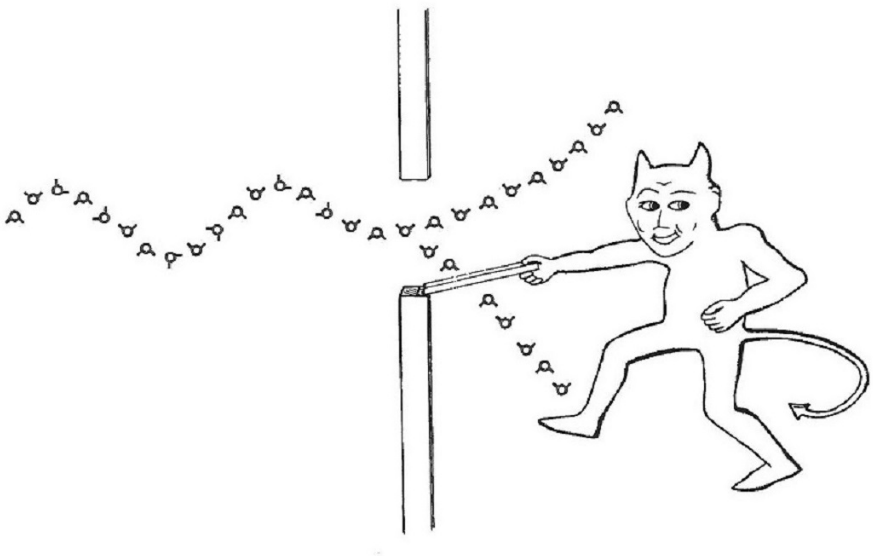
Thales' Legacy

Part 2

The Pixel Machine :

how information made water come alive



Chapters

Appendices

1. Ladders and Levels

The living have a future – the non-living have only a past. While this assertion is clearly an overstatement, it highlights an essential distinction. Living things are intimately connected with their futures. They expect and respond to stimuli, for they are replete with information to do so.

Before going any further, I will try at this early stage to pin down more precisely what is meant by that loosely used word, "information". In this book, it refers to an active quantity rather then the static concept usually understood by the term. For example, from the two new fields of science that figured so prominently in The Living Pixel (TLP), biology and information technology (IT), we learnt that the "information" in a string of symbols can be calculated with Shannon's formula, and for this reason DNA is often described as the "information molecule". However, the sequences referred to in examples such as these are recorded information, which could preferably be called "text" or "code" because of their static natures. On the other hand, the very fact that we make records indicates that we expect a future – today's stories are not written for yesterday's readers. It is this connection with the one-way flow of time that adds a dynamic dimension to the concept as it will be used for further development in this book.

The very idea of information implies that there is something missing. We have all experienced the feeling of being unsure of what decision to make or what action to take when we don't have enough information. We even feel that information can be kept secret from us, or as with something concrete like money, can be denied us. This quality, which appears to make it essential for the performance of some action or some function, highlights its role in the passage of time. As the discussion on the nature of machines unfolds over the coming chapters, the connection of information with future will reveal many unexpected facets that will crystallize eventually into a unified picture in Chapter 16.

The claim above that the living cell responds to stimuli because it is full of information, does not refer to DNA or some similar record. In the cell, information passes up and down through multiple levels of organization producing controlled internal and external movement. Like energy, information in this sense is transferable from one level to another, playing the role of the agent that orchestrates activity. To illustrate this layered complexity, we might, with some imagination, liken the cell's contents to the text of a written story – with the story itself representing the whole organism, paragraphs on the level below representing cellular organelles, then sentences representing protein complexes, words representing single protein molecules and at the bottom, letters representing amino acids. But the written story is a record and so is a static analogy. It does not possess the dynamic aspect of information manifested by cellular activity, however it does illustrate clearly the concept of layered organization, since sentences are not words and words are not letters. These objects are distinct from one another and populate different levels of the static hierarchy they jointly inhabit – the story.

The image of a ladder is a particularly apt way of depicting hierarchical organization as shown here in Figure 1.1. A ladder conveys a strong sense of direction, usually upwards, while its rungs indicate that progression is stepwise over gaps, rather than continuous. This diagram summarises, in a loose fashion, the physical and mental contents of our heads as a hierarchy. This type will be referred to as a "vertical" ladder. On first impression, the evolutionary path in Figure 1.2, reproduced here for comparison from Chapter 1 of TLP, paints a similar picture, although it represents something entirely different – the passing parade of the historical record, again loosely said. Such schematic representations could be called "historical" ladders. Yet in spite of this difference, the ladders themselves tell us we are dealing with whole systems which are composed of either contemporaneous strata or historical stages, and through which information passes or passed in stepwise flux from rung to rung.

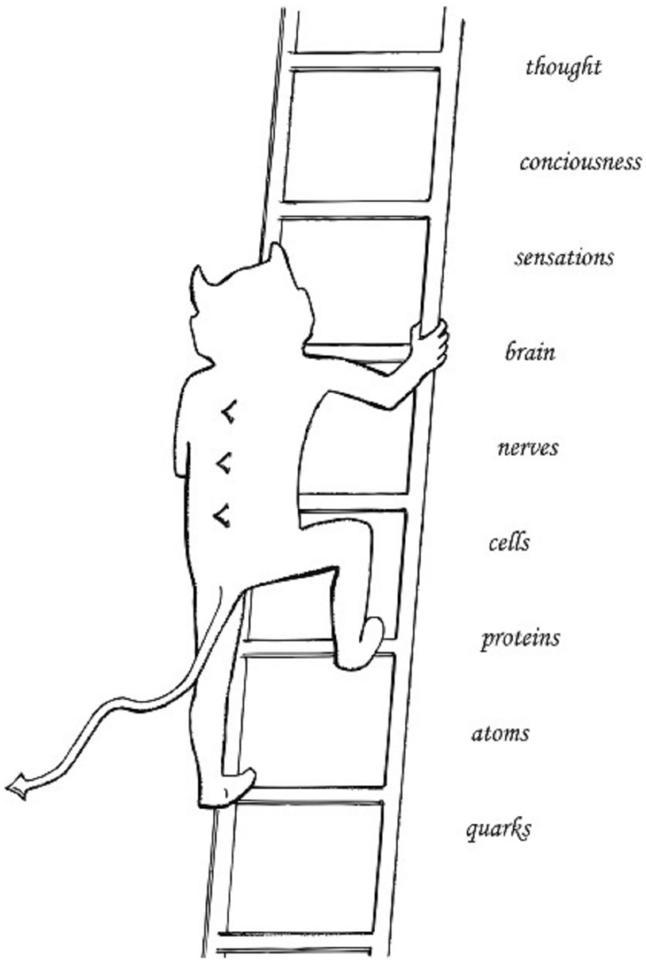
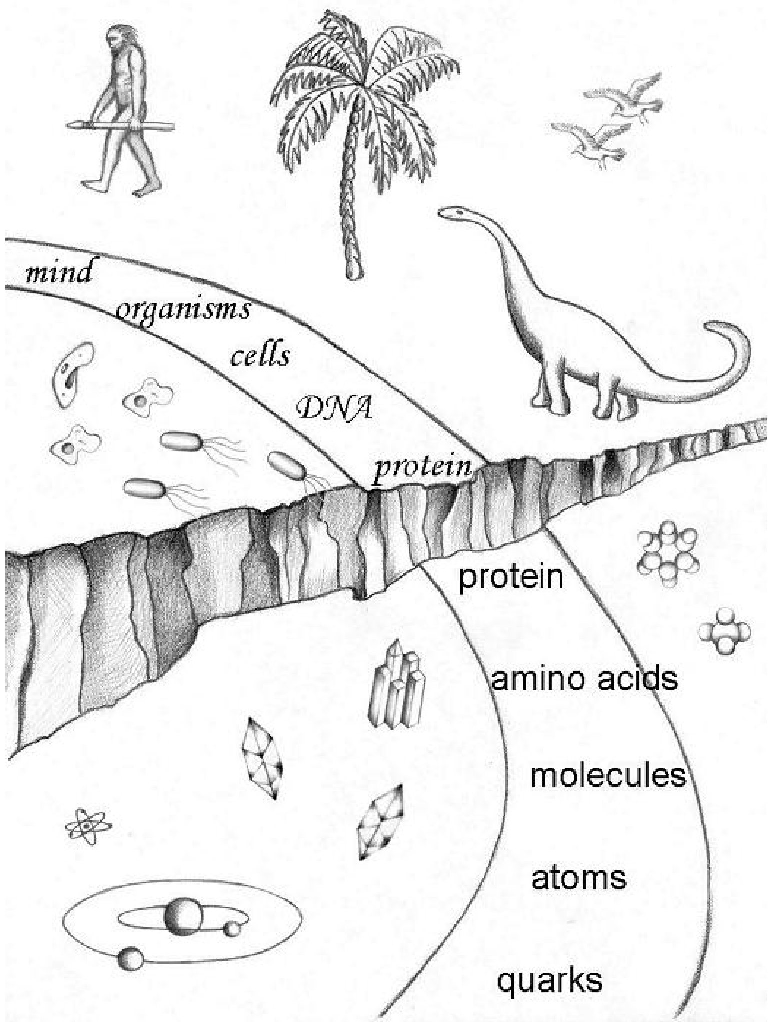


Figure 1.1 A vertical ladder. The ladder illustrates in a schematic way the constituents of our brains and minds in the form of a hierarchy based on size. The fundamental constituents are physical in nature and transform into the mental as we climb the rungs. This representation is called "vertical" because this type of hierarchy indicates a bottom-up perspective and hence gives a sense of structure built in the upward direction. It is a direct way of illustrating common notions of hierarchy we often use, like "higher forms are based on lower forms". It was shown in TLP how the Demon is needed in the upward development from rung to rung, especially on the lower steps where the constituents are of molecular size. We will refer many times to this ladder in the coming chapters.



<u>Figure 1.2 A historical ladder: the chasm between the sciences.</u> As explained in TLP, a "Grand Canyon" splits the large-scale map showing an overview of the history of planet Earth into two landscapes. The physical sciences are on the southern and biological sciences are on the northern side of the deep divide. In the reductionist landscape of the physical sciences, a road of deterministic logic leads from the most fundamental particles of all, the quarks, through atoms and molecules to complicated chemicals like amino acids and proteins. In the eyes of most scientists, protein (or DNA or RNA) appeared suddenly by chance on the northern edge of the canyon and a new type of logic, termed "neo-Darwinism" in this book, then dominated the historical development, in which random genetic changes resulted in the evolution of living forms through the northern landscape. In TLP, the pixel machine was introduced into the picture, which bridged the chasm and joined the two worlds together, so that both the non-living and the living could be seen as belonging to the one continuous holistic historical process.

Students of biology find the ladder concept useful for explaining the interrelationships within the biosphere. Ecologists study the food web in terms of the stratified populations of predators and prey. From these examinations they can construct the biomass pyramid to which every living organism belongs. Deeper analysis reveals the associated carbon, nitrogen and water cycles. All of these dynamic systems are underpinned by the most fundamental of all, the energy ladder, from which we learn that our ultimate energy source is the sun. This well established hierarchical model sets photosynthesis on the bottom rung of the ladder of biology, which transfers its products ever upwards, fuelling the levels above – our thoughts are transformed sunlight.

Ecology suggests yet other types of ladders based on non-physical factors in the biosphere. As Rachel Carson (1) taught in her pioneering opus "Silent Spring", the multiple interdependencies linking living organisms are crucial for the health of the whole – insects are needed for pollination, birds spread seeds and parasites. Such chains will be called "horizontal' ladders, since they are not hierarchical in the normal sense. Indeed, developing this line of thought further reveals that many have qualities of a more abstract nature, in that the rungs are not even connected in a material way. For example, birds actively recognize trees, branches and twigs, as well as the insects they need to eat. They use these objects to build their nests. This means that there is a copy of trees encoded in the birds' nervous systems associated with what we call instincts. So when we say "birds have an instinct to build nests", we refer to a horizontal ladder of a different sort. Here, instinct precedes twigs and twigs precede nests. We know that this natural system represents a hierarchy of objects of distinct classes, since nests are not twigs, and twigs are not instincts. So the puzzling question now poses itself: how does information flow through all these types of ladders?

Ladders also extend to the non-living. In Figure 1.2, objects inhabiting the purely physical world are depicted on the lowest rungs of the historical ladder of evolution. However, such objects are also involved in the horizontal ladders of the present. Let's examine the sequence of events we take for granted when we notice our bird catch an insect on the wing. To effect the catch, the bird's flight path must be guided with high precision. This means that its nervous system is able to constantly compute values for its position, direction, velocity, momentum, lift, thrust and so on, while simultaneously receiving input and delivering output. The computational and mechanical steps comprising this ladder are themselves amazing enough to the inquiring mind, but the almost faultless precision of their coupling, which brings about this ordinary biological event, now poses the additional questions of purpose and design. In "Nature's Solutions", Morris describes many examples which point to the role of design in evolution (2).

Critics may argue that birds clearly know nothing of Euclidean geometry, and therefore the model of ladders applied in this way is nonsense. My argument is however, not about the intellectual awareness of birds but about processes occurring at levels in the nervous system located on rungs well below consciousness. Yet others will of course say that it just happens. According to traditional precepts, examined in the next chapter, such displays of skill need no explanation as they represent simply another chance result honed by selection. But that's not how we humans approach these problems. It is unthinkable that a faculty of aeronautical engineering would graduate students who have no understanding of space, time and mass as well as an acceptable level of skill in manipulating these basic abstract concepts. Surely it is reasonable to propose that nature operates along similar lines, rather than to believe tacitly that this complex mesh, within which the concrete interlocks with the abstract – energy with information – is the unexpected result of happy accidents.

The concept of ladders is, of course, a crude one. It should be taken as a simplified structural model only of the objective world. It is introduced to help incorporate the more widely accepted concept of layers into our scientific thinking. For instance, a commonly held notion runs: the whole is more than the sum of its parts – a statement which clearly refers to layered organization. It puts the holistic point of view in counterbalance to the reductionist perspective of top-down analysis, namely that the whole is precisely the sum of its parts, which has dominated scientific thinking since Descartes' time, and still today dominates the thinking of most physicists. Yet that holistic statement itself still falls short of capturing the full picture, which might be put like this: a whole is more than the sum of its parts and is itself part of a whole. This now describes the objects of our understanding in their intermediate positions on a rung of a ladder that extends in both directions through nature's hierarchies. In the next two chapters, the historical factors underlying the reason why the reductionist, rather than the holistic, worldview became the basis for today's scientific methodology will become clearer.

