# Lucidity and science

## I: Writing skills and the pattern perception hypothesis

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**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 civilisation.**

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, aspects to be further explored in Parts II and III of this series.

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 recognising the shapes of letters, words, and punctuation marks, and far more than recognising word patterns and syntactic structures. It is the whole problem of decoding and understanding what is written, and so I am using a generalised, 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 reasonable working hypothesis – 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 will be discussed below. The hypothesis has practical value, though it would be difficult to test directly. 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 10 per cent 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, summarised 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 that could be described as iterated 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 crystallisation 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'. Recognisability 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 minimise repetition, mistakenly feeling that what bores the writer will also bore the reader. This urge to minimise 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:

> Example 1. 'Whereas the spectral method engenders Gibbs fringes, no discretisation oscillations are manifested by the TVD algorithm.'

The writer meant:

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

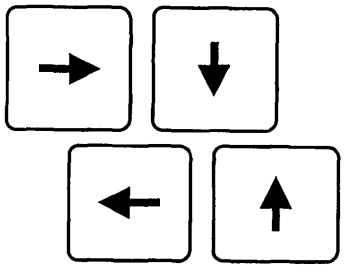
A series of needless variations like those in Example 1 can drag the reader into a quagmire of confusion. Fowler ironically calls them elegant variations. But they could well be called pseudoelegant or muddy variations or, more simply, gratuitous variations. The pattern perception hypothesis says that 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), 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 minimising 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 $a$, $M'_3$, $\varepsilon_2$, $\Pi''_{1,2}$ 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



**1 Arrow key layout: a choice of style?**

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.

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...',[28] 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 recognisable. 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:

> Example 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.

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 be lucid (Fig. 2 overleaf). For the rest of us it is wise to play safe, especially when making a first draft (Appendix 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

**2 'Emma La Forge' (1914), by Henri Matisse (*see* Acknowledgements)**

examples such as:

Example 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:

Example 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:

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

Here a different pattern involving a different grouping, three things in the same category, is recognised 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] Figure 3 below is a visual example from classic studies in experimental psychology.[27] It consists of 13 identical dots, which are automatically seen as four main groups. The first 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

**3 Visual grouping by proximity**

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 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 pre-existing 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] 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] 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 will be noted in Part II, with keys to the literature. Though not understood in detail, the hypothesised 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 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 a 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

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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 tantalising 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 organising '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]

## 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:

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

Example 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] Genius or not, and whatever the style, the writer who wants to be effective must give the reader's unconscious model fitting a chance.

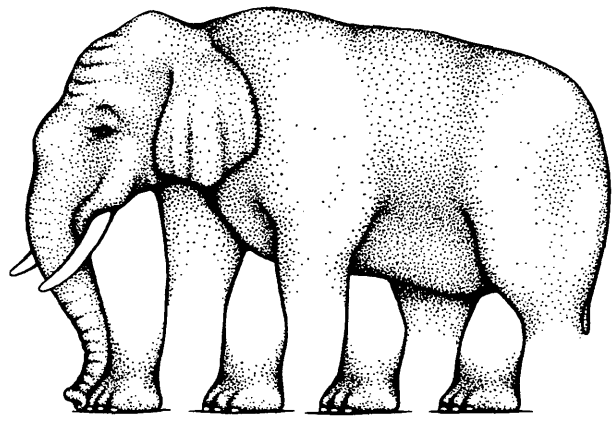
Such considerations underlie Strunk and White's challenge to the writer of literary prose 'who is being intentionally obscure or wild of tongue... Be obscure clearly! Be wild of tongue in a way we can understand!'[10] One might add, in some cases, 'Be ambiguous in a way that makes sense!' As well as 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. '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. 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,



**4 Roger N. Shepard's[28] drawing of an impossible elephant, an elephant not identical to itself[52] (*see* Acknowledgements). 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'**

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, 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 organised structures

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

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

(iii) 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 here 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 lacks automatic checking against this kind of thing; there is a strong biological reason for this, to be pointed out in Part III. 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

There is, of course, 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', of the mysterious 'number' $\mathcal{N}$, or of something ineffably 'not... identical to itself'.[49,52]

Figure 4 opposite 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.

