Emerging out of nature into history: the plurality of the sciences

By John Ziman†
Department of Physics, HH Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

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The idea of a ‘theory of everything’ is inconsistent with a natural feature of biological evolution: the spontaneous emergence of composite entities with completely new properties. At successively higher levels of complexity, from elementary particles and chemical molecules, through unicellular and multicellular organisms, to self-aware human beings and their cultural institutions, we find systems obeying entirely novel principles. The behaviour of such systems is not predictable from the properties of their constituents, so distinct ‘languages’ are required to describe them scientifically. The plurality of our sciences is thus an irreducible feature of the universe we live in. In particular, the reversible time coordinate of mathematical physics cannot cope with the natural ‘path dependence’ of biology. In the human sciences this extends into the imagined future as well as the remembered past. Furthermore, science nowadays usually arises in localized social contexts, where the ‘logic of the situation’ is continually being transformed by the emergence of cultural novelties such as unpredictable technological innovations. Thus, scientific knowledge cannot be restricted to generalized synchronic models, but involves historical narratives of specific events and unforeseen circumstances.

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1. The credo of Laplace

The boldest claim that was ever made for science was famously formulated nearly 200 years ago by Laplace, the greatest disciple of Newton. We all know the substance of what he said. In brief, it was that if a sufficiently vast and powerful intelligence were given all the forces of nature, and also knew the current situation of ‘all the beings that compose it’, then all the past, and all the future, would be ‘present to its eyes’. It seems that Laplace was not actually the first person to make such a daring assertion (Barrow 1991), but this vision of a ‘theory of everything’ has been with us ever since. It was put more jocularly by, I think, T. H. Huxley, the famous Victorian biologist. I cannot now recall his precise words, but it was to the effect that John Tyndall, a well-known British physicist, believed that it would be possible to predict Hamlet from a knowledge of the forces between the atoms in a mutton chop.

† Present address: 27 Little London Green, Oakley, Aylesbury HP18 9QL, UK.

One contribution of 13 to a Theme ‘Information, knowledge and technology’.
J. Ziman

Well, that sort of mental machismo was excusable amongst astronomers, but the people who studied the sources of *Hamlet* or the genesis of mutton chops were not taken in by it. In fact, their research led them to quite the contrary notion. By the late 19th century, it was becoming clear that the entities that they observed, classified and analysed were multiply composite. That is, biological species were composed of individual organisms, which were composed of cells, which were composed of chemical compounds, and so on. As we went back up this hierarchy we encountered entities with significant characteristics that were not found at all at lower levels. This feature of the natural world could, it seemed, be explained by Darwin’s theory of evolution.

In 1874, however, the biologist G. H. Lewes—partner of the now more famous writer George Eliot—suggested that it exemplified a more general principle, which he called *emergence* (Lewes 1874). This was, simply, that entities could (and sometimes did) come into existence with properties that could not be predicted from knowledge of their constituent parts.

From then on, the Laplacian doctrine could be countered by reference to this principle. But it was all too often confounded with ‘vitalism’, as if emergence were a manifestation of an ineffable ‘life force’. Lewes himself put it forward in a strictly naturalistic context, as an empirical scientific phenomenon without non-material or supernatural implications. For the next century, however, this unmetaphysical interpretation of emergence was only sustained by a few philosophers and theoretical biologists. In 1923, for example, C. L. Morgan wrote an influential book entitled *Emergent evolution* (Morgan 1923), clearly dissociating it from the intuitionist speculations of Henri Bergson on what seemed to be the same theme.

By the 1950s, however, this somewhat pessimistic train of thought had been shunted into a siding by the mighty intellectual engine of neo-Darwinism. Since then it has become commonplace to assert, in the spirit of Laplace and Tyndall, that a mutton chop was just the automatic resultant of its genes, which were themselves merely very cunning assemblies of totally lifeless chemical molecules. The socio-biologists and evolutionary psychologists have even extended this doctrine upwards to the personal and cultural level. Human behaviour, we are told, can be ‘reduced’ to the operations of our neurons, even to the heritable make-up of our genes.

2. Reductionism and its discontents

The trouble is that ‘reductionism’ is completely, absurdly, wildly impractical. Even its most zealous adherents admit that a genuine Laplacian calculation on even a tiny segment of the natural world will never be feasible. Indeed, Laplace himself uttered his dictum to justify the probability concepts that were needed to finesse all the practical difficulties. Reductionists fully accept that empirical observations and phenomenological theories will continue to be needed, at every level, to suss out all the messy details requiring explication. They entirely agree that for the foreseeable future there must be no faltering in the vigorous pursuit of all the different sciences. So they say that reductionism is true ‘in principle’, even if it cannot always be achieved ‘in practice’. They apparently envisage a scientific *last judgement*, where the findings of all these sciences will simply turn out to be specific instantiations of a *final theory*—ideally a mathematical equation.

This is not a suitable occasion for entering into the philosophical battle that rages around this exalted doctrine. In any case, from a naturalistic point of view, reductionism has always been a powerful research strategy. It has continually inspired the quest for a formalism uniting the fundamental laws of physics, and motivates the ‘reverse engineering’ that has elucidated such important mechanisms as the quantum physics that underlies chemistry and the molecular biology that explains genetics. But from that same point of view it can be considered a supposedly universal theoretical principle that invites empirical falsification. So let us consider the phenomenon of ‘emergence’ in that more limited scientific spirit.

