Part 4 – The Physical Sciences

What is matter?

Throughout senior school, I had a wonderful but fearsome physics teacher. He knew how to manage a bunch of obnoxious boys being educated in a private boarding school, one of the last Victorian bastions of the British Empire. We thought we knew it all and had every expectation of making an impact on the world when we grew up.

At the beginning of sixth form, he said: “You are my top class, and we have a choice. We can plod through the curriculum for two years and you’ll all get A grades. Or we can have some fun and then in the last six weeks before the exams we’ll sprint through the curriculum, and you’ll all get A grades.”

Needless to say, we chose the latter.

One morning at the beginning of a double lesson, he picked out a student, seemingly randomly, and asked the boy to come to the front of the class. “Andrew,” he said, “tell us what ‘matter’ is.”

Andrew was one of the brightest amongst us and had an opinion on most things. He started well. We all had access to journals such as *Scientific American* and regularly read science articles as part of our homework. So, we were all *au fait*, at least at a general interest level, with state-of-the-art thinking in the physical sciences in 1980s.

Our physics teacher slumped down into Andrew’s vacated seat, acting as if he was another student, and commenced firing question after question at him.

I remember, as if it was only yesterday, that by the end of fifteen or so minutes, a somewhat crestfallen Andrew finally summed up: “Well … matter is, well, it’s just stuff. The stuff the universe is made of.”

This elicited a large grin from our physics teacher, accompanied by some wise words about how arrogant we all were to think that we knew it all, because not even those scientists, writing those articles in the leading science magazines, could answer this child-like question. And then it was someone else’s turn on a different topic.

In the end, all but one of us got an ‘A’ in our A levels.

So, now we turn to the physical sciences and, as we used to say to each other as we went into lectures on quantum mechanics, “Time to put your crash helmet on.”

Chapter 22 - The matter with ‘matter’

“We have learnt a lot about the universe by smashing things to smithereens.”

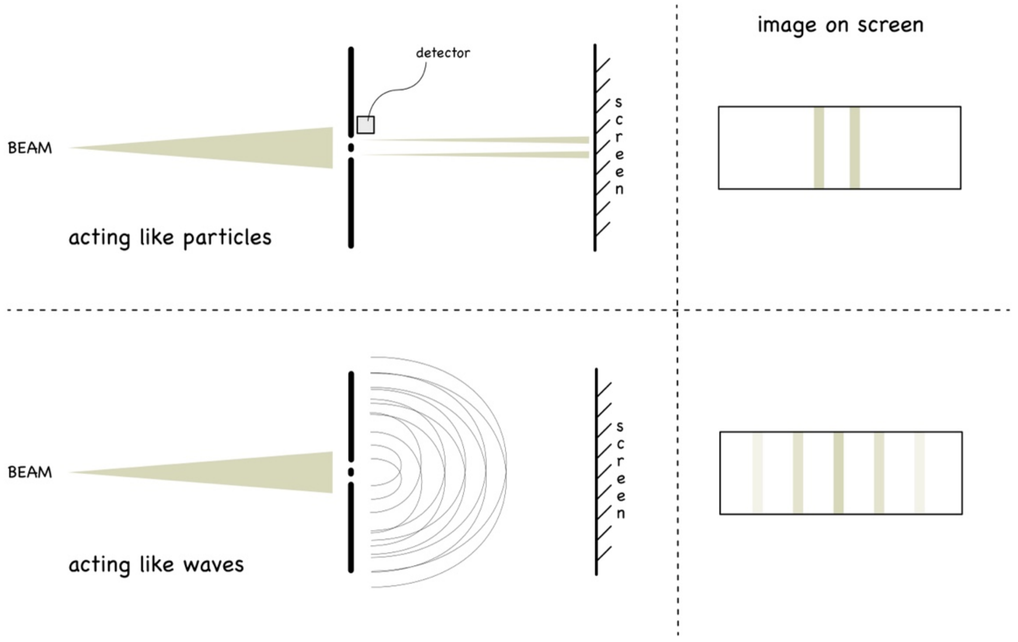
Quantum mechanics has been one of the major success stories of the twentieth century. Everyone, who has even the slightest interest in the physical sciences, has heard about it. But few have any idea what it is all about other than that it concerns really, really small stuff. Quantum mechanics was created by a collection of very clever people, mostly with strong mathematical credentials. Subsequent to Rutherford’s experiments bombarding gold sheets with alpha particles (as noted in chapter 2), these scientists were trying to fathom the inner workings of atoms as systems. What they came up with was something that they themselves found astounding and caused much controversy. Albert Einstein, whose early work inadvertently provided some of the foundations on which quantum mechanics was subsequently built, famously struggled to accept some of its implications.

Yet, quantum mechanics works. A major benefit that it has conferred is an ability to manipulate matter at the molecular level, such as the making of silicon chips, powering the computer on which I am typing. Through quantum mechanics we can predict the configuration of molecules. In the case of, say, water (made of an oxygen and two hydrogen atoms), this can then be used to determine the shape of a snowflake, which you can observe sitting in the palm of your gloved hand. It does not, however, explain how such beautifully symmetrical crystals grow.

Whilst quantum mechanics has been extremely useful, allowing us to invent all sorts of technological wizardry, it raises some intriguing mind-boggling puzzles both experimentally and theoretically. Perhaps one of the most well-known mysteries is the duality of matter at the atomic and sub-atomic scales.

Old chunky televisions - those before flat-screens were invented - relied on a cathode-ray vacuum tube, in which electrons acting as discrete particles were accelerated towards a screen to create regulated points of light, creating a moving image for us to watch. Repeated experiments have been run by physicists showing how electrons in other contexts behave like waves, not particles. The most common example of the latter is the double-slit apparatus, where electrons are fired one-by-one at two very close and very thin parallel slits. This generates an interference pattern (see Figure 22a) on a receptor behind the slits in the same way as would be achieved if a sea wave passed through two closely positioned narrow gaps in a harbour wall. It would seem that each electron passes through both slits at once. Yet, and this is what really messes with people’s heads, if you set up an apparatus to detect which slit the electron passes through, then, without changing anything else, all of a sudden, the electrons no longer act as waves but revert to being particles - apparently passing through only one slit or the other. The greatest human minds of the last century have been flummoxed by these coexisting observations.

Figure 22a – Wave-Particle Duality



Another oddity, which is more theoretical, is that the mathematical equations, on which quantum mechanics depends, require the use of complex numbers (see Box 22a). The use of such numbers is not particularly unusual in physics; they are frequently employed as a way to achieve shortcuts to get to results quicker. But, in all other areas, there are longer mathematical ways using real numbers to achieve the same outputs. However, quantum mechanics unavoidably necessitates the use of complex numbers and through this imagines the existence of virtual particles, or at least virtual influences on real particles. It is intrinsic to the maths. Yet, by definition, complex numbers cannot (or perhaps one might say, shouldn’t) relate to events in the real world. Again, no one can provide a good explanation other than accepting that such virtual particles do somehow exist in a non-existing sort of way.

Box 22a - Real and Complex Numbers

Primary school children are taught the concept of a number line, where zero sits in the middle, with positive numbers to the right and negatives to the left (the latter being those below zero, representing the removal of an amount). Pupils will also be familiar with multiplication such as the squaring of a number (+5 * +5 = +25). The more astute amongst them may realise that negative numbers do not have a square root (-5 * -5 also = +25). The square root of -25 does not practically exist.

Number Line:

-5 -4 -3 -2 -1 0 1 2 3 4 5

Complex numbers are introduced in mathematics through a term denoted 'i', which represents the square root of -1 and provides a means to represent mathematically the square root of any negative number. If -25 = -1 * +25, then the root of -25 can be depicted as root of -1 times root of +25 (sqrt(-25) = sqrt(-1) * sqrt (+25). Mathematicians can then say (5i * 5i = -25).

'i' has no meaningful representation in the real world. It cannot physically exist. You cannot have 'i' of something. You cannot in practice multiply 5 apples by i and have something that makes sense. Nor can you add or remove 5i apples from a bucket of apples. It is simply a way to represent a concept that can only exist virtually and more normally is kept to the abstract world of number theory.

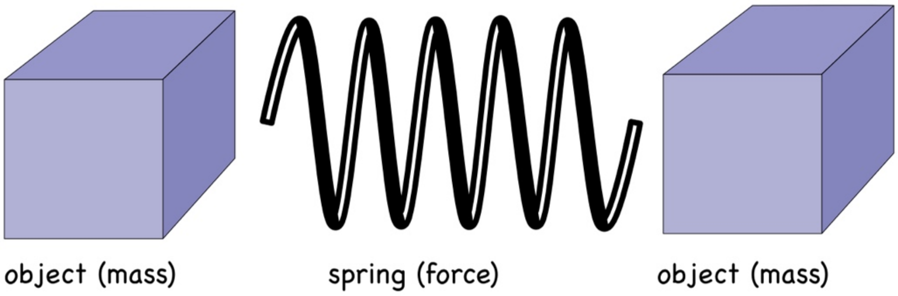
For quantum mechanics to rely on complex numbers suggests that the behaviour of atomic and sub-atomic particles is influenced by things happening virtually, not in our physical reality. That's quite challenging to grasp, especially for those brought up in a materialistic world.

With these inexplicable aspects to quantum mechanics, one is inclined to wonder whether there are some implicit assumptions that we are making about our universe that are stopping us from seeing what might otherwise be staring us in the face. The quandary is akin to those astronomers of old, in the days before Copernicus, building their contraptions to show the movements of, what we now know to be, planets. Whilst Copernicus' peers could create models of their cosmos, they could not explain it because they were erroneously assuming that the world sat at the centre of everything. Perhaps some of the problems, we are currently experiencing in physics, arise because our philosophical perception of the material universe has not yet caught up with our science and maths.

As it turns out, we don't have to go back very far to find the origin of those unspoken assumptions that we are making. Much of our modern physical sciences took form during the nineteenth century, through the labours of the Victorians. From part 2 on the social sciences, it was shown how our perspective of the material world around us is strongly influenced by the interactions that we have with each other. Victorian society underwent explosive economic growth through the Industrial Revolution. Level 2 interactions dominated, infusing the culture with characteristic traits such as strong dress codes, advocacy of the rule of law, a desire to collect things and an interest in history. Victorians saw structure as being of fundamental importance at every level from personal behaviour up to the whole of society. And so, it was also their belief that the universe must be highly regulated too. Their main scientific preoccupation was to deduce the rules and standards that governed all energy and matter. It is from the Victorians that we have inherited a philosophy, which is generally referred to as materialism.

In our modern Western societies, we collectively churn through huge amounts of material and measure our success on continuous growth - manufacturing vast quantities of things with a singular focus on wealth creation, only for the stuff we fabricate to be promptly thrown away, to make way for more. Materialism, as a philosophical approach, provides a perspective of the material world, which is a rather apposite accompaniment to these highly materialistic cultures of consumerism and capitalism. Materialism essentially sees matter as figurative Lego bricks - inanimate objects, which passively respond to the forces applied to them. If you push something, it moves. Conceptually we think in terms of matter made up from objects (inert masses) and springs (forces linking these objects together) (see Figure 22b). When Rutherford discovered that atoms are complex systems, our scientists moved to the next scale down and discovered protons and neutrons, which for a while they thought in turn to be the smallest Lego bricks. Next the scientific community built huge particle accelerators, such as CERN, which is a 27-kilometre long taurus, and on which billions has been spent. Conceptually, it is like a very large cathode-ray tube, albeit built as a ring so as to accelerate the particles round and round, going faster and faster. Using this, the physicists smashed protons together and found that these particles were themselves composed of even smaller things, which they called quarks. Given the experience of the last century, one is left wondering whether quarks are indeed the smallest units of matter.

Figure 22b – Objects and Springs



Using huge quantities of experimental data from facilities like CERN, the physicists have now formulated what they call the ‘standard model’ of sub-atomic particles, which comprises

12 quark particles (the weights) and 4 force carriers (the springs). However, of particular note, this model cannot account for gravity. The gravitational force, which we all experience everyday of our lives, does not feature, leading to endless scientific journal articles focused on the on-going search for a unified theory - combining gravity with the standard model.

Materialism, on the face of it, is an improvement on the Ancient Greeks’ concept of vitalism. Notwithstanding the reliance of quantum mechanics on complex numbers, materialism proposes that everything that we experience arises from matter and identifiable interactions between particles of matter. Where vitalism suggests that you are infused with some inexplicable vital energy, which provides your life force and differentiates you from the chair that you’re sitting on, materialism accepts that both you and your chair are ultimately made from the same matter components. Your sentience is then seen as something that emerges from the interactions between all those oxygen, hydrogen, carbon and other atoms, of which you are composed. But materialism does not think in terms of interactions as processes, in the manner discussed in previous chapters. Materialism sees interaction in terms of inert objects responding to forces applied to them. Consequently, materialism is no closer than vitalism in being able to explain how your apparent life force actually emerges from those interactions. Our new adopted philosophy simply provides a different label - ‘emergence’, instead of ‘vitality’.

The inconvenient truth is that a philosophical starting point of materialism is never going to be able to explain life. For so long as we hold onto this perception of the material world, it will be impossible to align the social and life sciences with the physical sciences. And, just as was the predicament of those astronomers of over five hundred years ago, in our age and our case, our dedication to materialism prevents us from being able to understand what the experimental observations and mathematical models behind quantum mechanics are really trying to tell us.

So, where do we turn next? Parts 2 and 3 on the social and life sciences respectively provide a clue.

If the needs-driven interaction hypothesis has any merit, then this sets out for us a way of seeing systems at one scale emerging from the myriad of interacting parts at the next scale down. A large bureaucratic social structure is built from the Level 2 interactions of hundreds of thousands of people. A teaming metropolis arises from the innumerable daily interactions of ten million human beings. A termite mound is created by, say, a million termites or a bee hive consists of 40,000 cooperating bees. In each case a new higher-order system is created by the collaboration of those smaller component living systems. Multicellular creatures, such as us, are formed from the cooperation of around 30 trillion cells and even more bacteria in our gut biome, each of which is itself a living system.

The smallest things that we accept as being genuinely alive are bacteria, systems which are somewhat smaller than our own cells. We normally stop there. Yet, bacterial cells are made from several trillion atoms. Could those atoms come together to create bacteria and other cells by means of the same set of processes proposed for the social and life sciences? What would that mean for our understanding of matter? We accept that bacteria have a life force, of sorts - they can sense their environment and respond to their circumstances, such as swimming upstream towards a sugar source. Our current perception of the material world precludes us from thinking any smaller than this.

It is certainly worth exploring whether we can take a step down to the atomic level. BUT, there is a problem, which extends beyond our ingrained philosophical bias. It exists in the form of one of those laws of the universe that the Victorians formulated and subsequently formalised in mathematical terms. It is the 2nd Law of Thermodynamics. And it locks in place our philosophy of materialism. Without addressing this Law, we can’t move forwards. However, I take the next step with serious trepidation. For the 2nd Law represents a navigational hazard, on which a number of the greatest minds of the last century have shipwrecked themselves. So, here goes … do you have your crash helmet ready?

