Lucidity, hypercredulity, and civilization, or

what has music

got to do with quantum mechanics?

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This is the Internet version (with somewhat out-of-date text, but more extensive Notes and References) of a report to the Raymond and Beverley Sackler Institute of the University of Tel Aviv, containing material that was the basis for a public lecture delivered on 26 April 1995 under the auspices of the Sackler Institute and some of which, after further development, has been published in three parts in the London based journal *Interdisciplinary Science Reviews*, volumes **22** and **23**, under the titles

> 'Lucidity and science I: Writing skills and the pattern-perception hypothesis' (**22**, 199–216),
>
> 'Lucidity and science II: From acausality illusions and free will to final theories, mathematics, and music' (**22**, 285–303),
>
> 'Lucidity and science III: Hypercredulity, quantum mechanics, and scientific truth' (**23**, 29–70).

I am leaving this version on the Internet because of its more extensive Notes and References. For a first reading, however, I would strongly recommend the published, more up-to-date and more polished Parts I–III, of which the last, Part III, is also available on this site with slight further updates in the files `lucidity3.ps` or `lucidity3.ps.Z`, together with `lucidity-figP1.gif`, `lucidity-figP2.gif`, and `lucidity-figP3.gif`. I would welcome comments on any of this material, which I plan to turn into a small book, a draft preface/prelude for which can be read at `http://www.atm.damtp.cam.ac.uk/people/mem/`. Please do not quote from unpublished portions of the material without checking with me first. — MEM.

Lucidity, hypercredulity, and civilization, or what has music got to do with quantum mechanics?

Michael E. McIntyre

Human perceptual processing has remarkable properties, the properties that enabled our ancestors to survive. Lucid writing exploits those properties. It makes efficient use of the reader's perceptual machinery. Anyone can use this idea to improve their writing and other communication skills, by taking account of verbal, musical, and visual perceptual phenomena. Such phenomena include unconscious gap filling and grouping, and the sensitivity to organically changing patterns.

There are wider aspects. For instance the origin and significance of the arts become clearer from this viewpoint, as well as the origin and significance of science and mathematics and the nature of what we call intuition and creative imagination. The arts, as well as the sciences, reflect a biological reality that explains their profound human importance. That reality includes the way perception works — as an unconscious model-fitting process, an unconscious 'science in miniature' — suggesting a simple yet coherent view of science itself, having far-reaching implications for the public understanding of science and, arguably, for future civilization.

I shall begin this journey with the problems of learning to write. Writing skills, and other communication skills, are important to most human activities and critically important to science. Scientific writing should not only engage the reader but should also be lucid. What is lucid writing? Why is it important? Why is it often found difficult to achieve? How can it be made easier? A little scientific thinking helps to answer these questions, and illuminates the nature and origin of science itself. The answers illuminate other aspects of our existence as well.

A good starting point is to think in terms of pattern perception. Writing is something to be read; and the reader's brain has to solve a pattern-perception problem. This is pattern perception of a deeply complex kind. It involves far more, of course, than the purely visual problem of recognizing the shapes of letters, words, and punctuation marks, and far more than recognizing word patterns and syntactic structures. It is the whole problem of decoding and understanding what is written, and so I am using a generalized, multi-level notion of 'pattern', the kind of thing hinted at by recent advances in molecular biology and in the computational theory of perception and cognition.[1–7]

A preliminary working hypothesis that seems reasonable — let us call it the pattern-perception hypothesis for written prose — is that the reader's brain solves the whole problem in essentially the same way in which it solves simpler pattern-perception problems. What that means has been hinted at in the Preface and will be further discussed below. The pattern-perception hypothesis has practical value, though too vague to test directly without further development. It says that general insights about perception can be brought to bear on the practical problems of writing.

Such insights can help one to see for oneself how to write more lucidly, and how to do it in fewer drafts. I shall give specific examples shortly; more are available on the Internet.[8]

If we assume, conservatively, a ten percent average saving of time and effort for writers, referees, editors, and thesis supervisors, then *Science Citation Index* statistics imply a potential productivity saving of at least half a billion US dollars per year from workaday publication alone.[9] On top of this there could be an incalculably greater long term gain both to science itself and to human society, coming from an increased ability of working scientists to alleviate confusion and to contribute to the public understanding of science.

Experts on perception and brain function tell me that they have not seen the pattern-perception hypothesis stated explicitly in this context, but that they think it likely to be valid and that many of them would take it for granted. The hypothesis can be supported by biological reasoning, summarized in phrases like 'economy of design' or 'modular design' or their non-teleologic equivalents; and it is also supported by personal experience. I have found it to be a powerful guide in my own efforts to write lucidly, as have many of my scientific colleagues and graduate students. It does far more than put syntax into perspective. It illuminates aspects of writing that even experienced writers find tricky, as I will try to show.

There are deeper ramifications. The process called scientific writing, like other forms of writing, is a process of trial and error involving repeated pattern manipulation and pattern perception. Seen in this way, the process resembles — and is part of — the process of scientific thinking itself, both individual and collective, including what we call the development of understanding, the crystallization of ideas, the rejection of hypotheses, and the preparation for large and small paradigm changes. The verbal patterns of speech and writing are intimately connected with the deeper, non-verbal patterns of scientific thinking, what we call 'images', 'analogies', 'concepts', and so on. Engaging the reader means activating such connections and patterns in the reader's brain. It might even mean developing them, helping to make new connections and new patterns. Lucidity increases the efficiency of these processes; and it does so in the writer's brain as well as in the reader's. When you achieve lucidity in a piece of writing, you have not only helped to engage the reader but also clarified, and probably expanded, your own thinking. What is involved, therefore, is far more than 'mere semantics'. What is involved is the full depth and complexity of human perceptual processing, which is inseparable from what we call 'thinking'.

How can one turn these ideas to practical use? The pattern-perception hypothesis explains why certain writing techniques work in favour of lucidity and why others do not. It helps one to distinguish what engages the reader from what indulges the writer, and to distinguish what clarifies one's thinking from what muddies it. It helps one to ignore the advice of 'experts in the art of bad writing', in Strunk and White's[10] words, and to appreciate the advice of real experts like Strunk and White themselves, and Fowler;[11] and it suggests that much of the real experts' advice is not an arbitrary matter of style or culture but, rather, a reflection of how the human brain works — the result of biological as well as social evolution.[12,13]

Here are some examples.

Repeat or vary?

Repetition is significant in purely visual patterns and, for instance, in music. The pattern-perception hypothesis says that repetition should be similarly significant in written prose.

According to the hypothesis, it is no accident that lucid, informative writing uses more repetition, and less variation, than the reader might think. For instance, it is surprising how often repeating a noun works better than substituting a pronoun such as 'it', 'this', 'them', 'ones', etc., and it is surprising how seldom a repeated noun jars upon the reader. The same goes for other noticeable words, such as the word 'surprising' in the last sentence. Another example is Fowler's 'We will be serious if you are serious'. Recognizability is enhanced, and perception accelerated, by the appropriate use of repeated words, repeated phrases, and repeated word patterns like 'surprising how often... surprising how seldom...'

The surprise comes from the fundamental difficulty of writing, the difficulty of seeing things from the reader's viewpoint. The writer cannot easily judge what it is like to encounter a sentence once only, in context and at reading speed. Repetition tends to bore the writer, especially after many readings of a draft sentence. It is no wonder, therefore, that writers commonly have an urge to minimize repetition, mistakenly feeling that what bores the writer will also bore the reader. This urge to minimize repetition explains the ubiquitous 'fatal influence', as Fowler calls it, of experts in bad writing who advise young writers 'never to use the same word twice in a sentence' and always to vary words and word patterns as much as possible. What this leads to is illustrated by the following sentence about numerical analysis:

Ex. 1. 'Whereas the spectral method engenders Gibbs fringes, no discretization oscillations are manifested by the TVD algorithm.'

The writer meant

Ex. 2. 'Whereas the spectral method produces Gibbs fringes, the TVD method produces no Gibbs fringes.'

A series of needless variations like those in Example 1 can drag the reader into a quagmire of confusion. Fowler ironically calls them elegant variations. But they could well be called pseudoelegant or muddy variations or, more simply, gratuitous variations. The pattern-perception hypothesis says that such writing is inefficient. It is like a scene containing camouflaged objects. It is harder to decode. Because this wastes everyone's time and energy, including the writer's (see Appendix 1), one could also speak of expensive variations.

Of course repetition can be overdone, and there is such a thing as its skilful avoidance. There are also such things as incongruous repetition, where the same word is used for two different things, and incongruous juxtaposition, where related pairs of words are used for unrelated things as in 'The experiments... concentrated upon rather dilute solutions.'[14] In practice, however, these cause less confusion than examples like 1.

The Three Mile Island nuclear accident

Example 1 and its like[15] are often defended, by their writers, not only as minimizing repetition but also as a matter of personal choice of so-called style. But the pattern-perception hypothesis says that the problems of writing are fundamentally like the problems of, say, computer programming and ergonomics.

Example 1, in other words, is like badly structured computer code. It is like bad road signposting in which different names are used for the same place. It is like bad mathematical notation[16] where four things of the same kind are written as $a,\ M_3',\ \epsilon_2,\ \Pi_{1,2}''$ instead of a, b, c, d, or bad computer keyboards whose layout of the arrow keys disagrees with the directions of the arrows (Fig. 1). And it is like the original control room displays of the Three Mile Island nuclear reactor. There, the colour coding to distinguish normal from abnormal functioning was varied,[17] as in a traffic system whose red lights sometimes mean stop and sometimes go.

1. Arrow key layout: a choice of style?

(Fig. 1 is in the file `lucidity-fig1.gif`)

The idea that such things are unimportant — that so-called 'ergonomic design' or 'user friendliness' is a mere luxury — has a cost that is hard to estimate but must be staggering. A wider appreciation of the pattern-perception hypothesis could help to alleviate the problem. In the case of writing, one does not need long apprenticeship as a professional writer — and one does not need to be a native speaker of the language, nor an expert on grammar and syntax — to see that Example 2 is quicker to understand than Example 1.

Appropriate and inappropriate pruning

Pruning superfluous material is another important technique for lucidity. As Strunk and White say, 'Omit needless words'. The pattern-perception hypothesis suggests why such pruning is important. Like gratuitous variation, superfluous material can act as verbal camouflage. It can activate irrelevant connections in the reader's brain, and impede perceptual processing by making word patterns needlessly complicated.

The hypothesis also suggests why, and how, pruning superfluous material differs from pruning to the fewest possible words. This important difference is not always appreciated.[15] If adding a word helps to clarify a word pattern — reducing ambiguity and accelerating the reader's perceptual processing — then the word cannot be described as needless or superfluous. It might be a case of repeating a noticeable word, or of making the 'then' explicit in the word pattern 'if....then...',[18] or of improving rhythm or changing emphasis. Good rhythm[11] is not a luxury. It accelerates perceptual processing. The word patterns, and the deeper patterns they connect with, exist in time as well as in space.

Dangerous omission

The brain is good at filling data gaps. A friend's face partly hidden from view may still be recognizable. A log behind bars does not look sliced up. The phenomenon of gap filling[19] and the pattern-perception hypothesis suggest why certain judgments can be tricky for the writer, even the experienced writer.

You can, sometimes, safely omit the 'then' from the word pattern 'if... then...', or safely omit a relative pronoun, as in 'the experiment she did', or substitute 'none' for 'no Gibbs fringes' in Example 2 — changing the rhythm and reducing the emphasis. The pronoun part of 'none' can be thought of as a gap to be filled by a noun. The substitution of 'none' for 'no Gibbs fringes' is safe provided you don't then make the sentence more complicated, as in

> Ex. 2′. 'Whereas the spectral method produces Gibbs fringes, associated with the non-uniform convergence of the eigenfunction expansions used to represent the model fields at increasing resolutions, the TVD method produces none.'

None of what? The reader has to stop and go back.

Other tricky judgments include whether to telescope two or more word patterns into one, and whether it is safe to omit a substantial, relevant piece of material altogether. In spoken conversation, such shortening devices are used all the time. We compensate for the slow data rate of the spoken word by taking advantage of body language and of shared assumptions, in order to fill gaps. Such shortening is so habitual and so automatic that, when writing, it is easy to be unaware that something is being telescoped or omitted. That is how one gets effects of the type 'Person wanted to wash, iron and milk three cows'. It is also how one can fail to detect actual mistakes in one's own thinking.[19a]

The writer therefore needs to view such telescoping and omission as highly dangerous. As the great mathematician J. E. Littlewood once wrote,[16] '*two* trivialities omitted can add up to an *impasse*.' Again, this is expensive. A classic example was the case of Adams, Le Verrier, and the discovery of Neptune. The omission of trivialities not only blocked communication but hid an actual mistake. The need to be boringly explicit is sometimes least appreciated by the most talented and, as Littlewood observes, 'it is just possible even for a bright young man to be overlooking something.'[20]

Masters of writing, like masters of drawing and masters of musical composition, know to a hairsbreadth not only *what* is being omitted but also how much omission they can get away with, for a given audience — how incompletely they can represent a pattern and still

Reproduced on p. 42 of
Leiberman, W. S., 1981:
Matisse.
New York, Braziller, 150 pp.

2. *Emma La Forge* (1914), by Henri Matisse (see Acknowledgments).

be lucid (Fig. 2; also, e.g., Ref. 317, drawings on p. 97). For the rest of us it is wise to play safe, especially when making a first draft (Appendix 1 below).

In any case, reading the written word is so much faster than listening to the spoken word that telescoping and omission are much less needed. This is illustrated by Example 2 above, which plays completely safe by repeating words and word patterns in full. Example 2 may seem absurdly pedestrian to the writer, but I suspect it didn't bother you when you first whizzed past it.

Omitting even so tiny a word as a preposition can be dangerous. You might question this, pointing to examples such as

Ex. 3. 'Lucid repetition is effective both at short range and long range.'

The missing 'at' produces only a slight muddiness. This hardly matters, you might say, again because the brain is good at filling gaps. You can see past mud on a windscreen. Or rather, you can often see past mud on a windscreen, but not always. Here is an example from real life, about a Christmas card:

Ex. 4. '...the Executive Committee hoped that members would send one to the Prime Minister, William Waldegrave, and others...' [21]

A small piece of mud, the first missing 'to', has for many readers hidden the fact that the Prime Minister and William Waldegrave are two different people.

Perceptual grouping

Unlike Example 3, Example 4 is syntactically consistent. The alternative form '...to the Prime Minister, to William Waldegrave, and to others...' is needed solely to reduce ambiguity — to stop the reader's brain from grouping 'the Prime Minister, William Waldegrave' together as a single entity, so-called nouns in apposition. Example 4 with this grouping may be set against

Ex. 5. 'Smith went to Yale, Harvard, and Princeton.'

Here a different pattern involving a different grouping, three things in the same category, is recognized instantly and unambiguously. This happens even though the word pattern has the same superficial form as in Example 4: 'to A', where A is a list of noun equivalents.

Examples 4 and 5 call to mind a whole range of perceptual phenomena involving grouping. Among countless other verbal examples[12] are old favourites of the type 'Eggs are to be stamped with the date on which they were laid by the farmer.' The pattern-perception process does the grouping automatically, involuntarily, unconsciously, and at prodigious speed — ahead of conscious thought about whether the sentence is ambiguous or factually correct.

It is well known that there are similar grouping phenomena for musical and visual patterns, and that they are fundamental to the way perception works.[5,7,17,22–25] Fig. 3 shows a visual example from classic studies in experimental psychology.[17] It consists of thirteen identical dots, which are automatically seen as four main groups. The first

3. Visual grouping by proximity.

group, on the left, is seen as two pairs, and the second group as a pair plus a single. The last group is seen as three singles and may be loosely compared to the noun list in Example 5. The third group has some ambiguity and may be loosely compared to the noun list in Example 4. In this visual example the brain is using spatial proximity as its cue. In the verbal examples, the brain is using proximity both at the superficial level of word patterns and also at deeper levels concerned with cognateness or closeness of category, matchability, context, and so on.[12] Again, everything happens automatically, involuntarily, unconsciously, and at prodigious speed, or so it seems subjectively.[26]

The nature of perceptual processing

The speed, and the largely involuntary character — the independence of conscious thought — are familiar general properties of perceptual phenomena. There are clear biological reasons connected with the survival of species. The late David Marr has referred to the remarkable computational machinery that the brain must be using: 'The computational requirements...are prodigious', but 'we have the machinery...to do it, and it's running all the time'.[27] We are normally unaware of all this computational activity,[28] if only because conscious awareness of it would distract us, and would have distracted our ancestors, from the urgent business of survival. 'No organism can afford to be conscious of matters with which it could deal at unconscious levels.'[29]

A large body of evidence shows, furthermore, that perceptual processing is not only fast and unconscious, but also active in a sense that is strongly counterintuitive. Vague, introspective talk of 'activating' connections and patterns scarcely begins to get at what is involved. Closer to the mark would be to say what I hinted at in the Prelude: that the alert brain incessantly tries, of its own accord — outside conscious control — to fit to the incoming sensory data its own internal models, built from preexisting components. By sensory data I do not mean the 'sense data' of certain philosophical traditions;[30] I mean the raw information in retinal images, eardrum vibrations, skin contact, and so on. By model I mean model in the usual scientific sense: a partial and approximate representation of reality.

The existence of some such active, unconscious internal model-fitting process is strongly indicated by, for example, visual structure-from-motion perception,[5,31] as already hinted in the Prelude. In one of the classic demonstrations, people walk across a darkened stage and are made almost instantly perceptible, as people walking, by nothing more than twelve small light sources placed at each person's principal joints, the wrists, elbows, shoulders, hips, knees, and ankles.[31] The dot patterns printed in the margins of these pages were generated by digitizing the data from just such an experiment. If there is no motion, the viewer sees only a constellation of small lights. As soon as the motion begins, the lights are perceived, within a few tenths of a second, as being attached to people walking. This is a robust perceptual phenomenon, hardly explicable otherwise than by unconscious model-fitting, indeed model-fitting to very sparse data. So strong is the impression of people walking that it takes a conscious effort to appreciate how little information the eye is receiving. Further relevant examples are noted in Appendix 2. Though not understood in detail, the hypothesized model-fitting seems to be some kind of multi-level process with two-way feedback between levels, in the current jargon 'both top down and bottom up'.[5–7,32,33] The pattern-perception hypothesis says that this must be true also of language processing.[6]

Perceptual processing is flexible. Consider again the dot pattern in Fig. 3. If the pattern is animated and the leftmost three dots start to move, performing a rigid rotation or translation, or both, then those three dots are immediately regrouped as a triplet despite their uneven spacing. There is an English phrase to describe the phenomenon: the three dots 'move as one'. Such grouping phenomena are basic to structure-from-motion perception. They seem to be part of how the brain uses Bayesian prior probabilities, drawing on genetic and non-genetic memory, to prune the enormous combinatorial tree of possible internal models while trying to maintain consistency with incoming sensory data. In this case large prior probabilities are assigned to internal models with rigidly connected elements.

Prior probabilities can of course be wrong. The co-moving dots might not belong to a rigidly connected element. The phenomenon of 'mind-set' or 'cognitive illusion',[34–36] another aspect of the Three Mile Island nuclear accident,[17] further illustrates how prior probabilities can be wrong and flexibility not great enough. The same can occur with ordinary gap filling: it is easy to demonstrate the perceptual filling of gaps with non-existent lines, edges, or other features.[19] The log behind bars *might* be sliced up. But the pruning of the combinatorial tree — coping with a combinatorially large number of possibilities — would be an amazing computational feat even if it succeeded less often, and even if it took far longer. As another reminder of what 'combinatorially large' means numerically, note that the number of ways to make a structure as simple as a linear, one-dimensional chain with 10 different links is 3,628,800, and with 100 different links, of the order of 10^{158}, i.e., of the order of

100,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000.

Perceptual processing must deal with still larger numbers of possibilities, corresponding to internal models with far more complicated structures — structures that can somehow represent, for instance, what you see in a three-dimensional visual scene. The problems thus posed are hopelessly beyond the reach of our most powerful electronic computers, and profoundly challenge our understanding.[7,37] They are problems of 'inverse theory' with vast data throughputs. That is part of why computers do not yet drive taxis. Multi-level, massively parallel processing of some kind seems essential to cope with such computational requirements. Advances in neuroscience, clinical neurology, psycholinguistics and other cognitive sciences[7,12,32–38] and in the detailed understanding of simpler but analogous biological systems[39] are now giving tantalizing glimpses of how such multi-level processing might actually work. In particular, there are computer programs[7] demonstrating what amounts to combinatorial tree pruning as a self organizing 'top down and bottom up' process, a multi-level process with feedback between levels, within drastically simplified universes but in essence like known biological mechanisms.[39] Psychophysical research is now making significant progress in inferring some of the simplest prior-probability rules.[317]

Levels of muddiness

The pattern-perception hypothesis and the idea of active, flexible, multi-level processing suggest why there are degrees and types of muddiness in writing. Compare the following two sentences:

Ex. 6. 'Skilled writers distinguish what helps the reader from what indulges the writer.'

Ex. 7. 'Skilled writers distinguish what helps the reader versus indulging themselves.'

Example 7 is muddy writing by most criteria, a case of what Fowler calls 'side-slip'. It gratuitously varies the standard word pattern 'distinguish A from B'. But what is interesting is its intelligibility despite this. With astonishing speed and flexibility, the deeper levels overcome the confusion at the superficial levels. Such effects may find artistic uses in poetry and in literary prose; and in the hands of a master they can lead to fresh and exciting new ways of using words. Reprogramming of the reader's perceptual machinery may be involved, changing the prior probabilities. The reader may have to 'learn the dialect'. But such reprogramming cannot be arbitrary. Even a literary genius is constrained by aspects of brain function that are independent of style, language, and culture, if only because of the immensely longer timescales involved, the timescales of genetic memory.[12,13] Evidence for the genetic roots of language is now very clear; Part III will show why. Genius or not, and whatever the style, the writer who wants to be effective must give the reader's unconscious model-fitting a chance.

Such considerations underlie Strunk and White's challenge to the writer of literary prose 'who is being intentionally obscure or wild of tongue... Be obscure clearly! Be wild of tongue in a way we can understand!'[10] One might add, in some cases, 'Be ambiguous in a way that makes sense!' As well as freshness and excitement there are considerations of coherence or integrity, involving self consistency within and between levels, and again reflecting culture-independent aspects of brain function. In the case of science and scientific writing, coherence is not just one of many considerations but the prime consideration.

Coherence, lucidity, and survival

Our interest in coherence — in what hangs together and 'makes sense' — is a key to understanding, in a very fundamental way, what lucidity is and why it is important. It is also a key to understanding what science is. The point is that our interest in coherence is far more than a conscious, intellectual interest. It is also a deepseated, unconscious *instinct*.

The existence of such an instinct follows from the way perception works, from the existence, and the automatic, unconscious nature, of the internal model-fitting process. (See also Appendices 2 and 3.) 'Making sense' of, or so to speak connecting with, the incoming sensory data can mean only one thing, which is that the brain has achieved what it decides to be sufficient goodness of fit between the incoming data and a coherent, self consistent internal model.[40] Only thus can we visually judge the distance to a nearby object, and its speed if moving; the incoming data may involve nothing but the light entering our eyes.

Coherence and self consistency of the internal model must mean, almost by definition, that the model is able or potentially able to represent something in the outside world; cf. Fig. 4 below. Were it otherwise, our ancestors would not have survived and we would not be here. The thing in the outside world might be a charging rhinoceros. We are instinctively, and unconsciously, interested in coherence and self consistency because they are matters of life and death.

Exercising, rehearsing, developing, and refining that instinctive, unconscious interest in as many ways as possible, from juvenile play onward, is therefore an important need. It is a prerequisite to surviving in the outside world. It is as important as the need to exercise our muscles; and it shows itself as the creativity and curiosity observable in healthy human beings, most conspicuously in young children at play. It is among the reasons why the arts and sciences exist, going all the way back through cave painting, ritual dancing, storytelling, ballad singing, and tool invention.[41–44]

In particular, one can begin to see the origin and nature of logic and mathematics (Appendices 2 and 3) and their relevance to science. Logic and mathematics are sophisticated aids to thinking consciously about, and checking for, coherence and self consistency in a very wide range of circumstances. So too is the exercise of striving for lucidity in writing. So too is the entire process of constructing what we call a good scientific theory, that is to say the manipulation of visual, mathematical, and, just as importantly, verbal patterns and their deeper connections into mutually consistent, well organized structures

(*a*) that are potentially able to represent things in, and hence to fit data from, the outside world (coherence and self consistency),

(*b*) that are free of unnecessary complications (Occam's razor, logical and mathematical beauty), and

(*c*) that can be checked against experiment or observation (disprovability, refutability).

In this sense, science is an extension of ordinary perception,[45–47] a conscious or partly conscious extension of the instinctive, unconscious, internal model-fitting process — a far-reaching extension that involves deliberate, meticulous, conscious thought dealing with a range of circumstances far wider than we can deal with by instinct, intuition, or common sense alone.[34–36,48] 'Model' has to be understood here in a broad sense that includes, for example, the high precision model building blocks that we call the laws of physics. Also included, in every case, are experimental concept and design: there is a 'scientific ideal' one of whose demands is that the whole edifice of experiment and theory should be self consistent.[45–51]

It should hardly need saying, but does need saying, that the consistent use of words and symbols requires the avoidance of any word, phrase or symbol whose definition is self-contradictory, as with a number $\mathcal{N}$ defined to be equal both to 1 and to 2. Before laughing too loudly, recall the celebrated and slightly less obvious example of the *heteroactive barber* — the adjective *heteroactive* being reminiscent, perhaps, of some of our impressive-sounding technical terms or trendy buzzwords. A heteroactive barber is defined as a barber who shaves those and only those who do not shave themselves. This, famously, is not a deep paradox but merely a self-contradictory definition — though not obviously so, for most of us, without a moment's careful, conscious thought: 'If the barber shaves himself, then he does not shave himself,' etc. Human language, for the reasons pointed out in Part III (`lucidity3.ps`), lacks automatic checking against this kind of thing. As with the ineffable 'number' $\mathcal{N}$, the idea of the heteroactive barber can be talked about, or written about — perhaps at great length — but being self inconsistent cannot correspond to anything in the outside world.[49]

Confusion and incoherence

The last point reminds us that there is another side to the biological reality under discussion. Camouflage and deception are also part of nature, are also rehearsed in juvenile play, and are also matters of life and death. Arguably, therefore, there must be an instinctive interest in confusion and incoherence if only because, in order to understand someone else's confusion and how to produce it, you need to be interested in confusion yourself. But there is more to it than that: an instinctive interest in confusion and incoherence seems also to be part of what excites curiosity and promotes adaptability. Part of the fascination of any puzzle, scientific or non-scientific, is the excitement of feeling that what looks incoherent might yet be made sense of, the excitement of straining to see shapes emerging from a literal or metaphorical mist.

The same fascination may be part of what underlies artistic 'wildness of tongue' and 'speaking in riddles'.[43] In poetry and in literary criticism, for example, incoherence sometimes seems to be played with for its own sake, or perhaps as an attempt to say the unsayable. It could be poetically valid to speak of a four legged, five legged rhinoceros, of 'one hand clapping', of 'isolated, interacting universes',[49] of the mysterious 'number' $\mathcal{N}$, or of something ineffably 'not... identical to itself'.[52]

Fig. 4 is a non-verbal counterpart, showing what could be described as a four legged, five legged, seven and a half legged elephant, or a solid, not solid elephant, or an elephant not identical to itself.

This is one way in which the arts and associated intellectual adventures may validly differ from science. As great artists have shown — be they labelled ancient, modern, post-modern, or timeless — it can be humanly important to celebrate the ineffable, the ever mysterious, the intractably incongruous. But that is not among the aims of science, whose distinguishing feature is the scientific ideal, which demands experimental disprovability, hence fittability to things in the outside world, hence strict coherence and self consistency.

Clarity in making the foregoing distinctions is important, it seems to me, not only for the improvement of thinking, writing, and communication skills as such, but also for a deeper understanding of what the arts are, what science is, what education is and could be, why they matter to us, and why rational thought and intuitive thought must, or rather do, necessarily work together. Such understanding seems especially important today for the health of science itself, for the public understanding of science, for the wise use and promotion of science and the arts and indeed, I would venture to say, for any kind of civilized future existence. For both science and art are rooted in our deepest being; and the estrangement of the one from the other is part of our spiritual malaise.

See Ref. 28, p. 79.
The drawing is in copyright and cannot
be distributed on the Internet

4. Roger N. Shepard's[28] drawing of an impossible elephant, an elephant not identical to itself[52] (reproduced with permission; see Acknowledgments). The drawing, considered as a model for the shape of a real elephant, violates coherence and self consistency in a way that illustrates the language-independence, the culture-independence, indeed the species-independence, of the concepts 'coherence and self consistency'.

Organic change, music, and coherent ordering

We can now see more clearly why lucid pattern-repetition, appropriately used — as in 'surprising how often... surprising how seldom...' or as in Example 2 — is such a peculiarly effective writing and speaking technique. The reader's or listener's response to it illustrates a basic perceptual sensitivity, and cognitive sensitivity, whose existence has to be expected on biological grounds. This is the sensitivity to what might be called 'quasi-organic change' in evolving patterns, or 'organic change' for short. An organically changing pattern is one that changes in some ways, by small enough increments, but stays invariant in others. We may speak of organic change both in sensory data and in the internal models to which the data are being fitted.

A sufficient reason to expect sensitivity to organic change is the need to distinguish living things from dead or inanimate things. A moving elephant has an invariant number of legs. It has other invariant properties that are reflected implicitly in the sensory data, and explicitly[5] in the internal model being fitted to those data. The ability to distinguish living things from dead things has been shown, not surprisingly, to exist in human infants and to be highly developed in preschool children;[12, pp.422–6 & refs.] and it hardly needs adding that the ability is basic to survival. Examples of sensory data showing organic change include the light scattered into your eyes from a charging rhinoceros, and the acoustic time series from a jungleful of animal sounds. As is well known, and evident to any careful observer, our eyes and ears are sensitive to rates of change; and I am saying that for survival's sake the brain must be good at extracting the invariant aspects of anything that is changing. Again for clear biological reasons, the sensitivity to organic change extends, furthermore, to longer timescales on which rates of change are not directly registered, from the opening of a flower to the march of seasons to the growing up of children.

Not surprisingly from this viewpoint, patterns that exhibit organic change are used in the arts, as well as in scientific communication and in other forms of communication. Such patterns can be a powerful means of attracting and holding attention. They are especially conspicuous in the art form called music, or rather the familiar, but remarkable, phenomenon called music. Music reflects deepseated biological realities, as is plain from its ubiquity in human cultures and from its large scale commercial exploitation. The existence and nature of music is one of the clearest demonstrations that the unconscious brain has an instinctive interest in coherence and organic change for their own sake, even when abstracted from more immediate, concrete, outside world associations. That instinctive interest is related to an unconscious power of abstraction that we all possess. It is required by the model-fitting process, by the need to cope with a combinatorially large number of possibilities. I argue in Appendices 2 and 3 that this same power of abstraction underlies the development of, for instance, mathematics, and may well account for Platonic feelings about mathematics — a mathematician's sense of discovering something from another world already there[53] — as well as for Pythagorean feelings that musical and mathematical beauty are deeply related. The worlds of mathematics and music are, indeed, already there, deep within genetic memory, inviting exploration.

Musical patterns that exhibit organic change — patterns that change in some ways but stay invariant in others — are used to arouse and to hold the listener's or dancer's attention by producing a sense of evolving, of going somewhere, of being alive. As in the real living world, the pace can be fast or slow: sometimes the feeling is of hardly moving at all yet being alive, the magical standing-still of a living creature. It is no accident that composers, and other artists, speak again and again of their work taking on 'a life of its own'.[54] And careful listening reveals organic change at the heart of practically every style of music. For instance, patterns like 'surprising how often... surprising how seldom...' commonly recur, one of many remarkable family resemblances between effective music, effective speech, and effective writing.[43,55,56] The famous tune of *Oh, what a beautiful mornin'*, by Richard Rodgers, is a simple but sufficient example. Further examples include George Gershwin's *I Got Rhythm,*, the *Finale* of Beethoven's Ninth, Johann Strauss' *Blue Danube* waltz, Leonard Bernstein's *America* from *West Side Story,* Frederick Loewe's *Wouldn't It Be Luverly* from *My Fair Lady,* Jeremiah Clarke's *Trumpet Voluntary* or *Prince of Denmark's March,* the slow theme from Antonín Dvořák's 'New World' Symphony, themes from Igor Stravinsky's *Rite of Spring,*[57] and the following nursery song, which I am told is familiar to this audience; you need not be familiar with musical notation to see which parts of the pattern are repeated:

Naughtily

Musical notation: this is the last example in the file `lucidity-piano12.gif`
(Treble clef, key of C major)

Jonathan, hakatan, ratz baboker el hagan, Hu tipess al haetz, efrochim chipess.

Organic change also permeates, for instance, the so-called rules of harmonic progression.[58]

More elaborate examples extend all the way to large scale symphonic development.

They illustrate yet another aspect of lucidity that applies not only to musical composition, but equally to writing and to speaking or lecturing, namely, the importance of finding a coherent order of presentation. Coherent ordering is overwhelmingly important. It is crucial that each new point is preceded by any necessary preparation, to set contexts and to establish key ideas (Appendix 1). Otherwise, one fails to exploit a large part of the listener's or reader's perceptual sensitivity; the argument does not unfold organically:

> Imagined, but typical, dialogue between a referee and the author of a scientific paper being considered for publication: *Referee:* 'The author uses three undefined terms and two undefined symbols on page 2. Besides, I don't see the point of doing this calculation at all.' *Author:* 'But if only the referee had read on, all would have become clear.' *Referee (to himself or herself):* 'After about five rereadings, I suppose. I think I'll switch attention to some other pressing commitments.'

As before, these things are not arbitrary matters of style. A given piece of music, for instance, whatever its style — from simple to complex, from serious to funny, from classically restrained to romantically wild of tongue — can be recognizably successful, or good of its kind; and in this there has to be an element of consistency and coherent ordering.[55] When well performed, such a piece gives a feeling of hanging together, of evolving coherently or becoming coherent,[59] of making sense at all levels. Small details serve the whole. Patterns and connections are developed in ways that can be highly varied, indeed startlingly varied or deliberately ambiguous or incongruous, but that meticulously avoid what a musician would call weak, gratuitous, pointless variation or mere inconsistency — the musical counterpart of Example 1.[60]

What then is lucidity? The foregoing discussion suggests an answer. Lucidity is something that satisfies our unconscious, as well as our conscious, interest in coherence and self consistency. Lucidity makes superficial patterns consistent with deeper patterns, avoiding what psychologists call 'Stroop interference', as when the word 'red' is printed in green letters.[16,32] Lucidity exploits natural, biologically ancient perceptual sensitivities, such as the sensitivities to organic change and coherent ordering, which reflect our instinctive, unconscious interest in the living world in which our ancestors survived. Lucidity exploits, for instance, the fact that organically changing patterns contain invariant or repeated elements. Lucid writing and speaking are more explicit than the writer thinks necessary, and where possible use the same word or phrase for the same thing, similar word patterns for similar or comparable things, and different words, phrases, and word patterns for different things (cf. Appendix 1). If mathematics enters, its symbol patterns are used with the same care as word patterns. Words, numbers, and mathematical symbols are firmly, consistently, and repeatedly tied together.[61,62] Context is built before new points are introduced. In these and in other ways, lucidity accelerates perceptual processing, pruning the enormous combinatorial tree of possible internal models in the reader's or listener's brain as quickly and appropriately as possible, ahead of conscious thought.

The late David Bohm has suggested that, contrary to popular belief, these things are not luxuries.[50] Rather, they are practical necessities when trying to understand anything non-trivial and unfamiliar. As Bohm compellingly argues, it is precisely here that we find clues to some of the most deeply embedded, and by now notorious, difficulties in understanding quantum mechanics.[49–53,63] I shall touch on another aspect of those difficulties in Part III (`lucidity3.ps`).

Conclusion

It is no accident that many successful scientists are skilled, careful writers. In today's complex, fascinating, but confusing world it is surely important for every scientist to try to emulate them. Most fundamentally, scientific writing is part of scientific investigation, as I have tried to suggest. Seeing similarities and differences, seeing connections and analogies, finding viewpoints that make data more intelligible or theories simpler, dispelling 'mind-sets' and cognitive illusions, exposing false dichotomies — and checking for strict coherence, self consistency, and completeness of thought in as many ways as possible — all entail what I began by calling multi-level pattern manipulation and pattern perception, both verbal and non-verbal, amounting to a conscious, or partly conscious, extension of the biologically ancient, unconscious, internal model-fitting process.

Scientific genius seems to consist of unusual power, flexibility, and depth in performing these feats. 'Genius is the ability to make all possible mistakes in the shortest possible time.'[64] To be sure, genius may well do most of this non-verbally; and the pattern manipulation and perception that lead to great discoveries may at first be very fuzzy, and again largely unconscious. This is true for instance in mathematics, according to Littlewood: 'Most of the best work starts in hopeless muddle and floundering, sustained on the "smell" that something is there.'[16, p.144] The aim is then to find, verify, and illuminate that something, and make it clearly understandable, to the discoverer as well as to others. This may become the work of many individuals.[50] But, and here is the main point, the whole process resembles what an individual does when trying to achieve lucidity in the humblest piece of writing. The effort to achieve lucidity and to engage the reader is never wasted. It is an essential part of good scientific training and professional practice; and it is far more than that. It is a game to exercise, exploit, and develop our unconscious as well as our conscious interest in coherence and self consistency, part of our heritage from life itself.

So here, finally, take it or leave it, is one working scientist's advice to young writers, especially those who want to write within or about science. I assume that you have something interesting to say and that you have decided what line to take — that you have a preliminary plan of your main points approximating a coherent order of presentation. I assume that you would like to engage the reader if you can. My advice is, first, check that you know something about perceptual phenomena such as the 'walking lights',[31] second, read Chapters 1–2 of Strunk and White with the pattern-perception hypothesis in mind, third, read Fowler's article on 'elegant variation' and, fourth, adopt the tactic 'safety first in first drafts', erring on the side of Example 2 above. It will save your time and that of others if you keep the mud off the windscreen from the start. With an ergonomically decent word processor there is little labour in repeating words and word patterns fully. Doing so, even if you shorten later, helps to check for hidden inconsistencies and to expose problems of coherent ordering.

Remember, above all, Littlewood's *impasse*. Littlewood was a genius by most standards. So you can forget any worries about insulting the reader's intelligence.[20] Remember that lucid, informative writing is like good road signposting, boringly explicit and unvaried from the writer's viewpoint. The lie of the land is what interests the reader, not the signposts as such. Remember above all that lucidity is important to science and important to your career. It is important whether you are writing for fellow scientists, for administrators and funding agents, or for members of the public. We live in a world where getting things clear scientifically is becoming increasingly urgent and increasingly difficult. Beyond assessing the balance of probabilities in this or that situation, we need to widen awareness, and appreciation, of the strengths, the beauty, the excitement, the crosscultural validity and equally the limitations of science. Most important of all, in the long run, we need to rediscover, demonstrate, and cogently argue, again and again, the cultural and human value of the scientific ideal, the respect for coherence and experimental evidence above personal gain or tribal or commercial pressures, the humility in the face of the unknown. For all these reasons, lucidity of thought and communication will be more than ever at a premium.

* * * *

Postscript: Hypercredulity, quantum mechanics, and scientific truth

Respect for science is on trial in today's world...

[Old version well out of date, and deleted. If you are interested, please download the files `lucidity3.ps` or `lucidity3.ps.Z`, together with `lucidity-figP1.gif`, `lucidity-figP2.gif`, and `lucidity-figP3.gif`, for the most up-to-date version of this section and its three figures, now published as Part III in *Interdisc. Sci. Rev.*, **23**, 29–70 (see copyright page at the start). Here is the updated abstract:

Abstract:

Scientific research can reasonably be described as a search for truth, in an important and nontrivial sense. But respect for the scientific ideal is incompatible with the myth, or instinctive, quasi-religious belief, that science is about discovering final, infallible, absolute or ultimate truth. That myth, if publicly endorsed by scientists, inadvertently or otherwise, is perilous because it fuels tribal conflicts like the current 'science wars' and increases public confusion about science. This in turn helps the psychological, social, and economic forces, including the forces within big commerce, that work toward discrediting the scientific ideal and ethic for reasons both conscious and unconscious, restricting our options for coping with an uncertain and highly dangerous future. Future possibilities include the risk of substantial sea level rise, continuing unstoppably for a century or more after first detection. Also possible — and arguably likely if the scientific ideal is too far discredited — is the destruction of the system of free market democracy and free trade, the government by consent and prosperity of individuals on which big commerce itself depends.

Our understanding of the actual and potential human behaviour patterns that might lead to such destruction is being sharpened by evidence from linguistics, palaeoclimatology, palaeoanatomy, and genetics, and from research on perception and cognition. It is remarkable that any such self-understanding is possible for us, and even more remarkable that any human society allows such matters to be openly discussed. Both things demonstrate our species' adaptability and the power of cultural evolution — more precisely the adaptive power of the intimate and intricate interplay, or dynamic, of what we falsely dichotomise as 'nature and nurture'. This adaptive power is one reason why our children and their descendents might dare, against the odds, to hope for some kind of civilised future existence incorporating a new covenant between science and society.

'I would know my shadow and my light, so shall I at last be whole.'
— Michael Tippett [400]

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[The foregoing are the Acknowledgements published in Part I; here is the supplement from Part III:]

I understand that the point made in Part II (Appendix 2 below) about Final Theories, that Gödel's theorem precludes them, has previously been made by John Barrow. I am grateful to the following people, as well as to the people and organisations listed in the Acknowledgements of Parts I, for helpful information and comments: Leslie Aiello, Ross Anderson, John Coates, George Efstathiou, Jonathan Gregory, Geoff Jenkins, Chris Jordan, Judy Kegl, Malcolm Longair, Albert Libchaber, Rose Mitchell, Walter Munk, Sandu Popescu, Jacques Prost, Sarah Raper, Daphne Sulston, John Sulston, Lonnie Thompson, Scott Tremaine, Jonathan Sahananda Wolfers, Peter Wolfers, and Carl Wunsch. Antony Pay again gave especially valuable help and encouragement. Mark Hull in the *ISR* office lent great editorial skill and took meticulous care, far beyond the call of duty, in seeing the rather massive three-part published version through the press.

Appendix 1. Safety first in first drafts

Commoner than extreme cases like Example 1 are cases intermediate between Examples 1 and 2, such as, in decreasing order of muddiness:

Ex. $1'$. 'Whereas the spectral scheme produces Gibbs fringes, the TVD method gives rise to no discretization oscillations.'

Ex. $1''$. 'Whereas the spectral method produces Gibbs fringes, the TVD scheme does not cause them to occur.'

Ex. $1'''$. 'Whereas the spectral scheme causes Gibbs fringes, the TVD method produces none.'

There are many more possibilities, anywhere in the range from quagmires of confusion to mere slipperiness underfoot. The writer who thinks that repetition should always be minimized or reduced has to keep on deciding between such possibilities, despite being immersed in the material and therefore in the worst possible position to make such decisions. For a conscientious writer the problem can be time consuming. It is simpler, quicker, and almost always better[65] — unless you know to a hairsbreadth what you are doing — to avoid gratuitous variation of words and word patterns from the outset.

