Chapter 9: conclusion

background reading

Simon, H. (1962), "The architecture of complexity", *Proceedings of the American Philosophical Society*, volume 106, pages 467−482.

notes

Constructive comments are welcome.

"**The hierarchy that we have explored**", also see the note to section 0.1. The idea of some sort of hierarchy, that has been called a "*scala naturae*" (Needham 1968:xii), in the physical universe has come up quite often in scientific writings.

A number of scientists have commented on the natural hierarchy and the levels of organisation of physical systems, both inanimate and biological, for example, Simon 1962, Bronowski 1977:chapter 13, Koestler 1979:chapter 1, Feynman 1992:124, Calvin 1997:34, Holland 2000:chapter 1, Morowitz 2002, Ellis 2006, and Laughlin 2006:chapter 1. However, there appears to be no recognition of the unifying concept of *communities*, and how they are bound together by *exchange* processes at every level of the hierarchy. Consequently, inanimate and biological systems are seen as unconnected hierarchies.

Richard Feynman recognised "*hierarchies of ideas*", with the fundamental laws of physics at one end and "*things like evil, and beauty, and hope*" at the other end. He considered that "*what we have to look at is the whole structural interconnection of the thing; and that all the sciences, and not just the sciences but all the efforts of intellectual kinds, are an endeavour to see the connections of the hierarchies*". However, he concluded that we can't "*draw carefully a line all the way from one end of this thing to the other, because we have only just begun to see that there is this relative hierarchy*" (all quotes from Feynman 1992:124−125).

In this book, I hope I've shown that our physical universe can be regarded as a single hierarchy of communities, and while I may not have drawn a line, I hope that I've managed to lay a series of stepping stones that will serve to get from one end of the thing to the other.

"**I have called this the universal hierarchy**", we need to remember that the fundamental particles of the standard model account for only ~5% of the universe's total matter-energy (section 1.2.6).

9.1 Themes and patterns in the universal hierarchy

9.1.1 a hierarchy of communities on eight levels

There has been an intermittent interest, going back many decades, in seeing the universe as an evolving hierarchy in terms of modern science (see the note to section 0.1). For example, Joseph Needham was writing in the 1930s and 1940s, and Jacob Bronowski and Arthur Koestler were writing in the 1970s. Recently, there has been a renewed interest, which is following two related approaches. One looks for major evolutionary transitions (METs), and the other looks for evolutionary transitions in individuality (ETIs).

major evolutionary transitions (METs)

John Maynard Smith and Eörs Szathmáry sought an explanation for the increasing complexity of living organisms in the course of evolution. They proposed that the increase depended on "*a small number of major transitions in the way in which genetic information is transmitted between generations*" (Smith 1995:3). They proposed a number of Major Evolutionary Transitions, usually shortened to METs (Smith 1995 and 2000, Szathmáry 1995). The original term was "major transition in evolution", or MTE, but the favoured term now seems to be "major evolutionary transition", or MET. I'll use the current term, which also harmonises with ETI.

They proposed 8 transitions (Szathmáry 1995:table 1, Smith 2000:17), starting with the first replicating molecules and ending with the origin of language. Some transitions were unique, such as the origin of eukaryotic cells, and the origin of the genetic code. Other transitions have occurred many times, such as the origins of multicellularity and animal societies.

Smith and Szathmáry observed a common feature of METs – "*entities that were capable of independent replication before the transition can replicate only as part of a larger whole after it*" (Smith 1995:6, and also see Szathmáry 1995:227 and Smith 2000:19). For example, the cells in animals and plants are descended from single-celled organisms that could reproduce independently. Today these cells can only exist within their host organisms (Smith 1995:6).

Eörs Szathmáry later updated the MET framework, revising the list of major transitions and emphasising the importance of individuality and of division of labour (Szathmáry 2015).

Not all are agreed on what counts as an MET, which can require a degree of pragmatism (Okasha 2022:2, West 2015:10117). Also, qualifying as an MET can be somewhat arbitrary, because it depends on the size of the subsequent adaptive radiation. Szathmáry introduced the concept of limited transitions which did not lead to "*vast adaptive radiations*" (Szathmáry 2015:10105). He concluded that "*if we see, even in rudimentary form, that independently reproducing units join, somehow use the functional synergies among the units, and that there is some novelty in the inheritance system as well, then the population is well on its way to a "major transition"*" (Szathmáry 2015:10110).

The emphasis on systems that replicate and pass on genetic information means that METs are limited to biological systems, so there are no inanimate systems in the list.

evolutionary transitions in individuality (ETIs)

The other approach has been to identify Evolutionary Transitions in Individuality, usually shortened to ETIs. These are "*rare evolutionary transitions where new higher-level evolutionary individuals (entities equipped to undergo adaptation by natural selection as wholes) arise from cooperating groups of lower-level evolutionary individuals. … Evolutionary individuality emerges during an ETI via cycles of cooperation, conflict, and conflict mediation. Selection and adaptation thereby move to a higher level of organization, producing an integrated type of entity whose lower-level units (originally evolutionary individuals) are co-opted and turned into parts of the whole*" (Davison 2021:214, with references removed).