Chapter 22 - Conventional Entropy

“Mathematics is a dangerous tool. It can prove almost anything.”

The 2nd Law of Thermodynamics is a foundation stone of our modern physical sciences. It is one of the more demanding concepts, which physics and chemistry students must absorb at university. It is a critical area of learning if you wish to make a career in the energy or chemical industries and many feel a sense of accomplishment once they have mastered it sufficiently to score what they need in their exams. Perhaps because of this, they defend it even more vehemently than they would other theories. Anyone who dares challenge any aspect of the 2nd Law in physics internet chat groups can expect to be acerbically belittled. By and large, the scientific community seem to have reached a point of accepting “It is what it is. Best get on message and get on with it.” Even Stephen Hawking relied on the 2nd Law when he posited how black holes very slowly evaporate through, what has become termed, Hawking Radiation.

The science of thermodynamics was mostly formulated by our Victorian great grandfathers as they sought to improve the performance of steam engines. The human appreciation, that you can heat water up to generate steam and this hot gas can be contained and directed, is traceable back to Roman times. However, early contraptions making use of this knowledge were essentially gimmicks. It wasn’t until the mid-1600s that the generation of steam was used in a meaningful way, such as pumping water out of mines. It took another 100 years to shortly before the Victorian era for people to realise that the pistons of a water pump could instead be used to drive wheels on a rail engine, as subsequently demonstrated by George Stephenson’s Rocket - the first commercial locomotive.

The harnessing of steam was the technology that drove the explosive growth of the Industrial Revolution, enabling mechanisation of a wide array of activities that previously had to be done much slower by hand. The energy source to boil the water to produce steam was primarily coal. And so, it became the preoccupation of Victorian scientists to work out ways to make this as efficient as possible - how can you pump the maximum amount of water out of a mine or push a train further and faster using the least amount of coal? It was science driven by economics.

In the lingo of thermodynamics, the word ‘work’ is used to represent the amount of energy required to do something mechanical, such as driving a train from London to Leeds. The basic premise of a steam engine is that you use the stored chemical energy in coal to generate heat to boil water and produce steam, which becomes pressurised and drives a piston, thus doing work. As the Victorian scientists and their European peers explored this aspect of the material universe in greater detail, they began to realise that, no matter how well they designed their machines, the amount of heat energy provided by a quantity of coal could never be fully converted (100%) into the same amount of work. There was always some inefficiency and a loss of some energy. They pried this phenomenon further and built what are referred to as reversible engines, where heat energy can be used to drive a piston to create more heat, which drives the piston back again, over and over. Again, no matter how efficient such apparatus was made to be, there was always some energy loss in the process. Hence was born the realisation that you cannot create a perpetual motion machine, whether it be driven by springs, pendulums, or steam. Even Foucault’s Pendulum in the Pantheon in Paris requires a little magnetic helping hand to keep it swinging back and forth, decade after decade.

These reversible gas-piston contraptions allowed the Victorian scientists to measure accurately the inefficiency of converting one form of energy into another - usually heat to work. The key measurable parameters that a thermodynamicist is working with are temperature (T), pressure (P) and volume (V) of the whole gas within some container. These are measurable macroscopic state variables of a system. As you may appreciate through pumping up a bicycle tyre, when you squeeze air to a higher pressure in a smaller volume it tends to heat up. And so, the scientists deduced a variety of mathematical formulae for the relationship between temperature, pressure and volume, which physics and chemistry students now must remember to pass their exams. These equations, involving T, P and V, were extremely effective and not changed to this day. But, because of the observed inefficiency, the Victorian physicists were forced to add another parameter, which became called ‘entropy’ and labelled ’S’.

Entropy is an attribute of a system, such as a certain mass of steam. It varies according to the macroscopic state of the steam - the volume it is occupying, the pressure it is under and its temperature. However, it is not something that can be measured but has to be deduced through those other parameters that can be. Using entropy, physicists can calculate how much work can be extracted from such gas. For example, at the beginning of a piston’s cycle, when the gas is at high pressure, then the entropy is low. When the gas has expanded, pushing the piston out, and the pressure has dropped to the same as the surroundings, then the entropy is high, and no further useful energy can be obtained from that quantity of gas. In any process involving the conversion of heat into work, entropy is seen to increase and there is a consequential loss of work that can be achieved.

As the Victorian scientists became more skilled at playing with chemicals and gases, they came to realise that this entropy phenomenon did not just apply when they were trying to extract useful work from steam. Rather, it could also be seen to take effect in other situations, such as chemical reactions, changing states of matter (such as ice thawing to water and water boiling to become steam) and the mixing of gases and liquids. In the latter case, a tendency for entropy to increase is construed to be the reason why adding that drop of milk to your black tea leads quickly to a cup of tan brown drinkable milky tea, which is a one-way process and very difficult to reverse.

Putting these various observations together, the nineteenth century scientists derived a universal law, known as the 2nd Law of Thermodynamics. This essentially says that anything that happens or any process that takes place in some way gives rise to an increase in entropy of the entire universe. For example, if you were to go about trying to extract the milk from the milky tea to return to the original state of black tea and milk, in doing so you would use so much energy (generating so much wasted heat, such as from burning coal) that, even though you may end up with a lower entropy system with separated liquids, the wider universe would still have increased in entropy.

So far, so good, and not so difficult to comprehend. But, whilst the Victorian scientists now had a name and label for this phenomenon and called it a universal law, it didn’t make any sense to them. In their view of things, they saw atoms as miniature Lego bricks, perhaps more like microscopic marbles. They presumed that these miniature incompressible spheres followed the laws of motion deduced by Newton some hundred years earlier. Newton’s laws are the subject matter of applied mathematics, as learnt by any maths pupil at senior school. They allow you to calculate what happens when, say, two billiard balls collide and what direction and how fast they travel when they bounce away again. Newton’s laws are all entirely reversible. For example, a video of two balls colliding can be played forwards and backwards without an observer being able to tell which was the original sequence. Combined with a philosophical Weltanschauung of materialism, with particles of matter being inert objects which automatically respond to forces applied to them, the Victorian philosophers perceived that time doesn't really exist at the microscopic scale of atoms and sub-atomic particles.

To the Victorians, the macroscopic world should be just a scaling up of the microscopic - from one reversible collision to many trillions. Consequently, large scale measurable phenomena (such as a gas expanding) should logically be entirely reversible too. The scientists couldn't see what gave rise to the appearance of this entropy factor. All they could deduce was that when you are dealing with large numbers of things, such as the atoms in a canister of gas (numbering orders of billion trillion particles), then something comes into play which in effect creates an arrow of time. Processes, at a scale that we can measure, are invariably irreversible (milk mixing in tea). With all other parts of our physical sciences being temporally reversible, it has subsequently been construed that this phenomenon, the appearance of irreversibility, is in effect the essence, or even cause of, the arrow of time as we experience it.

This paradox exposes one of the first philosophical problems with the concept of entropy, because if that's what you think, then the question must be asked: at what scale does an arrow of time become apparent? There is no satisfactory answer - is it at two or three atoms, one hundred atoms, one million, or more? Or, perhaps it's a gradual process, the larger the system the more irreversible it becomes? But that doesn't make sense either. Something is either reversible or irreversible, it can't be somewhere in between.

With this dilemma circulating the scientific community through the latter half of the nineteenth century, the challenge was on to solve it. Bring on Ludwig Boltzmann, a brilliant physicist from Austria. He took an unorthodox approach by turning to statistics. Through his life, his approach was treated with disdain by his contemporaries, leading him eventually to commit suicide for not being taken seriously. But despite this, Boltzmann persisted, and he created a whole new area of mathematics called statistical mechanics, from which he was able to provide a theoretical derivation of entropy. This has nowadays become a mainstay of modern physics. Furthermore, Boltzmann's statistical mechanics represented a key part of the groundwork for the future development of quantum mechanics, which itself has a strong statistical component.

It is at this point that students of thermodynamics begin to struggle, especially if they like to understand things in terms of what's happening in the real world as opposed to some mathematical construct.

Starting out from an assumption that matter at the smallest scale is made up of inert, indistinguishable objects following Newton's laws of motion, Boltzmann's mathematics shows that when you put a drop of milk into a cup of black tea, then the most likely end state will be for the liquids to be fully mixed. He turned the entropy, which we appear to experience at our scale of observation, into a probability and the things that we see genuinely happening are simply the most probable (see Box 23a).

Box 23a - States, Microstates, Probabilities and House Parties

Imagine that you're having a house party, and you have four downstairs drawing rooms and forty guests. Different readily observable macroscopic configurations of the whole system would be represented by different numbers of guests in each room – say, five in Room A, ten in Room B, fifteen in Room C and ten in Room D. You could easily observe these differences from a distance, such as looking into the house from the garden. Each change in these numbers in each room would be a different state or global configuration. If five people moved from Room B (reducing to five) to Room A (increasing to ten), then this represents a different macroscopic configuration.

A microstate is represented by different mixes of people within each configuration. For the original configuration given above, one microstate would represent you in Room A with four other guests, while another microstate would be represented by you swapping with someone in Room B, keeping the same total number of people in each room. For most macro states, there are many microstates - simply different mixes of people across the rooms but keeping the total number in each room the same.

The macro configuration that has the greatest number of microstates is where there are ten people in each room, equally distributed through the four rooms. By having the greatest number of microstates, this configuration turns out to be the most probable and thereby deduced to be the highest entropy solution. If all four rooms are similar and of equal size and the guests are all largely indistinguishable from each other, then Boltzmann's construct suggests that no matter how many times you repeat your party, each time you would expect to see arise an even distribution of people with ten in each room. Converting into gases, this corresponds to having the same pressure of gas in each room, regardless of which exact molecules are present in whichever room.

When you scale this up to large numbers, such as the number of atoms in a cup of liquid, numbering billions of billions, then the probability of your milk and tea fully mixing becomes by far the most probable state for the system to adopt by a very, very, very large margin.

Boltzmann's mathematics was able to emulate what the Victorian engineers had discovered in their experiments. And, through this, the idea that the particles of matter, the gaseous atoms, were inanimate balls of matter, all bouncing around and bumping into each other according to Newton's laws of reversible motion, became fully locked in. In an ironic twist, it could be argued that all Boltzmann did was prove his starting assumption about the inanimate nature of matter. Regardless that we now know, through Rutherford's experiments and much garnered knowledge since then, that atoms are nothing like mini-ball bearings, but instead are themselves complex systems, we find ourselves stuck with this view of matter because Boltzmann's clever mathematics so neatly theoretically imitates real world observations.

Many find the idea that irreversibility in nature is purely down to probability to be unpalatable. Yet, because experiments and theory align, it proves to be extremely difficult to challenge. And then, every Springtime, we see green shoots sprout from barren ground, completely defying all this hard science and convoluted mathematics. Whilst Boltzman's mathematics works for the inanimate world of gases, solids and liquids, it cannot account for living things.

The two most noted attempts to reconcile the 2nd Law with life were by Nobel laureates. The first try was by Erwin Schrodinger, who won his Nobel prize in 1933 for his contribution to quantum mechanics through demonstrating wave-particle duality (as discussed in the last chapter). About a decade later, he gave a series of lectures and summarised these in a short popular science book titled *What is Life?*, in which he introduced the notion of negative entropy, since abbreviated to negentropy, as a way to explain the existence of living things. Schrodinger did not consider that life broke the laws of physics so far discovered by the 1940s but did believe that new laws needed to be found to explain its existence. If nothing else, his book formally acknowledged the riddle that life doesn't seem to abide by the same rules as the inanimate world of gases, cups of tea and the chair you're sitting on.

The baton to solve this puzzle was picked up by a chemist by the name of Ilya Prigogine. He was born in Russia but spent his early academic career in Belgium before eventually migrating to Texas. To understand Prigogine's work, it is necessary to introduce a few other concepts.

Firstly, when your cup of un-drunk tea has cooled down to room temperature, it has achieved 'equilibrium' with its environment. This means that there is no further net flow of energy into or out of your tea. To you and me, it means that the tea is now cold, the same temperature as the air around it. This is also the state of maximum entropy - you can't extract any further energy from your tea to, say, warm your hands. Earlier, when making the tea and seeing the milk fully dispersed into the black tea to create a uniform tan brown mixture, you were observing the different molecular components achieving an equilibrium mix. Equilibrium generally equates to uniformity - the tea and milk are fully mixed throughout, equal temperatures, equal pressures - and all those situations where no further change appears to take place at the macroscopic level, even though we fully know that at the molecular level the particles are all bouncing around wildly.

Secondly, for the 2nd Law to be tightly defined, the nineteenth century scientists were careful to specify that it applies to 'isolated' systems. The closest that you or I might experience an isolated system in day-to-day life is a vacuum flask, which is designed to minimise the flow of energy into or out of the tea contained therein to make it stay warm for longer. We'll come back to consider isolated systems in more detail in a subsequent chapter. For now, simply consider that they represented contexts where a quantity of matter, such as a gas or liquid, is prevented (as far as is possible) from interacting with its wider environment - i.e. it is effectively self-contained and energy is prevented from flowing in or out.

Now, rather clearly, living systems are neither at equilibrium nor isolated. While you are alive, you are demonstrably not at equilibrium with your environment because your body maintains its own temperature independent of the room you are sitting in. And, by definition, as explored in earlier parts, living systems need to interact with the world around them to satisfy their survival needs.

Prigogine's area of research focussed on far-from-equilibrium systems, including living things, through which energy and materials flow and which do not settle down to become uniform either internally or with their surroundings. There are a variety of chemical reactions, which are known never to achieve equilibrium, and there are liquids, which undergo intriguing transitions when the flow of heat through them is varied. Prigogine sought to carefully measure the flows of energy into and out of these various systems and hence to quantify the consequential changes in entropy. He formulated mathematical solutions, which were intended to establish the universal entropy changes associated with these non-isolated, non-equilibrium systems and which showed how local reductions in entropy could be construed to be offset by global increases. Reverting back to the action of un-mixing your cup of tea, you might end up with a lower entropy outcome inside your cup (black tea and milk now separated). But in doing so, you've consumed so much energy that you have increased the entropy of the wider universe. This has become known as 'entropy export' - you effectively export the entropy from your local system (your cup) to the wider universe.

If you thought that Boltzmann's probabilistic approach to entropy was already a struggle to comprehend, then Prigogine's thinking begins to get really tangled. It has, however, become the doctrine for anyone now looking at the question originally posed by Schrodinger. According to the popular interpretation of Prigogine's work, the reason why you can exist is because (for some inexplicable reason) the atoms in your body maintain a low entropy state that is deemed far-from-equilibrium and that you are able to do this because you generate more entropy by being alive. Simply by existing, you continually export entropy to the world around you. Through your body temperature warming the air around you, through taking in clean water and peeing out urine (water mixed with excreted contaminants) and through converting distinct food items into homogenous faeces, you generate a large amount of waste around you, equating to higher entropy. Prigogine provided lots of intricate mathematics to prove it. But he never properly explained why? Why are the atoms in your body motivated to keep you in a state of living and exporting entropy, where those indistinguishable other atoms in your cup of tea are doing their irreversible utmost to achieve internal uniformity and equilibrium with their surroundings? In reality, his solution is no closer to explaining our apparent vital force than any other approach.