Such avoidance, illustrated in Example 2, is part of the tactic that I call 'safety first in first drafts'.[8] The tactic is simply to play safe and give lucidity, including explicitness, first priority from the outset, leaving other things like neatness and succinctness to be considered later.

The 'safety first' tactic has a useful side effect. It forces you to decide what to call things. If you can't decide what to call something, you can put down a dummy word or phrase such as XXX, and globally replace it later. Other lucidity principles become more obvious as well, including the need to find a coherent order of presentation and in particular the need to indicate the sense of technical terms, and mathematical symbols, at their first occurrence, especially when accepted conventions permit the use of more than one term to mean the same thing and vice versa. Like it or not, such ambiguity occurs surprisingly often: old terms are incessantly being given new meanings, deliberately or inadvertently.[12,66] First-occurrence signposting can use constructions like 'Gibbs fringes, i.e., truncation oscillations, are produced by the spectral method but not by the TVD method', 'We use the idea of such and such, also known as so and so...', 'We use the idea of such and such, in the sense of..., not to be confused with...'. (The 'we' refers to the hoped-for 'you and I, dear reader'.[67]) Further notes on 'safety first' and related matters are available on the Internet.[8]

Anyone who thinks that all this will cramp their 'style' — and that unlimited variation, and departures from coherent ordering, are needed for 'interest, variety, and stylishness' — should look at the many writing techniques that offer interest, variety, and stylishness without sacrificing lucidity.[10,11,68] Some of the techniques involve the control of rhythm and emphasis, itself part of the exploitation of pattern perception. The use of long and short sentences, of passive and active verbs as appropriate,[67–69] of parenthetical comma pairs, and of sentence and paragraph endings are all cases in point, as well as the rhythmic and emphatic uses of repetition. Where shortening a word pattern would be a safe option, you can choose to shorten or not to shorten, with different rhythmic and emphatic effects. Variety can come from finding an apt word or phrase to convey an image, metaphor, or analogy. It can come from using different words for different things, including things that are subtly different. It can come from good control over levels of conceptual precision. You might want to deal with more than one level of precision and to keep the levels clearly distinguished. This needs good signposting for the shifts in level: 'Roughly speaking, the idea is such and such. More precisely,...'. Or, again, 'Roughly speaking, the Gibbs fringes are due to non-uniform convergence of the spectral expansions. More precisely,...'. In conceptual matters, it helps to be clear how fuzzy one is.

Lucid repetition and lucid pattern-repetition are not, of course, to be confused with repetitiousness, which means saying the same thing without developing it. Organic change does involve change.

Lucid repetition is an important technique for forging links between sentences, and at longer range. (And it takes the pressure off overworked linkage devices such as demonstrative pronouns.)

There are inappropriate uses of pattern-repetition. Strunk and White[10] give an example under the heading 'Avoid a succession of loose sentences.'

> 'The third concert of the subscription series was given last evening, and a large audience was in attendance. Mr Edward Appleton was the soloist, and the Boston Symphony Orchestra furnished the instrumental music. The former showed himself to be an artist of the first rank, while the latter proved itself fully deserving of its high reputation. The interest aroused by the series has been very gratifying to the Committee, and it is planned to give a similar series annually hereafter. The fourth concert will be given on Tuesday, May 10, when an equally attractive programme will be presented.'

A conspicuous overall pattern, having a strong rhythmic effect, is insistently repeated when to do so is pointless. The strong rhythm has no correspondingly strong deeper connections. For instance comparable things are not being compared or otherwise dealt with except, slightly muddily, in the second and third sentences.

The slight muddiness comes not only from the gratuitous variations embedded in the larger scale repeated pattern, but also from 'trivialities omitted'. Are we being told indirectly that Mr Appleton is a singer? Or is 'furnished the instrumental music' no more than a gratuitous variation, and pattern-variation, stemming from the writer's urge not to repeat the verb 'was'? Are we meant to laugh at the slightly incongruous 'furnished'? In any case, it is easy to replace the sentence containing 'furnished' by an explicit, lucid version: 'The solo tenor [pianist, violinist, oboist, horn player,...?] was Mr Edward Appleton. The orchestra was the Boston Symphony.'

Tailpiece: Within today's international English usages there is a strange habit of using Greek and Latin plurals, such as 'phenomena', 'criteria', 'media', 'tori', etc., as substitutes for the standard singular forms 'phenomenon', 'criterion', 'medium', 'torus', etc. despite *not* using 'phenomenas', 'criterias', 'medias', ‘toris’, etc., as the plurals. The urge to create grammatical irregularity — to introduce gratuitous pattern-variation even into grammatical or syntactical mechanisms — seems to be another example of the urge to vary. Perhaps the unconscious is urging that the standard singular forms, ‘phenomenon’, ‘criterion’, ‘medium’, ‘torus’, and perhaps even more their anglicized plurals ‘phenomenons’, ‘criterions’, ‘mediums’, ‘toruses’ are not trendy enough (though, curiously, ‘mediums’ seems to be accepted for people who claim contact with other worlds, which I thought was fairly trendy). The subconscious is a cunning beast, tempting you to pretend that you know Greek and Latin even if you don’t know the first thing about them.

A special case is, of course, the newsmedia, or The Media. Like ‘sheep’, these terms seem unassailably established, in defiance of their Latin origin, as uninflected nouns — simultaneously singular and plural — and the singular sense does not seem to mean a single newspaper or broadcast channel. I presume that the singular sense denotes an imagined monster, the putative monolithic *thing* that exerts an awesome control over human populations and human lives. It is lucky that the reality is multipartite, and has a good chance of remaining so. Personally, I never use ‘newsmedia’ as a singular noun.

Appendix 2. Acausality illusions and other perceptual phenomena

(This plus Appendix 3 is an out-of-date version of the published Part II.)

2.0 Preamble

A good metaphor for our time, especially for those demanding absolute certainty from scientists, is ‘science as our eyes and ears on an uncertain future’. On page 10 above I gave reasons for thinking that this metaphor is far from superficial. Not only can science be viewed as an extension of ordinary perception — with, of course, suitable precautions and cross checks[48] — but such an extension is fundamentally what science is. This is because ordinary perception, as well as science, works by fitting models to data from the outside world, of which more in a moment. And if you think that this idea makes science seem less wonderful than you would like it to be, then you may have forgotten how wonderful, how near miraculous, so-called ordinary perception is.

Like ordinary perception, science can make certain aspects of the outside world vividly clear to us, and with impressive, indeed awesome, accuracy in some cases. The electron is a sufficient example.[316] Conversely there are, and always will be, aspects that are unclear, illusory, or out of sight altogether, beyond the research frontier. Trying to make sense of things near the research frontier will always be — fundamentally — like driving a vehicle in swirling fog on an unfamiliar, unmapped, twisty road with many branches, and with plenty of oncoming traffic. One has to live with uncertainty, one has to keep one’s eyes and ears open, and one has to expect surprises.

Does it make sense to harass, criticize, or sack the driver who admits to uncertainty about what lies ahead? It might be a better idea, in the real world, *Star Wars* notwithstanding, to sack the driver who shuts his eyes and blocks his ears and claims infallible prior knowledge. This is accurately relevant to public issues involving science. It is relevant for instance to the ongoing fight against new diseases,[160] and — to take an example where I have some specialist knowledge of my own — relevant to the problem of monitoring and predicting environmental change, for instance whether the sea level will rise, and if so how quickly, and by how much, over the next century or two, say by three centimetres or three metres, or whether deep ocean circulations could flip chaotically and devastate local climates and economies. For well understood reasons,[310,311] there is great uncertainty over questions like these last two: we are indeed, collectively, driving in the fog, and the ‘vehicle’ at risk — strong in some ways and vulnerable in others — is our planetary life support system.[110]

I shall return to such public issues in the third and final part of this series. Here I want to look more closely at the central, all-important, and sometimes controversial idea that both science and ordinary perception work by fitting models to data from the outside world. That science works by such model-fitting must be obvious to anyone who knows anything about science. For the moment I shall take this for granted. That ordinary perception works by model-fitting is perhaps less obvious, and has been controversial for centuries, perhaps because of the way it seems to contradict subjective experience. For good biological reasons, as remarked earlier, this model-fitting is not only prodigiously fast but also automatic and unconscious. A keen observer will sometimes notice hints of it when the incoming data are sparse, as when straining to see things through fog, or when trying to identify someone’s face at a distance. A common experience is the ‘perceptual xenomorphosis’ in which a familiar face sighted at a distance turns into a stranger’s on approach. Before the change, the familiar face is experienced as the perceived reality: the wrong model is fitted at first. This is related to what psychologists call ‘categorical perception’. Other examples include the spontaneous flipping of ambiguous drawings like the famous Necker cube.[5,17,24,25,28,32] Usually, such a drawing appears to represent one of two ‘perceived realities’: first you see the one, and then, if you look long enough, the other. Also noteworthy is the ‘walking lights’ demonstration, described on page 7 and available on the Internet[31] — the demonstration that a mere twelve or thirteen moving dots, conveying a relatively tiny amount of information, can be enough to generate *unambiguously* the percept of a person walking.

There are far-reaching implications, not just for law courts and identity parades, but for understanding most aspects of our existence. Practically everything we do depends on the way perception works; and the way perception works is intimately bound up with the way cognition works. There is no clearcut boundary between the two; and it is no accident that cognition is often called perception, as in stock phrases like 'scientists are perceived as arrogant.' The effect of the walking lights demonstration is not so much to 'see' a person walking but to 'know that you are looking at' a person walking.

The brain must, of course, be using entities that can reasonably be called models, in the sense of being partial and approximate representations of reality. That much is obvious. But the important additional idea is that perception and cognition not only involve using, but also actively building and fitting, internal models or, if you prefer, unconscious symbolic structures:[5] actively fitting hierarchies of model components and subassemblies together in a prodigiously versatile and efficient way, such that relevant parts of the structures are consistent with, and remain consistent with, the relevant sensory data, including data that might be of more than one type, such as visual and auditory — as with the lipreading or 'McGurk' effect, a visually induced change in auditory speech perception,[22,211] and other multisensory perceptual phenomena.[220–222a] The biological point of all this is to have, as far as possible, a single, interconnected, self consistent symbolic structure that when fitted to all available sensory data can represent the surrounding reality, and our place in it, well enough to give us a chance of surviving.

The evidence suggests that the processes involved are not only highly active but also characterizable as self organizing, multi-level processes, simultaneously 'top down and bottom up',[7,22,32] that is, with feedback between levels. Such processes are unconsciously 'theory laden', i.e., model dependent; but they are also closely and sharply constrained by sensory data. In a fundamental sense, they are unconscious scientific investigations performed at lighting speed.

The metaphors I am using can hardly be perfect. If there are 'top down and bottom up' aspects then surely there are 'sideways' aspects too, unconscious lateral thinking if you will. The whole cognitive–perceptual complex must indeed be densely and multiply interconnected, or interconnectable, in more than one sense and in many 'dimensions'.[7]. However, the basic idea, that both science and ordinary perception work by model-fitting, is not only a simple idea in itself but also helpful, I shall argue, toward clarifying many otherwise perplexing problems — far more than how to write and speak lucidly, my starting point on this journey.

As already hinted on page 10, the model-fitting idea is helpful toward understanding, for instance, the very origin of our symbolic and linguistic cognitive abilities — unconscious as well as conscious — including, I shall argue, the cognitive abilities associated with mathematics and music, more fundamental to our nature than is often supposed. The model-fitting idea contains important clues as to why some educational methods work better than others. It is basic to understanding the phenomena called free will and consciousness. And, as I shall try to show in Part III, it can help to blow away the philosophical confusions about science now threatening the stability of democratic nations; in particular, it offers hope of reconciliation in the current and deeply damaging 'science wars'.

All this deserves serious discussion, more serious and more careful than the foregoing. What follows is an attempt toward providing such a discussion, on the basis of key evidence and in a way that avoids getting too technical.

2.1 The model-fitting hypothesis

Though hardly novel, the assertion, more properly hypothesis, that perception works by model-fitting is bold — some would say brazen — not only because of the necessary complexity and interconnectedness of the internal models but also because we have so little detailed physical, chemical, biological, and computational knowledge of how the model-fitting might work. We have only the merest glimpses of how neurons, synapses, protein molecules, and other elements in the brain might carry out perceptual processing, and of how its mechanisms develop in infancy and childhood through the intricate interplay of so-called nature and nurture.[2,5,22,23,32,38,210] All that can safely be assumed about such details is that the usual textbook models of brain function do not adequately represent them.[1–4,71] Such textbook models, which idealize neurons or nerve cells as simple logic elements, undoubtedly describe important aspects of brain function. But there are a billion or more protein molecules, all in thermal motion on picosecond timescales, within each single one of our tens of billions of neurons.[32] Many of these protein molecules are themselves precisely functional logic elements. So it would be more accurate to view the brain as a hypermassively parallel computational system of which neurons and their synaptic interconnections are, so to speak, merely the tip of the iceberg.[2–4,71]

But, as already suggested, the case can be made independently of detailed mechanisms. The basis on which support for the model-fitting hypothesis is claimed here is the usual scientific basis, as touched on earlier (p. 10). I shall return to this crucial point ('On epistemology' etc., below), but, in brief, if we hypothesize that perception works by model-fitting then we can easily explain, and greatly clarify, in a coherent and self consistent way, a host of perceptual phenomena that would otherwise be incomprehensible. Just how completely incomprehensible is well brought out by, for instance, the historical and philosophical sketch and the scientific discussions in Chapter 14 of Ref. 17. The same point is underlined by the celebrated intellectual struggles of the great philosophers themselves.[291a,291]

The model-fitting hypothesis is also in keeping with general knowledge about biological systems, and with detailed knowledge at molecular level in some cases. One such case is that of a mammalian immune system such as our own, which can be thought of as a perceiving system — a system that perceives and knows about invading foreign material, for instance detailed molecular patterns on the surface of a virus or bacterium. 'Perceive' is a better term than 'recognize' because the immune system can do it with wholly novel patterns, chemically synthesized patterns that were non-existent until human chemists made them. The system works by actively constructing, from preexisting components, its own approximate internal models of the incoming patterns.[319] Models are selected from a combinatorially large ensemble on the basis of goodness of fit. The selection mechanism is a clearcut Darwinian mechanism. The information defining the models thus selected is then stored within special memory cells. Here, despite massive complexity, the mechanisms are known in considerable detail at molecular level; and they include a means of iteratively tightening the fit by successive approximations.[319a] The whole process has the general character I am talking about, and whose wider significance I am trying to suggest: it is hypermassively parallel, self organizing, and simultaneously 'top down and bottom up'. This general character seems typical of biological systems,[3,71] and there seems no reason why the brain should be an exception, its vastly greater complexity notwithstanding.

Rather than trying to discuss all the relevant classes of perceptual phenomena in what follows, I shall single out just two, the first involving hallucinatory phenomena and the second involving what I shall call 'acausality illusions'. Acausality illusions seem less widely known than their importance warrants, and will be discussed in some detail.

I am not claiming, by the way, that any of the points made here are original. Most if not all of them can be found in a widely scattered literature, though not always interrelated nor put in the simplest possible terms. Ideas equivalent to, or foreshadowing, the model-fitting hypothesis for perception can be found in very many publications, going back for instance to Berkeley and Kant[17,291,291a] and perhaps even, stretching a point, to some of the Ancient Greeks. See for instance Refs. 5–7, 22–38, 45–47, 155*b*, 209, 211, 216, 217, 309, 291, 291*a*, 294, 302, 314 and their bibliographies, within a still vaster literature. Sometimes the idea that there are mental models is made use of without recognizing its full generality, nor its full significance. References 45–47 trace the more recent philosophical history back by a century or more, to the time of Charles Darwin, and show in more detail why the model-fitting hypothesis has been controversial and to some extent still is. My purpose is merely to bring out the simplicity, accessibility, and checkability of the main points and to argue, from the experimental evidence, that there is little room for controversy today. The evidence is plentiful, important parts of it can easily be verified by any observant person, and there are very many consistency checks. The discussion will lead us naturally toward the wider implications already mentioned, practical as well as philosophical, including the implications for the public understanding of science.

2.2 Hallucinations, 1–1 mapping fallacies, writing, and education

The existence of perceptual experience in the absence of sensory data, or in conflict with sensory data, is one of the plainest and most direct lines of evidence in support of the model-fitting hypothesis. There are ordinary nocturnal dreams and there are waking hallucinations, occasionally having the full force of perceived reality.[38,166,215] To anyone who discounts the traditional, magical or demonological, 'explanations', such phenomena are incomprehensible — practically impossible to explain — without hypothesizing the existence of internal models of some kind.

One such case is described in detail by the neurologist Oliver Sacks.[38] It is the case of the painter Franco Magnani, whose work was exhibited at the San Francisco Exploratorium in 1988. The paintings all depicted Magnani's childhood village of Pontito, Tuscany, which at the time of the exhibition he 'had not seen for more than thirty years'. Some were painted as if from 'an imaginary aerial viewpoint fifty or five hundred feet above the ground', to which he could not have had access in reality, ruling out simplistic photographic memory hypotheses. The exhibition compared the paintings to photographs taken after the paintings were done, including photographs from 'a camera aloft on a pole'. 'It was as if Magnani held in his head an infinitely detailed three dimensional model of his village, which he could turn around and examine, or explore mentally, and then reproduce on canvas with total fidelity.' Magnani himself, in other respects an ordinary human being, reported waking 'visions' in which he saw, heard, smelt, and *felt* countless aspects of the village 'with a minute and three dimensional quality that he compares to holography'.

Such evidence is gradually helping to dislodge a philosophical tradition, still influential today, that begs all the questions by presuming ordinary perception to be what it seems to be subjectively: a cameralike or microphonelike process, a passive 1–1 (one-to-one) mapping or veridical imprinting of so-called sense 'data',[30] a sharp and straightforward correspondence between appearance and reality. This traditional presumption could be called the *1–1 mapping fallacy*, or *veridical perception fallacy*, or *cat on the mat*[229] *fallacy.* It underlies some of the difficulties in the philosophy of science (§2.8 and p. 29, points (i)–(iv)); and Sacks[38] notes how persistently its influence has impeded the recognition and understanding of non-trivial perceptual phenomena and their clinical pathologies, sometimes with tragic personal consequences.[269]

There is a similar fallacy that probably contributes to the expertise in bad writing referred to on pages 2–3. It could be called the *1–1 lexical fallacy*, or *explication-of-concepts fallacy.* This is the tacit presumption of a fixed, sharply defined 1–1 mapping between individual words or synonym groups (more precisely, lexemes[68]) on the one hand, and the things they refer to on the other, implying a correspondingly unimportant role for context — as if context and word patterns were somehow secondary. Exactly such a fallacy led to the early fiascos in language translation by computer,[246] and probably underlies, also, the feeling that writers can safely indulge in the gratuitous variation of words and word patterns, as if intelligibility were merely a matter of recognizing synonyms, a simple matter of dictionary lookup and nothing else. How profoundly wrong this is can be seen from the experience of learning to write, and from the evidence and the careful discussions in, for instance, Refs. 6, 7, 12, 45, 62, and 68 As a simple illustration, consider French sentences of the type 'Je ne sais rien' and their counterparts in some dialects of English, 'I don't know nothin'. These illustrate how human language works with perceptually grouped, syntactically functional word patterns, ahead of conscious thought, rather than working with isolated words or phrases. The one thing our language instinct does not do, whatever the 'Procrustean grammarians' may say,[11,12] is to apply rules of logic at the superficial level of word-by-word dictionary lookup.[270]

One may surmise that 1–1 mapping fallacies also underlie a general misconception that often seems to confuse the politics of education. There seems to be a strongly held lay view of education itself as a process of 1–1 mapping or passive imprinting, to be most efficiently implemented by intimidation and rote learning. This is cognate with the cultural relativist *blank slate* or *tabula rasa*[17,12] fallacy.

2.3 Acausality illusions: the theoretical possibility

A further line of evidence is the existence of acausality illusions, in which effects seem to precede causes, usually by some fraction of a second. They were perhaps first noticed by speech perception researchers,[212] and awareness of them has recently begun to clarify discussions of free will and consciousness, as noted below. They have sometimes been called 'after going effects', or 'backward referral in time', and put forward as posing a deep mystery — perhaps demanding a solution to the entire 'problem of consciousness' [53,247b] and perhaps, it has even been suggested, overthrowing elementary and thoroughly checked principles of physics as well. Here I argue that, on the contrary, acausality illusions are indeed illusions, and that to understand them we do not need a full understanding of brain function and consciousness, let alone a revolution in physics. On the contrary, I argue, acausality illusions are robust perceptual phenomena, easy to study experimentally, and straightforward to explain by the model-fitting hypothesis. I would also argue that their existence is incomprehensible without some such hypothesis.

The existence of acausality illusions provides, in particular, a very direct refutation of the 1–1 mapping fallacy. When applied to the time domain, 1–1 mapping says — obviously, it is assumed, because it seems so obvious subjectively — that perceived times must always be in 1–1 correspondence with the temporal order of events in the sensory data. But that is contrary to what is found experimentally, especially over timespans less than half a second or so; and it is something that anyone can check for themselves.

Before turning to examples let us note why something of the sort has to be expected. The reason is clear from a biological viewpoint.[33,216,223] Perceived times must make allowance for finite cortical processing timespans in fast moving survival situations like hunting and fighting. As with today's sports, such situations demand eye–body coordination over timespans of the order of milliseconds. In some ball games the ball can travel several centimetres in one millisecond. The best ball players must therefore, like the best musicians, be timing their actions to within a small number of milliseconds. Such timespans are around a hundredth of the associated cortical processing timespans. Many stages and levels of cortical processing must be presumed to be involved in generating a conscious percept from, say, visual and auditory data, such as the perceived time of hitting a ball or of sounding a note on the piano; and the psychophysical and electrophysiological evidence indicates typical processing timespans of the order of hundreds of milliseconds.[229a] The implication, counterintuitive yet inescapable, is that perceived times, in order to be useful when coordinating an action like hitting a ball, must not only be accurate to milliseconds but must also be able to *precede* some of the cortical processing involved. If something is perceived to happen at 12 noon minus, say, 100 or 200 milliseconds, as with a piano note struck just before the 12 noon time pip heard on the radio,[320] then some of the cortical processing required to generate the percept is likely to have taken place after 12 noon.

There is no conflict with ordinary physical causality, i.e., with the well checked principle that physical causes precede physical effects,[227e] if perceived times are properties of an internal model. There is then no need for perceived times to coincide with, for instance, the physical times of any cortical processing events involved in the construction, testing, and updating of that model, nor with the physical times of any other events in the nervous system. There is then no mystery about the exquisitely precise performances of the most skilful musicians and sportspeople, despite cortical processing timespans of hundreds of milliseconds during which a ball might travel tens of metres. Rather, that precision means just two things. First, there is an internal model that has goodness of fit, to data from the outside world, at time resolutions of the order of milliseconds in some cases. Second, the internal model has predictive power over timespans of hundreds of milliseconds or more. It must have at least that much predictive power in order to be useful. These are the same goodness of fit and predictive power that keep us on the road when driving a vehicle at high speed in good visibility. The predictive power is deployed automatically, involuntarily, and ahead of conscious thought, something that becomes noticeable after narrowly avoiding a high speed collision. One observes oneself avoiding the collision, but the action takes place ahead of conscious thought.

Once these simple though counterintuitive points have been grasped — of which the most important is that a perceived time, being a property of an internal model, need not coincide with the physical time of any cortical or other neural event — it becomes obvious that perceived times can, at least as a theoretical possibility, precede even the arrival of relevant sensory data. Much confusion has arisen from tacitly ignoring this possibility. And, as already indicated, the possibility is realized. Perceived times do indeed, in many circumstances, precede the arrival of relevant sensory data. This is the most easily studied type of acausality illusion. Examples of such illusions are accessible to any careful observer. There are examples from speech and music perception, from tactile perception, and from vision.[211,212,216,217,223]

2.4 Visual acausality illusions

The visual examples include the classic apparent-motion illusions.[17,22,216 & refs.] The simplest case is what one sees when a small, stationary object in the field of view disappears and then reappears in a neighbouring position. Under suitable conditions and with suitable timing, over timespans, again, of a few hundred milliseconds, one sees an illusory motion. The object appears to move away from the old position toward the new, and to begin to do so before the arrival of the light signal carrying information about the new position. The effect is familiar from certain kinds of illuminated advertising displays and from the warning lights, a side-by-side pair flashing alternately, used in some countries to warn motorists that a railway train is about to cross the road at a level crossing. As the designers of such warning lights must have realized long ago, the apparent motion is more powerful at attracting attention than the flashing of a single, stationary light, and well worth the extra cost.

Such apparent motion is a robust, repeatable perceptual phenomenon that anyone can investigate for themselves, with commonly available equipment. Nicholas Pinhey and I have investigated it with a computer driven cathode ray screen. The screen showed a bright disc about a centimetre in diameter on a dark background, at viewing distances of the order of half a metre to several metres. The exact colours, dimensions, and viewing distances were not critical. The disc was displayed for 200 ms (milliseconds) in one position and then, after a 200 ms pause with the screen blank, displayed for another 200 ms in another position several centimetres to the right. Then, after another 200 ms pause with the screen blank, the whole cycle was repeated a number of times.

In the clearest version of this demonstration, among those we tried, the time of appearance of the disc in its right hand position was emphasized by a bright flash, created by making the disc white for the first 20 ms then red for the remaining 180 ms. In its left hand position the disc was red for the full 200 ms; there was no white flash. With this display, the apparent rightward motion plainly began before the perceived time of the flash.[320a,218] The only assumption made here, which could be criticized but which I believe will stand scrutiny, for the reasons already discussed, is that any mismatch between the perceived and physical times of the flash is much less than 200 ms. We know that it must be much less in other cases, such as the perceived time of hitting a ball. A ball travelling 3 cm in 1 ms travels 6 m, nearly 20 feet, in 200 ms.

Our usual subjective experience of perception, as not only passive but also instantaneous — our subjective unawareness that perceptual processing, by all the evidence, takes at least hundreds of milliseconds — could itself be taken as an example of an acausality illusion.

2.5 Auditory acausality illusions

Music, 'the art that is made out of time',[262] gives us outstandingly clear and simple auditory examples. These deserve careful discussion. Consider for instance the change of harmony at the third bar, shown by an arrow, in the slow movement of Mozart's C major piano sonata, K.545:

Musical notation: this is the first example in the graphics file `lucidity-piano12.gif`; the corresponding audio is in PC `.wav` format, with mono (`m`) and stereo (`s`) versions available; 22 kHz sample-rate file sizes are ∼0.7 and 1.5 Mbyte respectively; file names are `lucidity-piano1-22m.wav` etc. All these files are for download in binary mode.

Even at the fairly slow tempo shown by the time markers, the harmony change is perceived to occur at the time of the arrow, even though the information defining the change is entirely contained in the following two notes, the first of which does not sound until 1/3 second later. This acausality illusion depends only on the listener's general familiarity with the 'language' of Western tonal music. It does not depend on the listener's having previously heard the particular piece of music, any more than understanding a sentence of speech depends on having previously heard the particular sentence. The perceived time of the harmony change is especially clear to a musically trained listener because, as with sports training, musical training cultivates an acute awareness of perceived times through the need to monitor and control timings in performance.

Once again we are dealing with perceptual grouping.[22,23] Recall again the simplest visual examples, such as the following example of visual grouping in fours:

•••• •••• ••••

In the auditory (Mozart) example, the notes of the lower part are also grouped in fours, and perceived as coherent units.[22] In particular, the four notes starting at the arrow are grouped together, as might be expected from their significance for the harmony. The same grouping is encouraged by the invariant qualitative shape of each foursome within an organically changing pattern-sequence. Such grouping phenomena are essential, also, to speech perception[211,12] — compare the spoken sentence 'I'll get the ten to ten train' with 'I'll get the tentative plan checked'.

The perceived timing of the harmony change at, not after, the time of the arrow in the Mozart example is confirmed by the way in which a composer or arranger skilled in Western tonal music would devise an orchestral accompaniment for this example, if intending to preserve its musical sense. The following would be typical:[321]

Musical notation is in the graphics file `lucidity-orch1.gif`; the corresponding audio is in PC `.wav` format, with mono (`m`) and stereo (`s`) versions available; 22 kHz sample-rate file sizes are ∼0.7 and 1.5 Mbyte respectively; file names are `lucidity-orch1-22m.wav` etc. All these files are for download in binary mode.

The accompaniment changes harmony exactly at the time of the arrow. Contrast this with the way in which the accompaniment, from the arrow onward, would need to be written if musical perception worked by temporal 1–1 mapping:

Musical notation is in the graphics file `lucidity-orch2.gif`; the corresponding audio is in PC `.wav` format, with mono (`m`) and stereo (`s`) versions available; 22 kHz sample-rate file sizes are ∼0.7 and 1.5 Mbyte respectively; file names are `lucidity-orch2-22m.wav` etc. All these files are for download in binary mode.

From the arrow onward this last version postpones the changes in the accompaniment, by 1/3 or 2/3 second, so that they match, rather than anticipate, the times at which corresponding information arrives from the piano. The musical sense produced by listening to this version, at and immediately after the arrow, is different from — is a distortion of — the musical sense produced by listening to the piano alone. It is also unlike anything I have ever heard in Mozart's music, discounting accidents of performance. In the bar beyond the arrow, the musical sense is changed very strongly. To deliberately arrange the accompaniment in such a way would probably not even cross the mind of the average musician.[321]

If you happen to be familiar with the particular Mozart piano solo quoted above, and think that such familiarity might be influencing how you hear things at the time of the arrow, then try listening instead to the following piano solo (audio again available on the Internet[321]):

Musical notation: this is the second example in the graphics file `lucidity-piano12.gif`; the corresponding audio is in PC `.wav` format, with mono (`m`) and stereo (`s`) versions available; 22 kHz sample-rate file sizes are ∼0.7 and 1.5 Mbyte respectively; file names are `lucidity-piano2-22m.wav` etc. Orchestral accompaniments to this example are in `lucidity-orch3.gif` and `lucidity-orch3-22m.wav`, etc. All these files are for download in binary mode.

There is a new harmony change, strongly audible and very different from Mozart's. But its perceived timing still corresponds to the time of the arrow, even though the example is identical to Mozart's for a full 2/3 second beyond the arrow. A suitable orchestral accompaniment (omitted for brevity, but available on the Internet[321]) would again change harmony at, not after, the time of the arrow.

Timespans of 2/3 second are by no means the longest that can be claimed for musical acausality illusions.[217] But 2/3 second is already interestingly different from 1/3 second: 2/3 second seems to be long enough[229a] for the updating of the internal model to be made consciously noticeable through a sufficiently strenuous concentration of attention. At least it can be made thus noticeable to myself. Individuals may well vary. By listening to the last piano solo while concentrating hard on the instant marked by the arrow, I think I can catch an audible, though fleeting, impression of Mozart's version being superseded by a strong perception — a perception having the subjective force of actual experience, of unique 'perceived reality' — that the harmony change at the arrow was, 'in fact', the new one. This is an example of what Dennett,[216] in his interesting discussion of these matters, would call a genuinely 'Orwellian' or revisionist phenomenon. My experience with the last example also seems consistent with Dennett's remarks about subjectively probing perceptual content in different ways, also-called consciously driven or 'top down' effects in the literature. (This again is where one-dimensional metaphors like 'top', 'high', 'deep', 'multi-level', etc., begin to show their limitations.) When listening to the last example as music, in the ordinary way, I do not hear even a fleeting impression of Mozart's version. I hear only the new harmony change at the arrow, even though I may well imagine, not hear, Mozart's version in a mental comparison.

The subjectively noticeable difference between 2/3 and 1/3 second is consistent with available information about cortical processing timespans. In ensemble averaged, event related electroencephalograms,[229a] for instance, the recorded activity often has a strong peak at about 1/3 second and weakens thereafter.

2.6 Consciousness, and the unconscious drive to prune

All the perceptual phenomena described above are easily accommodated by the model-fitting hypothesis, which requires that internal models be continually updated, on penalty of losing goodness of fit and any chance of useful predictive power. As with the avoidance of a high speed collision on the road, the updating of an internal model has to take place whether or not the updating is consciously noticeable as such. As has been pointed out in the literature,[211,213,216,217] the updating must, inevitably, involve pruning a tree of model possibilities that extends forward into the future at any given instant, each forward pointing branch having its own prior probability and predictive implications. The set of model possibilities needs to have some such branching structure, in order to allow the evolving internal model to be efficiently and rapidly updateable by parallel processing. Dennett[216] aptly calls this a 'multiple drafts' structure. Because of finite cortical processing timespans, the branching of model possibilities must extend forward not from the present but from times hundreds of milliseconds in the past or earlier. We are normally conscious of one branch only, the end result of the pruning, for an obvious reason: to be *conscious* of more than one would be fatally confusing in a survival situation.

The unconscious drive to prune down to one branch, to perceive a unique reality, to fit a single model, is therefore overwhelmingly strong. In the absence of sufficient data the pruning tends to take place anyway, using prior probabilities. It is easy to find musical examples in which the harmonic motion is heard as unambiguous even when the scoring is sparse and not all the notes of the perceived harmony are sounded; Mozart's famous string serenade *Eine Kleine Nachtmusik* has a conspicuous example halfway through the second full bar of the slow movement, at the high point of the melody. The still sparser musical sketch shown in Fig. 6, occupying page 27, is perhaps even more striking in this respect.[234] The corresponding point in speech perception — no perceived ambiguity despite substantial actual ambiguity — is well illustrated by the work of Swinney, Seidenberg, Tanenhaus, and others (Ref. 217 p. 144), and in vision it has already been well illustrated by the walking lights demonstration,[8,31] and by the Matisse drawing in Fig. 2 above. See also, for instance, Bregman's[22] insightful remarks about the 'all or nothing' character of the internal model-fitting process, as indicated by psychoacoustic experimental data. The phenomena called 'cognitive illusion', 'mental tunnel', and 'mind-set',[34,35] even if involving other, 'more cognitive' aspects of brain function, illustrate what seems to be fundamentally the same point.

What is remarkable is not so much the tree pruning but, on the contrary, having even the slightest ability to postpone it, even in the 'more cognitive' parts of our minds — to be able to stay conscious of multiple branches, of multiple possibilities, for any purpose whatever. The ability thus to live with uncertainty, an important part of our adaptability, could be one of the biological reasons for consciousness itself. Nevertheless, staying conscious of three or more possibilities is more difficult, and probably more energy consuming, than staying conscious of two. There is a noticeable human tendency toward false dichotomization, the urge to prune to just two simplified, mutually exclusive branches or possibilities even when it makes little sense to do so — as with 'capitalism or socialism', 'science or religion', 'nature or nurture',[206] and 'strong Earth or fragile Earth'. There are further biological reasons for this tendency toward false dichotomization, beyond the mere saving of energy, as discussed in Part III (`lucidity3.ps`).

The unconscious drive to prune trees of possibilities becomes almost conscious, almost papable, it seems to me, in the form of another musical phenomenon. This is the intuitive feeling, flying in the face of the evidence, that the number of musical melodies is small. The actual combinatorial largeness of the number of melodies is strongly counterintuitive. For instance the refrain of *'Oh, what a beautiful mornin'* has 30 notes. With 12 choices of nominal notes at each of 29 steps, i.e., discounting transposition into different keys, there are 12^{29} or about 20,000,000,000,000,000,000,000,000,000,000, or twenty thousand billion billion billion possibilities for the nominal note sequence alone. Rhythmic patterns and octave shifts are just as important as note choice — a standard composers' exercise being to devise something musically interesting using only one nominal note — and so the actual number of possibilities is greater still. This is lucky for the music industry.

Could the list of acausality illusions include the effects that sometimes seem noticeable in ordinary conversation? 'You interrupted me!' 'No, *you* interrupted *me*!' The model-fitting hypothesis says that it is possible, in principle, for each person genuinely to perceive — with the subjective force of actual experience, of unique reality — the other's speech as starting a small fraction of a second later than their own. Using a tape recorded dinner table conversation, I have checked that this has indeed happened to me: I experienced my speech as starting fractionally before another's, but the tape showed the reverse. In such cases, by contrast with cases of eye–body coordination in hunting and fighting, the accuracy of perceived timings would seem less important for survival; so perceived timings in conversations might fit acoustic events less precisely.

I have not, by the way, seen the term 'acausality illusion' used in the psychological or philosophical literature, but I dare to use it here because it seems both simple and apt, emphasizing as it does that nothing mysterious is involved — that there is only an apparent, not a real, conflict with physical causality. As already suggested, acausality illusions exist for a clear biological reason, the need to grasp space and time together, to have an accuracy in perceived times commensurate with the accuracy in perceived positions of fast moving objects. In fast moving survival situations, spatial accuracy would have little value without a corresponding temporal accuracy. The spatiotemporal character of internal models must, indeed, be biologically ancient, almost as ancient as predators and prey. Seen in this light, the existence of temporal as well as spatial perceptual illusions is not at all surprising.

2.7 Consciousness and free will

The biological need to grasp space and time together includes the need to coordinate internal decisions with external events. So, again not surprisingly, there is a second kind of acausality illusion, which concerns the perceived time of taking a decision to act. This point has been overlooked in some of the debates about consciousness and free will.[247b]

Perhaps the most striking example, with the clearest experimental evidence, is the acausality illusion evoked in the slide projector experiment of Grey Walter. This was first described in 1963 in an unpublished report, summarized in Refs. 216 and 223 and more recently discussed, along with related phenomena and philosophical issues, in Refs. 219. Neurosurgical patients were invited to entertain themselves to a slide show by pressing a button to advance the slide projector, at times of their choosing. But the projector was wired not to the button but directly to a certain part of the patient's motor cortex; and the subjective effect — startling and disconcerting to the patients, who must have wondered whether they were going crazy — was that the projector seemed to behave acausally, to anticipate their decisions. The projector seemed to advance itself just before they decided or, rather, perceived themselves as deciding, to press the button.

This too is easily accommodated by the model-fitting hypothesis, which says that perceived times, including perceived times of taking decisions, and perceived times of pressing buttons, are properties of the brain's internal models rather than the physical times of any associated cortical activity. It also underlines the point about free will. The existence of acausality illusions implies that questions about the perceived times of decisions are entirely separate from questions about whether the decisions were taken freely or not. There was no reason, in this experiment, to doubt the patients' freedom to decide to press the button, where freedom is understood in the ordinary, everyday sense related to personal responsibility. The experiments add to our knowledge about perceived times and acausality illusions, but say nothing at all about personal freedom of choice, and personal reponsibility for our actions. They do not say, in other words, that free will is illusory. What is illusory is the perceived time of willing the action.

In principle, the experiment could be repeated with a gun instead of a slide projector. The point is that questions about whether the patient intended to murder someone are separate from — are nothing to do with — questions about the precise timing of the murder, about whether the bullet struck the victim a fraction of a second earlier than intended.

The model-fitting hypothesis says that the conscious self, the perceived self that I experience as having intentionality, as being free to make choices, as planning things and taking decisions, must, like any other percept, arise from an internal model: the single internal model that my brain fits to my real, biologically diverse, multi-component, multifariously subtle self.[33,216,209] As Ref. 209 aptly puts it, the brain viewed from outside looks more like a committee, composed of different parts that evolved at different times for different purposes, echoed in common experience: 'something tells me that....', 'my head says one thing but my heart another', and so on. Yet[209] 'I am utterly convinced that there is only one me... not some kind of committee.' The model-fitting hypothesis makes sense of this paradox: the brain has multifarious parts, but only one self-model.

However diverse our internal makeup may be, in order to survive we need, continually, to make sense of our surroundings and our own location and orientation in those surroundings. So the repertoire of internal models and sub-models that are used to construct the perceived world, with its stationary and moving objects, has to include a self-model. Simultaneously with other models, this has to be fitted to the incoming sensory data including, now, internal data from one's own body, such as proprioceptive data about limb positions. The end result is a single spatiotemporal model of oneself in one's surroundings. If this model-fitting process fails, one may become 'disoriented'. Because of the need to coordinate internal decisions with external events in fast moving situations, the model property called perceived time must be a single property, defined consistently, of the entire model of oneself in one's surroundings. It is this single model property that represents not only the 'when' of when a ball is hit, or a piano key struck, but also the 'when' of taking decisions or initiating action. Because cortical processing is necessary to arrive at even a snap decision, the perceived 'when' of such a decision must, inevitably, be preceded by cortical activity, such as that causing Grey Walter's slide projector to advance.

In summary, then, the model-fitting hypothesis predicts that perceived times of internal decisions must be later than, and perceived times of outside-world events earlier than, at least some of the associated physical events in the nervous system. Only thus can the brain, with its finite rate of information processing, typically taking hundreds of milliseconds, consistently represent both sets of times in its internal model of the self in its surroundings at the far finer, millisecond, accuracies needed for survival. Free will and intentionality are properties of the self-model.

Not measured, in the slide-projector experiment, was the delay needed to eliminate the acausality illusion. Such a measurement would have great scientific importance. It would give a clean, quantitative lower bound on the relevant cortical processing timespans. The sharpness of that bound would obviously depend on the sensitivity of the experimental setup, particularly the location and sensitivity of the cortical electrode or electrodes. Such experiments can be looked on as simpler and cleaner versions of the much-discussed experiments of Libet and others,[247b] which rely much more heavily on human subjective judgments but show similar effects over timespans of, again not surprisingly, hundreds of milliseconds.

2.8 On epistemology and Final Theories: model-fitting is the best we can do

The philosophically minded reader will have noticed that the entire discussion so far, including the discussion of perceptual phenomena, has been based on the usual working scientist's adherence to what I called the scientific ideal, giving primacy to coherence (including self consistency) and goodness of fit of models to data. In particular, the hypothesis that perception works by unconscious model-fitting is itself a model, as yet incomplete and sketchy: a consciously constructed model, a scientific theory, though still a rudimentary one, to be tested against relevant data. It has passed many such tests, including those discussed here (and see, for example, Refs. *e.g.* 220–222*a* and 38, among many others), and it has no serious rivals.

Of course the testing of the model-fitting hypothesis involves treating as data what other people say or write about what they do, see, hear, and feel, especially experimental psychologists and their subjects. I am being consistent in accepting this precisely because, like most scientists and some philosophers, I respect the scientific ideal in the form adopted here. This means that I am prepared to do the best I can with repeated trial and error plus multiple consistency checks, rather than looking for anything like absolute proof, seeing the latter as unattainable;[216,45,46,47,231c,309] and I expect to find errors in the data as well as in the model building and model-fitting, relying on the consistency checks to detect most errors sooner or later. This attitude is no different, in principle, from that adopted in other scientific investigations. Precautions against human wishful thinking and deceit are no different, in principle, from precautions against laboratory contamination.