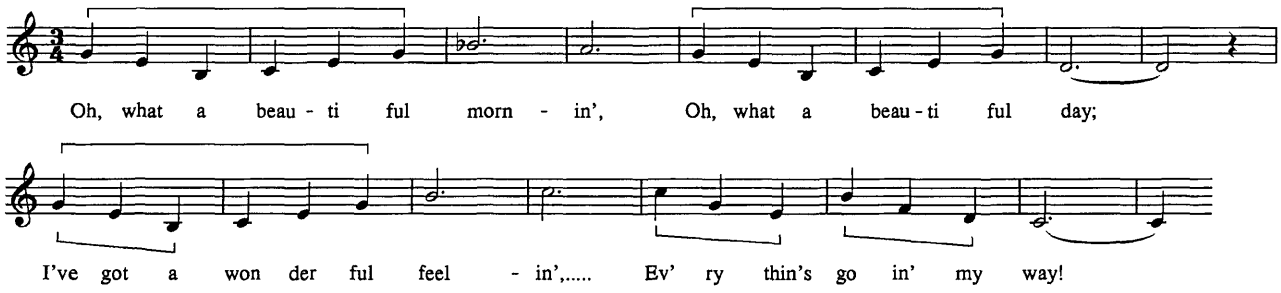
This is one way in which the arts and associated intellectual adventures may validly differ from science. As great artists have shown – be they labelled ancient, modern, postmodern, or timeless – it can be humanly important to celebrate the ineffable, the ever mysterious, the intractably incongruous. 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 civilised 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.

## 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,




**5 The refrain from Richard Rodgers' 'Oh, what a beautiful mornin'' (*see* Acknowlegements). In the first line, for instance, both the words and the music show an organically changing pattern of the type 'Surprising how often ... surprising how seldom'**

to exist in human infants and to be highly developed in preschool children, (Ref. 12, pp. 422–426 and references); 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 known as music, or rather the familiar, but remarkable, phenomenon known as music. Music directly 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 shall argue in Part II 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 mimic 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.[23,43,55,56] The famous tune of Richard Rodgers' 'Oh, what a beautiful mornin'', is a simple but sufficient example. It is reproduced in Fig. 5; further examples are mentioned in Note 57. In Fig. 5, notice the organic change not only in the tune itself, but also in the total pattern of words and music. Organic change also permeates 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. It is crucial that each new point is preceded by any necessary preparation, to set contexts and to establish key ideas (Appendix below). 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 recognisably 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 highly explicit, 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). 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 argued 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 the 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.

## 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.' (Ref. 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',[8] second, read Chaps. 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.

# Appendix

## 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:

> Example 1′. 'Whereas the spectral scheme produces Gibbs fringes, the TVD method gives rise to no discretisation oscillations.'
>
> Example 1″. 'Whereas the spectral method produces Gibbs fringes, the TVD scheme does not cause them to occur.'
>
> Example 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 slight slipperiness underfoot. The writer who thinks that repetition should always be minimised 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 – unless you know to a hairsbreadth what you are doing[65] – 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'. 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.

There are inappropriate uses of pattern-repetition. Strunk and White[10] give an example under the heading 'Avoid a succession of loose sentences.' A conspicuous pattern, having a strong rhythmic effect, is insistently repeated when to do so is pointless: there are no correspondingly strong deeper connections. One might speak of inappropriate or incongruous pattern-repetition. Further discussion of this example is available on the Internet.[8]