Prigogine's work has had an unfortunate influence on the whole environmental movement. It is interpreted to mean that for you to maintain your apparent low-entropy state, you need continually to degenerate your immediate environment. It leads people to think in terms of each of us as waste generating machines, relentlessly producing high entropy in the world around us, where the only truly effective way of resolving environmental problems, such as plastic pollution, is by removing humanity from the equation. The inescapable conclusion is that we must de-populate the planet before we collectively destroy it. Expanding the same thinking to a universal scale, the logical conclusion of Prigogine's work is that the universe is relentlessly heading towards a cosmic heat death to eventually become as cold and bland, just like your old cup of tea.

Returning to the 2nd Law, despite it being doctrine science taught to all university chemistry and physics students, when you start delving into it, you begin to realise that it is a wonderfully contrived theory with some beautifully constructed logical contradictions … at least at a philosophical level. It stands as the main reason why we can't find a way to reconcile our physical sciences with our life sciences. As computational power increased at the end of the 20th century, there was much hype with book after book being published on the newly discovered concepts of chaos and complexity theories. Suddenly, certain aspects of those far-from-equilibrium chemical reactions, which Prigogine had previously experimented on, could be modelled in computer environments. These new theories helped explain a variety of natural phenomena, providing insights into areas such as meteorology, and it was dearly hoped by their authors that these new fields of thinking would progress to help discern the emergence of an apparent life force in complex systems, such as us. But to no avail. Interest has now moved onto other areas, like big data and artificial intelligence. Notwithstanding our skill at manipulating microbes, such as CRISPR editing, manufacturing RNA vaccines, and producing genetically bespoke cancer treatments, we are no closer than ever at explaining our vital drive and the emergence of life.

This inability to reconcile basic physics with biology provides an opportunity for the creationists, who want to denounce Charles Darwin's theory of evolution, to claim that because life cannot be explained through the physical sciences, we, and therefore all life, must ergo be God's creatures. But if, as discussed in part 2, God is something we dream up as a mythology (Level 3) to persuade everyone to contribute more to their communities for the benefit of all, then another explanation is surely required.

There is a way out of this conundrum, but it requires setting aside our purely materialistic philosophy and opening our minds to conceive alternative ways of understanding this great big universe that we find ourselves in. And so, to get things started, let's begin with a thought experiment. Imagine that we have two systems. One is a small canister of gaseous atoms sitting within a large box, where the larger box is filled with other gases. Gas pressure inside both is the same. The second system is a shipping container full of tigers sited within a large game reserve - a vibrant jungle ecosystem, filled with all the normal species that you would expect, except tigers.

Focusing on the atomic system, if we puncture the canister, we know that the atoms within will spill out and spread throughout the larger box of gases. It happens remarkably quickly. In accordance with the 2nd Law of Thermodynamics, the system will rapidly move towards a state of maximum entropy with the new gas uniformly mixed throughout the larger box. And it will remain that way forever after.

Turning to the tiger system, we release all the tigers at the same moment. The tigers hastily spread out across the game reserve until they, too, are evenly distributed across the area, fully occupying the space. And they, too, will remain that way.

So, what’s the difference?

Macroscopically, these two systems are behaving the same.
Mathematically, these two systems are behaving the same.

Yet, we interpret what’s happening in completely different ways. At the microscopic level of one system, we see individual matter particles as inanimate objects. In the other, we see tigers as material energetic systems with needs. According to physics, the gaseous atoms are responding to this universal phenomenon that we call entropy; they are dispersing outwards to mix with all the other gases in that volume to culminate with an evenly distributed mix of gas atoms. Boltzmann’s mathematics indicates that full mixing is the most probable final state. In contrast, according to what we know from everyday observation at a scale we can understand, the tigers are competitive creatures on the landscape. They are spreading out to be as far apart from each other as possible, so that each experiences the least level of competition and can thereby access sufficient food to stay alive. They are responding to Level 1 Passive Competition.

How about trusting what we can see with our own eyes, rather than believing some convoluted mathematics. What if the atoms are doing the same as the tigers? But that’s absurd. Isn’t it?

Chapter 24 - A day in the life of a particle

"Putting the quantum into quantum mechanics."

If you take an iron rod and place it in a furnace, it starts glowing a dull red, then brighter crimson and eventually ends up a dazzling yellow-white. To our forefathers, this was the equivalent of turning up the volume of light being emitted from the surface of the hot metal. They saw rays of light as continuous beams, radiating from a light source. A stronger light effectively meant that the emitted rays were essentially more vigorous, carrying with them more energy, which you can see in terms of brightness and feel through the emanating heat. But this line of thinking didn't concur with what an array of experimenters were increasingly observing through two principal areas of investigation, which took place over the course of the nineteenth century: one is referred to as black body radiation and the other as the photoelectric effect. These fields of research eventually came together at the beginning of the twentieth century to provide the first important step on the path to quantum mechanics.

On a sunny day, when the sunlight pours in through a south facing window, you can see those rays of light picked up by flecks of dust and you can feel that warmth on your skin. It makes sense to think of those rays as continuous beams. It was also generally recognised that sunlight was a form of energy, which can generate heat. But that's about all anyone knew. It was Newton (in the 1660s), who was the first to fully appreciate that white light from the sun is composed of a variety of colours. He famously identified six hues of the rainbow, which he artificially made into seven because that felt more religiously appropriate - there being seven days of the week. Wind forwards around 150 years and a German astronomer by the name of William Herschel made a remarkable discovery about this band of colours.

In appreciating that sunlight could be split into hues, in 1800 Herschel wondered whether there was any difference in the energy carried by those different chroma. He set up an experiment whereby he used a prism to split the white light into a rainbow and then sought to measure the heat transmitted to a thermometer from each colour. He was surprised to find that that there was a significant amount warmth produced beyond red, outside the visible range. This was the first step on the path to the realisation that the light we can see is just one small part of a much larger range of types of radiation. Over the next hundred years, the community of European physicists gradually came to realise the full extent of, what is now known as, the electromagnetic spectrum from gamma rays to radio waves. They fabricated an array of apparatuses to emit and detect this wider range of rays. This engineering knowledge has become a defining feature of the technological marvels of the twentieth century, including radios, televisions, satellites, microwaves, mobile phones and x-rays.

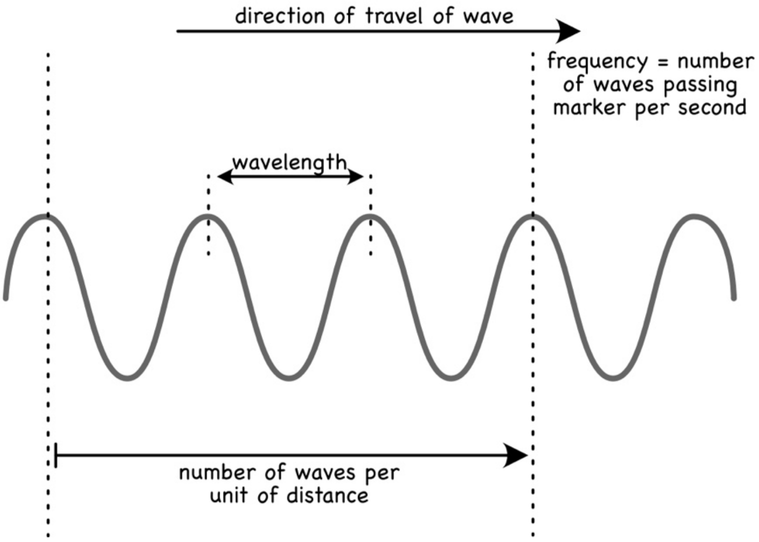
Side-by-side with the experimentation, theory on this subject area progressed such that it became understood that light came in the form of waves. Our Victorian ancestors perceived radiation as ripples through some undetectable ether, travelling in a manner synonymous to the way waves travel through water. As waves, light beams therefore have frequency and wavelength (see Box 24a).

Box 24a - Light - Wavelength and Frequency

When you shine sunlight into a prism, it produces a rainbow effect. The prism diffracts the light and thereby causes the incident white beam to separate out into the different colours. Each colour represents a different wavelength.

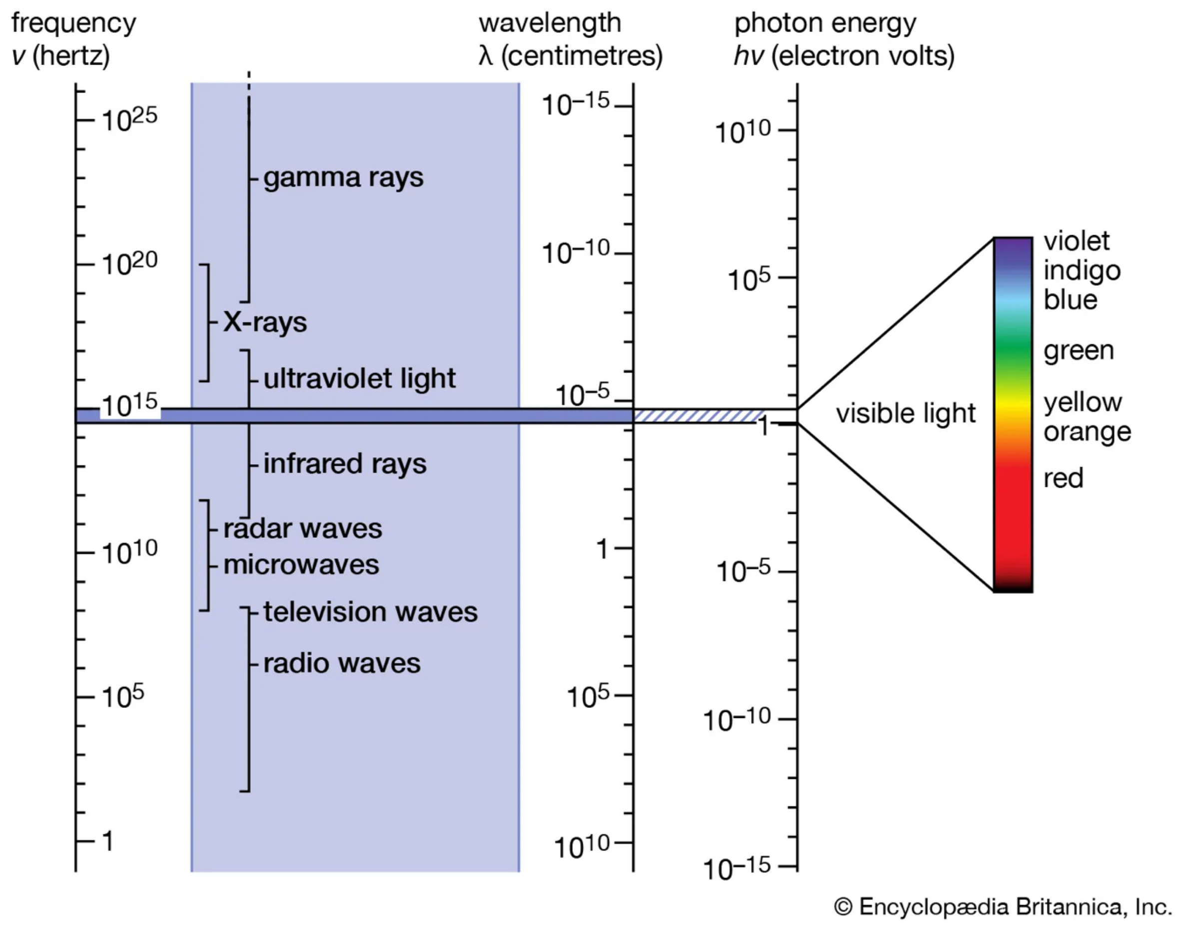
When at the beach you observe waves coming ashore, you will see that the waves on different days will have varying wavelengths and frequencies. There is a relationship between wavelength and frequency as follows: frequency is inversely proportional to wavelength (frequency = constant / wavelength). The diagram below (Figure 24a) helps explain. Wavelength represents the length of each wave from crest to crest. Frequency represents the number of waves that occur within a given unit distance or, alternatively, the number of waves that pass a marker within a given timespan.

Figure 24a - Waves



Within the visible spectrum, red has the longest wavelength (lowest frequency), whereas indigo has the shortest wavelength (highest frequency). The light, which we can see, represents only a very small part of the overall electromagnetic spectrum. The diagram below (Figure 24b) shows the broader range of radiation. At the extreme of radio waves, then the wavelength is measured in metres to kilometres. At the other extreme of gamma rays, then the wavelength can be as short as picometres (a trillionth of a metre). The wavelength of visible light ranges between 400 and 700 nanometres (that’s one billionth of a metre).

Figure 24b – Electromagnetic Spectrum



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As scientists became more aware of this electromagnetic spectrum, they discovered that everything you can see and touch is continuously emitting radiation. They measured this. They came up with an idealised version of this effect and called it ’black body radiation’ (the reason for the name is not relevant to this discussion). Gradually more sophisticated devices were used to explore this phenomenon, revealing a relationship between temperature and the character of the radiation being emitted by an object. For that iron bar inserted into a furnace, as it heats up the major component of radiation being emitted slowly rises up through the colours of the spectrum, from red towards violet, as more colours are added it changes its appearance from that dull red to eventually being close to white, being the combination of all the colours. But there was a concomitant observation that didn’t make sense. The experiments revealed that, for any specific temperature, there is a very definite cut off such that there is no radiation emitted below a certain wavelength. Again, considering that glowing iron bar, at low temperatures there is no blue light emitted from it whatsoever. It's not a matter of there being less blue light; there is none.

At the end of the nineteenth century two theoretical approaches were formulated to attempt to explain the observed spectral variation with temperature. In Germany, a Wilhelm Wien came up with Wien's Law, which provided a good approximation to experimental results for short wavelengths, in the order of the ultraviolet range; but it fails to match data at longer wavelengths. In the United Kingdom, two Cambridge mathematicians-cum-physicists formulated a theorem known as the Rayleigh-James Law, which accurately estimates the amount of observed radiation at longer wavelengths. But their predictions differed significantly for shorter wavelengths in the region above the visible spectrum. This inexplicable divergence subsequently became known in the physics world as the Ultraviolet Catastrophe. Both approaches depended on the extant perception of light as continuous rays. It took one of the intellectual giants of the early twentieth century to solve the puzzle.

Max Planck (1858 to 1947), though a gifted musician, took an interest in physics as a teenager, while attending the German equivalent of grammar school. He was required at university to carry out experimental work, but as soon as he was able progressed into theoretical physics and avoided the laboratory thereafter. His doctoral thesis was on the 2nd Law (see last chapter) and thermodynamics represented a key interest through his early career, enabling him to establish himself as a theoretician. Later in his career, Planck became a close friend with Albert Einstein, and played a prominent role in promoting some of Einstein's early work. The two were known to play music together to relax.