It follows that I am rejecting certain behaviourist and positivist views of so-called scientific method. These forbid treating as scientific data what people say about their subjective experiences. We can reject such views if only because they are self inconsistent, hence self refuting: their adherents expect scientific colleagues to take seriously what they themselves say they did, saw, heard, and felt. Underlying this superficial inconsistency is a deeper inconsistency, which replaces cautious respect for good experiments and data by a tacit assumption that observational or experimental 'facts' are perceptible in some absolute sense — unambiguously and directly, with no dependence on conscious or unconscious model-fitting hence no dependence on unconscious modelling assumptions — and that only such ‘directly perceived facts’ are to be taken note of, and regarded as ‘real’, by the rigorously objective scientist. This means first that the veridical perception fallacy is built in from the start, and second that telling anyone else about what was perceived is strictly speaking futile, making the intended objectivity hardly distinguishable, in principle, from the ultimate subjectivity of solipsism.

Positivism even goes to the extreme of claiming that ‘observed facts’ are the only meaningful entities. Positivism was historically important as a stepping stone to relativity and quantum mechanics, at a time when trying to think about ‘reality’ was becoming impracticably difficult; but its oversimplifications and inconsistencies are now increasingly recognized as such by serious thinkers.[45,63,293a] One might characterize the positivist viewpoint as putting an apt emphasis on science as model-fitting, while, with breathtaking inconsistency, saying that, apart from the aspects we ‘perceive directly’, we can never say that the models represent reality. To put it more sharply, and to underline the inconsistency, positivism says that consciously fitted models cannot claim to represent reality but unconsciously fitted models can.

Such absurdities and dead ends are avoided by the scientific ideal in the form adopted here. The ideal avoids other philosophical complications as well, such as infinite regressions of $(\text{meta})^n$-languages and $(\text{meta})^n$-models.[45] It does all this by acknowledging what working scientists are familiar with from experience, that science works by model-fitting and that we therefore cannot do better than repeatedly checking for coherence, self consistency and goodness of fit in as many ways as possible, and using Occam’s razor, or explanatory parsimony, to mitigate the combinatorial explosion of model possibilities. There is a principle of humility or, if you will, an ‘epistemological uncertainty principle’ that is useful to recognize. This accepts that there is no way of proving anything absolutely, even the existence and uniqueness of the outside world. It accepts that the best we can do is to adopt coherence, self consistency and goodness of fit, supplemented by Occam’s razor, as the most central and fundamental requirements.

Humility does not necessarily mean being apologetic. The best we can do may be very good indeed. As noted in Part III (`lucidity3.ps`), the requirements are stringent. To be sure, they permit non-uniqueness, what Kuhn and Feyerabend[229] have rather sweepingly called the ‘incommensurability’ of scientific theories. More than one simple model might fit the data adequately. But the requirements do not permit the kind of arbitrariness that has been read into this by, for instance, some of the cultural relativist and social constructivist philosophies[227d] and by the journalists they have influenced,[201] the idea that ‘theory laden observation’ means seeing what you like. Scientific experience argues strongly against such arbitrariness, just as does ordinary experience, as when driving in fast traffic. No-one would claim that, under conditions of good visibility, the perceived positions and velocities of vehicles are arbitrary, any more than that they are absolutely and perfectly accurate.

The requirements imposed by the scientific ideal mean that, for a scientist, or for anyone who respects the ideal, to change one’s mind when necessary is a virtue and not a fault. Making this clear seems to be a perennial difficulty in exercises to improve the public understanding of science; and the difficulty is worsened by the mythical, quasi-religious belief that science is about discovering absolute and final truth (pp. 18 ff.). Science is, or should be, self-correcting:[166] change is necessary whenever inconsistencies emerge, as may happen when new experimental data become available. When a driver on a foggy road catches glimpses of what might or might not be an oncoming vehicle, it is a virtue and not a fault for the internal model in the driver’s brain to change, at least provisionally. In the scientific counterpart of this, ‘internal model’ has to be understood in a broad sense that includes not only scientific ‘theory’ but also experimental concepts and technicalities. As emphasized on p. 10 above, the scientific ideal demands that the whole conceptual edifice, ‘experimental’ and ‘theoretical’, should be self consistent — never a trivial matter.[50]

For example, the significance of the proverbial ‘pointer readings’ of experimental physics, more likely nowadays to be groups of pixels on a computer display, is not that they represent absolute, directly perceived ‘facts’ independent of, for example, the experimenter’s conceptual models of how the apparatus works. Rather, the pointer readings or pixel intensities provide some of the sensory data that have to fit into the whole conceptual edifice in ways that withstand consistency checking by, for instance, a second experimenter looking at the same apparatus and thinking about how it works, and about what the first experimenter thinks he or she is measuring.

Philosophically tricky though it may be, I can also reasonably claim — without having to enter the mind–brain debate — to be consistent, for present purposes, in having stretched the concept of ‘outside world’ to include aspects of my own brain function. A sufficient justification is that I am avoiding the behaviourist and solipsist views and can therefore admit that my brain function could be investigated by any scientist. Being one of Grey Walter’s neurosurgical patients need not stop me from accepting his experimental results. At least it need not do so unless an inconsistency were to be found, such as my not feeling startled when he said I behaved as if startled. The scientific ideal, in the form I have stated it, copes well with this problem even when the term ‘outside world’ becomes inadequate. (One can switch to other accepted usages such as ‘real world’, ‘objective world’, or ‘physical world’, at the risk of bringing in other prejudices.) Anyone with lingering philosophical worries about such issues can find careful and insightful discussions in Refs. 33 and 216, the latter under the heading 'heterophenomenology'. But the philosophical problems are most simply and quickly circumvented, it still seems to me, by the scientific ideal in the form adopted here, which emphasizes consistency checking and goodness of fit and avoids, from the outset, prior judgments and taboos about detailed methodologies and domains of applicability.[45,209,260,309]

Finally, mathematicians, logicians, and other careful thinkers may well feel uncomfortable about giving a more fundamental status to consistency checking, which can include circular chains of reasoning, than to time honoured, economical, powerful, and elegant serial reasoning. I share this discomfort; but it is clearly unavoidable. No knowledge about the 'outside' world, the real world, the physical world, physico–chemico–biological reality, whatever you want to call it — nor even any assurance of the existence of that world — can possibly be deduced from serial reasoning alone. Serial reasoning has to start somewhere, but there is no guaranteed starting place. We are not given any self consistent set of axioms from which we are guaranteed beforehand to be able to deduce anything, let alone everything, about the world. To be sure, the existence, in principle, of such a set of axioms is tacitly assumed, or could reasonably be said to be assumed, by advocates of the famous but putative Theory of Everything, or Final Theory of the world or universe. More precisely, the assumption implicit in the words 'everything' and 'final' as usually understood — and as would surely be understood by most lay people — is that one can have a self consistent set of axioms, prescribed in advance, from which everything that can be said about the world, such as the probability of radioactive decay of an atomic nucleus, can, in principle, be deduced by explicit, rigorous rules, also prescribed in advance. But that is exactly what is known, from Gödel's theorem,[53] not only to be impracticable but also *impossible* in principle if the set of axioms is rich enough for the purpose.

Indeed, and more clearly to the point, Gödel's theorem tells us that we cannot even know, from the axioms and rules of deduction alone, whether or not those axioms and rules are self consistent. This in itself — leaving aside the question of how goodness of fit is to be finally, absolutely, and infallibly tested — should be enough to warn us that belief in the existence of a Final Theory, even in the weak sense of being knowably the best fundamental theory that can ever be found by humans, is strictly a matter of faith. Stronger beliefs require stronger faiths; and I discuss this point further in Part III (`lucidity3.ps`) because of its political and humanitarian importance.

Steven Weinberg, perhaps the most impressive, aesthetically compelling, and intellectually powerful advocate of something approaching belief in a complete and final theory of the universe — not just a major breakthrough but the final breakthrough — candidly and honestly admits that such belief is indeed no more than a matter of faith,[63] and moreover that today's hopes of finding such a theory rest on a further article of faith, the very shaky assumption that today's quantum mechanical principles are themselves complete and final. This is in fascinating contrast with what, in my opinion, is Weinberg's most deeply perceptive remark, following Bohr (Ref. 63, p. 121), that in the evolution of fundamental physical theories 'the beauty sometimes survives when the principles themselves do not'.

Careful serial reasoning has an important place in science. It can cover large parts of the logical ground very efficiently, especially when used in its more abstract mathematical forms, handling vast numbers of possibilities at once. In some cases it can help to expose the aesthetic beauty and economy, the insightfulness, of the theoretical structures that physicists like Dirac, Einstein, Feynman, Salam, Weinberg, and others have used to such awesome effect. Careful serial reasoning systematizes and economizes large parts of the consistency checking process, by eliminating needless circularity. Knowing so and so's theorem might save you twenty years' hard labour. It is the notion that serial reasoning is *the* way to think that gets us into trouble — the notion that it is the *only* logical tool — especially as such a notion makes the impossible demand that all definitions, axioms, and deduction rules must be finalized before any reasoning can take place. Taken literally, this would stop us from discovering anything new about the world, because the thing would have to be defined before it could be discovered.

2.9 Mathematics, music, and the unconscious power of abstraction

I want to return briefly to mathematics, music, and the origin of the Platonic, hinted at on page 12. The model-fitting hypothesis implies that perceptual processing handles — somehow — a combinatorially large number of possibilities. Such processing must therefore have a way of handling vast numbers of possibilities at once. This requires, or one could say amounts to, an unconscious power of abstraction.

The perceptual grouping of dots in Fig. 3 illustrates the point. Relative spatial proximity, 'motion as one', and 'belonging to a group' are abstract properties. They are abstract in the sense of being general enough to include or exclude vast numbers of special cases, hence vast numbers of model-fitting possibilities. The same goes for the perceptual grouping of similar or related sounds, basic to speech and music perception,[22,211] as with the groups of notes evoking harmony changes in the musical examples discussed earlier.

Perceptual grouping is recognizably a Platonic seed — part of the unconscious, primeval origin — of the consciously abstract ideas of set theory and integer used in mathematics. These ideas include for instance a recognition that the sequence of positive integers $1, 2, 3, \ldots$ has no end. One can think of adding 1 to any positive integer, arbitrarily chosen, or equivalently of adding one object to any group of objects arbitrarily chosen. Though simple, the example is typical of mathematical thinking. I take this a little further in Appendix 3.

Again, consider structure-from-motion perception, further generalizing 'motion as one'. The walking lights demonstration is a sufficient example. It shows among other things that our visual system, after normal development in infancy, has unconscious knowledge of the branch of mathematics called three dimensional Euclidean geometry.[5,31] Images like the Necker cube, or any perspective drawing, show the same thing. In this sense the conscious discovery of Euclidean geometry by human mathematicians was a Platonic discovery, a discovery of something 'already there', transcending the concrete. To put it the other way round, infants groping for and looking for nearby objects are, among other things, unconsciously learning Euclidean geometry. They are abstracting geometric principles from a small number of concrete examples, in other words building general purpose internal model components that incorporate the relevant visual abstractions and idealizations, to which mathematicians, in later life, attach words like 'angle', 'straight line', 'plane', 'projection', 'perfect circle', 'rotation', 'translation', 'dilation', 'optical flow', etc. Someone deprived of this unconscious early learning cannot, in later life, cross the road safely, let alone — imagine it! — land an aircraft.[38,210]

And again, consider the phenomenon of illusory contours, illustrated in Fig. 5. Their geometrical properties, including the strikingly smooth shape, are abstract properties — general enough to include vast numbers of special cases of smooth object outlines, from the edge of the moon and the edge of the sea to the curve of a perfect banana or elephant's tusk, the arch of a leaping dolphin, or the outline of a hanging grape or drop of water. Here is a Platonic seed for the conscious abstract ideas that mathematicians call curvature, continuously turning tangent, rate of change, and extremum principle, part of what is called differential geometry and the calculus of variations in space and, by extension, in spacetime.[211a]

Drawing is in the files `lucidity-fig5.gif` and `".ps`

5. Simple demonstration of an illusory contour, a white or whitish edge grazing the inner ends of the black marks. Examples with still sparser data, and still showing a wonderfully smooth curvature, have been much studied and can be seen for instance in Fig. 2-6 of Marr's book[5] and Fig. 15 of Crick's book.[32] In constructing the contour, which does not exist physically on the paper, the visual system is unconsciously solving what mathematicians call an extremum problem of the calculus of variations.

Indeed, we directly experience the extension to spacetime. We feel it kinaesthetically, through our sense of continuously evolving motion, for instance through athletic grace in humans and in other creatures and through the subtlety and elasticity of dance and music. In Fig. 5 the shape and clarity of the illusory contour is sensitive to the precise locations of the ends of the black segments. In a musical performance the kinaesthetic feel, the motion and continuity, is similarly sensitive to the precise timings of the onsets of sounds. The discussion of acausality illusions suggested that 'precise' means milliseconds. Even so gifted a musician as Mozart had to earn, by hard work at the keyboard, his legendary ability to make fortepiano passages sound like 'flowing oil'.[237] One might say that the difference between the performances of a great pianist and an average pianist is, in this respect, like the difference between the inner and outer illusory contours in Fig. 5.

Musical performances that successfully use rhythmic elasticity or rubato have a kinaesthetic feel that can be likened, in the spacetime analogy, to illusory contours that bend in interesting ways without breaking up. Such performances can have analysis defying qualities of aliveness, as with organically changing images of living creatures in graceful motion, which we inwardly imitate. If our cave painting ancestors could have made movies, they surely would have. And none of this is accidental. As already noted, there are compelling biological reasons why perceptual processing has to treat space and time together. The spatiotemporality of internal models is a matter of life and death.

2.10 Constructivism versus Platonism: a false dichotomy

The hypothesis that perception works by model-fitting points toward reconciliation of the constructivist and Platonic views both of mathematics and of music, indeed toward a natural harmony between those views.

The constructivist view is right, indeed far more so than is often realized. But a great deal of the construction involved is automatic and beyond conscious reach — including the construction of a vast repertoire of model subassemblies or 'schemas'[22] in infancy, in childhood, and beyond.

The Platonic view is right, because much of what mathematicians and composers and other artists feel they discover rather than construct, and find unutterably marvellous,[34,53,54] is something 'already there', at least potentially, within the vast resources of the subconscious brain, our heritage from hundreds or thousands of millennia of biological evolution (explaining why mathematics, in particular, has real-world relevance[309]). What is 'already there' is a manifestation not only of our prodigious, and unconscious, early learning in the womb, in infancy, and in young childhood, but also of the subtle, multifarious, biologically ancient genetic inheritance that enables and drives such learning. The illusory contour of Fig. 5 is constructed, unconsciously. To wonder at its perfection is to glimpse the Platonic.

What is 'already there' includes the unconscious power of abstraction itself, and the unconscious interest in coherence and self consistency, on both of which the model-fitting process we call perception depends and without which we could not handle — could not begin to cope with — the combinatorially large tree of possibilities that confronts us every millisecond of our lives. To think that the constructive excludes the Platonic, and vice versa, is yet another of our false dichotomies. The evidence is clear that both views articulate complementary, and indispensable, aspects not only of music and of mathematics,[324] but of perception and cognition itself and our very existence and survival.

The Platonic has its dark side. This is relevant, among many other things, to the crises in science policy and public understanding and to the threatened crisis in democracy itself. What is fundamental here is faced up to in Part III (`lucidity3.ps`).

[But I think a degree of rational optimism, or rational hope at least, is still possible, despite everything; and, in case you haven't read it already, and are interested, that is what I argue for in Part III (`lucidity3.ps`).]

Appendix 3. On mathematical truth

In a remarkable recent book,[53] the mathematical physicist Roger Penrose presents speculations about brain function and consciousness that rely heavily on an intuitive view of what human 'understanding' is, in particular mathematical understanding — the vivid and compelling 'perception of unassailable mathematical truth' experienced by mathematicians, palpably independent of, even if built on, particular mathematical techniques and arguments. I share Penrose's sense of wonder at this, but I also suspect that, when it comes down to biological fundamentals, mathematical perception is not different in kind from other forms of perception and cognition. I would argue that it is profoundly and fundamentally similar, for the reasons hinted at in Appendix 2. Indeed it could hardly be otherwise if you accept that we are part of the biosphere, and that we evolved from simpler organisms. This has implications for the arguments in Ref. 53 about algorithmic soundness and brain function, as I shall now try to show.

The model-fitting hypothesis for perception suggests that vivid and compelling perceptions are associated with superlative goodness of fit, as judged by the brain's perceptual–cognitive apparatus. My visual examples included the illusory contour of Fig. 5 and the smoothly curved outlines of the moon's disc and the 'edge of the sea'. Let us imagine the edge seen under the clearest of skies, as I sometimes used to see it in my childhood in New Zealand, in the marvellously clear air of the Southern Hemisphere: an edge of the most exquisite sharpness, exactness, and perfection; one would naturally say a 'mathematical' curve.

One would naturally say the same thing of the curved outline of a hanging drop of water, seen in perfect focus through a magnifying lens.

Now the brain's unconscious interest in coherence and self consistency of internal models, and in goodness of fit to sensory data, must be presumed — for the reasons most cogently argued, to my knowledge, in Ref. 7 — to extend to goodness of fit *between* different internal model structures, i.e. to extend to what we call cognitive association. Subjectively, mathematical perception seems to me to be an experience of sharpness, exactness, and perfection in certain kinds of cognitive association, which involve our unconscious power of abstraction in a special way. Indeed, mathematical experience expands and extends the power of abstraction, by small steps and occasional leaps, conscious and unconscious, into a world seemingly far removed from everyday experience. This is a combinatorially vast inner world, indeed an infinite world by extension, the Platonic mathematical world. Those who make journeys into it have encountered, again and again, self consistent structures of supreme beauty that fit together, as we perceive them, sharply, exactly, perfectly, and intricately. This is all the more wonderful because some of the structures that thus fit together seem quite unrelated at earlier stages in the journey. This is what mathematicians call 'non-triviality' and 'depth'. A celebrated example is that of functions of a complex variable and their relation to prime or indivisible numbers.[323]

But most mathematicians would admit, I think, that mathematical perception begins with — grows organically from — perceptions of a much simpler kind, as already hinted in §2.9. They would admit, I think, that the whole idea of 'unassailable mathematical truth' begins at the beginning of the same journey, with the simplest things like noticing the difference between two apples and three apples, and then, as already mentioned, noticing and making conscious the underlying abstraction — what we 'always knew about' intuitively — that in principle there is no end to the process of adding one more apple to the pile, or one more dot to the dot pattern, that there is no end to the sequence of integers $1, 2, 3, ...$, that the sequence is what mathematicians call 'infinite'. It seems to me that the perception of unassailable mathematical truth has exactly this character. We can perceive it, in this case the infinitude of the sequence of integers, through our unconscious power of abstraction, despite not having the slightest ability to imagine directly the size of integers like $10^{10^{10^{\cdots}}}$.

Going on from such beginnings, one may notice the endless sequences of dot patterns associated with the integers and their arithmetic: squares, triangles, rectangles, parallelograms, and other shapes made from rows of dots, their higher-dimensional counterparts, and the endless ways of dissecting them, as with 'cubes into hexagons' (Ref. 53, §2.4, p. 71). A few steps further on is Euclid's famous argument showing, unassailably as before, that the sequence of prime numbers is infinite (*op cit.*, §2.6/Q5, p. 80). Much further on — historically, many centuries on — we encounter the first really mindboggling non-triviality, the discovery that the dot patterns are intimately, organically, and precisely related to smooth curves like the illusory contour of Fig. 5, through what are called the theory of real numbers and the calculus of functions of real numbers. This has been known, and accepted as unassailable mathematical truth, for only a few centuries, with an increasing variety of cross-checks and progressively tightening standards of evidence for 'unassailability'. And to get from there to such things as the relation between prime numbers and complex functions required major expeditions in several further directions,[16] opening up routes still being explored today — to say nothing of the epic journey to Fermat's last theorem, only just completed.[322]

Ref. 53 reminds us that, throughout such endeavours, mathematicians use a combination of intuitive perception and serial reasoning and that the latter is a mechanical, algorithmic process conforming to prespecified rules, hence programmable on a conventional electronic computer with a large enough memory, hence equivalent to what is called Turing computation. This is important for consistency checking and for the refinement and correction of intuitive perception — for keeping conscious and unconscious model-fitting connected to each other. Crucial here is the notion of 'soundness' of an algorithmic process having a declared mathematical purpose, such as determining whether certain mathematical statements are true or false. Soundness means that the rules defining the algorithm are not only logically self consistent, but also such that the algorithm never delivers a result contradicting intuitively perceived unassailable mathematical truth (*op cit.*, §2.5). Thus an algorithm whose purpose is to determine whether there is a largest integer, or a largest prime number, would be called unsound if it ever came to a halt and gave the answer yes. There are of course less trivial examples.

Now the central point in Ref. 53 is that, whatever is going on in the brain of a human mathematician intuitively perceiving mathematical truth, for instance through the shapes and symmetries of dot patterns (*op cit.*, §2.4), it cannot be equivalent to a Turing computer running an algorithm that is sound in the mathematical sense just referred to. This is a consequence of Gödel's theorem, and is unassailable in the same way as the infiniteness of the integers is unassailable.

The deduction from Gödel's theorem is also consistent with the two hypotheses I am making here, first that mathematical perception is fundamentally similar to ordinary perception, and second that both work by unconsious model-fitting. For those hypotheses imply that — however definite, and unassailable, the difference between two dots and three dots may be, and however vividly exact the edge of the sea or of a hanging drop may seem to be — perception, when viewed algorithmically, at its most basic functional level, in the way it uses neurons and protein molecules, must be an inherently approximate process. Indeed, if one thinks of perceptual processing in algorithmic terms, then the algorithms involved must have purposes far removed from that of determining mathematical truth, even supposing that the notion of 'purpose' has any meaning in this context. Such algorithmic purposes, even if meaningfully definable, would have to include things like measuring approximate goodness of fit, and pruning combinatorially large trees of possibilities. Moreover, as a biological imperative, such purposes would have to be achieved quickly and efficiently rather than perfectly and infallibly. Infinite accuracy and zero error rate have zero biological importance, whereas speed and efficiency have overwhelming biological importance. This predicts that algorithmic soundness — for any purpose at all — is unlikely to be relevant to a biological system like the brain at its most basic functional level; and this is enough for consistency with the deduction from Gödel's theorem.

It is noteworthy, in this connection, (*a*) that recent developments in electronic computing have recognized the power and practical usefulness of unsound but highly efficient algorithms,[239a] and (*b*) that the theory of computation implies that an algorithm may well, in any case, be 'its own shortest description' in a large number of instances, not least in biological systems (e.g. Ref. 71, p. 22). Thus the notion of 'purpose' need not enter the picture at all, except in the trivial sense that the 'purpose' of the algorithm is whatever the algorithm does.

The foregoing, then, provides an alternative to Ref. 53's suggestion that the action of the brain must be non-Turing and must therefore use a novel kind of quantum computation. To be sure, the suggestion of quantum computation has a certain seductiveness in itself, because quantum computation has vast potential for solving combinatorially large problems,[278,293a] which the brain needs to do anyway, whether for consciously mathematical or other purposes. Whether a role for quantum computation would ipso facto imply failure of Turing computability is yet another question, which might well be decided, in the end, on purely physical and not biological grounds.[53,249,309] I shall resist the temptation to speculate further, except to say that my own bet, for the time being, is that the brain is equivalent to a Turing computer of an unimaginably complex kind, running algorithms that are unlikely to be sound with respect to any independently definable purpose — essentially the kind of picture described in Ref. 7 and 71.

Another remarkable recent book,[293a] by another mathematical physicist, David Deutsch, is of interest here; it presents a view very different from that of Ref. 53, closer to that of Ref. 309 on the matters under discussion and complementary to my own view. Chapter 10 of Ref. 293*a* on the nature and history of mathematics asks why outside-world reality should be perceivable and understandable at all, even to a limited extent, and points out the intimate connection between understandability on the one hand, and self consistency and abstractability thence, at least implicitly, mathematics and computation on the other. Mathematics is, on this view, not merely an ingeniously constructed aid to understanding physical reality, but intimately an aspect of physical reality. The detailed arguments elaborate the point I made earlier (p. 9) that '... self consistency of the internal model must mean, almost by definition, that the model is able or potentially able to represent something in the outside world'. The arguments in Chapter 10 of Ref. 293*a* imply that, even if we were unaware of examples as clearcut as those given above, we should still expect our perceptual–cognitive apparatus to have a significant unconscious knowledge of mathematics.

What emerges from all this, it seems to me, is that our intuitive understanding of mathematical truth stems not at all from the nuts-and-bolts *algorithmic activity* required to build and fit internal models but, rather, from the *model properties* themselves. Those model properties evolved under selective pressures to enable our ancestors to survive in the world, and therefore embody both abstractness and self consistency. Mathematics could be regarded as a way of consciously accessing, and stimulating the further development of, such model properties, many of which are normally beyond conscious reach.

Notes and literature cited

1. In assuming that perception involves computation, or information processing, I make no assumption about the precise sorts of computational machinery or unconscious symbolic manipulation that the brain might, or might not, use on different timescales. For present purposes there is no need to discuss whether the brain is equivalent to a Turing machine,[53] let alone whether it has any simple resemblance to today's electronic computers and artificial neural networks. It seems clear from today's evidence that any resemblance cannot be simple, and that the old textbook neuron–synapse picture merely scratches the surface.[2,70] We may recall, however, one point that is uncontroversial: both neurons and protein molecules can compute.[2–4] (This is further discussed in the Appendix to Part II, with reference to the nature of mathematics and some ideas of David Deutsch and Roger Penrose.)

2. Koch, C., 1997: Computation and the single neuron. *Nature*, **385**, 207–210. Summarizes the rapidly accumulating evidence for 'previously unimagined complexity and dynamism' in the computational behaviour of dendrites, the timing of action potential spikes, and synaptic plasticity in neural systems — pointing ever more strongly to the possibility that computations involved in perception, cognition, and memory on different timescales take place 'not only at the cellular but also at the molecular level.' See also, e.g., Refs. 3, 4, and 71: 'Hundreds of different types of receptors [for neurotransmitter molecules] have already [by 1995] been located in the human brain, and the list is growing rapidly'.

3. Monod, J., 1971: *Chance and Necessity*, transl. A. Wainhouse. Glasgow, Collins, 187 pp. This classic gives a lucid and penetrating discussion of what was already known, in the 1960s, about molecular-scale cybernetics. That knowledge included details of the computational functionality of certain protein molecules, called allosteric enzymes, and, more importantly, a clear grasp of the general principles on which such functionality is based (Chapter 4). The far-reaching implication, further discussed in Ref. 71, is that an arbitrarily specified logical or computational system can be realized as an interacting collection of protein molecules. Monod also offers, in the final chapter, some important, clear-headed insights into human nature and belief systems and their likely biological origins.

4. Bray, D., 1995: Protein molecules as computational elements in living cells. *Nature*, **376**, 307–312. This review gives examples with up to eight inputs per molecule, more elaborate than the allosteric enzymes described in Ref. 3, and some simple 'circuits', i.e., computational subsystems, already known in detail. See also for instance Barkai, N. Leibler, S., 1997: Robustness in simple biochemical networks, *Nature*, **387**, 913–917 (commentary, p. 855), and Dickson, R. M., Cubitt, A. B., Tsien, R. Y., Moerner, W. E., 1997: On/off blinking and switching behaviour of single molecules of green fluorescent protein, *Nature*, **388**, 355–358. See also *Science*, **277**, 1059–1060. These are but the tiniest random sample from a vast and burgeoning literature.

5. Marr, D. C., 1982: *Vision: a computational investigation into the human representation and processing of visual information.* San Francisco, Freeman, 397 pp. On perceptual grouping, see for instance Figs. 2-5, 2-33 and surrounding discussion. 'Was the foundation of modern computational vision' (Colin Blakemore, personal communication). Very clear about the evidence pointing to the brain's multi-level internal models, or 'explicit internal symbolic representations'.

6. Jackendoff, R., 1987: *Consciousness and the Computational Mind.* Cambridge, Mass., MIT Press, 356 pp. Draws on analogies with vision, as well as linguistic studies, to argue cogently for the multi-level computational nature of language processing; see e.g. pp. 101–104.

7. Hofstadter, D., and coworkers, 1995: *Fluid Concepts and Creative Analogies: Computer Models of the Fundamental Mechanisms of Thought.* New York, BasicBooks, 518 pp. See esp. Chapters 4 and 5, and the Epilogue, for a profoundly insightful perspective on real and artificial intelligence. The title could well have been extended to *'...Thought and Perception.'* to emphasize the seamless unity of the two.

8. Fuller notes and references, including more detail on 'safety first in first drafts', are available on the Internet at the web and ftp sites `http://www.atm.damtp.cam.ac.uk/people/mem/` , `ftp://ftp.damtp.cam.ac.uk/pub/papers/mem/lucidity*` . A string searchable ASCII file `lucidity-supplem.txt` gives the 'safety first' notes plus some more nuts-and-bolts details on writing technique, for instance discussions of stray adjective and equation-bound thinking, and a 'draft repair toolkit' of marginal notations for use by harassed journal editors and thesis supervisors, and anyone running a course on writing. There are also some relevant visual animations, including two `.mpg` (MPEG) files illustrating the 'walking lights' phenomenon,[31] and some relevant audio (PC `.wav`) recordings (mono, `m`, and stereo, `s`, at 22 kHz and at 44 kHz, CD-quality, sample rates), for download in binary mode. All relevant file names begin with the eight characters `lucidity`.

9. Science Citation Index statistics say that the number of papers published per year is of the order of 5 $\times 10^5$. Assume that the total full time work on publication by authors, PhD supervisors, PhD examiners, referees, editors, and other scientific colleagues adds up to about 10^{-1} scientist year per published paper; this is conservative if only because it ignores work on rejected papers, grant proposals, and the time expended by scientists reading papers already published. Assume that a wider appreciation of the pattern-perception hypothesis — reducing readers' backtrackings and impasses and writers' redraftings — yields a ten percent saving on average. Ten percent will seem very conservative indeed to a conscientious scientific journal editor, referee or PhD supervisor. Assume that the average cost per scientist year (support staff salaries, office and laboratory space and facilities, computers and other equipment large and small, plus the scientist's salary itself) is, again conservatively, US\$ 10^5 per year. Then the productivity saving is of order $5 \times 10^5 \text{year}^{-1} \times 10^{-1} \text{scientist year} \times 10^{-1} \times \text{US\$}10^5 \text{scientist year}^{-1} \sim \text{US\$}0.5 \times 10^9 \text{year}^{-1}$.

10. Strunk, W., White, E. B., 1979: *The Elements of Style*, 3rd edn. New York, Macmillan, 92 pp. A miniature gem on writing technique — an elegant pocket book showing profound insight and compressing the essentials into a few dozen small pages.

11. Fowler, H. W., 1983: *A Dictionary of Modern English Usage*, 2nd edn, revised E. Gowers, reprinted with corrections). Oxford University Press, 725 pp. The 2nd edn, 'Fowler Two', is not to be confused with the so-called 3rd edn or *New Fowler's;* see below. Fowler Two is a treasurehouse of insight into the workings of the English language, erudite yet highly practical: a fine weapon against substandard copy editing and the different brands of pedantry and stylistic idiocy;[12,15] see also the excellent though massive (University of) Chicago Manual of Style (14th edn., 1993, Chicago, University Press, 921 pp.), especially when publishing in the USA where it commands wide recognition; see also, for instance, Mermin, N. D., 1989: What's wrong with this prose? *Phys. Today,* **42(5)**, 9–11, an appeal against the kind of copy editing, all too common today — the dead hand of idiocracy — that thinks Shakespeare got things the wrong way round in 'books in the running brooks, sermons in stones'. In Fowler Two see for instance, among many other wonderfully insightful articles, those on **side-slip** (cf. Ex. 7 above),

and on **rhythm** and on **grammar**: 'It is... despite the grammarians, not thanks to them, that over the centuries our language has won ease and grace by getting rid of almost all its case-inflections; some day perhaps this good work will be completed....'. Fowler Two is not to be confused with what is called the 3rd edn of 1996, an entirely different work with an entirely different aim. Along with Crystal[68] it is a useful source of information on recent trends in vocabulary and usage, but omits much of Fowler's original insight. Among items unfortunately omitted is the very fundamental insight on gratuitous or (pseudo-)**elegant variation**. But there is a good article on **split infinitive**, with many splendid examples from the fourteenth century onward, though missing the rhythmic and emphatic significance, as in 'to **BOLDLY** go'.

12. Pinker, S., 1994: *The Language Instinct: the New Science of Language and Mind.* London, Allen Lane (Penguin), 494 pp. This landmark synthesis brings together linguistic, psycholinguistic, and biological evidence to argue powerfully for the existence of a crosscultural language instinct — suggesting, in turn, that language itself has existed for hundreds of thousands of years at least, far longer than the conventionally quoted but speculative tens of thousands. The existence of a language instinct in genetic memory, including an instinctive sense of syntactic coherence, is shown for instance by recent studies of 'creolization' or instinctive language reinvention by children.[286b] Also, relevant to my discussion of 'organic change', pp. 422–6 describe psychological studies on infants and very young children demonstrating a powerful, culture-independent and manifestly instinctive sense of 'living versus dead' and an instinctive categorization of living creatures. Some of this seems to be demonstrable even in infants around 1 year old. Ref. 23, within a growing literature, has evidence about other infant abilities that might or might not surprise you.

   Pinker, as does Sacks,[38] gives a telling but humane riposte to cultural relativism,[200,48] giving culture its due but rejecting the naive idea that all cognitive processes are handled by a single general intelligence — assumed to be some kind of *tabula rasa* or blank slate to be written on exclusively by something called culture — and the equally simplistic idea, the false dichotomy, of thinking that there are no alternatives beyond pure nurture versus pure nature,[156] the fear that the only alternative to cultural relativism is brutal 'biological determinism', an idea long abandoned by geneticists along with the eugenics or good-versus-bad-genes fallacy, as used by the Nazis, to all of which cultural relativism is an understandable reaction. Pinker also gives a valuable historical commentary on the pervasiveness of wordbound thinking, including its numinous or hypercredulistic power, facilitating the 'collective suspension of disbelief' illustrated by myths like the myth, now exploded, about the 'fundamentally different' Hopi Indian concept of time (essentially a hoax: pp. 63, 412). These things are so close to the bone that they will surely continue to be controversial. For an idea of the earlier struggles and controversies in, for instance, linguistics and psycholinguistics, and the academic minefield that Pinker negotiates, and transcends, so skilfully, see for instance Harris, R. A., 1993: *The Linguistics Wars.* Oxford, University Press, 356 pp.

13. Wills, C., 1994: *The Runaway Brain.* London, HarperCollins, 358 pp. A beautifully written, thoughtful, and penetrating book informed by a detailed knowledge of modern genetics and its molecular basis, and knowledge of the fossil record, clearly exposing the simplistic nature–nurture fallacy[156] (and the equally simplistic eugenics or good-versus-bad-genes fallacy and associated genetic engineering fantasies) and providing important clues about brain and language evolution[12] as well as about evolution in general. Here is abundant and cogent evidence — see for instance discussions of genotype–culture feedbacks and the 'Baldwin effect'[209] — for a most intimate and subtle interplay between nature and nurture, between biological and cultural evolution.

14. This is a real example from *Proc. Roy. Soc. Lond.,* **A 440**, 530 (1993), 11th line from bottom. Also Edwards, D., *et al.*, 1986: *My Pear Tree Has Gone Bananas: The Collected Philosophy of Don Edwards.* London, Reader's Digest Assoc. & Mult. Scleros. Soc., 33 pp. ISBN 0-276-40231-6.

15. Gregory, M. W., 1992: The infectiousness of pompous prose. *Nature*, **360**, 11–12. This *Commentary* rightly complains about what pretends to scientific professionalism but amounts to a sort of tribal pressure to write in obscure and pompous ways — see also Avery, L., 1996: Write to reply, *Nature*, **379**, 293 — which pressure, in my opinion, should be soberly but stoutly resisted even when it comes from journal editors and referees. See also Ref. 66 for a real example, from a published scientific paper, that outdoes even Ex. 1. Gregory also perpetuates the minor misconception that one should write with the '...fewest possible words', and the major misconception, far more serious — and dangerous because of its despairing cynicism — that writing is too difficult for most scientists and should be delegated to professional writers.

16. Littlewood, J. E., 1953: *A Mathematician's Miscellany.* Paperback reissue as *Littlewood's Miscellany*, with further material, edited B. Bollobás 1986, Cambridge University Press, 200 pp. A frank, and sometimes hilarious, inside view of genius. Littlewood was a wide ranging scientific thinker as well as a great mathematician, and much of this book was written for a non-specialist audience. The example of gratuitous pattern-variation I mentioned, the notation $a,\ M_3',\ \epsilon_2,\ \Pi''_{1,2}$ for four things of the same kind, is jokingly attributed to the mathematician Camille Jordan. Consider also 'Let N be a linear and L a nonlinear function' — a kind of 'Stroop interference'.[32]

17. Hunt, M., 1993: *The Story of Psychology.* New York, Doubleday, 762 pp. The reference to the Three Mile Island nuclear accident, which began at 0400 hours on 28 March 1979, is in Chapter 18, p. 606. See also, e.g., Cordes, C., 1983, in *Amer. Psychol. Assoc. Monitor,* **14(5)**, May 1983, pp. 1 and 13–14. Hunt also gives a convenient collection, with historical commentary, of standard examples of visual perceptual phenomena in Chapters 10 and 14 (e.g., grouping, pp. 287ff., apparent motion or 'phi', p. 282), and, in Chapters 1–3, a useful brief history of the oldest recognized precursors to modern thinking about perception and cognition, including the ideas of Plato, Descartes, Spinoza, Locke, Berkeley, Hume, and Kant. For these last in more detail, see for instance Ref. 291. The book also shows indirectly, through its copious but readable accounts of controversies among psychologists, the practical impossibility of understanding cognitive and perceptual phenomena without some organizing concept equivalent to the model-fitting hypothesis.

18. See 'false scent' in Ref. 11 and 'garden path sentences' in Refs. 217, 12.

19. Gap filling is perhaps best known in vision. A melon behind bars does not look sliced up. We are normally unaware of our retinal blind spots (Ref. 32, pp. 55–6; Ref. 24). Speech and music provide many auditory examples,[6,22] with masking sounds taking the place of gaps or obscuring bars. There is a philosophical dispute about whether the phenomenon of gap filling should be regarded as a real process within the brain[32,216] as well as a perceptual phenomenon. Such disputes are circumvented, or, rather, transcended, if one accepts the hypothesis made here that perception works by unconscious model-fitting (page 7 and Appendix 2). No useful internal model will have features corresponding to incidental gaps in, or masking of, sensory data.

20. See Ref. 16, chapters on the discovery of Neptune and the 'Adams–Airy affair'. In this case the bright young man was the mathematician John Couch Adams, failing to persuade the Astronomer Royal, Sir George Biddell Airy, to be the first to point a large telescope toward the predicted position of Neptune. Adams' mistake was to think that a certain statement (about the smallness of changes in Uranus's angular momentum) was not only correct but also so obvious that it, and its consequences, were trivial matters that need not be explained to Airy, perhaps for fear of insulting the great man's intelligence. If Adams had attempted an explicit explanation, he might have persuaded Airy as well as seeing that the 'trivially obvious' statement was, in Littlewood's words, 'dead wrong'.

    Addendum: To my great embarrassment, I let exactly such a mistake slip into an argument summarized in Part III hereof, as originally published in *Interdisc. Sci. Rev.*, **23**, 29–70. So I inadvertently illustrated my own point. See the published retraction on my home page (`http://www.atm.damtp.cam.ac.uk/people/mem/`).

21. Minutes of the Sixth Annual General Meeting of the excellent Save British Science Society (Oxford, P.O. Box 241, OX1 3QQ, `http://www.dspace.dial.pipex.com/sbs/`).

22. Bregman, A. S., 1990: *Auditory Scene Analysis: the Perceptual Organization of Sound.* Cambridge, MA, MIT Press, 773 pp. This cogent, insightful, and lucidly written book is particularly strong on the evidence for perceptual grouping in acoustic time series and its biological significance, and on the evidence for internal model-fitting. The visual analogies are carefully discussed, along with the brain's simultaneous use of auditory and visual sensory data.[220] (I would add that this book can usefully be read by anyone learning musical composition, most especially for its fundamental insights into how counterpoint works, the musical power of independently moving melodic lines.) and, for instance, the classic apparent motion illusions.[17]

23. Trehub, S. E., Trainor, L. J., 1993: Listening strategies in infancy: the roots of music and language development. In: McAdams, S., Bigand, E. (eds.), *Thinking in Sound: The Cognitive Psychology of Human Audition*, 278–327. Oxford, Clarendon Press, 354 pp. This contains important evidence, and thoughtful discussion, bearing on the roles of genetic and individual memory in the development of perceptual processing.

24. Gregory, R. L., 1970: *The Intelligent Eye.* London, Weidenfeld and Nicolson, 191 pp. See especially p. 39 (Chapter 3).

25. Frisby, J. P., 1979: *Seeing.* Oxford, University Press, 160 pp. See especially pp. 110–111.

26. The relevant cortical processing timespans, though variable and not precisely known, are almost certainly of the order of tenths of a second; the subjective impression of still greater speed is likely to be an 'acausality illusion'. These points and the experimental evidence that bears on them are discussed in Appendix 2. What is important for the moment is that the grouping takes place ahead of conscious thought.

27. Maddox, J., Marr, D. C., 1979: Theorems of Vision. Radio interview in the series *Mind, Matter and Mechanism* ('Scientifically Speaking', BBC Radio 3, 19 March 1979. See also Ref. 6.

28. Shepard, R. N., 1990: *Mind Sights.* New York, Freeman, 228 pp. 'Our perceptual experience of a stable, continuous, and enduring three dimensional surrounding retains no trace of the prodigiously complex neuronal machinery that so swiftly constructs that experience. Nor are we aware of the shifting, intermittent, pointillistic, upside down, curved, two dimensional patterns of retinal excitation from which the machinery of the brain constructs our visual world.' See also Sacks'[38] report (*op cit.*, Chapter 1) of a case of brain damage that did, seemingly, allow some slight direct awareness of that same shifting,

intermittent retinal imagery — enough to cause great distress, disorientation, and inconvenience to the person concerned, the painter 'Jonathan I'. Another of Sacks' cases, described in his chapter 'To see and not see',[38] illustrates the impoverishment, indeed complete failure, of three dimensional visual model building and fitting when normal infantile learning is interfered with or atrophies. A similar case has been described by Richard Gregory and Jean Wallace.[210] Infants groping for and looking for nearby objects are, indeed, among other things, unconsciously learning Euclidean geometry; and people with normal vision reinforce that learning every time they bump into something.

29. Bateson, G. L., 1972: Style, grace and information in primitive art. In: *Steps to an ecology of mind: collected essays on anthropology, psychiatry, evolution and epistemology*, pp. 101–125. San Francisco, Chandler; Aylesbury, Intertext; Northvale, New Jersey, Jason Aronson. 510 pp. Gregory Bateson, son of the genetics and embryology pioneer William Bateson (1861-1926), began as an anthropologist working with, and marrying, Margaret Mead. His writings contain much wisdom.

