigating a commonsense model of causes of motion with 7 to 16 year old pupils' *International Journal of Science Education* Vol 13, No 3, pp 321-340

Child development

- Byrnes J (1992) 'Meaningful logic: developmental perspectives' in Beilin H, Pufall P (Eds) *Piaget's Theory: Prospects and Possibilities* Lawrence Erlbaum: New Jersey
- Carey S (1985) *Conceptual Change in Childhood* MIT Press: Cambridge Mass.
- Donaldson M (1978) *Children's Minds* Fontana: London

- Langer J (1980) *The Origins of Logic: six to twelve months* Academic Press: New York
- Piaget J (1926) *La Représentation du Monde chez l'Enfant* Alcan: Paris
- Piaget J (1927) *La Causalité Physique chez l'Enfant* Alcan: Paris
- Piaget J (1936) *La Naissance de l'Intelligence chez l'Enfant* Delachaux & Niestlé: Paris
- Piaget J (1937) *La Construction du Réel chez l'Enfant* Neuchâtel & Niestlé: Geneva
- Piaget J, Garcia R (1983) *Psychogenese et Histoire des Sciences* Flammarion: Paris
- Piaget J (1971) *Les Explications Causales* Presses Universitaires de France, Paris translated as *Understanding Causality* Norton: New York
- Piaget J (1986) 'Necessity' in *Human Development* Vol 29, pp 301-314
- Piaget J, Garcia R (1987) *Vers une Logique des Significations* Murionde: Geneva; translated 1991, *Toward a Logic of Meaning* Lawrence Erlbaum: New Jersey
- Rizzo R B (1990) 'Necessity and the logic of entailment' in Overton W F (Ed) *Reasoning, Necessity and Logic: developmental perspectives* Lawrence Erlbaum: New Jersey
- Rosch E, Lloyd B B (1978) *Cognition and Categorisation* Lawrence Erlbaum: New Jersey
- Spelke E (1990) 'Principles of object perception' *Cognitive Science*, Vol 14, pp 29-56

“Naïve physics” and mental models

- Bliss J (1994) 'Children learning science' in Jennison B, Ogborn J (Eds) *Wonder and Delight* Institute of Physics Publishing: Bristol
- Bloor D (1976) *Knowledge and Social Imagery* Routledge and Kegan Paul: London
- Boohan R, Ogborn J (forthcoming) *WorldMaker*
- Boyd R (1979) 'Metaphor and theory change: what is "metaphor" a metaphor for?' in Ortony A (Ed) *Metaphor and Thought* Cambridge University Press: Cambridge
- Cartwright N (1983) *How the Laws of Physics Lie* Clarendon Press: Oxford
- Forbus K (1983) 'Qualitative reasoning about space and motion' in Gentner D, Stevens A L (Eds) *Mental Models* Lawrence Erlbaum: New Jersey
- Forbus K (1985) 'The role of qualitative dynamics in naive physics' in Hobbs J R, Moore R C (Eds) *Formal Theories of the Commonsense World* Ablex: New Jersey
- Forman G, Pufall P B (Eds) (1988) *Constructivism in the Computer Age* Lawrence Erlbaum: New Jersey
- Gardin F, Meltzer B (1989) 'Analogical representations of naive physics' *Artificial Intelligence* Vol 38, pp 139-159
- Gentner D, Gentner D (1983) 'Flowing rivers or teeming crowds?' in Gentner D, Stevens S (Eds) *Mental Models* Lawrence Erlbaum: New Jersey
- Gentner D, Stevens A L (Eds) (1983) *Mental Models* Lawrence Erlbaum: New Jersey
- Hayes P (1978) 'The naive physics manifesto' in Michie D (Ed) (1978) *Expert Systems in the Micro-Electronic Age* University of Edinburgh Press: Edinburgh
- Hayes P (1985) 'The second naive physics manifesto' in Hobbs J R, Moore R C (Eds) *Formal Theories of the Commonsense World* Ablex: New Jersey
- Hobbs J R, Moore R C (Eds) (1985) *Formal Theories of the Commonsense World* Ablex: New Jersey
- Johnson-Laird P N (1983) *Mental Models* Cambridge University Press: Cambridge
- Johnson-Laird P N, Byrne M.J. (1991) *Deduction* Lawrence Erlbaum: New Jersey

- McCarthy J (1968) 'Programs with common sense' in Minsky M (Ed) *Semantic Information Processing* MIT Press: Cambridge Mass.
- Schank R, Abelson R (1977) *Scripts, Plans, Goals and Understanding* Lawrence Erlbaum: New Jersey
- Schank R (1982) *Dynamic Memory* Cambridge University Press: Cambridge
- Schank R (1986) *Explanation Patterns* Lawrence Erlbaum: New Jersey
- Wiser M, Carey S (1983) 'When heat and temperature were one' in Gentner D, Stevens A L (Eds) *Mental Models* Lawrence Erlbaum: New Jersey