In the mid-1890s, Planck focussed on the on-going unanswered question of black body radiation. After several attempts, his resolution of the problem proved to be profound. He realised that the experimental data could only be explained by assuming that radiation existed in the form of particles, which became known as photons. His thesis was that each photon carries a very specific quantity of energy, which can be calculated from its frequency (or wavelength). The ‘quantum’ in quantum mechanics is a reference to this quantisation of energy. The inference from Planck’s work is that energy is not a continuum but always comes in discrete, albeit sometimes very small, quanta. And a ray of light is not a continuous beam (a ripple through an ether) but rather a stream of very fast travelling, massless photons. There is no background ether. Intensity of light then represents number of photons.

Turning to the other area of interrogation, the photoelectric effect, from early in the Victorian era scientists became interested in the relationship between light and electricity. They discovered that the surface electrical properties of selection of materials varied according to the light shone onto them. This field of work eventually led to those cathode ray tubes inside twentieth century televisions, which depend upon causing a material to emit electrons from its surface and thereafter accelerating those electrons towards the front screen for us to watch. The scientists theorised that, if you shone enough light onto a surface, then electrons in the solid material would absorb the incident rays and, when the electrons had acquired enough energy, they would achieve sufficient speed to leave the surface. What instead the physicists were seeing was that the emission of electrons did not depend on intensity of light. Rather electrons would only be emitted from a material if the light rays were of a sufficiently short wavelength (say, blue light instead of red light). If the rays were of a longer wavelength (say, red), no electrons at all would be produced regardless of how strong was the light.

It was Max Plank’s friend, Albert Einstein, who ultimately pieced this puzzle together and worked out what the experimental data was telling us. Picking up on Planck’s thinking on photons, Einstein realised that electrons don’t aggregate energy from a beam or multiple incident photons. Rather, for any electron to be emitted from the surface of a photoelectric material, it must be hit by a single photon of sufficient energy. The photon imparts all its energy to give the electron a minimum necessary escape velocity from an atom. If the incident photons of light fall below a defined energy threshold (i.e. too long a wavelength), then no matter how strong the light (how many photons hit the material every second), they will not impart sufficient energy to any individual electrons and no electric current will be observed.

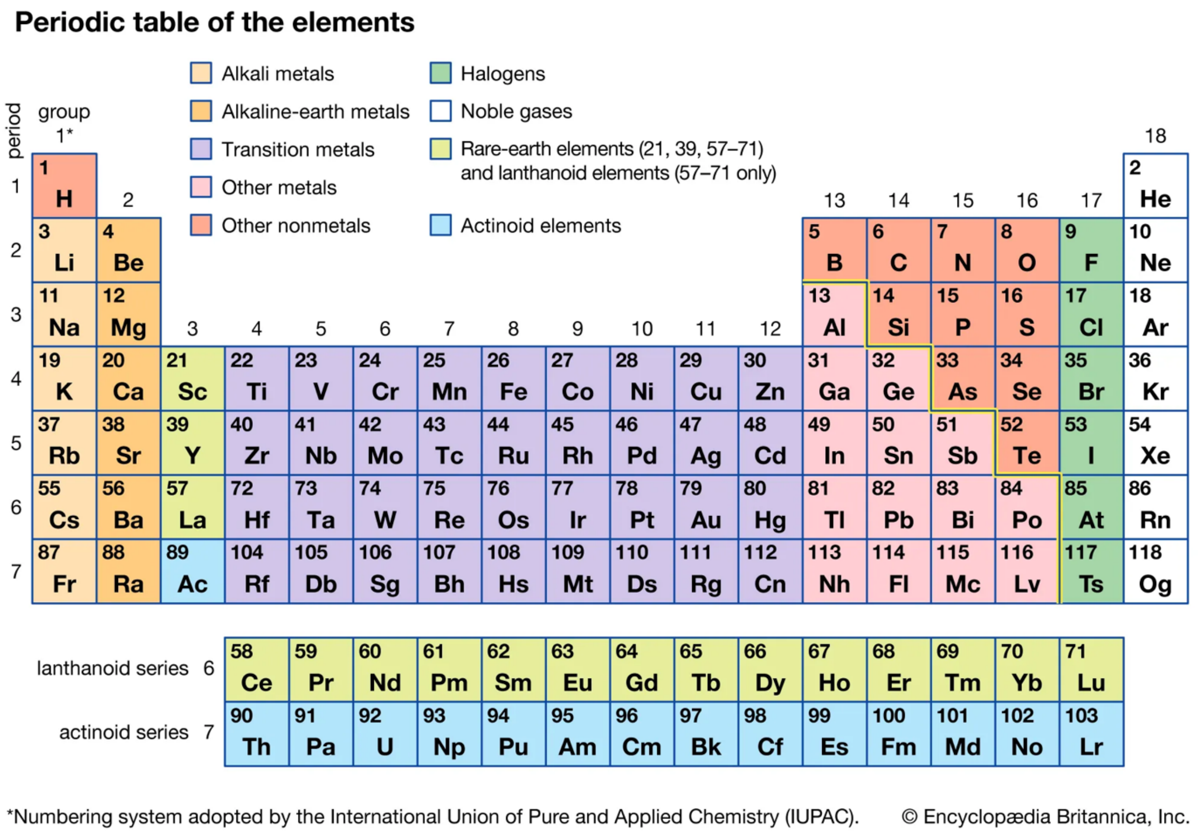
Jumping forwards to today, all the above learning represents core curricula for chemistry and physics students at university as they grapple with modules on spectroscopy. The original prisms used to split visible light into a rainbow have now become highly sophisticated laboratory machines, which enable scientists to accurately identify the precise wavelength of light absorbed and/or emitted by materials, including gases. Astronomers make use of spectroscopy to identify the elemental components of distant stars and of the stellar gases, through which such starlight has travelled on its way to Earth.

Building on Planck’s and Einstein’s revelations, it is now understood that gaseous atoms are very particular about which quanta of energy they absorb and/or emit. Using spectroscopy, very clear lines of radiation can be found for each different element. For example, excited atoms within sodium vapour (as used in sodium lights) emit two very specific spectral lines of yellow-orange light at 589.0 and 589.56 nanometres wavelength. These are not the only bands that gaseous sodium atoms emit but are the most prominent and hence the orange glow that used to be produced in such streetlights. With a precise wavelength corresponding to a specific quantum of energy, each different elemental free gaseous atom (running through the periodic table of elements (see Box 24b)) has its own very particular bands of radiation with which it can interact.

Box 24b - Periodic Table

The Periodic Table (see Figure 24c) is another of the amazing discoveries made during the Victorian era. It is the table of elements running from Hydrogen upwards to Uranium and beyond, where each step up in the table represents the addition of one proton (with a +ve electric charge) and one electron (with a -ve electric charge). The structure of the table (see below) is linked to the structure of the atoms, where columns indicate elements with common characteristics. Both the structure of the atoms and their corresponding behaviours are now predictable and explicable through quantum mechanics. Further, through quantum mechanics we can predict the spectral fingerprint for each element (see Figure 24d).

Figure 24c – Periodic Table



Periodic table of the elements

🟨 Alkali metals
🟧 Alkaline-earth metals
🟪 Transition metals
🟥 Other metals
🟥 Other nonmetals
🟩 Halogens
☐ Noble gases
🟨 Rare-earth elements (21, 39, 57–71) and lanthanoid elements (57–71 only)
🟦 Actinoid elements

period \ group	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

lanthanoid series 6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
actinoid series 7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).

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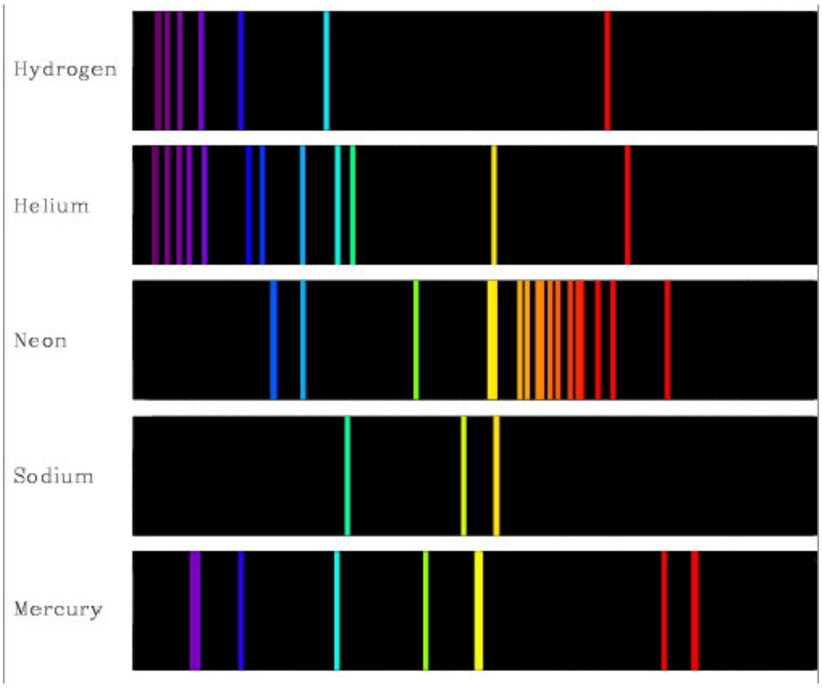
Figure 24d – Atomic Spectral Fingerprints



So, free gaseous atoms are very selective about what radiation they interact with. If you shine yellow-orange light at a sodium gas with a wavelength of 589.0 nanometres, then it will be absorbed by the atoms and will heat up the gas. If you shine light with a wavelength of, say, 580.0 nanometres, then it will pass straight through and not interact with the atoms at all. (Note there is always a slight variation because the atoms in the gas are themselves moving around at high speed and this acts to spread out a little the preciseness of the spectral line.)

Returning to the black body radiation phenomenon, the temperature of an object indicates the range of wavelengths, which are emitted (see Figure 24d). High temperatures emit a range of shorter wavelength photons. Low temperature objects produce a range of longer wavelength photons. This can be demonstrated by looking at the black body radiation curves for the Sun and the Earth. The outer atmosphere of the Earth absorbs and emits radiation at wavelengths that are much longer than those produced by the Sun (see Figure 24f). This is why those visible light rays from the Sun can penetrate through our atmosphere and reach ground level to allow us to see and sunbathe. Other than ozone and water in clouds, none of the other atmospheric gases around and above us absorb in the visible light range.

Figure 24e – Black Body Radiation – temperature variation

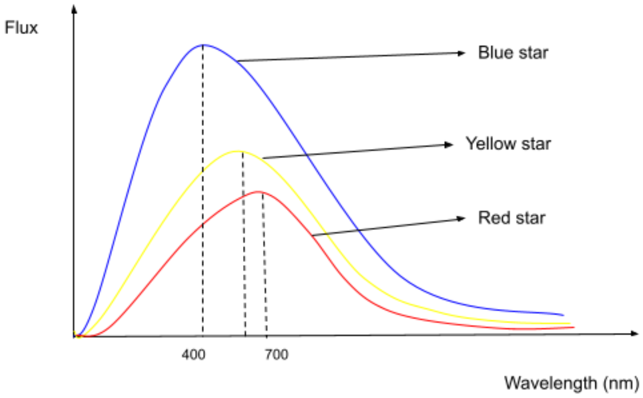
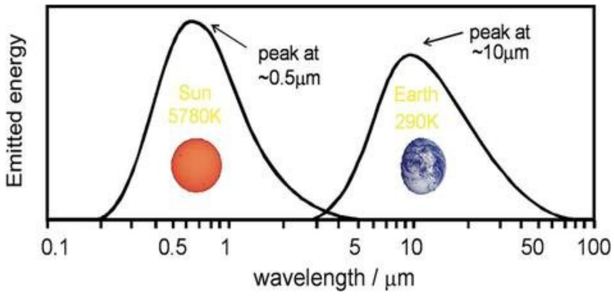


Figure 24f - Black body radiation curves - Sun / Earth



This is all very interesting. But what does it tell us? Let's turn everything on its head and instead think of the universe from the perspective of an atom.

Atoms, as systems, interact with wavelengths of radiation, which are of a relatively similar size to the atoms themselves. Gamma rays, with extremely short wavelengths and very high energies, either pass straight through or threaten the integrity of atoms, by being absorbed by the nuclei and causing the atom to decay to something else. Much longer wave radiation - microwaves, radar and radio waves - pass straight through with no interaction. So, if you are an atom in a gas, you will only interact (and at the same time be sure to maintain your integrity as a whole system) with this relatively narrow band of radiation around the ultraviolet, visible and infra-red spectrum. Any other radiation is either dangerous or invisible.

This might be a bit of a stretch as an analogy, but one could compare the experience of atoms to that of the leopard on the savannah. It hunts other animals that are of similar size, and which provide an appropriately digestible quantity of energy. Mice are pointless; they provide so little energy that they are not worth the effort. Rhinoceroses and elephants are avoided because of risk of injury. So, the leopard focusses its attention on large hares, warthogs, antelope and small bison, all of which provide a good meal and are worth chasing without fear of being damaged in the process. Regardless of the appropriateness of the analogy, gaseous atoms can only interact with a narrow range of radiation, and, within that range, different elemental atoms are very fussy about what they can interact with.

Whilst we don’t see atoms as being alive, they are very definitely systems and would seem to be a lot more interesting than inanimate objects responding to forces. They very clearly interact with their energetic environment, and they seem quite particular about how. So, what do we make of this? Before conjecturing a solution, it is worth exploring another phenomenon discovered by the Victorians, one which caused them to draw up another law, in this case the 3rd Law of Thermodynamics.

Chapter 25 - Universal Impossibles

"Particles have needs too."

Over the last two hundred years we have discovered three things about our universe which are impossible. Two of these are encapsulated by the 1st and 3rd Laws of Thermodynamics. The other is Einstein's realisation that no matter object can travel faster than the speed of light. Putting aside questions around time travel, pretty much anything else is possible. Pigs flying and other equivalent anecdotes are extremely improbable - perhaps even as unlikely as your milky tea spontaneously un-mixing - but not theoretically impossible. Taken together these three unattainable eventualities can provide a profound understanding of the nature of our universe.

The 1st Law of Thermodynamics has a rather convoluted history. This is in large part because, by definition, it covers all those different types of energy that students learn about in physics and maths lessons in their early years at senior school and which were therefore explored by a whole variety of researchers in various scientific and engineering disciplines.

There is potential energy associated with gravity, which can be released when you drop your cup of tea on the floor. There is the mechanical or kinetic energy, which your cuppa achieves on its downward travel to destruction on the floor. There is the spring energy that drives your old-fashioned watch, which you were trying to look at when you dropped your cup. There is chemical energy, which drives your modern battery watch, which you should have been wearing instead. And then, there is the nuclear energy that is now used to generate electricity (another type of energy) to light (yet another energy) your house and power your vacuum cleaner to clear up the mess of the broken cup. And so, it goes on. And we haven’t touched upon the energy that enables you to live.