In particular, what we shall find is that we now have something like a theory of ‘emergence’ itself, and we can understand why it is not just an adventitious phenomenon. It first became evident as a little local difficulty in evolutionary biology, but is now seen to have much wider epistemological implications. It is sometimes thought that emergence signifies a cognitive defect, corresponding to a regrettable limitation of the human mind. We shall see, rather, that it is associated with certain general features of the natural world and cannot be eliminated by more enlightened analysis.

The argument rests mathematically on recent findings in the theory of complex systems, that is, of dynamical systems that are so large and complicated that it is fruitless to try to calculate or compute their behaviour exactly. It is now common knowledge that the behaviour of such systems is often ‘chaotic’. It is not so widely known, however, that there are also some circumstances where they can exhibit quite orderly behaviour. What is more, the actual nature of this order is often completely unpredictable. In other words, although a very complex system may be perfectly deterministic in every detail, it can have overall properties that only ‘emerge’ as it is set in motion.

This is not to suggest that every instance of ‘emergence’ in the natural and human sciences can be modelled theoretically by such a system. It just implies that any aspect of the world that can in fact be modelled naturalistically in this way is theoretically capable of exhibiting irreducibly ‘emergent’ behaviour. Thus, after more than a century, we now have a rationale for Lewes’s rejection of supernatural explanations for this familiar scientific phenomenon. His recognition of the epistemological significance of the different levels of complexity in nature is also well justified. It is often thought, for example, that the traditional lines of demarcation between the physical, biological and human sciences are just arbitrary social constructs. The main conclusion of this paper is that these epistemic dividing lines actually correspond to almost insurmountable barriers between genuinely distinct realms of knowledge, all of which are equally ‘fundamental’.

It must be emphasized, however, that I am not pretending to say anything particularly original. This is a field of theory into which I was led personally by my interest in technological innovation (Ziman 2000b), but where I have done no primary research. Fortunately, the relevant findings are well covered by three excellent, non-technical yet authoritative, books (Auyang 1998; Cohen & Stewart 1994; Kauffman 2000), from which I have drawn liberally. Although these books are different from one another in style and tone, they are all beautifully clear, readable and intellectually responsible. They scarcely cite one another, yet they depict much the same rich landscape of fascinating ideas. All that I am doing here is trying to show that there is a path through this landscape that may bring us a little nearer to a far-distant goal.
This path starts in the realm of general theory. What do we mean by a 'system'? It all depends on the context. For mathematical purposes, a system is just any composite entity with constituents that interact dynamically with one another. Each constituent can be treated as a module: a 'black box' whose internal workings are invisible but which reacts to external forces according to prescribed rules. To make any intellectual progress at all, one has to assume that the interactions are relatively simple and 'local'. One must imagine, for example, that if a limited set of the constituents were disconnected from the rest of the system their behaviour could be calculated, or computed, or estimated with reasonable plausibility, step by step, in a Laplacian spirit.

But suppose that the system is truly complex, in that it has so many constituents and/or their interactions are so complicated that any such overall calculation is manifestly not feasible. Suppose that we were trying to model the behaviour of, say, a drop of water, containing $10^{23}$ molecules, or a human brain, containing $10^{10}$ neurons, or a social institution with thousands of highly individualistic members. Can anything definite be said about its properties as a whole?

The first thing to say is that formal mathematical analysis has not progressed beyond the most elementary cases. Onsager’s famous analysis of the two-dimensional Ising lattice (see, for example, Ziman 1979) did prove rigorously that even a very simple thermodynamic system could undergo a phase transition. In other words, at a certain temperature an orderly structure could 'emerge' in a system that was effectively chaotic at higher temperatures.

That was in 1944. Since then, theoretical physicists and chemists have done an immense amount of work on more elaborate model systems showing this sort of behaviour. But this work has one very serious limitation: the nature of the emergent order is almost always fed into the calculation at the beginning, not derived analytically as the final outcome of deterministic dynamical processes (Laughlin & Pines 2000).

Take, for example, the case of water. At high temperatures it is quite reasonable to treat each H$_2$O molecule as a tiny hard sphere, and to use statistical methods to calculate the behaviour of the gas. But what happens when the gas is cooled? What sort of orderly structure will emerge? You say that it condenses into a 'liquid'? What is that? I once spent years studying the physics of liquids, but never came across a formal mathematical definition of this perfectly familiar state of matter. The best we can do is a picture of randomly packed spheres (Ziman 1979). There still seems nothing like a proof that this is what must emerge in a system of hard spheres when it is cooled sufficiently.

And then again, cool water further and it forms ice. Taking into account the rules about the chemical bonds between the molecules, that makes sense. But it turns out that there are 13 different varieties of ice, depending on the temperature and pressure (Klug 2002). Could all of these structures have been cerebrated in advance of their emergence in experimental situations? And yet this is quite a simple system in terms of its basic constituents and rules of interaction.