## Acknowledgements

I thank the Engineering and Physical Sciences Research Council for generous support in the form of a Senior Research Fellowship, and the Raymond and Beverley Sackler Institute of the University of Tel Aviv for its kind support and invitation to air these thoughts in a special public lecture, delivered 26 April 1995. I thank also the many patient teachers, referees, editors, graduate students, and colleagues who have influenced or helped me. I am especially grateful to my wife Ruth, whose perceptive and penetrating comments, and whose supreme artistry as a musician, have long been an important influence, and to Grigory Isaakovich Barenblatt, who saw the wider implications more clearly than I did at first and who greatly encouraged and stimulated me with several key suggestions. I am also extremely grateful to George Batchelor, Douglas Gough, and James Woodhouse, from whom I first learned some of the techniques of lucidity, to James Maas who kindly supplied data for the walking lights demonstration,[31] to the clarinettist and conductor Antony Pay, who contributed several crucial insights about speech, music, and writing technique, and, for further stimulation, advice or information, to Michael Atiyah, Terry Barker, Horace Barlow, Colin Blakemore, Walter Bodmer, Dave Broutman, Gillian Beer, Gustav Born, Oliver Bühler, Maxine Clarke, Francis Crick, Ian Cross, Anna Cutler, Margaret Davies-Mitchell, David Deutsch, Anne Edgeworth, Artur Ekert, Kerry Emanuel, Marie Farge, Chris Frith, Peter Goddard, Alexander Goehr, Richard Gregory, Jack Harris, Sarah Hawkins, Chris Heron, Antony Hewish, Robin Holloway, Brian Hoskins, Bryony Hoskins, Jackie Hoskins, Nicholas Humphrey, Cuyler Hunt, Julian Hunt, John Inglesfield, Robert Inglesfield, Gunnar Jansson, Sergei Kapitza, Bernard Katz, Adrian Kent, David Klausner, Vassilis Koronakis, Paul Kushner, Vivien Law, Roger Lemon, James Lighthill, John Lynch, Ian McDonald, Iain MacKenzie, Robert MacKenzie, Houari Merabet, Anthony Michaelis, Robin Milner, John Mollon, Philip Mote, Nick Nikiforakis, Roger Penrose, Max Perutz, Nicholas Pinhey, Brian Pippard, Virginia Seay Ploeser, Keith Ryan, Uri Samir, Trevor Samols, R. Saravanan, Mark Schoeberl, Richard Scott, Nick Shackleton, Yuval Shay-El, Keith Shine, Alison Sinclair, Abner Shimony, Roderick Skeaping, Sean Spence, Barbara Spiegel, John Thuburn, Suki Towb, François Vial, Bruno Voisin, Judith Weiss, Marie Wells, Paul Whittle, Estelle Wolfers, Lewis Wolpert, and Hugh Wood. Last but not least, I am grateful beyond measure to my parents, Anne McIntyre and Archie McIntyre, who first, from my earliest childhood, encouraged and nurtured my curiosity about what hangs together.

Figure 2 is reproduced by permission of The New York Metropolitan Museum of Art, Harris Brisbane Dick Fund, 1929 (29.89.13).

Figure 4 is from: MIND SIGHTS by Shepard.[28] Copyright by Roger N. Shepard. Used with permission of W. H. Freeman and Company.

Figure 5 on p. 206 reproduces a lyric and music excerpt of 'Oh, What A Beautiful Mornin'' By Richard Rodgers & Oscar Hammerstein II



## 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 the evidence so far that any resemblance cannot be simple, and that the old textbook neuron–synapse picture merely scratches the surface.[70] We may recall, however, one point that is uncontroversial: both neurons and protein molecules can compute.[2–4]
2. C. KOCH: 'Computation and the single neuron', *Nature*, 1997, **385**, 207–210. Summarises 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'.[71]
3. J. MONOD: 'Chance and necessity', (transl. A. Wainhouse); 1971, 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 (Chap. 4). The far reaching implication, further discussed in Ref. 71, is that an arbitrarily specified logical or computational system can be realised 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, a theme to be revisited in Part III.
4. D. BRAY: 'Protein molecules as computational elements in living cells', *Nature*, 1995, **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 N. BARKAI and S. LEIBLER: 'Robustness in simple biochemical networks', *Nature*, 1997, **387**, 913–917 (commentary, p. 855), and R. M. DICKSON, A. E. CUBITT, R. Y. TSIEN, and W. E. MOERNER: 'On/off blinking and switching behaviour of single molecules

of green fluorescent protein', *Nature*, 1997, **388**, 355–358.