It took the whole of the Victorian era and a good half of the last century for us to be fully committed to the 1st Law. It applies to every one of these different energy types. It is now accepted doctrine and is absent of all those on-going questions that linger around the 2nd Law. There were many attempts at the 1st Law’s derivation, especially by thermodynamicists, but perhaps as good as you get is that “*energy can neither be created nor destroyed*”.

This seems to be a universal truth. The energy that exists in our universe can disperse, as per the 2nd Law of Thermodynamics. It can (albeit never perfectly efficiently) be changed from one form into another: for example, using the chemical energy stored in petrol to drive your car forwards; or, pouring water (with initial potential energy) down a mountain side to drive a turbine (mechanical energy) to create electrical energy to power your home. Energy can be trapped as mass, where it was Einstein who discovered the famous equation $E=mc^2$. This shows how much energy is released from a very small amount of matter: for example, one gram of matter converts to around 21 kilotons of TNT equivalent in explosive energy; that’s of the order of magnitude of the atomic bombs dropped on Japan at the end of WWII. Both nuclear and chemical energy involve the conversion of microscopic amounts of matter and turning this into heat. So, you can transform all sorts of energy from one into another, including energy stored as mass. But you cannot get rid of energy. Nor can you artificially generate energy or, for that matter, ‘matter’ from nothing.

Whilst it is difficult to definitively prove the apparent universality that energy cannot be created or destroyed, scientists now consider this observation to be inviolable. When people come up with ruses to create cheap fuels, the first question asked by the scientific community is “does this violate the 1st Law?” Fail that test and any proposal is automatically discarded out-of-hand.

Energy, especially in the form of photons and thereby heat, is everywhere. Wandering around your nicely warmed centrally heated house, you might be mostly oblivious to your energetic environment. It all feels very comfortable. Passing by a south facing window with sunlight streaming in, you may become aware of the heat from the sun’s rays. The part of you facing into the house will, however, continue to feel the ambient temperature in the room, which you might not really notice. On a cold winter’s day, when the sun has dipped behind a cloud and when outside temperatures have dropped below zero, the side of you facing the same window will instead feel as though you’re being bathed in coolth. You’re not. What’s happening is that you’re radiating out your warmth, which is not being replaced. There is a net flow of energy away from you. You are very definitely not at equilibrium with your environment.

Through investigating black body radiation, the Victorian’s became aware that all materials are continuously absorbing and emitting radiation. Within your home, all surfaces - the floor, the walls, the ceiling, the windows and any furniture - are absorbing and radiating energy all the time. The ambient temperature you experience, as you go about your daily business, is determined by this perpetual flow of photons from all these things around you. In every cubic metre of air at room temperature, there are several hundred trillion photons always passing through. It is a constant flux of energy. The temperature that you experience is a consequence of the quantity and wavelength distribution of all those photons flying around. Stand near a fire and you are bathed by shorter wavelength photons; it feels hot. Open the freezer door and you experience only longer wavelength radiation. As per the black body thesis, there are no higher energy photons coming out of your freezer and, therefore, those shorter wavelength photons that your face is emitting (being that it is at a higher temperature to the freezer) are not being replaced and you feel that energy sapping away from you.

You might imagine that you're immersed in a constant bath of photons, but the analogy is poor because those photons are perpetually moving through at the speed of light. Yet that is effectively what it is. Without all those photons constantly hitting you, it would feel like deep space cold - and that's really cold and not conducive to your comfort … or survival. And even in deep space, there are a few hundred million photons within each cubic metre at any moment, albeit most with much longer wavelength, making it feel that much colder.

Temperature is one those macroscopic parameters of systems, which are of interest to thermodynamicists. During the first half of the nineteenth century, these scientists spent much time carefully measuring how temperature varied against volume and pressure, such as when you squeeze air, as you pump up your bicycle tyre, it warms up. The experimenters used their results to derive equations. With this basic knowledge of gases, a brilliant young man, born as William Thomson, started exploring "what if" one were to extrapolate these results to more extreme temperatures. Thomson had a prestigious career, publishing his first scientific paper at the age of 16 and culminating in him being ennobled for his contribution to thermodynamics. He became Baron Kelvin of Largs in the County of Ayr near Glasgow and his lasting legacy is the absolute temperature scale, known as the Kelvin. One of his other theories was much shorter lived: he construed that atom represented miniature vortices.

Thomson extrapolated those equations predicting how gases respond to changes in temperature, pressure and volume. As you cool a gas down at constant pressure, its volume shrinks, eventually in theory reaching zero, which he rightly presumed demarcated a minimum possible temperature. Outside of the USA, most countries use the Centigrade scale to measure temperature. This takes zero as the melting point of water and one hundred as the boiling point, thereby creating a single degree as a hundredth of that range. Kevin used the same centigrade steps and formulated his own temperature scale. He derived the minimum temperature to be around minus 273 degrees Centigrade. His scale then takes this to be, what is now known to be, absolute zero. Using his scale, the temperature of your room at 20 degrees Centigrade is the equivalent of 293 Kelvin. It took another fifty years for a mathematician to use Boltzmann's statistical mechanics to identify an alternative way to derive the same result. And then in the 1930s, two researchers from the Tokyo University of Engineering finessed the result to its modern day accepted standard of minus 273.15 degrees Centigrade.

With the theory well established, the practical challenge was set to try and cool something down to as low as possible. By the early twentieth century, cold enough temperatures had been reached to be able to liquify all gases, excepting Helium. The lowest value achieved in laboratories around the world has gradually been pushed lower and lower until in recent years temperatures within a fraction of a degree above zero Kelvin have been reached. But, as predicted by theory, reaching zero has proven to be impossible. It is interesting, however, to ponder on what reaching such a target would mean?

Science magazine articles about absolute zero tend to focus on the notion that at this temperature all matter is perfectly ordered and genuinely motionless. At any temperature above zero, the atoms within a material are vibrating. And, because they are moving, the atoms are constantly absorbing and emitting photons. Down close to absolute zero, those photons are much longer wavelength than those that dominate at comfortable room temperature. By way of example, in the 1960s, two American astronomers accidentally discovered the cosmic background microwave radiation, thinking it was noise in their apparatus. After much scratching of heads, they eventually realised that microwaves infuse the whole universe, wherever you are, just like much warmer photons fill your comfortable living room. This cosmic radiation has wavelengths of the order of 3 millimetres to 30 centimetres (the length of a typical school ruler) - somewhat longer than the infra-red and visible spectrums (measured in nanometres). The microwave radiation indicates that the background temperature of deep space is just under 3 Kelvins - definitely too cold for house guests. But as you go lower still and approach zero Kelvin, the dominant photons have even longer wavelengths. And eventually, reaching absolute zero necessarily means that there is no radiation at all. Literally everything stops.

Now, if radiation were eliminated and there are categorically no photons absorbed or emitted by an object, then by definition it is no longer interacting with the wider universe. In thermodynamic terminology, it has become an isolated system - the theoretically perfected vacuum flask - no energy in, no energy out. Thermodynamicists spend much time talking about isolated systems in the full knowledge that they are practical impossibilities. Such systems are, by definition, no longer part of our universe. If something is no longer interacting with its environment, then the question arises as to whether it exists at all. For to reach absolute zero would effectively contravene the 1st Law of Thermodynamics. It would equate to destruction of matter. It would seem that our cosmos doesn't like that.

Turning this around and looking at it from the perspective of particles of matter, a quintessential attribute of matter is the need to remain interacting with the universe of which it is a part. It *needs* to interact…

From one extreme to another, it turns out that there is also a maximum temperature. In seeking to understand why light seemed to travel at the same speed, no matter which direction you sent it in or from what frame of reference you are observing it, Einstein derived his special theory of relativity. This is the theory that gives first year university physics students serious headaches as they try to grasp why space travelling twins visiting different worlds would age at different rates. In Einstein's special theory, it is apparent that objects with mass (i.e. anything other than photons) cannot achieve the speed of light. This theoretical prediction is tested to destruction daily at particle accelerators such as CERN, where physicists pump more and more energy into protons (note protons, not photons) circulating those 27 km tunnels to smash them into each other at as high a temperature as they possibly can. But no matter how much energy they use (and it's a lot), they can never get these protons to reach, let alone exceed, the speed of light.

For a lump of matter to exceed the speed of light would mean that it would also lose contact with the universe. It could no longer be bathed in constant radiation. This is not because it is outracing all the photons around it. Rather (and this is one of those things that physics students must get their heads round), according to Einstein's special relativity and as proven experimentally since, as a piece of matter speeds up, it's experience of time slows down. At the speed of light, time would reach a complete standstill. Photons do not experience time. They can travel across the whole universe in, what is to them, an instant. It is a fundamental differentiator between matter and energy: matter experiences time, energy does not. If time were to stop for a material object, then it could no longer be interacting with the universe we know. It seems that material things becoming disconnected from our universe somehow contravenes the very nature of matter and the sensibilities of our cosmos.

If all of this is true, then atoms cannot function as figurative Lego bricks. They are not inanimate objects, merely responding to forces as perceived through the philosophical mindset of materialism.

They need to interact.

I'll say this again for added impact.

Atoms are material systems, which need to interact with their environment.

So, if our universe is not composed of figurative Lego bricks, then what is it made from?

Chapter 26 - Social and Anti-social Matter

“~~The 2nd Law of Thermodynamics~~”

Thunderstorms are both exhilarating and scary at the same time. We have come a long way over the last 1,000 years from thinking that they are caused by gods doing battle in the sky, beating their chests and throwing lightning bolts at each other. But there are many aspects of thunderstorms, which are still inexplicable. Working with our current thinking on thermodynamics, as originally constructed by Boltzmann and a host of others, then these heavenly displays are quite impossible. Such storms are clear evidence of a localised build-up of energy in the sky. But there’s nothing in our toolkit of basic physics to explain how this can happen in a gaseous system.

Many weather events are clearly driven by the atmosphere seeking to achieve equilibrium - that state of deemed maximum entropy as predicted by conventional thermodynamics. Wind and air currents flow to resolve spatial differentials in pressure and temperature: the wind blowing from high to low pressure, or air warmed by hot ground rising upwards causing invisible updrafts in a clear sky, on which eagles and paragliders can soar. All these currents act to disperse energy and water vapour, all moving towards gaseous uniformity. These align with the perspective that the universe, abiding by the 2nd Law, seeks to smooth energy differences and drive everything towards homogeneity and ever-increasing entropy.

Our atmosphere is made up of a variety of gases - mostly nitrogen, oxygen, and water vapour - which behave according to various laws for gases deduced by our Victorian forefathers at the same time as they were formulating their ideas on entropy. These more specific laws are all consistent with the broader ideas on thermodynamics. Within this way of thinking about gaseous systems, gases expand to fill volumes; gases mix irreversibly; gases expand or increase in pressure when heated and contract when cooled. The way gases respond to any changing circumstances always works to dissipate temperature and pressure differentials. Applying these to our atmosphere, when you look up, you would expect to see cloud cover or clear skies but not distinct fluffy white clouds floating by. That water vapour should disperse out to uniformity.

With the Earth being a rotating sphere, the weather's business is never done. The sunny side warms and the dark side cools, so the air is constantly on the move to dissipate differences, trying to achieve global equilibrium. There is, then, no logical explanation for extreme localised build ups of energy that can then lead to dramatic light and sound displays. So, how come this extreme concentration of energy occurs within a gaseous system?

A key test of the approach proposed in the earlier chapters of this book is whether and how it can be applied to the material world of atoms and molecules. This alternative way of understanding our universe can be construed to be an agent-based construct. All definable things in the universe, differentiable from their wider environment, are taken to be agents, otherwise known as systems. And all such systems are deemed to be 'chasing' quanta of energy, as already explored with respect to all those larger and more complex living objects, which we come across in the social and life sciences. Applying this to the material world, we would also expect to see agents competing or cooperating for quanta of energy - those very fast-moving photons.

Now, whilst we might construe that we and other highly evolved animals act with volition, we don’t mentally consider bacteria to operate with any intention. They simply respond spontaneously to changes in their immediate environment. Yet, we still consider them to be living systems and they manifestly compete and cooperate. And some of them can swim - really swim - some can move upstream around ten times their body length in a single second, seeking out concentrations of sugar. So, the question stands: can we think about atoms in the same way? Given that the materialistic mindset, with which we have all grown up, is so entrenched, it can require some mental acrobatics to transpose this other way of thinking onto the material universe. But it is worth trying.

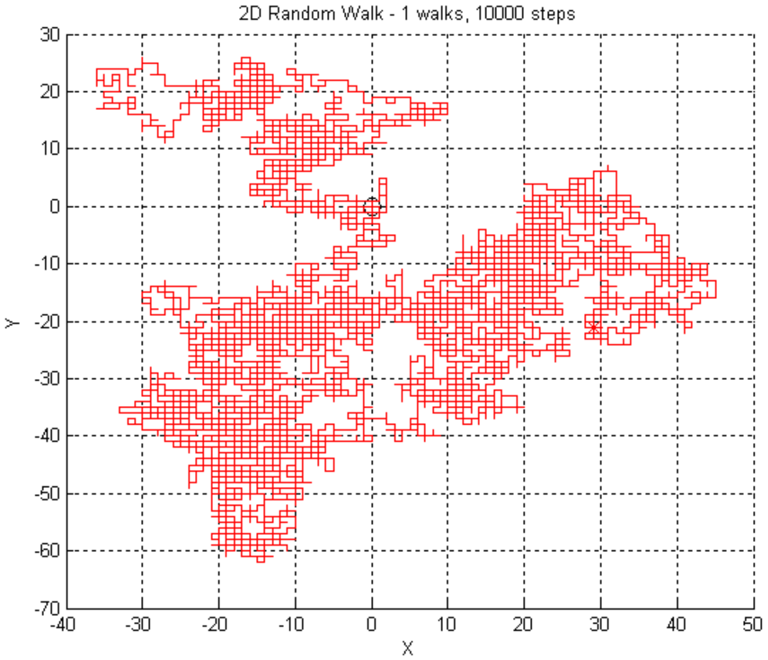
Within this construct, when seeking to explain the occurrence of events or the formation and existence of any larger systems, one must consider how and why the participating agents are behaving the way they are. Are they competing or are they cooperating? And, why? As already discussed, atomic agents are quite particular about the wavelengths of radiation, with which they can interact. This recognised ‘choosiness’ is a core thesis of quantum mechanics. However, in the material world, energy and interaction are arguably synonymous: absorption or emission of a photon is itself an interaction. It therefore becomes a philosophical question for another day as to whether atoms respond to situations to optimise their access to energy or to optimise their interaction with their environment and by deduction the universe at large. It essentially boils down to the same thing.

So, let’s zoom in with our figurative microscope, diving down from the wriggly animate bacterium towards the scale of molecules and atoms. If this approach is valid, then the same principles would apply at the even smaller scales of nucleons and quarks, since atoms are themselves systems. But we will focus here on Level 1 systems in the atomic world, with which we are much more familiar. In the following chapter further consideration will be given to higher level material events and systems.