More significantly, take a layer of liquid water, and heat it uniformly from below, while keeping its upper surface cool. It is elementary physics that heat will be transferred through the liquid by convection, that is, by the movement of warm, buoyant
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liquid from the bottom to the top, where it is cooled down and sinks back again. A regular cellular arrangement of rising and falling columns of liquid is soon established; an orderly structure has emerged spontaneously in the system. Once it is established, one can easily show that it is thermohydrodynamically optimal and stable, etc. Structures like these—for example, the vortex streets that are produced in the turbulent wake of a moving body in a fluid—are commonplace in nature. They are typical 'features' of real complex systems. Yet until they have actually been observed they seem to be almost impossible to 'predict' from the basic equations.

Indeed, as Philip Anderson pointed out (Anderson 1972), condensed matter physicists are accustomed to the emergence of entirely novel structures in the systems they try to model. He associated this with the principle of 'broken symmetry', and used it to discredit the reductionist fantasies of the elementary particle theorists. He also suggested that this principle could be extrapolated up the hierarchy of complex systems, and thus provided a conceptual justification for the independent pursuit of the natural and social sciences at each and every level of complexity. But Anderson fully admitted that this analysis was highly speculative: can it now be made more rigorous?

4. Methodological modularity

One point is obvious: once an unforeseen structure has emerged in a complex system, our whole mathematical strategy has to be changed. When a fluid becomes turbulent, for example, one can no longer assume that its constituents—little local packets of moving fluid, say—interact with one another on an equal footing. The place of each packet in relation to the vortex structure is the primary factor in its behaviour. To make any sense of the situation, one has to treat the vortices themselves as something more than 'features' of the system. They begin to be seen as distinct objects, apparently moving as units and interacting with one another according to simple rules. Indeed, this was precisely the conceptual step that transformed meteorology into a predictive science. The cyclones and anticyclones that appear on the weather map are vortex structures that emerge naturally and are treated as more or less persistent entities by the forecasters.

At this point, of course, a lot of questions arise about the nature and properties of these emergent entities. How stable are they? Do they have a variety of forms? How do they interact with one another and so on? Research devoted to these matters is needed. A whole new science develops. But surely we must not stop there. We are well aware that the 'system of the world' is far larger and more complex than our basic model could ever have hoped to encompass. Have we any way of extending our analysis further?

The answer is well known. We simply treat these newly discovered entities as the constituents of a greater system. Yes, of course, we know that each of these constituents is actually a composite system. But it might turn out to be sufficiently stable and self-contained to operate as a module in a larger scheme. Remember that Descartes depicted the Universe as an assembly of interacting vortices. What are the molecules in our thermodynamic model of water but electronically bonded systems of oxygen and hydrogen nuclei? What are nuclei, but systems of baryons? Baryons, so we now believe, can be decomposed conceptually into quarks, and so on.

Well, of course, we are right back at the conventional paradigm of a multi-levelled scheme of ever more inclusive systems. But it is not intellectually honest to treat this as an abstract scheme that we have worked out in our heads. Scientists did not develop it step by step upwards in order to facilitate their scientific thinking. It is only really available to us because it is a fact of nature. Human beings were presented with a world that they could indeed dissect into a nested hierarchy of relatively stable composite entities of various levels of complexity. The baryons, nuclei, molecules, living cells, multicellular organisms, conscious beings and social institutions that we found in nature were related to each other in just that way. So at each level of the hierarchy we not only found entities that could be analysed into lower-level constituents: we were also supplied with modular constituents for a higher-level model.

This is such an obvious feature of the scientific world picture that we often forget that it is an empirical fact of nature, not a theoretical necessity. It may be, of course, that our brains are so constructed that we could only have made progress in understanding the world by filtering its booming buzzing confusions through a set of perceptual nets of this kind. Certainly, we need to be very careful not to treat as distinctive ‘natural kinds’ all the compound substances or physiological organs or biological species or societal institutions that were discovered and described by the first scientific explorers of each domain of nature. We know of many naturally occurring entities that are actually capable of nearly independent existence. As Auyang (1998) points out, however, these are not necessarily satisfactory, just as they stand, as the theoretical constituents of a conjectural higher-level system. A lot of science goes into studying their properties and reshaping them hypothetically into suitable modules for that sort of model.

Nevertheless, all such abstractions and idealizations have to have a basis in facts, and those facts could have been quite otherwise. We just happen to be living in that sort of world. The multilevel hierarchy that we take for granted is not a logical necessity like a mathematical theorem. It developed spontaneously in the course of time. It is an emergent ‘feature’ of the whole world system, and like all such features it was ‘unpredictable’. Its actual incidence and structure could not—and still cannot—be cerebrated in the absence of considerable knowledge of what they would turn out to be, or now are.

5. The emergence conjecture

At this stage in the discussion, my instinct as a theoretical physicist is to try to produce some sort of mathematical justification for my statements. What we need are a few theorems. Unfortunately, the general theory of complex systems has little to say about emergence as such. We do know, however, that the dynamical behaviour of such a system need not be just either boringly uniform—like a frozen crystal, for example—or else completely chaotic. It can also fall spontaneously into any one of a number of other more or less regular patterns: regular in the sense that they repeat themselves endlessly in a fixed cyclic order over time.