5. D. C. MARR: 'Vision: a computational investigation into the human representation and processing of visual information'; 1982, 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. R. JACKENDOFF: 'Consciousness and the computational mind'; 1987, Cambridge, MA, 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. D. HOFSTADTER and co-workers: 'Fluid concepts and creative analogies: computer models of the fundamental mechanisms of thought'; 1995, New York, BasicBooks, 518 pp. *See* especially Chaps. 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'.
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.atmos-dynamics.damtp.cam.ac.uk/ and ftp://ftp.damtp.cam.ac.uk/pub/papers/mem/lucidity*. A string searchable ASCII file lucidity-supplem.tex 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 MPEG (.mpg) files illustrating the 'walking lights' phenomenon,[31] 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 $5 \times 10^5$. (Gratzer[66] implies $3 \times 10^7$, a horrifying 'one per second', but let us stick with the more conservative estimate.) 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 10 per cent saving on average. Ten per cent 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 $5 \times 10^5$ year$^{-1} \times 10^{-1}$ scientist-year $\times 10^{-1} \times$ US$10^5$ scientist-year$^{-1} \sim$ US$0{\cdot}5 \times 10^9$ year$^{-1}$.
10. W. STRUNK and E. B. WHITE: 'The elements of style', 3rd edn; 1979, 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. H. W. FOWLER: 'A dictionary of modern English usage', 2nd edn', (revised E. Gowers); 1983, Oxford University Press, 725 pp. This work, 'Fowler Two' – as distinct from 'Fowler Three', see below – 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 'Chicago manual of style' (14th edn; 1993, Chicago, University Press, 921 pp.), especially when publishing in the USA where it commands wide recognition; and *see* also, for instance, N. D. MERMIN: What's wrong with this prose? *Physics Today*, 1989, **42**, (5), 9–11. Typical and fundamental insights can be found in the articles in Fowler Two on gratuitous or (pseudo-) **elegant variation**, **rhythm**, and **grammar**; *see* also **side-slip**, cf. Example 7 above. 'Fowler Three', the so called 3rd edn or 'New Fowler's' of 1996, is a different work by a different author with an entirely different aim and, along with Crystal,[68] is a useful source of information on recent trends in vocabulary and usage. It features a good article on **split infinitive**, with many wonderful examples from the fourteenth century onward, though missing the rhythmic and emphatic significance as in 'to BOLDLY go'.
12. S. PINKER: 'The language instinct: the new science of language and mind'; 1994, 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 'creolisation' or instinctive language reinvention by children. Also, relevant to my discussion of 'organic change', pp. 422–426 describe psychological studies with infants and very young children demonstrating a powerful, culture independent and manifestly instinctive sense of 'living versus dead' and an instinctive categorisation of living creatures. Some of this seems to be demonstrable even in infants around 1 year old. Reference 23, within a growing literature, has evidence about other infant abilities that might or might not surprise you. Pinker, as does Sacks,[38] also gives a telling but humane riposte to cultural relativism, dispelling the notion that the only alternative is 'brutal biological determinism'; *see* also:
13. C. WILLS: 'The runaway brain'; 1994, 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 (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 evolution in general. Here is abundant evidence – *see* for instance discussions of genotype–culture feedbacks and the 'Baldwin effect' – for a most intimate and subtle interplay between nature and nurture, between biological and cultural evolution.
14. This is a real example from *Proc. R. Soc. (London)*, 1993, **A 440**, 530, 11th line from bottom. Also D. EDWARDS *et al.*: 'My pear tree has gone bananas: the

collected philosophy of Don Edwards'; 1986, London, Reader's Digest Assoc. and Multiple Sclerosis Soc., 33 pp.