Level 1 - Passive Competition - agents acting independently

We return to the comparison between atoms and tigers made in chapter 23. Let's say we have a container filled with normal Earth atmospheric air. We perceive this gas composed of particles, as Boltzmann did, being miniature inanimate objects randomly bouncing around. The progression of any one atom or molecule through a volume of space is, so we believe, entirely haphazard and necessarily slow. Watching a random path generator on a computer, you can see how long it takes a cursor move any significant distance: randomly going left, right, up, down, almost returning to the origin, then moving away again, and back and forth until after a while it eventually leaves the screen (See Figure 26a).

Figure 26a - Typical Random Path (2D)



In the corner of our large container, we have a small canister of some other gas at the same pressure as the air in the larger volume. On opening a hole in the canister, this different gas spreads out and starts mixing throughout the air, eventually uniformly dispersed. It takes a while for complete mixing to take place. This can be directly observed by taking a coloured gas, such as bromine (brown), and leaving it to mix with air in a bottle. However, what is completely inexplicable through current mathematics and physics is the speed at which the leading molecules expand outwards into the larger volume (see Box 26a).

Box 26a - Canine Physics and Cheese Explosions

The speed, at which gaseous molecules spread out from a source, can be experienced on a daily basis in any household where a dog resides. As you merrily prepare lunch, opening and shutting the fridge door, spreading butter on bread, cutting up some cucumber and tomato, you might be watched going about your business by your canine companion, tucked up on its bed on the far side of the room - say, five metres away. You open a tupperware containing a selection of cheeses. And you continue to be observed by that motionless creature with her super-sensitive nose. There is no obvious immediate reaction to the sight or noise of the plastic container being opened. But count to about five seconds and she raises her head, sniffs the air and in a trice is by your side with an expression that says: “I luv cheese!”

Clearly your dog has eyes and ears and could have registered the opening of the box with the likelihood of cheese nibbles forthcoming, based on remembering what you did yesterday. But it doesn’t tend to happen that way. Rather, it’s when she smells the cheese that she comes trotting over. This suggests that those front-running cheese scent molecules have made it across to the far side of the room in about the same time as it takes to walk over the same five metres. There are no doubt air currents gently swirling around the room. But they’re not sufficient to transport the scent that fast over to your dog’s nose. That would require a gale blowing through the house. So, how did they get there so quickly?

The known physics is as follows. Molecules in the air at room temperature travel at speeds in the order of 500 metres per second (or 1,100 miles per hour). That's fast. But the distance that we think they travel before they bump into another molecule is in the order of 30 to 60 nanometres, which is around 100 times the particle's diameter. (That's the equivalent of you being able to run full pelt through a crowd for a distance of 30 metres before bumping into someone else and ricocheting off them in some random direction.) Through the continuous bumping into other molecules, enforcing a random path, the resultant mathematically estimated diffusivity co-efficient for molecules in air is around 0.2 centrimetres per second. So, when you open the box of cheeses, unless you actively waft the whole volume of air upwards towards your face, it should take the cheese scent particles around 4 minutes to reach your own nose! Not, essentially instantaneously, which you actually experience.

The inconvenient truth is that the speed at which those leading molecules spread out through your kitchen cannot be explained by means of our modern mathematics or physical sciences. If dogs were physicists, they would have challenged our assumptions about gaseous diffusion long ago.

Treating atoms and molecules as systems responding to their energetic environment, each type of particle interacts with discrete wavelengths of radiation. Whilst the total quantum of photons in any instant passing through a volume, such as a cubic metre, can be measured in the trillions, the number of photons with which those particles specifically interact is invariably a small fraction of that total. Competition is also intense: the number of gaseous particles in that same volume of air is also measured in trillions. The available energy that each atom or molecule can interact with is limited. The particles of the new gas released from that small canister are competitive entities, which need to interact with a very specific set of wavelengths of photons. So, they rapidly spread out to be as far apart as possible from each other because doing so optimises the level of interaction that they can each have with the ambient radiation, and thence the universe at large.

Once the initial scattering has taken place, the particles remain in a state of maximum dispersal because of the innate competition between them. If macroscopic variables, such as temperature, pressure and volume remain the same (as would be the case if the system were isolated), then no further change will be seen to occur to the mix of gases, even if at the microscopic level the particles are continually moving around, maintaining their distance from each other - akin to tigers in the jungle, perhaps. Whilst it takes a while for complete mixing to occur, to explain the speed at which the frontrunners of those newly added molecules disperse outwards requires conceding that somehow those frontrunners can travel through the molecular ecosystem without following a truly random path - just like a lead tiger might navigate its way through the forest without bumping into every tree.

Level 1 - Active Competition - the stealing of energy

Level 1 active competition in the material universe manifests as dispersal of energy and not necessarily the spreading out of material objects – though frequently both passive and active competition occur concurrently. That active competition is expressed as dispersal of energy may at first appear counter-intuitive. An easy way to visualise this is to think about a game of pool. When you fire the white ball (an agent) with high velocity at the colours, those other balls effectively steal its energy. The white ball, having lost its initial momentum, slows down. The maths teacher at secondary school may not describe such events using language such as ‘stealing’. But that is essentially what is happening. At the start of the game, this may lead to a spreading out of the balls across the green felt (Level 1 Passive Competition). But once the game is in full flow, each shot of the queue ball simply leads to a re-arrangement of the balls on the table, no further material dispersal, but very definitely a dispersal of that original focussed energy.

In many situations, with which we are familiar in the material universe, atoms and molecules are already fully dispersed, such as in the air we breathe. So, when you create a heat source, such as a hot poker, the gaseous molecules nearby absorb the radiative heat and express this through greater motion - they speed up. The local temperature of the air correspondingly increases. As those with higher velocity bump into other molecules further away, this extra energy is quickly stolen from them and so the heat disperses outwards through the air.

It is this active competition, which so fascinated the Victorians, preventing them from being able to construct perpetual motion machines, prohibiting them from being able to convert one form of energy into another with 100% efficiency. The molecular world always stole some heat away. Whenever there is some differential of energy, such as a point source of heat, this is the primary response of all material systems, gaseous or otherwise - particles steal the heat off each other and the energy is quickly dissipated outwards.

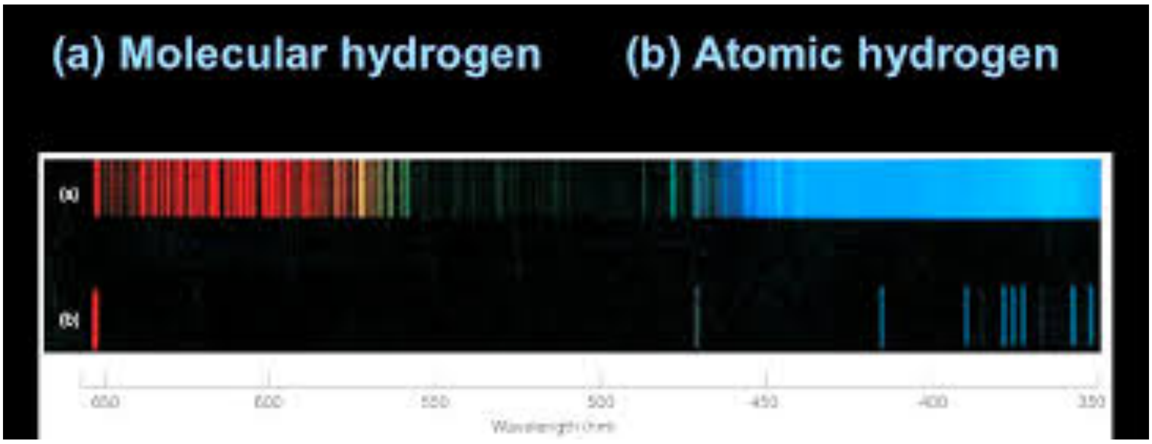
This action of dispersal is an event and continues for so long as there is a localised temperature differential. This is the primary cause of your tea cooling down to the ambient temperature in your kitchen and thereafter remaining at equilibrium with its surroundings, not changing any further. It ends up in a state of so-called maximum entropy, which equates to a competitive equilibrium – after all, the act of stealing, as discussed previously, is a repetitive zero-sum game. At the microscopic level of atoms and molecules, the agents are continuously stealing energy off each other such that no further macroscopic change can ever take place for so long as that wider environment, the air in your kitchen, remains at room temperature. Competition ensures that there is no net flow in any one direction.

Level 1 - Active Cooperation - sharing energy

Molecules represent the families and tribal units of the atomic world. We are taught that they are held together by covalent bonds, being the strongest chemical binding that exists. But, if we are to switch our description of matter particles to that of agents responding to their energetic environment, then we come to realise that these apparent covalent bonds are energetic processes. Each atom is bound into the molecule because it is in that atom's 'interest' to do so. And it will remain bound into the molecule for so long as it continues to be in its 'interest'.

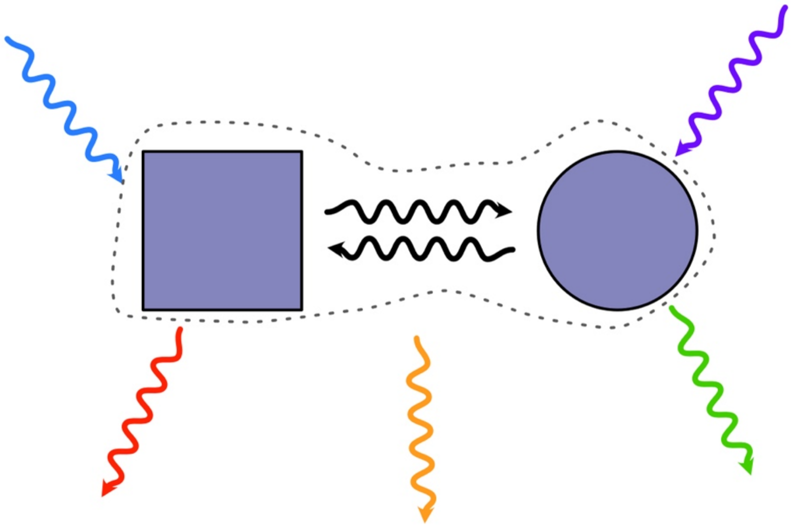
By being part of a molecule, an atom can increase its interaction with the wider energetic environment. This is achieved through active sharing of incident energy. By way of example, hydrogen atoms are the most studied atoms in physics. They are composed of just one proton and one electron. Consequently, the quantum mechanics mathematics is relatively simple compared to all other atoms and molecules. This means the spectrum of absorbed and emitted photons for hydrogen atoms can be accurately predicted and tested experimentally. Hydrogen is the most bountiful element in the universe. Most of it floats around in space as individual atoms. However, at the temperatures and pressures with which we are accustomed on planet Earth, hydrogen is found in its molecular form - H-H. The diagram (Figure 26b) below shows the atomic and molecular spectra for hydrogen. Where separate hydrogen atoms can only absorb and emit at very specific wavelengths, the molecule can interact with a much broad range of photons.

Figure 26b – Hydrogen – Atomic and Molecular Emission Spectra



When different elemental atoms are bound together, they can each interact with different wavelengths of radiation and share this with each other (see Figure 26c). Further, through the formation of molecules, radiation from different parts of the electromagnetic spectrum can be accessed. For instance, when oxygen binds to two hydrogen atoms to create a water molecule, these three atoms can vibrate against each other in such a way that they can now absorb much longer wavelength photons. This is why you can heat up your soup in the kitchen microwave.

Figure 26c – molecule absorbing / emitting photons



One of the confusing things about particles bonding together is that, at least at the atomic and nuclear levels, they weigh less as coherent objects than as separate entities: the total weight is less than the sum of the parts. So, a Hydrogen molecule weighs less than two hydrogen atoms. A Helium nucleus weighs less than its constituent two protons and two neutrons. In conventional thinking, this is attributed to a binding energy, which is construed to be negative. However, it can equally be understood as a trade-off, whereby cooperating entities need less retained energy to exist and maintain interaction with (or access to energy from) a wider universe. This can be explained by means of an analogy in the human context, remembering that money is a proxy for energy (see Box 26b).

Box 26b - The Freelancer's Dilemma

Imagine the scenario where two freelancing consultants are debating whether they might join up to form a company. They each consider their situations before and after such link up. As individuals, they command high day rates. However, both their incomes are quite irregular. With such high day rates, there are times that they each bring home a very sizeable salary. But, with void times factored in, this averages out to just a reasonable income. To account for the irregularity, they each must retain a sizeable ‘rainy day’ allowance in their bank accounts.

If they were to join up and create a company, they would be in a better position to secure bigger, longer-term contracts, albeit probably on lower day rates. Their maximum potential day rate incomes would be reduced but be less erratic, so they would need to retain less total back-up money in the new company’s bank account. Counter to this, they would now be committed to working together, forever coordinating with each other, and covering for each other.

They weigh up the options, looking to the economic forecast, which suggests a recession ahead. They decide to form a new company. In so doing, they are each able to release a proportion of those back up funds (release some energy). They are each aware that, if they were to go separate ways in the future, then it would cost both of them money, as they would need to replenish their bank accounts with those ‘rainy day’ allowances.

In coming together to form higher level systems, whether molecular or in the formation of liquids or solids, then atoms can exist in, what might be construed to be, a lower energetic state. They can ‘ditch’ some energy and this manifests in the atomic context as weighing less - noting Einstein’s equation $E=mc^2$. To retrieve their freedom as individual gaseous units, they would need to absorb extra energy from their environment to break any relationships, which they may have formed. There is, then, a trade-off between freedom (gaseous atom) and ability to access energy from the environment. Lower the temperature (equating to poor economic forecast) and atoms gather, and in the process release energy. But now as larger units they can interact with the longer wavelengths of photons corresponding to that lower temperature environment. It is simply an economic decision, responding to optimise their interaction with the wider universe.

Level 1 - Passive Cooperation - exchanging energy

What is a cloud? When you look up and see fluffy white things float by, high above your head, what are you observing? Returning to the definition of systems, provided in chapter 2, clouds are clearly objects, which are identifiable against their surroundings. To be logically consistent with this agent-based alternative construct of reality, they must arise from some form of cooperative interaction. So, what is really happening up there in the sky?

In parallel with examining how best to use steam to convert heat energy into useful work, our Victorian forefathers also studied various other properties of water. We are all familiar with the idea that air can carry moisture; it can be humid or dry. Further, warm air can hold higher levels of evaporated water than cold air. Consequently, when you cool air down, it reaches a point of saturation, which is known as the dew point. This is the temperature for that level of moisture content, at which things will become damp. For example, when you take a hot shower, you steam up your bathroom, making it so humid that when this air, laden with water vapour, encounters your cold mirror, it condenses out, causing the glass to mist up. This is dew.

The basic formation of a cloud can be shown through the ‘cloud in a bottle’ party trick, where there are many videos on the internet showing how this can be done. There are two important ingredients. One is that moist air must be cooled down. The other is that there must be minute, too small to see, particles of dust in the air, on which the water vapour can condense. We are not overly aware of such dust particles in day-to-day life; but in every cubic centimetre there are hundreds of such pieces of dust; in polluted city environments, these can approach a thousand or more; even in air that we might otherwise presume to be crystal clear - say over the ocean, in the arctic, high up in the sky - these will often exceed a hundred. A combination of mathematical proof and experimentation has shown that such minuscule particles are essential for the formation of clouds.