An interesting result that emerges from analysing the world in this way, is that these systems are interlocked, or put another way, a rung of one ladder can also be the rung of another. A basic principle in physiology lends a clear example of crossing ladders in the way it describes the integrated animal body – living cells on the bottom level differentiate and develop into organ tissues on the next level, which in turn constitute the whole intact body on the highest level. Having the path of evolution in mind, our anthropocentric tendency naturally places the brain at the top of the tree, but to students of physiology it occupies an intermediate position, since it is simply one of our bodily organs.

It is now evident that the same object, our bird for instance, occupies a rung on different ladders. The bird is simultaneously a player in the web of predator and prey, while also participating in nest building activity. Further consideration reveals that the mesh of ladders is multidimensional, extending far beyond the three classifications so far described – vertical, horizontal and historical. The multiple activities of humans offer perhaps the most obvious examples of this complex scene. We accept without question, even without thought, that one and the same person occupies a rung on the ladder of the family, of their employment organisation and of the wider community governed by legal obligations. And it is a triviality to us that these ladders exist to guide our actions, that is to say, what is to be, not what has been. And so it is for all living organisms – birds build nests for their future.

This picture of the biosphere as a world of dense interconnections is not new. Darwin wrote of the tangled web in describing life in general. That the web is structured rather than tangled, is a more recent development initiated by the insightful work of biologists like Carson, which is extended in this book to a system of criss-crossing interconnections running through different dimensions – material, temporal, organizational.

It is generally agreed that the more advanced living forms are those possessing greater complexity, so for the moment, let's put the human brain back at the top of the tree. The consequence now presents itself that nowhere, at least not within the limits of our solar system, is to be found a higher concentration of fine-grained, interlaced hierarchical systems than within this organ. We can then further speculate that it must be in the realm of human creativity where we would find the highest concentration of intersecting ladders, some of which stretch back through the eons of evolution, crossing others which stretch horizontally through the mind of a single individual. Where, for example, does Beethoven's Moonlight Sonata fit in nature? One explanation might run: Beethoven first ingested energy to fuel his brain cells and therefore his mind to hear music, which in turn directed energies back down to his brain, so that his motor neurons could be stimulated to control the muscles of his eyes, arms, hands and fingers as he recorded his musical ideas as black dots on manuscript paper . . . . . Trite and mundane replies the musicologist: the Moonlight Sonata belongs to an evolving category of objects of far superior quality compared to mere animal metabolism. Its true origins lie in the birth of the sonata form in the hands of the Venetians, developed to maturity for the keyboard by the German school reaching perfection under Beethoven . . . . . Arcane and pedantic replies the concert-goer: Beethoven was not interested in his food intake nor in how many composers had already written sonatas before him. His Moonlight Sonata is a sequence of events that leads to a spiritual experience for the listener. That sequence begins with a concert pianist interpreting the printed black dots on the musical score and ends with an emotional response elicited in the listener. When it is not being heard, it does not exist . . . . .

These various points of view demonstrate that, although we all may have an opinion on what the Moonlight Sonata is, this work holds positions on three very different types of ladder – the vertical ladder of metabolism, the historical ladder of musical forms and the horizontal ladder of artistic performance. Yet it fits still other ladders too: for example, it holds a place in the evolution of keyboard instruments in western music, or again, the student completing a PhD on the composer would place it on a line through developmental stages labelled early, middle and late periods – that is youth, man and God, according to Franz Liszt – or again . . . . . .

The nature of non-scientific disciplines does not lead researchers in those fields to ask questions about physical mechanisms – historians and art critics are not interested in energy. Information is the bread-and-butter of their professions. Likewise, when taking part in a conversation we are not aware of physicalities like the air vibrating between us, even though they are germane to the problem of the mechanism of information transfer, as we will see in the next chapter. Indeed, this is also the case in some scientific fields. For example, the evolutionary record of the animals in Figure 1.2 is a depiction of advancing biological information. However the stepwise transfers of information were achieved at bottom by energetic cellular events, which had a physical reality now no longer visible in that record. The facts that, in the field of artistic endeavour these steps take place in the human mind, whereas in the evolution of organisms they happened within the living cell, compounded with the present circumstance that we know so little about how processes occur in those environments, mean that such events are ignored, or better expressed, do not make themselves evident to us. For this reason we tend to think that information is merely a record or a sequence of external objects, like printed symbols or the fossil catalogue, devoid of movement and mechanism.

Following this line of argument a stage further has led the main body of scientific thinkers to the conclusion that evolutionary advance is synonymous with increasing complexity of the code hidden in a string of symbols, in this case DNA. The analogy of a written story for the living cell used at the beginning of the chapter can be recast here as an apt illustration of this concept. Again, the interesting feature is the hierarchical organization of text, but this time, let's imagine that it represents a historical ladder illustrating the story of living things. The information content of higher organisms, chapters and paragraphs, grew and developed out of that of the lower, words and letters, so that biologists now see present-day life as a rich literary heritage that emerged in stages over time out of the original basic alphabet of isolated letters – the complex layered on top of the simple as a vertical ladder, or the modern on top of the archaic as a historical ladder. But what lies behind the emergence of the higher layers? How can a ladder extend itself if it does not already have a built-in extension? What mechanism underlies the change over time? The question is not, where did life come from, but where does growth come from – or put in a more abstract frame, why does energy continually re-organize itself? What other quality must be added to a static hierarchy like a written story for it to become a dynamic scene, like the one we all imagine is depicted in Figure 1.2?

2. Mechanism or No Mechanism?

Mainstream science today is founded on the two pillars of Darwinism in biology and thermodynamics in physics. Both place chaos, one random mutations and the other random motion, as the foundation stone of their intellectual domains. It is an interesting fact that these branches of science were born in the same era when the industrial revolution was at its height – the era of heat and pressure. For over a century and a half, both have grown in strength and acceptance through mutual support and so become firmly entrenched. Today's versions of those pillars are the modern fields of molecular genetics and statistical mechanics. And so in the final analysis, the scientific explanations of the events of both worlds, the biological and the physical, have been built upon statistical bases. Recently though, cracks have begun to appear. One important factor for the onset of uncertainty is, I feel, their failure to accommodate the growing awareness of the role of complexity in natural phenomena among people interested in new technologies. For example, that principle claimed by many to be above all others, the Second Law of Thermodynamics, has traditionally been accepted as the light to guide us in the search to understand change in the natural world, and therefore to answer just that question of evolutionary development posed in the paragraph immediately above at the close of Chapter 1. However, the Second Law has today turned out to be a very confusing scientific law in the way it deals with new concepts born out of recent biological discoveries. As we will now see, it can be used either to support or to refute the generally accepted interpretation of life's origin and evolution.

It is truly surprising how many famous scientists use the word "miracle" in discussing the origin of life – Hoyle, Monod, Crick, deDuve and Davies among them. Hoyle, with colourful pointedness, compares it to a whirlwind sweeping through a junkyard and producing a jumbo jet, and Davies' analogy is an explosion under a pile of bricks producing a house. In fact, these two authors are among those who publicly do not accept the chance event theory – Hoyle (3) advocating the deep reaches of space at a time predating the Earth's appearance as the scene of life's beginnings, and Davies (4) suggesting a new physical law that describes how gravity is converted into information and information into life. Other eminent thinkers including Bohr, Schroedinger, Polanyi and Popper have also suggested that life cannot be explained by classical physics if violation of the Second Law is to be avoided. In contrast, the majority of scientists and, as I have thoroughly discussed in TLP, surprisingly biologists, believe valid strategies can be adopted which reconcile the random events origin with the Second Law. Life is only apparently miraculous it is claimed, in truth it is determined by the Second Law. Let us recall the advice of some well known commentators promoting this popular view (5):

"The law that entropy always increases holds, I think, the supreme position among Laws of Nature" (Eddington).

"The progress of the human race in understanding the universe has established a small corner of order in an increasingly disordered universe" (Hawking),

"The local increase in order is paid for by the entropy: the disorder of the system as a whole augments to the extent stipulated by the Second Law" (Monod),

"Entropy is not merely a downslide toward disorganisation. Under certain conditions, entropy itself becomes the progenitor of order" (Prigogine),

"Nor do evolution and biological production of vast amounts of organic substances such as coal and oil violate the Second Law, for they too draw on the torrent of energy from the sun to pay for the local decrease in entropy" and "The Second Law remains beyond proof, an axiom consistent with all that we know about the universe including life" (Harold),

"The Second Law is regarded as the most fundamental law in all of science" and "Taking the sun and planets together, the Second Law is not violated" (Gribbon),

"We know the Second Law to be a disordering principle which establishes the directions of all natural processes. The Second Law acts to dissipate order" (Wicken),
"Evolution is not in violation of the Second Law of Thermodynamics. This is what any reasonable scientist believes" (Yockey),

“Our planet is continually bathed by massive influxes of solar energy, and earthly order may therefore increase without violating any natural law” (Gould).

“The decline of the universe is essential for maintaining the flux of free energy that makes life possible” (Lovelock),

I have chosen here a broad selection of authors ranging from cosmologists to environmentalists to illustrate the extent of the tentacles of the Second Law with its contradictory message of how the winding down of the universe underpins the genesis and expansion of living matter.

And so we find that some thinkers use the Second Law to reject the chance event theory, while others use it to support the theory, or even as a basis for it. This odd circumstance leads our non-technical colleagues to ask: what is the relevance of such a law to the issue at hand? Educated people are all of the opinion that a law helps to guide scientists in their work, so they might well begin to wonder how strange it is that the law of laws paints such a muddy picture – or none at all – of life, and so ask themselves, what is the use of such a law if both claim and counterclaim can call upon it for support?

The Earth receives about one billionth of the sun’s radiant energy, of which almost all is lost to outer space. The ever-popular proposal that this astronomic stream of chaotic energy is the ultimate cause of life on this planet is a grandly unscientific proclamation. If one traces the cause of local phenomena on any planet to the totally of the sun’s radiant energy, then one can claim almost anything. And if the theory were indeed true, then plant biologists who are studying the light-harvesting apparatus in the chloroplasts of leaves would be wasting their time, since those workers should be searching for the dissipaters, not the harvesters. But they believe that sunlight is captured, quantum by quantum, and further that it is this trapped light – itself only the tiniest fraction of the one billionth received – which then proceeds on to become the cell’s energy, and thus drives the biosphere. I too believe that research along these lines will tell us how the sun’s energy became involved in life’s origin. The fact that it is only an insignificant fraction of the sun’s total radiation is an irrelevancy. When we look at a tree, we see stored, not lost energy standing before us. In admiring its growth and strength we embrace a realisation of its ability for conversion and conservation, not dissipation and wastage.

The miracle interpretation of life and its origins has wider ramifications than the simple picture of evolution as a collection of serendipitous outcomes of the roulette of history. The discussion in TLP already pointed out that, in addition to this long chain of lucky events, we must accept that each spin of the wheel of fortune occurred just at the right moment and in the right order, for otherwise it could not have produced its miraculous result. From the discussion presented in the previous chapter, it is obvious that the picture must now be elevated to yet a higher stratum. We saw how evolution is more than a linear development, it is a growing multidimensional network of both concrete and abstract interconnections – a vast matrix in a state of flux. When viewed in the same way as the historical ladder describing how our human technology has developed, the evolution of the bird’s flight capability would imply a wing design laden with experience, which has been recorded, collated, corrected, updated and fed back into the construction handbook kept in the bird’s cellular library. We take it for granted that education and training underpins our know-how. This comparison with our history makes it clear why belief in the alternative success-just-happens explanation has to rely on a view of history as a miraculous stream of miracles.

Let’s be more direct on this point: could the growing interlocking grid we call the biosphere be the result of an ever-accelerating game of chance played out in the chaotic jungle of the survival of the fittest? If indeed it did so, then we would be forced to conclude that it continues to function successfully also by chance. This consequence can be convincingly demonstrated by making a simple analogy to the scenario depicting the remarkable achievements of those imaginary pilots, who graduated from flying school solely by making lucky guesses to their exam questions. Like the random mutations of evolutionary development, they too lacked purpose and direction at every stage during their training, so the only course of action left open to them now as they progress to the next step in their careers – flying real planes – is to continue to rely on their run of good luck!

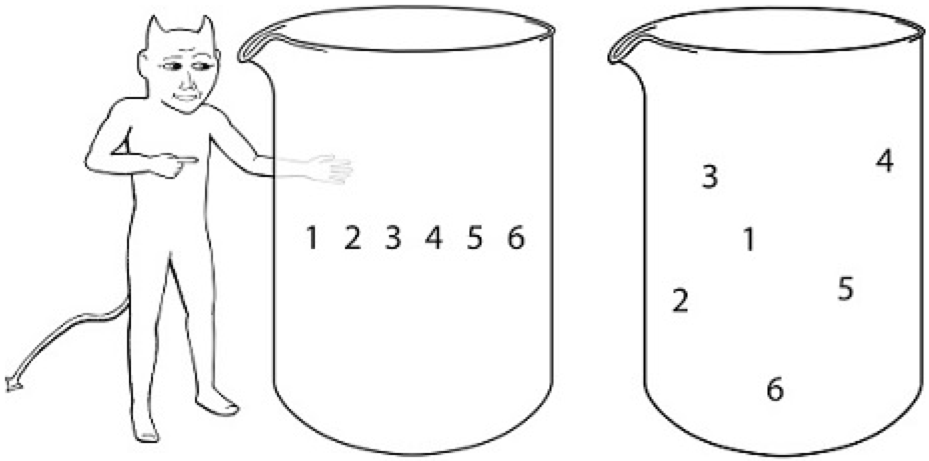
In addition to the failings in the traditional approach, the recent spectacular successes in the new fields of bioengineering and IT have begun to widen the cracks that have started to appear, even to the point of dominating modern thinking. Broadly speaking, these fields deal with complex phenomena where workers analyse problems in terms like feedback, code, translation, reverse transcriptase, loops, subprograms, switches, nodes ……….. and not in terms of mass, space and time – in other words, in terms of networks and connections. Little wonder then, that these fields have become detached from the traditional sciences and little wonder too, that the Second Law has been unable to assist and guide their progress. When the role of machines is examined in the next chapter, we will come closer to pinpointing the limitations of the Second Law with regard to the new concepts emerging from these rapidly expanding fields.