The hierarchical structure of the living world is the result of repeated ETIs. For example, "*groups of cooperating genes evolved into the first cellular genome, groups of bacteria-like cells evolved into the eukaryotic cell, groups of eukaryotic cells evolved into multicellular organisms, and groups of multicellular organisms evolved into social insect colonies*" (Davison 2021:214).

Other examples of proposed ETIs are the emergence of Oldowan hominin culture around 2 mya (Davison 2021) and the Neolithic Revolution around 11 kya (Shavit 2023).

The theoretical ETI framework is based on processes in population biology, which include cooperation, conflict and its mediation, division of labour, and multilevel selection (Hanschen 2017a:258). The emphasis on adaptive evolutionary individuals means that ETIs are limited to biological systems, so inanimate systems are not considered.

common stages in ETIs

ETIs are considered to be a natural kind of transition because they follow similar stages, even in systems with different interacting units, leading to the evolution of a new kind of individual (Davison 2023:2). There appear to be a number of common stages in an ETI. The following are from Hanschen 2017a:258, and Davison 2021 and 2023:2−10, and others have proposed similar, though simpler, schemes (Carmel 2023, Griesemer 2023).

First, a number of individuals come together as a group. These may be different, as occurs in symbiosis, leading to egalitarian transitions, or they may be identical, where cells stay together after reproduction, as occurs in some cases of multicellularity, leading to fraternal transitions.

Second, the members of the new group will cooperate if they benefit from working together. The benefits can be additive, such as sharing a piece of food, or synergistic, such as feeding on each other's waste products.

However, group living will lead to individuals cheating, and to conflicts of various types, where individuals pursue their own fitness interests at the expense of the group. In the third step, these conflicts must be mediated so that the group can stay together. For example, programmed cell death acts to mediate conflict between cells in a complex organism (Hanschen 2017a, and see section 6.2.5).

High biological fitness depends on success in both reproduction and survival, and it is difficult for a single cell to be good at both. In the fourth step, cells specialise in either reproduction or survival, leading to division of labour. We've seen this in the division of slime mould cells into stalk cells (somatic body cells) that will die, and spores (germ cells) that can be reborn as new cells (section 6.1.4). In general, the "*germ cells specialize in group level reproduction but contribute little to the survival of the group. Similarly, nonreproductive somatic cells specialize in group-level survival but contribute little to the reproduction of the group*" (Hanschen 2017a:258). Each type of cell depends on the other, resulting in "*individuality arising at the group level, the level of the new multicellular organism*" (Hanschen 2017a:259).

Specialisation is very likely to reduce a cell's individual fitness. For example, a cell that is specialised for reproduction may not be able to survive outside the group. Conversely, a cell that is specialised for survival may have lost its power to reproduce, and can only survive within the group. But while specialised cells may have low individual fitness, they may "*constitute a good team when in a group and bring high fitness to the group*" (Davison 2023:8). The fifth step in an ETI is a shift in fitness, where fitness becomes transferred from the lower-level single cells to the higher-level multicellular organism. The fitness of the collective group becomes independent of the fitness of the individual units, and this is sometimes called "fitness decoupling". This is a key step in an ETI, and is fundamental to the creation of a new individual.

criteria for biological individuality

Defining an evolutionary individual is not straightforward. A number of criteria for individuality appear to be commonly accepted, and some of these are given below (Hanschen 2017b:2, Davison 2021:217).

- spatial and temporal boundaries that are localised in space and time
- genetic homogeneity, whereby all the lower-level parts of the higher-level individual have the same genotype.
- reproductive division of labour, which often takes the form of germ-soma differentiation, in which cells specialise in either group survival or group reproduction.
- indivisibility, so the lower-level units can't leave the higher-level group, and the group "*cannot be divided into smaller units that still maintain the properties of the whole*" (Hanschen 2017b:4). This may arise from the presence of a boundary or from division of labour.

METs and ETIs

Some evolutionary transitions qualify as both ETIs and METs, and there are some that are seen as one but not the other (Hanschen 2017a:260). There appears to be no formal connection between the two viewpoints.

Hanschen *et al*. see the MET approach as providing a starting point for understanding the increase in complexity in the evolution of life. They see the ETI framework as providing "*a narrative that underpins major transitions in units of evolution*" (Hanschen 2017a:262).

the volvocine green algae

The volvocine green algae are a genetically related group of ~90 species that live in freshwater puddles and ponds. They are photosynthetic and move about in their watery environment using their flagella (Hanschen 2017b:7). These algal species range from unicellular to multicellular, and they have been widely studied as a model system for the evolution of multicellular individuality (Hanschen 2017b:7−12 and table 1, and Davison 2023). This transition is one of the best studied ETIs, and the stages are fairly well understood (Davison 2023:2).