To demonstrate this, mathematicians imagine a very abstract space in which every possible configuration of the system is represented by a point. The forces acting inside the system cause this configuration to change, so this point is continually moving. When the system is chaotic, it just moves around all over the place. But sometimes
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it finds itself on a closed cyclic path called an ‘attractor’. This path may be very long and convoluted. Nevertheless, it only passes through an almost infinitesimal fraction of the absolutely enormous number of points in the configuration space. That is, it must correspond to a regularly repeated configuration—i.e. an orderly pattern of dynamical behaviour—of the system as a whole.

So we do have a mathematical rationale for the possible emergence of higher-level patterns of behaviour in any dynamical system which is sufficiently complex. We also have some ideas about the circumstances in which this is most likely to occur. Thus, for example, there are good arguments favouring Kauffman’s dictum that ‘living systems exist near the edge of chaos’, and that this is where ‘avalanches’ of emergent change are most pervasive (Kauffman 2000). Similarly, Cohen & Stewart (1994) argue that new patterns are most likely to emerge in systems where several distinct configuration spaces are combined, as in the closely linked co-evolution of biological phenotypes and genotypes, of chickens and eggs, so to speak.

But these are only conjectures, not theorems. Although there must be innumerable forms of order that could in principle appear, we have no assurance that any of them will actually be simple enough to be recognizable as a distinctive ‘feature’. And even if we had a formal proof—something like Gödel’s theorem in mathematical logic—that such ‘features’ must exist, this theorem would not give us any information about their properties. Anderson’s proposition that these must somehow correspond to a change of ‘symmetry’ does not seem very helpful above the level of physics and chemistry. In mathematical terms, knowledge of the properties of an emergent ‘feature’ could only be obtained by actually solving the dynamical equations, step by step, until we happened to hit upon a configuration that was near enough to an invisible ‘attractor’ to be unexpectedly captured by it. In reality, it is more practical to just set the actual system running and then wait patiently for some new form of order to appear.

Much of the discourse about complex systems is concerned with the geography of their configuration spaces. Biological evolution, for example, is often depicted as the search for peaks in a ‘fitness landscape’ spanning such a space. But that is just an abstract mathematical metaphor, which should not be taken too literally. Indeed, it may be that the notion of a set comprising all the ‘possible’ configurations of a particular complex system is not always meaningful (Kauffman 2000). In statistical mechanics it is useful because physical systems such as gases are normally ruled by their most probable configurations, that is, by the multitude of configurations that are outwardly almost identical. But once evolutionary selection begins to operate, the outcome may easily derive from an extremely improbable configuration, for example, the one bacterium in a billion that just happens to be resistant to an antibiotic.

This is not, of course, to deny the scientific value of speculation about ‘alternative worlds’. For example, cosmology has surely benefited from debate about the Anthropic Principle—the idea that the fundamental physical laws and constants had to be what we find them to be, otherwise we could not have been there—or, rather, here—to find them (Barrow 1991). Similarly, the biological and human sciences are enriched by fictional scenarios that thoughtfully imagine non-terrestrial biospheres and explore their ecology and sociology. But such intellectual exercises could never cover more than an infinitesimal proportion of all the ‘possible’ world systems that would surely have to be included in a serious analysis of how this particular one actually eventuated. Indeed, their principal lesson is to reinforce the contingency

principle of systems theory; that is to say, that an emergent 'feature' owes many of
its characteristics to the accidental circumstances of its appearance rather than to
any a priori necessity. This, too, is a conjecture rather than a theorem, but is almost
certainly true.

6. Novel features and entities

Thus, the most important finding of general systems theory is negative: it seems
quite fruitless, if not absolutely impossible in principle, to try to predict the emer-
gence of higher-level 'features' with novel properties. And here, by 'novel', I mean so
unprecedented that they delineate entities of a completely new type.

Go back, for example, to the molecules that condense out of the atoms in the
primeval plasma. These still have *physical* properties as localized spatial structures.
But they have also acquired the interactive properties that we have learnt to repre-
sent conceptually as chemical reactivity. For some of these, such as catalysis, there
would have been no precedents in a monatomic world. But perhaps, in very simple
cases, these properties too might possibly have been imagined prior to their actual
appearance on the scene.

Suppose, however, that we want to treat such molecules as the constituents of
a very complex system representing a thick, warm soup. Their *chemical* properties
then become dominant. The immense variety of molecular entities that might be
formed can only be represented manageably by a correspondingly immense array
of abstract symbols. The properties that allow them to combine, divide, recombine,
etc., are summed up in formulae for the manipulation of these symbols. In other
words, we have to model the system in an entirely new way. Its whole conceptual
framework—the nature of its constituents, the domain in which they are defined,
and the rules by which they are deemed to interact—is of a completely new type.

This, again, is not a particularly novel observation. It is perfectly obvious that the
entities that emerge at each level in the natural hierarchy have very different prop-
erties. A living cell has properties that far transcend those of a very large chemical
molecule and so on. This is the essence of the phenomenon of emergence. But in
our enthusiasm for unifying theories we may overlook just how very different these
entities really are.

In a *multicellular organism*, for example, the constituents are spatially localized
and interact mainly with their immediate neighbours: in an *ecosystem*, the con-
stituents are widely distributed populations of distinct species that interact over
time through competition for resources. The *molecules* that react chemically in an
organic cell are material entities: the *commercial firms* that react economically in
an industrial society are intangible social constructs. Below the biological level, all
the entities are lifeless: above this level they are 'autonomous agents' (Maturana &
Varela 1992), whose system properties are continually subject to evolutionary selec-
tion. Again, the emergence of the genetic code fundamentally altered the conceptual
domain in which complex macromolecular systems are thought to evolve. And below
the consciousness level the constituents do not generate 'holistic' fields of interac-
tion: in social systems this property—via the mass media, for example—can become
paramount.