On the other hand, the model of the biosphere and its history as a growing matrix of interconnected layers does not exclude the occurrence of random events – our lives are full of accidents. We've already seen in Chapter 1 how a member of one biological stratum can also occupy rungs on other ladders. This means that an action belonging naturally to one sequence of events can cross from one ladder to the other, and in doing so, introduce unpredictability into the second sequence. That accidents happen when worlds collide is a common notion. For instance, falling sick with the flu can be viewed within the framework of a biological or a social ladder. After certain cells in my air passages become infected with the influenza virus, there is a definite sequence of events that leads to illness. Viruses target specific types of cells, which they enter and subsequently control, using the cells' metabolism for their own ends. That I then become sick is the end result of this well-defined biological sequence. On the other hand, I may have been expected to attend a special occasion involving other people, which I must suddenly cancel because of illness. Everyone involved now finds my new circumstance an inconvenience, since it suddenly disrupts the course of our planned events.

But according to the mainstream view, all energy moves about the world, levels or no levels, in a chaotic way. Specific examples we often read about range from mulitple cases of radiation sickness following an accident in a nuclear reactor, on one extreme, to a city damaged by an earthquake, on the other. The body of radiation streaming outwards from the sun occupies a level within the physical hierarchy of a world much bigger than Earth. It obeys laws that astrophysicists have discovered for us. And when one element of this body, a high-energy gamma ray, strikes a molecule of DNA in a skin cell, this event is also explicable by the laws of physics. But it can have far-reaching unforeseen consequences on another ladder, where the laws of genetics, not physics, now have control. Likewise in the case of the earthquake. Tectonic events clearly occupy a well defined place in the hierarchy of geological movements, but their unpredictable behavior has played a role of quite a different nature in the course of human history.

Nevertheless, in spite of the undeniable advent of accidents like mutations and earthquakes, they cannot be held responsible for the obvious forward development of evolution. They supply no direction and no drive. They are anti-future. Evolution is the transformation of simple, robust, large-scale energy into organised, fine-grained, delicate energies. The evolution of living organisms on our planet is the latest phase of this overriding process, which compared to earlier stages, is distinguished by its high degree of complexity. As argued in TLP, it did not suddenly begin with the spontaneous appearance of the first protein (or DNA or RNA) molecule. There were prior stages involving structures built of minerals and water, whose own organization gave rise to the ability to guide simple energetic changes. And as was concluded there, this means that there were mechanisms already present manipulating basic energies long before life appeared.

The diagram in Figure 2.1 illustrates the contrast between the two world approaches in a facile way. Although only very rudimentary, this scheme represents a simple evolutionary process by depicting the time sequence of steps, which give rise to a basic type of organization. Since random collisions between molecules are examples of the simplest of molecular events, the sequence chosen for this illustration are the locations of a series of random collisions. For increasing degrees of organization to emerge over time, the collisions must show initially how they can occur in an ordered way, say, in a straight line. Let's now consider what is required to ensure that a natural system would be able reliably to deliver precisely this unique outcome.



<u>Figure 2.1 Random versus controlled events.</u> The question of mechanism or no mechanism is illustrated by showing graphically the odds against the occurrence of a hypothetical event which is mimicked here by a game of dice. The diagram represents a chemical beaker containing a solution of (say) sugar in water, in which two versions of the event take place. In the left hand beaker, we follow the movement of one given sugar molecule as it moves in equally spaced steps to the right as a result of the collisions it experiences with its surrounding water molecules – in technical language, it is diffusing to the right. We recall from Figure 2.1 of TLP Chapter 2, "Two Motors", that this is just the type of path followed by a sugar molecule in our biological motors.

Since the process of diffusion is random, we can simulate a more realistic path taken by the molecule as a series of equally probable chance events. Each of the positions labelled 2 to 6 shown in the right hand beaker was obtained by throwing dice to determine the moves 1 – 6 places left or 1 – 6 places right and 1 – 6 places up or 1 – 6 places down counted each time from its present position. There are thus 144 possible outcomes for the next location on the grid for each of the 5 collisions, giving a total of 62 billion paths. Although only rudimentary, this simple diagram illustrates that the chance of any given molecule following the ordered sequence on the left without the help of a mechanism is one in 62 billion.

In biological systems the locations of events is predetermined and not random. In Figure 14.1 we will see how this problem is solved by pixellated protein machinery ensuring that function is determined with certainly and not by the roll of the dice. Without this machinery, there can be no doubt that the demon would be needed to work his magic in order to secure such an ordered diffusion path.

At this point, I'm sure readers recognize that we are now confronted in a more urgent way by the recurring problem of mechanism in the molecular world. Posed already at an early stage in Chapter 2 of TLP, "Natural or Man-made", this fundamental question runs continuously in the background through both books. At that point, the demon was called upon to lead us out of the difficulty, but since more realistic assistance is expected here, let's consider for a moment what those new scientific investigators, computer technologists and engineers, might suggest as an initial approach. I think we can readily guess what the computer technologist would offer as a solution to the problem of reliability: "well, your system – any system – needs to be able to handle information to do that!" On the other hand, we can just as readily imagine the engineer observing with confidence: "you obviously need to operate machines to do that!" These new concepts, information and machines, do not figure in the explanation of molecular phenomena given in traditional science, where we find instead terms like thermal motion and diffusion. In fact, the modern viewpoint carries the strong implication denying any causative role being attributable to the old statistical model of molecular behavior. When we return to this problem in Chapter 14, "The Enzyme Machine", it will be reset in the concrete terms of enzyme action – the underlying chemical events that distinguish living from non-living matter. The fact that enzyme function is ordered, means that it faces the same statistical challenge illustrated here in a fanciful way by a linear sequence of collisions. We will also discover that biological systems call on both the computer technologist and the engineer to solve the problem, for without their help, these basic processes that underpin life would have to rely on the same good fortune as must those lucky pilots to guide them through their dance of perfect precision in each and every one of our 200 billion cells.

So we come to the conclusion that energetic events can be divided into two classes – accidental and directed. In the first, mechanism is irrelevant, while in the second, it is essential. The first is governed by the Second Law, which is generally thought to extend to all natural events – ladders or no ladders, levels or no levels. The second is the subject of the following chapters. But clearly, vague descriptions of the behavior of birds and composers will not do for the task ahead – it is now time to focus on real mechanisms in more detail. To begin, let's examine the familiar scenario of speaker and listener illustrated in Figure 2.2. This chain of events offers an apt example, since the very essence of verbal communication is information flux. Here the sequence starts in the mind of the speaker, passing then through voice, air, ears, auditory nerve, to arrive finally in the mind of the listener. Now although the thermodynamicists tell us that such a sequence of outcomes is, in the final analysis, a chance result, I think most readers will agree that this common activity is quite reliable. In other words, it is not simply by good luck that we are able to converse, but we expect without question that the speaker's intended message can reach us free of transmission errors. Our expectation in turn implies that there is controlled, not accidental, transfer of information from rung to rung along this multidimensional ladder. However, the elements in this flowchart depicting the familiar practice of conversation are too general to be analyzed if our aim is to discover the necessary machine-like steps along the line of communication. Where are the discrete acts of transfer which operate in sequential order through the chain? And how do we know they are non-random, indivisible, one-way steps? Or put more bluntly, where are the machines?

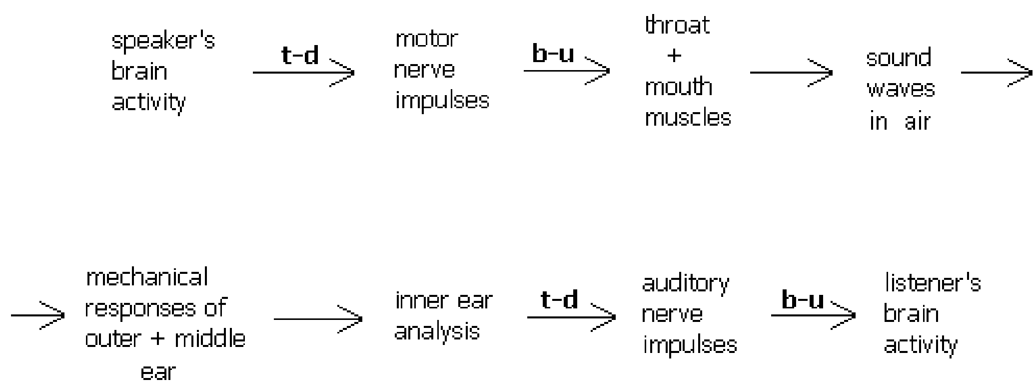


Figure 2.2 A horizontal ladder: the path of information flow. In our everyday activity of conversation we are never aware of the ordered sequence of steps followed as the ideas of the speaker are heard by the listener – an information transfer from mind to mind. This flow-chart lists the familiar steps only. In the next chapter the steps are described in more detail as we begin the tasks of locating and analyzing machines. In Chapter 15, "The Missing Bit", we will return to this analysis, since it proves to be a useful tool in the search for an explanation of the relationship between information and coding mechanisms.

b-u = bottom-up, t-d = top-down, indicating the direction of flow up or down the natural hierarchy of size on the ladder: molecule ↔ cell ↔ tissue.

3. Four Machines

For machines to play their guiding role at the interface connecting two levels, they must be designed to transmit both energy and information. Normally, man-made machines are concerned with only one of these, that is energy, in fact the second attribute of their function is usually ignored. For example in car motors, we are not interested in the manipulation of information, but in the conversion of chemical energy to heat and finally to transporting us along the road. The processing of information is too low for us to be aware of it. It is totally overwhelmed by our prime interest – the production of motion-for-us.

At the other extreme, we have machines like televisions, telephones and computers. In these cases, it is the processing of energy that is irrelevant. These information devices are cheap in their energy usage. We plug the computer into the electricity supply in the wall, never aware of the energy cost of running this machine which holds our attention for reasons of our job, entertainment and so on – the production of messages-for-us.

In the motor car, information processing is robust and crude. Rigid pistons move with precise regularity, valves open and close in perfect synchrony. Variations in input via the driver to cope with traffic and road conditions are processed with the brake and cog mechanisms, but changing the driving ratio up and down four or five gears does not compare with the humble abacus for processing power. Then at the other end of the spectrum, the energy supplied to an integrated circuit is also robust and crude. The conducting connections are too thick, the switches too large, with the result that the device delivers more heat than the output we seek.

Between the two extremes are the machines in which the quantities of energy and information are commensurate with one another – the biological machines. In these, the quantity of energy needed to trigger a switch is of the order needed to rearrange the molecular bonds constituting that switch. There is of course a degree of wastage but, while it is common knowledge that our man-made devices often fail through overheating, I have not heard of anyone dying from a burnt out brain – biological machines work rather efficiently in this regard. For instance, in composing the Moonlight Sonata, the primary energy source was glucose produced by Beethoven's liver, which fuelled not only his brain but also the peripheral nerves and the muscle contractions used to record the music on paper. He may have wasted a lot of energy during this creative process, but it was not enough to injure his biological machinery (as far as I know).

There are as well familiar examples of man-made machines which fall into the category of energy-information balance. In an old clock, the spiral spring is wound up by muscle power, which is exerted in just sufficient force to turn the key. This muscle energy is now stored in the spring, to be released in separate quanta which are just sufficient for turning the cogs of the mechanism and the hands on the face. In such time pieces, muscular energy is converted into mechanical energy under the control of programs recorded in their hardware producing information-for-us. A more spectacular example is the computer built by Babbage. In the 1830s, Babbage constructed his Difference Engine by assembling cogs and axles together with a handle in such a way that turning the handle performed arithmetic calculations. There was no plug in the wall behind his machine delivering energy on demand. If you were strong enough to turn the handle, then it supplied the information.

These machines are human-size, so the energy involved is of the size appropriate to our world – large and crude. If we scale down the clock size one million times and keep the efficiency of its operation on par with Babbage's computer, then the energy supply would also have to be reduced in kind. This is precisely what biological machines achieve. The powerful computations constantly performed by every cell are successful and they do not need an electric cable – they just need the required amount of glucose. How far down in size can we go? Is there a limit? Does Heisenberg's Uncertainty Principle apply here? The central theme of this book is the proposal that the lowest level is the pixel machine. When objects of this size change their energetic state, there are also alterations in their connections to their neighbors. In these objects, a quantum of energy is simultaneously a flick-of-the-switch.

Let's return to the horizontal ladder of speech communication and examine in more detail those machines producing flows and transfers in our world. In Figure 3.1, the sound wave emanating from the larynx is modulated to produce recognizable sounds by the muscles of the tongue and lips. Muscle is a bottom-up machine, as we will see in detail in Chapter 12. But these muscles are under the control of a larger machine located in the brain, and thus they are preceded in the chain of command by a top-down flow. Between the motor nerves from the brain and the muscles of the mouth are protein machines at the subcellular level supplying the nerve impulses that cross the neuromuscular junction, and therefore there are even more machines transferring information downwards and then upwards than are shown in this simple flow diagram. Sound waves enter the ear of the listener carrying energy and information. They are transferred through the eardrum and microscopic bones of the middle ear – hammer, anvil and stirrup. Taking a tally at this stage shows that most of the information has been retained (hopefully) but most of the energy has been certainly lost in all directions into the surrounding air. The bones of the middle ear channel the vibrations onto the surface of the inner ear, which prevents their dissipation into general sound waves spreading in all directions through the head as had occurred a few stages earlier in the air outside. The special membrane of the inner ear then upgrades the information passed on by the stirrup, by analysing the wave, and transfers the rearranged information to the hair cells. At this stage, large quantities of metabolic energy are added to the chain of events, as these cells convert mechanical energy from the vibrating membrane into electrical impulses. Transmission of electrical signals between cells occurs down at the molecular level and therefore this step occurs in the top-down direction. In the final transfer of information to the auditory nerves of the listener, bottom-up processes convert the pattern of molecular activity generated by the hair cells into information on a larger scale, appearing now as patterns of neural activity. In summary, an extended sequence of events such as these produces brain activity in the listener, which is a copy of that which had occurred in the brain of the speaker a split-second earlier.