The alga *Chlamydomonas*, shown in figure 6.1(b), normally lives as single cells, but will respond to predators by aggregating into clusters of varying sizes, up to many thousands of cells. The cells in a cluster appear to stick together by forming an adhesive extra-cellular matrix. The clusters have no fixed size, and cells can leave a cluster. A cell in a cluster has a restricted growth rate, but also has a lower chance of being eaten by a predator.

Whereas *Chlamydomonas* has no control over the numbers of cells in its clusters, the alga *Tetrabaena* spontaneously forms colonies of 4 cells. However, these colonies break apart under environmental stress, suggesting that cells are not fully committed to group living.

The alga *Pandorina* forms spherical colonies of 8−16 cells, which have a multilayer boundary. The cells of this species seem to be committed to group living because the colonies don't break up under stress.

So far, the cells in a cluster or colony are undifferentiated, but the alga *Pleodorina* forms spherical colonies of 32−128 cells, in which the cells are differentiated. These cells have specialised functions so they enable the colony to have a division of labour. About 20−50% of the cells are non-reproductive, somatic cells confined in one hemisphere, and the remainder are general-purpose cells that can reproduce (so they are germ cells), and also have whip-like flagella, so they enable the whole colony to be mobile. Since the somatic cells can't reproduce, the group-level fitness of the colony is not the average of the fitness of the individual component cells. Instead, group-level fitness, depends on the combination of the traits of these cells. Thus, "*group-level fitness is strongly decoupled from cell-level fitness. … The colony is indivisible in the sense that, if a colony were broken up, the somatic cells could not produce offspring*" (Hanschen 2017b:11).

Finally, we arrive at the genus *Volvox*, whose species form colonies that are indivisible, and have a complete germ-soma division of labour. For example, colonies of *Volvox carteri* hold ~12 reproductive germ cells, which don't develop flagella, and ~2,000 somatic cells, which can't reproduce, but do have flagella. The somatic cells enable the colony to move around in its watery environment and to draw in nutrients and disperse waste, which benefits the whole colony (Davison 2023:9). A specialised colony "*can simultaneously reproduce and remain motile, something a single cell cannot do*" (Hanschen 2017a:260). All the cells in a *Volvox* colony are specialised in either group-level reproduction or group-level survival and so "*group fitness emerges from interactions between cells*" (Davison 2023:9).

The full range of the volvocine algae show us a "*plasticity of individuality*" that changes from being a property of individual cells to being a property of the multicellular group, and varies with species and environmental context (Hanschen 2017b:2 and 13). We can see three kinds of multicellular individuals: uncommitted multicellular individuals (*Tetrabaena*), committed multicellular individuals (*Pandorina*), and committed, differentiated multicellular individuals (*Pleodorina* and *Volvox*).

evolutionary transitions in individuality (ETIs) and the universal hierarchy (UH)

The universal hierarchy (UH) contains a basic repeating sequence: a number of individual "things" at one level come together as a community, bound by exchange processes, which becomes a unitary "thing" at the next level, with new emergent properties. We can summarise this as: things → community → new emergent thing. The universal hierarchy of communities comprises all the material systems in the universe, so it includes the inanimate material systems (levels 1−4) and the living biological systems (levels 5−8).

Figure 9.3(a) is a simple schematic view of three intermediate levels of the UH. We see four individual "things" at the lowest, *n*−1, level come together to make a community at the next level. This new community, comprising the lower level things and their exchange interactions, has new emergent properties and powers. It also has a dual nature, depending on how it is viewed; it's a community with respect to the levels below, but it's a unitary individual with respect to the levels above. The individual things at level *n* come together to make a new community at the next, *n*+1 level.

In an evolutionary transition in individuality (ETI), "*groups of previously existing individuals evolve into a new kind of individual*", which is capable of independent evolution (Davison 2023:2). We might summarise the ETI process as: individuals → new individual.

Figure 9.3(b) is a simple schematic view of two successive ETIs. We see four lower-level individuals come together to make a new higher-level individual. The transition follows a standard sequence of stages, in which conflicts are mediated, specialisation develops, and finally fitness is transferred to the higher-level individual. A second ETI creates another, even higher-level individual. The recognition that there have been many ETIs in Earth's history leads to the idea of a hierarchy, but the emphasis on "*evolutionary individuality*" restricts this to biological organisms (quote from Davison 2023:2).