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The most striking difference between the various types of entity that can be constituents of complex systems is in their relation to time. Let me quote Sunny Auyang (1998):

mechanical processes lack a preferred temporal direction. Directionality appears in thermodynamic processes, which nevertheless have neither past nor future. Evolution is a historical process in which past changes are frozen into the structures of present organisms. Economic agents use the capital accumulated from the past and determine their action according to their expectations of the future. As dynamic processes become more complicated, so do the corresponding concepts of time.

Whole libraries have been written, of course, on whether we ought to treat time as a unitary dimension, or whether its passage is marked out by a different clock in each domain of being. Is the ‘arrow of time’ a cosmological primitive or a perceptual construct of the human mind? That is not the point. What is clear is that physical, biological and social entities have very different time-related properties, and that these differences must surely play a vital role in the behaviour of any complex system of which they were the constituents.

Let me repeat: this is not a supernatural phenomenon. The process of autopoiesis (Maturana & Varela 1992), by which entities with novel properties emerge spontaneously at successively higher levels of complexity, is not entirely mysterious. Remember that the whole systems hierarchy is a theoretical model. At each level, the relevant constituents are not perfectly natural kinds. They are idealized versions of real entities, shaped into ‘modules’. That is, they are deliberately constructed so that they can relate outwardly to similar ‘modules’ at the same system level, without direct reference to their own inner nature.

In practice, of course, each such ‘module’ is a composite entity, with ‘lower-level’ constituents. So the theoretical ‘properties’ attributed to it are never supposed to be absolute: they just have to be a reasonable approximation to reality, and yet simple enough to facilitate understanding of their role in the dynamics of the higher-level system. Thus, in order to operate as a ‘module’, a composite entity has to be reasonably self-contained and autonomous. It must also interact relatively weakly with other ‘modules’.

But these ‘intermodular’ properties are extremely difficult to characterize formally. They are usually residual effects, left over when all the forces within each entity have nearly balanced out. For example, the emergent quasi-autonomous entities that we call living organisms are stabilized dynamically rather than statically. This means that they each have a powerful internal clock, which makes their external behavioural traits and interactions peculiarly time dependent. Again, the interpersonal relations that activate economic systems are, so to speak, loose ends of the much more vigorous thought processes within each individual mind, and thus not at all identical with what would appear most salient to each inward eye.

This analysis does not, however, explain away the sheer novelty of emergent properties. It simply shows that they are, to some extent, theoretical artefacts of our whole multilevel scheme. Because this scheme is always applied retrospectively, it can never help us to predict ‘properties’ that have not yet actually emerged. But it can provide, after the event, a consistent and coherent naturalistic rationale for the particular forms that they have been found to take.

7. Emergent ‘properties’ are indescribably novel

To most scientific theorists, the differentiation of entities in terms of their ‘properties’ would seem a sufficient basis on which to go to work. But the conventional scientific notion of a ‘property’ can be somewhat misleading. It hints at a standard scale of comparison, even a quantitative dimension, against which some characteristic feature of an entity is to be assessed. It thus implies prior information about this feature, and criteria for deciding what aspect of it is relevant to the ‘property’ in question. This is what Einstein had to do, for example, when he suggested that quanta of light must have the property of gravitational mass.

But entities can emerge with features that are so novel that they do not conform to any such pre-existing criteria. It is not just that these new entities have different ‘properties’. Previously unimaginable notions of what constitutes a ‘property’ are required. Take, for example, the characteristic of being a ‘parasite’. This is a perfectly ordinary ‘property’ of many living organisms, and yet it makes no sense in a pre-biotic world. Even the ‘vast and powerful intelligence’ hypothesized by Laplace would have no reason for conceiving such a relationship until it had actually evolved between the ‘autonomous agents’ that were emerging as the Earth cooled down. Of course, once you have seen this ‘property’ in action, you can say a lot about it in physico-chemical terms. But until then, a flying saucer held up by anti-gravity would be easier to imagine than our humble companion the tapeworm.

Indeed, as Kauffman points out, novel concepts like these do not emerge singly. They emerge as co-defining clusters along with the entities to which they relate. This applies, for example, in the social domain, where ‘the web of economic activities, firms, tasks, jobs, skills and learning self-consistently came into existence’ (Kauffman 2000). These were not just extreme forms of the scientific concepts that were already familiar to biologists: they delineated a system of entities obeying entirely different laws of interaction, combination and exclusion.

Thus, theoretical physics has no symbolic operator corresponding to biological ‘reproduction’ or to the physiological ‘function’ of a bodily organ. Again, going up to the human level, an ‘intention’ signifies a general relationship between thought and action which cannot be described at all in strictly biological language. And at the societal level we find legal terms such as ‘contract’ and ‘statute’ which embody principles that would seem quite illogical by the criteria of individual psychology.