As rudimentary as this thumbnail sketch of the chain of events may be, it illustrates several aspects in a clear way. The levels do not follow a simple sequence like the rungs in a unidirectional ladder – there is rather a criss-crossing of ladders involving a mixture of top-down and bottom-up machines connected in no obvious order. Also their physical natures are quite heterogeneous, for example, they are not all cellular. Muscles are high-level integrated tissues, while electrical impulses are produced in single nerve cells by proteins. There is therefore crossover between horizontal and vertical hierarchies. But most importantly for the central issue of this book, there appears to be no quantitative correspondence between energy and information. This might well be taken as a disappointing conclusion, since our intuition aims, or at least hopes, for a relationship. We remember Brillouin who ardently promoted Boltzmann's entropy formula to quantify information on the basis of Shannon's definition of information as probability (7). To help throw some light on this problem, the chain of events will now be analyzed one step deeper by examining the sequence in terms of either energy or information separately in the schematic flow charts shown in Figure 3.2.

The source of energy for the transmission of the message is the speakers lungs. A smaller amount originated in the speaker's brain associated with the ideas to be conveyed, and in some languages additional energy may be injected by the mouth, although this would be secondary to that already carried by the sound wave emanating from the larynx. A major fraction of this original energy is lost even before entering the listener's ear, because of the way sound dissipates in air. Extra energy is probably not added to the sequence until later stages when the message reaches the hair cells of the inner ear. Therefore up to the point where the vibrations are converted into neural patterns, the energy originates in the speaker's lungs, and of that, the great majority is lost during transmission. The new contribution is made by bottom-up machinery composed of membrane proteins which produce electrical effects that proceed on to become nerve impulses in the listener's brain.

The information flow has a different source to that of the energy, originating as it does in the speaker's brain (or better, mind – but we know nothing of this interface). Another interesting point is that the chain of events is much more intricate than for energy transfer. There are top-down machines in the form of the larynx and mouth, and later, in the inner ear membrane. There is a great deal of information processing in the later stages of the auditory system, translating the mechanical vibrations of sound waves into a sequence of elementary bits. Then there is bottom-up processing by the hair and nerve cells as the sequences of vibrations are selected and summed, thereby lifting the information to higher levels.

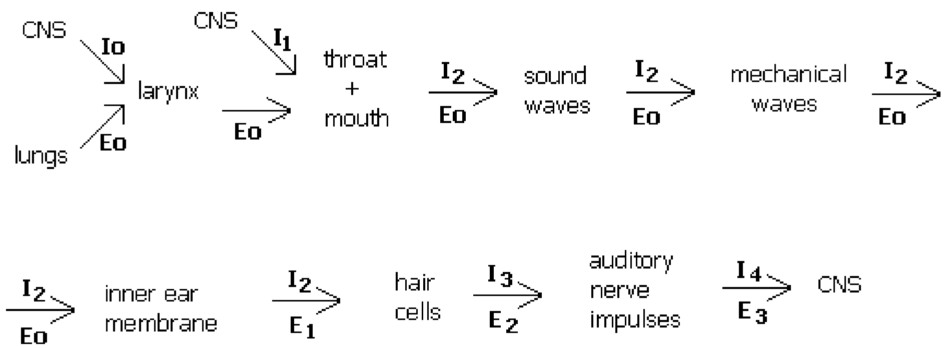
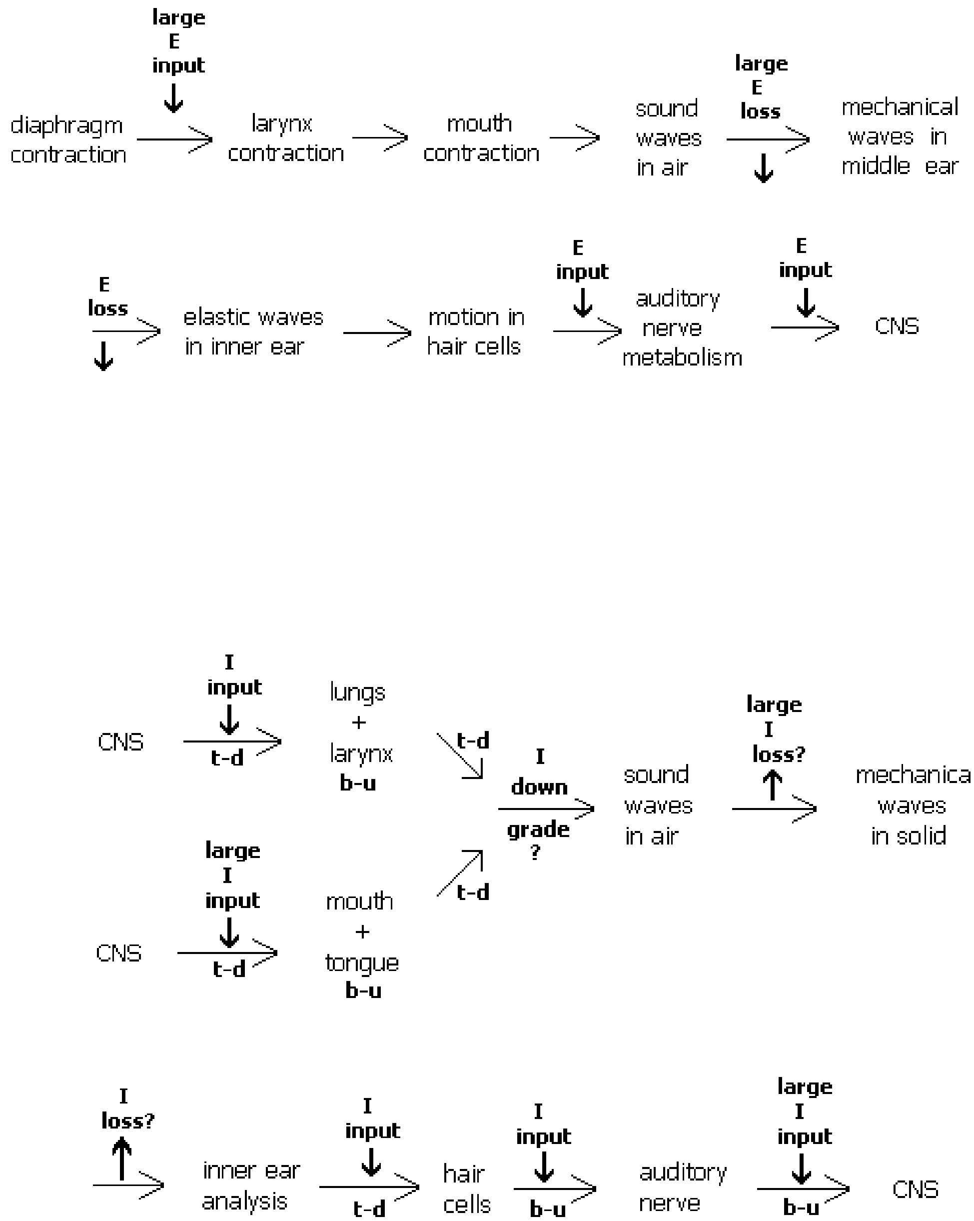


Figure 3.1 Inputs along the path of verbal communication. In this diagram proposed inputs of energy (E) and information (I) are shown at those steps where it is known that conversions and transfers occur. The indications are qualitative only. They suggest where there is an additional input to the flux by an increase in numbering (for example, I_2 to I_3 at the machinery of the inner ear), so that where the numbers do not change, they suggest that the flux is being transferred only and is not being up-graded by injection of new input at that point.

CNS = central nervous system.



<u>**Figure 3.2 Separate flow-charts for energy and information fluxes.**</u> In order to clarify the interconnection between energy and information fluxes, it is instructive to follow each quality independently as they are transferred along the pathway. This increase in detail reveals that the steps taken by each are similar but not identical, and that they therefore do not follow the same chain of events.

Since the purpose of speech is to have the ideas originating in the mind of the speaker replicated in the mind of the listener, it might reasonably be concluded that the information flux through the chain remains constant. This assumption raises the question of the quantitative relationship between energy and information, and, as noted above, whether indeed there is any relationship at all, in view of the fact that most of the energy is lost along the way. The puzzling nature of information can be illustrated by posing the question again, but this time introducing a second listener into the scene – or indeed, an audience of hundreds! Since most of the energy is lost, so is the information which it carries – or better expressed – so is the information-to-be which it carries. In other words, information can be weighed on the basis of its effect, not on the basis of its cause. It projects into the future, and for the same amount of energy to have greater influence on the future by causing more non-random and fewer random events, it must enter more machines, in this case, ears. However this multiplying effect is an amplification rather than an upgrade, since the quality is not changed. Nevertheless, information increases with the size of the audience, while the size and power of the source remains constant. As the audience grows in number, so does the effect at the end of the chain. Viewed from the opposite perspective we would say, there is no effect if there is no audience – if there is no-one in the forest the falling tree makes sound waves, but no sound.

This simple analysis highlights once more the problems raised in the introductory chapters of TLP, which are inherent in the neo-Darwinist explanation of evolution. Some readers may be surprised that such a connection can be made at this stage, so let's examine the implications a little closer. According to that view, information played no role because that would put effect before cause in its reliance on purpose and design to influence the future. Therefore, the upgrade and spread of information, which is unquestionably the essence of evolution, is nothing more than a fortunate by-product of natural selection – the real driver of evolution. Some would even say that there is upgrade in appearances only. From the neo-Darwinist standpoint then, it may appear that the human ear is a remarkably refined information processing machine, but we would fall into the Lamarkian trap if we should go on to claim that its refinement had anything to do with making sense of the sounds made by our fellow humans – there is no causal connection between the larynx and the eardrum. The neo-Darwinist, and indeed the Darwinist, position holds that the chain of events represented in Figure 3.1 did not evolve as one – as a system – but that each of its biological elements changed in an ad hoc way independently of the others. And even more astonishingly, the whole functions better for us now than it did for lower animals in bygone ages – those lucky pilots now fly fighter jets!

A qualitatively different picture emerges when one views the enrichment of information as the driver of evolution. The refinement of the larynx is connected not only to the eardrum, but also to brain function, to the whole of the body, and to social behavior in general. With the machines of the throat and mouth, we can make, say 50 sounds. This is not a happy accident, but is commensurate with the complexity of the concepts we wish to express. Birds do not have to master Latin to communicate what they want to say to one another. Likewise, we do not need to produce a thousand sounds, because we do not possess the level of intelligence to cope with the variety and content of the messages that could be generated with such a powerful capability. When a system evolves as a functioning whole, its parts evolve in measure with one another.

Before the sound waves reach the inner ear for analysis, they pass through the outer ear canal, ear drum and the tiny bones of the middle ear. These structures function as machines in the sense that they help to capture and redirect energy and information, however, they do not change its quality because there is no redirection of the flux up or down to a new level. They include the simplest types of machines exemplified by our familiar levers, cogs and cams. Lever action like that of the middle-ear bones, is very effective in changing the magnitude and direction in which force acts, but does not change its quality. Energy and information are still mechanical in nature at this stage, just as they were in the vibrating air outside. Henceforth such mechanisms will be called mechanical devices, to distinguish them from machines which for the purpose of this book, is the term reserved for mechanisms effecting transfers to different levels. One important feature of mechanical devices is that they can function reversibly – they are two-way mechanisms. Another is that the flux through them cannot pause, because to be able to pause, information must be recorded. But this requirement would involve an encoding machine and therefore a shift in level, which would in turn involve manipulation of energy or information or both. A third feature is that both energy and information are important for their function. In using a lever as a simple tool to shift a load, we feel instinctively confident about the force we can expect to exert on that load. But we are equally as confident about which direction and how far we can move it, because we can adjust where to position this simple device. Leverage is a concept that conveys more than just brute force. On this basis every sportsman knows instinctively that his muscular exertions will effectively reach his hands and feet, and in addition, that these forces will be at the right place, at the right time, and in the right direction.

Many other examples of superdevices come to mind. For example, the optical apparatus forming the front of the eye – the cornea, pupil and lens – which upgrade incoming light signals. Yet although nature employs these same-level tools, they are not enough for the construction of living systems. As emphasised in the previous chapter, life is characterised by the energy and information fluxes between levels, and to understand these requires a deeper classification of machines.

Let's look a little closer at the production of speech by the mouth region. Because the muscles involved surround the mouth cavity through which the sound waves are travelling, this mechanism on the whole is a top-down machine. But on the other hand, the action performed by each individual muscle is bottom-up. Muscle contraction is a very common mechanism employed by organisms and, as will be explained later on in Chapter 12, it is a bottom-up machine because molecular energy stored in ATP is transferred up to the level of the muscle tissue. A further property of this type of action is that it is directed inwards. The distinction between inward- and outward-directed action was one of the main findings of the examination of osmotic forces in TLP, where the concept was developed at length. Thus muscle is a bottom-up-out-in machine. In contrast, the piston machines of our invention have a bottom-up-in-out action. Of the man-made machines this is without doubt the commonest, though as will be seen later, they are not as common throughout the biosphere where the inward-directed force of tension exerted through water pervades the living gel.

These cumbersome notations can be shortened to the two-word forms, up-in and up-out. In these two machine types, tension drives inwards and pressure outwards. The first preposition indicates the direction of energy flow from one level to the next, and the second indicates the direction of the drive. The way in which a simple metal spring works provides a facile scheme for categorizing the four types of action:

1) up-out = squeezed spring pushing a load

2) up-in = stretched spring pulling a load

3) down-in = force pushing a squeezed spring

4) down-out = force pulling a stretched spring

At first sight, it may appear that the last two categories are not real machines because the spring is not performing work-for-us. In these cases it is we, that is to say, an external agent that is fuelling the machine by actively squeezing or stretching it, and in so doing supplying energy to it. The spring is acting as a device which transfers energy from the human-centric mechanical level down to the molecular level. It is subdividing and storing this supplied energy downwards by straining the bonds between its metal atoms. Strained chemical bonds contain extra energy, and so are often called high-energy bonds, which we will meet again as important players in Chapters 7 and 8. Human ingenuity has produced only few inventions that work along these lines. The laser immediately comes to mind. With this instrument, macro level electricity is converted into equally sized energy quanta of atomic dimensions. There are as well other more spectacular devices that function on the grounds of their microstructure – the ubiquitous products of today's IT industry. We recall at the beginning of the chapter, that computers were classified on the information end of the spectrum of machines. Computer programmers are not interested in the energy output of their machines and no-one is concerned about the energy efficiency of a computation. Operators can use as much energy as desired to send pulses of electricity through the circuit where it is subdivided trillions of times into bits of information on the micro, or even better, nano, level. So the phenomenon that occurs on squeezing a spring parallels that of a precise, even though simple, calculation – a perfect arithmetic division. A macro sized quantum of energy is pixellated into a vast number of micro quanta through the perfect order of the spring's solid crystalline structure. Here we see a machine in action where energy and information play equally important roles. All the energy of compression is downsized and stored as forces between the atoms of the entire population that make up the spring, in contrast to the computer though, here energy and information are in measure with one another.