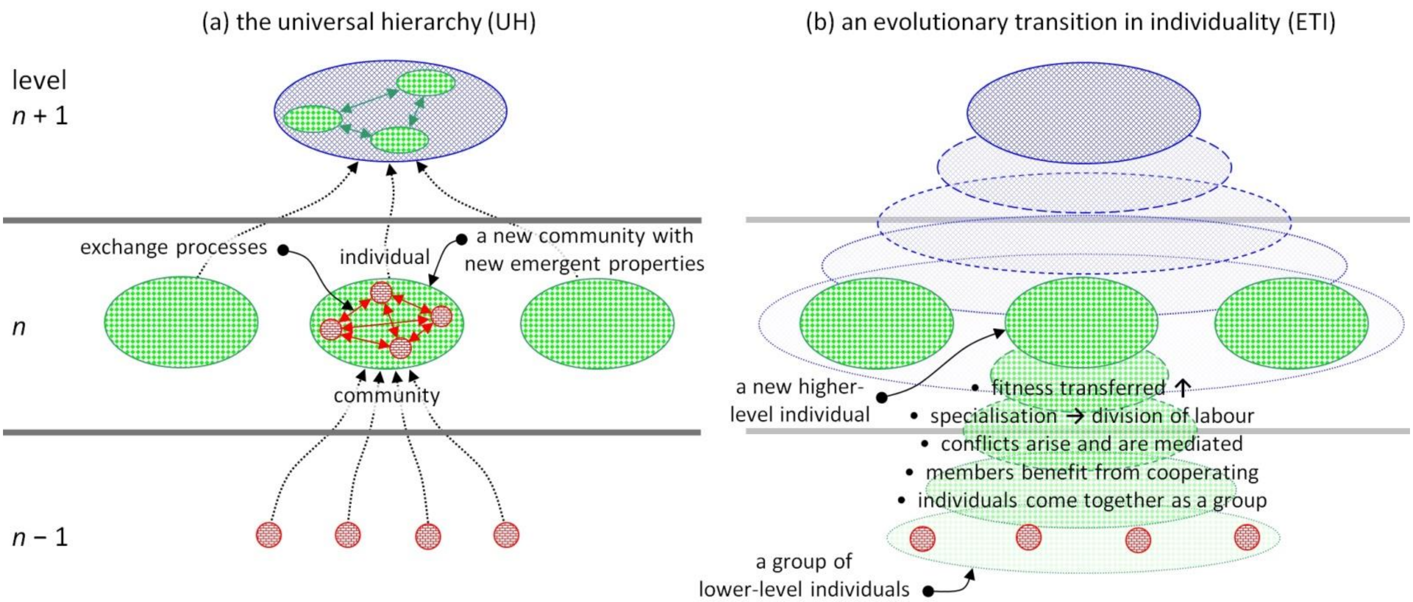

Figure 9.3. A comparison of the UH and ETI perspectives on a hierarchy of collective transitions.

It seems clear that the UH and ETI views of the universe are essentially the same in describing a hierarchical universe that has evolved through a sequence of collective transitions. So, the transition from one level in the universal hierarchy to the next is an ETI. The terms "community" and "individual" are two sides of the same coin. A succession of ETIs have naturally brought about the "*integrated hierarchical organization of life*" (Davison 2021:1).

The UH's emphasis on communities, regardless of the nature of their members, brings inanimate and biological systems together in a truly universal scheme. The ETI approach focusses on evolutionary individuals, so only biological systems qualify, and this leads to a limited hierarchy of life. But these living systems are highly complex, and so the ETI viewpoint pays close attention to the common stages in their formation. In contrast, the UH viewpoint, that is described in the book, pays more attention to the dynamic nature of communities, and how they are bound by continual exchange processes, and less attention to the processes by which they are formed.

The universe has evolved by things coming together in "*ever more complex communal arrangements*" (section 0.1), and the UH is the minimal description of the hierarchy that has resulted. Clearly, within each level of the UH, there are very many collective transitions that qualify as ETIs. To take examples of ETIs given above, the evolution of multicellularity is the transition from Level 5 to Level 6 in the UH, but the evolution of the eukaryotic cell falls within Level 5.

It's worthwhile ending this section by taking some of the features of ETIs, as listed above and shown in figure 9.3, and looking for them at the lower levels of the UH.

stages in a collective transition

The UH viewpoint emphasises that communities become more complex at higher levels in the hierarchy, and the same is true of the collective transition processes that create these communities. At the lower levels, collective transitions are very simple – a bit like flipping a switch from off to on – and I've paid little attention to the processes of formation of these communities. I've imagined building up an atom by dropping electrons, one by one, on to a nuclide (section 3.71), and I've sketched the tumble of interactions in the combustion of a methane molecule (figure 4.25, and see the note on this figure). At the higher, animate levels, collective transitions become much more subtle, complex, and protracted, as shown by the evolution of multicellularity in green algae, which is part of the transition from Level 5 to Level 6 in the UH.

indivisibility and individual fitness

One of the criteria for biological individuality is indivisibility. All the UH communities at levels 1−4 are indivisible, in the sense that breaking up the community loses the properties of the whole. While atoms survive outside molecules (Level 4) and electrons survive outside atoms (Level 3), free neutrons are unstable outside nuclides (Level 2 and section 1.4.6), and free quarks are unknown (Level 1 and section 1.3.5).

benefits from working together

At all the inanimate levels 1−4, the communities benefit from being together by having less mass-energy than their separate components. These communities are bound systems, and we have to supply a community's binding energy to pull it apart (sections 1.3.5, 2.2.3, 2.3.2, 3.6.3).

conflict and mediation

The protons in a Level 2 nuclide are in conflict because they repel each other by the electromagnetic force, but they are bound together with the neutrons by the strong nuclear force (figure 2.6). However, the cumulative repulsion between protons sets a limit to stable nuclide size (figure 2.9).