8. Distinct modes of discourse

It is often remarked that each level of the hierarchy of complexity has its own distinctive ‘language’. But science is not just lexicography or even linguistics. It is not just a matter of inventing new words for the novel creatures we discover, or of translating into our own pedantic lingo the names by which they have been known for thousands of years by the local residents. In the large, scientific knowledge includes entities that are so different in kind that they require distinctive modes of discourse (Ziman 2000a). At each level of complexity they obey a distinctive ‘logic’, a novel phenomenology (Maturana & Varela 1992), which could only be represented formally, if at all, by a distinctive ‘calculus’ or a distinctive ‘geometry’.

Until the early years of the 20th century, this would have seemed absurd. But relativity physics taught us that we could not represent space-time mathematically...
without using a novel geometry: a geometry that becomes more and more wildly non-Euclidean the further we go out into the Universe or back in time. Again, the dynamical principles of quantum theory were found to be inconsistent with the supposedly universal logic of classical physics, and could only be expressed symbolically through a completely novel calculus of states and operators in a Hilbert space of an infinity of dimensions. So scientists have long accepted the need for alternative modes of discourse, embodying different logical principles, to represent different realms of knowledge.

What is not yet accepted, however, is that other modes of discourse may also be needed to account scientifically for what actually goes on in much more familiar domains. Take, for example, the domain of social institutions. Kauffman (2000) points out that the hierarchy of autonomous agents can be sliced up in terms of the categories of 'know-how' proposed by Daniel Dennett (1995). What he calls the 'transformation rules' of science change as we move upwards from 'Darwinian creatures', which are organisms that cannot learn, to the level of 'Popperian creatures', which can run 'internal models'. Yet another change in these rules is needed when we encounter 'Gregorian creatures' (from the cognitive psychologist, Richard Gregory), who 'share a world of facts and processes'.

Indeed, human know-how is more than 'Gregorian'. The emergence of consciousness not only requires a vastly enlarged 'Popperian' capacity for 'making plans for the future'. It also requires what might be called a 'Meadian' capacity—after the American sociologist George Herbert Mead—for recognizing 'others' as persons like oneself (Ziman 2002). Only then do we reach 'the level of organization where action and goal talk become essential'. But then the rationale of even-handed dialogue between social actors ceases to be 'logical' in the Aristotelean sense. As the Greeks fully recognized, discourse has to become 'rhetorical' if it is to achieve closure. This is one of the reasons why economic models that claim to include the 'rational expectations' of its autonomous agents do not work. They simply cannot factor into their formulae the intersubjectivity that is a perfectly familiar feature of all human systems.

9. Differentiating the sciences

We can now understand and sympathize with the epistemic pluralism that is the practical philosophy of most working scientists (Ziman 2000a; Ziman & Midgley 2001). They would like to think they believed in the unity of scientific knowledge, and that they only accept its fragmentation as a pragmatic necessity. In reality, however, they are quite happy to go on cultivating the wonderfully productive walled gardens that they have inherited. As sociologists and philosophers, we are tempted to argue that the division of academia into separate scientific disciplines is an accident of academic history (Ziman 1997). But we now see that it has deep roots in the rich earth of reality.

Start from an empirical fact of nature. It does seem as if the world is indeed differentiated into distinctive domains of being, and that these correspond to the various levels of a single, nested hierarchy of complex systems that emerged in succession over time. In order to make sense of each domain, research scientists found that they had to develop a special language in which to talk to each other about its features. As we have seen, the language at a particular 'level' could not be the same as the
Thus, the disciplines into which we divide scientific knowledge are not arbitrary constructs of our own enquiring minds. They correspond to the distinct modes of spontaneous order that have actually emerged in the evolution of that totally complex system we call the Universe itself. It is quite conceivable that these modes might have been otherwise. What sort of social science would emerge amongst beings with the telepathic capabilities that Fred Hoyle attributed to extraterrestrial ‘black clouds’? The modes of scientific discourse are also subject to chance. If the dinosaurs had not been wiped out catastrophically, would the mental facilities they might have evolved be akin to human consciousness? Would their political economy necessarily have conformed to the principles laid down by Adam Smith or Karl Marx? But the actual world of today is of our very own human species—love or hate us as we will.

Thus, the plurality of the sciences is itself an emergent feature of the natural order. The multiplicity of distinct scientific languages is not just a sign of inadequate research effort: it is a direct reflection of the multiplicity of intelligible aspects of the natural world. It is impossible in principle to cerebrate or communicate full knowledge of any one of these domains in terms of knowledge of the others. The languages of the major scientific disciplines are not completely ‘incommensurable’, to use a fashionable but self-contradictory term. But they are not epistemologically equivalent, and cannot be translated fully from one to another. That is to say, they are not just ‘provincial dialects’ of some universal language spoken perfectly in an imperial metropolis of the mind. In their specific domains of science they are each ‘fundamental’ and worthy of equal attention and esteem.

In a nutshell, the traditional scientific disciplines really are different in the forms of knowledge that they produce. This conclusion may seem very conventional and reactionary. Scientific progress surely demands whole-hearted multidisciplinary research on interdisciplinary problems, to reach transdisciplinary outcomes. But the nature of the differences between the sciences must be properly understood if we are ever to produce genuine knowledge that transcends them.