This comparison brings us to an important characteristic – upward-directed work is achieved by a machine consisting of an external structure, which can collect small-scale energies, whereas downward-directed work is achieved by a machine consisting of internal structure, which can pixellate large-scale energies. When a gas is squeezed, it also stores the work directed downwards into it just as the metal spring does as indicated in Figure 3.3. But it lacks internal micro, (or nano, or molecular) structure and consequently randomizes, rather than pixellates, energy delivered to it by transferring it to the expanding worlds of pressure and heat – the increased chaotic movement of entropy. In this type of motion there is no order on the lower level as there is in the arrangement of the metal atoms in the spring, and although the energy transfer is top-down, it is not directed into chemical bonds in an orderly way. In contrast, the familiar metal spring is a very efficient top-down mechanism or computer. All the force imposed upon it is captured as equally sized quanta in the perfectly arranged network of chemical bonds that make up the metal crystal.

However, there is a material that possesses even more versatility – liquid. The following chapters will reveal how liquids, like springs, also store energy of compression in chemical bonds, even though like gases, their molecules are in motion which prevents any crystalline order of quanta being established at the lower level. Let's enter the intriguing world of liquids and examine how they respond to imposed forces.

In the upper panel of Figure 3.3, the transfer of energy to lower levels is compared for solids, liquids and gases. We see that energy from outside is transferred down to the molecular level. But in liquids, pressure is exerted by clusters, which are multimolecular particles of intermediate size occupying the meso level. The entry of the pressure pixel into the picture means that the diagram must be modified as shown in the lower panel, since by definition of the pressure pixel the energy introduced into a gas is also now found at this meso level. When the energy is downsized in a gas, the new micro quanta are not relocated into a precisely ordered, fine-grained pattern as we have in a crystal, because each gas molecule is in free chaotic motion within a large empty space compared to its size. In fact the size of the pressure pixel can be thousands of times larger than that occupied by its molecule. In the air we breathe for instance, each molecule of oxygen and nitrogen occupies a volume that is about 1500 times larger than their size. And in the thin atmosphere on Mars the empty space is about 30 000 times larger than the size of the actual air molecules. As seen now in the lower panel, the macro quantum of energy imposed from outside is moved to different levels in gases on the one hand, and solids on the other.

Liquids are incompressible, that is, they do not reduce their volume under pressure. This in turn means that the imposed pressure does not inject energy into the medium from outside. But since pressure inside the medium must rise to meet the pressure imposed, the clusters at the intermediate level need to be energized just as the molecules of a compressed gas are. As technical arguments developed later in Chapter 6, "Mechanical or Structural", will show, this extra energy comes from below, as the bonds between the individual liquid molecules link up to form clusters. Since the signal for this transfer comes from outside at a higher hierarchical level, the response of liquid media to pressure is an example of information from one source stimulating energetic action at a distant source. It can be summed up as a downward information flow coupled to an upward energy flow – or top-down control over bottom-up action. Top-down control is of course very common in nature and especially so in human activity. In our example of control by the brain over the intensity of the sounds waves leaving the larynx, a series of top-down machines going down to the level of proteins in nerve cells controls the functioning of the bottom-up muscles of the throat, and in so doing, directs the flow of energy from a source that is distant from the brain. But the energetic effect illustrated in Figure 3.3 is the result of a single mechanism located in a single medium, and is therefore simplicity itself compared to the neuromuscular junction. Yet a transfer mechanism is still involved, since an action exerted on the meso level of pixels elicits a reaction on the level below achieved through molecular restructuring. In identifying this effect we have come a step closer to the role of information in the operation of elementary machines.

The greater versatility of liquids over solids and gases is obviously not easily exploited, at least by human efforts, since by far the majority of man-made machines are composed of the latter two materials. In contrast, the machines of life are made of water. We recall that in our machines, the information content is robust and inflexible, in fact it is of such a basic nature that it is not mentioned in text books of physics. As far as I am aware, all scientific theories which investigate the nature of information, can be traced back to the Clausius-Boltzmann concept that entropy production is a direct measure of increasing disorder. The historical circumstances that led to this famous dictum were a result of the simple fact that the study of machines dealt with energy manipulation only. It did not, and still does not, deal with information processing except to stipulate that information is always lost. The intellectual achievements in this field of physics are thoroughly covered in Brillouin's book (6), yet it is noteworthy that this definitive opus is now more than half a century old.

Let's return for a moment to the early discussion on the Second Law of Thermodynamics in TLP Chapter 2, "Natural or Man-made". There we learnt that the crux of Clausius's historic achievement can be illustrated by the simple scheme shown here in Figure 3.4. The energy E_1 entering the machine is split into two parts, the unused energy E_3 flowing out, and the work done for us W (which was earlier called E_2). Clausius proved that for any machine, the entropy leaving with E_3 exceeds the entropy entering with E_1, and therefore its operation results in an increase in the entropy of the surroundings – or the universe, as some text books prefer to say when enunciating the Second Law. But there is no consideration given to the work done, and so the claim that entropy will always increase is not valid, unless it is also specifically demonstrated that the transformation appearing as W makes no contribution to entropy. On this point however, I think that most readers would feel that the production of work must surely have some bearing on order in our world. The concept takes on particular pertinence if we ponder the grander scheme, in which the biosphere (or as some might say, the Living Planet, or Lovelock's Gaia) takes on the role of the machine as illustrated in the next diagram. Here, sunlight plays the role of E_1 fuelling the conversion of the raw materials, mainly water and carbon dioxide, into living organisms as the output, W. Figure 3.5 makes it amply clear that the entropy content of living structures should indeed be included in balancing information output with input.

It is therefore here, at the diagram of Figure 3.4 where our fundamental understanding of information has remained stalled. I believe that this apparently intractable problem led many thinkers including Schroedinger to their conclusion mentioned earlier, that information, and with it biology, involves a fundamental physical principle yet to be discovered. And it is clearly this problem which is responsible for the opposing claims made upon the Second Law reported in the previous chapter.

So we can now legitimately ask: is the relationship between entropy and order as laid down by the Second Law correct? With this question we have reached the point where we can now rejoin the discussion on entropy broken off in Chapter 2 of TLP – broken off there because of the arcane technical language employed by thermodynamicists. And there, the same point had been reached: what about W? It is precisely the production of work that tells us the function of a machine is to direct energy from level to level – or put another way, is to change the character of the quanta. One of the main conclusions of the above discussion is that the piston machine of the industrial age belongs to just one of the four categories – it is an up-out machine. It operates in an expanding world where energy loss means its random fragmentation and dissipation into the environment. But in contrast, for a top-down machine such as a mitochondrion or microprocessor, the flows E_1 and E_3 have a different significance. High-level energy, osmotic or electrical in these cases, is subdivided with precision and directed downwards in a controlled way into lower-level locations. In these cases, W stands for a population of pixellated energy quanta.

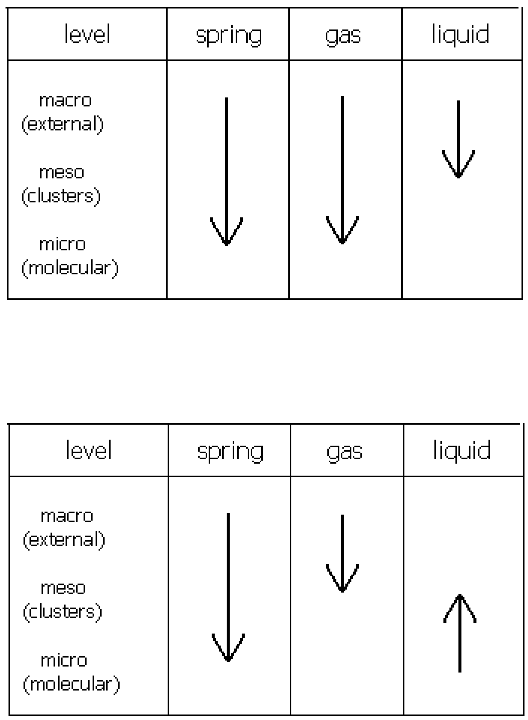


Figure 3.3 Energy transfer in compressed solids, liquids and gases. In the upper panel the arrows indicate the expected direction of transfer of energy when pressure is imposed upon the three states of matter. In the lower panel the arrows for liquids and gases are redrawn to show that the energy is transferred to the meso level of the pressure pixel, and that this transfer is from above in the case of gases but from below in the case of liquids.

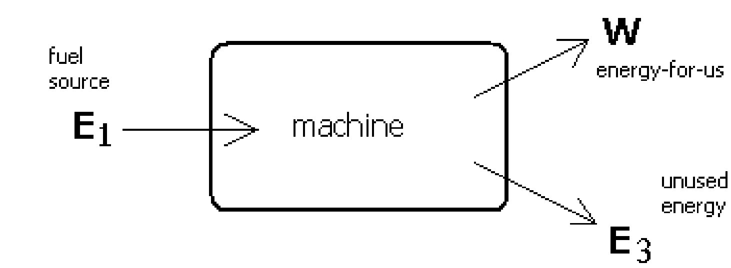


Figure 3.4 What about W ? This diagram illustrates one of the pillars of the study of thermodynamics associated with the names of Carnot, Kelvin and Clausius. Based on this fundamental model Clausius was able to prove that the entropy entering with the energy, E_1, is always less that that exiting with energy, E_3. In his analysis Clausius did not consider entropy entering or exiting with the work output, W.

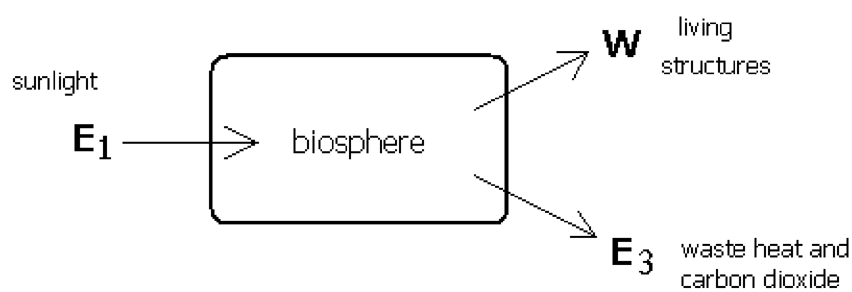


Figure 3.5 Life and the Second Law. Clausius's concept is expanded such that his heat machine now encompasses the entire biosphere. Fuelled by solar radiation, it converts the raw materials of the biosphere, mainly carbon, oxygen and hydrogen, into living matter and waste products, mainly heat and carbon dioxide. Because the overall work output of this machine consists of complex higher-level structures, W possesses much lower entropy than the starting materials.

Clausius was interested in the steam engine – that basic up-out device which delivers work to us through a pushing action (piston derives from the Latin "pistillum" meaning "pounding implement"). Although it is automatically clear to all that the piston moves with a pushing force, it is important to include this third element of characterisation because it indicates the essence of the action. Applying this additional notation modifies the four classifications as follows:

1) up-out-push

2) up-in-pull

3) down-in-push

4) down-out-pull

The description of the action as either "push" or "pull", tells us the type of reaction the recipient of work must be able to generate in response to the drive. For example, the steam engine works by the piston reacting with pressure back against the expansion of the hot gas inside the cylinder – or looked at from another perspective, you cannot achieve work from a machine that pulls on an expanding gas. Such a response only helps the energy available in the gas to escape and spread out into the environment increasing its entropy even further. So the other four combinations obtained by interchanging the push and pull notation do not describe machines – they describe situations of flux in which the only result is to increase disorder. They describe dissipative systems.

A simple illustration of the two essential components of machine function, drive and response – Newton's action and reaction – is given by the constraints that must be operating when energy is trapped and held under the following circumstances:

1) the walls of a balloon holding in pressurised gas

2) the rim of a drum holding the drumskin taut

3) the rubber molecules of aircraft tyres taking the load on landing

4) molecular bonds maintaining a guitar string as it is tightened.

In the first two examples, the constraints surround the body of energy, while in the last two they are internal. In 1) and 4) the reactions prevent the energy escaping outwards, while in 2) and 3) they prevent it collapsing further inwards, and so the constraints function as external or internal barriers to energy flows. In our anthropocentric world, external barriers are more familiar than internal, because for us the scenario "trapped inside trying to get out" comes quite naturally to mind as a constraint on movement in contrast to "trapped outside trying to get in". However, there are spectacular natural examples of the latter type, for instance, consider the weight of the atmosphere of a gas giant like Jupiter. This massive large-scale force bears downwards towards its center, but the planet is prevented from collapsing in on itself and igniting its nuclear fire by the molecular collisions deep in its interior generating the high pressures that push back on the outer regions above. Under certain configurations, which with hindsight we like to call design, these different types of constraints become the agents offering a dynamic response to the trapped energy, and then we have a machine.

In Figure 3.6, this concept is illustrated in an indicative way. Although only schematic, I think the diagram shines a light of understanding on why the generally accepted arguments claiming how energy dissipation and entropy increase must go hand-in-hand, has remained dogma for so long. The two types of machine with pulling action, up-in-pull and down-out-pull were not studied by thermodynamicists, because gases cannot go under tension and pull on the piston. The third type, down-in-push, was never considered, because the industrial age did not consider top-down machines to be of any interest in producing work. So in effect, the only machine of the four which has been thoroughly studied – and there can be no doubt about thoroughness when we remember it is now 200 years since engineers first examined the steam engine – is the up-out-push piston action of the industrial age. Since then, it has been tacitly assumed that the secrets revealed by this device apply automatically to all energy conversions, whether they be natural or man-made.