30. There are philosophical traditions that use terms like 'sense data', 'sense perceptions', 'sense impressions', or 'Sinnesempfindungen' to mean not the raw sensory data but, rather, the percepts themselves, as apprehended subjectively. That, as Kant, Popper, and other careful thinkers recognized long ago, begs all the questions about how perception works; indeed it begs just about every epistemological question there is. Appendix 2 and Part III (`lucidity3.ps`) give further discussion of this point, with reference to the cognate philosophical viewpoints called 'behaviourism', 'instrumentalism', and 'positivism'.

31. Johansson, G. 1975: Visual motion perception. *Sci. Amer.,* **232**, June issue, 76–88. This review article by the experimental psychologist Gunnar Johansson beautifully describes and discusses the 'walking lights' and related perceptual phenomena. Awareness of such phenomena is now the stock in trade of video game designers and television animators. Digitized versions of two 'walking lights' demonstrations made by Johansson and colleagues James Maas and Gunnar Jansson — these are slight variants of the original version described in the review article — have been placed, with their kind permission, on the Internet web site[8] in the standard (`.gif, .mpg, .mov, .avi`) formats. One of the (`.gif` versions displays automatically on my home page (`http://www.atm.damtp.cam.ac.uk/people/mem/`). I am extremely grateful to James Maas, Stuart Dalziel, Nicholas Pinhey, and Steve Lay for their help in supplying and processing the data. For further discussion of structure-from-motion phenomena and the underlying mathematics, see Marr's book[5] and the book by Ullman, S., 1979: *The Interpretation of Visual Motion.* Cambridge, Mass., MIT Press, 229 pp. Recent work on the walking lights phenomenon is reported in P. Nerl, M. Concetta Morrone, D. C. Burr: 'Seeing biological motion'; *Nature*, 1998, **395**, 894–896. Chapter 6 of Ref. 317 gives an excellent recent review of work on motion perception in general.

32. Crick, F., 1994: *The Astonishing Hypothesis.* London, New York, Simon and Schuster, 317 pp. Gives a useful feel for what is known and not known about brain function at the level of neurons and synapses.

33. Humphrey, N., 1992: *A History of the Mind.* London, Chatto & Windus, Vintage, 230 pp. This book develops what to me seems an unusually clear, and lucidly expressed, view of the nature of perception and consciousness, based on careful biological reasoning and on experimental evidence from perception research and clinical neurology. The discussion bears on, and refines, the distinction I am making between sensory data[30] and the internal models fitted to such data. What I have been calling unconscious model-fitting Humphrey calls the brain's 'Grand Old Duke of York strategy', emphasizing feedback between levels, i.e., the 'top down and bottom up' character of the process,[7,319a] and conveying insight into how such processes might have evolved from primitive beginnings. He also draws a clear and important distinction, well supported experimentally, between 'perception' (of what is happening *out there*) and 'sensation' (of what is happening *to me*). The latter denotes the direct impact of sensory data on conscious awareness, something that can occur whether or not it leads to perception, i.e., to awareness of something 'out there'. One can experience flashes of light without any sense of whence they come, as distinct from, for instance, being aware of a fire engine emitting flashes from a definite position twenty metres away.

34. Abercrombie, M. L. J., 1989: *The Anatomy of judgment: An Investigation into the Processes of Perception and Reasoning.* London, Free Association Books, 156 pp. Abercrombie gives a well illustrated general discussion of perceptual phenomena and their practical implications, with special attention to 'mind-set' or inappropriate perceptual stability, and group exercises to loosen it. See also, for instance, Refs. 35 and 36.

On the unconscious aspects of creative thinking, see also, e.g., within a vast literature, Littlewood[16], Bollobás edition, p. 192 ('odd and vivid experience'), Hofstadter *et al.*,[7] ('conceptual slippages' and so on), and the extensive discussion and bibliography in the review by Campbell[46] including the experiences famously reported by Poincaré and other great scientists.

35. Piattelli-Palmarini, M., 1994: *Inevitable Illusions: How Mistakes of Reason Rule Our Minds.* New York, Wiley, 242 pp. Mainly about the work of Amos Tversky and Daniel Kahneman on cognitive illusions and 'mind-sets', or, as they call them, 'mental tunnels'. In the terminology used here, these can be understood as effects of prior-probability-driven combinatorial tree pruning. The book has a good collection of telling examples, including the famous 'three boxes' or 'three cards' trick. The trickster deals, face-down, three shuffled cards of which one is an ace. The victim chooses a card by putting a

finger on its back. The trickster, who knows where the ace is, then removes another card that is not the ace and shows it to the victim. Most people, in the role of victim, intuitively feel — ahead of conscious thought — that given the new information their probability of having fingered the ace must now be 1/2. This is the brain's unconsious Occam's razor getting things wrong. It takes conscious mental effort to see that the probability is still 1/3 and that the probability of the remaining, unfingered card being the ace is now 2/3. See also Ref. 17, pp. 547, and Ref. [36]. (Many sales pitches and incentives use exactly this kind of technique, as well as the more straightforward forms of camouflage and deception: Ref. 17, pp. 623–4, gives specific examples. See also Griffiths, M., 1997: Health and the National Lottery. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Spring 1997 issue, 5–7.)

36. de Bono, E., 1971: *Practical Thinking.* Republished 1976, London and New York, Penguin, 189 pp. Discussion centres around a simple exercise in scientific model-fitting, tried out on 1000 people, analyzing 'why the black cylinder fell over', with insightful discussion of different kinds of mistakes and different kinds of correctness. 'The most important point is that mistakes arise directly from the way the mind handles information'; cf. Ref. 34, 35.

37. That human vision, for instance, is 'hopelessly beyond the reach of our most powerful electronic computers' can hardly be disputed today. It does not seem to be thus disputed even by the most optimistic enthusiasts for robotics and artificial intelligence:[70] artificial vision has come nowhere near rivalling human vision despite the huge economic incentive and the decades of research effort.

38. Sacks, O., 1995: *An Anthropologist on Mars: seven paradoxical tales.* New York, Alfred Knopf, 330 pp. This is full of cogent lessons and wisdom about brain function, perception, and cognition drawn from clinical experience and shrewd observation. Of special interest here are the discussions of (i) colour vision, including Goethe's ideas and the Land effect (in the chapter on the colourblind painter 'Jonathan I.'), (ii) the work of the painter Franco Magnani, and (iii) the careful extended description, from personal acquaintance, of the behaviour of the demonstrably blind, brain damaged, amnesic 'Greg F'. 'Greg' always insisted that he could see — and, for example, spent time 'watching' television — despite a total lack of visual data, implying, if taken at face value, the existence of a permanent, adaptive visual hallucination. There is no mystery if we hypothesize the existence of an internal model having subjective visual force, for its own internal reasons, but being fitted to acoustic, tactile, and olefactory data alone.

39. Mammalian immune systems make a good analogy. They are 'perceiving systems' that appear to be much simpler than the brain, in some ways at least, yet far more complicated than the computer models described in Ref. 7. Key aspects are now understood in detail at the molecular level; one sees the typical 'top down and bottom up' character. For more detail and keys to the literature, see notes 319–319*b*.

40. 'Sufficient goodness of fit' bears further scrutiny. 'Sufficient' must mean, broadly speaking, sufficient for survival, under the limitations imposed by data and internal models. It cannot mean exact fit, even though there is a subjective illusion of exactness, of perceiving reality directly and unambiguously.[292] The accuracy of the incoming data is finite, the time available to process the data is finite, and the number of internal models available must be finite though combinatorially large. The available internal models are presumably, as with those in the immune system,[319a] constructable from finite numbers of preexisting components or, metaphorically speaking, finite numbers of building blocks or versatile subassemblies of building blocks, some of which come straight from genetic memory and others of which are created, or selected, during infantile learning or later. Such hypothetical subassemblies, at various levels of versatility or abstraction, themselves encompassing combinatorially large numbers of possibilities, are sometimes called 'schemas'. See for instance Bregman's excellent book[22] which, however, reserves the term 'schema' mainly for those abstract subassemblies that are called into play by conscious attention, making them more accessible to psychophysical experimentation.

Regardless of their detailed nature, the numbers of model components and subassemblies must be limited by an Occam's razor of some kind in order to mitigate the combinatorial explosion of possibilities. In other words, the internal models to be fitted must be kept as simple as possible in some sense or other, if the combinatorial tree of possibilities is to be pruned fast enough for survival. A clear example of this *unconscious* use of Occam's razor is the unconscious piecewise rigidity assumption that permits structure-from-motion perception, as in the walking lights demonstration.[31]

Research on perceptual and cognitive illusions has given us striking examples of what the brain considers to be sufficient goodness of fit, and tolerable misfit. One only has to think of classic examples like the familiar 'barber's pole' illusion: the apparent axial motion of a rotating helix, in which the visual system takes as sufficient an internal model with axial motion only. (Again recall the subjective experience: the axial motion is the 'perceived reality'.) More interesting still, a significant degree of misfit can be biologically advantageous in its own right, as strikingly illustrated by recent experiments on speech perception from combined auditory and visual data, in which the brain seems to exploit the 'ventriloquist effect' to improve discrimination between one auditory signal and another seemingly coming from a different direction, certain circumstances.[220] in

41. Bateson, G. L., 1972: A theory of play and fantasy. In: *Steps to an ecology of mind: collected essays on anthropology, psychiatry, evolution and epistemology'* 1972 and 1973: San Francisco, CA,

Chandler/London, Intertext/ London and Northvale, New Jersey, Aronson/London and New York, Paladin; 545 and 510 pp. This essay points out something that could hardly be more basic but is often overlooked, that juvenile play is essential for learning the difference between 'fact' and 'fiction', an abstract concept crucial to survival.

42. Barnett, S. A., 1993: Of course, some of my best friends study Eng. Lit. *Interdisc. Sci. Rev.,* **18**, 158–162. More remarks, from animal behaviourist, about the importance — the seriousness — of juvenile and adult play. Also a plea for universities 'to introduce courses orthogonal to the usual presentation of more and more about less and less.'

43. Davies-Mitchell, M., 1994: Poetics now? *Europ. Rev.,* **2**, 177–192. Professor Davies-Mitchell brings out the playfulness and elusiveness in poetry and introduces the reader to, among other delights, a marvellously musical riddle-poem by Seamus Heaney. She also delivers a splendid riposte to cultural nihilism: '...the demise of poetry... has frequently been predicted; but the patient, declared terminally ill one day, is reborn the next, proliferating like Proteus in new and surprising shapes — that capacity for self renewal offering proof, if proof were needed, that poetry, the writing and reading of it, is an intrinsic and essential aspect of human activity.' Like children's spontaneous storytelling (Part III (`lucidity3.ps`) and Ref. 167), the spontaneous creation of poetry, by some individuals at least, is just what is to be expected on biological grounds.

44. Markl, H., 1997: Language and the evolution of the human mind. *Europ. Rev.,* **5**, 1–19. A lively and perceptive survey by an animal behaviourist with a clear vision of the role of juvenile, and adult,270 play. There is also a useful bibliography of recent references, including many on primate behaviour and 'machiavellian intelligence'. Another highly intelligent and perceptive essay trying to expose the false dichotomies that underlie so much muddled human thought, especially the nature–nurture fallacy. From his perspective as a researcher in behavioral biology and evolution, Hubert Markl (a professor of biology at the University of Konstanz) reminds us that "we are in the middle (not, as some see it, only at the beginning) of one of the major extinction events in the evolution of life on earth", with the inevitable consequence, the radiation of new niche-occupiers many of which will take advantage of the "new superabundant opportunities of 6, 8, or even 10 billion human individuals and the multibillion tons of biomass of our slave species of domesticated agricultural plants and animals... an entirely new surge of bioevolutionary creative developments, certainly not to our pleasure, but clearly bearing witness to the creative powers of natural selection". This begins to give environmental change a realistic perspective. Also tries to address genetic superstitions, including the eugenics myth.

45. Popper, K., 1992: *Unended Quest*, revised edition. London, Routledge and Kegan Paul, 276 pp, and references therein. Trivializing Karl Popper's ideas still seems to be in fashion,[236] though they are highly relevant and anything but trivial. This personal overview by Popper himself gives a quick idea of the breadth and penetration of his thinking, and of the philosophical traditions or 'isms' preceding and provoking his work. The idea of ordinary perception as a model-fitting process, as automatic, unconscious 'conjecture and refutation', emerges clearly on p. 139. Popper also gives, for instance, a clear warning (e.g., pp. 17–31, 82) about the pervasiveness of what I am calling the 1–1 lexical fallacy (Appendix 2) and related ideas, such as the idea that the 'explication of concepts' is the main task of philosophy.

46. Campbell, D. T., 1973: Evolutionary Epistemology. In: *The Philosophy of Karl Popper*, ed. P. A. Schilpp, 413–463. Library of Living Philosophers, Vol. 14, LaSalle, Illinois, Open Court Press, 1323 pp. This surveys some relevant philosophical traditions from Kant onwards, expanding on Popper's aphorism that 'the growth of scientific knowledge may be said to be the growth of ordinary human knowledge writ large.' See also:

47. Shimony, A., 1993: Integral Epistemology. In: Shimony, A., *Search for a Naturalistic World View, vol. 1, Scientific Methods and Epistemology*, 3–20. Cambridge University Press, 333 pp.

48. Wolpert, L., 1992: *The Unnatural Nature of Science*. London, Faber, 191 pp. Gives much interesting history from the viewpoint not of a philosopher but of a leading scientist, and a very clear explanation of the *difference* between commonsense knowledge and scientific knowledge, with emphasis on the intellectual courage required to reach the latter, the courage required to take the scientific ideal seriously.

49. Understanding that words and symbols can have self-contradictory definitions is a key to seeing through a good deal of philosophical fog, to say nothing of political and commercial fog.[35,36,62] The late John Bell (Ref. 231, p. 166) has argued that the term 'measurement', as often used in discussions of quantum mechanics, is likewise an example of a self-contradictory term.

50. Bohm, D., 1971: On Bohr's view concerning the quantum theory. In: *Quantum Theory and Beyond*, ed. T. Bastin, 33–40. Cambridge, University Press, 345 pp. Bohm's point, taking Bohr's important pioneering efforts a step further, is that consistency and lucidity — within the entire theoretical–experimental edifice, and applying to words and word patterns as well as to mathematical symbols, equations, and algorithms — is so important as to compel the verbal language itself to evolve, to whatever extent is necessary. The mathematics is easy; it is the verbal side that is hard. Bohm, 'perhaps our most profound thinker about the nature of quantum reality',[51] may have been one of the first to say clearly that language evolution is especially critical in the case of quantum mechanics, as well

as to recognize that for practicality's sake the evolution does indeed have to be an evolution — in a very Darwinian sense — implying among other things that the needed changes will have to take place organically, because that is the only way they can take place. Thus, the 'unspeakability problem'[231] or 'words problem'[252] in quantum mechanics does not signal any absolute taboo, as Bohr has been read as saying. Rather, it shows among other things that some aspects of the verbal language are insufficiently evolved as yet. The language has to coevolve with the conceptual and mathematical theory — see also Ref. 231, p. 166 — and the feeling is that quantum mechanics is emerging, very slowly, from what the admirable Doctor de Bono calls an 'intermediate impossible' or 'crazy ideas' stage.[36] Bohm's discussion well illustrates my points about Stroop interference (p. 13 above) and, more generally, about the effort to achieve lucidity becoming 'the work of many individuals'. The late John Bell has been another notable contributor to this effort.[231]

51. Goldstein, S., 1997: A theorist ignored (Review of a recent biography of David Bohm.[230c]) *Science* **275**, 1893–1894, and other papers at `http://math.rutgers.edu/~oldstein`. Also: Goldstein, S., 1996: Quantum philosophy: the flight from reason in science. In: *The Flight from Science and Reason*, ed. P. R. Gross, N. Levitt, and M. W. Lewis, *Ann. N.Y. Acad. Sci.*, **775**, and other papers at `http://math.rutgers.edu/~oldstein`.

52. Derrida, J., 1993, translated by P.-A. Brault and M. B. Naas: The other heading: memories, responses and responsibilities. *PMLA (Publ. Modern Lang. Assoc. Amer.),* **108**, 89–93. The phrase to which I refer comes from a sentence stated as an 'axiom' or 'law' on p. 90: 'What is proper to a culture is to not be identical to itself.' As with Fig. 4, this is designed to tickle our confusion-and-incoherence instinct. It is also a clever play on the words 'cultural identity'. The article is a kind of poetic meditation on what might be called cultural schizophrenia. I think there is confusion between such poetry on the one hand, especially when presented charismatically, and philosophy aspiring to rational thought on the other. The idea, going back to Hegel or earlier, is to blur the distinction between coherence and incoherence — a natural human urge, as I have argued, and a dictator's dream.[200,42,165]

It seems plain that some styles of journalism exploit the confusion-and-incoherence instinct. The late John Bell put it aptly, in talking about quantum-mechanical 'intermediate impossibles',[50] on p. 194 of Ref. 231: 'It is easy to understand the attraction... for journalists, trying to hold the attention of the man in the street. The opposite of a truth is also a truth! Scientists say that matter is not possible without mind! All possible worlds are actual worlds! Wow!' One might add 'Isolated universes interact!' (from a journalist's garbled version of ideas in Ref. 293*a*), or 'Reality is unreality!', or 'Nonlogic is logic,' or 'Fig. 4 shows the *real* elephant,' or, with Hegel, 'Pure being is pure nothingness!' Hegel seems to have been talking, in a characteristically obscure way,[165] about the unconscious power of abstraction (Appendix 3). 'And', Bell continues, 'the journalists can write these things with good consciences, for things like this have indeed been said... by great physicists.' See Part III (`lucidity3.ps`).

53. Penrose, R., 1994: *Shadows of the Mind: A Search for the Missing Science of Consciousness.* Oxford, University Press, 457 pp. This remarkable book presents the Platonic view of mathematics as experienced by a leading mathematical physicist; see Appendix 3 above. The book is also very clear on quantum mechanical fundamentals and their implications, and in this regard is an important reference for specialists and non-specialists alike (Chapters 5 and 6, pp. 237–347). The Aspect *et al.* experiments on quantum entanglement or Einstein–Podolsky–Rosen–Bohm phenomena are discussed in §5.4, p. 246–8; they demonstrate quantum entanglement over a distance of 12 metres though not over distances the size of the Universe. See especially the caption to Fig. 5.6; and for further details and updates Refs. 230, 231, 239, and 251*a*. The book also conveniently reviews two of the most outstanding examples of the accuracy of the great theories, the great models, of physics, as tested against data of exquisitely high precision (pp. 227–234 (§4.5)), the first being Einstein's gravitational theory, as tested against binary pulsar behaviour, and the second the blackbody radiation law, as tested against the cosmic background microwave radiation; for updates on the latter see also Ref. 264. For the third celebrated example, quantum electrodynamics as tested against atomic spectroscopy, see Ref. 63, also remarks in 231*d*.

54. Stravinsky, I., 1942: *Poetics of Music.* Cambridge, MA., Harvard University Press, 142 pp. A great composer presents, soberly yet passionately, a Platonic view of musical lucidity and of music as having 'a life of its own'.

55. I have discussed these matters with the composers Alexander Goehr, Robin Holloway, Virginia Seay Ploeser, Yuval Shay-El, Roderick Skeaping, and Hugh Wood, and heard corroborative remarks by Luciano Berio (BBC Radio 3, Promenade Concert interview, 29 July 1994), Julian Anderson (BBC Radio 3, Promenade Concert interview, 27 Aug 1994) and many others. Anderson's remarks, confirmed by Goehr (personal communication), were mainly about the composer Harrison Birtwistle and include a piece of history that seems to me artistically, psychologically, and biologically interesting, and relevant to my points about organic change and coherent ordering. It is also relevant to the crosscultural common elements in music; see also Refs. 22, 23, and Note 58. Anderson referred to a time in the middle of the twentieth century, the brief heyday of total serialism as embraced by the Darmstadt group, in which both Goehr and Birtwistle had been involved for reasons that included reaction against sterile academic musical conservatism. Total serialism, in some interpretations at least, included a taboo against repetition. It was held that, in Anderson's words, 'you couldn't repeat, and you certainly

couldn't repeat rhythmically: it was regarded as passé.' Anderson continued, 'Sandy Goehr told me about a walk he took with Birtwistle, in about 1964 I think. And Birtwistle said quietly, 'You know, I do think it's time we started repeating things.' And then said nothing else. It wasn't until *Tragoedia* came out the following year that Goehr realized exactly what he'd meant.' This was the first of a series of powerful, and now very influential, Birtwistle compositions that make extensive use of pattern-repetition.

56. Pay, Antony, 1996: Phrasing in contention. *Early Music* (Oxford University Press), **24**, 291–321 (also at `http://www.sneezy.org/clarinet/Study/Phrasing.html`). A deeply perceptive essay by a world class musician, illuminating some of the profound connections between speech and music and noting some widely overlooked implications for musical performance. As Fowler's article on **rhythm** reminds us, speech for this purpose includes prose just as much as poetry. See also the remarks on perceptual grouping and perceptual units in Ref. 22.

57. Stravinsky's *Rite of Spring*, like much of his music, relies on patterns that are often rather irregular. (The composer Yuval Shay-El has pointed out to me that some of these patterns are like the elephant's feet in Fig. 4, playing on ambiguities between strong and weak beats.) Despite all this, however, the simple ABAC or 'surprising how often... surprising how seldom...' type of pattern is still conspicuous here and there (perhaps coming from the folk roots). Examples are the principal melodic patterns at rehearsal numbers **91** and **94** and elsewhere in *Mystic Circles of the Young Girls*, (pp. 84–87 in the 1967 Boosey & Hawkes edition). Also essentially of the same type, despite subsidiary variations, are the opening of the second part, rehearsal number **79** (p. 76), and the theme of *Glorification of the Chosen One*, rehearsal number **104** (p. 91). In this last case one might quibble that the pattern is better described as ABA′B′, closer to 'surprising how often it happens that..., and more surprising how often it happens, happens, happens again that....' Even the opening bassoon melody has a strong ABAC feeling, though again in detail it is more like AA″A′A‴, or, loosely, with American pronunciation, '*sur*—prising how often it's surprising in some way, and *sur*prising how seldom it isn't so surprise, well I mean, *sur*-'. This kind of variation, with interruption effects, is rather typical of the music of the *Rite*.

58. **A journey into musical hyperspace. Preamble:** In Parts I and II (or pp. 12–14 and Appendix 2 above), I touched on the peculiar power of music to go somewhere, or take us somewhere. This is especially characteristic of Western polyphonic music. But in what kind of space does it move? Indeed, why does music exist at all? There are intriguing clues from psychoacoustics and neurophysiology, and from the practicalities of how harmony works. They connect with two central threads in my discussion: the relation between play and survival, and the perceptual and cognitive importance of organic change.

Many of the rules or guidelines about powerful harmonic progression, or motion, or function, in Western music — representing discoveries made by composers in a vast range of so-called tonal and atonal, classical, jazz and other styles, from the simplest popular songs to Bach, Debussy, Schoenberg, and beyond — can be summarized, and generalized, by reference to the idea of organic change. This captures much of what is relevant in a fundamentally simpler way than one might think possible from the music-theoretic literature. Indeed, the perspective developed here, relating musical practicalities to biological fundamentals, may well seem strange to a music theorist. But the simplicity must have been noticed by many composers, some of whom may well have regarded it as a trade secret.

Wagner might be a case in point, as suggested by the much-discussed *Ring* and *Tristan* examples below. From the present perspective these examples bear a close family resemblance to examples from Mozart and Gershwin, as I shall demonstrate. Related to all this, though left aside here, is a view of so-called 'consonance' and 'dissonance' that avoids any absolute dividing line between them purporting to be independent of timing, context, and musical motion including contrapuntal motion, the power of voices moving against each other.[22] Also left aside are the larger-scale or 'architectural' aspects of harmonic function. What I shall focus on is elementary. But it is also far-reaching because, in a strong sense to be explained, it is culture-independent.

The last point is worth stressing because of today's common assumption, or article of faith, that 'Western music' is an arbitrarily determined cultural affair, dependent on an arbitrary subdivision of the octave into 12 intervals. Indeed, the idea that art and culture are *arbitrary* constructions — as distinct from the reasonable idea that culture is important — seems so widespread that in order to show exactly how and why it is wrong, for present purposes, I need to go into a little more detail than elsewhere in this book. The point is so important, at a deeply fundamental level — beyond music as such, or particular types of music — that the digression would seem well justified. The discussion is self contained, and should be intelligible to any interested person who responds to music and who can pick out a few notes on a keyboard, or can ask a keyboard player to do so. Audio clips will be provided on the Internet and in the multimedia version [not yet done, sorry!]. Points for musicians are confined to footnotes.

Two kinds of perceptual proximity: By powerful harmonic motion or function I mean sequences of harmony changes that, with suitable timing — and the timing is always crucial — are powerful in reinforcing the melodic and contrapuntal motion so as to help the music to 'go somewhere'. A sense of going somewhere depends not only on a sense of continuity but also, still more fundamentally, on a sense of what is nearby and what is further away. Harmonic motion has the interesting property of depending not on one but on two basic, style-independent, culture-independent, and subjectively very different kinds of perceptual proximity. In this respect musical space has some kinship with the 'hyperspace' of science fiction stories. It is possible to go somewhere that is both nearby and far away.

The first kind of perceptual proximity is the obvious one, that of semitones or adjacent notes on the Western keyboard, or adjacent notes in other scale systems, or of the continuous pitch variations that are natural to the human voice. Psychologists call this 'height' proximity, or 'height' similarity. The second is what psychologists call 'chroma' proximity or similarity, especially in connection with the near-identity of octaves, echoed in the repeating pattern of black and white keys on Western musical keyboards. It has also been called Pythagorean, circle-of-fifths, long-pattern, or, most plainly for present purposes, *harmonic-series* proximity. Here I will stick to the last term, because it is the clearest and most self-explanatory as will be seen in a moment.

Whatever we call it, harmonic-series proximity is just as basic — just as primordial and culture-independent — as height proximity. This is an inescapable consequence, I will argue, of the model-fitting involved in auditory perception. Different musical cultures differ only in the ways in which they exploit the two kinds of proximity.

Two notes are near each other in the harmonic-series sense if, to good approximation, they have vibration periods or cycle times in a simple ratio. This means that their vibrations have a high degree of synchrony. Equivalently, two such notes have overlapping harmonic series, in the sense that some of the members of one series coincide to good approximation with members of the other. The members of a harmonic series, it will be recalled, are the fundamental frequency and its integer multiples. Thus the 1st, 2nd, 3rd, 4th,... members have frequencies equal to the fundamental frequency multiplied by 1, 2, 3, 4,..., and cycle times equal to the fundamental cycle time multiplied by $1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots$

Unisons aside, pairs of notes an octave apart are the closest possible in this harmonic-series sense. The fundamental cycle times are in the ratio 1:2. Every member of the harmonic series of the upper note coincides with a member of the lower. Every second vibration of the upper note synchronizes with a vibration of the lower. Notes an octave apart are perceptually so similar that musicians give them the same name, as with 440 Hz A or *la*, the note to which orchestras tune, and 220 Hz A, an octave lower, shown here together with the first four and the first nine members of their respective harmonic series, enough to show part of the pattern of coincidences:

vignette 1 in `lucidity-note58-vignettes-eroica.gif`

Harmonic-series overlap implies that the two notes produce strongly overlapping excitation patterns on the basilar membrane of the inner ear. Still more important, they produce synchrony or near-synchrony of many features in the trains of nerve impulses sent to the brain, and in the reverberating neural circuits within the brain that must be involved in the model-fitting. Neurophysiological research has provided strong evidence that such synchrony should be relevant.[153] This idea leads to what is called the 'long pattern hypothesis',[153a] which says that to produce the octave and other musical percepts of 'consonance' the synchrony must be good enough to keep approximately in step over a time interval that is 'long' in some suitable sense. The results of psychophysical experiments suggest that 'long' means time intervals up to one or two hundred milliseconds,[150b,153a] though circumstance-dependent. Such time intervals are roughly of the right order to be consistent with musicians' pitch perception accuracies, as far as one can say in the present state of knowledge, i.e., without a detailed understanding of the brain's pitch perception mechanisms.[155]

The next closest in the harmonic-series sense are pairs of notes a musical perfect fifth apart, as at the start of 'Baa, *baa, black* sheep', 'Twin*kle, twin*kle, little star', 'Ah, *vous dir*ai-je, Maman', etc., e.g. 220 Hz A or *la* and 330 Hz E or *mi*, four white keys to the right:

vignette 2

Musicians call two such notes 'harmonically close', as distinct from 'melodically close'. They have only slightly weaker overlap and synchrony. The fundamental cycle times are in the ratio 2:3. Every even-numbered member of the harmonic series of the upper note coincides with a member of the lower, because every even integer gives another integer when multiplied by $\frac{3}{2}$. Every third vibration of the upper note synchronizes with every second vibration of the lower. Similarly, the perfect fourth, the major third, etc., with cycle-time ratios 3:4, 4:5, etc., represent successively greater distances or dissimilarities in the harmonic-series sense, though successively smaller in the height sense.

But why is harmonic-series proximity just as basic, primordial, and culture-independent as height proximity? The reason is simple: it is biological necessity. It is simply that the harmonic series, or equivalent long-pattern time-domain information, has to be represented among the brain's model building blocks. Such information is needed to build internal models that can fit, hence make sense of, the very complex spatiotemporal excitation patterns produced by 'a jungleful of animal sounds'.† More precisely, the harmonic series or equivalent time-domain information is needed as a model building block whenever the jungleful of sounds, or any other sounds, have amongst them the almost-periodic signals produced by vibrating syrinxes, larynxes, or other acoustic oscillators — whistles, hoots, yowls, and so on, all the way to human speech and song. This is a matter not of culture but of the most basic physics — the patterns associated with almost-periodic sound signals — and the most basic biology. Nature–nurture polemics are beside the point. We need not debate whether the ability to recognize yowls and whistles is fully formed at or before birth, or whether unconscious learning from auditory input has a role, which probably it does. One way or another, survival compels the ear–brain system to perform feats of pattern perception in which, inescapably, the harmonic series or equivalent information, internally represented in one way or another, has to be one of the most crucial patterns the system must deal with.

Once again we see the relation between play and survival. It is for survival's sake that the brain takes pleasure in playing with such patterns. This is a biological imperative that is plainly part of why music exists at all. It is not the whole explanation, of course. Music — song and dance — must have been intimately part of our ancestors' tribal cohesion. It is no accident that the *internal musician* in us has emotional power, and is both a dancer and a singer. In a prehistoric world full of large predators, group bonding was another survival imperative.‡

Much of what composers have discovered about harmonic motion can now be summarized in just one sentence. Powerful, continuous harmonic motion involves organic change — some things changing while others stay invariant — with the amount of change, usually small, referring to either or both kinds of perceptual proximity. This is part of why 'good voice-leading' in a musical score can include surprisingly large height jumps in some voices. Jumping by a fifth, for instance, is a small change in the harmonic-series sense even though large in the height sense.

Let me be more specific. The two most basic techniques for powerful, continuous harmonic motion — out of which more elaborate structures can be built and against which other harmonic effects can be contrasted — are **(a)** to change some pitches by small amounts (small in either sense), keeping other pitches invariant, and **(b)** to change all pitches by the same small amount (small in either sense), keeping the chord shape invariant — i.e., to use parallel motion of an invariant chord shape. This summarizes, and generalizes, much of what can be learnt from a good practical harmony textbook. Examples of techniques **(a)** and **(b)** will be given shortly. Claude Debussy (1862–1918) may have been the first great composer to use them both with something like the present day freedom.[150,150a]¶

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†Because the model-fitting aims at identifying sound sources,[22] it must be phase-sensitive for the purpose of direction-finding but *insensitive* to phase differences between harmonic-series members. Such phase differences vary wildly as the source and receiver move, causing variations in the ensemble of (frequency-dependent) sound transmission paths. This bears on a much-discussed point in the psychoacoustical literature.[150b,153] The 'jungleful' allusion is to the introductory discussion on p. 13 above, or p. 206 of the published Part I. See also the fuller discussions on pp. 7ff. and in Appendix 2 herein, or in Part II and in Note 142 of Part III (`lucidity3.ps`). Parts I–III appeared in *Interdisciplinary Science Reviews* **22**, 199–210, **22**, 285–303, and **23**, 29–70, 1997–8.

‡This obvious point seems to be missed surprisingly often, even by professional scientists, perhaps through the unconscious persistence of naive ideas about Darwinian natural selection. There is a mind-set that 'nature red in tooth and claw', 'every man for himself', and so on, is the whole story — that 'selfish genes' are selfish in a simplistic sense. This might be more reasonable if every species had a solitary lifestyle. It forgets that our own ancestors, in particular, had to survive predation in open country, as forests shrank two thousand millennia ago. Group cohesion must have been essential. To think that social skills, bonding through gesture and vocalization, love, altruism, and so on, are difficult to explain in Darwinian terms is a bit like thinking it difficult to explain why birds have wings. Darwin's hypothesis is that anything a species has come to depend on for survival *must have developed with the aid of selective pressures.* And group bonding was plainly essential to our own ancestors' survival. I return to this point in Part III. It is further discussed by Cross, I., 1999: Is music the most important thing we ever did? Music, development and evolution. In: *Music, Mind and Science* ed. Suk Won Yi, Seoul: Seoul, National University Press. Also http://www.mus.cam.ac.uk/~cross/MMS/ and snubook@plaza.snu.ac.kr.

¶Changes that are small in the height sense give rise to what musicians call 'chromatic' effects, and 'leading note' effects. Changes that are small in the harmonic-series sense give rise to what musicians call diatonic or 'non-chromatic' effects, especially 'dominant', 'subdominant', and associated 'neighbouring key' effects. The 'dominant' and 'subdominant' of a given note are its nearest non-octave neighbours in the harmonic-series sense, a fifth above and a fifth below; these neighbours are used with or without added notes that reinforce, decorate, elaborate, or contrast with their harmonic series.

It should be cautioned that, while proximity or similarity, in the harmonic-series sense, has a clear meaning

Debussy's frontier: Debussy also seems to have been the first great composer to exploit systematically the other most basic corollary of the foregoing, of the biological imperative just explained. Multi-note chordal sonorities that correspond to subsets of a harmonic series inherit the long-pattern synchrony of that series. Integers multiply to give integers. This makes such sonorities perceptually special — along with melodic fragments made of harmonic-series subsets.

We can now see why, for instance, chords like the following have long been recognized by musicians as perceptually special:

vignette 3

They occur very frequently throughout classical and popular music. In this example, each chord corresponds to a subset of the harmonic series of 55 Hz A. The first corresponds to members 4, 5, and 6 (220 Hz A, 275 Hz C♯, and 330 Hz E), the second to members 4, 5, 6, and 7 (add 385 Hz G), and the third to members 5, 6, 7, and 9 (remove 220 Hz A and add 495 Hz B). Melodic fragments made from members 6, 7, and 8 are commonplace in children's chants:

vignette 3b, in `lucidity-note58-vignettes-chrissy.gif`

This is no accident: members 6, 7, and 8 form the harmonic-series subset that is easiest to sing recognizably. The musical effect is close to that of the next easiest:

vignette 3c, in `lucidity-note58-vignettes-chrissy.gif`

Here the two versions are made from members 5, 6, and 7 of two harmonic series. The second series is again that of 55 Hz A, of which members 5, 6, and 7 are the bottom three notes of the third chord shown above.

Musicians will recognize the three chords above as, first, an A major triad or 'common chord', second, a so-called dominant seventh (A7), and third, a so-called 'Tristan chord' or minor triad with added sixth

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for present purposes — whether described as strong harmonic-series overlap or near-synchrony in the time domain — 'large distance' or 'dissimilarity' is something far more complex, ill understood, and probably ill defined.[153b] This is hardly surprising in view of the greater complexity produced by asynchrony. It is doubtful whether the notion of 'distance' or 'metric' really applies in its strict mathematical sense, with the usual additivity properties (triangle inequality etc.), as often hypothesized in experimental psychological studies. The problem is most acute for the case of large distance, better described as large perceptual dissimilarity. It has been argued, by R. N. Shepard and others, that if there is a suitable perceptual space having a metric then it would have to be many-dimensional.[152,154] As many as 7 dimensions have been suggested.[154] If anything like this were correct, it would imply that the perceptual space is far too big to be open to exploration by experimental-psychological methods, and probably far too unstable as well — or ill-fitting, as a model of reality — because of the strong effects of musical context and motion, the musical arrow of time, which may destroy even the presumed equivalence between 'X similar to Y' and 'Y similar to X'.[153b,154a]

The reader venturing into the literature of experimental psychology needs to be warned, too, that there is a clash between the musical term 'chromatic' and the psychological term 'chroma'. What musicians call 'chromatic' effects are associated with large, not small, perceptual dissimilarities in the chroma or harmonic-series sense. Further potential for confusion lies in the use of the term 'chroma' in connection with the two ways in which music theorists tend to arrange the 12 notes of the keyboard in a circle, by semitones on the one hand (i.e. by height proximity) and by fifths on the other (i.e. by harmonic-series, alias chroma, proximity). To close each circle, notes an octave apart are regarded as identical. The term 'chroma circle' is customarily used to mean the first (height-proximity) circle and not the second (chroma-proximity) circle — perhaps because the latter has traditionally been called the circle of fifths. Thus chroma proximity — in all cases *except* the octaves now regarded as identical — corresponds to large, not small, distances around what is called the chroma circle. This is why I am avoiding the term 'chroma', even though it is well established in the psychological literature. I am grateful to Ian Cross and Brian Moore for information and references.

(E minor 6), also called a half diminished seventh. (For the sake of simplicity and, more importantly, for the sake of the widest possible generality, I am going to take what a music theorist might call outrageous liberties with chord names. I will use them in a naive way that refers to the static sonorities alone, in the practical manner of jazz and popular musicians.§) Debussy exploited the fact that there are many other subsets of a harmonic series, and therefore many other such special harmonic-series sonorities.

Notice now that parallel motion of any such chordal sonority is related to my primordial whistles and yowls — or at least low pitched versions thereof — revealing them as special cases of technique **(b)** using continuous change. In a deeply unconscious sense, a jungleful of animal sounds is also a jungleful of technique **(b)** in action.

The tuning of chordal sonorities in general, and of special harmonic-series sonorities in particular, involves nontrivial practical questions. This is because of the perceptual relevance of long-pattern synchrony. It takes consummate skill and mental concentration on the part of, say, orchestral musicians, to tune such sonorities accurately enough for best effect. The pitch of a given note has to be slightly flattened or sharpened, depending on how it is contributing to the sonority of the moment. Accuracy in such corrections contributes to the wonderful luminosity of sound that can arise in great performances. (The idea that the best musicians play to a fixed 'scale', persistent though it may be in the literature, has been shown by careful experiments to be wrong.[150c,155b]) I will postpone discussion of imperfect tuning except to warn that the theoretical 'just tuning' enshrined in musical-acoustics textbooks is, despite its name, inaccurate for the second and third chords above — this may be part of why they were traditionally regarded as dissonant — and to make the further points that perception is robust and long patterns are finite. Were this to cease to be the case, orchestras would immediately go out of existence, keyboard instruments would become museum pieces, and music would be playable only with the aid of computers. We may also note that certain kinds of tuning imperfections and fluctuations are themselves perceptually significant. They include the deliberate fluctuations called vibrato, on 'intermediate' timescales between vibration-cycle and long-pattern timescales.[155] Fluctuations over some limited range can help the ear–brain system to disentangle junglefuls and roomfuls of multi-note sonorities.[22] Builders of electronic musical instruments take trouble to create such fluctuations artificially, with varying degrees of success.

The ways in which Debussy developed the unrestricted use of organic-change principles and of special harmonic-series sonorities and melodic fragments, thereby opening up vast new musical vistas — he called it 'crossing a frontier' — have been beautifully illustrated in an essay by the late, and much-loved, composer and musicologist Sir Peter Platt.[150a] As the biological and spiritual significance of music comes to be more widely understood, historians may yet see the crossing of this frontier as the most important turning point of all in the transition from nineteenth to twentieth century music. For it was not the invention of a great intellectual scheme or manifesto. It was not the creation of a sphere of influence, of a new band of disciples or zealots. It was a simpler, rarer, and more significant thing altogether. It was as if someone working in the visual arts had suddenly found out how to use vast numbers of new shapes and colours, all belonging to an organically related family whose existence and significance had remained undiscovered until then — despite being under everyone's nose.

The harmonic series was certainly under the nose of, among others, the great physicist and polymath Hermann von Helmholtz, author of the celebrated treatise *On the Sensations of Tone*, with his sure grasp of mathematical and physical principles and his intense interest in musical sounds. Indeed, Helmholtz is famous for having devised an elegant experimental technique, today called the Helmholtz resonator, for making the separate members of a harmonic series audible in the manner of jew's-harp playing. Yet even in the 4th edition of *Sensations*, published in 1877, one still finds the unconscious, or unstated, assumption that for practical musical purposes the harmonic series stops at member 6.

Perhaps this was bound up with the oft-repeated myth or mind-set that the 7th member is always 'too flat', as if that were a universal principle. Here in a very real sense was Debussy's frontier, even though the common occurrence of the three chords above — to say nothing of plain minor triads, the top three notes of the third chord — shows that practical musicians aware of fine tuning corrections had long made, so to speak, nighttime excursions across that frontier in particular directions. Some especially

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§The naming of chords involves disparate traditions as well as complex issues of musical motion, and is an area of perpetual disagreement, especially between composers and music theorists (e.g. Piston and de Voto[150], p. 359 & Ex. 23-41, p. 364). The composer Robin Holloway (personal communication) tells me that he steers clear of all this and doesn't concern himself with chord names — the important thing being to find 'the right notes'. The effect of a chord is, of course, context-dependent: it may 'function' in different ways, and theorists favour names that say something about context. Names that give advance warning of the next move are especially favoured. Thus in the view of many theorists the third sonority shown above should be called a 'Tristan chord' only when followed by a certain kind of 'hyperspace move', as I shall call it, in which the key changes to F major via C7. There may also be restrictions on what precedes the chord. But because I am taking a more general view, applicable to many styles of music and to contexts that might or might not be describable as being in a definite key — or as moving toward, or 'revealing themselves as being in' a definite key — I need some way of talking about the static sonorities themselves, independent of particular contexts. *And the number of possible contexts is combinatorially large.*

striking evidence has come down to us from Purcell: the sonority of the third chord above is used very persistently, not to say insistently, in his famous and achingly beautiful aria *Dido's Lament*.[150c] Purcell directs the keyboard to be silent, one consequence of which would have been to allow the singer and string players full freedom to make the finest possible tuning corrections.

From Helmholtz' assumption, by contrast, there flows the whole mythology of 'just tuning', along with an exaggeration and rigidification of the distinction between consonance and dissonance. To ignore the harmonic series beyond member 6 is to think that, for instance, there is only one sort of perfectly tuned minor third, the wide one needed in the first chord displayed above, ratio 5:6, as distinct from the narrow one needed in the second and third chords and in plain minor triads, ratio 6:7 (e.g. the top pair of the second chord, the middle pair of the third chord, and the bottom pair of a minor triad). The same mythology is perpetuated in today's musical-acoustics textbooks, where it never seems to be pointed out that the equal-tempered tuning of modern keyboards, by a strange and wonderful accident, or stroke of luck (see below), manages to hit a compromise between the wide and narrow minor thirds and between the correspondingly narrow and wide major thirds, such as the bottom pair of the first chord above (cycle-time ratio 4:5) and the top pair of the third chord (cycle-time ratio 7:9). You cannot, of course, point this out if you think, perhaps unconsciously, that there is only one sort of minor third and one sort of major third.