15. M. W. GREGORY: 'The infectiousness of pompous prose', *Nature*, 1992, **360**, 11–12. This 'Commentary' 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. Gregory rightly complains about what pretends to scientific professionalism, but amounts to tribalistic pressure to write in obscure and pompous ways – *see* also L. AVERY: 'Write to reply', *Nature*, 1996, **379**, 293 – which pressure, in my opinion, should be stoutly resisted even when it comes from journal editors and referees. *See* also Ref. 66 for an example of obscure and pompous prose, from a published scientific paper, that outdoes even Example 1.
16. J. E. LITTLEWOOD: 'A mathematician's miscellany'; 1953, Paperback reissue as 'Littlewood's miscellany', with further material, (ed. B. Bollobás; 1986, Cambridge, 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 that I mentioned, the notation $a$, $M'_3$, $\varepsilon_2$, $\Pi''_{1,2}$ 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', as when the word 'red' is printed in green letters.[32]
17. M. HUNT: 'The story of psychology'; 1993, 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 Chap. 18, p. 606. *See* also, for instance, C. CORDES: *Amer. Psychol. Assoc. Monitor*, May 1983, **14(5)**, pp. 1 and 13–14. Hunt also gives a convenient collection, with historical commentary, of standard examples of visual perceptual phenomena in Chaps. 10 and 14, e.g., grouping, pp. 287ff.
18. *See* 'false scent' in Ref. 11 and 'garden path sentences' in Ref. 12.
19. Gap filling is perhaps best known in vision, as with the log behind bars. We are normally unaware of our retinal blind spots (Ref. 32, pp. 55–56; 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] as well as a perceptual phenomenon. Such disputes are circumvented, or, rather, transcended, if one accepts the hypothesis made here, and further discussed in Part II of this series, that perception works by unconscious model fitting. No useful internal model will have features corresponding to incidental gaps in, or masking of, sensory data.[30]
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 at once that the 'trivially obvious' statement was, in Littlewood's words, 'dead wrong'.
21. Minutes of the Sixth Annual General Meeting of the excellent Save British Science Society (Oxford, PO Box 241, OX1 3QQ, UK, http://www.dspace.dial.pipex.com/sbs/).
22. A. BREGMAN: 'Auditory scene analysis: the perceptual organization of sound'; 1990, 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.[30] (Essential reading, in my opinion, for anyone learning musical composition, more so than the average counterpoint text. I am grateful to Ian Cross for drawing my attention to this reference and the next.)
23. S. E. TREHUB and L. J. TRAINOR: 'Listening strategies in infancy: the roots of music and language development', in 'Thinking in sound: the cognitive psychology of human audition', (ed. S. McAdams and E. Bigand), 278–327; 1993, Oxford, Clarendon Press, 354 pp. This contains important recent evidence, and thoughtful discussion, bearing on the roles of genetic and individual memory in the development of perceptual processing.
24. R. L. GREGORY: 'The intelligent eye'; 1970, London, Weidenfeld and Nicolson, 191 pp. *See* especially p. 39 (Chap. 3).
25. J. P. FRISBY: 'Seeing'; 1979, 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 (e.g. Ref. 32 p. 111–112); the subjective impression of still greater speed is likely to be an 'acausality illusion'. These points and the experimental evidence that bears on them will be discussed in Part II. What is important for the moment is that perceptual grouping takes place ahead of conscious thought.
27. J. MADDOX and D. C. MARR: 'Theorems of vision'; 1979, Radio interview in the series 'Mind, matter and mechanism' ('Scientifically Speaking', BBC Radio 3, 19 March 1979). *See* also Ref. 5.
28. R. N. SHEPARD: 'Mind sights'; 1990, 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' description (Ref. 38, Chap. 1) of a case of brain damage that did, seemingly, allow some slight direct awareness of that same shifting, intermittent, pointillistic retinal imagery – enough to cause distress, disorientation, and inconvenience to the person concerned, the painter 'Jonathan I'.
29. G. L. BATESON: 'Style, grace and information in primitive art', in: 'Steps to an ecology of mind: collected essays on anthropology, psychiatry, evolution and epistemology', 101–125; 1972, San Francisco, CA, 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, Goethe, Popper, and other careful thinkers recognised long ago, begs all the questions about how perception works; indeed it begs just about every epistemological question there is. Parts II and III will give further discussion of this point, with reference to the cognate philosophical viewpoints called 'behaviourism', 'instrumentalism', and 'positivism'.
31. G. JOHANSSON: 'Visual motion perception', *Sci. Amer.*, June 1975, **232**, 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. Digitised versions of two 'walking lights' demonstrations made by Johansson and colleagues James Maas and Gunnar Jansson have been converted to MPEG (.mpg) files and placed, with their kind permission, on the Internet web site.[8] I am extremely grateful to James Maas, Stuart Dalziel, and Nicholas Pinhey 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 S. ULLMAN: 'The interpretation of visual motion'; 1979, Cambridge, MA, MIT Press, 229 pp.
32. F. CRICK: 'The astonishing hypothesis'; 1994, 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. Be warned, however, that the research frontier is moving very fast.[2]
33. N. HUMPHREY: 'A history of the mind'; 1992, 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', emphasising feedback between levels, i.e., the 'top down and bottom up' character of the process,[7,39] 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[30] 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 20 metres away.