In the downward-directed action of types 3) and 4), the reactions push and pull cannot be taken in the mechanical sense as in the familiar large machines of our world. To date, we have invented only limited energy conversions on the micro, and as yet none at all on the nano, scale. I have often mentioned the computers of the IT industry as examples, although their components are quite large in comparison to enzymes – biology's lower level machinery. To clarify, let's recall the original statement of the problem posed at the beginning of the story illustrated in TLP Figure 2.1 "Two Motors", reproduced here along with Figure 3.6. The type 1), up-out-push, motors of our invention were contrasted with the type 4), down-out-pull of metabolism, in which the reaction, pull, is of course not the same type of force as the familiar, push, of our motors. Both burn energy-rich fuel, hydrocarbons or carbohydrates, whereby the end waste products are released into the environment. Thus in both the drive is the tendency for energy to expand outward. However, the components of the biological machine capture the metabolite molecules, which become bound to them because of the positive glue factor, in order to catalyse their precise individual chemical steps. This inward pull resulting in the unison of the fuel and machine part is crucial for the work step, which then captures the released energy. It plays the role of the Newtonian reaction to the natural tendency of the energy to escape from the site of oxidation – the action. This picture illustrates how it is ordered structures on the nano level, which provide the path for the down-out flow, in contrast to the piston-in-a-cylinder construction that delivers our up-out mechanical power. Readers already interested in mechanisms that pump energy down into chemical bonds can fast-forward to Figure 14.5, "Dynamics that move energy down", for a general classification.

I am aware that this mechanical line of thought is foreign to many biologists, indeed it may even be viewed as irrelevant to their study. However, to the engineer it is basic. For students of statics, the field of study that helps us understand how structures are stabilised, the analysis of the forces experienced by structural components into tensile and compressile is compulsory (happily). Once armed with this knowledge, every curious traveller, engineer or not, looks at a bridge with different eyes, and one of the objectives of this book is to encourage every biologist to look at the living cell with different eyes. The cell is also constructed out of components which have essential mechanical roles – the fluid regions under pressure and gelled regions under tension. Like the bridge, the cell owes its structural integrity to the balance of these forces – the osmotic forces which act throughout the medium of living matter. But more complicated than the bridge, the cell is further a dynamic system, in which the regions can switch their mechanical states as they drive its internal traffic as well as its external locomotion.

Indeed, use of the term "machine" to describe my overarching concept is problematic, because for many readers it automatically carries a meaning associated with "mechanical" (as these words are used in the English language). The picture of levels developed in the preceding chapters has already linked machines with processes of the mind, as exemplified in acts of artistic creation. For us here, the term "machine" simply represents a set of circumstances that effects directed energy flow – all forms of energy, not only mechanical energy. With this in mind, let's return to the analogy used in the first chapter where the cell was compared to a written story, to illustrate for the less mechanically- and more literary-minded reader the difference between the classical up-out-push machine and the up-out-pull non-machine, In that introductory analogy, there were no spontaneous driving forces to consider, but now let's imagine that words have their own natural tendency to fragment into smaller words, and pieces of words like syllables and single sounds, that is, to move down a level. Next imagine that a machine exists, say the mind of a poet, which can plug into this natural tendency and use it to compose sentences. But to write meaningful creations the poet must impose restrictions on the spontaneous word break-up, such as the rules of grammar and verse, to avoid a jumble of unconnected elementary sounds resulting from his efforts – or put more abstractly, his sentences must react back upon the tendency of words to fragment with their own constraints of containment. In effect, his sentences must press downwards and inwards from the level above.

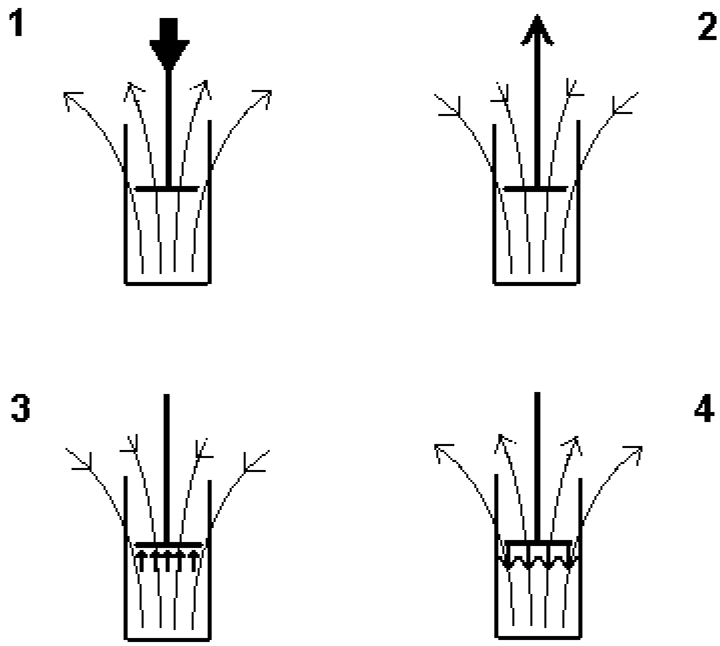
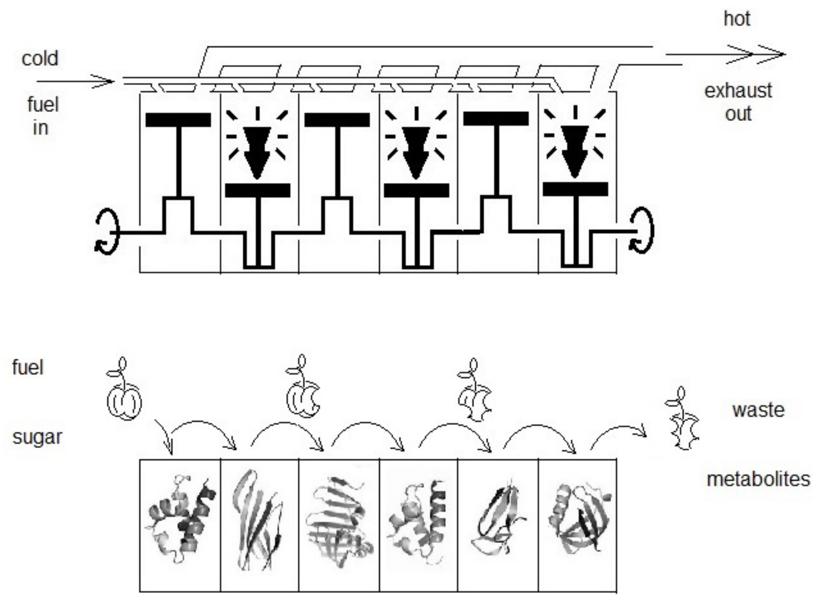


Figure 3.6 The four machines. Schematic representation of the energetic principles underlying the four types of machine action showing the reaction of the piston in bold type arrows to indicate the level where work is being performed:

1) up-out-push
2) up-in-pull
3) down-in-push
4) down-out-pull

curved arrows = direction of drive imposed by the energy source
large arrows = macro forces
small arrows = micro forces
thick arrows = pressure
thin arrows = tension



2.1 Two Motors Two versions of motors, man-made and natural, which burn similar chemicals, petroleum and sugar, as their fuel.

Upper panel: The row of 6 cylinders is a schematic representation of a car motor. The pistons are pushed downwards by the force of high pressure inside the cylinders when the fuel suddenly ignites and burns explosively. This is illustrated by the pressure arrows in cylinder numbers 2, 4 and 6, which alternate their action with cylinders 1, 3 and 5, as the cam shaft along the bottom rotates. However this type of reciprocating action is not essential for our story. The important feature of the design is that each cylinder receives the same quantity of fuel, exerts the same force, and produces the same quantity of exhaust. Fuel is fed into each group of three cylinders simultaneously through the fuel line from the left of the diagram, and the hot exhaust gases, mainly carbon dioxide, are expelled simultaneously to the right.

Lower panel: For this illustration we have zoomed in by a factor of about one billion times (from a meter to a nanometer) to the level of the molecular machine of biology. Instead of 6 identical cylinders, we have 6 distinct jack-in-the-box enzymes which burn their fuel in a sequence of steps as it is passed along the row. The fuel, single molecules of glucose represented by the apples, is consumed in 6 different precise chemical steps until it is all converted into the waste products, carbon dioxide and water, as in the car motor. The 6 squares are in keeping with the pictorial jack-in-the-box image of enzymes. They are drawn in order to aid the eye to define a region of space, they do not represent the sides of real boxes. The curved lines inside each box are schematic representations of the protein chains which are the real material of enzymes. Where they make side-to-side contact, a positive glue factor is in force between them. Likewise the apple at a certain stage of consumption has a strong positive glue factor with the enzyme which is designed to take the next bite. This step then alters the chemistry of the local fuel-enzyme contact region so that the attraction between them is switched off. The fuel apple has now a different shape and size, and is attracted instead to the next enzyme in the line. This generalized picture of enzyme function highlights an essential design implicit in biological machinery. Indeed, the fact that the picture is greatly oversimplified suggests that the degree of design surpasses even that of our man-made inventions.

On the other hand, we also have a group of unconventional writers who call themselves the antipoets. These writers place no restriction on the fragmentation process – quite the opposite, they use it in creating their avantgarde texts. Their sentences are long strings of elementary sounds lacking layered structure. These ever-expanding sentences pull on the words below and in so doing aid the natural process of on-going disintegration, and with it, the loss of meaning.

For a parallel pictorial analogy of the up-in-pull machine and its impossible up-in-push counterpart, we could propose the obverse fanciful scenario, whereby elementary sounds naturally tend to coalesce forming long polysyllabic words. In this literary society, the creative poets who wish to invent meaningful imagery must maintain the integrity of small sounds and prevent them from disappearing into one long unbroken sequence. So here again, there is reaction from above – informative sentences pull outwards on the words below to keep them apart and avoid the fusion process. By way of contrast, we have the up-in-push antipoets who accelerate the already natural tendency of verbal fusion by exerting pressure from the level above. Here, many separate sounds become compressed together forming one long word, into which the distinct meanings of the original separate sounds disappear.

Although these imaginary machines and their partner non-machines make no reference to the real world, they do hint at how information can be lost through opposite processes. Comparison of the inward-directed with the outward-directed natural drives leads to a new interpretation of entropy, which is broader than the classical view depicting the relentless process of dissipation. The approach here includes fusion along with fragmentation as a tendency that destroys order. We will return to the poets and antipoets when their fanciful creative methods are placed on a quantitative basis in Chapter 10, "Reversing Entropy", where the up-out-push and up-in-pull osmotic machines are discusses in technical detail.

In addition to broadening the concept of entropy, comparison of the four classes helps to explain the one-way feature of machine operation. The discussion in Chapter 1 points out that ladders display a strong vectorial character. The sequence of processes along a ladder take place in one direction – we do not open our mouths to listen to someone talk through their ears. What factor introduces irreversibility into a stepwise chain of natural events? This intriguing phenomenon demonstrates the duality of information – it is output from one machine, but input into the next. Information is the link between the levels. At one instant it is a pattern of muscular contractions, at the next it is vibrating air, at the next it is the rhythm of the bones of the middle ear, as it continues its journey up and down intersecting ladders. At each transfer, the information passed on must exist in a form acceptable to the second machine, and although it moves continuously from level to level in either direction, up or down, it passes through different machines on the way up compared to those on the way down. In other words, the fact that the traffic flow is one-way is ensured by the type of machine carrying out each step. Since those designed to move energy upwards have an external construction, they cannot achieve fine-grained order at lower levels when used in reverse – by pushing a piston you can make gases hot, but the energized molecules won't calculate the value of pi. Likewise, those designed to move energy downwards cannot fuse small-scale quanta into a single burst, because their internal construction lacks the ability to capture and collect – you can play the Moonlight Sonata to a radio and make its speakers vibrate, but the music won't charge its battery.

Readers will recall the model put forward in TLP, in which clusters populating the intermediate hierarchical level can assemble themselves into machines. The main message conveyed there, was that, operating in both the bottom-up and top-down directions, those watery demons are responsible for the link between the micro and macro worlds – that role essential for the emergence of living matter. In the final stages of this present book, the machinery of internal cellular movement will be examined in Chapter 12, "The Muscle Machine", as this well studied biological function provides a familiar example of bottom-up energy transfer. Then to illustrate flow in the opposite direction, the connection linking clusters to metabolic molecules on the level below via those engines of life, the enzymes, will be discussed in Chapter 14, "The Enzyme Machine". Finally, the ideas that took shape in developing the picture of the pixel machine will be brought together in an overview of the role of information in living systems. However, before moving on to discuss next the technicalities of the osmotic machine, let's recall the main points that have already emerged at this introductory stage:

Energy flows spontaneously under the influence of two tendencies – either under the outward drive of disintegration as postulated by the Second Law, or under the inward drive of unification, ignored by the Second Law.

Flow caused by both tendencies incurs the loss of information.

Both types of energy flow can be utilized by structures which offer a reaction to the flow, that is, by machines.

Machines with an external construction collect energy shifting it to a higher hierarchical level, while machines with an internal construction pixellate energy shifting it to a lower level.

Machines can therefore be classified into four types based on the nature of the drive and the direction of the shift in level.

There are also simple mechanical devices composed of one structural element only, through which energy flows reversibly without resulting in a shift in level.

4. The Osmotic Machine

Ideal solutions which are in osmotic equilibrium with one another lie on the line shown in Figure 4.1 where their pressure is given by van't Hoff's equation

$$P = zkT + P_o \qquad 4.1$$

P_o is the ambient pressure on the pure solvent (usually atmospheric), z is the volume concentration of non-volatile solute (eg molecules/L), and kT are Boltzmann's constant and temperature. Although experimental results gathered over the last century have convinced scientists of the validity of this relationship, see the historical coverage up to 1976 by Hammel and Scholander (7), it remains still today without a theoretical explanation. Serious problems associated with this failure are not discussed herein, as they are fully dealt with in TLP Chapter 4, "The Puzzle of Osmosis".

For purposes of comparing the Carnot cycles of osmotic and gas machines, it is more convenient to plot van't Hoff's equation as a familiar isotherm by replacing z = Z/V, where Z is the number of solute molecules and V is the final volume of the solutions made by adding solvent to this constant amount of solute (Figure 4.2).