Some trade secrets: Let us return to the organic-change principle and to techniques **(a)** and **(b)** — the most basic techniques that make musical harmony work, in which some pitches change, usually by small amounts, while others stay invariant. To illustrate how these techniques work in practice and to discover for yourself a few composers' trade secrets, if you don't know them already, the quickest way is to consider the height-proximity neighbours of a 'diminished seventh' chord such as C♯ dim7:

vign.4

This is not a special harmonic-series sonority. But it is special in another way. It is at the crossroads of a large, powerful, versatile set of harmonic moves using techniques **(a)** and **(b)**. They are an intimate part not only of Debussy's style but also of a vast range of other styles from Purcell and Bach to Stravinsky, Duke Ellington, Lutosławski, and practically everyone else. They provide a rich variety of ways to go somewhere that is nearby in the height sense and almost anywhere you like in the harmonic-series sense, including some of the most thrilling 'hyperspace leaps'. For this reason, some English composers have called the diminished seventh chord the 'Clapham Junction' of harmony, referring to a famous branching of railway lines in London with its many possibilities for going to, and coming from. The power and versatility depend on the symmetry of the diminished seventh. Its adjacent notes are 3 semitones apart, dividing the octave into 4 equal portions: 12 is divisible by 4 to give 3.

If we start by restricting attention to the closest possible height-proximity neighbours, holding three out of the four notes invariant and changing the one remaining note by a semitone — let us call these 'one-note neighbours' — we see that a single diminished seventh already has eight different such neighbours. In other words, the eight ways of moving one or other of the four notes up or down by a semitone all produce different results, illustrating technique **(a)** in eight different ways. It is worth listening to them all, one after another, if you have not tried it before. Notice for instance that E minor 6, the Tristan chord shown above, is one of these neighbours to C♯ dim7. Only the top note differs. So also is A7, the dominant seventh chord shown above, apart from an octave shift. For the moment, let us count notes an octave apart as being the same.

In fact, every one of the eight closest possible one-note neighbours is either a Tristan chord or a dominant seventh. This is a consequence of the abovementioned symmetry. The symmetrical subdivision of the octave implies that a diminished seventh chord is translationally invariant, in the sense that the same four notes are obtained when the whole chord is translated, i.e. transposed or shifted, three steps up or down the keyboard, or any multiple of three steps. It follows that the eight closest neighbours consist of four different Tristan chords, each obtainable from the others by 3-step translations or transpositions, and four different dominant sevenths obtained similarly. Conversely, we might characterize the diminished seventh sonority by saying that it is poised delicately, and unstably, between four closely adjacent pairs of special harmonic-series sonorities.

Translational invariance also implies that there are three different diminished sevenths. Between them they give access, as one-note neighbours, via technique **(a)**, to all twelve Tristan chords and all twelve dominant sevenths. (This hints at what I meant by power and versatility, but there is more to come.) Any two diminished seventh chords are, of course, neighbours to each other in the sense of technique **(b)**. The use of such neighbours is conspicuous in, for instance, the music of Mozart and of the jazz violinist Stéphane Grappelli, and in many other styles of music.

By putting two such neighbours together, such as D dim7 and E♭ dim7, say, we discover another interesting structure, the eight notes of what is now called an octatonic scale:

vignette 9

Another great composer, Igor Stravinsky, made brilliant use of this scale from early in his career. The Stravinsky scholar Richard Taruskin tells us that the usefulness of the scale, picked up from Rimsky-Korsakov who had noticed its use in Liszt's music, was for a long time one of Stravinsky's most closely guarded trade secrets. According to the Taruskin, Stravinsky carefully avoided talking about it.[155a] This would explain why the octatonic scale is still, even today, hard to find in textbooks or in curricula for basic musical training, despite its close relationship with the diminished seventh including, of course, exactly the same translational invariance property.

A first example: The examples to follow will all be centred for convenience around D dim7, which by translational invariance is the same chord as F dim7, G♯ dim7, and B dim7, if we continue to count notes an octave apart as being the same:

vignette 5

Musicians call these 'inversions' of the same chord, meaning that some notes are changed by octaves. It is worth listening carefully to all four. The musical ear perceives them as very similar to each other, though not identical, as expected from the perceptual similarity of octaves. In a nutshell, translational invariance says that a diminished seventh is the same chord as all its inversions.

Here is a famous example that can be understood in terms of the foregoing:

vignette 6

Opera-lovers will recognize the slow, quiet transition into Act 2 scene 4 of Wagner's *Die Walküre*, the second opera of the *Ring* cycle, when, just after Sieglinde has collapsed from fear and exhaustion, the supernatural takes a hand: the Valkyrie Brünnhilde appears to tell Siegmund his fate.

The three-chord motif after the double bar signals Brünnhilde's presence. It recurs throughout the rest of the *Ring* cycle and is usually called the 'fate' or 'destiny' motif. Here it sounds slowly and mysteriously on the tubas, followed by a quiet drumbeat. Its powerful effect depends on the transition from the second chord, D dim7 with B omitted, to the last chord, C♯7, a dominant-seventh closest neighbour.

As always, the full power of the effect depends on context. Everything that precedes the move to C♯7 has the feel of coming to rest in or somewhere near the key of E major or A major, with 'near' understood in the sense of harmonic-series proximity. Siegmund is tenderly kissing the sleeping Sieglinde, a moment of peace in a turbulent drama. Instead of the C♯7 chord we could easily have had another closest neighbour that is also close in the harmonic-series sense, namely E7/D (a E dominant seventh with D in the bass). (And this could have been followed by, say, A/C♯ (an A major triad with C♯ in the bass), settling thereafter into a stable A major.) So the move to C♯7 is felt as a hyperspace move — a magical twist to match the supernatural twist in the story. The supernatural is felt as both nearby and far away.††

A few other points are worth making. Notice that the first chord after the double bar, a plain D minor triad, is another closest neighbour to the chord that follows it, the D dim7 with its B omitted. The first chord would have been a Tristan chord if the B had not been omitted from both chords. The minor triad, if accurately tuned, is still a special harmonic-series sonority, as already mentioned, and a very smooth one; and the omission of the B from the second chord does not, in this context, change its D dim7 character very much. This may be partly because the missing B is already very much 'in the air'

††In this case the 'hyperspace move' is practically the same thing as what musicians call modulation from one key to another, because there is a clear sense of key at the outset. But 'hyperspace move' is a more general idea than 'modulation'. For instance it applies — see below — to the *Tristan* example, where, famously, there is no clear sense of key at the outset. Moreover, there are some hyperspace moves that are not counted as modulations, by a convention arising from their frequency of occurrence in certain contexts. Notable among these are the standard harmonic gestures using 'Neapolitan sixth' and 'augmented sixth' chords.[150] The sense of 'key' is itself, of course, to do with keeping the emphasis on particular sets of special harmonic-series sonorities, as distinct from more general uses of larger sets of such sonorities.

through its emphasis in the preceding bars (arrows above), and through its immediate reappearance in the last chord.

Two-note neighbours, and a second example: Let us explore further, and consider the next closest types of neighbouring chord. This leads us straight away to some interesting sonorities not yet encountered. For instance, starting from D dim7 you can raise two of its notes by a semitone, taking say F↑F♯ and B↑C, keeping D and G♯ invariant:

vignette 7

If you listen to this, you may well be reminded of Scriabin's later compositions, such as the *Poem of Ecstasy*, or of certain kinds of operatic or film music suggestive of magic, wonderment, or visionary experience. This particular two-note neighbour is an incomplete wholetone cluster, or so-called 'French augmented sixth', the latter term arising historically from its earliest typical uses and contexts. (I continue here with my 'outrageous liberties'.) A moment's thought shows that a single diminished seventh chord has four different such French augmented sixth neighbours. A single French augmented sixth chord is also a one-note neighbour to two dominant seventh chords, D7 and G♯7 in the case shown above, and to two Tristan chords, F minor 6 and B minor 6.

The total number of two-note neighbours, with two notes invariant and the other two raised or lowered by a semitone, in all possible combinations, works out to be 24, not counting inversion. Each one of them is an interesting and much-used sonority.§§ Two of these two-note neighbours

vignette 8

are, for instance, significant for a famous passage in the first movement of Beethoven's *Eroica* Symphony, the magnificent climax at bar 280, shown here transposed and simplified for playability on the piano keyboard:

§§Musicians will recognize all these two-note neighbours as one or another of five distinct types, not counting inversion: (1) 'French augmented sixth' (an incomplete wholetone cluster, sometimes named differently depending on context), (2) dominant seventh with raised fifth (= augmented triad plus minor seventh, another incomplete wholetone cluster), (3) major triad with added sixth (= minor triad with added seventh), (4) dominant seventh with raised third (appoggiatura to the third, tonic pedal etc., giving some of the most radiant and widely-used sonorities, whether 'resolved' or not), (5) major triad plus sharpened seventh (as in the Beethoven *Eroica* example to be quoted next, and in countless others; also, this sonority permeates mainstream jazz). A single diminished seventh has 4, 4, 8, 4, and 4 different neighbours of these respective types, 24 in all. Inversion, vertical spacing, and instrumental colour multiply still further the available sonorities, and their precise effects are multplied more vastly yet by context and by counterpoint, the power of contrary motion, the pull of cross-relations, etc., etc. The Mozart, *Tristan* and other examples to follow will again remind us, as did the *Ring* example above, of the importance of context. Here is D dim7 alongside just *one* representative of each of its five types of two-note neighbour:

vignette 10

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Musical notation: this is the version in the graphics file `lucidity-note58-vignettes-eroica.gif`, for download in binary mode.

The first neighbour is made more consonant by omitting the note D, turning it into a plain F major triad and increasing the impact of the relatively dissonant second neighbour, whose vertical layout further emphasizes the dissonance. Notice also that despite the omission of the D the change from the first to the second neighbour is strongly organic, with the two invariant notes A and F offsetting the impact of the sonority change and the wholetone step that restores the D in the bass. (Invariant notes leading to dissonances in the manner of the A are traditionally called suspensions.) D dim7 continues in a central role after the climax, along with its closest neighbour E7, making the next two moves strongly organic as well, with notes an octave apart counted as being the same for this purpose, as before. The original version for orchestra is scored with a greater vertical span, for maximum effect, and is centred around A dim7 rather than D dim7.

From Mozart to Gershwin to 'the' Tristan chord: Let us look finally at three more examples, from Mozart, Gershwin, and Wagner, the last being the famous *Tristan* opening itself. The three examples may at first seem quite different; but we shall see and hear that harmonically speaking, from the present viewpoint, they are closely related to each other and to the *Ring* example, surprising though this may seem. The Gershwin example illustrates technique **(b)** as well as technique **(a)**.

The Mozart example is from the Clarinet Quintet. For me it remains, over two centuries after it was written, one of the most thrilling examples of a 'hyperspace leap'. Despite long familiarity it still makes my spine tingle — illustrating the independence of the unconscious brain from the consciously intellectual, in this case the deeply unconscious nature of what we simplistically call musical 'expectation'. The example is found at bar 167, or 30 bars before the end of the first movement, at the moment marked by the arrow:

Musical notation: this is the first example beyond vignettes 3b,c in the graphics file `lucidity-note58-vignettes-chrissy.gif`, for download in binary mode.

As always, the effect depends for its full power on the skilful preparation of context, on the control of instrumental texture, and on exquisitely judged timing. Once again, the way the harmony works can easily can be understood in terms of the neighbours to D dim7, seen now in an A minor key context. I leave the details as an exercise for the interested reader. But it is quicker to use one's ears. One can listen to the Mozart passage, stopping just before the arrow, and then listen to the first three chords of the following:

vignette 11

It is also interesting to listen to all four chords and then again to the last two chords of the *Ring* example. This makes its resemblance to the Mozart easily audible, despite the telescoping of the latter to omit the D dim7. It could be said, perhaps stretching a point (or should I say warping it?), that in Mozart's version the D dim7 acts as a science-fictional 'hyperspace wormhole'.

The Gershwin example is from the famous song *I Got Plenty o' Nuttin'*, at the words 'no misery':

Musical notation: this is the second example beyond vignettes 3b,c in the graphics file `lucidity-note58-vignettes-chrissy.gif`, for download in binary mode.

Except for the important difference in the bass line, and the omission of the seventh from both chords rather than just the first, this is harmonically very like the *Ring* and Mozart examples, as listening to it will confirm.

The subsequent C♯/C♯ → D/D, leading back to the tonic or key chord G/G, illustrates, in addition, the use of technique **(b)** above, parallel motion of an invariant chord shape including, in this case, two parallel fifths. The first parallel progression uses height proximity. The second uses harmonic-series proximity, somewhat like the famous and very exposed parallel fifth in bars 11–12 of Beethoven's Sixth Symphony, which was 'against the rules' in Beethoven's time even though it, too, works perfectly well musically. (It is when using technique **(a)** that parallel fifths in independent voices often sound clumsy.)

The final example is the famous opening of *Tristan und Isolde* itself. It has special interest here because the notions of organic change, harmonic-series proximity, and 'hyperspace move' are applicable without any trouble, despite the lack of a clear sense of key at the outset — something that has always troubled conventional music theory. The tempo is very slow:

Musical notation: this is the third example beyond vignettes 3b,c in the graphics file `lucidity-note58-vignettes-chrissy.gif`, for download in binary mode.

The example has been transposed down a minor third to emphasize certain points of similarity with the *Ring*, Mozart, and Gershwin examples. It then involves, as before, two closest height-proximity neighbours to D dim7. The first neighbour is a Tristan chord — 'the' famous Tristan chord — here an F minor 6 or half diminished seventh on D. (I continue still further with my 'outrageous liberties', referring only to the chordal sonority and not to the subsequent moves.) The second neighbour is the last, C♯7, chord, the same neighbour as in the other examples. The first and last chords are two-note neighbours to each other.

But why does the first chord, as such, have its famous and peculiarly powerful impact? It can only be because of the three bare notes that precede the chord. The chord takes on its peculiar colouration whether or not one listens to what follows, or imagines what follows. Yet the three bare notes establish no unambiguous sense of key.‡‡

Notice, however, that the organic-change principle still applies. In terms of height proximity, the first chord is close to all three of the bare notes that precede it. Indeed the second bare note, D, is invariant in the move to the first chord, apart from dropping an octave. The other two, F♯ and C♯, are height neighbours to notes in the chord.

Notice, furthermore, that none of the three bare notes is close to the chord in terms of harmonic-series proximity. This aspect is rather clear because of the fact, already remarked on, that the chord is a special harmonic-series sonority. (One wonders whether this was the clue that got Debussy thinking.) In the case shown, the chord corresponds to a subset of the harmonic series of a low B♭ (29.135 Hz). None of the three bare notes have harmonic series that overlap especially strongly with this B♭ harmonic

‡‡In other words, the effect cannot be convincingly described in terms of modulation from one key to another. To be sure, the key at the beginning *could* be F♯ minor, as the standard analysis assumes.[150] But if, for instance, one were to listen to the first three notes above followed by, say, two-note chord consisting of the opening F♯ with the D just below, then the first three notes would be perfectly comfortable as part of a melody in the key of D major. (This could be continued à la Kurt Weill.) Again, more subtly, one can make it part of a tune in E♭ minor/major, as Debussy did in his well known spoof in the *Golliwog's Cakewalk* from the *Children's Corner* suite. (The original is G♭ minor/major, the melodic line matching Wagner's original, a minor third higher.)

series. The D is closest: there is coincidence at every 10th member of the B♭ series. For the F♯ it is every 32nd member at best, depending on the precise tuning, and for the C♯ it is every 48th member at best.

So the chord is nearby in the height sense, and relatively far away in the harmonic-series sense: the musical motion that produces its impact and peculiar colouration can reasonably be thought of as a hyperspace move.¶¶ Notice, by the way, that the chord has much the same colouration — it still 'sounds like the Tristan chord' — if the three preceding notes are played in any other order, or even played simultaneously to make a dissonant chord of their own. The Tristan chord also sounds much the same if the three preceding notes are transposed up by a perfect fifth leaving the rest of the example unchanged, i.e. if one replaces the bare F♯, D, and C♯ by a bare C♯, A, and G♯. Apart from changing the melodic line, this leaves us with what the above analysis predicts to be a closely similar situation. That is, the three bare notes are still neighbours to the Tristan chord in the height sense — in fact, one of the three is still invariant — but relatively far away in the harmonic-series sense. In fact they are further away, in that there is even less harmonic-series overlap.

As for the subsequent moves, as already hinted they bear a family resemblance to the earlier examples, though the details are more elaborate. The 'French augmented sixth' sonority is used twice, at the beginning of the last bar and just before it.†††

12 per octave is not arbitrary: We can now begin to see the full import of J. S. Bach's advocacy, a century earlier, of the equal-tempered tuning of keyboard instruments — establishing the symmetrical subdivision of the octave into 12 equal intervals as a central reference system for practical music-making. It was nothing to do with an arbitrary culture, politics, or artistic imperialism. It was partly to do with a reality familiar to the best professional musicians: the ability of first-rate singers and string and wind players to make fine tuning corrections, away from any reference system,[150c] in which the same nominal note has different tunings. Because of the ubiquity of the dominant seventh, such corrections are called for even in simple music in a single key,[155b] implying from the outset that compromise is inescapable for keyboard instruments.

It was also to do with the musical power and manner of functioning of countless examples like those just considered — the power that comes from unrestricted motion in a large musical hyperspace. Bach himself discovered many such examples and used them with unerring mastery, as generations of musicians have acknowledged.

The robustness and the cross-stylistic, cross-cultural penetration of the equal-tempered 12 note system — and its continuing use by prodigiously talented musicians of many kinds, even in the computer age — are remarkable and significant psychophysical phenomena in themselves. They amply vindicate Bach's vision, besides teaching us something profoundly significant about human perception.

The equal-tempered 12 note system has withstood much *avant garde* experimentation, is commercially exploited on a vast scale, and seems destined to occupy an important place in music for the foreseeable future. It is a practical benchmark, a reference system that captures, by relatively simple means — to a degree of approximation often adequate to the purpose — a large part of the pattern-creating potential that can interest the auditory human brain. Computerized keyboard systems that automatically perform context-dependent fine tuning,[155b] trying to replicate what skilful non-keyboard players do, are beginning to become available. But this interesting development, while potentially important for solo performance on keyboard instruments, seems unlikely to have any profound effect on the procedures of musical composition — particularly composition of the spiritually most important kinds of music, those performable by human musicians, with or without computer assistance but with scope for meaningful aural feedback. Bach would surely have been interested, but not much influenced.

¶¶The degree of closeness of the bare D to the B♭ harmonic series could also be thought of as something like the closeness, in the harmonic-series sense, of the two notes of a major third, if we are prepared to discount rather a large number of octaves. So there is some kinship — though I don't find it directly audible — with the standard move from the major tonic to an augmented sixth or to a major triad on the flattened sixth degree, e.g. the jump from the key of D major to the key of B♭ major. This too has the feel of a 'hyperspace move'. With suitable timing, it is the critical move at countless magic moments in classical music, such as the last fortissimo chord before the military-march episode in Beethoven's Ninth Symphony.

†††It may be noticed that my 'outrageous liberties' with the naming of chordal sonorities have extended to the musical notation as well. Conventionally, for a start, only the first 'French augmented sixth', at the higher F♯, would be named as such. The one immediately following would be described quite differently as an 'appoggiatura' or 'accented passing note' to C♯7. (Notice the continuing illustration of technique **(a)**.) The first chord would not be called a minor triad with added sixth, nor a half diminished seventh, but, rather, an appoggiatura (the top note) to the first French augmented sixth. The top three notes of the first chord would be rewritten (in upward order) as G♯, B♯, and E♯. This gives the theoretically knowledgeable score-reader — though not the listener — advance notice of the subsequent hyperspace move to C♯7.

What, then, is not arbitrary about the subdivision of the octave into 12 intervals, rather than some other number? This is the strangest story of all. What Bach and others recognized comes from a remarkable combination of arithmetical and psychophysical happenstances, a strange and wonderful gift from heaven, which does involve approximation but is no more arbitrary than physical principles and our genetic makeup. It has to do with the limits to harmonic and polyphonic complexity set by the finite pitch discrimination of the ear–brain system, together with a set of three numerical accidents, complete flukes of arithmetic, that sharply distinguish the 12 note system from all other equal-tempered systems coarser than 24 notes per octave.

The first accident, a truly breathtaking fluke, is the closeness of $1{:}2^{7/12}$ to $2{:}3$. As you can easily check on a pocket calculator, $1{:}2^{7/12} = 1{:}1.4983 = 2{:}2.9966$, almost exactly $2{:}3$. That is, the perfect fifth is approximated very closely indeed by its equal-tempered counterpart, within 2 cent or 2% of a semitone ($1200 \log(2^{7/12}/1.5)/\log(2) = -1.96$ cent). Because of octave similarity, the perfect fourth is likewise approximated within 2 cent. This is an extremely fine difference, close to being inaudible except by listening for beats, and far smaller than typical pitch fluctuations in even the most stringently controlled human performances. For a working musician it is practically the same as perfection. So the approximations of equal temperament are more than good enough to express the most crucial kinds of harmonic-series proximity beyond the unison and octave.

On top of that we have the second accident. It is is that 12 — the same 12 that generates the number $2^{7/12}$ — is a highly divisible number. This makes possible the translational invariance of diminished seventh chords already emphasized, corresponding to the divisibility of 12 by 4. Because 12 is also divisible by 2, 3, and 6, as well as by 12 itself, there are four more such translational invariances, giving a total of five classes of translationally invariant chords — bare tritones, augmented triads, diminished sevenths, and wholetone as well as semitone clusters. These are all usable, and are much used, in the kind of way just illustrated — an astonishing proliferation of ways of moving in musical hyperspace. They include the wild sounds of hyperspace moves through augmented triads, the headlong *Ride of the Valkyries* and its echoes in Dvořák's *New World Symphony* and in countless other places. They include the gentler hyperspace move that jazz musicians call 'tritone substitution', e.g. G7 followed by C♯7, another case of proximity to D dim7.

It is interesting to ask what other subdivisions of the octave might give remotely comparable results. If we ask what other subdivisions give at least as good an approximation to the perfect fifth and perfect fourth, we obtain only the subdivisions into 29, 41, 53, 58, 65... parts, in addition to the multiples of 12. We have $2^{(17/29)} = 1.5013$, $2^{(24/41)} = 1.5004$, $2^{(31/53)} = 1.4999$, $2^{(34/58)} = 1.5013$, and $2^{(38/65)} = 1.4996$. But 29, 41, and 53 are all prime numbers, hence barren of translational invariances, and 58 and 65 have only two prime factors, $58 = 2 \times 29$, $65 = 5 \times 13$, hardly fertile. The implication is clear: beyond the standard 12 note system, the next four serious candidates for equal-tempered systems that give access to well connected musical hyperspaces are all multiples of 12: the 24 note, 36 note, 48 note and 60 note systems, and those systems alone. It is difficult to imagine human pitch discrimination getting us much beyond 24, the quarter-tone system; and 24 is not nearly enough to make material improvements in fine tuning, because of the nature of the third accident, as we shall see in a moment.

So what is the third accident? It is that all the intervals that occur naturally in the harmonic series up to its tenth member, including the wide and narrow major and minor thirds, can be matched, to an approximation usually acceptable to the ear, by an equal tempered interval. Even though some of the approximations involved are audibly imperfect — which is why they have always been corrected for in the finest performances — those approximations are not, on the whole, drastically coarser than the ear–brain's typical pitch discrimination; and they are usually quite a bit better than in some of the more routine orchestral performances.

The worst approximations are those to the narrow minor third and the wide major second of intervals 6 and 7 of the harmonic series, with cycle-time ratios $6{:}7$ and $7{:}8$. The largest mismatch is 33 cent or a $\frac{1}{3}$ semitone, the narrow minor third being 267 rather than the equal-tempered 300 cent ($1200 \log(7/6)/\log(2) = 266.87$). Even this $\frac{1}{3}$-semitone difference, though easily audible, is not enough to spoil the musical sense of dominant seventh, minor triads, or Tristan chords when played on an equal-tempered keyboard.

Can we do any better, then, with finer subdivisions? An equal-tempered system of 36 notes per octave would provide accurate narrow minor thirds. But the wide minor third is 316 cent ($1200 \log(6/5)/\log(2) = 315.64$). So to make those accurate as well, along with the narrow major third of the simple major triad or common chord, one would need 72 notes per octave! I suspect that this will always be far beyond our aural capabilities, and that 12 notes per octave plus small corrections are here to stay.

Let us reflect once more, then, on how completely off target, how precisely the wrong way round it is to repeat the myth that the seventh member of the harmonic series is always 'too flat' and to think that 'in theory' one should adjust the seventh of a dominant seventh chord toward, not away from, the equal-tempered keyboard pitch — or, even worse, that it should form a traditional 'just', i.e. wide, minor third with the fifth. One only has to close the textbooks, and open one's ears as Purcell did,[150c] as Debussy did,[150a] and many, many others, including members of the world's great orchestras, bands, and chamber groups, to rediscover that the keyboard is the servant, not the master, of the exquisitely subtle human ear–brain system — as Bach well understood.

Note on 'atonality' [this probably wants shortening]: The word 'atonality' seems to be used in so many different ways, and with so many political undercurrents, that it may have outlived its usefulness. Avant-garde composers have always usefully jolted our imaginations. But they sometimes seem to claim, or at least seemed to claim, in the heyday of the mid-twentieth century Darmstadt school,[55] that Future Music Will be Fully Atonal, in the purist or extremist sense that is the most logical sense of the word atonal. This means, or logically should mean, making no use whatever of harmonic-series proximity, or, rather, suppressing all aural reference to the harmonic series and associated patterns apart from the octave. There must be, it was held, no hint of 'tonality': ideally, no glimmer of harmonic colour, and certainly no reliance on any kind of harmonic function. This of course is difficult to take seriously except as a kind of politics or psychological warfare on the one hand, or as a composers' exercise on the other.

It is surely interesting, as an exercise, to try to write atonally in this purist sense, despite the implied restriction — a drastic restriction — on the motion in musical hyperspace. To make the result interesting to the musical ear–brain system is therefore, indeed, a considerable challenge. Because strictly atonal music in this sense has to function with no reliance on pitch relations beyond melodic contour — on motion in the height dimension only — it could be said to be a bit like poetry or prose that avoids the use of verbs, equally an interesting and challenging exercise for a composer of literature or, for the visual artist, drawings in which all lines are to be straight and vertical, or, for the dancer, staying on one spot, with only vertical motion allowed.

One way to make fairly sure of such strict atonality is to write music for instruments none of which produce a clear single pitch, as with some arrays of percussion instruments. Another, it might be thought, would be to use a non-standard scale deliberately chosen to be barren of translational invariances, i.e. in which the octave is divided into a prime number of equal intervals, say 5, 7, or 11. However, the likely result then would not be pure atonality but a restricted tonality, like many kinds of folk music. Whatever the composer's theory or manifesto, the ear-brain system will fit harmonic-series subsets to the incoming acoustic data, to whatever extent it can, as must surely happen with the (wonderful, I think) sound from a gamelan orchestra. A real and interesting musical effect is the tense feeling, and special tone-colour, of intervals that audibly stretch or compress harmonic-series intervals. Ordinary bell sounds involve just such colours. (So too, in a subtler way, do the sounds of the piano — not only because it is tuned in equal temperament with compromise major and minor thirds, but also because it has freely vibrating strings whose overtones are very slightly sharper than the members of a harmonic series — a feature that has been shown, moreover, to have a positive impact on the perceived character of piano sound.[155c])

A third and surer way, for the true purist, is the composer's exercise to try to write something interesting using a single note only, say 440 Hz A, and its octave translations. This makes quite sure of imposing a rigorous and drastic restriction of motion in hyperspace. A fourth way is to sound all notes at once all the time, to write music in maximal tone-clusters, or at least in textures sufficiently dense in spacetime as to guarantee adherence to the Schoenbergian ideal of strict equality of all 12 notes. Filling, or saturating, the harmonic dimensions of hyperspace is another way to make sure that there is no harmonic color or motion; and some composers have achieved striking effects in this way. This is the Schoenbergian ideal taken to its most rigorous logical conclusion (as distinct from Schoenberg's actual music, a different thing altogether, and far more interesting).

As the reader will realize, I am putting things in this outrageously strawmanlike way to expose what I think is the absurdity of the notion of strict atonality, taken literally to its logical extreme — to say nothing of the still greater absurdity, and pretentiousness, of purporting to predict the course of Future Music. Such ideas are taken less and less seriously today. I have even noticed respected composers of 'serious' music daring to use the word 'harmony' in public, with no implicit frown of disapproval. What was, and is, taken seriously is that there was, and is, every reason to look for freedom from 'tonality' in what might be called the Beckmesser sense, the very restricted sense of demanding that the music be in a definite 'key' most of the time and that the composer obey strict 'rules' — here is where culture and politics again come in — rules such as having to end in the same key as you started in, or having to exclude certain cases of organic harmonic change that use technique **(b)**. Such rules are indeed, to a considerable extent, arbitrary, and they, too, restrict the motion in hyperspace, though not nearly so much as the pure atonalist's rule forbidding all harmonic motion. Today is a wonderful time for anyone interested in contemporary music. More and more of today's music moves rather freely in hyperspace, some of it in interesting and exciting ways, just as most of today's best literature uses, I think, verbs in interesting and exciting ways, and drawings and paintings use lines and curves with more than one orientation, and dancers make us airborne.

59. Goehr, A., 1990: Music as communication. In: *Ways of Communication*, ed. D. H. Mellor. Cambridge, University Press, 165 pp., 125–142. Alexander Goehr, one of our leading and most highly respected composers, has reminded me that in music and the other arts one has to include 'becoming coherent': there are many examples of musical 'shapes emerging from a... metaphorical mist'. His essay discusses

this and other aspects of musical composition including aspects of the perception of music, and of the uses and associations of music in our own and other cultures.

60. Mozart, W. A., 1787: *A Musical Joke*, K.522. Mozart's light-hearted dig at unskilful amateur composers and performers provides, among other things, examples of musical gratuitous (pseudoelegant) variation, such as the gratuitous modulation or key change at bars 37–8, and the gratuitous change in harmonic colour on the second beat of bar 38. (Refs. 151 discuss, with profound musical insight, the use of modulation and colour in ways that are anything but gratuitous.)

61 The basic techniques are care over first-occurrence signposting (Appendix 1) and sufficient repetition of phrases that tie verbal to mathematical symbols (such as 'the potential energy P'). Such precautions — and generally being more explicit than the writer thinks necessary — can reduce, even if not eliminate, the chances of the words and symbols being used inconsistently.

Mathematical notation can be chosen to minimize gratuitous variation and Stroop interference.[32,16] The reader who thinks that such things are unimportant should remember Littlewood's remark about Jordan.[16]

A colleague of mine, Professor J. D. Woods, hit on a wonderful idea to make climate and energy problems more vivid to financiers, civil servants, and politicians. Instead of quoting the Sun's irradiance in watts per square metre — it is about 340 of those units, averaged over the Earth's surface — he quoted it in megawatts per square kilometre. The unit and the number are the same, 340 megawatts per square kilometre, but the connections in the listener's brain can be very different. References 35, 36, and 62 give further telling illustrations, the first two from scientific experimentation and the third from business experience.

62. MacNeal, E., 1994: *Mathsemantics: Making Numbers Make Sense.* New York, Viking Penguin, 310 pp. A businessman's plea, based on harsh experience with staff recruitment in the USA, not only for numeracy but also for numeroliteracy or, as he calls it, 'mathsemantic sophistication': the elementary aspect of lucidity that demands the consistent use of words and numbers, including clarity and verbal explicitness, and consistency, about *what* you are counting or measuring. The author uncritically accepts the Korzybski–Sapir–Whorf hypothesis and should therefore be read in parallel with Pinker;[12] but that is not fatal to the main message, which is that the artificial separation of numeracy and literacy is one of the ways in which nations damage themselves educationally, economically, and also politically through camouflage and deception by numbers — if you agree that the weakening of democracy counts as damage. The book points to known and tested educational countermeasures, referring to work by Constance Kazuko Kamii and collaborators on techniques that successfully use juvenile play to build a solid understanding of numbers and arithmetic.[238]

63. Weinberg, S., 1993: *Dreams of a Final Theory — the Search for the Fundamental Laws of Nature.* Vintage Books, 260 pp. This is one of the most eloquent and cogent non-specialist discussions I have read on just how far we have come in physics by using the power of mathematics — using the requirement for self consistency in model building together with the strongest form of Occam's razor: the assumption, or faith, that the relevant simplicity includes aesthetic considerations of elegance and beauty. See also Ref. 268. The author also reveals how deeply embedded is the inclination, in some of our most brilliant physicists' minds, to make an absolute distinction between 'mere models' and 'true theories', as opposed to a judgment of the goodness of of a model or theory in terms of its accuracy, beauty, economy, insightfulness,[293a] etc.

64. Klauder, J. R., 1972: *Magic without Magic* (John Archibald Wheeler Festschrift). San Francisco, W. H. Freeman. See page 482; the quotation about genius is attributed to Wheeler.

65. Masters of writing occasionally, for exceptional reasons of rhythm or euphony, use what would otherwise be gratuitous variation. An example — it is quite hard to spot — can be found within Strunk and White's[10] paragraph under the heading 'Omit needless words', p. 23 in the third edition. A discussion of this example can be found in `lucidity-supplem.txt`[8]: string search 'Masters'. For the rest of us, it is still wise to play safe!

66. Gratzer, W.: 'Usage and abusage', *Nature*, 1983, **306**, 134. A review of Fowler Two[11] and an appeal for its wider use. Gratzer gives one of the reasons for indicating, explicitly, the sense of crucial technical terms at their first occurrence. This is necessary if only because, as he reminds us, '... words with a precise technical meaning escape into the outside world, are mangled by journalists and politicians, and are then received back' [by scientists!] 'in their new and perverted sense.' It is all part of the inexorable process of language evolution,[12] the biological reasons for which are touched on in Part III (`lucidity3.ps`). (A good illustration is the term 'symmetry breaking'. Nowadays this is often used in a trivial sense: becoming asymmetric because the externally imposed conditions are made asymmetric. The original, non-trivial sense is almost the opposite: becoming asymmetric despite the externally imposed conditions being symmetric. The original sense actually makes sense, the externally imposed symmetry being the thing that is 'broken'. Symmetry breaking in this second, non-trivial sense now has to be called "spontaneous symmetry breaking" — at first occurrence at least — because of the trivialization of the original, shorter term.)

67. Ziman, J. M., 1968: *Public Knowledge: the Social Dimension of Science.* Cambridge, University Press, 154 pp. A perceptive essay about the nature of scientific knowledge and about the indispensable role of communication, including lucid writing, in establishing that knowledge. Gives a good explanation of the 'diplomatic we' of scientific writing, the use of 'we' in the sense of 'you and I, dear reader' — not to be confused with the 'incongruous royal we' in which a single author refers to himself or herself only, as in Queen Victoria's 'We are not amused.' The 'diplomatic we' is typified by 'We use the idea of such and such...' (because the reader as well as the writer will use the idea, or so it is hoped), or again by 'Adding x to both sides of the equation, we obtain.....' (because the reader is expected to be able to do it too). The quite different 'incongruous royal we' is typified by 'We took the first 100 samples on the first day' (if one person took the samples). Such incongruities may come from the mavenly[12] condemnation of the passive voice, to give in to which would be like tying one hand behind your back. The passive voice, as in 'The first 100 samples were taken', is a perfectly good solution here. There is also a mavenly condemnation of the active voice. But we — you and I, dear reader — can, if we wish, adopt a craftsmanlike attitude that omits needless words and avoids egotism, yet keeps both hands free.[69]

68. Crystal, D., 1995: *The Cambridge Encyclopaedia of the English Language* London, BCA, by arr. with Cambridge University Press, 489 pp. A vast, lavishly illustrated, up to the minute and stylistically eclectic compendium, full of practical insight and interesting background information, and with much useful cross referencing. See for instance pp. 225, 231–2, and 373 for handy summaries, succinctly illustrated, of some of the writing techniques for variety without muddiness and for connectivity between sentences. Especially useful are the many examples bringing out the importance of word patterns and their functioning, and the overwhelming importance of context. For instance p. 161 has a large diagram showing at a glance the present-day 'collocational range', or cloud of possible usages and associations,[7] of the word 'line'. There are 'nearly 150 predictable contexts..., which can be grouped into 30 or so senses', highlighting the ambiguity of the word 'line' when removed from the word pattern and context it is used in, e.g., 'high-voltage line', 'brought into line', 'what line to take', etc.

69. Freedom to use either the active or the passive voice of a verb, as appropriate, is important for more serious reasons than avoiding the 'incongruous royal we',[67] which though mildly absurd does little harm. Careful choice of active or passive can be important for controlling rhythm and emphasis, e.g., to emphasise, or not to emphasise, the doer or the object of the doing. Such choice can also be important for controlling word order in the interests of lucidity. It is usually safest to put a pronoun close to its antecedent, the condition violated in Example 2′ above. Therefore the antecedent, the noun or other noun-like entity to which the pronoun refers, might need to occur late in the preceding clause or sentence whether or not it represents a doer. (I have sometimes thought that a significant aid to lucid writing might be a 'smart' word processor that could make the words 'this' and 'these' — the most dangerous pronouns because of their wide reach, hence scope for ambiguity — flash quickly, or turn bright red, on the screen unless followed immediately by a noun or noun phrase that turns the pronoun into an adjective. Pronouns like 'it', 'they', 'them', 'their', 'none', etc., could perhaps flash a touch more slowly. This flashing of pronouns can usefully, in any case, take place in the writer's mind.)

70. Warwick, K., 1997: *March of the Machines: Why the New Race of Robots will Rule the World.* London, Random House (Century Books), 263 pp. The book asserts, with prodigious assurance, that manmade computers now have the brainpower of insects, will soon be comparable to cats, and will definitely have overtaken humans by about the middle of next century. I find this prediction grossly implausible, if only because it seems to ignore what is already known about biological systems, including the unimaginably complex systems called insects. The assumptions seem to be that intelligence is the same thing as raw computing power and that real neural networks are like artificial neural networks in every respect, in other words that real neurons or nerve cells are equivalent for this purpose to simple logic gates. Such an assumption ignores the massively parallel nanocybernetics[2–4,71] of the billion (10^9) or more protein molecules within the dendrites, body, axon, and synapses of a single neuron. (The neurons themselves, in the human brain for instance, number between 10 and 100 billion by most estimates; so we are talking about nearly 10^{20} protein molecules in all, many of which are themselves logic gates.) See also Ref. 7 for an important independent critique of estimates of the kind in question, on purely computational and cognitive grounds.

71. Kauffman, S., 1995: *At Home in the Universe: The Search for Laws of Self-Organization and Complexity.* New York and London, Viking Penguin, 321 pp. This passionate, penetrating, and well informed essay is about our world of 'stunning biological complexity', where 'cells interact with cells to form organisms; organisms interact with organisms to form ecosystems, economies, societies' — emphasizing the power yet incompleteness of the traditional Darwinian theory and using modern molecular biological knowledge to the full, referring especially to the arbitrariness, or freedom, of protein logical and computational functionality, and its self organizational abilities. This same freedom, also emphasized and explained by Monod,[3] lies at the heart of the 'nature–nurture' dynamic. Kauffman provides cogent reasons why a deeper understanding of, and respect for, such complex systems can be hoped for in the very near future, along with many practical spinoffs such as new weapons against the new disease epidemics; it is a question of putting hypermassive parallelism to work to solve combinatorially large problems.

72. Part I, i.e. pp. 1-16 of this Internet version, `lucidity.ps`

150. Piston, W., DeVoto, M., 1978: *Harmony*, 4th USA and 2nd UK edn. Norton, Gollancz, 594 pp. A beautiful textbook, explanatory rather than prescriptive, and firmly based on cogent illustrations from a broad cross-section of great music from the eighteenth to the twentieth centuries, including some references to jazz as well as to Debussy and Stravinsky (though, surprisingly, not to Nielsen). I am indebted to Andrew V. Jones (personal communication) for confirming that the opening of *Tristan und Isolde* is usually analyzed as it is on pp. 364 and 421 of this book, presuming that the key is A minor in the original, equivalent to F♯ minor in my transposition.

150*a*. Platt, P., 1995: Debussy and the harmonic series. In: *Essays in honour of David Evatt Tunley*, ed. Frank Callaway, pp. 35–59. Perth, Callaway International Resource Centre for Music Education, School of Music, University of Western Australia. ISBN 086422409 5. This is a beautiful discussion, with detailed examples, of some of Debussy's far-reaching innovations. These amounted to recognizing the perceptual importance of the harmonic series and its subsets, with no arbitrary restrictions on the choice of subsets. Debussy thereby opened up a huge range of possibilities not only for new chordal sonorities and note-sequences but also for new forms of powerful, continuous harmonic motion — going far beyond Wagner in both respects — including many examples using what I called 'technique **(b)**', parallel motion of an invariant chord shape. Platt also gives an insightful comparison with aspects of Indian classical music and its styles of organic change. See also Thomson, W., 1991: *Schoenberg's Error*. Philadelphia, University of Pennsylvania Press, 217 pp. Platt quotes this 'controversial but insightful' book for its idea of the harmonic series as an ever-present 'template'.

150*b*. E.g. G. B. Henning, 1970, 1971: A comparison of the effects of signal duration on frequency and amplitude discrimination. In: Frequency Analysis and Periodicity Detection in Hearing, pp. 350–361, ed. R. Plomp and G.F. Smoorenberg, Leiden, Sijthoff, 482 pp. [The years 1970 and 1971 are given on the title and copyright pages respectively.] See also p. 260–263 of Green, D. M., 1976: *An Introduction to Hearing*. New York, Wiley, 353 pp. The relation between duration and frequency discrimination is not simply Heisenbergian, though approximately so in a limited range.

150*c*. What I am calling the sonority of the Tristan chord occurs more than thirteen times in *Dido's Lament*, which was probably written around 1683. Thirteen occurrences can be counted on p. 71 of the score published by the Purcell Society (ed. Margaret Laurie and Thurston Dart; p. 177 of the Norton re-issue). The remarkably persistent use of this particular sonority at a slow tempo, and the scoring for voice and strings only — the continuo keyboard is directed to be silent — suggest that Purcell's fine ear must have anticipated Debussy's[150a] in noticing the subtle beauty of the sonority *when accurately tuned*, as well as its aptness in a harmonic scheme for conveying tragedy and pathos, along with the various related sonorities and other devices: passing notes, appoggiaturas, suspensions, and so on, all used to achingly poignant effect. Accurate tuning, requiring as it does the narrow minor third at nearly every moment of the aria (cycle-time ratio 6:7), is in conflict with all the practical keyboard tuning systems that Purcell might conceivably have used — be it just, mean-tone, or equal-tempered, or other compromise accommodating major triads as all keyboards must. I am grateful to Andrew V. Jones for help with this example and for advice as to the authenticity of the published score.