An atom and a community of baboons are analogous in that there are both attractive and repulsive forces between the members of these communities. An atom is a "*conflict of inclinations*" (page 77) because all the electrons repel each other, but they are bound together by their stronger attraction to the nucleus. The baboons in a social group regularly come into conflict, but they are bound together by their stronger attraction to family and grooming partners (page 330 and section 7.5).

We can perhaps see the way electrons occupy different orbitals as a form of conflict mediation, which enables them to keep out of each other's way, while remaining in the same atom. Contrast this with the complex mediation of conflict in baboon society (section 7.5), and the advanced cognitive skills needed by Mama to resolve conflicts in the chimpanzee colony in Arnhem Zoo (page 412). An atom is a much simpler community than a baboon social group, so we can measure binding energies of electrons in an atom but we can't use that metric for baboons.

specialisation and division of labour

I'm not aware of any specialisations in the communities at levels 1 and 2. However, at Level 3, we can see the outer valence electrons in atoms as specialised, compared to the electrons in inner orbitals, because they form chemical bonds with other atoms (sections 4.1.1−3, and see the note to section 4.1.1). The communal sharing of valence electrons between atoms creates the metallic state (page 145).

There are a number of examples of specialisation in molecules at Level 4. For example, carbon atoms form the backbone of octane, and the many-sided rings that form the structural centres of diazepam and saccharin molecules (figure 4.6). We can see specialisation more distinctly in biomolecules. For example, –OH and –NH groups can form hydrogen bonds (pages 151−2), which bind the two strands of the DNA molecule (Figure 4.6), and bind alpha-helixes and beta-sheets in proteins (figure 5.8). The heme group is a specialised ring structure that holds an iron atom in myoglobin (figures 4.6 and 5.10).

a community of A, bound by B, exchanging C, create and sustain D

many become one

"**It is a fundamental feature of the hierarchy**", Arthur Koestler uses the term "holon" to mean a member of a hierarchy, at whatever level. It would seem that Koestler's holon is equivalent to a community in the universal hierarchy. Koestler considers that "*'parts' and 'wholes' in an absolute sense do not exist anywhere, either in the domain of living organisms, or in social organizations, or in the universe at large*". This is because "*each member of this hierarchy, on whatever level, is a sub-whole or holon in its own right*". But, at the same time, these members "*function as quasi-autonomous wholes. They are Janus-faced. The face turned upward, towards the higher levels, is that of a dependent part; the face turned downward, towards its own constituents, is that of a whole of remarkable self-sufficiency*" (all quotes from Koestler 1979:27).

exchange processes at every level

"**There are exchange processes**", Joseph Needham saw a similarity between social ethics and molecular bonds: "*Ethics are the rules whereby man may live in social harmony … Such rules perhaps correspond to the valency bonds and other forces which hold particles together at the molecular and sub-molecular levels*" (Needham 1986:23).

Mark Moffett perceives that our "*shared imaginings bind people with a mental force no less valid and real than the physical force that binds atoms to molecules, turning them both into concrete realities*" (Moffett 2019:18). In the case of material communities, such as molecules and atoms, we can measure a simple binding energy. See, for example the hydrogen atom in section 3.6.3. But clearly, the "binding energy" of a social community is a much more complex matter.

the exchange process can change the receiver

interactions are specific to each level

"**In this respect, the transfer of thoughts and feelings**", this may relate to the idea of memes as the means of transfer of ideas and culture (Dawkins 2006:192 and 323, Dennett 1996, Aunger 2002).

no theory of everything

"**Because interactions in the universal hierarchy**", this leads to "level-specific" rules, so science is divided into separate disciplines, each with its own principles and understanding, from nuclear physics to psychology, as mentioned in section 0.5.

One set of laws can generate another set of laws, so, for example, "*the laws of electron motion beget the laws of thermodynamics and chemistry, which beget the laws of crystallization, which beget the laws of rigidity and plasticity, which beget the laws of engineering*". (Laughlin 2006:7). Laughlin 2000 has observed that it is generally impossible to deduce the higher organising principles from the underlying behaviour of systems at a lower level.