Since this plot has the form of the P,V hyperbola of Boyle's Law , it suggests an interpretation in terms of an analogy to the Gas Law

$$P = n\,kT \qquad 4.2$$

In this familiar equation, n is the concentration of gas molecules in a body of gas. In the case of clusters, the term "density" is perhaps preferable to "concentration", because there is no empty space in liquids as there is between molecules in a gas. In any case, rewriting this basic expression in the form of Boyle's Law gives

$$P\,u = kT \qquad 4.3$$

where u is the volume occupied by a single cluster, that is, u is the size of the pressure pixel. As we saw in the previous chapter, this meso-level entity is responsible for pressure in both liquids and gases.

The work cycle of the osmotic machine illustrated in Figure 4.3 is directly analogous to Carnot's heat machine. The work is performed by a piston in a cylinder containing Z molecules of solute immersed in a surrounding reservoir of the pure solvent. The walls of the cylinder are permeable to the solvent molecules only. During the expansion step AB, solvent enters the cylinder from the first reservoir at pressure P_1, diluting the solution inside so the osmotic pressure falls as it moves down the isotherm from volume V_1 to V_2. In the step BC, the machine is immersed in the second reservoir at external pressure P_2 and the pressure on the piston is relaxed without changing V_2, so that the internal pressure now corresponds to the new osmotic pressure at C. The step CD reverses AB while the machine is in contact with the second reservoir, and step DA reverses BC.

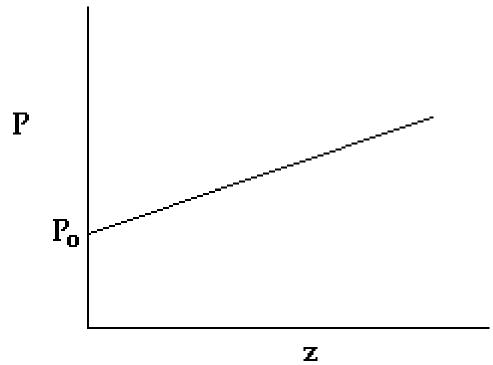


Figure 4.1 Van't Hoff's law of osmotic pressure. The pressures, P, developed by solutions which are in osmotic equilibrium with one another are proportional to the concentrations of solute measured in number of molecules per unit volume, z. P_0 is the pressure of the pure solvent, usually atmospheric.

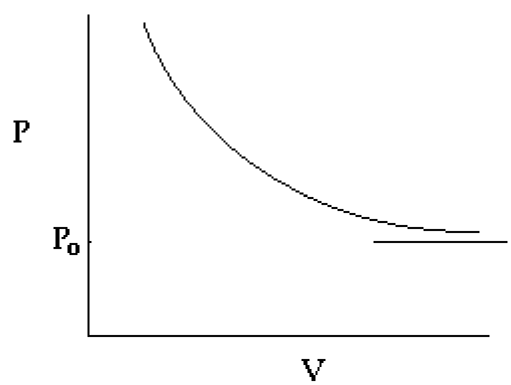


Figure 4.2 Van't Hoff's isotherm. The linear relationship of the previous figure is replotted as the familiar P,V isotherm describing the behavior of gases, where z has been replaced by Z/V. Z is the constant number of solute molecules in the solution of volume, V.

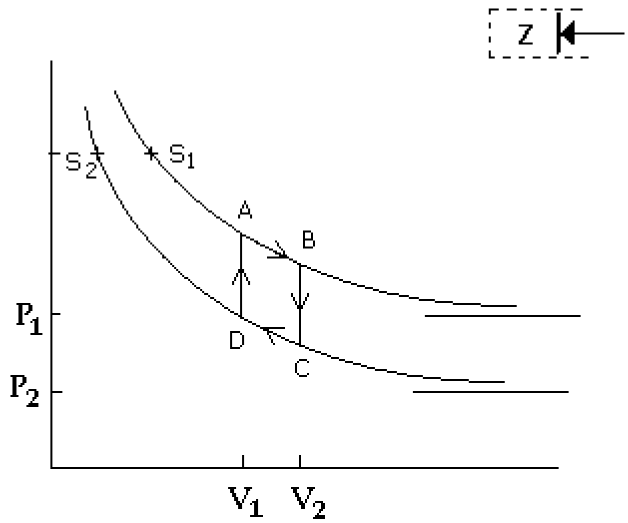


Figure 4.3 The osmotic machine. ABCD represents the work cycle of the machine constructed of a piston in a cylinder with walls permeable to the solvent, but not the solute, Z. The power stroke occurs along the isotherm, AB, and the return stroke along CD. The reservoirs, source and sink, must also be on the isotherm, say a solution at pressure, S_1, or the pure solvent at P_1, as the source, and a solution at S_2, or the pure solvent at P_2, as the sink. The thick arrow represents pressure on the piston.

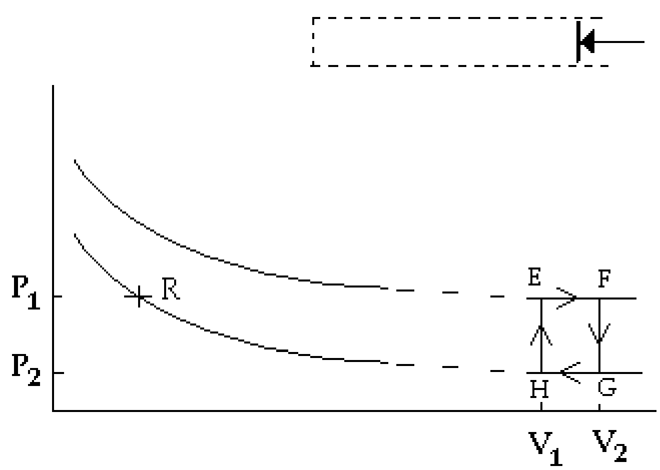


Figure 4.4 Osmotic or mechanical? The machine now operates at large volumes so that the concentration of solutes can be neglected, that is, there is pure solvent only inside the cylinder. The power stroke, EF, is performed in equilibrium with the pure solvent at pressure, P_1, as the source. When the return stroke, GH, is equilibrated with the sink of the pure solvent now at P_2, then the energy is supplied by the mechanical pressure difference in the reservoirs, but when it is in equilibrium with the sink, R, on the lower isotherm at pressure, P_1 as the sink, then the energy is supplied by osmotic forces.

thick arrow = pressure

The step AB is thus a power stroke operating along the isotherm

$$P = z\,kT + P_1 \qquad 4.4$$

from V_1 to V_2, while CD is the return stroke operating along

$$P = z\,kT + P_2 \qquad 4.5$$

from V_2 to V_1. The work done given by the area of the cycle is therefore

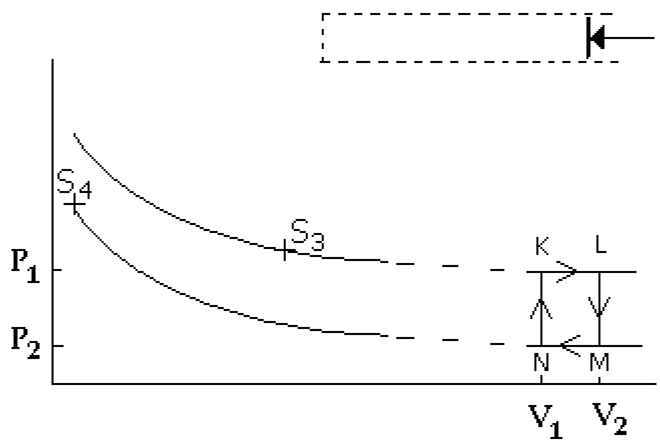
$$W = (P_1 - P_2)\,(V_2 - V_1) \qquad 4.6$$

This result raises the following point: the elevated pressures produced by osmosis above the external pressure on the reservoirs do not contribute to the overall work done. Indeed, the work done equals that obtained by simply transferring the solvent in its pure state from P_1 to P_2. We can illustrate this result graphically by increasing the volume of the machine to large values along the V-axis, where the isotherm asymptotically approaches the external pressure in Figure 4.4. Here the area of the rectangle EFGH now gives the work done, whereby solvent enters the machine which contains pure solvent only during the step EF at P_1, and leaves during the step GH at P_2. There is no osmotic effect involved in this cycle and the energy is supplied by the pressure difference in the environment. Writing the work in Equation 4.6 as energy per unit of transferred volume gives

$$w = P_1 - P_2 \qquad 4.7$$

This result can be interpreted simply as showing that pressure is a measure of the concentration of mechanical energy in a liquid.

However, we cannot conclude that the osmotic effect does not exist. The work delivered by the power stroke AB is greater than that delivered by EF – it is simply cancelled during the return stroke CD. So the question remains: what supplies the extra osmotic energy converted into work by the step AB, in view of the absence of familiar sources such as thermal gradients and chemical reactions?



<u>Figure 4.5 The general work cycle.</u> The machine again operates at large volumes such that z = 0. The power stroke, KL, is performed in contact with the source at pressure, S_3, and the return stroke, MN, in contact with the sink at S_4. In this instance energy for work is obtained from a reservoir at a lower pressure than that of the sink.

thick arrow = pressure

This question can be posed in clearer outline when we eliminate the energy source used here – the external pressure difference between the reservoirs. In this case, the second reservoir is the solution labelled R on the lower isotherm with a composition of z_1 in solute concentration under pressure P_1. Again the pressure on the piston is still P_2 during the return stroke, but the volume (V_2-V_1) is delivered back into this second reservoir at P_1 and therefore there is no work done by the environment. We now see the machine can perform the same work fuelled from two different sources: pressure differences in the environment or osmotic forces within the liquid. We may also further speculate that the machine can interconvert these mechanical and osmotic energies in either direction. For example, when the machine operates between solution reservoirs S_3 and S_4 in Figure 4.5, there is a complicated interchange of both types of energies, but the overall difference is still equal to (P_1-P_2). This means that Equation 4.7 can be rewritten more generally as

$$w = (P_3 - P_4) - (z_3\, kT - z_4\, kT) \qquad 4.8$$

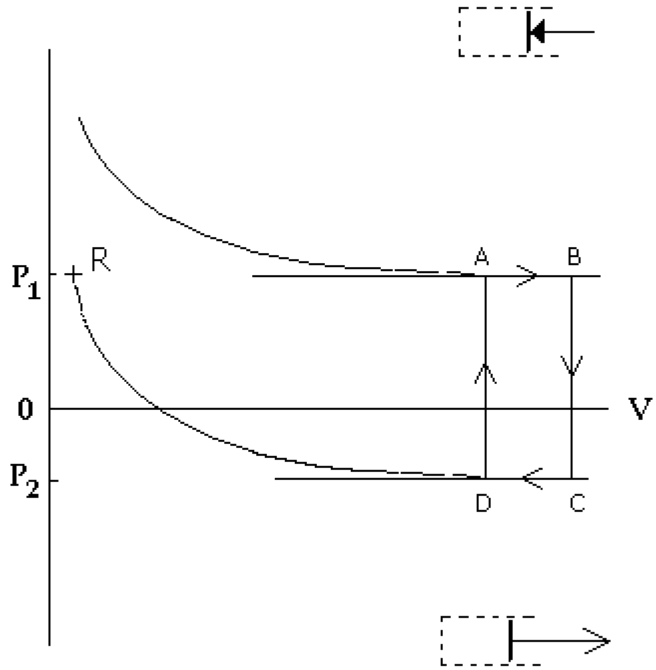
where (P_3-P_4) corresponds to purely mechanical work done by the environment and $(z_3-z_4)kT$ to the osmotic work. Since the nature of this source of osmotic energy has yet to be identified, the cases of interest to us are those where the source and sink are under equal pressures, say the reservoir solutions marked S_1 and S_2 in Figure 4.3, for then all the work appears in the osmotic term.

The operation of the osmotic machine presents us with other puzzles, as illustrated in Figure 4.6, where it delivers a greater amount of work than it extracts from the energy source. As explained more fancifully in TLP Chapter 6, “The Impossible”, this conflict with the Second Law of Thermodynamics arises because the return stroke CD is also a power stroke in addition to AB. The machine is actively contracting during the step CD, because the liquid inside is under tension. Therefore, even when the machine operates under positive external pressures in its reservoirs, its internal tension will make extra positive contributions to the work done. This means that the statement following Equation 4.7 must be modified, since it is now obvious that a body of liquid of volume, V, contains more energy available for mechanical work than given by its pressure.

Osmotic equilibrium cannot be explained by forces acting on the macro level alone. The isotherm of Figure 4.2 shows that two, or any number of, liquid bodies can be in contact and yet be under different pressures. For example, during the return stroke in the machine illustrated in Figure 4.4, we have the external pressure, P_1, in the reservoir R exerted on the lower pressure, P_2, inside the machine, and since these are clearly not in mechanical equilibrium, some other forces have to be found. In the cluster model, the macro level pressures are balanced by two pressures of opposite sign, Q_1 and Q_2, acting on the micro level in volumes smaller then the pressure pixel. As discussed in detail in TLP Chapter 10, “Pixel and Antipixel”, the full statement of mechanical equilibrium runs

$$P_1 + Q_1 = P_2 + Q_2 \qquad 4.9$$

One of the central issues arising out of the concept of the pressure pixel is the relationship between the macro and micro pressures P and Q, that is, between the externally imposed pressure and that exerted inside the cluster. In Chapters 6 and 7 we will discuss this relationship in terms of that versatility exhibited by liquids, when energy transfer between levels will become the focus of attention.



<u>Figure 4.6 The demon delivers the impossible.</u> This diagram is the technical rendition of the fanciful cycle performed by the piston fish in Chapter 6 of TLP, “The Impossible”. Again there is pure solvent only inside the machine. The step, AB, is the normal stroke under pressure but the return stroke, CD, is under tension. Both are therefore power strokes and the area of the cycle, ABCD, exceeds the maximum amount of work that is possible according to the Second Law. The arrows on the piston represent the forces exerted there. They are opposite to the direction of its movement and indicate its reaction to the drive as explained in the illustration of machine types 1) and 2) in Figure 3.6.

thick arrow = pressure
thin arrow = tension.

5. Wave-Clusters and the Liquid Spring

Pressure is a macroscopic phenomenon. As Pascal taught, pressure is transmitted from wall to wall throughout a fluid body – or put another way, each wall of its container feels the presence of the others. The Kinetic Theory of Gases explains pressure in terms of molecular collisions on the micro level, however this interpretation cannot be extended to liquids because in liquids the molecules are pulling on one another. So the question that immediately arises is: what entities are colliding in liquids?