34. M. L. J. ABERCROMBIE: 'The anatomy of judgment: an investigation into the processes of perception and reasoning'; 1989, 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. M. PIATTELLI-PALMARINI: 'Inevitable illusions: how mistakes of reason rule our minds'; 1994, 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 $\frac{1}{2}$. This is the brain's unconsious Occam's razor getting things wrong. It takes conscious mental effort to see that the probability is still $\frac{1}{3}$ and that the probability of the remaining, unfingered card being the ace is now $\frac{2}{3}$. *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 M. Griffiths: 'Health and the National Lottery', *Science and Public Affairs*, Spring 1997, 5–7.).
36. E. DE BONO: 'Practical thinking'; 1971, Republished 1976, London and New York, Penguin, 189 pp. Discussion centres around a simple exercise in scientific model fitting, tried out on 1000 people, analysing '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. Refs. 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 even today come nowhere near rivalling human vision, despite the huge economic incentive and the decades of research effort.
38. O. SACKS: 'An anthropologist on Mars: seven paradoxical tales'; 1995, 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 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 hypothesise 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. See for instance T. FRÄNGSMYR and J. LINDSTEN (eds.): 'Nobel lectures in physiology or medicine'; 1993, 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. I am grateful to Max Perutz for drawing my attention to Tonegawa's work. The analogy will be touched on again in Part II; further notes are available on the Internet.[8] Again one sees the typical 'top down and bottom up' character.
40. 'Sufficient goodness of fit' bears further scrutiny. 'Sufficient' means, broadly speaking, sufficient for survival, under the limitations imposed by data and internal models. It clearly cannot mean exact fit – even though there is a subjective illusion of exactness, of perceiving reality directly and unambiguously.[30] 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. 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 need only think of classic examples like the 'barber's pole' illusion,[32] 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, in certain circumstances. Further notes and recent references are on the Internet.[8]
41. G. L. BATESON: 'Mind and nature: a necessary unity'; 1979, New York, Dutton; London, Wildwood then Fontana, 238 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. S. A. BARNETT: 'Of course, some of my best friends study Eng. Lit.', *Interdisc. Sci. Rev.*, 1993, **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. M. DAVIES-MITCHELL: 'Poetics now?', *Europ. Rev.*, 1994, **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, this is just what is to be expected on biological grounds – and it now seems likely that art forms that would today be called poetry must have been in existence for hundreds of thousands of years or more. I return to this in Part III.
44. H. MARKL: 'Language and the evolution of the human mind', *Europ. Rev.*, 1997, **5**, 1–19. A lively and perceptive survey by an animal behaviourist with a clear vision of the role of juvenile, and adult, play. There is also a useful bibliography of recent references, including many on primate behaviour and 'machiavellian intelligence'.
45. K. POPPER: 'Unended quest', revised edition; 1992. London, Routledge and Kegan Paul, 276 pp, and references therein. Underestimating, or trivialising, Karl Popper's ideas still seems to be fashionable, even though they are highly relevant to today's problems 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.[30] The idea of ordinary perception as a model fitting process – as automatic, unconscious 'conjecture and refutation' – emerges clearly on p. 139. *See* also:
46. D. T. CAMPBELL: 'Evolutionary epistemology', in: '*The philosophy of Karl Popper*'; Library of Living Philosophers, Vol. 14, (ed. P. A. Schilpp), 413–463; 1973, LaSalle, IL, USA, 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. A. SHIMONY: 'Integral epistemology', in 'Search for a naturalistic world view', Vol. 1, 'Scientific methods and epistemology', 3–20; 1993, Cambridge, Cambridge University Press.
48. L. WOLPERT: 'The unnatural nature of science'; 1992, 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 much philosophical fog, to say nothing of political and commercial fog.[35,36,62] The late John Bell ('Speakable and unspeakable in quantum mechanics', 166; 1987, Cambridge University Press, 212 pp.) has argued cogently to the effect that the term 'measurement', as often used in discussions of quantum mechanics, is likewise a self contradictory term.
50. D. BOHM: 'On Bohr's view concerning the quantum theory', in: 'Quantum theory and beyond', (ed. T. Bastin), 33–40; 1971, Cambridge, Cambridge University Press. Bohm's point here 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. 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 for quantum mechanics, as well as to recognise 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. Further notes and references will be given in Part III and are also on the Internet.[8] The feeling is that quantum mechanics today is still emerging, very slowly and painfully, from what the admirable Doctor de Bono calls an 'intermediate impossible' or 'crazy ideas' stage.[36] Bohm's discussion well illustrates the points I make in the last two sections of the main text about Stroop interference and, more generally, about the effort to achieve lucidity becoming 'the work of many individuals'. The late John Bell[49] has been another notable contributor to this effort.