"**So, rather than there being a single Theory of Everything**", at the end of his book on Theories of Everything, John Barrow concludes that "*they are necessary parts of a full understanding of things but they are far from sufficient to unravel the subtleties of a Universe like ours. … There is no formula that can deliver all truth, all harmony, all simplicity. No Theory of Everything can ever provide total insight.*" (Barrow 1992:210).

"***we appear to face a hierarchy of Theories***", Laughlin 2000:30.

open and closed systems

branched and nested hierarchies

"**There are two fundamental types of hierarchy**", Koestler has considered different types of hierarchical organisation (1967:chapter 4 and 1979:chapter 1).

9.1.2 patterns of centring and extension

"**As we ascend the hierarchy**", an earlier version of the universal hierarchy was organised in 4 major levels (1−4), each with 2 minor levels (a and b), so the hierarchy had a total of 8 levels, from 1a to 4b.

In the new 8-level scheme, all the old "a" levels become the odd-numbered levels, in which there is a "centering" activity, and all the old "b" levels become the even-numbered levels, in which there is an "extending" activity.

levels 1, 3, 5, and 7 – a pattern of centering

levels 2, 4, 6, and 8 – a pattern of extension

"**The pattern continues at Level 8**", whereas biological cells can have a single fixed rôle, such as a muscle or nerve cell, individuals in a social culture have a number of rôles, which may be defined by a number of factors, such as profession, location, interest, and age.

9.1.3 novel emergent properties

"**The universal hierarchy emerges level by level**", see also the note to section 0.5.

Peter Hoffmann asks if it is possible to predict a cow from particle physics. "*Is it just too complicated to predict the existence of cows from particle physics, or is it fundamentally impossible to predict a cow from the properties of quarks and electrons? … Thus, we could say that a cow can be explained by particle physics, since quarks and electrons (and the forces acting between them) make atoms with different properties, which in turn make molecules, which in turn make cells, which in turn make cows*" (Hoffmann 2012: 241). He concludes that "*there is no formula for "cow" based on the laws of particle physics. Particle physics may be necessary to make a cow (because we need atoms and molecules), but it is clearly not sufficient*" (Hoffmann 2012: 242).

Thus, understanding the parts at level *n* is crucial, but then complex interactions between these parts "*create new processes, structures and principle that, while based materially on the underlying parts, are conceptually independent of them*", and so a new level, *n*+1, comes into being, with totally new principles and rules (Hoffmann 2012:238). Peter Hoffmann concludes that there is "*no meaningful conceptual connection between a highly complex entity and the most fundamental levels of matter and energy*" (Hoffmann 2012:240).

The only way we can understand the generic entity that we call "cow" is to follow the universe as it evolves, level by level up the universal hierarchy. Even then, we can only describe the sequence of events that have led to cows at Level 6, and we can't, in principle, predict their existence from fundamental particles at Level 1, and certainly not from the formless energy at Level 0.

And we can go further, to consider individual cows, which are now recognised as having their own distinct personalities and range of complex emotions (Marino 2017). To be able to "explain" an individual cow, we would have to start at the Big bang and follow the interactions of a selected group of fundamental particles, as they come together, level by level, finally to become the ensemble of molecules that constitute this particular individual organism. This select group comprises just four types of particles – *up* and *down* quarks, electrons, and neutrinos (section 1.5.1).

This is the basis of the argument in section 0.5, which considers a unique human brain. Carl Sagan considered apple pies, and wrote, "*If you wish to create an apple pie from scratch, you must first invent the universe*" (Sagan 1981:218).

"**But the new community follows its own level n+1 rules**", a reductionist approach takes an existing system, and takes it apart to discover the component parts and their properties. In contrast, a holist (sometimes called an "anti-reductionist") looks at how individual things can come together, subject to principles of interaction that did not apply before, and create a new, more complex whole, with new properties.

Paul Davies notes that "*All physicists concede that at each level of complexity new physical qualities, and laws that govern them, **emerge**. These qualities and laws are either absent at the level below, or are simply meaningless at that level. … The question we must confront, however, is **so what**? What, exactly, is it that the anti-reductionist is claiming **emerges** at each level of complexity?*" (Davies 2006:36).

But this is to risk thinking that the new emergent properties must somehow be similar, or comparable, at each level. Tables 9.1 and 9.2 show that the communities at each level in the universal hierarchy are profoundly different, and become more complex as you ascend the hierarchy, so they will interact in new and more complex ways. The new emergent properties and principles must be profoundly different at each level, because this is the only way to build up a universe of increasing complexity. The nearest we seem to get to a "standard pattern" of emergence is the alternating sequence of centrings and extensions shown in table 9.2.

"**Electrons belong to the family of fermions**", see section 1.2.1, figure 1.5, and section 3.7.1.

"***it is impossible***", Lincoln 2012:80.

"**Consequently, when electrons are clustered**", the atomic orbitals that electrons can occupy are specified by 4 quantum numbers (see note to section 3.6.2). Pauli's exclusion principle (Atkins 1995:chapter 9 and 2006:337) states that "*no two electrons in an atom can have the same set of four quantum numbers*" (Atkins 2002:36). Quantum numbers only apply to electrons when they come together in atomic orbitals around a nucleus.