One might count as a fourteenth occurrence, in bar 22 on p. 71 (Norton p. 177), a C minor 6 lightened by omission of the note G. It sounds very similar to, and functions in the same way as, several earlier occurrences of the full sonority, as the 'IV(II)' stage of a 'IV(II)–V–I cadence' in the notation of Piston and DeVoto.[150] (On the notation IV(II), see their discussion on p. 359.) This fourteenth occurrence is reminiscent of the first bar of the Mozart Clarinet Quintet extract quoted above, whose second half uses a similarly lightened D minor 6 sonority (A omitted) functioning in just the same way, as a IV(II) subdominant, and making an effect of supreme beauty when accurately tuned. Not surprisingly, there are countless examples of sonorities like these in the music of J. S. Bach.

151. Simpson, R., 1970: *Beethoven Symphonies* (Music guides, British Broadcasting Corporation), re-published by London, Ariel Music, 1986, ISBN 0 563 20484 2, 62 pp., and Simpson, R., 1979: *Carl Nielsen, Symphonist*, revised and expanded edition with an added chapter on 'Sibelius, Nielsen, and the Symphonic Problem', London, Kahn and Averill, 260 pp. Both books are about great symphonic music seen as architecture in musical hyperspace, more aptly spacetime. They well illustrate 'the importance of finding a coherent order of presentation' in which 'each new point is preceded by any necessary preparation'. The technically simplest, and breathtakingly simple, example of the powerful architectural use of 'hyperspace effects' is Beethoven's Seventh Symphony.

152. Cross, I., 1997: Pitch Schemata. In: *Perception and Cognition of Music*, edited by J. A. Sloboda and I. Deliège, Hove, UK, Psychology Press, 357–390. An erudite summary of recent efforts to relate psychophysical to music-analytical studies, noting some of the past and current approaches to defining what I am calling 'musical hyperspace'; see also, for instance, the early paper by Bachem, A., 1950: Tone height and tone chroma as two different pitch qualities. *Acta Psychol.*, **7**, 80–88, which, however, confined itself to noting the perceptual near-identity of octaves; thus 'chroma' was conceived to be the quality of musical pitch that is almost the same for two notes an octave apart.

153. Moore, B. C. J., 1997: An introduction to the psychology of hearing, 4th edn. London and San Diego, Academic, 373 pp, esp. chapters 5 and 7. This is an up to date review of present-day knowledge

from psychoacoustics and auditory neurophysiology. On harmonic-series proximity, see also the early experimental and theoretical contribution by:

153*a*. Boomsliter, P. C., Creel, W., 1961: The long pattern hypothesis in harmony and hearing. *J. Mus. Theory* (Yale School of Music), **5**, 2–31. Apart from one slight lapse where the authors forget the context-dependence of tonal 'major–minor' distinctions, this is an outstandingly cogent, lucid, and succinct discussion of the early experimental evidence and biological arguments pointing to temporal correlation and near-synchrony in trains of nerve impulses as, very probably, the primary mediator of harmonic-series proximity and of musical harmonic function in general. They point to the long known ability of the auditory brain to make fine time discriminations for other purposes such as directional hearing, and to the stability of our perception of simple musical intervals whether presented melodically, in successive notes, or simultaneously, and many other telling points, supported by some beautiful psychophysical experiments.

153*b*. Tversky, A., 1977: Features of similarity. *Psychol. Rev.*, **84**, 327–352. This cogently makes the case, supported by many telling examples, that perceptual similarity does not often behave as distance in the strict metric sense.

154. Shepard, R. N., 1982: The structural representation of musical pitch. In: Deutsch, D., *Psychology of Music*, Academic, 344–390. For the suggestion of a 7 dimensional pitch-perceptual space, see p. 365. See also, however, Ref. 153*b*.

154*a*. Krumhansl, C. L., 1990: Cognitive foundations of musical pitch. New York, Oxford, Oxford University Press, 307 pp. See p. 130 for experimentally established examples of 'X similar to Y' not being equivalent to 'Y similar to X'; these are cases in which the order of presentation of two pitches in a given tonal context had an influence on judgements of similarity, just as might be expected from ordinary musical experience, in which certain harmonic gestures point strongly to particular parts of musical hyperspace. So, when using spacelike metaphors, one has to remember these pointing arrows, like the gestures of dancers moving in physical space, reminding us that more than simple 'distance' is involved. See also the very apt general remarks in Ref. 153*b*. I am grateful to Ian Cross for drawing my attention to these references.

155. McIntyre, M. E., and Woodhouse, J., 1978: The acoustics of stringed musical instruments. *Interdisc. Sci. Rev.*, **3**, 157–173. The timescales, of the order of tens of milliseconds, on which 'vibrato' is effective are intermediate between vibration cycle timescales and long-pattern timescales. (Here time*scale* means about a sixth of a vibrato period, because $2\pi \simeq 6$.) The timescale-dependence and the surprisingly large frequency excursions during vibrato — it is always startling to hear a recording of violin sound at half speed or less — has implications for the brain's pitch perception mechanisms. One implication is that pitch perception cannot be equivalent to simple spectral or Fourier transformation. This discourages expectations of a precisely Heisenbergian pitch-uncertainty relation. A more interesting implication is that the brain must be extremely flexible about accommodating temporary asynchrony over intermediate timescales. Some kind of elasticity, time integration, or temporary data cache must be involved.

155*a*. Taruskin, Richard. Interview in a programme about the origins of Stravinsky's *Rite of Spring*, on BBC Radio 3's *Sunday Feature*, 3 October 1999. Also discussed was the origin of the idea for the *Rite*. The idea appears to have been suggested to Stravinsky, courtesy of Diaghilev's network of contacts, by the Russian artist and archaeologist Nikolai Konstantinovich Rerikh (Roerich).

155*b*. Boomsliter, P. C., Creel, W., 1962: Ratio relationships in melody. *J. Acoust. Soc. Amer.*, **34**, 1276–1277. This briefly reports on careful and systematic psychophysical experiments with musically trained subjects, showing that skilled musicians playing variable-pitch instruments do not tune to a fixed scale — even when playing simple monophonic melodies in a single key. Rather, a given nominal note tends to be given slightly different tunings that depend on where it occurs in the melody. Thus the old question 'which scale do musicians prefer' is exposed as a classic case of asking the wrong question.

It is only recently that computer technology has made context-dependent fine tuning possible in practical keyboard instruments, three centuries after Purcell[150c] and a third of a century after Boomsliter and Creel's paper. Such keyboard instruments began to be commercially available in 1997 (e.g., `http://www.justonic.com`), though I have not yet had an opportunity to hear the results.

155*c* Blackham, E. D., 1965: The physics of the piano. *Scientific American*, December issue, p. 88. Reprinted in *The Physics of Music*, San Francisco, W. H. Freeman, 1978.

156. Maddox, J., 1995: The prevalent distrust of science. *Nature*, **378**, 435–437. Maddox tells of a distinguished architect who said at dinner 'I suppose you must be one of those frightful darwinists', representing the feeling that scientific understanding 'could only undermine people's sense of their own dignity and self respect, and sap their will to aspire to better things.' It seems that, to many thoughtful and intelligent people, the word 'darwinism' not only labels a tribal creed but is also understood to *mean* the 'nature only' or 'brutal biological determinism', branch of the false 'nature–nurture' dichotomy, pitting nature against nurture as if it had to be one or the other. This is often taken to be synonymous with the 'selfish gene' metaphor. See also the discussion of the 'standard social science model' in Chapter 13 of Ref. 12. (My personal, and I believe, strong answer to the architect's question is in Part III (`lucidity3.ps`), in the sections 'Respect and humility' and 'An optimist's millennium'.)

157. Postgate, J., 1996: Public 'understanding', did you say? *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Autumn 1995 issue, 8–10. Some positive thinking about 'bizarre and muddled' newsmedia images of science, reflecting the predictable 'backlash' from scientists' efforts to improve public understanding of science. But 'it means that science is at last being talked about, even thought about.'

158. Potts, M., 1993: Unmet demand for family planning. *Interdisc. Sci. Rev.,* **18**, 103–111. Gives hard evidence for the unmet demand, and 'the remarkable fact.... that fertility has fallen in a number of developing countries two to four times as rapidly as it did in the West at a comparable stage of the demographic transition'. See also: Perutz, M., 1993: The fifth freedom. *Europ. Rev.,* **1**, 243–248, and Hagenfeldt, K., 1994: Current status of contraceptive research and development. In: *Population — The Complex Reality: A Report of the Population Summit of the World's Scientific Academies* ed. Graham-Smith, F., 271–285. London, Royal Society; Golden, Colorado, Fulcrum, North American Press; 404 pp. This last paper finds that population control is a case in which market forces have had a clear negative effect. During the period 1965–74 of a review sponsored by the Ford Foundation, for instance, support by the pharmaceutical industry for research on improved contraception methods was 'cut by more than half', from 34% to 16% of the total support, 'apparently as a result of the revised assessments of the potential profitability of new contraceptive methods'.

160. Davies, J., 1996: Bacteria on the rampage. *Nature*, **383**, 219–220. This is one of many news reports on MRSA (methicillin-resistant *Staphylococcus aureus*) and other emerging 'superbugs' showing resistance to increasing numbers of antibiotics. Such resistance, now spreading both inside and outside hospitals, a natural result of the profligate use of antibiotics, can be passed from one bacterium to another in genetic packages called plasmids. Davies reminds us that 'The breakdown of public health measures due to famine, poverty, and war contributes to the dissemination of resistance,... compounded by the growth of international travel...' and, it might fairly be added, accelerated by market forces.[172] See also Notes 132 and 276 of Part III[411], and:

160*a*. Barker, Rodney, 1997: *And the Waters Turned to Blood: The Ultimate Biological Threat.* Simon and Schuster, 352 pp. ISBN 0684831260. A single cell organism, *Pfiesteria piscicida*, has recently destroyed fisheries in the Chesapeake Bay region of the USA and made the water too dangerous for humans to swim there. It is suspected that this sudden development, thought to be unprecedented, was an adaptation triggered by the buildup of chemical pollution, perhaps destroying whatever the organism used to feed on. If confirmed, this would illustrate what is self evident, in any case, from the slightest knowledge of biological systems, namely that when you change an environment then you must expect to see evolutionary adaptations of one kind or another.

160*b*. The evolution of transmissible spongiform encephalopathies, such as bovine spongiform encephalopathy (BSE or mad cow disease), counts as another example, if you count unnatural cattle foodstuffs as 'pollution' in the relevant sense, that of exerting new selective pressures on disease agents.[160a]

161. Fern, Y., 1994: *Gene Roddenbury: The last conversation — a dialogue with the creator of Star Trek.* University of California Press, 228pp. Makes an eloquent case for the role of science fiction in helping with the public understanding of science. Reviewed by L. J. Sage in *Nature*, **372**, 141. Roddenbury and his character Spock 'take a positive delight when someone says "I disagree with you because..." ' — the delight of serious discussion and argumentation with no thought of personal rancour, with no thought other than to get a problem solved. (This for me is exactly what makes life as a scientist worth living.)

162. Rees, M. J., 1997: *Before the Beginning: Our Universe and Others.* London, Simon and Schuster. 282 pp. One of today's most respected scientists discusses, with great insight and lucidity — and marvellous succinctness — what we know, what we do not know, and what it might be well to know, about the world we live in especially in its smallest and largest scale aspects. Any thoughtful person reading this book will see why giving up the pursuit of such knowledge would be a dangerously head-in-sand attitude. The book also shows, perhaps more clearly than any other I have read, how to use the working scientist's shorthand terms 'proof', 'decisive evidence', 'fact', 'truth', etc., in plain and simple ways that respect the scientific ideal. Indeed it shows just what respect for the scientific ideal means in practice: both its astonishing power to advance our understanding of the world we live in through experiment, observation and appropriate theorizing or model-fitting, and also, equally, the implied respect for the limitations of science and humility in the face of the unknown.

163. Martin, B., *et al.*, 1996: *The Relationship Between Publicly Funded Basic Research and Economic Performance — an SPRU Review: Report prepared for HM Treasury by the Science Policy Research Unit at Sussex University.* London, Her Majesty's Treasury. Obtainable via 0171-270-4558, fax 0171-270-5244, £2.50. The terms of reference were to review the literature on the relation between basic research and economic performance (same question as from science minister Ian Taylor earlier in 1996: 'What does Britain gain from... money spent on funding basic research?'). The report points out that 'current methodologies for measuring such benefits are seriously flawed', and why. For instance, beyond published output, 'Research is also a learning process, yielding "tacit" knowledge in terms of the skills and routines without which it is not possible to make use of state of the art ideas and techniques.'

164. Keats, John, 1817: *On First Looking into Chapman's Homer.*

165. E.g. Popper, K., 1966: *The Open Society and its Enemies*, vol. 2, 5th edn. London, Routledge and Kegan Paul, 420 pp. On Hegel and Heidegger, see pp 76–77. On Heidegger's 1933 inaugural Rector's Address to the university community in Freiburg, see also the discussions in Allan Bloom's book *The Closing of the American Mind*, p. 311, and in Gross and Levitt[200], p. 77. Bloom is quick to point out that the phenomenon is not peculiar to the former Nazi Germany.

166. Sagan, C., 1996: *The Demon-Haunted World: Science as a Candle in the Dark.* London, Hodder Headline/Random House, 436 pp. Chapter 6 gives a clear summary of the evidence concerning the commonplace perceptual phenomenon called hallucination. Chapter 24 on medieval witch hunting was written in collaboration with Ann Druyan. It includes an extensive quotation from Friedrich von Spee, who dared to publish a clear and explicit exposé of witch mania and its amplification by market forces, the *Cautio Criminalis*, in 1631. The basic procedure was to induce self-incrimination through torture of a victim selected at random, a state of things made possible because of hypercredulous belief, a phenomenon clearly recognized by von Spee: 'No longer God or Nature, but witches are responsible for everything.' More recent examples include the McCarthyism in the USA of the 1950s — 'communists are responsible for everything' — and, with apt irony, the Cultural Revolution in communist China.[171] The process may self-limit when too many of the hunters become the hunted, but, typically, only after terrible devastation.

167. Meticulous and laborious work on paleoclimatic isotope and other records for the past 150 millennia or more is being described in a burgeoning literature, showing the glacial climate fluctuations at ever improving time resolution and in an increasing number of ways, especially in ice core records over the last few tens of millennia. Particularly striking is the evidence in Thompson, L. G., *et al.,* 1997: Tropical climate instability: the last glacial cycle from a Qinghai–Tibetan ice core, *Science*, **276**, 1821–1825. This core from the Guliya ice cap shows persistent oscillations of about 200 year period whose large amplitude suggests drastic fluctuations in the Asian monsoonal circulation. With a timescale for significant change of the order of 3 decades ($200\,\text{years}/2\pi$), we are again looking at large changes within an individual's lifetime. The oscillations studied in detail — about 100 of them in more or less continuous succession — occupied a time interval centred on about 28 millennia before the present. So if one human generation took 20 years or less, then at least 1000 generations of humans would have been subject to ceaseless environmental fluctuations over this period alone. Further back, the time resolution to see such oscillations has not yet been achieved, but it seems reasonable to assume tentatively that significant portions of the 2 million years of the Pleistocene would have been similar, if we recall the far longer timescale, tens of millions of years, for plate tectonics hence gross geographic change. The Guliya climate oscillations remind us that the love of storytelling, so deep-rooted in us today,[293,304] could well have been an important aid to a tribe's long term memory across the generations, including the memory of past climate oscillations and information about how to survive them. See also:

167*a*. Bond, G., *et al.,* 1993: Correlations between climate records from North Atlantic sediments and Greenland ice, *Nature*, **365**, 143–147, & refs. therein to celebrated work by Dansgaard and Oeschger ('Rates of change in... ocean temperatures must have been... several degrees within decades' in the North Atlantic region). See also, for instance, Severinghaus, J. P., *et al.,* 1998: Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice, *Nature*, **391**, 141–146. This shows very clear evidence from a Greenland ice core, obtained using a new technique, for a step-like temperature rise 'in less than a decade', of magnitude tentatively estimated at 5–10°C, marking the end of the so-called Younger Dryas cold interval 11.6 millenia ago. This event appears to have been the last abrupt warming before the climate became relatively settled around 10 millennia ago. [In the geological literature, 'before present' means before 1950, by convention; timing accuracies are not yet quite good enough for this to matter very much.] I am grateful to Nicholas Shackleton for expert advice on these matters.

168. Creolization, remarkable though it is, need not surprise an observant parent. English children when small will tend to say 'I keeped mouses' before learning to say 'I kept mice'. It is not syntactic function and syntactic coherence that young children have to learn from the language they hear around them. Rather, what they have to learn are the irregularities of the language, the culturally determined departures from coherence, at the level of superficial patterning. Creolization,[12,286b] also-called nativization, is, as already said, the creation of a new, syntactically complete, coherent and consistent language by a single generation of children up to 6 or 7 years of age. It happens under certain rare social conditions in which there is no linguistic input from adults beyond, at most, a syntactically incomplete, incoherent and inconsistent 'pidgin' such as that resulting from improvization by migrant adults forced into a Tower of Babel situation — or even, in a recent, uniquely clearcut and well documented case in Nicaragua, practically no adult input at all.[286b] This last occurred with sign language, after the change of government in 1979 brought deaf children together for the first time in State schools after long social isolation from other deaf people. In this case the result was two new sign languages, the prior absence of which is well documented:[286b] first, a pidgin-like sign language created by children over 7 years or so, syntactically inconsistent and highly unstable and variable, and second, a creole-like sign language, syntactically complete, coherent and consistent, now displacing the pidgin. It is clear that this second sign language was created by the children younger than about 7 years, responding to the stimulus of the older children's pidgin.

169. For information about the commercial, legal and political battles involving scientific issues, see almost any issue of *Science* or *Nature* in the 1990s and, for instance, the Spring 1997 issue of *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science). Also, especially, Ref. 198. One battleground, global environmental change, where I have some specialist knowledge of my own, can be glimpsed through Ref. 318 and independently through the news items and correspondence in, for instance, *Nature*, **381**, 639, **382**, 665, and **386**, 131–133, 164–167. On the scientific uncertainties about global environmental change, including sea level change, see e.g. the recent book by Schneider[310] as well as the 1995/6 IPCC report.[342] I agree with Schneider's remarks on p. 156 about the 'conflict, frenzy and distortion' resulting from conflation, by the newsmedia and others, of scientific with commercial, legal and political questions, and further complicated by the espousal of scientific crankishness by the newsmedia.[203,297] I also agree with him about (*a*) the very high uncertainty in our present conceptual and numerical models of global environmental change, (*b*) the possibly serious and potentially catastrophic consequences of such change, and (*c*) the 'outrageous' yet widely reported public claims by a few scientists that (p. 154) 'their special knowledge of the future allows them to know with high certainty something virtually everybody else in the expert community disputes: that the probability of any non-negligible outcomes' of anthropogenic global change 'is virtually zero'. This again is the driver on the foggy road 'who shuts his eyes and blocks his ears and claims infallible prior knowledge' of what lies ahead. Cases of powerful newsmedia support for such irresponsibility are documented in Ref. 318 and in Avery, S. K., Try, P. D., Anthes, R. A., Hallgren, R. E., 1996: An open letter to Ben Santer. *Bulletin of the American Meteorological Society* (Boston, MA), **77**, 1961–1966 (September 1996).

170. Our closest living nonhuman relatives, the chimpanzees, have been observed to go to war in the sense that, when living freely under natural conditions, one small community of chimpanzees exterminated another and took over their territory. See Chapter 10, 'War', of Goodall, Jane, 1991: *Through a window: My thirty years with the chimpanzees of Gombe*. Boston, Houghton Mifflin, 268 pp.

171. More recent examples of the same (witch hunting) behaviour pattern include those recorded in eyewitness accounts of the Chinese Cultural Revolution of the mid-1960s, as documented for example in David Hinton's BAFTA-award-winning television documentary *Children of the Revolution* (BAFTA = British Academy of Film and Television Arts).

172. Consider for instance the power of unregulated market forces in driving not only the profligate use of antibiotics but also, at the same time, the explosive growth of prostitution in Russian cities and elsewhere, providing fertile ground for the spread and rapid evolution of today's and tomorrow's dangerous viruses and bacteria.[160] For instance medical professionals have already noticed a resurgence of syphilis in the West, emanating from Eastern European sources, and expect the usual consequence of increased HIV infection thence AIDS to follow (BBC news item of 4 April 1997; updates should be available on the World Health Organization's web pages, `http://www.who.ch/`). Market forces are also, just now, acting against the development of improved ways to limit population growth.[158] Other relevant examples include the clear role of market forces in the spread of medieval witch hunting and in the spread of today's cult of 'alien abduction', both clearly explained in Ref. 166. I would agree with those who argue that market forces can, in suitable circumstances, be a good thing, but the belief or feeling that they are the Answer to Everything, often unspoken, needs to be recognized as hypercredulous.

173. Conway, F., Siegelman, J., 1978: Snapping. New York, Lippincott, 254 pp. Valuable for its case studies of personal experiences in the American fundamentalist cults, and in other organizations exploiting what I am calling the hypercredulity instinct.[45] For more recent information, see for instance the book by Steven Hassan,[174] a former high-ranking official in the Unification Church (Moonies).

174. Hassan, S., 1990: *Combatting Cult Mind Control*. Wellingborough, Aquarian, 226 pp. First published in 1988. Since the publication of Ref. 173, there has been an important move to replace the old, partly coercive technique of 'deprogramming' by the strictly non-coercive 'exit counseling'.

198. Take for instance this year's legal battle (1997) to get the USA's Academy Complex (the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council) legally recognized as independent, and not as a federal government agency subject to the FACA (Federal Advisory Committee Act) and its so-called 'sunshine laws', one of which requires all committee meetings, no matter how technically abstruse the subject matter, to be held in public under civil service supervision. See, e.g., *Nature*, **387**, 746, **387**, 220, **386**, 309, **385**, 755, and **386**, 525, the last being an editorial defending the 'track record of the academy... in producing studies that the nation can trust', a track record that distances such studies, by a distinct 'credibility gap', from studies by government agency committees subject to FACA hence subject to the full pressures of commercial and other vested interests.[258a] The Congressional hearings reported in Chapter 3 of Ref. 318, pp. 63ff., are enough to illustrate what can happen when institutions fail to recognize that 'science and politics don't mix'. *Note:* Progress toward securing independence for the Academy Complex through a special bill of the US Congress has been reported in *Nature*, **390**, 104, 13 November 1997.

199. Gunsalus, C. K. 1997: Ethics: sending out the message. *Science*, **276**, 335. This editorial is one of countless public statements by scientists that call attention to the importance of respect for the scientific ethic. It reminds us too that such respect will be in jeopardy unless university students, in particular,

perceive their mentors as respecting the ethic, rather than being wholly driven by the commercial and other narrow forms of self-interest that scientists are now under pressure to espouse. This in itself is a strong argument not to push too far the reliance on funding by commercial industry, or by research funding councils whose priorities are dictated by politics or commerce.

200. Gross, P. R., Levitt, N., 1994: *Higher Superstition: the Academic Left and its Quarrels with Science.* Baltimore, Johns Hopkins University Press, 314 pp. Typical of scientists' first reactions to, and I think we would now have to say contributions to, the very tragic 'science wars' situation — tragic, that is, to the whole enterprise of free enquiry of which the scientific ideal and ethic are, or ought to be, important parts. Having received my first impressions about all this from the Derrida affair at Cambridge University in 1992, and more strongly from the 1994 television programmes mentioned in Notes 201 and 203, I have to confess that I shared these reactions, and to some extent still do, because of the widespread impressions — not wholly unjustified, though thoughtful discussions like that in Ref. 3328 correct some of these impressions — about the philosophies called postmodernism, cultural relativism, and social constructivism. Those philosophies, which have been influential among sociologists and among some professional writers and journalists, correctly say that scientific theories are non-unique and actively constructed but then, absurdly, seem to say — though their advocates would probably deny this — that the constructions are arbitrary and determined wholly by cultural presumptions and pressures, ignoring questions of coherence, self consistency, and goodness of fit to data from the outside world.[204] See also the last chapter of Ref. [12], and Ref. 328.

201. Take for instance, among countless examples, the attempt to confuse the US National Academy of Science's draft document on standards of science teaching in schools (*Science* **265**, 1648–1650, 1649; *Nature*, **375**, 439; *Nature*, **378**, 528), and the advocacy of extreme cultural relativist views, rather like those in Ref. 329, in a major BBC television documentary, *The Far Side* (Horizon/WGBH, 30th Anniversary, BBC2 Television, 23 May 1994). These views reasonably say that scientific theories are constructed by humans, but unreasonably ignore goodness of fit and the power of Occam's razor[227d] — seeming to say, with Jonathan Livingstone Seagull, that what happens when you step off a tenth storey window ledge is purely a matter of culture or opinion. That a team of high powered professional journalists, to say nothing of professional educators, could so confuse fantasy and reality was to me a profound shock, especially after having seen many excellent, coherent and well informed science documentaries in the Horizon/WGBH series. It is plain from the burgeoning literature that many other scientists have been similarly shocked; e.g. Ref. 200. Unfortunately, however, the resulting situation looks more and more like tribal conflict, and is increasingly referred to as the 'Science Wars'. As usual, and it bears repeating, we have a false dichotomy: 'Science as Mere Opinion' versus 'Science as Absolute Truth'. The test for scientists is now whether we will be collectively smart enough to see the falseness of both sides of the dichotomy, and find a lateral way out. See for instance Refs. 227*b*–227*d*, the recent *Nature* editorial 'Science Wars and the need for respect and rigour' (30 January 1997, *Nature*, **385**, 373), and the 'Science Wars Briefing' in *Nature*, **387**, 331–335. Also, e.g., Silvan S. Schweber 'Reflections on the Sokal Affair: what is at stake?' (March 1997, *Physics Today*, **50**(3), 73–74). The challenge is to contribute seriously to the debate, with the utmost care over professional standards of argument,[227d,317] and in particular to understand the origins and valid aspects of cultural relativist and social constructivist perceptions[317,328] — not least because some of those perceptions are indeed valid, and some are in any case shared in high places and will continue to be politically influential, for instance having 'a key role in debates about the public perception of science-related risks'.[272,274,227c] Good examples are being quietly set here and there; see e.g. the news item in the 3 January 1997 issue of *Science*, **275**, 29, about students' and others' interest in a program of lectures and seminars run by Dr Helena Cronin, an evolutionary biologist and co-director of the Centre for Philosophy of Natural and Social Sciences at the London School of Economics (`http://www.blpes.lse.ac.uk`). See also the particularly thoughtful discussion in Ref. 328, and other essays in the same volume.

203. One clear example, among those I have seen for myself, was the recent series *Heretic* (BBC2 Television, Tuesdays July–August 1994). By not allowing discussion between experts and cranks, but presenting them as separate but equal, with no opportunity to point out inconsistencies (as with $2 + 2 = 5$), this grossly misrepresented the nature, scope, and limitations of science. Further examples of crankish attitudes to science, mixing opinion and speculation with well checked knowledge, have been appearing from time to time in influential and widely circulated newspapers and magazines; see, for instance, Refs. 169 and 310 and the comments and references in *Nature*, **370**, 584, *Nature*, **373**, 90 and

204. Further relevant discussion may be found for instance in the books by Chalmers,[229] Gross and Levitt,[200] Pinker,[12] Popper,[165] Sacks,[38] Wolpert[48], and Bloom.[165] Part of what is involved in the more extreme cultural relativist philosophies seems to be a self refuting exaggeration of the humane ideal that all opinions should be tolerated. Everything is arbitrary, it is said, so you must not only tolerate but also give the same weight to all opinions, including the opinion that $2 + 2 = 5$ (except, of course, the opinion that all opinions should be tolerated).

205. Luckily, genetic engineering is not what popular mythology and science fiction sometimes say it is. Genetic engineering might prove capable of repairing isolated damaged genes, but it cannot unmake parts of genetic memory. Genetic memory is unbreakably encrypted in myriads of genes; an educated

guess is that the human genome will prove to have something of the order of 100,000 genes (J. E. Sulston, personal communication). According to Ref. 206, p. 219, something like 30,000 of them are active, and interactive, within the brain, though we should avoid the mistake of thinking of the brain as if it were isolated, and not intimately connected to other parts of us. To imagine that the genetic code could be 'broken' (to make explicit our learning and behavioural abilities and potentials) would be a bit like trying to guess the shape of the Mandelbrot set, an infinitely complicated geometrical object,[309] from its very simple 'genome', the equation $z_{n+1} = z_n^2 + c$.

206. Jones, S., 1996: *In the Blood.* London, HarperCollins, 302pp. A witty and insightful extended essay, by a respected geneticist, on what we know and do not know about human genetics and its social relevance. Jones takes good care to debunk the simplistic racist, eugenics, nature–nurture and genetic engineering myths. On these points see also, for instance, among many others, Refs. 13, 207, 156, and 208.

207. Medawar, P., 1982: Science and the sanctity of life. In: Medawar, P., 1982: *Pluto's Republic*, 311–323. Oxford University Press, 351pp.

208. Davies, K. E., Clarke, A. J., Harper, P. S., 1997: The genetic revolution and medicine in the 21st century. *Europ. Rev.,* **5**, 39–54. 'Is having the wrong genes going to become an acceptable line of defence in a court of law in cases of violence? Fortunately,... the biological basis of behaviour... is unimaginably complex, and is open to modification by numerous environmental influences.'

209. Cohen, J., Stewart, I., 1994: *The Collapse of Chaos: Discovering Simplicity in a Complex World.* New York and London, Penguin, 495 pp. See for instance the excellent discussion of the intimacy of nature–nurture interactions, 'a rich, fascinating, and largely unexplored joint dynamic', p. 314ff., convincingly arguing, like Wills,[13] Kauffman,[71] and others, that the genes are only part of the story. See for instance the section on 'genetic assimilation', otherwise known as the 'Baldwin effect'.[13]

210. Gregory, R. L., Wallace, J. G., 1974: Recovery from early blindness: a case study. In: Gregory, R. L., *Concepts and mechanisms of perception*, London, Duckworth, 669 pp. Perhaps the most careful and detailed psychological case study (of the total of 20 or so known cases[38]) on what happens when infantile visual model-building is prevented, or atrophies — analogous to Sacks' case in 'To see and not see', and similarly tragic. To pursue an analogy drawn in Appendix 2, one might say that a visual system not exposed to data is, apart from the enormous extra complexity, like an immune system not exposed to invading material.[319]

211. Hawkins, S., 1995: Arguments for a nonsegmental view of speech perception. In: Proc. Int. Congr. Phonetic Sci., Symposium on Dynamic, Nonsegmental Approaches to Phonetics., ed. K. Elenius and P. Branderud, vol. **3**, pp.18–25. ISBN 91-7170-836-7.

211*a*. The mathematician Leopold Kronecker is reputed to have said 'God made the integers; all else is the work of man'. He must have been unaware of illusory contours.

212. Miller, J. L., Liberman, A. M., 1979: Some effects of later occurring information on the perception of stop consonant and semivowel. *Perception & Psychophysics,* **25**, 457–465. Here the acausality illusion is referred to as an 'after going effect'. Other terms, such as 'backward referral in time' can be found in the literature. I have not yet come across the simpler and more straightforward term 'acausality illusion'.

213. Bever, T. G., Garrett, M. F., Hurtig, R., 1973: The interaction of perceptual processes and ambiguous sentences. *Memory and Cognition,* **1**, 277–286.

214. Wyttenbach, R. A., May, M. L., Hoy, R. R., 1996: Categorical perception of sound frequency by crickets. *Science* **273**, 1542–1544. Presents clear evidence that the Polynesian field cricket (teleogryllus oceanicus) has a single perceptual category for ultrasonic pulses, with no frequency discrimination above about 16 kHz (triggering an escape reaction when airborne), as tested by the 'habituation–dishabituation' technique used also in studies of birds, monkeys, and human infants. Relevant bat species that exist today emit pulses between 25 and 80 kHz.

215. See for instance Frith, C. D., Fletcher, P., 1995: Voices from nowhere. *Critical Quarterly,* **37(2)**, 72–83. This brief review, written by a research neuropsychologist and a research psychiatrist, gives a readable and well-referenced discussion of the auditory hallucinations reported by people suffering from schizophrenia. These occur in 'about 65 per cent' of cases, and are experienced as wholly realistic, often distressingly so. See also Ref. 219.

216. Dennett, D. C., 1991: *Consciousness Explained*, London, Penguin, 511 pp. This insightful book by a well known philosopher discusses several examples of what I am calling acausality illusions, including the important Grey Walter slide projector experiment (§2.5 above), apparently not published elsewhere. On the consciousness debate itself, see also Ref. 33, and Dennett, D. C., 1996: *Kinds of Minds: Towards an Understanding of Consciousness.* London, Weidenfeld and Nicolson and New York, HarperCollins (Science Masters series), 184 pp.

217. Jackendoff, R., 1992: *Languages of the Mind: Essays on Mental Representation.* Cambridge, Mass., MIT Press, 200 pp., ISBN 0 262 10047 9. See the allusion to 'temporal anomaly' on p. 141, and

the hypothesis of 'parallel multiple analysis' on pp. 140–145, the latter first published in 1991, Music Perception, **9**, 199–229.

218. We also tried the bicolour version, a red disc followed by a green disc, recently discussed by Dennett[216] under the heading 'color phi',[17] in order to test his interesting claim that a colour change from red to green is perceived at a definite intermediate time. However, we could not get this to work convincingly, even though we used the exact timings mentioned in Dennett's book,[216] namely, 150 ms on and 50 ms off (cf. 200 ms on and 200 ms off, as used in the demonstration described in Appendix 2). above. We clearly saw a red disc departing and a green disc arriving, but no definite perceived time for the colour change.

219. Spence, S. A., 1996: Free will in the light of neuropsychiatry. *Philos., Psychiat., & Psychol.,* **3**, 75–90; see also pp. 91–100 for commentaries by C. Frith, B. Libet, G. L. Stephens, and reply by Spence.

220. Driver, J., 1996: Enhancement of selective listening by illusory mislocation of speech sounds due to lip-reading. *Nature*, **381**, 66–68. Visual cues, in the form of the moving lips of a human speaker seen on a television screen, cause a 'ventriloquist effect', an illusory displacement in the perceived spatial location of the corresponding sound source, like the illusory sound-source displacement that occurs when watching television in the ordinary way. The experiments show that this illusory displacement can help the listener to distinguish two speech signals emerging from a single loudspeaker. Thus the internal model assumes two spatially separated sound sources, leading to improved discrimination even though this worsens the fit to the actual acoustic data, there being only one sound source in the outside world. Notice incidentally that this is a non-trivial consistency check on the model-fitting hypothesis itself; it makes sense only if a single internal model is being fitted to both sets of sensory data, visual and auditory. See also the excellent discussions in Bregman's book[22] of related phenomena like the 'duplex perception of speech' and the 'McGurk effect'; and see also Refs. 38 and 221–222*a*, All these studies clearly suggest not only that perception works by model-fitting, but also that different sets of sensory data — for instance auditory and visual — are fitted to the same internal model.

221. Sekuler, R., Sekuler, A. B., Lau, R., 1997: Sound alters visual perception. *Nature*, **385**, 308–308. Another multisensory psychophysical experiment, with a clearcut result that is easy to make sense of if we assume that visual and auditory data are fitted to the same internal model. Experiments were controlled against a popular alternative explanation in terms of attention switching.

222. Logothetis, N. K., Leopold, D. A., Sheinberg, D. L., 1996: What is rivalling during binocular rivalry? *Nature*, **380**, 621–624; see also p. 587. This reports new experiments adding powerfully to the evidence for model-fitting by showing that the percept, i.e., the internal model, chosen by the visual system is insensitive to changes in the route taken by the incoming sensory data. Included are experiments that present conflicting stimuli to the two eyes and, at intervals of 1/3 second, swap which stimulus goes into which eye. The resulting pairs of percepts exhibit bistability not at intervals of 1/3 second but at longer, randomly variable time intervals, qualitatively like Necker cube flipping. This firmly rules out hypotheses that assume 1–1 mapping, like monocular dominance or fatigue.

222*a*. Pellegrino, G., Làdavas, E., 1997: Seeing where your hands are. *Nature*, **388**, 730–730. The results of this experiment, on a perceptual phenomenon called 'cross-modal extinction' resulting from certain kinds of brain damage, become intelligible if we hypothesize that the subject's brain was fitting two modes of sensory data, visual and tactile in this case, to a single internal model of his own hands and their spatial positions.

223. Dennett, D. C., and Kinsbourne, M., 1992: Time and the observer: the where and when of consciousness in the brain. *Behav. Brain Sci.*, **15**, 183–247. *Behav. Brain Sci.*, **18**, 810–811.

224. Williams, Patricia J., 1997: *The Geneology of Race — Towards a Theory of Grace.* Reith Lectures, London, British Broadcasting Corporation, July 1997.

226. Mach, E., 1886ff: *The analysis of sensations, and the relation of the physical to the psychical.* Transl. from 1st German edn, *Analyse der Empfindungen*, by C.M. Williams, revised and supplemented from 5th German edn. Republ. 1959, New York, Dover, 380 pp.

227. Sagan (ibid.), p. 28

227*a*. Gould, S. J., 1997: Bright star among billions. *Science* **275**, 599. Like Ref. 162, this important *Science* editorial paying tribute to Carl Sagan includes an eloquent and perfectly apt use of the words 'true', 'real', and 'provable', in the scientist's shorthand sense, the sense of green pencils not falling upward: '...for all his pizzazz and charisma, Carl always spoke for true science against the plethora of irrationalisms that surround us. He conveyed one consistent message: Real science is so... exciting, transforming, and provable, why would anyone prefer the undocumentable nonsense of astrology, alien abductions, and so forth?'[166]

Stephen Jay Gould, who is Alexander Agassiz Professor of Zoology at Harvard University, also uses the editorial to comment on the 'narrow-minded error', on the part of some scientists, of 'equating popularization with trivialization, cheapening, or inaccuracy', and of downgrading 'the professional reputation of colleagues who can convey the power and beauty of science to the hearts and minds of a fascinated, if generally uninformed, public.' I agree with Gould and with Sagan that, on the contrary, we should recognize the public understanding crisis, and give special recognition to scientists who succeed in the difficult art of clear and accurate popularization.

227*b*. Clocksin, W., 1996: Cyborg discourse. *Nature*, **381**, 34–35. 'Cyborg' means 'cybernetic organism', an intelligent system composed of people and machines, 'considered to be interchangeable' — an astonishing mistake that overestimates, by a combinatorially large factor, current levels of machine 'intelligence'.[70,279] It also shows profound ignorance of what a biological organism is.

227*c*. Yearley, S., 1997: Restoring respect for science. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Spring 1997 issue, 42–45. The author, a sociologist, highlights the role of 'trust and judgment' in successful and credible science and argues that their role — and, by implication, the role of the scientific ideal and ethic — needs to be made publicly clearer.

227*d*. E.g., Gottfried, K., Wilson, K. G., 1997: Science as a cultural construct. *Nature*, **386**, 545–547. Gottfried and Wilson give a scientist's view of what is sometimes called the Edinburgh 'strong programme' in the sociology of scientific knowledge (SSK), as illustrated for example in the influential book *Constructing Quarks* (A. Pickering, 1984, Edinburgh University Press, 468 pp.). Though substantial and 'well informed', this book appears to make the usual cultural relativist mistake of ignoring Occam's razor and goodness of fit, and undoubtedly conveys, to a non-specialist reader, the notion of 'Science as Mere Opinion'. The resulting correspondence, in *Nature*, **387**, 543–546, **388**, 13 and **389**, 538,... gives Pickering's replies plus some clear and specific examples of goodness of fit. See also the 'Science Wars Briefing' in *Nature*, **387**, 331–335.), and a burgeoning number of other books and articles, e.g. Refs. 200, 201.

227*e*. Well checked, in this case, means really well checked, for a vast range of situations. It is checked, for instance, every time you make use of an electronic device such as a television set or a personal computer, because any such device would fail to work if physical causality failed to hold, in its usual sense, over timespans of the order of a millionth of those relevant to cortical processing. There are checks on far smaller timescales still, for instance from the detailed dynamics of chemical reactions, including biomolecular chemical reactions. Further telling examples are given in the correspondence referred to in Ref. 227d.

227*f*. For other examples see for instance the correspondence in *Nature*, **387**, 543–546. One of them, not yet popularly known, is high-precision 'pocket navigation' using the artificial satellites of the Global Positioning System. A cheap pocket receiver can tell you your position and altitude to within hundreds of metres, i.e. to better than one part in ten million of the Earth's radius, or which block on which street.

228. Born, G., 1991: Problems with limits. *Science and Public Affairs* (Roy. Soc. London), **6(2)**, 17–25. Gustav Born discusses the limitations of science, another point widely misunderstood by the public, and puts on record the passage written by his father, Max Born, that I have quoted.

229. Chalmers, A. F., 1982: *What Is This Thing Called Science? An assessment of the nature and status of science and its methods.* 2nd edn. Milton Keynes, UK, Open University Press, 179 pp. This book gives a useful quick introduction to recent thinking among historians and philosophers of science, carrying on from naive inductivism to Popper, Lakatos, Kuhn, and Feyerabend. In Chalmers' own admirably honest words, 'We start off confused and end up confused on a higher level' (page xix). The difficulties show up on p. 155, for instance, where the unconscious — and, of course, fallible — internal model-fitting involved in making sense of everyday visual scenes, such as the proverbial cat on the mat, is not recognized in the discussion. The presence of the cat is tacitly accepted as some kind of independently known truth, fundamentally different from scientific knowledge — the veridical perception fallacy (Appendix 2 above). This may be compared with the discussion of 'seeing is believing' on p. 31 of the book by Francis Crick,[32] which takes account of the psychophysical evidence, and of neurophysiological and neurological evidence as well. The evidence consistently shows what is also obvious from a biological viewpoint, that what you see, what you are directly aware of, is — can be nothing other than — 'what your brain *believes* is there' (Crick's italics). What you are directly aware of is — can be nothing other than — the internal model itself, the model that your unconscious brain has fitted to the incoming sensory data. In other words, the unconscious model-fitting that makes you aware of the cat is no different, in principle, from the more conscious model-fitting that makes you aware, if you are a scientist, of DNA molecules or uranium atoms or neutrons or radio waves or Einstein–Podolsky–Rosen–Bohm phenomena,[230,231] or anything else in the outside world. If you accept the foregoing, then you must admit that your powerful sense of 'reality' and outside world 'truth' is *fundamentally* a matter of goodness of fit (§2.8 above).

By not recognizing the existence of the unconscious internal model (of the cat on the mat), the discussion in Ref. 229, p.155, is precluded from recognizing that the internal model of the cat is, inevitably, simplified — indeed, grossly simplified — to 'pick out certain properties or characteristics' of what is modeled, and to ignore other properties or characteristics (such as the DNA molecules in the cat's cells). In this respect the internal model of the cat is not, as stated on p. 155, 'fundamentally different' from the model of aspects of the outside world that we call 'the laws of physics'. On the contrary, it is fundamentally similar.