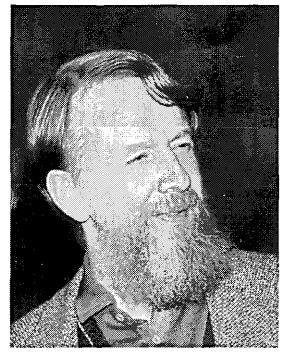
51. S. GOLDSTEIN: 'A theorist ignored: review of *Infinite Potential: The Life and Times of David Bohm*, by F. D. Peat', *Science*, 1997, **275**, 1893–1894, and other papers at http://math.rutgers.edu/oldstein. *See* also reviews in *Nature*, 1997, **385**, 592, by Chris Philippidis, and in *Physics Today*, 1997, **50**, (3), 77–78, 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".'
52. J. DERRIDA (transl. P.-A. Brault and M. B. Naas): 'The other heading: memories, responses and responsibilities', *PMLA (Publ. Modern Lang. Assoc. Amer.)*, 1993, **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.
53. R. PENROSE: 'Shadows of the mind: a search for the missing science of consciousness'; 1994, Oxford, University Press, 457 pp. This book presents among other things a passionate, lucid, and superbly knowledgeable advocacy of the Platonic view of mathematics by a leading mathematical physicist. Further notes are on the Internet.[8] The book is very clear on quantum mechanical fundamentals, and in this regard is an important reference for specialists and non-specialists alike.
54. I. STRAVINSKY: 'Poetics of music'; 1942, 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 elements in music; *see* also Refs. 22 and 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, had 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 realised 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 strongly rhythmic pattern-repetition.
56. A. PAY: 'Phrasing in contention', *Early Music* (Oxford University Press), 1996, **24**, 291–321. 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. Further examples of this type of pattern include Gershwin's 'I Got Rhythm', the 'Ode to Joy' from Beethoven's Ninth Symphony, 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', the 'Goin' home' theme from Antonín Dvořák's 'New World' Symphony, and some of the themes from Igor Stravinsky's 'Rite of Spring'. Stravinsky's 'Rite', 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. 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 famous opening bassoon melody has a strong ABAC feeling, though broken up and interrupted – in detail, more like AA″A′A‴, or, loosely, '*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. Many of the 'rules' or guidelines about powerful harmonic progression, or motion, or function, in Western polyphonic music, helping the music to 'go somewhere' – and representing the discoveries made by composers working in a vast range of so called