"**The exclusion principle is the key**", Atkins 1995, 1998:362.

"***moves matter at a specific place***", Davies 2006:39.

"**Instead, it is a fundamental principle**", Bertulani 2007:section 12.11.

"**So, electrons don't behave differently**", the concept of "downward causation" is sometimes invoked to explain how the "global" properties of a whole system can influence the "local" interactions between its components (Davies 2006:39). One such case is "*Pauli's exclusion principle, where the laws governing two or more electrons together are completely different from the laws governing a single electron*", and this is an example where "*global restrictions affect local physics*" (Davies 2006:42). I think there are two errors in reasoning in these statements.

The 1st statement is equivalent to saying that the motoring laws are completely different when I exceed the speed limit. In fact, the laws are the same, whatever speed I drive at, but the laws against speeding only apply when I drive faster than the local speed limit. It's correct to say that the "*Pauli exclusion principle severely restricts the behaviour of a collection of electrons, but not of a single electron*", but this does not mean that the laws are completely different (Davies 2006:36). The physical laws governing the behaviour of electrons in any situation, including Pauli's exclusion principle, are all "present", but the exclusion principle only applies when electrons gather in the same location, attracted by a nuclide.

In the 2nd statement, the word "global" implies a top-down control, but in fact, it's the other way up. One electron is attracted to a nuclide, and settles in a standing wave orbital around it, and a 2nd electron can join the 1st in this orbital. However, when a 3rd electron tries to join the first two, it is prevented by the exclusion principle, and has to occupy a different orbital. The exclusion principle is a universal principle, because it applies everywhere in the universe, but it operates locally, according to local circumstances. Because every electron obeys the exclusion principle, they can't form orbitals holding more than 2 electrons. So, when you "drip" electrons on to a nuclide, you see the rising "tide" of filled orbitals, each holding 2 electrons (see figure 3.17). As each orbital is filled, the exclusion principle applies locally to the next electron attracted to the nuclide.

So, in the case of the atom – a community of electrons tethered to a nuclide – we see that "*local physics operates in such a manner as to comply with global principles*", and we can understand it without invoking the concept of downward causation (Davies 2006:42).

Paul Davies considers that complex, open systems may be open to downward causation. Thus, "*once a system is sufficiently complex, then new* *top-down rules of causation* ***emerge****. … Thus a living cell commandeers chemical pathways and intermolecular organization to implement the plan encoded in its genome. The cell has room for this supra-molecular coordination because it is an open system, so its dynamical behaviour is not determined from within the system.*" (Davies 2006:48).

The biological cell is an open system, taking in nutrients and excreting waste, and it functions in an environment over which it has no control. But the cell's responses to environmental conditions are very much decided within the cellular system. For example, an *E. coli* cell pursues its chosen nutrients by chemotaxis, and responds to the presence or absence of the amino acid tryptophan (section 5.1.7), but a different cellular species will respond in its own way, which may be quite different. It's not the uncontrollable environment, but the cell's response, that's important. Again, we don't seem to need to invoke downward causation.

"***new causative relation***", Davies 2006:39.

9.2 a progressive pattern

9.3 a self-assembling universe

"**There seem to be four principles**", basically, these are the first two laws of thermodynamics (section 4.3.6), the standard model of fundamental particles (section 1.2), and evolution by natural selection (section 5.7.5). The nature and evolution of our physical universe rests on these fundamental principles of chemistry, physics, and biology.

"**The existence of a sequence of stable levels**", see the section on Darwin ("**From this viewpoint**") in the notes on section 5.7.1.

a self-understanding universe?

We've seen that from Level 5 onwards, living things form a series of "selves", as they learn more about the causal relationships in the world around them, at increasingly sophisticated levels.

At Level 5, a single-celled organism functions as a "metabolic self", and "*builds an image of the world … in the language of chemistry*" so it is able to seek out nutrients (Bray 2009:*x* and 164, and see section 5.7.6).

At Level 6, a complex organism with a nervous system can associate different events in its physical environment, and so it learns the causal relationships between them, and functions as a "causal self".

At Level 7, an animal can learn the causal relationships between individuals and their actions in a shared social environment, and so it can function as a "social self", and play its part in sustaining a simple social hierarchy.

At Level 8, an individual can understand the causal relationships between someone's personal experiences and his or her consequent – and possibly false – beliefs, and so can function as an "empathic self".

At each of these four levels, knowing causal relationships enhances survival, so organisms are adapted to seek them. In fact, all sentient organisms appear to be engaged in the search for causal relationships – in effect, trying to make sense of the world around them, at their particular level in the universal hierarchy. If we consider this pattern and allow ourselves a little poetic imagination, we might conclude that the universe is trying to understand itself. Certainly, modern science is the most comprehensive, self-consistent, and evidence-based set of causal relationships we have come up with so far.