The same considerations show why philosophical difficulties arise whenever attempts are made to portray science either as something completely definable by rigid, universal rules of so-called ‘scientific method’, or as something completely and arbitrarily culture dependent — both extremes being absurd, of course, to anyone familiar with scientific knowledge and how it is obtained. Both extremes ignore the biological reality under discussion: a complete, detailed prescription of how science works would require a complete, detailed understanding of how the human brain works.

The literature on creative thinking and innovation in scientific research demonstrates, again and again, the key role of unconscious processes, no less than in artistic creativity (e.g., Refs. 7, 16, 34, 38, 48 and very many others). See also §2.8 of Appendix 2.

229*a*. An adequate review of the literature on cortical processing timespans is beyond our scope here, but it can safely be assumed that the relevant timespans for multi-level processing are far longer than a few milliseconds, and likely to be of the order of hundreds of milliseconds. Direct electrophysiological evidence, from cortical activity evoked by sudden perceptual stimuli, visual or auditory, is illustrated by the ensemble averaged, event related electroencephalograms shown in Fig. 35 of Crick's book[32], Chapter 9, p. 112. It is typical for the activity observed in this way to continue for ‘400msec or longer’ (C. D. Frith, personal communication). In Crick's examples, the ensemble averaged signals last around half a second, each showing one peak near 200msec and another near 300–400msec. Crick states that a prominent peak near 300ms–400ms is ‘fairly common’, and ‘usually correlates with something that is surprising’, or attention grabbing or eye catching, like visual ‘pop out’ (p. 111 and caption to Fig. 35). Psycholinguistic experiments reveal similar timespans, corresponding to two or three syllables of speech, for pre-conscious processes in speech perception. Examples include the work of Swinney, Seidenberg, Tanenhaus, and others summarized in Refs. 217, pp. 143 and 12, pp. 210–211. The same goes for music perception, as in the simple examples described in Appendix 2. For experimental evidence from neurophysiological and psychophysical studies of reaction times, see for instance Hanes, D. P. and Schall, J. D., 1996: Neural control of voluntary movement initiation. *Science* **274**, 427–430.

230. Mermin, N. D., 1985: Is the moon there when nobody looks? Reality and the quantum theory. *Phys. Today,* **38(4)**, 38–47. A lucid and cogent discussion of Einstein–Podolsky–Rosen–Bohm correlation phenomena; see reference to Einstein's relativity in the following notes.[231] For more recent developments, see for instance Ref. 251*a*.

230*a*. This vagueness is well brought out in Gell-Mann, M., 1994: *The Quark and the Jaguar: Adventures in the simple and the complex.* New York, Freeman; London, Little Brown, 392pp. See the section ‘Measurement situations and measurements’ and the first half of the following section, i.e., pp. 154–155, and note for instance, regarding fission tracks in ‘rocks that are hundreds of thousands of years old’, the statement that, according to the standard principles of quantum mechanics, ‘the actual measurement could have been carried out by a cockroach or any other complex adaptive system. It consists of “noticing” that a particular alternative has occurred...’ (p. 154). There is no explicit description of how, why, or in what sense the cockroach could have ‘noticed’ the fission track, nor discussion of the implications for radioactive decay of rocks on lifeless planets or for nuclear reactions within the Sun.

230*b*. Bohm, D., 1971: On the role of hidden variables in the fundamental structure of physics. In: *Quantum Theory and Beyond*, ed. T. Bastin, 95–116. Cambridge, University Press, 345 pp.

230*c*. Peat, F. David, 1996: *Infinite Potential: The Life and Times of David Bohm.* Reading, MA, Addison-Wesley, 353 pp. Reviewed in *Nature*, **385**, 592 (1997), by Chris Philippidis, in *Science*[51] by Sheldon Goldstein, and in *Physics Today*, 50(3), 77-78 (1997) by James T. Cushing: ‘...this book does make a prima facie case for Bohm as a fascinating and important scientist... But it probably has not given David Bohm his due.’

231. Bell, J. S., 1987: *Speakable and Unspeakable in Quantum Mechanics.* Cambridge University Press, 212 pp. The quotation in the main text is from p. 194. More fully: ‘It is easy to understand the attraction’ [of ‘quantum philosophy’] ‘... for journalists, trying to hold the attention of the man in the street. The opposite of a truth is also a truth! Scientists say that matter is not possible without mind! All possible worlds are actual worlds! Wow!’ On the many worlds hypothesis see especially pp. 136–137 and 189–195 (also Ref. 251), and on von Neumann's theorem and the first ‘sharp quantum theory’, the pilot wave theory of de Broglie and Bohm, see pp. 159–168 (also e.g. Ref. 250). As always in science, some of the trouble comes when (pp. 165–6) we fail to ask *Which experiment?* or *Which thought experiment?*’. Bell's lucid and penetrating discussions show that quantum phenomena do not force us into any ‘quantum philosophy’ that renounces the scientific ideal of strict coherence and self consistency. Nor do they force us into any renunciation of what is arguably the most basic application of Occam's razor, on which not only physics but also all the other hard sciences depend, namely the hypothesis that we live in a single world that exists independently of ourselves. Phenomena of ‘quantum non-locality’ may well force us — a point underlined by the famous Aspect *et al.* experiments on such non-local phenomena, e.g. the so-called Einstein–Podolsky–Rosen–Bohm phenomena [230,231] — either toward a revision of one of Einstein's relativity principles (to say that ‘no *information carrying* effect can propagate faster than the speed of light in a vacuum’), where ‘information’ is understood in its ordinary classical sense, or toward some other drastic revolution, such as a revision of our ideas about spacetime,[53] or about the algorithmic computability of physical theories.[53,249]

231*a*. Bell's[231] Chapter 9, 'How to teach special relativity', beautifully shows the desirability of getting more than one angle on a problem before claiming good understanding.

231*b*. Pages 8–13 of the next reference (Bondi[231c]) give a charmingly cogent debunking of the search for a Theory of Everything[231d] and an early warning of some of its dangers. See also Ref. 209, pp. 363–365, the Feynman Lectures in Physics, vol. II, page 25-11, and remarks at the end of Appendix 2 above (§2.8).

231*c*. Bondi, H., 1967: *Assumption and Myth in Physical Theory.* (The 1965 Tarner Lectures). Cambridge, University Press, 88 pp.

231*d*. It is not known today whether the quantum-gravitational inconsistency is removable by conventional means, i.e., within the framework of standard quantum mechanics. There is a possibility that it could be thus removed, in a natural way, by the recent developments in the branch of standard quantum mechanics called string theory. See for instance the recent writings of two respected experts, Steven Weinberg[63,268] and Edward Witten (*Nature*, **383**, 215–216). But Witten also writes (in essential agreement with, for instance, Penrose[53,247a] and a number of other experts today) that '...we face a contradiction between quantum field theory and general relativity similar to the contradictions [in classical physics] that led to quantum mechanics. Many physicists believe that this contradiction contains the seeds of an upheaval as profound in its own way as the discovery of quantum mechanics or relativity.' (See also the article by Witten in Physics Today, **50**(5), 28–33, May 1997.) It can fairly be added that some such upheaval has long been pointed to, in other ways, by the careful arguments of thinkers like Bohm[50,51,230b] and Bell,[231] arguments whose essence is very simple and which I summarize briefly in Part III (`lucidity3.ps`): one outstanding difficulty being to find a sharp quantum theory[231] that is Lorentz invariant in a natural way while respecting quantum non-locality.[51,250] The reason that these arguments have been so much ignored*e.g.* 63, 247*a* — despite their simplicity, cogency, and meticulous attention to the scientific ideal — seems, again, to have something to do with the workings of our perceptual and cognitive instincts. In particular, there is the powerful feeling, expressed so well in Weinberg's book,[63] that *if only we could keep standard quantum mechanics as it is*, then the consequent narrowing down of possibilities might be enough to determine a unique — or apparently unique — Theory of Everything. This looks very like the instinctive, and often necessary, urge to prune the tree of model possibilities: again see Appendix 2.

The quantum-gravitational inconsistency itself, implicit for instance in standard quantum electrodynamics (QED), is well known. To put it more sharply than usual, QED is like the 'elephant not identical to itself': it implicitly says that electrons feel gravity yet do not feel gravity. The electron is treated as lacking structure at the Planck scale $\ell = \sqrt{(G\hbar/c^3)} \sim 10^{-33}$centimetre, where G is the universal gravitational constant, $\hbar$ is Planck's constant, and c is the speed of light. In other words the electron is treated as if ℓ were exactly zero, i.e., as if G were exactly zero, despite the need to suppose that the electron has finite mass–energy, necessary to make sense of the way a television tube works, for instance. That the electron, in virtue of its finite mass–energy, must feel gravity is supported, in turn, by the experimental checks on the equality of inertial and gravitational mass and the logical edifice built on that equality — Einstein's gravitational theory — itself having exquisite goodness of fit to observational data of extraordinarily high precision, notably the famous measurements to check the cumulative effects of gravitational radiation on the orbital period of a binary pulsar.[53,247a] The well known consequence of all this is that QED has to be 'renormalized', a process that works marvellously as a practical computational prescription, producing further examples of exquisite goodness of fit to experimental data.[63,268] But the same computational process is also describable, and has been so described by such careful and brilliant thinkers as Dirac and Feynman, as sweeping the inconsistency 'under the rug'. The theory must postulate that the electron has a nonsensical property equivalent to infinite, negative, non-electromagnetic or 'bare' mass–energy. It is reasonable to assume, and I think most physicists assume, that the subtraction of infinities to give a finite answer would — if gravitational effects were self consistently taken into account — become a subtraction of finite quantities to give a finite answer; but there is no complete and detailed check on this.[53] For one thing, 'self consistently' might yet mean that 'a space of objectively defined events must be restored to the theory'.[250]

234. Page 27, consisting of Fig. 6 (musical notation), is available on the Internet[8] in a separate file `lucidity-fig6.ps` and at lower resolution in `lucidity-fig6.gif`. The sketch is a mildly irreverent musical joke. A sound recording is available in the file `lucidity-trombone.wav` (only low quality, 8-bit, mono, 22kHz sample rate, 900 Kbyte, at the time of writing). Alternatively, a MIDI file (making its best effect when played through a Roland or other high quality sound module, with a good crisp trombone sound) is currently available as `lucidity-trombone.mid` (1 Kbyte).

236. Storr, A., Music and the Mind. New York, Ballantine/Random, 212 pp.

237 Mozart admitted this himself; see Mersmann, H., Bozmann, M. M., 1928 and 1972: *Letters of Wolfgang Amadeus Mozart.* New York, Dover, 278 pp. Relevant quotes can be found, for instance, on pp. 40, 221.

238. Kamii, K. C., and DeClark, G., 1985: *Young Children Reinvent Arithmetic: implications of Piaget's theory.* New York, Teachers College Press, 269 pp., ISBN 0807727075. Also 1989, with L. L. Joseph: *Young Children Continue to Reinvent Arithmetic — 2nd Grade*, 205 pp., ISBN 0807729582; and 1994,

with S. J. Livingston: *ibid., 3rd Grade*, 225 pp., ISBN 0807733237. For another, more general view of such techniques and their recent development, see, e.g., Dryden, G., and Rose, C., 1995: *Fundamentals Guidebook: The Building Blocks to Raise Brighter, Happier Children.* Aylesbury, Bucks., UK, Accelerated Learning Systems Ltd., 273 pp. A parents' manual containing specific, practical suggestions based on experience with Lozanov's method of 'accelerated learning', which uses the play instinct (at any age) and efficiently exploits our perceptual and cognitive abilities. See also Ref. 270.

239. Penrose, R., Shimony, A., Cartwright, N., Hawking, S. W., 1997: *The Large, the Small and the Human Mind* (ed. Longair, M. S.). Cambridge, University Press, 185 pp. Based on the 1995 Tanner Lectures on Human Values, and the minisymposium that followed: contains summaries of, and discussions of, the ideas in Ref. 53, including the intriguing, astonishing, and unlikely-sounding suggestion, following Herbert Fröhlich, based on on what he called 'the extraordinary dielectric properties of biological materials', that molecular-level biological computing makes use of quantum coherence effects beyond those that hold atoms and molecules together, and operating on far larger spatial scales. The suggestion is especially intriguing because, in theory, non-Bose quantum coherence effects provide an exceedingly powerful way of solving combinatorially large problems.[293a,278] But, as Penrose admits, quantum decoherence poses a formidable obstacle. Appendix 3 offers some further comments, on Penrose's use of the idea of algorithmic soundness.

239*a*. E.g. work on 'genetic algorithms' at the Santa Fe Institute and elsewhere; also, e.g., Huberman, B. A., Lukose, T. H., 1997: An economics approach to hard computational problems. *Science*, **275**, 51–54. 'Portfolio' or risk-spreading algorithms make tradeoffs between speed and algorithmic unsoundness.

240. Maddox, J., 1995: Valediction from an old hand. *Nature*, **378**, 521–523. Looking back on his experience as editor of Nature during 1966–73 and 1980–1995, John Maddox puts it perfectly: 'there can be no more important goal for the research community... than to cut the link between publications and success' (creating, as it does, such a strong incentive to corner cutting and even to outright scientific misconduct,[240a] that is, to gross violation of the scientific ethic). Maddox cites his own experience of the 1980s. He also lists some of the major advances in hardcore scientific knowledge that took place in the 1980s, despite human lapses. On the insoluble, ethic-damaging, and bureaucratically amplified problem of who should be first, second, third,... author, see *Nature*, **388**, 320 for an excellent defence of alphabetical order as the normal practice, and what to do about young scientists' career advancement through means other than first authorship. See also the editorial in *Nature*, **387**, 831, stressing the 'hyper-collaborative' nature of most of today's significant research, and **388**, 14 and 511 for the statistical controversy over 'Aabel's Advantage'.

240*a*. James, W. H., 1995: Fraud and hoaxes in science. *Nature*, **377**, 474–474. This gets fraud into perspective, making the point that — though, under today's pressures, fraud is inevitably an increasing problem — honest error in science is still 'far more common than outright fraud' despite, a cynic could add, today's market-style incentives[258b,258c] to fraud. There is also a societal counterpressure, the knowledge that fraud still risks catastrophic destruction of a scientist's career — a counterpressure that exists mainly because professional peer review, with all its imperfections, is still in use despite the bureaucratic dream of replacing it by so-called objective performance indicators.[258b,312]

240*b*. Lachmann, P., Rowlinson, J., 1997: It's *what* not *where* you publish that matters. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Winter (December) 1997 issue, p. 8. The authors are, at the time of writing, the Biological and Physical Secretaries of the Royal Society of London, the UK's national science academy. They 'are firmly of the view that the practice of judging the quality of the work by the journal in which it is published not only corrupts the process of peer review but also promotes *a form of scientific misconduct* [my emphasis]. The use of bibliometric analysis [including journal impact factors] for judging individual authors has promoted a publication culture where papers proliferate in number and results are published in increasingly small aliquots [if only to give everyone a chance of first authorship] and where there is excessive citation of other papers, even where this is not frankly corrupt as in the formation of "citation rings"... We strongly deprecate this practice... We have as far as is in our power tried to prevent its use in the [UK Universities' triennial] Research Assessment Exercise.' The latter, as far as I know, has indeed tended to use a 'few best publications' system in which the onus is on the assessees, the authors, to judge and declare which few of their own publications are best, in the knowledge that those publications might actually be read by assessors. A more general shift from 'many worst' to 'few best' might yet limit the damage being done to science by the audit culture.[312,313a]

241. Pippard, A. B., 1991: Footnote to history. *Nature*, **350**, 29. Argues from the cold fusion debate that 'the institution of science is robust.'

242. Sime, R. L., 1996: *Lise Meitner: A Life in Physics.* Los Angeles and London, University of Calif. Press, 526 pp. A historically and philosophically important book containing much information, hitherto not widely available, about the epic story of early twentieth century physics. See p. 174, concerning the premature, 1937 announcement of absolute certainty about the transuranic elements.

243. Reanney, D. L., 1991: The Death of Forever: a New Future for Human Consciousness. London, Souvenir Press, 270 pp. (ISBN 0 285-63271 X). A bit shaky on quantum mechanics, but has some

important ideas on 'human becoming', on the avoidance of the spiritual abyss, and on acknowledging that questions about subjective experience near death are questions of personal faith and not science.

244. Tippett, Michael, 1995: *Tippett on Music*, ed. Meirion Bowen. Oxford, University Press, 318 pp.

245. Casti, J. L., 1989: *Paradigms Lost.* London, Little, Brown & Co., 567 pp. This massive yet entertaining book takes us on a romp through many of the fashionable philosophical debates and is useful for getting a quick idea of what the fuss is about. It gives a vivid impression of the dichotomization instinct at work.

246. Lighthill, J., 1973: *Artificial Intelligence.* Swindon, Wilts., Science Research Council, 21 pp.

246*a*. Leggett, A. J., 1987: *The Problems of Physics.* Oxford, University Press, 192 pp. Page 20 mentions a lecture given by Lord Kelvin in 1900, in the course of describing late nineteenth century attitudes — '...how unthinkable the idea that their whole conceptual framework might be in error....' See also Ref. 268.

246*b*. Ashby, J., 1996: Mad cows, bats and baby milk. *Nature*, **382**, 109. Breaking the vicious circle (openness → sensational headlines → scientists' reaction → coverup charges) requires education 'in the scientific process and... relative risks.'

247*a*. Hawking, S. W., Penrose, R., 1996: The Nature of Space and Time. Princeton, University Press, 141 pp.

247*b*. Ref. 53, pp. 385-7, gives a brief discussion of the neurological experiments of Benjamin Libet and the controversies they have triggered; more extensive discussions and debates, with large bibliographies, can be traced through Refs. 216, 219, and 223. There have even been suggestions to the effect that physical causality principles be abandoned.

248. Percival, I. C., 1995: Quantum spacetime fluctuations and primary state diffusion. *Proc. Roy. Soc. Lond.,* **A 451**, 503–513.

249. Palmer, T. N., 1995: A local deterministic model of quantum spin measurement. *Proc. Roy. Soc. London,* **A 451**, 585–608. The idea is to replace quantum non-locality by algorithmic non-computability arising from 'riddled basins' of attractors in phase space. For an excellent lay person's description see Ref. 309, 2nd edn., pp. 348–356.

250. Samols, T. M., 1995: A stochastic model of quantum field theory. *J. Statist. Phys.,* **80**, 793–809. 'To a realist,... a space of objectively defined events must be restored to the theory.'... The model is discrete ('light-cone lattice theory'), and there is no claim to have overcome the difficulty of going to the continuous limit. 'One may think of the model as simply... [the Bell–Everett theory]... but with its two defects — absence of sensible histories and frame-dependence — simultaneously cured.'

251. Kent, A., 1990: Against many-worlds interpretations. *Int. J. Modern Phys.,* **A 5**, 1745–1762. This usefully and cogently supplements Bell's classic discussion[231] 'Quantum mechanics for cosmologists', with more technical detail. For the latest experimental checks on Bell's inequalities and EPRB effects, see Ref. 251*a*:

251*a*. Bouwmeester, D., Pan, J.-W., Mattle K., Eibl, M., Weinfurter, H., Zeilinger, A., 1997: *Nature* **390**, 575–579. Boschi, D., Branca, S., De Martini, F., Hardy, L., Popescu, S., 1997: Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels. *Phys. Rev. Lett.*, submitted Oct. 1997; Preprint quant-ph 9710013, available from `http://xxx.lanl.gov/archive/quant-ph`, October 1997. See also the news item in *Nature* **390**, 551–552.

252. Dowker, F., Kent, A., 1996: On the consistent histories approach to quantum mechanics. *J. Statist. Phys.,* **82**, 1575–1646. This admirably lucid paper contributes to the debate about quantum mechanics and its domain of applicability. Note incidentally that the word 'consistent' in the title is short for 'probability-consistent', a specialist technical meaning that differs from the standard logical meaning, freedom from contradiction, used in my discussion. Roughly speaking, the 'consistent histories' approach, now more often called the 'decoherent histories' approach, is an attempt to force the (Everett) many worlds theory into a single world. It has not yet become a quantitatively precise model.

Additional note: I recently had a chance to ask Professor Murray Gell-Mann, one of the eminent physicists advocating the consistent histories approach, a basic question to check on the last point. The occasion was question time after his lecture to a geophysics conference at the Hotel Santa Fe, New Mexico, on Wednesday 19 June 1996. I asked whether any explicit predictions had been made for the timescale or timescales of the quantum mechanical branch-pruning events that are hypothesized to replace what is usually called the collapse of the wavefunction (Ref. 230*a*, p. 156). The answer was to the effect that there is, as yet, no definite prediction: the timescale will 'depend on the parameters of the problem.'

253. Lewis Carroll (Charles Lutwidge Dodgson), 1904: *The Story of Sylvie and Bruno*, Chapter 7. Republished London, Macmillan, 1980, 329 pp.

254. The optimist can point not only (*a*) to the technological and economic pressures favouring supranational markets and accessible information technologies and (*b*) to the known technological possibilities

for using market forces contructively[257a,b], but also, for instance, (*c*) to the new 'men's movement'[257] with its non-violent ideals and new ways toward spiritual health, and (*d*) — perhaps this will surprise you — to the ascendant supranational power of the mass newsmedia industry. That industry has already demonstrated its ability to think on a far longer timescale than most politicians,[255] and its communication professionals are anything but naive about psychological realities and human instincts. The same mass newsmedia industry must also be becoming ever more aware of its large stake in non-totalitarian social stability.

In this latter regard, the optimist may note furthermore how different is our present situation by comparison with, for instance, the situation exploited by the Nazis in the 1930s. Then, for economic and technological reasons that no longer apply, a small group of politicians was able to gain almost exclusive control of information and disinformation. By contrast, the non-totalitarian social stability that underpins the commercial success of the mass newsmedia will require societies whose governments are based on some degree of informed consent. If such a state of things is to be sustainable, then 'informed' will have to involve, as one of the hard realities, increased respect for the scientific ideal and a better understanding of what science is and is not useful for. So the present tendency for large parts of the mass newsmedia to fail to promote, or to work against, such informedness is likely, sooner or later, to be seen by the industry as self threatening and is therefore likely to be reversed, despite short term market forces. On other aspects of the supranationalization of power and the technological reasons for it, see also Ref. 255.

255. Anderson, R. J., 1996: *Cryptography in Europe — markets, law and policy.* This short, cogent, and well documented essay (15 pp.) is available at `ftp://ftp.cl.cam.ac.uk/users/rja14/queensland.ps.Z` on the Internet. It takes a close look at one of the present battles between nationalist and supranational forces, which supranational forces, working largely out of sight of ordinary politics, already seem likely to win for a combination of overwhelming economic and technological reasons including the need, as yet unmet, for secure and independently auditable electronic transaction systems. Exactly where all this will lead is, of course, unclear as yet.[285]

256. Levin, B., 1977: (*The Pendulum Years: Britain and the Sixties*, London, Pan Books, 1977; Sevenoaks, Sceptre, 1989, 447 pp. The quotation is from Chapter 4.

257. E.g., Biddulph, S., 1995: *Manhood: An Action Plan for Changing Men's Lives*, 2nd edn. Sydney, Finch Publishing, 261 pp., ISBN 0 646 26144 4. The publication of this insightful book about 'the women's movement's missing half', by Steve Biddulph, an Australian family psychologist, is one among many signs of the sort of organic cultural change that is possible. The tendency for industrial revolutions to separate fathers from sons has led to dangers that are obvious once you think of them, yet are only just beginning to be widely recognized.

257*a*. von Weizsäcker, E., Lovins, A. B., Lovins, L. H., 1997: *Factor Four: Doubling Wealth, Halving Resource Use — The New Report to the Club of Rome.* London, Earthscan Publications, 322 pp., ISBN 1 85383 407 6, `http://www.earthscan.co.uk`. An important new book presenting hard-headed economic arguments based on many well documented, detailed examples of what has happened and what is happening. It shows in detail the nature of market force hypercredulity and the devastation beginning to be caused by it (e.g., Chapter 13, references to Richard d'Aveni's recent promotion of 'hypercompetition', or economic competition as a form of total warfare, related also to the 'winner take all' or 'star system',[344] the aim being to annihilate competitors regardless of the human or social consequences). Along with Refs. 288 and 257*b* 'Factor Four' also shows, on the other hand, and again with detailed examples, how market forces can be — and have been — put to work constructively and sustainably. Such a change in the use of market forces illustrates what I mean by organic cultural change, helped by respect for the scientific ideal in the sense I am using the phrase: respect for coherence and self consistency, for what hangs together and makes sense.

257*b*. Berger, J. J., 1997: *Charging Ahead: the Business of Renewable Energy and What it Means for America'.* New York, Henry Holt, 399 pp. The author, John J. Berger, 'has apparently talked to almost everyone involved' in the US renewable energy industry, and the book includes 'many fascinating case studies': see the review of this and Ref. 257*a* by Robert Day in *Nature*, 1997, **389**, 247–248. Berger argues that renewable energy technology will soon be technologically advanced enough to be competitive, despite the present large government subsidies to nonrenewables like fossil fuels.[257a,318]

258. A rational defence of Market Forces as the Answer to Everything would have to defend their role, for instance, in suppressing accurate journalism,[297,318] in accelerating the spread and evolution of AIDS and other serious diseases,[160,172] in creating *new* diseases,[160b,282] in impeding rational approaches to population control,[158] in squandering resources and devastating the environment,[257a] in choking off long term investment in national infrastructure, including scientific capability,[258a] and in building the immense power of organized crime in general[314] and the international drug trade in particular — the latter now reportedly considering whether to acquire Russian tactical nuclear weapons.[314a] If you happen to love classical music, then you may also have noted how international market forces have worked to devastate its spiritual value, and how a resistance movement has begun to emerge.[344]

258*a*. Kurland, C. G., 1997: Beating scientists into plowshares. *Science*, **276**, 761–762. Points out some of the devastating consequences to research and education, and, by implication, to other kinds of infrastructure, of unconstrained market forces, citing detailed documentation in the case of the author's field of molecular biology. The focus is on what are perhaps the most powerful identifiable market forces at work today, those associated with the private financial 'transaction sector', which deals with money alone,[297] whose timescale is that of the quarterly financial report and whose practitioners, including financial advisors, economists, and market analysts, consume a very substantial fraction of the world's total business turnover (Wallis, J. J., North, D. C., 1986: In: *Long Term Factors in American Economic Growth*, ed. S. L. Engerman, R. E. Gallman, Chicago, University Press, 95–163) — far greater than the resources of any present-day institution that is trying to think on longer timescales, including even the military. Kurland reminds us that forces of such magnitude pose, in particular, one of the gravest threats to the openness of academic research and hence, by implication, to the survival of the scientific ethic and the credibility of public statements by tomorrow's scientists. See also Refs. 258*b* and 258*c*, to the first of which Kurland's article was in part a reply, and Pimm, S. L., 1997: The value of everything. *Nature*, **387**, 231–232. This points out that unconstrained market forces, being blind to 'overarching moral issues', would be likely, on their own, to ensure the reintroduction of, for instance, child labour where it is not already established, especially if the forces are those brought into play by the kind of opinion poll run by market analysts, reinforcing market force hypercredulity by asking questions of the type 'What would you personally pay each year to prevent the reintroduction of child labour?'

258*b*. Fears, R., Ferguson, M. W. J., Stewart, W., Poste, G., 1997: Life-sciences R & D, national prosperity, and industrial competitiveness. *Science*, **276**, 759–760. The extreme 'scientists on tap' view, showing the threat to credible, independent science from unregulated commercial interests, essentially similar to the threat to credible, independent journalism.[297] One quote is sufficient: 'All scientists [sic] must [sic] be prepared to accept and, more usefully, propose productivity measures for invention and innovation.' (The text then refers to a book by Anderson, J. and Fears, R., 1996: *Valuing and Evaluating: Assessing the Success of R & D.* Oxted, Surrey, UK, Cross & Associates.) 'Without such willingness, the scientific community will come to be seen by politicians and the public as wanting to escape public accountability. Performance needs to be defined in terms of the quality of ideas generated and selected, the scope and scale of eventual industrial adoption' (and in terms of no other criterion, not even understanding industrial hazards). Note especially the tacit presumption that it is possible, in principle, to predefine numerical 'productivity measures' that in some relevant sense automatically measure 'invention and innovation' and 'quality of ideas'. Note also the use of the phrase 'public accountability'[312,313] to mean 'conformity with what private industry considers its requirements to be'.[258a] If the authors' strictures were to be put into universal practice, as seems to be demanded by their phrase 'All scientists must...' — see also Ref. 258*c* — then there would be no longer be significant numbers of independent scientists and there would no longer be credible, independent scientific opinion on any matter of public concern. See also Ref. 258*d*, for a more sober assessment and historical perspective, and 312, 313 for commentaries on the hypercredulous, as they arguably are, belief systems centered on the word 'accountability' and its conflations.

258*c*. Kealey, T., 1996: *The Economic Laws of Scientific Research.* London, MacMillan and New York, St Martin's Press, 382 pp. This book sets out the belief — in the mind of a skilful and persuasive writer representing a politically significant trend — that Market Forces are the Way to manage scientific research and scientific careers: more precisely, that all scientific research should be funded privately, if at all. The implication is that there should be no scientists independent of commercial interests. (Perhaps the author would say that, by the same token, there should be no courts of justice independent of commercial interests; see also p. 56 of Ref. 318, concerning the belief that the US federal government 'should get out of the research business altogether' and that there should be 'a privatized research establishment funded by those industrial interests that are most directly affected', meaning the fossil fuel lobby, to inform us about the effects of fossil fuels on the environment.) Kealey's book, going beyond Ref. 258*b*, cleverly positions the reader — manipulates unconscious prior probabilities — to accept that there are such things as 'economic laws' of scientific research. It then, referring to the funding of scientific research and development (R& D), claims with prodigious assurance that 'public and private funding displace each other' and that 'public funds displace more than they do themselves provide.' Colin Humphreys (*Europ. Rev.,* **5**, 443–445) has pointed out that these claimed 'laws' are disproved by, indeed are grossly inconsistent with, official OECD figures (Organization for Economic Cooperation and Development) for the period 1981 to 1993: 'Government funding of R& D was cut by 20% in the UK, but increased by 60% in Japan. Industry funding of R& D increased by 58% in the UK, but by 115% in Japan' (directly contradicting the claimed 'laws'). 'In fact,' Humphreys continues, 'over the period 1981 to 1993, the UK was the only major nation actually to *reduce* the government funding of R& D, and the percentage increase of industrial funding of R& D was *lower* in the UK than in any... competitor countries' — not higher, as Kealey's 'laws' would predict.

258*d*. Danielmeyer, H. G., 1997: What industry expects from science. *Europ. Rev.,* **5**, 185–191. A brief and useful historical perspective on the relation between science and industry, and a sober assessment of current trends that every scientist should read and think about — though like Refs. 258*b* and 258*c* it still ignores society's need for a science base that is independent of commercial interests.

259. Tenner, E., 1996: *Why Things Bite Back: Technology and the Revenge Effect.* London, Fourth Estate, 346 pp. A thoughtful discussion of the unexpected side effects of new technologies: 'Whatever

happened to the paperless office?' and so on, to say nothing of antibiotic resistance.[160] See also *Science* **275**, 41, suggesting that the asthma epidemic is a revenge effect, perhaps from the battle against tuberculosis.

260. Pollack, R., 1997: A crisis in scientific morale. *Nature*, **385**, 673–674. One among many recent testimonies in the columns of *Nature* and *Science*: a biologist's personal solution to the problem of too much scientific competition and not enough cooperation. See also, for instance, the 'advice to whistleblowers' in *Nature*, **385**, 669. Additionally, Pollack's testimony illustrates the damage done by the naive behaviourist or positivist philosophies against which I argue in Appendix 2, with their false dichotomizations and prior judgments about methodology, restricting the opportunities to understand brain function.

262. Le Guin, Ursula, 1974: *The Dispossessed* 1974, London, Gollancz and 1996, London, HarperCollins, 319 pp. The quote is from Chapter 6. See also Ref. 263:

263. Le Guin, Ursula, 1972: *The Lathe of Heaven.* London, Gollancz 1972, Panther/Granada 1974, 156 pp. This wise and wonderful tale is more fantasy than science fiction, and so far as I remember does not even mention genetics or eugenics. But it is about a well-meaning scientist's attempt to save the world through superhuman power, and the carnage that results. I think a similar tale could be told about a superhuman power capable of meddling with the Platonic (see text), of manipulating the genetic underpinnings of human perception, cognition, and behaviour.

264. Mather, J. C., Boslough, J., 1996: *The Very First Light: The True Inside Story of the Scientific Journey Back to the Dawn of the Universe.* London, BasicBooks, 328 pp. About the COBE (Cosmic Background Explorer) satellite project and its recovery from the Shuttle disaster. Reviewed by Joseph Silk in *Nature*, **385**, 691, who suggests that the book is a bit unfair on one of the project leaders, George Smoot, and points out that 'the sky maps of the fluctuations that appeared in the press showed mostly experimental noise rather than the more subtle cosmic signal.'

266. Belloc, H., 1938: This sonnet, not in the original collection published in 1923, is Sonnet 36, the third last of the 1938 collection of *Sonnets and Verses*, renumbered as Sonnet 31 of the 1954, posthumous, collection (London, Duckworth, resp. 203 pp., 183 pp.). It is given the date 1938 by the *Oxford Dictionary of Quotations*, 4th edn. The next sonnet, the second last of 1938, touches a similar chord: '... For all believing's but a dance of shades.' It is noteworthy that Belloc (1870–1953) was a professing Christian, with Roman Catholic loyalties, a humanist and polemicist for civilized values — at some cost to his career as a historian and literary man — as well as an astute observer of human nature and of 'things as they are'. He seems to have tried again and again, against the odds, to clarify the distinction between personal faith and hypercredulous belief.

267. One striking and well-checked example — see also Refs. 3 and 71 — is the mitochondrial protein molecule, more accurately molecule assembly, H^+-ATP synthase. It or its subunits are also variously referred to as F_1-F_0-ATPase and F_1-ATPase, depending on which aspect of its functioning is being emphasized. It is about 10 nanometres in diameter and is made of around 10^5 atoms. It functions as a rotary dynamo or motor, with one subunit rotating continuously with respect to another. The rotary action was first deduced from indirect lines of evidence and subsequently made visible through a microscope, in a recent experiment giving a beautiful consistency check on the whole picture: Noji, H., Yasuda, R., Yoshida, M., Kinosita, K., Jr., 1997: Direct observation of the rotation of F_1-ATPase. *Nature,* **386**, 299–302. In the mode of functioning used in the experiment, the power source for the rotation was the 'fuel' ATP (adenosine triphosphate) that powers most cell processes. The normal functioning is in the opposite sense, not consuming but manufacturing ATP as fuel to sustain the rest of the cell. The manufacture of ATP draws on a kind of electric power source in which the 'pulling power of free oxygen' sustains a counterflow of electrons and protons through H^+-ATP synthase molecules embedded in the mitochondrial inner membrane (Ref. 13, p. 19; also, e.g., commentary by S. M. Block in *Nature,* **386**, 217–219). When functioning in this mode, H^+-ATP synthase could be called the world's smallest electric motor.

268. Weinberg, S., 1997: The first elementary particle. Nature 386, 213–215. Musings by a leading physicist on the centenary of Joseph John Thomson's discovery of the electron and on which, if any, particles can be regarded as 'elementary'. Here Weinberg, with admirable caution, ends by saying 'We do not know in advance what are the right questions to ask, and we often do not find out until we are close to an answer.'

269. See the historical remarks on pp. 18–29 of Ref. 38, also the chapter 'To see and not see', about a personal tragedy that could have been avoided, almost certainly, had those involved had the slightest inkling of how perception works. For another such case, see Ref. 210

270. I recently saw a striking demonstration of just how efficient the teaching of a foreign language could become when it works with, or, more aptly, plays with, context and word patterns as the basic elements rather than single words, exploiting also the perceptual and cognitive sensitivity to organic change. It took a mere few days, starting from scratch, for a group of half a dozen English sixth form teenagers to learn to speak simple, everyday French with little conscious effort, almost as small children do. The sixth formers were from among the school's 'language failures', those who had previously found French

difficult to impossible. The basic technique was to get the pupils to play at building organically growing sequences of word patterns, such as (with English pupils learning French): (1) I see, *Je vois;* (2) I see you, *Je vous vois;* (3) I see you there, *Je vous vois là;* (4) I see you in there, *Je vous vois là-dedans.* After getting the pupils' attention, the teacher (holding eye contact with one or other pupil) would pronounce one English phrase and its French translation, then immediately invite pupils to pronounce the French phrase. There was no dissection into single words, no explanation of the word order, and no technical talk of verbs, adverbs, and pronouns. Freed from such distractions, and using their language instincts[12], the pupils effortlessly grasped — to their obvious delight — the word patterns, their functionality, their pronunciations, and the word orders within them. Efficiency was further increased by removing the fear of being tested. The pupils were told at the start to put away all writing materials, and on no account to try to remember anything. Instead the teacher gave, as necessary, minimal prompting, and constant reassurance that forgetting was not a problem. Organic-change sensitivity was also used to build confidence at the start, simply by getting the pupils to pronounce a few everyday French words already familiar from their knowledge of English, such as garage, *garage,* table, *table,* comfortable, *confortable,* and to compare the French and English pronunciations.

To my knowledge there are as yet no publications about this particular teaching system, developed by a self-made communications expert, Michel Thomas. It contains of course elements used in other good systems,[238] including an extremely skilful choice of examples, and personal attention to each pupil. The foregoing description is based on having seen Thomas in action in a sixth form teaching experiment as presented in an excellent television documentary (*The Language Master*, BBC2 Television, 23 March 1997). Thomas is plausibly said to have been earning high fees as a language tutor to Hollywood actors and others, to have 'spent 40 years perfecting his methods', and to have claimed that he can 'teach a foreign language to a novice in five days'.

271. Neidhardt, F. C., Umbarger, H. E., 1996: Chemical composition of *Escherichia coli.* In: *Escherichia Coli and Salmonella: Cellular and Molecular Biology*, 2nd edn, F. C. Neidhardt *et al.*, eds., 13–16. Washington DC, ASM Press (Amer. Soc. Microbiology), 2822 pp. See also Note 279. For variations during the life cycle, see Bremer, H., and Dennis, P. P., *ibid.*, pp. 1553–1569. I am grateful to Dr Vassilis Koronakis for his advice and for drawing my attention to these references.

272. Durant, J., 1997: Beyond the scope of science. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Spring 1997 issue, 56–57. Both this and the article by Fisk in the same issue[274] give sensible discussions of the usefulness and limitations of science, showing very clearly why scientists, and politicians, must resist the pressures to conflate science and politics.

273. Blundell, T., 1997: The Foresight Saga and other stories from the Science Budget. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Spring 1997 issue, 2–4. This commentary is by an eminent scientist who was in a position of national responsibility (Head of the UK Biotechnology and Biological Sciences Research Council) at the time of a sudden research priority switch imposed from above, followed by even more sudden budget cuts imposed on the research councils and universities — sudden in the sense that their announcement broke previous promises and left little time to plan for damage limitation. The general picture is corroborated by much other anecdotal material, including my own personal experience on a policymaking committee of another UK research council, the Natural Environment Research Council. Still more deeply damaging, in the UK, was the earlier whittling-down of the so-called 'dual support system' that used to permit low-cost, exploratory research within the universities, free of onus to produce commercial or other short-term justification. I personally am lucky enough to have had a chance to do research, under the old UK dual support system, that is now recognized as having been important for understanding the fluid dynamics of the stratosphere and the ozone layer. Most of that research would have been impossible to justify at the time. Indeed, in Littlewood's words, the best of it started 'in hopeless muddle and floundering, sustained on the "smell" that something is there.'

274. Fisk, D., 1997: Sound science and the environment. *Science and Public Affairs* (London, Royal Society and British Assoc. for the Advancement of Science), Spring 1997 issue, 46–49.

277. Also included are considerations of experimental design. What needs to be coherent and self consistent is, of course, the whole edifice of experiment and theory. This is further discussed in Appendix 2, §2.8.

278. Shor, P. W., 1994: Algorithms for quantum computation: discrete logarithms and factoring. Proc. 35th Ann. IEEE Symp. on Foundations of Computer Science, IEEE Computer Society Press, Los Alamitos, CA, 124–134.

279. It is worth contemplating what would be involved in simulating not the human brain, nor even an earthworm's brain, but one of the much simpler (prokaryotic) single-celled organisms called bacteria. Even this is, as yet, 'hopelessly beyond the reach of our most powerful electronic computers'.[37] The achievement and validation of such a computer simulation would be an extraordinary scientific advance, helpful, for instance, in the race against antibiotic-resistant bacteria. That race is currently being lost[160] despite the emergence of basic knowledge that should lead to fundamentally more powerful antibacterial weapons — using techniques that, ironically, solve combinatorially large problems by *molecular-biological* rather than by electronic means.[71]

Anyone wanting to simulate a bacterium on an electronic computer will need to recall that a single bacterium is a large system in comparison with a single protein molecule, with a combinatorially vast number of molecular conformations and arrangements in thermal motion on picosecond timescales. For instance the well studied bacterium *Escherichia coli* typically has length $\sim 2\mu$m and mass $\sim 10^{-15}$kg and contains an incessantly interacting and varying population of some millions of protein, nucleic acid, and other large molecules of thousands of different kinds.[271] The complete DNA sequence is now known for the K-12 strain of *E. coli* (Blattner, F. R., et al., 1997: *Science*, **277**, 1453–1474) and appears to imply that the bacterium is potentially able to manufacture up to 4288 different kinds of protein. Note also that the *E. coli* bacterium has less than a thousandth of the volume of a single human neuron,[32] itself a far more complicated (eukaryotic) type of cell.

281. Not surprisingly from this viewpoint, 'rhetorical and poetic speech forms', as well as music, have been noted in many so-called primitive cultures, e.g. by the anthropologist Donald E. Brown (Ref. 12, p. 413).

282. Within the vast literature, see for instance the *Nature* editorial of 27 March 1997 (**396**, 307) on short termism, both in private capital investment and in government management of the science base. UK government research funding of work in, for instance, problems like BSE[160b] is described, consistently with my own and others' experience,[273] as being 'switched on an off like a tap.'

283. There could be no more telling example of such underestimation than the US State Department's mistake over Bosnia, in thinking of the Bosnian and other Balkan problems as 'only religious' [sic] — as if that made them minor problems. According to a lecture by Conrad Russell on BBC Radio 3 (8 August 1995), this showed a profound ignorance not only of human nature but also of the historical record, for instance of the meticulous factual studies of past 'religious' turmoil by the respected historian Dame (Cicely) Veronica Wedgwood. See also, for instance, Refs. 284 and 325.

284. Keneally, T., 1994: Schindler has much to tell us. *The Times* of London, 22 March 1994, p. 20. Thomas Keneally's suggestion that 'people discover race hatred the way lovers discover love....', quoted more fully in Part III (`lucidity3.ps`), seems to put its finger on the essential phenomenon and to explain what is repeatedly observed within many cultures. Keneally describes himself as 'an Australian of Irish Catholic background', and is the author of the book *Schindler's List*, also known as *Schindler's Ark*.