When you create a cloud in a bottle, the instant the pressure is released and the entire body of air cools down, water molecules condense onto each of these dust particles. The reason why a cloud is opaque is because these hundreds of dust particles per cubic centimetre, now each covered with tens of millions of water molecules, are of a size that they scatter visible light. These water-coated dust particles are generally known as hydrometeors. Clearly, the more dense the original dust, the more opaque the cloud - hence why pea soup smogs can form in urban areas with very poor air quality.

The hydrometeors, being the active agents which make up a cloud, are very dynamic. Each one is continuously growing and shrinking at the same time. Each droplet is surrounded by a swarm of water molecules, which are condensing onto it as others are evaporating off. It’s a delicate balance. A slight tipping towards evaporation and the cloud quickly dissipates, as seen when your foggy breath on a cold dry winter morning floats away and disappears. A marginal increase in condensation and the droplets can exponentially grow until they rain or snow out. Yet, up there in the sky, despite this continuous flux at the microscopic scale, the clouds are surprisingly stable, as they slowly float by. So, the question must be asked as to why they manage to perpetuate for so long? This returns us to the puzzle of what is a cloud, as a coherent thing, differentiable from its wider environment.

There are three features of clouds, as whole objects, which are worth noting. Firstly, when you fly through a cloud, you quickly lose all sense of direction. In the heart of the cloud, you can no longer see from which direction the sun is shining. If it weren't for gravity, it would be impossible to tell up from down. Internally, the cloud is completely uniform. Secondly, the cloud has an outside surface (albeit a very rough surface, as modelled by Benoit Mandelbrot with his fractal mathematics). And, thirdly, we know that clouds can retain and store energy, which under the right conditions can lead to thunderstorms. These don't happen in cloudless skies.

Having explored how energy interactions give rise to social processes in the human domain, it is possible to understand better what could be happening within clouds at the microscopic level, why they appear to hold together and why they can aggregate energy.

The hydrometeors are acting analogously to those proto-cities of thousands of years ago, such as Catal Huyuk in Anatolia. The watery particles are floating around within a body of air, which contains large numbers of free-roaming water molecules. Given that hydrometeors may contain tens of millions or more of water molecules surrounding a dust particle, they may as well be stationary relative to the speed of motion of free water molecules around them. They represent fixed points in the system - just like those early cities became pegs on the map of human geography. This helps to provide the whole cloud with a small degree of inertia, relative to surrounding air. Where physicists describe competing dynamic activities of condensation and evaporation, these are equivalent to people coming and going to trade with the city - bringing with them specific quanta of energy reaped from the wider environment and departing with different quanta (albeit summing to the same total) - exchanging. For this process to happen, all those water molecules must now be operating cooperatively, no longer seeking to disperse to be as far apart as possible from every other of their own kind.

In totality, the cloud is now functioning as a society of water molecules. It is a nested system with three levels of operational agents: (1) individual water molecules (economic agents), (2) hydrometeors (marketplaces) and (3) the whole cloud (society). There are dynamic relationships between the water molecules and the hydrometeors, and also between the hydrometeors and the whole cloudy body. These processes function to stabilise the cloud as a coherent cooperating system. Fundamentally, however, the water molecules themselves have undergone a phase change from competition to cooperation.

Clouds inhabit locations where there are temperature and pressure differences - warm humid air rises off the sea, cooling until it reaches its dew point and hydrometeors start to form. Once the cloud has appeared, it creates its own differential. The radiative environment above and below is quite contrasting: above, hydrometeors surrounded by cold air yet sun beating down imparting lots of energy in the form of short-wavelength photons in visible spectrum, and, beneath, surrounded by warmer air with Earth radiating upwards longer wavelength infra-red photons. A cloud functions analogously to a trading society. By means of these hydrometeors, the cloud can absorb a much wider bandwidth of incoming radiation, both from above and below, and distribute this homogeneously throughout its interior. Despite the very different conditions surrounding the cloud, through exchange interactions the system acts to achieve much greater uniformity within, thereby maintaining itself as a discrete entity from its context. The scattered light, transmitted in every direction, is part of this process of exchanging energy between all the agents in the system. What’s more, the cloud can accumulate energy through increasing levels of interaction between all the component parts - essentially energy becomes stored as a continuous flux being perpetually exchanged between all those hydrometeors and onwards with their surrounding swarms of water molecules.

Whilst the individual processes, such as the way that hydrometeors respond to changing temperature, can be explained by means of basic physics, the behaviour of the cloud, as an entire object, does not conform with a conventional entropy construct. According to normal thermodynamic thinking and theories on gases, differences in water molecule concentrations and energy associated with any temperature differences should all rapidly disperse - proceeding towards uniformity between clouds and their surroundings. Away from locations where clouds are forming, such as over the seas or when humid air hits land, our skies should be cloud covered or clear. But instead, we see highly stable systems floating overhead, maintaining their integrity over time. And, when the temperature differentials around the cloud are extreme, such as when a cold front collides with warm humid air, then the resultant cloud cannot only accumulate energy, but as a whole system convert that store of energy into electric charge, to give us an exhilarating display of the wrath of nature.

The 2nd Law re-visited

So, looking at our physical universe from the perspective of seeing atoms as particles responding to their energetic environment, what then is this concept of entropy?

The phenomenon, which the Victorians first observed, studied in detail, and eventually decided warranted being crafted into a universal law, was simply the innate competition that exists between particles. The dissipation of heat within gases arises because the constituent atoms and molecules steal energy off each other. Any gaseous particle with a higher momentum than average quickly loses this to the surrounding other particles until a competitive, dynamic equilibrium is achieved. This can be explained through Newton's mathematics of elastic and inelastic collisions. What is much more difficult to explain through basic mechanics is why similar atoms migrate so quickly to be as far apart as possible from all others of their own kind, so that any collection of gases rapidly mixes and then stays that way forever after. There are two ways to explain this observation: Boltzmann's statistical mechanics, in which the outcome of this event is seen as being the most probable, or a common-sense perspective, seeing the particles as competing entities.

When you combine passive competition (dispersal of agents) with active competition (dispersal of energy), you have the main observational platform on which the 2^{nd} Law of Thermodynamics is built. Being competition at Level 1, these two events are the most common behaviours that we can expect to see within the material world – the first response of any system to a change in its environment. And so, just as Darwin's theory of evolution represented the first step in a much more complicated picture, so is Boltzmann's theory. And, as with the life sciences, the extant physical sciences have a good coherent explanation for competition but not a consistent understanding of how cooperation takes place.

Choosing the agent-based perspective does not de-value all the work that's been done over the last century. It does not detract from the fact that Boltzmann's mathematical formulae have allowed and continue to enable physicists to model and predict how physical systems respond to events. But, looking at systems in terms of competition and cooperation of interacting agents allows us to better understand how and when to use this mathematics and appreciate better what the results of such modelling may be telling us. Furthermore, it gives us the capacity to align the physical with the life and social sciences.

If you choose the agent explanation, then entropy represents a measure of or proxy for the degree of competition within any system. Understanding it thus helps resolve some misconceptions that have arisen over the last hundred years, largely because of Prigogine’s work. There is no inevitable tendency towards some mythical universal increase in entropy. So, you can relax, our cosmos is not undergoing some form of slow heat death. Rather, competition (and thence entropy) is specific to each system, as was originally construed by the Victorians. A change within one system may have a consequential impact on another. But entropy itself cannot be exported. It is an attribute of each system of interacting agents.

Increasing temperature (adding energy) will generally allow for particles within a system to break bonds and act freely - solid or liquid turns into gas; gas turns into plasma (freely moving electrons and atomic nuclei). Simply put, with more energy around, individual agents find that they can perfectly happily interact with the photonic environment on their own and don’t need to be part of any larger structure. The smaller and lighter a piece of matter is, then the shorter the wavelengths need to be for it to ‘choose’ to be free. Reduced temperature, and thence available energy, intensifies competition causing component parts to switch to cooperation to maintain their interaction with the wider universe. They come together to create larger coherent systems, such as molecules or aggregated systems (liquids and solids).

Referring to the last chapter and consideration of absolute zero, conventional wisdom says that as you approach zero Kelvin, then entropy becomes zero too. Ostensibly, that’s because there is no molecular motion taking place, so any structure is perfectly ordered. But another way of looking at this is to say that at absolute zero there is no competition between component particles; they are necessarily cooperating to work together as a single system to share or exchange any possible lingering photons in the vicinity.

By seeing particles as systems responding to their energetic environment, you can now much better understand why milk automatically mixes into black tea without you having to explain this through mathematical contortions nor rely on statistical probabilities to create a universal arrow of time. Your tea will then cool to room temperature and stay that way forever after - cold bland, fully mixed tea, at equilibrium with its environment - not because that’s the most likely configuration (although that might also be the case) but because those surrounding crafty air molecules have stolen the heat away before you could get around to benefitting from a warming drink.

Now, that would be a far more fun way to explain thermodynamics to students, even primary school students.

Chapter 27 – Electronic Money

“Chemistry is just accountancy using electrons.”

Harnessing electrons has been one of the defining technological achievements of the twentieth century. We use them to convert sunlight into electricity which can power work. We deploy them to transmit energy over long distances. We store them in batteries (sort of). We use the interaction between electric currents and magnetic fields to generate mechanical energy to drive elevators and cars. And they enable us to store data, compute and communicate.

So, it’s not overly surprising to realise that electrons play a role akin to money within the atomic world. A significant part of the chemistry taught at high school and university is effectively electron accounting, making sure that all electrons are accounted for on both sides of reaction equations. For atoms, they provide a means to share and trade (to track transactions) and a way to store and relay energy. In this respect, they facilitate those same Ideal Type interactions, which we experience in our social world. Wherever we rely on money to participate in social contributions or social exchanges, atoms do the same using electrons.

As far as we can tell, electrons appear to be fundamental particles - genuine lego bricks, which cannot be broken down into smaller parts. This is supported by the observation that, unless accelerating or decelerating, such as being steered round a bend by means of a magnetic field, free electrons, which are not bound into atoms, cannot directly absorb or emit photons, or at least no photons that we’ve ever been able to generate. This suggests that electrons have no internal structure. And, when they do interact with photons, it is usually in the manner of simple collisions, as if both particles were acting like miniature ball bearings.

Electrons are small – really small. Protons and neutrons are almost 2,000 times the mass of an electron: if an electron was a grain of sand, then a proton would be the weight of a marble. Volumetric size, however, is a different matter. It’s nigh impossible to work out how small an electron is because it seems to differ depending on circumstances. They can, after all, act like particles or waves. As particles, outside of any atom, it has been estimated that the upper limit to the radius of an electron is about a thousandth of that of a proton, which itself is a trillionth of a millimetre. This is comparable to the weight difference. But as part of an atom, it is a completely different matter.

At the beginning of the twentieth century, Rutherford deduced from his experiments, firing alpha particles at gold sheets, that atoms are composed of a small hard nucleus (made up, as we now know, from protons and neutrons), surrounded by a seeming soft outer shell (comprised, as we now know, of electrons). When electrons combine with nucleons to create atoms, then the size of the resultant whole system is of the order of 100,000 times the size of the nucleus, containing all the protons and neutrons. The inference is that electrons, as waves, are both light and seemingly capable of being very diffuse. Or, they are perpetually moving so fast that they appear like a blur. No-one has yet been able to work out a way to definitively measure their size, if indeed they do occupy a definite volume of space. As part of atoms, quantum mechanics treats them more like little malleable ghosts, called wave functions, taking on different shapes in differing situations (though the word ‘shape’ is a bit misleading).

When bound into atoms, electrons enable whole atomic systems to absorb and emit photons at much longer wavelengths (lower quanta of energy) than can atomic nuclei. Atoms can use electrons to effectively slice and dice quanta of energy, emitting lower value radiation (longer wavelengths) as suits. This could be construed as analogous to you or I going to a marketplace with a bucket of apples, receiving a lump of money, which we can then divide into smaller components to purchase other things. The consequence of this is that, wherever atoms interact with energy, they tend to break quanta down into smaller components. In a sense, like with larger energetic systems, you could say that atoms generate waste too. When a solid object is sitting at equilibrium with its environment, it is nevertheless perpetually absorbing and emitting radiation. The flow of energy in and out is the same. But the quality of the energy received is subtly different to that emitted.

In that electrons occupy the role of currency within the atomic world, then the sharing, exchanging or passing on of electrons from one atom to another is suggestive of cooperation taking place within any higher-level systems. At the macroscopic level, this manifests through conduction of heat and electricity. Conversely, where matter systems are good insulators, whether of heat, electricity or both, then this is indicative of competition between the component agents. In this respect, gaseous systems are almost invariably good insulators because all those free atoms and molecules are participating in Level 1 active and passive competition. And clouds, of course, being cooperative systems can transmit electricity in the form of exhilarating lightning. With these observations in mind, consideration is given below to some of the higher-level systems in the material world.

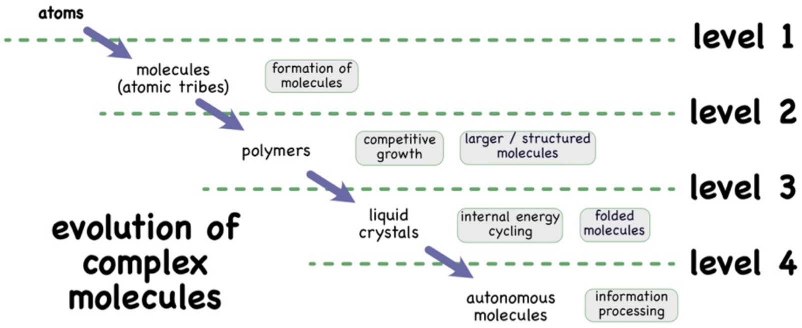
The Internal Evolution of Complex Molecules as Competitive Agents

Once formed, molecules represent whole systems and can respond at Level 1 in just the same way as atoms do. They are the tribes of the atomic world. In this respect, they can disperse within a gaseous ecosystem (Level 1 passive competition) and steal energy off each other (Level 1 active competition). Progressing up the cooperative ladder, explored earlier for other social or living agents, the same sequence of events occur. However, in the atomic world everything is speeded up by many orders of magnitude. Things that happen over centuries for us take place in microseconds for atoms and molecules. The consequence is that we often don't appreciate the evolutionary process but just experience the end results.

As with the progression of human tribes, when molecules form at Level 1 and they compete against each other at higher levels, then to be successful they must internally evolve. This is dependent on increasing internal cooperation between the atoms within each molecule. Such cooperation can happen through a variety of mechanisms. One obvious example is where molecules become convoluted. In these situations, atoms are interacting with more than just their immediate neighbours, thereby strengthening the internal structure of the molecule and providing new types of functionality, such as folding and unfolding into different conformations. Other examples include atoms sharing the electrons more tightly or gaining the ability to move electron density to different parts as an effective defence mechanism. Complex molecules such as proteins are not just pretty structures; there is very clear evolutionary method behind the knots, which they wrap themselves into.