This unexpected conclusion presented itself in April 2025, as the book was being printed. Shortly after, I found that Herbert Simon appears to have arrived at the same conclusion, but from a quite different starting point, and in different language (Simon 1962:479). It's better to let Simon present his argument in his own words, rather than try to paraphrase. He starts by using the example of a circle to illustrate the distinction between state and process descriptions.

"*"A circle is the locus of all points equidistant from a given point". "To construct a circle, rotate a compass with one arm fixed until the other arm has returned to its starting point". It is implicit in Euclid that if you carry out the process specified in the second sentence, you will produce an object that satisfies the definition of the first. The first sentence is a state description of a circle, the second a process description.*

These two modes of apprehending structure are the warp and weft of our experience. Pictures, blueprints, most diagrams, chemical structural formulae are state descriptions. Recipes, differential equations, equations for chemical reactions are process descriptions. The former characterize the world as sensed; they provide the criteria for identifying objects, often by modelling the objects themselves. The latter characterize the world as acted upon; they provide the means for producing or generating objects having the desired characteristics."

So, the state description of a circle tells you what a circle is, but does not tell you how to make it; the process description tells you how to make a circle, but not what it is. In general, state descriptions represent the world as it is, as perceived by our senses. Process descriptions represent the world as we act upon it, and try to change it to a more desired condition.

Simon goes on: "*The distinction between the world as sensed and the world as acted upon defines the basic condition for the survival of adaptive organisms. The organism must develop correlations between goals in the sensed world and actions in the world of process. … Given a desired state of affairs and an existing state of affairs, the task of an adaptive organism is to find the difference between these two states, and then to find the correlating process that will erase the difference*".

Subsequently, I found that Philip Ball also appears to be saying something very similar (Ball 2023:36−40). He sees natural selection as a "*process by which goals and functions are created*", and so "*we need to acknowledge what evolution does to matter: it gives matter goals and functions*" (Ball 2023:40). When living organisms have goals and functions, then "*things in their environment may take on meaning*" (Ball 2023:36). Thus, "*life can be considered to be a meaning generator. Living things are, you could say, those entities capable of attributing value in their environment, and thereby finding a point to the universe*" (Ball 2023:37).

Philip Ball's living things strive to achieve goals in a meaningful universe. Herbert Simon's adaptive organisms are seeking the "*correlating process*" that will harmonise their actions and goals. I see the higher organisms at levels 6, 7, and 8 in the universal hierarchy as seeking the causal relationships that are appropriate to their level. These three viewpoints seem to be compatible. They seem to be saying the same kind of thing, which I've summarised as the universe trying to understand itself.

9.4 the universe within ourselves

"**Each of us is a universe in microcosm**", Albert Einstein is commonly quoted as saying, "*The most incomprehensible thing about the universe is that it is comprehensible*", which is catchy, but a misquotation (Andrew Robinson, at https://primemind.com/we-just-cant-stop-misquoting-einstein-19ad4efab26e). For example, one version of this, with "*world*" instead of "*universe*", is on the title page of "The Comprehensible Cosmos", by Victor Stenger. What Einstein actually said was, "*the eternal mystery of the world is its comprehensibility. … The world of our sense experiences is comprehensible. The fact that it is comprehensible is a miracle.*" (Einstein 1936:351).

Anthony Zee sees the realisation that the world is comprehensible as one of humanity's most profound insights, and points out that there have been many sophisticated civilisations that never took this view (Zee 2007:293).

However, if the material universe was created in a single event, and has evolved continuously from that time and place, then it must be comprehensible. What is perhaps more significant is the idea that the universe came into existence with certain intrinsic features and "rules", and then found its own way forward through the evolution of matter, life, and mind (for an outline of these "rules", see Stenger 2006). The universal hierarchy embodies that evolution, from a state of extreme simplicity, just after the Big Bang, to a state of extreme complexity, with the existence of human brains and societies.

After nearly 14 billion years, with the existence – on at least one planet – of material entities capable of empathy and abstract thought, the universe has evolved to a state where it is beginning to understand itself. There is a nice symmetry here; a comprehensible universe is beginning to be comprehended by the products of its own evolution. Is it a "miracle" that the universe is comprehensible? … or that a species has evolved to comprehend it? Maybe there is not one miracle here, but two.

End-matter

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"**While my name is on the cover**", Cat Bohannon expresses our collective debt to the original researchers much more clearly and fully: "*But most importantly, every single scientist whose work is represented in these pages – their labs, their toil, their lost sleep, their grant proposals, their endless reanalysis of data, their internecine squabbles and tenure gauntlets and conference awkwardness and submissions and revisions and little victories and years and years and years of stubborn resistance to the perfectly reasonable urge to give up … we owe them so much*" (Bohannon 2023:439).

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