For example, how distinct are the conventional subdivisions across the academic spectrum? Many traditional disciplines actually share the same scientific language. Throughout the physical sciences, for example, from fundamental physics to hydraulic engineering and theoretical chemistry, reality is represented in terms of partial differential equations. But this symbolic unity may be an illusion induced by certain ‘higher-organizing principles’, whose applicability to a great variety of macroscopic physical systems is ‘protected’ at low energies and/or long wavelengths (Laughlin & Pines 2000). Thus, it is doubtful whether we yet have a complete formal proof of the equivalence of the statistical and continuum accounts of fluid mechanics, especially where micro-level ‘quantum logic’ has to be interpreted in the terminology of macroscopic classical physics. Peter Galison (1997) has drawn attention to the distinction between the theoretical and phenomenological languages of high-energy particle physics: can we be perfectly sure that these are no more than different ways of saying exactly the same thing?

Again, there are suggestions that chemistry really requires a new calculus to deal with the complexities of molecular biology. New ‘mesoscopic’ organizing principles, that is, a new phenomenology, may be waiting to be discovered in physical systems approaching the biological level of structural complexity (Laughlin et al. 1999).

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And biology itself is so diverse that it used to be differentiated into quite separate sciences—botany, zoology, mycology, etc.—according to the types of organisms being studied. Modern (or even post-modern) attempts to redraw the demarcation lines in terms of cells, evolutionary clades, organic functions, ecological niches, etc., have not unified this vast epistemic field. Perhaps the natural boundaries are the eight ‘major transitions in evolution’ identified by John Maynard Smith and Eörs Szathmáry (Maynard Smith & Szathmary 1995). These correspond theoretically to successive leaps up the hierarchy of biological complexity, from the level of replicating molecules up to the level of human societies. In each transition there emerge novel composite entities that can be treated as the constituents of a higher-order system. In other words, there are conceptual discontinuities within biology that are almost as profound as the original emergence of life forms.

Again, one of the perennial controversies in the human sciences is whether the only genuine entities in social systems are quasi-independent individuals, or whether the analysis should be conducted in terms of relatively coherent institutions. Because social institutions are composed of individuals, we tend to assume that they emerged later, and are thus, in some sense, less fundamental, perhaps not even quite ‘real’ (Searle 1995). But there never seems to have been a time in the past when conscious hominids were separable from their social frames. Both were novelties that emerged together out of the biosphere. As Sunny Auyang points out, the only way to deal with economic systems is to realize that their constituents are neither solitary individuals nor abstract collectives such as ‘firms’. They are composite entities where the people are always heavily clothed in social forms and the institutions heavily personalized.

10. Can the sciences be re-unified?

These are not just philosophical issues. They drive research strategies and influence science policies. The continued differentiation of the disciplines goes against the grain of economic progress. In the effort to solve problems defined in ‘contexts of application’ (Gibbons et al. 1994), techniques and concepts are increasingly traded from domain to domain in science and technology. The sciences are more and more closely linked by common methodologies and paradigms. What degree of ‘federal unity’ (as Sunny Auyang calls it) can thus be achieved?

The general theory of complex systems is itself a good example. The model that I have been discussing in this paper is being applied right across the board, from micro-physics to macro-economics. Schematically, it is very instructive. It highlights some very general characteristics of a great variety of self-organized critical systems, not only the biosphere of ecology, but the ‘technosphere’ of technology, the ‘econsphere’ of commerce, and the more abstract ‘spheres’ of scientific knowledge and common law. At every level of the world system, one can identify ‘ecological’ phenomena such as chaos, proliferating complexity, spontaneous order, emergent novelty and ‘avalanches’ of ‘creative destruction’ on every scale. The Darwinian paradigm of evolutionary change by interlocking processes of variation, selection and replication is obviously of much wider application than in its original biological context (Wheeler et al. 2002).

But, as we have seen, it does not seem feasible to construct a general analytical formalism, or even a general computational algorithm, that can fully depict the behaviour of all such models. The same structural principles do not apply all the way
up the hierarchy, so there is no guarantee that the same phenomena will be observed at every level. In the biosphere, for example, it is not unreasonable, for some purposes, to treat organisms as systems of 'genes'. But the technosphere is certainly not a sort of 'Lego World' of recombinable parts, while the attempt to characterize cultural entities in terms of discrete 'memes' is absurd. Thus, empirical phenomenologies typical of systems in one scientific domain, e.g. biological parasitism, cannot automatically be extended to systems in another domain, e.g. economic enterprises.

I am not denying, of course, that 'higher-level' entities have 'lower-level' properties. The human sciences have to be consistent with the elementary constraints of the biosphere, and living organisms cannot defy the laws of physics and chemistry. But we should be very wary of trying to project concepts 'upwards' through the epistemic hierarchy. The mathematical formalisms developed to deal with physical systems do not necessarily apply in biology or sociology, and human behaviour cannot be explicated in purely biological terms. The only knowledge that we can truly transfer between these domains—even in highbrow, mathematical symbolism—is metaphorical. Very often, such metaphors are immensely fertile and instructive; but their transdisciplinary validity has to be checked, case by case.