tonal and atonal, classical, jazz and other styles – can be summarised in a fundamentally simpler way than one might think from the music theoretic literature. This simplicity must have been noticed by many composers, some of whom may well have regarded knowledge of it as a trade secret. The essence of it – which is culture independent – is that the patterns of pitch change are usually organic in the sense discussed in the text above, with the notion of 'small enough increments' of pitch change referring to the two kinds of perceptual proximity to which the ear–brain system is sensitive. These are adjacent-pitch proximity and Pythagorean or circle-of-fifths proximity, the latter reflecting the role of the harmonic series as a model building block necessary to make sense of 'a jungleful of animal sounds'. In this respect musical space can be like the hyperspace of science fiction stories: it is possible to go somewhere that is both nearby and also far away. Further discussion and references are available on the Internet,[8] together with a few examples, including the so called 'Tristan chord', in an expanded version of this note in the file lucidity.ps.

59. A. GOEHR: 'Music as communication', in: 'Ways of communication', (ed. D. H. Mellor), 125–142; 1990, Cambridge, University Press. Alexander Goehr, one of our most respected masters of musical composition, 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. W. A. MOZART: 'A Musical Joke'; 1787, 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 37–38, and the gratuitous change in harmonic colour on the second beat of bar 38.
61. The basic techniques are care over first-occurrence signposting (*see* Appendix) 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 in turn reduce, even if not eliminate, the chances of the words and symbols being used inconsistently.
62. E. MACNEAL: 'Mathsemantics: making numbers make sense'; 1994, 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 especially to work by Constance Kazuko Kamii and collaborators. They have developed techniques that successfully use juvenile play to build numeroliteracy in young children.
63. S. WEINBERG: 'Dreams of a final theory – the search for the fundamental laws of nature'; 1993, Vintage Books, 260 pp. *See* especially pp. 64–66.
64. J. R. KLAUDER: 'Magic without magic' (John Archibald Wheeler Festschrift); 1972. San Francisco, CA, 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.tex:[8] string search 'Masters'.) For the rest of us, it is still wise to play safe.
66. W. GRATZER: '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 will be discussed in Part III. (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, literally, 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 trivialisation of the original, shorter term.)
67. J. M. ZIMAN: 'Public knowledge: the social dimension of science'; 1968, 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. Ziman also 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 uses 'we' to refer to himself or herself only, in the manner of 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. D. CRYSTAL: 'The Cambridge encyclopaedia of the English language'; 1995, 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 rapidly, 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. K. WARWICK: 'March of the machines: why the new race of robots will rule the world'; 1997, 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. S. KAUFFMAN: 'At home in the universe: the search for laws of self-organization and complexity'; 1995, New York and London, Viking Penguin, 321 pp. This passionate, penetrating, and well informed essay on biological complexity refers especially to the arbitrariness, or freedom, of protein logical and computational functionality, and its self-organisational abilities, also emphasised and explained by Monod.[3]

The manuscript was received 15 May 1996.



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