Taking a first step up the evolutionary ladder, competition between molecules at Level 2 manifests as competitive growth. This can be expressed as a positive feedback process, exemplified in polymerisation reactions, where seed molecules rapidly accumulate others of their kind to become long chains consisting of millions of the original. This is the way we make all those plastics, now polluting our world. During such reactions, carbon chains are competing to be the longest. Level 3 external competition pushes molecules to gain autocatalytic behaviours, where they develop the ability to promote the formation of more of their own kind, or parts thereof. And, if the interpretation of the evolutionary ladder in earlier chapters is correct, then Level 4 external competition will lead to the appearance of molecules that are capable of self-directed movement. By way of example, there is a class of molecule now referred to as mobile genetic elements, which appear to be able to move up and down DNA chains, carrying out specific tasks. It is these types of molecules that we are now beginning to be able to harness in technologies such as CRISPR. (see Figure 27a)

Figure 27a – Evolution of Complex Molecules



As explored in the first two chapters, it took hundreds of millions of years for molecular evolution to evolve to the point of creating the first complex systems that could be construed to have some form of vitality. Through inter-molecular competition forcing ever-increasing internal cooperation within molecules, eventually sophisticated systems such as proteins, RNA and eventually DNA came into being. This process continues, as we have recently experienced through the Covid epidemic. Viruses are not alive in the sense of being able to self-replicate. They are highly complex molecular systems, which competitively exploit our biochemistry to make more of themselves. And errors in their replications enable them to improve their effectiveness.

Level 2 Systems – Passive Competition

Within the human context, a good example of passive competition at Level 2 is the way the Wild West of North America became inhabited by European immigrants. From the growing cities on the east coast, families headed westward, settling on the first potential farmland that they could. If it was not already occupied by someone else, then they took it for their own. Gradually the landscape was parcelled up into a jigsaw puzzle of farming plots, each occupied by a family unit or group of families, which became wholly dependent on that piece of land for their survival. In the early days there was very little in the way of any wider social cooperation - no formal road network and no legal system (to speak of). Rather, each farmstead operated in competition with their neighbours, eking out an existence the best they could.

This is an analogy for a class of materials known as amorphous solids, including for instance glass. When temperature drops quickly, populations of atoms or molecules competing at Level 1 lose their kinetic energy until such point that they are forced to coalesce together. They slow down and stop, each agent occupying a volume of space, in which they are stuck thereafter, accessing whatever energy comes their way. They do so in a haphazard manner, locked into place next to their new accidental neighbours, creating a solid with no long-range order, with the particles staying together for so long as the temperature remains low. Where, as discussed in the last chapter, cooperation in molecules gives rise to apparent bond energies, within these amorphous solids there is no binding energy holding the material together. When temperature rises again, rather than there being a defined melting point, such as with water, these substances slowly soften until they eventually turn back into liquid or gas.

These solid structures tend to be good insulators - the atoms or molecules seek to hold any absorbed energy to themselves and do not readily conduct either heat or electrons onwards. These substances can be formed from single species or a variety of different elements and compounds. Either way, there is expressly no cooperation within the so-formed solid system.

Level 2 Systems – Active Competition

Returning to those clouds in the sky, if hydrometeors represent Level 1 cooperative entities, then following the logic of the layered evolutionary construct, we should be able to observe Level 2 active competition taking place between them. Those hydrometeors should, theoretically, be able to undergo competitive growth. And indeed, they do. The outcome is rain or snow (see Box 27a).

Box 27a - The Formation of Snowflakes through Competitive Growth

When the air temperature within a cloud is reduced marginally further below the dew point, the water molecules 'run for shelter'. They need to join up with other water molecules to continue to optimise their interaction with their environment - now consisting of slightly longer wave photons. The water molecules are thereby incentivised to condense onto anything that they encounter. The outcome is that the condensation rate onto hydrometeors becomes greater than the evaporation rate and these particles of dust coated with water start to grow. In colder conditions, the hydrometeors may have turned to ice or be supercooled water and newly depositing water molecules simply freeze onto them to create snow crystals. Conventional thinking suggests that this growth is an entirely haphazard affair. This is difficult to believe, when one considers the rate of growth - being around a quadrillion molecules every second (see chapter 2, Box 2c).

When hydrometeors originally form, such as in the cloud in a bottle trick, then, from our perspective, they are created in an instant - a blink of an eye. These original hydrometeors may comprise, say, a hundred million water molecules. In terms of order of magnitude, this is a negligible amount compared to the notion of a quadrillion every second … the same as a trillion every millisecond … or a billion every microsecond. Granted that a second to an atom is an aeon, the speed of growth seems too fast to be completely random.

Every time a water molecule condenses onto a hydrometeor, as considered earlier in relation to covalent bonding, it necessarily releases some energy. When there is an even balance of condensation and evaporation, then each packet of energy released by a condensing molecule is taken up by a different evaporating molecule. These packets of energy are thereby circulated around between the hydrometeor and the surrounding swarm of water molecules, just like a city might generate its own currency which circulates around the system. But, as soon as the balance is tipped towards increasing levels of condensation, then a runaway process emerges. Rather than being taken up by evaporating molecules, this released energy must be radiated outwards from the particle. Given that this energy is just what those other free-roaming water molecules are after in the now cooler air, they are attracted towards what has essentially become a mini-radio transmitter, saying ‘come here, to get your security’.

As this radio transmitter grows in size, its surface area enlarges and an ever-increasing number of water molecules are attracted towards this rapidly growing system, now visible as a newly formed raindrop or snowflake, until it grows sufficiently large that it falls out of the cloud, heading groundwards as rain or snow.

Level 2 Systems – Cooperation

On the cooperative side of the evolutionary ladder, active cooperation is seen between self-same agents, leading to homogeneous systems. Passive cooperation arises from mixtures of agents, producing heterogeneous systems.

Pure crystals arise from atoms or molecules actively cooperating together at Level 2 to create highly regular structures with long-range order. These solids invariably show properties involving cooperation that extends well beyond immediate neighbours. Vibrations can span a whole crystal, enabling these types of materials to interact with much longer wavelengths of photons, thereby allowing the individuals atoms or molecules access to a much wider spectrum of radiation energy. These types of solids invariably conduct heat and are frequently able to conduct electricity too. All metals fall into this category of materials.

The human comparison to crystal structures can be seen in the form of suburban sprawl - regular street patterns stretching outwards across the landscape. While each family occupies a plot of land, just as with those Wild West farmsteads, each house is now connected into a cooperative system - road network, utilities systems, communications infrastructure, all in the context of a socially regulated environment (legal system).

Passive cooperation at Level 2 can be seen where crystal structures involve a variety of different types of atoms or molecules, either mixed in regular patterns or connected serially together (mixtures of pure crystals). These substances can exhibit additional types of cooperative behaviour. One of the most interesting is the thermoelectric effect, where thermal energy (in the form of photons) travels in one direction and electrons move in another. This could be construed to be analogous to supply chains within our domain - energy being exchanged for currency at each step along the way.

Level 3 Systems – Competition

Passively competing systems at Level 3 come in the form of emulsions. These are substances involving a combination of immiscible liquids, such as water and oil. Essentially, they comprise small droplets of one liquid within another. Given that molecules are more mobile in liquid contexts, such mixtures tend to be unstable and, within a gravitational field, naturally separate out into layers, such as oil over water. The very fact of being immiscible is indicative that there is no cooperation taking place between the different molecular species at the atomic scale. As with amorphous solids, these substances are generally poor conductors.

Actively competing systems at Level 3 lead to the formation of liquid crystals. Remember the liquid crystal displays (LCD) of early calculators. These screens were made from a material which is somewhere between crystalline and liquid, which can flow like a liquid but has an internal crystalline structure. The crystals in a liquid crystal do not all align. Rather they tend to take the form of a patchwork of crystals (cults?) with different orientations (see Figure 27b). Liquid crystals are used extensively in nature. They include structures such as micelles and vesicles (see Figure 27c), which make up the walls of cells.

Figure 27b - Liquid Crystals

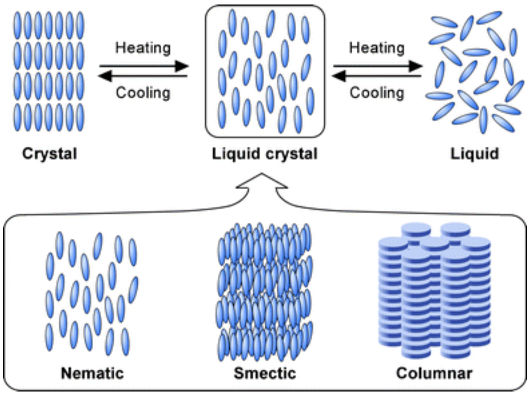
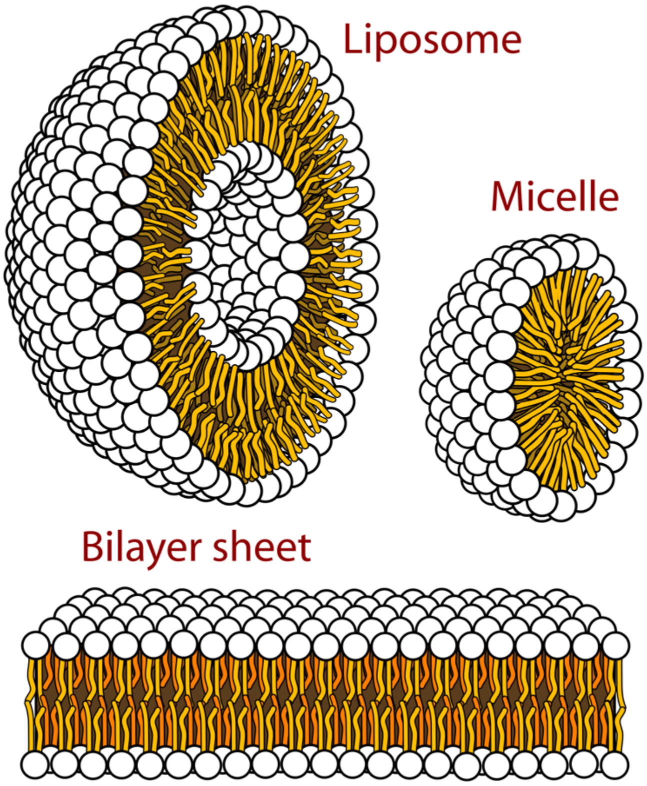


Figure 27c – Liquid Crystals in Nature



Level 3 Systems – Cooperation

Active cooperation at Level 3 produces pure liquids. These systems are generally good heat conductors relative to gases and amorphous solids. This is why you can chill off so quickly, if you fall into cold water, which is one of the best non-metallic liquid conductors.

Conventional thinking says that liquids such as water are held together by what are called Van Der Waals forces. These are described as rapidly fluctuating forces, flipping back and forth between temporarily adjacent molecules. Using an agent-based perspective, then these apparent forces arise from mutual nurture, transferring energy to and fro at high speed between neighbouring particles.

Level 3 exchange systems manifest in the form of ionic solutions, where other materials are dissolved into, say, water - for example a saline solution. This can significantly increase the electrical conductivity of the liquid system. In our social world, we saw how the switch from Level 3 sharing to exchange systems arose from the appearance of indirect reciprocity, where mutual support flows around a community, giving aid to those who need it, not relying entirely on direct reciprocal relationships. Treating each interaction as being fundamentally energetic, this allows for energy to flow more freely through the system of agents, passing from one to another. This is why salt solutions can conduct electricity better than pure liquids. Recently, it has been discovered that some salt solutions also exhibit the thermoelectric effect - heat flowing one way and electrons the other.

Level 4 Systems - Competition and Cooperation

You can observe the Level 4 transitions when watching a candle. Immediately above the flame, the smoke follows laminar flow (Level 4 active cooperation), this transitions to vortices (Level 4 active competition), which eventually devolves into turbulent flow (Level 4 passive competition). Where laminar flow facilitates the smooth transmission of energy from the flame upwards, when the gaseous system switches to competitive modes, then the energy is quickly dissipated.

Vortices of all types are a difficult concept to comprehend through our conventional way of looking at the material universe. They arise at a variety of scales, from water running down your bath's plughole, to weather (including hurricanes and tornados), up to the scale of star formation and galaxies. Vortices can perpetuate for so long as a temperature differential or other variation in energy exists across spatial locations. They are observable entities. At the molecular level, the movement of the particles becomes aligned through transmission of information from one particle to the next. How this happens is beyond our current knowledge in the physical sciences. If and when someone does discover the mechanisms by which this happens, it may lead to some very interesting new technologies.

Cooperating and Competing Particles

So, there we have a small snapshot of examples, showing how the evolutionary ladder manifests within the material world (see Table 27a). Played out over billions of years, the competition and cooperation between molecules has sat behind the evolution of all those species that we can interact with at our scale of observation. It operates at its own scale within us and without us. The interplay between cooperation and competition takes on a level of complexity that we are only just beginning to unravel as we gain ever-increasing insights into the biochemistry of life.

Table 27a – Material Expressions of the Cooperative Ladder

	Passive Competition	Active Competition	Active Cooperation	Passive Cooperation
Level 1	dispersal of self-same atoms and molecules	dispersal of energy	formation of molecules	hydrometeors, etc

Level 2	amorphous solids	polymers / fractal structures	crystalline solids	mixed lattices
Level 3	emulsions	liquid crystals	liquids	ionic liquids
Level 4	turbulence	vortices	laminar flow	???

Molecular evolution is facilitated by atoms having co-opted electrons as a form of currency - enabling the sharing and exchanging of energy. Yet electrons themselves are matter systems, which can compete and cooperate. Electrons vigorously repel each other, seeking to disperse, just like atoms participating in Level 1 competition (active and passive) - seeking to be as far apart from each other as they can. Being so small, electrons tend to express this repulsion directly in their physical motion. Furthermore, due to their size, electrons really, really do not like being free and out in the open at the temperatures and pressures, with which we are familiar and consider to be temperate. It must get very hot, such as within the sun, for electrons to be happily free from the constraint of being part of atoms or stuck within solid or fluid systems.

Despite ‘wanting’ to spread out, they still generally prefer to be confined to a copper wire, than be exposed to the air or try to run through you. It takes high concentrations of them - all forced together, but wanting to spread apart - to break cover, such as giving you an electric shock or as demonstrated violently through lightning strikes. Electrons also cooperate, as demonstrated through the way they come together to form atoms. In another example, one of the explanations for superconductivity sees electrons pairing up to travel together through a crystal lattice. But the behaviour of electrons, which has scientists seriously scratching their heads, is their ability to express particle-wave duality. In a materialistic universe, where matter is seen in terms of inanimate objects dictated by forces, then this behaviour is completely inexplicable. Can the agent-based approach to matter provide a solution to this ultimate of 20th century questions?