Thus the 'themata' ('waves', 'fields', 'particles', 'forces', etc.), which seem of universal scope to a physicist, may be misleading, even as similes, in other sciences. Properties that are taken for granted for entities in their native domain may not actually apply elsewhere. Can statistical methods developed for passive agricultural crops be transferred holus bolus to self-aware, ethically valued hospital patients? Is there a coherent logic for heterogeneous networks of human and inanimate 'actors'? Can we really ignore the element of conscious design in technological innovation so as to fit it into a Darwinian model? A pluralistic perspective on the sciences may reveal analytical deficiencies that are often glossed over in the name of universal scientific correctness.

Those who fear that the end of science is nigh (Horgan 1996) should be attracted by the enigmatic ambivalences of the 'boundary objects' between scientific domains. Thus, technological artefacts are interesting and puzzling because their cultural meanings cannot be deciphered from accounts of their physical properties and vice versa. The same applies to the concept of 'information', which can apparently operate biophysically even though it can only be defined cognitively. The notion of 'Gaia' was long rejected by many Earth scientists because it was expressed in an uneasy mixture of biological and physical concepts and also had humanistic resonances. Sociobiology and evolutionary psychology arouse controversy because a 'gene' is a significant entity in the physical, biological and social domains, but has a different meaning in each scientific language (Rose 1997). Biologically speaking, the human brain is a neural network: in psychological discourse, it is an organ of consciousness.

11. The birth of history

Making an explanatory bridge between disparate accounts of the same natural circumstances is wonderfully challenging. In some cases, it may be like trying to square a scientific circle. But that famous defeat in the mathematical sciences was also another beginning, for it shifted attention to the wider landscape in which the problem was set.
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As we have seen, the property that most clearly differentiates the entities that are studied in the major domains of science is their relationship to time. And yet our Laplacian notion of a universal theory is couched in the language of physics, where time is just one of the 'dimensions' that label the nodes of a network of dynamical interactions whose space-time scope is so limited that only the present moment counts. With the advent of biological evolution, however, it is no longer feasible to let bygones be bygones. Every entity is uniquely fashioned by the events of its own specific past. The whole record of life on Earth is evidence of what the economist Brian Arthur called 'path dependence' (Arthur 1994). Convincing scientific discourse about the biosphere cannot avoid the influence of historical contingencies. And when it comes to the 'technosphere' and the 'econosphere', where both remembered pasts and imagined futures are also highly active, you can say that in spades.

This emphasis on the historicity of all serious epistemology is a common theme in the latest theorizing about complex systems. Stuart Kauffman puts it succinctly:

in short, we do not deduce our lives; we live them. Stories are our mode of making sense of the context-dependent actions of us as autonomous agents... Our inability to pre-state the configuration space of a biosphere foretells a deepening of science, a search for story and historical contingency, yet a place for natural laws.

Kauffman (2000)

In a luminous 10-page section on Narratives and theories in natural history, this is precisely how Sunny Auyang responds to the same challenge (Auyang 1998).

And of course, this is just what the poets, philosophers and prophets have always been proclaiming. It is to the benefit and credit of our science that we can at last build a bridge of understanding to that other continent of the mind. Indeed, the scientific anchorpoint of that bridge is 'emergence'. As it becomes more prevalent and frequent, we are forced to move from generalized models to narratives to account scientifically for what is going on. The argument is as follows.

Look again at the hierarchy of complexity. Each transition to a higher level corresponds to the appearance of very much more complicated new entities. Scientific discourse about what goes on at that level requires a sound knowledge of the nature of these entities. Since their emergence was unpredictable, this knowledge can only be gained by direct empirical research. One might say that this is the 'normal' state of science at this particular level of complexity.

Now according to Maynard Smith & Szathmary (1995), the biological domain is actually subdivided into a number of levels of complexity. What is more, the transitions between these levels occurred at shorter and shorter intervals of time. And as we enter the domain of the human sciences, we can identify a number of other revolutionary changes—agricultural, industrial, digital, global, and so on—each corresponding to a major transition in the degree of complexity of our social system. These are occurring at an ever-increasing rate. In fact, we seem now to be in a situation where the various levels of complexity are no longer sharply differentiated in historical succession. In the modern world, quite novel technological, economic, political and cultural 'features' keep appearing, each time with profound causal effects.

In other words, we seem to have entered a regime of 'continuous emergence', where evolution is no longer 'punctuated' by brief epochs of rapid change separating long
periods of apparent stasis. In these circumstances, strongly ‘predictive’ science is not feasible, while a rational explanation of current events requires a wide knowledge of numerous, recently emergent ‘features’ that may have influenced what is now observed. Even a Laplacian intelligence would now be challenged to take in the whole human domain and discern the innumerable novelties and contingencies from which quite unprecedented general outcomes have actually eventuated.

In our endeavour, then, to make sense of what is going on, we are forced to adopt another intellectual strategy. We choose a particular local situation and try to find out what particular circumstances brought it into being. We uncover the purely contingent events that shaped it and the factors, forces and features that might have influenced its development at each stage in the past. But, because many of these were historically ‘emergent’ rather than rationally predictable, they do not fit into any large theory or grand scheme, and can only be discovered and evaluated by empirical research. In other words, our findings do not depict a pre-determined trajectory, where all the action was already implicit in the initial conditions. Our scientific knowledge takes the form of a narrative, meaningful and causal in spirit but with many unexpected incidents and accidents along the way. Is that what is called ‘history’, on the other side of the campus?

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References

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