285. Brown, D., 1997: *Cybertrends: Chaos and Accountability in the Information Age.* London, Viking–Penguin, 280 pp.

286*a*. Aiello, L. C., 1996: Terrestriality, bipedalism and the origin of language. *Proc. Brit. Acad.*, **88**, 269–289. Reprinted in: *Evolution of Social Behaviour Patterns in Primates and Man*, ed. W. G. Runciman, John Maynard Smith, R. I. M. Dunbar. Oxford, University Press and British Academy, 297 pp. This is the best brief survey I have seen on this topic, valuably supplementing Wills' book.[13] It describes several lines of paleoanatomic evidence pointing to the development of the human language ability, along with ever increasing brain size and dependence on a high-energy diet, over perhaps the past 500 millennia or so, along with cogent speculations as to what could have preconditioned and driven such a development.

286*b*. Kegl, J., Senghas, A., Coppola. M., 1997: Creation through contact: sign language emergence and sign language change in Nicaragua. In: M. DeGraff, ed., *Comparative Grammatical Change: The Intersection of Language Acquisition, Creole Genesis, and Diachronic Syntax.* Cambridge, MA, MIT Press. In press. See also Kegl, J. A., McWhorter, J., 1997: Perspectives on an emerging language. In: *Proceedings of the 28th Annual Child Language Research Forum* (Stanford), ed. E. V. Clark, 15–38. New York and Cambridge, Cambridge University Press and Palo Alto, Center for the Study of Language and Information.

287. Kevorkian, J., 1991: *Prescription: Medicide — The Goodness of Planned Death.* Buffalo, N.Y., Prometheus Books. 268 pp. (ISBN 0-87975-677-2; available from bookshops and from The Right to Die Society of Canada, P. O. Box 39018, Victoria, British Columbia, Canada V8V 4X8.) This remarkable book presents an outspoken and well documented personal view, based on clear thinking, careful observation, and an exceptional, perhaps unique, fund of experience. It shows the scientific ideal and ordinary human compassion both being applied in the legal and political front line of battle, to some human and social problems that very much underline Gandhi's point.[288] The problems are little recognized because of present taboos against discussing them seriously, but the whole business seems to me typical of what underlies our spiritual malaise. Kevorkian argues that, regardless of whether a society uses the death penalty, judicial and medical behaviour in matters of life and death should become humane, rational, and above all respectful of personal faith and autonomy, as they are not at present, on the whole, in most parts of the world including parts that claim to be civilized. For instance, he reports on interviews he has carried out with prisoners on and off death row, i.e., facing the death penalty, in a number of states in the USA, with results that might surprise some people. Some prisoners not facing the death penalty said that they would nevertheless choose humane death, should such a choice become available, preferring it to many years incarcerated in an overcrowded, cacophonously noisy prison with little privacy among what one prisoner called 'brutal men'. Some of those prepared,

or preparing, to die, said clearly — by written testimony in a fair number of cases — that they would be more, not less, easily reconciled to their own deaths if medical or scientific benefit were to result, such as the saving of other lives by organ transplant or the testing of otherwise untestable medical procedures. The book also points out that, contrary to popular assumption, few medical doctors, in the USA at least, take the famous Hippocratic Oath or even know what it contains. The few doctors who take the oath also break it, in most cases, if only because the oath commits them to an allegiance to certain ancient Greek deities and to sharing their income with their teachers, and to other things not done today. More important, however, Kevorkian's experiences of observing the reality behind the various taboos have let him to argue (*a*) that respect for individual lives, for personal faith and personal autonomy, is widespread among ordinary people, probably a majority, in the USA and other Western democracies, but (*b*) that such respect is, by contrast, minimal among the politicized authorities and professional associations of the same countries, governed, he says, by a mixture of economic incentives, bureaucratic inertia, and fear of fanatical, vociferous minorities powered by hypercredulous belief and hence disproportionately influential. One bizarre and tragic result is that condemned prisoners who petition the authorities to have their organs used to save other lives — and lives would unquestionably be saved because usable organs are scarce — have such petitions routinely and repeatedly refused.

Updates are currently available on `http://www.rights.org/deathnet/Kevorkian_one.html`.

287*a*. On this and on capital punishment, see `http://www.rights.org/deathnet/USnews_9703.html`, which summarizes an interview published in the *Detroit News* of 2 March 1997 with 'top officials from Right to Life of Michigan, a large and powerful lobbying group' in Kevorkian's home state. This lobbying group not only campaigns against assisted suicide but also has many members — as many as fifty percent, by the officials' estimates — who approve of the death penalty. Such approval was put forward, by the same officials, as justifying the group's decision, contradicting its own name, 'Right to Life', to tacitly condone a move to repeal Michigan's present 'constitutional ban on capital punishment'.

288. Schumacher, E. F., 1979: *Good Work.* London, Cape, 148 pp. See Chapter 2 for the Gandhi quote about civilization being 'a good idea', and Chapter 4 for the 'third great illusion' of our time, the illusion that 'science can solve all problems' (the first and second great illusions being that there is room for infinite exponential growth and that society has an infinite supply of mindless labour). The book describes some successful yet humane small business enterprises, some of them meeting third world needs. Schumacher also, in his best known book *Small is Beautiful: A Study of Economics as if People Mattered* (1973), finds words that capture very well the phenomenon I am calling market force hypercredulity: 'Call a thing immoral or ugly, soul-destroying or a degradation of man, a peril to the peace of the world or to the well-being of future generations: as long as you have not shown it to be uneconomic you have not really questioned its right to exist, grow, and prosper.'

289. Harrison, D., 1994: Harmonic Function in Chromatic Music. Chicago, University Press, 337 pp.

290. Bronowski, J., 1973: *The Ascent of Man.* London, British Broadcasting Service; New York, Little Brown, 448 pp.

291. Magee, B., 1987: *The Great Western Philosophers.* Oxford, University Press, 352 pp. An excellent introduction to the classical philosophical background, in the form of an unusually clear, wide-ranging, and accessible discussion. See also Ref. 17, 20*a*, 31, 63, and 245 for, in their different ways, a more specifically scientific perspective. As regards the nature of perception, one might say that the essential intellectual struggle has been to avoid being fooled by subjective introspection.

291*a*. Russell, B., 1961: *History of Western Philosophy and its Connection with Political and Social Circumstances from the Earliest Times to the Present Day,* 2nd edn. London, Routledge, 842 pp. An incisive, authoritative, single-volume summary of 'the celebrated intellectual struggles of the great philosophers', all the way from the Ancient Greeks to the early twentieth century. Referring to 'philosophies' in the sense of theories of knowledge, Russell remarks on p. 592 that, at the time of writing, 'No one has yet succeeded in inventing a philosophy at once credible and self-consistent.' On the origin of 'instrumentalism' (and its emphasis on model-fitting while seeming to ignore the reality to which models are fitted), see pp. 775ff.

292. The positivist view of science is often attributed to Ernst Mach,[226] whose advocacy of it reportedly contributed to Ludwig Boltzmann's suicide. Positivism as advocated today overlaps with several other philosophical 'isms',[45] including versions of so-called 'instrumentalism',[229,245,291a,293a] and Watson–Skinner 'behaviourism',[17] all of which seem, as with the blind men and the elephant, to ignore one or another aspect of the four points (i)–(iv) of the section on 'Scientists in public' of Part III (`lucidity3.ps`). Behaviourism and positivism, especially, use a preconceived notion of 'direct perception' or 'direct observation' — tacitly regarding 'observed facts' as absolute truths, infinitely precise and unambiguous in principle even if not in practice, and certainly not involving any kind of model-fitting or modelling assumptions whether conscious or unconscious. This is the 'veridical perception fallacy' or 'subjective illusion of exactness' mentioned in Note 40 and Appendix 2. See further remarks in §2.8.

293. There have always, of course, in storytelling from time immemorial,[167] been suggestions of other worlds nearly or completely isolated from ours; for the latest such suggestion see Ref. 162 and Smolin, L., 1997: *The Life of the Cosmos.* Weidenfeld and Nicolson. Lee Smolin hypothesizes that the formation

of each black hole spawns a new universe, with dimensions orthogonal to the universe we live in. Whether or not you think this plausible,[162] there is no conflict with the single world hypothesis on which today's science is based. The single world hypothesis need only refer to the world or universe that we observe, live in, and otherwise interact with. There is no difficulty in accommodating observable or unobservable extensions to the hypothesized single world. What arguably violates Occam's razor is the quite different quantum many worlds (Everett) hypothesis that we ourselves, or proliferating copies of us, live in an increasing number of proliferating worlds. The rate of proliferation is unspecified, but its magnitude would have to be combinatorially hyperastronomical (as with the, also unspecified, branch-pruning rates in the partly analogous 'decoherent histories' or 'consistent histories' theories[252]). A slightly less extreme version, not involving proliferation — see also the discussion on p. 135 of Ref. 231 — has recently been advocated in Ref. 293*a*. It permits us to retain the single world hypothesis in its most useful sense, that we ourselves live in a single world or universe even though there is hypothesized to be an infinitude of others. Still unsolved, however, in that version, is the problem of the unspecified trajectory divergence or 'differentiation' rate.

293*a*. Deutsch, D., 1997: *The Fabric of Reality.* London, Allen Lane, 390 pp. This wonderfully perceptive, provocative, and erudite book is, in important ways, less dogmatic and hypercredulous than its more breathtaking assertions might at first suggest. The book talks a great deal about 'truth', but mostly in a clear-headed way that is concerned with 'reality', 'truth', and 'understanding' in what I have called the scientist's shorthand sense, which (p. 241) 'precludes the possibility of certainty'.

Chapter 7 of the book also gives, among other things, an excellent, and superbly lucid, philosphical discussion of the practical workings of the scientific ideal (somewhat like my briefer version in §2.8 above), emphasizing Popper's important contributions. And Chapter 13 gives an excellent brief but typical illustration, for a lay audience, of the scientific ideal and ethic in action 'despite human lapses' (pp. 325–7): 'You need only attend a research seminar in any fundamental field in the "hard" sciences to see how strongly people's behaviour *as researchers* differs from human behaviour in general.' This has been exactly my own professional experience; and such experience helps to expose the flaws in the Kuhnian and social constructivist views, as popularly interpreted,[227d] which point to 'human behaviour in general' as implying the non-existence of any scientific ideal or ethic. The book furthermore develops philosophical notions of 'reality', 'insight' and 'understanding' with which I for one wholeheartedly agree, as would, I think, many other working scientists. They come down to saying that understanding some aspect of reality means, almost by definition, possessing and being deeply familiar with a 'good' model of the reality, where 'good' refers not only to coherence, self consistency, and goodness of fit in the domain of applicability but also to strong, 'aesthetic' constraints from Occam's razor — to just those properties of lucidity, beauty and simplicity that make the model and its implications most 'graspable', most accessible to our deep-seated intuitions, i.e. that facilitate the closest and most harmonious integration of the conscious and unconscious aspects of the model.

The book also makes a case, with passionate eloquence — but now relying solely on the same aesthetic or 'strong Occam's razor' consideration — for accepting a variant of many worlds quantum theory. It appears perhaps less extreme than the original theory of Everett, as usually described (but see Ref. 231, p. 135) because the idea of *proliferating*[293] universes is avoided by postulating a fixed 'multiverse', within which we may distinguish the single universe in which we ourselves live. Proliferation at an unspecified rate is replaced by divergence or 'differentiation', at an unspecified rate, of quasi-classical observer trajectories within the (preexisting) multiverse (p. 280ff.). The strongest point is the argument that what we usually call counterfactual effects in quantum mechanics[53] must reflect something that has objective, outside-world reality: thus, for instance, in the standard single photon interference experiment something real must be going through all the holes or slits. Similarly, one might add, something real must be stabilizing atoms and molecules. This is exactly the 'objective reality of the wavefunction' that 'sharp quantum theories' try to accommodate, beginning with the theory of de Broglie and Bohm, with all its mind-spinning implications of 'quantum non-locality'.[53,231] Trying to picture a multiverse is perhaps one way of beginning to grasp intuitively the enormous dimensionality of wavefunctions and state spaces (Hilbert spaces) needed to account for, among other things, the enormous power of quantum computation (p. 217) with given energy resources. Far less convincing is the implicit claim that the multiverse theory is complete in principle, a close and uniform fit to all aspects of reality — to all of reality — over all time scales and over all spatial scales. Such a claim and various deductions from it would seem premature in view of the vagueness about the trajectory divergence or differentiation rates, and indeed about the extent to which those rates are hypothesized to depend on observer consciousness (Everett's 'radical solipsism'[231]) and hence on a full knowledge of brain function — a vagueness uncharacteristic of the rest of the book, and representing a large gap in the theory that to my knowledge is nowhere near being filled,[53,251,252] let alone tested against experiment. To suppose that Occam's razor is enough by itself to bridge such a large gap seems to me to verge on hypercredulity and to be reminiscent of late nineteenth century feelings about the principles of classical physics — also argued for, at the time, from Occam's razor in just the same way. If and when the gap is successfully filled, there may well be a profound change in how Occam's razor is seen to operate and how the high dimensionality of state spaces — itself surely, I would agree, an aspect of reality — will end up being most lucidly and understandably described. Again, not only the crucial experiments but also the achievement of lucidity becomes 'the work of many individuals'.

294. Chemero, A., 1994: Review of Ruth Garrett Millikan's *White Queen Psychology and Other Essays for Alice* (Cambridge, MA., MIT Press). *Electronic J. Analyt. Philos.*, **2**(6). ISSN 1071-5800 `ejap@phil.indiana.edu` or `http://www.phil.indiana.edu/ejap/`. Anthony Chemero reviews and helpfully discusses not only the above collection, especially the essay 'Truth rules, hoverflies and the Kripke–Wittgenstein paradox', but also Millikan's earlier philosophical writings. These argue, using biological reasoning, for the existence of internal models as necessary for biological function while, in addition, beginning to escape from philosophical traditions that oversimplify the notion of internal model and regard it as passive and static — e.g., 'picture like', or even 'sentence like'. The arguments are made in a general form equally applicable not only to human perception but also to the functioning of the immune system, to bacteria, and to any other organism or sub-organism capable of surviving in the world.

295. As in Appendix 2, I am arguing that this powerful unconscious drive — the drive to prune the combinatorially large tree of possibilities — is an inevitable part of perception and cognition. Survival clearly requires some such process, working ahead of conscious thought.

296. Walzer, M., 1997: *On Toleration.* London, New Haven, Yale University Press, 126 pp. A wise, deeply thoughtful, humane, and practical view of the relevant history and its implications — of the several ways in which the human societies of the last two and a half millennia have, rarely, found it possible to tolerate different belief systems within them, and of the social conditions likely to be crucial to such toleration in the future. The last two chapters explore ways toward what might be called constructive tribalism; see also Biddulph.[257] In his discussion of the most recent kinds of relatively tolerant society, what we call the free market democracies, dependent on the separation of church and state and on having a secular 'civil religion' of national stories, heroes, celebrations etc., hence national identity, Waltzer points out that 'toleration is most likely to work well when the civil religion is least like a... religion' (p. 77), and furthermore that 'Democracy requires yet one more separation, one that is not well understood: that of politics itself from the state... The winning party, though it can turn its ideology into a set of laws, cannot turn it into the official creed of the civil religion; it cannot make the day of its ascension to power into a national holiday, insist that party history be a required course in the public schools, or use state power to ban the publications or the assemblies of other parties. This is what happens in totalitarian regimes, and is exactly analogous to the political establishment of a single monolithic church' (pp. 81–82). See also Perutz, M., 1997: By what right do we invoke human rights? *Europ. Rev.,* **5**, 123–133, & refs. therein.

297. Bell, Martin, 1997: *The truth is our currency.* Four 15 minute radio talks, first broadcast on BBC Radio 4, 16 May to 6 June 1997, by a BBC television war reporter widely respected for his integrity. Transcript available from BBC Videos for Education and Training, 80 Wood Lane, London W12 0TT, UK, fax +44-181-576-2916. The second talk, *News and War*, gave an inside view of what happened in the television reporting of the Gulf and Bosnian wars, and a carefully argued discussion of the implications, some of which are positive: '...in an age of satellite television, crimes against humanity are harder to commit, or at least to get away with, and will ultimately do most damage to those who commit them. The Bosnian conflict occurred at a point of intersection between warfare and news...' But the third talk, *News and Money*, pointed out how market forces, as interpreted by what Kurland[258a] calls the private 'transaction sector' of international financial advisors, economists, and market analysts, are increasingly pressurizing journalists, even reputable international news agencies like Reuters, to do whatever sells newsmedia output regardless of anything else, even human life: '...if...nothing matters but money... then in that case news is only what you say it is. It is whatever sells newspapers or pulls in viewers... Money knows no realities but its own.' This is also a good answer to the science marketeers.[258b,258c] If nothing matters but money, or numbers of publications, or other irrelevant measures of so-called productivity,[312,313] then the results of an experiment are what you say they are — offering, too, the 'efficiency gain' of not having to do the experiment at all.

302. Johnson-Laird, P. N., 1983: *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness.* Cambridge, University Press, 513 pp. See also Ref. 17, p. 545.

303. Milner, R., 1996: Semantic ideas in computing. In: *Computing Tomorrow: future research directions in computer science*, ed. I. Wand and R. Milner, 246–283. Cambridge, University Press, 373 pp. This surveys a research programme that promises deep, general, and practically useful insights into what is involved, conceptually, in building reliable and maintainable computer software. Today's typical haphazard, short term or hand to mouth approach could be superseded by one in which we understand far better what is done with computers and how to use computers safely.

304. The UK Society for Storytelling has plenty of evidence for this. Given a little encouragement, children will 'automatically' create and tell their own stories... 'one form of *Let's Pretend*'... 'everyone can do it'... 'just a matter of boosting confidence'... 'eye contact is important'... 'when the imagination is engaged, people come alive'... 'everyone has a story...', etc. (BBC Television 1, 14/8/97). I have a clear recollection of improvising stories as an 11 year old, for my younger brother and sister — they were about a fantasy underwater world — and even writing some of them down, complete with crude colour

illustrations. I don't think they were exceptional in any way; the point is that, despite being a shy and reticent child, I must have felt a strong urge to create them.

305. The 'growing threat from biological terrorism' was the subject of an expert conference in August 1997 (*Nature*, **388**, 703). Biosensors useful for food safety inspection and disease epidemic monitoring are already under development; but the combinatorially large number of possibilities makes it likely that new concepts and strategies will be needed as well.[71]

307. Easterbrook, G., 1997: Science and God: a warming trend? *Science*, **277**, 890–893. This extended news article usefully summarizes the confusion between questions about spiritual health on the one hand, and questions about explaining natural phenomena on the other. 'In postmodern academic culture, the majority of scientists think that to be taken seriously they must scoff at faith.' (If such scoffing is considered to be part of professional scientific behaviour, then we, the human species, are indeed heading for trouble.)

308. Michaels, A., Malmquist, D., Knap, A., Close, A., 1997: Climate science and insurance risk. *Nature*, **389**, 225–227. A well argued example of how open, credible science can benefit business, in this case the insurance and reinsurance business, with emphasis on the essential role of openness and peer review. See also Ref. 318.

309. Stewart, I., 1997: *Does God Play Dice?* 2nd edn. London, Penguin, 401 pp. Along with Ref. 209, this gives an insightful view of how science works as a model-fitting process, and why mathematics is relevant: 'To criticize mathematics for its abstraction is to miss the point entirely' (p. 363). My remarks in appendices 2 and 3 above are, in effect, an elaboration of this point.

310. Schneider, S. H., 1996: *Laboratory Earth: The Planetary Gamble We Can't Afford to Lose*, London, Weidenfeld and Nicolson and New York, HarperCollins (Science Masters series), 184 pp. This gives a good lay person's explanation of some of the reasons for our large uncertainty about future environmental change — including what is simplistically called 'climate change' — and about what its early warning signals might be. For instance, there are straightforward uncertainties about the numerical magnitudes of critical parameters, concerning cloud droplet sizes for instance, and the rates and modes of transport of water, carbon dioxide and other chemicals and pollutants in the atmosphere–ocean–cryosphere–biosphere system and the concomitant biological adaptations.[160a] Another, more subtle, reason is cogently argued in Ref. 311. For more technical detail see Ref. 342, and for more about the politics see Ref. 318.

311. Palmer, T. N., 1998: A nonlinear dynamical perspective on climate prediction. *J. Clim.*, submitted Sept. 1997. The atmosphere–ocean–cryosphere–biosphere system is a nonlinear dynamical system. What is already known about the general behaviour of such systems[309] implies still greater uncertainty than one might gather from Ref. 310, especially about early warning signals. Palmer's paper uses simple but apt analogies to bring out these points.

312. Strathern, M., 1997: 'Improving ratings': audit in the British University system. *Europ. Rev.,* **5**, 305–321. A thoughtful essay by a distinguished social anthropologist, discussing the audit culture and Goodhart's Law that 'when a measure becomes a target, it ceases to be a good measure'. See also:

313. Neave, G., 1997: On looking both ways at once: scrutinies of the private life of higher education. *Europ. Rev.,* **5**, 305–321. This takes a pan-European view of what is happening to university systems, acknowledging cross-national heterogeneities but also mincing no words about the limitless cost of replacing trust and reponsibility by 'mutual recrimination' and limitless neo-accountability, that is, accountability in the new, incoherent, self-contradictory sense implicit in the audit culture (main text and Ref. 312). One consequence is that 'very few university management models have been tried and weighed in the balance before being put into place': our inability to get the audit culture in perspective has put us, in nautical language, 'at sea with our sails all ahoo and our sheets a-drabble.'

313*a*. A major news feature in the 11 September 1997 issue of *Nature*, (**389**, 113–115) reports that the hypercredulous belief in publication counting, and impact factor counting, is now taking hold in the Asian Pacific Rim countries and causing increasing confusion: one physics professor is quoted as directly conflating quality with quantity: 'Without enough quantity [sic] as a base [!!], high academic quality can rarely if ever be achieved.' This is building the Taj Mahal by dumping rubbish.

314. E.g. Behan, T., 1996: *The Camorra*. London and New York, Routledge, 225 pp. A historical study of the development over nearly two centuries of a powerful and politically sophisticated crime organization, whose first opportunity to establish itself came from the high unemployment in the slums of Naples in the early nineteenth century. This is a clear example of unregulated market forces in action, in much the same way as is now happening most notably in Russia and Eastern Europe.[172,314a].

314*a*. An offer by Russian mafiosi to sell Russian tactical nuclear weapons to supranational drug barons has already been reported on BBC Radio 4, *The World Tonight*, 9 December 1997. If true it would further illustrate the operation of unregulated market forces. Perhaps not surprisingly, I have been unable to confirm this, nor have I any idea whether drug barons or others besides kamikaze terrorists consider such weapons useful...

315. The irrelevance of such passive storage is also underlined by the ways in which the visual arts function. This goes especially for flat pictures, which persistently and successfully use many kinds of

non-photographic representation. The artist and psychologist John Willats has recently made a strong case that pictures by children, and by mature artists from many cultures, hold important clues about the nature of the internal models involved: Willats, J., 1997: *Art and Representation: New Principles in the Analysis of Pictures.* Princeton, University Press, 394 pp. See also the review by John M. Kennedy in *Nature*, **388**, 240–242. The numerous examples remind us that there are many different kinds of flat picture intelligible to us as representing aspects of the outside world. Particularly striking is the commonplace use, in the pictorial art of many cultures, of multiple representational techniques within the same picture, such as different geometric projections for different objects or even for different parts of the same object — all photographically impossible. Willats points out that all this becomes comprehensible as soon as we suppose that the child or artist is representing not so much aspects of the outside world in any photographic sense, but aspects of the corresponding internal models, or 'object centred representations'.

316. Franklin, A., 1997: Are there really electrons? Experiment and reality. *Physics Today*, **50**(10), 26–33. One of the many centenary celebrations, and historical discussions, of what may reasonably be called the discovery of the electron.

317. Mermin, N. D., 1997: What's wrong with this reading? *Physics Today*, **50**(10), 11–13. Another cogent plea for the highest professional standards of argument, with clear examples of how misunderstanding can arise, in discussions of science and its cultural and sociological aspects.

318. Gelbspan, R., 1997: *The Heat is On: The High Stakes Battle over Earth's Threatened Climate.* New York, Addison-Wesley, 278 pp. Important as a substantial and courageous piece of investigative journalism that documents, as far as corporate secrecy permits, the politics and financing of, and newsmedia collaboration with, the fossil fuel industry's propaganda campaign on global environmental change aimed at keeping the heads of the US public, Congress, and Senate firmly in the sand. This is a case of the scientific ideal and ethic, and scientists personally (see also *Nature*, **390**, 649), coming under direct attack by short term commercial interests wielding supranational economic power. Gelbspan's book includes extracts from hearings of the US Congress, and factual material (e.g. pp. 232–236) whose publication was suppressed by one of the major collaborating newspapers, the *Wall Street Journal*; further details of such suppression or watering down is documented in the publicly available article by Avery et al. referred to in Note 169. Although the book contains extensive quotations from testimonies by respected scientists, it does not itself purport to be scientifically definitive; for the scientific aspects see Refs 310 and 342, also the very recent summary and update in *Science*, **278**, 1416–1417.

319. I am grateful to Max Perutz for kindly vetting my statements about the immune system. He prefers to call the immune system's internal models 'templates' — because the model information resides in the shapes of 'antibody' molecules that complement or fit the incoming material hence 'recognize' it and clamp on to it — and to say that the system works by, in his words, 'constructing, by a stochastic mechanism, many millions of different templates, one or other of which may happen to be complementary to any particular chemical compound or viral or bacterial component.' Once the particular compound or component is thus recognized, 'the cell carrying that template on its surface is stimulated to proliferate and make multiple copies of that template' (M. F. Perutz, personal communication). Such proliferation, of a template pattern selected, in a very Darwinian sense, by its goodness of fit to the incoming material, is the main mechanism whereby the immune system can be said to 'fit an internal model' to the incoming data. The system's repertoire of possible models — consisting of its 'many millions of different templates' — is constructed stochastically, by a kind of 'genetic roulette', from preexisting, permutable model components or, so to speak, permutable building blocks, made of DNA segments. See Refs. 319*a*, 319*b* for more detail, including recent work on how the system iteratively improves the goodness of fit.

319*a*. See for instance Frängsmyr, T., Lindsten, J. (eds.), 1993: *Nobel Lectures in Physiology or Medicine.* Singapore, World Scientific, 584 pp, concerning the Nobel Lectures of Nils Jerne (pp. 203–225) and Susumu Tonegawa (pp. 373–405), delivered 8 December 1984 and 1987 respectively. This work is now seen as basic to understanding the more recently evolved parts of mammalian immune systems that give rise to what is called 'acquired immunity',[319b] the system's perception and knowledge of detailed patterns in foreign material. Tonegawa's work, in particular, led to molecular-level knowledge of the actual mechanisms whereby the immune system plays 'genetic roulette' to construct, by trial and error, its basic repertoire of approximate internal models available to be fitted to patterns in incoming foreign material.[319] Recent progress in understanding how the system iteratively improves the goodness of fit is reported in *Science*, **276**, 1658–1659 & refs. therein, particularly Wedemayer, G.J., Patten, P. A., Wang, L. H., Schultz, P. G., Stevens, R. C., 1997: Structural insights into the evolution of an antibody combining site, *Science*, **276**, 1665–1669. An ingenious experiment has illustrated in great detail, in one case, just how far the fit can be tightened through 'the well understood process of antibody maturation'.

319*b*. Fearon, D. T., 1997: Seeking wisdom in innate immunity. *Nature*, **388**, 323–324. A useful discussion of acquired and innate immunity, summarizing an emerging understanding of how the evolutionarily more ancient components of a mammalian immune system seem to direct the 'attention' of the less ancient model-fitting process, as I am calling it. The more ancient components, 'innate' in the sense of being fixed in genetic memory, and lacking a large repertoire of models to fit to incoming patterns, are found also in invertebrates and seem more oriented to detecting general damage caused by invaders.

In mammals, such damage or 'danger' information seems to be part of what tells the model-fitting system[319,319a] when and where to look for an invader, and part of what stops it looking for and attacking its owner's own tissues. See also, e.g., earlier correspondence and controversy in *Science*, **272**, 1405–1408. Such an attention-directing role of more ancient parts of the system seems to me to deepen the partial analogy between immune system function and brain function.[32]

320. Anyone with normal hearing can easily and effortlessly tell that the sound of the piano note precedes the sound of the pip in such cases. Audio demonstrations are available on the Internet[8] in the PC `.wav` files `lucidity-radiopips100.wav` and `lucidity-radiopips200.wav`, giving the 100 and 200 ms cases respectively (low quality, each just over 100 Kbyte), and in the MIDI file `lucidity-radiopips.mid` (just over 200 byte), giving both cases together. In musical language, the effects in the 100 and 200 ms cases could be described as a leisurely 'dotted rhythm' and 'grace note' respectively.

320*a*. An animated .gif file with these nominal timings is displayed on my web site: `http://www.atm.damtp.cam.ac.uk/people/mem/`, click on 'lucidity and science'. If correctly displayed, one complete cycle should take just under one second.

321. Recordings of the musical examples used in Appendix 2 are available on the Internet[8], for download in binary mode, as audio PC (`.wav`) files at sampling rates 22 kHz and 44 kHz (standard compact disc quality). The recordings use a standard high quality computer driven sound module. Though unable to match the delicacy and subtlety of the best human performances, they are accurate realizations of the written scores and sufficient illustrations of the points under discussion. The files, in the order mentioned in the text, are named `lucidity-piano1...`, `lucidity-orch1...`, `lucidity-orch2...` (the 1–1 mapping version), `lucidity-piano2...`, and `lucidity-orch3...`, where the dots denote a suffix like `-22m.wav` or `-44s.wav` indicating the sample rate and whether mono or stereo, `-22m.wav` files being the smallest, about 0.7 Mbyte each. The corresponding written scores are in the graphics files `lucidity-piano12.gif`, `lucidity-orch1.gif`, `lucidity-orch2.gif`, and `lucidity-orch3.gif`. I am grateful to Ben Finn of Sibelius Software (`http://www.sibelius-software.com`) and Jeffrey Ginn of Ginn Music (`http://www.ginn-mus.demon.co.uk`) for lending their professional expertise with the audio recordings, and to the composers Alexander Goehr, Robin Holloway, Virginia Seay Ploeser, Yuval Shay-El, Roderick Skeaping, and Hugh Wood for advice on the scoring. (They all agree that an accompaniment designed to preserve the musical sense of the piano solos would have to change harmony at, not after, the time of the arrow.)

322. Fermat's last theorem, that the equation $x^n + y^n = z^n$ has no positive integer solutions (x, y, z) when n is an integer greater than 2, has challenged mathematicians ever since Pierre de Fermat stated it well over three hundred years ago. The chapter on it in Ref. 16, p. 74–79, gives a view from the 1920s; the theorem was not proven until the 1990s. The proof draws on deep and wide-ranging concepts, far beyond anything Fermat is likely to have known, and was found by the ex-Cambridge mathematicians Andrew Wiles and Richard Taylor. Readers interested in a brief commentary by an expert in the field may consult Coates, J. H., 1996: The work of Andrew Wiles. *Not. Amer. Math. Soc.*, **43**(7), 760–763. A more substantial survey for a nonspecialist but mathematically literate reader, explaining some of the key ideas but stopping short of the full, and very formidable, technicalities, is that of Ribet, K., 1995: Galois representions and modular forms. *Bull. Amer. Math. Soc.*, **32**, 375–402. Full technical details are given in a 139-page survey of the problem and its history by Darmon, H., Diamond, F., Taylor, R., 1997: Fermat' last theorem. In: *Elliptic Curves, Modular Forms, and Fermat's Last Theorem*, 2nd edn. only, ed. J. H. Coates and S.-T. Yau, Internat. Press, 2–140. I am grateful to John Coates for providing these references. The reader may also like to note the popular accounts, both entitled 'Fermat's Last Theorem', by Simon Singh (Rhône–Poulenc shortlist 1998). and Amir D. Aczel, 1996, New York, Four Walls Eight Windows, 147 pp.

323. See pp. 5, 89 of Ref. 16 for comments on the relations between prime numbers and complex functions. Note also the vivid description, on pp. 249–256 of Ref. 53, of how complex numbers, a key stage in the journey toward complex functions, were discovered, against all the odds, by Gerolamo Cardano in the 16th century.

324. The creation of anything worth creating, in the arts and sciences equally, *always* seems to involve an intricate interplay between conscious and unconscious contruction. This is well described on pp. 191–6 of Ref. 16. There are the celebrated 'eureka moments': 'illumination, which can happen in a fraction of a second, is the emergence of the creative idea into the conscious', and there is the less celebrated, but arduous, preparation for such moments, impossible without 'an intense conscious curiosity about the subject... a craving to exercise the mind on it, quite like physical hunger' lasting for many years. There is the need to find ways, different for different individuals, of 'giving the subconscious every chance'; see also Note 34 of Part I. There is the 'devastating experience' of losing the curiosity and the drive to undertake such arduous labour. All of this should be required reading for science policymakers and bureaucrats.

325. Ehrenreich, B., 1997: *Blood Rites: Origins and History of the Passions of War* London, Virago/Little Brown, 292 pp. This is the most cogent attempt I have seen to explain what is perhaps the oldest of all ritual magic, the evocation of the religious ecstasy of war and martyrdom and the transformation of ordinary humans, male or female, into killers or sacrificial offerings or both. The book points out that

the associated behaviour patterns and animistic–theistic imagery, beginning with the infantile fear of the dark, could well have had pre-linguistic origins arising simply from the dependence on large predators, as well as exposure to attack by them, that was probably associated with our ancestors' transition to a migratory, ground-dwelling existence in open country around 2 million years ago. Lacking highly developed hunting skills and weapons, those early ancestors of ours would not only have been regular victims of large predators but would also, very probably, have depended on scavenging from kills by the same predators. This, plus the increasing dependence on a high quality diet[286a] demanded by increasing brain size, and the fact that we became predators ourselves, goes further than most theories toward explaining why our psyche and mythology are so full of deities combining the roles of fickle benefactor and devouring monster, to whom humans must be prepared to become martyrs for the sake of the group or tribe and with whom humans must also, from time to time, do battle — what is called wrestling with angels. The ecstasy of war, of martyrdom, and of other blood rites must indeed have had survival value, and its connection with today's warmaking psychology is conspicuous. Anyone who thinks that human sacrifice is a thing of the past should read this book as well as Ref. 418.

326. Ouyang, Q., Kaplan, P. D., Liu, S., Libchaber, A., 1997: DNA solution of the maximal clique problem. *Science*, **278**, 446–449.

328. Keller, E. F., 1996: Science and its critics. In: Menand, L., (ed.) *The Future of Academic Freedom*, 199–213. Chicago, University Press, 239 pp. This is a thoughtful and serious reply to Gross and Levitt,[200] and to my own first horrified reaction to the cultural relativist and related philosophies.[200–204,227d]

329. Fuller, S., 1997: Is science policy superstitious? The view from Mars. *Interdisc. Sci. Rev.*, **22**, 194–198. The author, a sociologist, answers 'definitely yes', and with some justification — though my ideas on what to do about it are quite different from his, as can be seen from my discussion. This article seems typical of the 'science wars' literature, very much in line with the 30th Anniversary BBC Horizon programme.[201] It minces no words about science as something 'loathsome', and anything but 'objective' or 'rational'. It is worth reading in order to get an idea of the sort of fury that has been evoked by attempts to sell Science as the Answer To Everything.[288] Afterwards, I recommend reading Ref. 328.

330. Kennedy, D., 1997: *Academic Duty*. Cambridge, MA, Harvard University Press, 310 pp, ISBN 0-674-00222-9. A passionate and well informed plea for taking professional responsibility seriously, with emphasis on university teaching, the other side of the 'academic freedom' bargain.

342. Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., Maskell, K. (eds.), 1996: Climate Change 1995: The Science of Climate Change (Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge, University Press, 572pp. ('IPCC 1995/6'). For most of the essential points, see also Mahlman, J. D., 1997: Uncertainties in projections of human-caused climate warming. *Science*, **278**, 1416–1417. This is a brief but careful summary and update by a highly respected expert, with clear emphasis on the balance of probabilities.

343. Warrick, R. A., Le Provost, C., Meier, M. F., Oerlemans, J., Woodworth, P. L., 1996: Changes in Sea Level. Chapter 7 of Ref. 342, 361–405. See Fig. P1.9, p. 385.

344. Lebrecht, N., 1996/1997: *When the Music Stops... Managers, Maestros and the Corporate Murder of Classical Music*. London, Simon and Schuster/Pocket Books, 455 pp. Note the dawning of hope at the end, from the small music festivals and recording companies that have escaped the clutches of international market forces, e.g. 'Marlboro radiates a moral counter-culture', p. 411.

400. The words 'I would know my shadow and my light, so shall I at last be whole' were written, and set to music of great simplicity, power, and beauty, by the English composer Michael Tippett, during the darkest years of the Second World War. They express a vision of hope that is needed today. See p. 136 of Tippett, M. K., 1944: *A Child of Our Time*, oratorio for soli, chorus and orchestra London, Schott & Co. Ltd., 157 pp.

401. The options are not only the numerous and surprising options that stem directly from science and technology. (Kauffmann's book, Ref. 71, is a good reminder of just how numerous, and just how surprising, such options are becoming.) There are also the burgeoning numbers of options for new ways of organic cultural change, especially now that global scale information technology is beginning to emerge from its infancy and, for powerful economic reasons, developing a degree of resistance to partisan control and censorship at national and subnational level.

402. S. Jasanoff *et al.*: 'Conversations with the community: AAAS at the millennium', *Science*, 1997, **278**, 2066–2067. A useful summary of recent thinking by the AAAS, the American Association for the Advancement of Science, about the crisis in public understanding and the role of science in society. There is a web site for an open forum on these issues: http://www.sciencemag.org/feature/data/aaasforum.shl/

403. J. Lubchenko: 'Entering the century of the environment: a new social contract for science', *Science*, 1998, **279**, 491–497. A followup to Ref. 402, written by the President of the Association, making the case for a new social contract for science — meaning mainly its financial support — in return for a

commitment by scientists to something that is unprecedented, namely to recognise that 'we now live on a human-dominated planet' and that this requires something else that is unprecedented: serious attention to what is happening to our planetary life support system. At present, for instance, 'only a few of the thousands or so new chemicals released each year are monitored; the biological effects of most are unknown...'

403*a*. R. A. Pielke Jr and R. Byerly Jr: 'Beyond basic and applied', *Physics Today*, 1998, **51**(2), 42–46. More discussion of the putative new social contract for science, which will be determined by 'political decisions with scientific input... not scientific decisions implemented through politics'. The crisis in science *is* the crisis in public understanding.

404. Medawar, P., 1982: Hypothesis and imagination. In: *Pluto's Republic*, Oxford, University Press, 351 pp. Also in *The Art of the Soluble*, London, Methuen (1967). A spirited defence of the role of imagination and intuition, the unconscious side of scientific thinking, which is always important: 'The belief that great discoveries and little everyday discoveries have quite different methodological origins betrays the amateur' (p. 124).

406. 'Memetic' is from 'meme' as 'genetic' is from 'gene'; a meme is an infectious idea regarded as an element of cultural evolution, that can self replicate and undergo mutation; thus one might say that the nature–nurture dynamic is 'genetic–memetic', involving an intricate and complex interaction of genes and memes.[13,206,209] The word 'meme' was coined by Richard Dawkins in his justly famous though also much misunderstood[156] 1976 book *The Selfish Gene*; see also, for instance, Dawkins, R., 1986: *The Blind Watchmaker.* London, Longman 1986 and Penguin 1988, 332 pp., and, for instance, Goodenough, O. R., Dawkins, R., 1994: The 'St Jude' mind virus. *Nature*, **371**, 23–24.

410. McIntyre, M. E., 1997: Lucidity and science II: From acausality illusions and free will to final theories, mathematics, and music. *Interdisc. Sci. Rev.,* **22**, 285–303. Roughly equivalent to the (out of date) Appendices 2 and 3 above (Internet version `lucidity.ps`).

411. McIntyre, M. E., 1997: Lucidity and science III: Hypercredulity, quantum mechanics, and scientific truth. *Interdisc. Sci. Rev.,* **23**, 29–70.

412. Andersen, S. O., Miller, A., 1996: Ozone layer: the road not taken. *Nature*, **382**, 390. This briefly but cogently argues for the enormous benefits, political and economic, of allowing technologies and markets to respond early to environmental change — of keeping our collective heads out of the sand. The 'ozone wars' of the 1970s and 1980s and their resolution provide a telling example, and grounds for hope. Once the scientific picture became clear enough, 'industry helped policy-makers to choose schedules that were technically feasible and allowed time for wise choice' while, conversely, a late start would have forced industry and customers 'to select from among the very first technologies available', reducing cost effectiveness as well as public confidence. Earlier action would have been still more beneficial.

414. E.g. Gopnik, M., Dalalakis, J., Fukuda, S. E., Fukuda, S., Kehayia, E., 1996: Genetic language impairment: unruly grammars. *Proc. Brit. Acad.*, **88**, 223–249. Reprinted in: *Evolution of Social Behaviour Patterns in Primates and Man*, ed. W. G. Runciman, John Maynard Smith, R. I. M. Dunbar. Oxford, University Press and British Academy, 297 pp. This presents strong psychphysical evidence that the impairment of syntactic or grammatic function such as the ability to form regular plural nouns from singular nouns, as with 'wugs' from 'wug', can be a heritable genetic defect.

416. E.g. Mithen, S., 1996: The early prehistory of human social behaviour: issues of archeological inference and cognitive evolution. *Proc. Brit. Acad.*, **88**, 145–177. Reprinted in: *Evolution of Social Behaviour Patterns in Primates and Man*, ed. W. G. Runciman, John Maynard Smith, R. I. M. Dunbar. Oxford, University Press and British Academy, 297 pp. This interesting and scholarly discussion concentrates on prehistoric visual arts and visual symbolisms and their social uses, such as body adornment with beads, bracelets, and pendants. Such arts, symbolisms, and uses are evident in the archeological record for the Upper Paleolithic, the last few tens of millennia of the glacial climate starting between about 35 and 60 millennia ago in different parts of the world. For the preceding period going back perhaps several hundred millennia, called the Early Paleolithic, there is strong evidence from 'numerous well preserved sites' that 'no objects of art were produced'. The author suggests that the transition to cultures with visual arts signalled 'a dramatic increase in cognitive fluidity'.

418. Hinde, R. A., 1997: War: some psychological causes and consequences. *Interdisc. Sci. Rev.*, **22**, 229–245. An eminent animal and human behaviourist analyzes the nature and cost of modern warfare, and the cultural and institutional aspects of its perpetuation. Complements Ref. 325's insight into the 'predisposing factors' and 'eliciting factors'.

420. Blakemore, C., 1977: *Mechanics of the Mind.* Cambridge, University Press, 208 pp.

422. Elliott, R., 1997: Threats to full and open access to scientific data, *ICSU Focus*, Autumn 1997, **10**, 3–4. Further information from Dr Peter Collins, Science Advice Section, The Royal Society, 6 Carlton House Terrace, London SW1Y 5AG, UK, tel. +44 171 451 2584). For an update on the growth of this threat, see e.g. a news item by Tony Reichhardt in *Nature*, 30 July 1998, **394**, 410, concerning the USA's Coble and Grams bills and the World Intellectual Property Organization.