In the cluster model, it is the clusters that carry the momentum causing pressure as they strike the boundaries. But since there is no free space in a liquid body, clusters are in contact and so cannot be modelled as performing Newtonian collisions. In this type of medium, it is wave motion which carries the momentum, and in order to comply with Pascals Principle, the wave must travel back and forth in all directions throughout the whole body and be reflected at its boundaries. In contrast to gases then, the mechanism at the micro level in liquids resembles the way force is produced by a spring pressing against the walls of its container. Ongoing build-up and break-down of clusters at the molecular level results in the motion of the structure wave, whereby each wavelength can be pictured as one turn of a spring. This means that the space occupied by one turn and the energy it carries are determined by the pressure pixel. Clusters are mesoscopic entities above the level of molecules, which are both particles and waves. They are the physical manifestation of the pressure pixel in liquids.

Let's examine the spring analogy a little deeper. When a metal spring is compressed, work is done on it which it stores by straining its chemical bonds. Then on release, this energy can be regained using the force exerted as the spring expands. In the case of liquids, the force exerted by the spring is a reactive force and disappears when the imposed force of compression is removed – liquids do not bounce back. Yet the turns of the spring do squeeze together, because in the wave-cluster model, the concentration of wave-clusters is given by the Gas Law

$$P = n\,kT \qquad 4.2$$

Or, the higher the pressure, the more turns of the spring and the smaller their size.

In this model we see that, as the imposed pressure is released, the cluster size and therefore the wavelength increases, becoming infinitely long as the pressure approaches zero. But here, the expanding spring does not perform work as the length of its turns increases, because the liquid body itself does not expand. So is energy stored in chemical bonds at the molecular level when a liquid goes under imposed pressure? And if the answer is yes, then where – and can it, like in a spring, be released later to do work?

According to Equation 4.7, work can be performed by a liquid body if it is first transferred from pressure P_1 to P_2

$$w = P_1 - P_2 \qquad 4.7$$

However, it was established that the original source of energy for this work was external, since it was obtained from the higher pressure, P_1, in the source reservoir. This energy was next stored in the liquid during the step BC of Figure 4.3 in readiness for the return stroke CD, during which a smaller amount was returned to the sink. So where was this energy of pressure stored?

In terms of the wave-cluster model, Equation 4.7 becomes

$$w = (n_1 - n_2)\, kT \qquad 5.1$$

which shows that the amount of energy converted into work is equivalent to the drop in cluster concentration between the source and sink. From the point of view of the spring analogy presented in this chapter, we now know that this energy is only temporarily stored in the liquid inside the machine, since the energetic difference between the compressed spring, P_1, and the relaxed spring, P_2, was located in the surroundings. Or explained another way: the energetic difference between the strong spring with n_1 turns and the weaker spring with n_2 turns is due to unspecified external conditions which are responsible for the different pressures imposed on the source and sink. Therefore work is not supplied by intrinsic forces operating within the liquid.

What about the case that interests us most, where the energetic difference has a purely osmotic origin when the sink reservoir, R, at the same pressure as the source is used? This question brings a new twist to the puzzle, since in this case the liquid itself, not the surroundings, must supply the work. And since the step BC is identical in the purely mechanical and purely osmotic cycles, the new question we must ask – in addition to the question of where, posed above – is: may we now therefore conclude that an equivalent amount of energy is converted into work in each cycle?

6. Mechanical or Structural ?

Clusters are held together momentarily by the intermolecular bonds which are responsible for structure. At zero pressure, there are no defined clusters and all the energy resides in these bonds. In this high energy state, the bonds can be pictured as existing at the point between making and breaking – the molecules are attracting each other, but their tumbling motion is just sufficient to prevent bond formation. As the pressure builds up, bonds start to form and clusters start to appear. This process releases energy, which is transferred to the macroscopic spring and is therefore now expressed as pressure. In fact, viewing the Gas Law, $P = nkT$, from the standpoint of the wave-cluster model, we can see the macro level pressure on the left-hand side equated to properties of individual clusters on the right. In this general form however, we do not see the differences between liquids we would expect from comparing them to springs. Because springs of different metals (or elastic materials) have different spring constants reflecting the individual nature of the metallic bond, it is probable that different liquids also possess individual elastic properties reflecting the chemistry of their bonds. However, this type of detail is peripheral to the central issues of this book, and is dealt with using the simplifying assumption that in any particular liquid the total concentration of possible intermolecular bonds, N, is independent of pressure.

The pressure can now be plotted in the form of Hooke's Law as seen in Figure 6.1 with kT in the role of the spring constant. The analogy can be extended a step further, for we can now calculate the mechanical energy appearing in response to the imposed pressure by following the same line of argument used to calculate the energy stored in a spring. Just as work is required to concentrate the turns of a spring, mechanical forces within the liquid must work against pressure as they introduce new clusters into the medium. The discussion comparing the responses between springs and liquids to imposed forces is continued in Appendix 6. In this picture, the work needed to squeeze clusters closer together as their population increases is found by integrating Fndn, where the spring constant, F, is proportional to kT

$$\text{stored spring energy} = Fn^2/2 \qquad 6.1$$

At the molecular level the picture is more complicated. As new clusters are created, they cause changes in the distribution in the strength of the bonds holding them together, for example, the number of broken bonds increases, because at the edges of fresh clusters there must be new discontinuities introduced into their internal tension. On the other hand, at their centres the bonds would be strongest. We can simplify this picture of a wide range of bond strengths by assuming that, on average, there remains an amount of energy, b, per bond out of a total amount available from the formation of each bond, B. Or viewed in a different way: at zero pressure, all the energy, NB, is structural and stored in the bonds which are on the point of forming, then at intermediate pressures, the structural energy released as they strengthen now appears as mechanical energy in the spring.

$$N(B - b) = Fn^2/2 \qquad 6.2$$

This equality is a form of the conservation of energy, since it states that the electronic energy of chemical bonds is converted into the energy of wave-clusters. This energy is the stored mechanical energy, which expresses itself as pressure at the boundaries delivered by the action of the spring. Since the energy term on the left-hand side, N(B-b), varies with b only, it arises from the forces exerted on the molecular level. The existence of such a force was argued from a different standpoint in discussing Equation 4.9, where it was concluded that osmotic equilibrium requires the action of the micro level tensile force, Q.

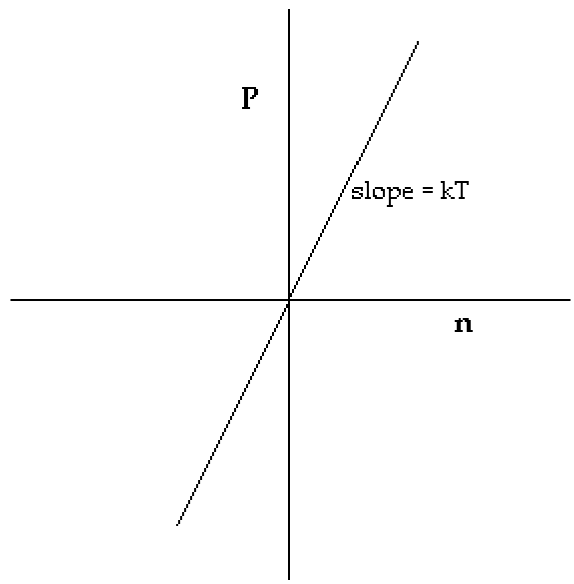


Figure 6.1 Pressure dependence on cluster concentration. Plot of the wave-cluster model according to the general relation, P = nkT, showing its extension into the negative regime. For a particular liquid its spring constant, F, depends on N and B as well as kT. For explanation based on the spring analogy see Appendix 1.

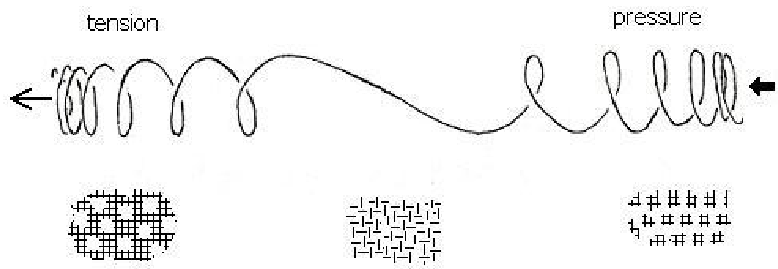
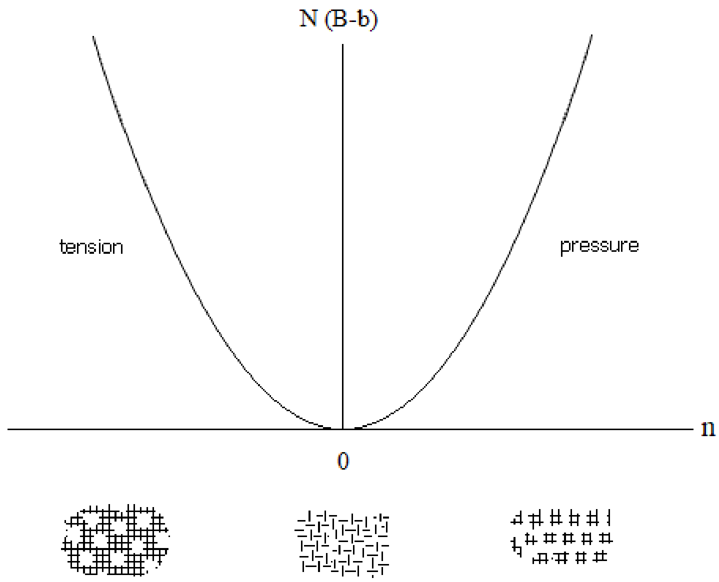


Figure 6.2 The liquid spring. This pictorial representation of the liquid spring illustrates that at larger pressures or tensions there is more force in the spring, in analogy to the response in a real metal spring when its coil is squeezed closer together. In the centre of the diagram the pressure is zero, so the liquid is depicted as a uniform medium in which its intermolecular bonds are on the verge of forming. Positive clusters of pressure are depicted on the right and negative anticlusters of tension on the left. In clusters, the molecules link together forming separate islands of interconnected molecules. In anticlusters, the molecules link together forming unbroken chains through the liquid containing islands of unconnected molecules.

thick arrow = pressure
thin arrow = tension



<u>Figure 6.3 Parabola of structures.</u> Integration of the plot of pressure shown in Figure 6.1 gives energy stored in the liquid spring, in analogy to the integration of Hooke's Law giving spring energy as a function of extension. Since liquids are incompressible, this energy is not supplied by the external imposed force, but by the molecular bonds that link together to form the clusters on the right, and the anticlusters on the left.

At the same time as the clusters are increasing in number, they are decreasing in size. They reach their maximum concentration at the highest pressure where wave motion becomes impossible at the point of phase transition to a solid. At this pressure they consist of just one or two molecules each, and all the energy, NB, is mechanical, that is $b = 0$ and so

$$NB = Fn^2/2 = nkT = P_{max} \qquad 6.3$$

giving

$$B = (n/N)kT \qquad 6.4$$

The value of B, the maximum energy a bond can hold, is germane to the subject of liquids, since their very existence derives from the on-going making-breaking cycle of their bonds fuelled by the opposing influences of attractive chemical forces on the one hand, and thermal motion on the other. This implies that B is of the same order as the thermal energy, kT. Since n in Equations 6.3 and 6.4 has reached its maximum value, the ratio, n/N, is expected to be close to unity, having risen from the infinitesimal value of 0/N as the pressure rose from zero to the maximum possible for the liquid state. In other words, this analytical development based on the argument that a liquid behaves analogously to a compressed spring, leads to the expected conclusion that the bond energies characteristic of liquids are similar in value to the thermal energy supplied by their environment. Or put in different terms: there is only a limited range of temperature which gives rise to the liquid state, and it is found when values of kT lie near the value of B.

Equation 6.2 does not throw any light on the arrangements adopted by bonds as they form. A detailed description including pictorial representation of the molecular patterns resulting from the co-operative linking processes at work can be found in TLP Chapter 10, "Pixel and Antipixel", and is illustrated again here as a spring in Figure 6.2. In the positive pressure regime, bonds group together so as to build separate clusters, whereas under tension they extend an interconnected network throughout the medium, in which the negative unconnected regions become the anticlusters. The energy associated with these structures shown in Figure 6.3 is a symmetrical parabolic function in relation to their concentrations. Therefore in both directions along the n-axis there is the same micro-to-macro hierarchical transfer from structural to mechanical – in both directions energy is moved upwards.

7. Hard and Soft Clusters

In 1987, I proposed that osmotic equilibrium between two solutions obtains under those conditions where the frequency, f, of clusters crossing the membrane from each side, and the quantum of energy, kT, carried by each cluster are equal (8).

$$f = n_1 v_1 = n_2 v_2 \qquad 7.1$$

and

$$kT = M_1 v_1 = M_2 v_2 \qquad 7.2$$

where v and M represent velocity of and momentum carried by the structure wave. These conditions mean that the net energy flux across the boundary is zero. Here again, strong analogy with the Kinetic Theory is obvious. Equation 7.1 can be interpreted in terms of velocities of two different types of gas molecules with that of the more concentrated one travelling at the slower speed to give the same striking rate on the boundary. Likewise, those molecules with higher speed will have lower momentum to keep the kinetic energy of the two gases equal. Combining the equations shows that the energy flux through each gas must also be equal.

$$P_1 v_1 = P_2 v_2 = f\,kT \qquad 7.3$$

But this analogous picture is purely imaginary. The molecules of different gases cannot cross the boundary and mix into each other while maintaining the equilibrium, because they cannot change their velocities or momenta. However returning to the case of the two solutions in contact, we see the equations are applicable, since the flexibility of wave motion permits clusters to adjust their parameters.

Equation 7.3 applies to two distinct liquid bodies. It describes how mechanical energy flows between them. We can extend it to a series of solutions in contact, or with some imagination, even to a continuous medium containing regions of varying pressures. Put succinctly, the energy flux, A, through a liquid medium, which is in a state of osmotic equilibrium throughout, is constant

$$P\,v = A \qquad 7.4$$

Furthermore, as $A = f\,kT$, the flux of clusters themselves, f, through the medium is then also independent of pressure since each is carrying the same energy quantum, kT. Figure 7.1 shows how the variables introduced with the wave-cluster model, u, v and M, depend on P in the new expanded expression $Pu = kT = Mv$.

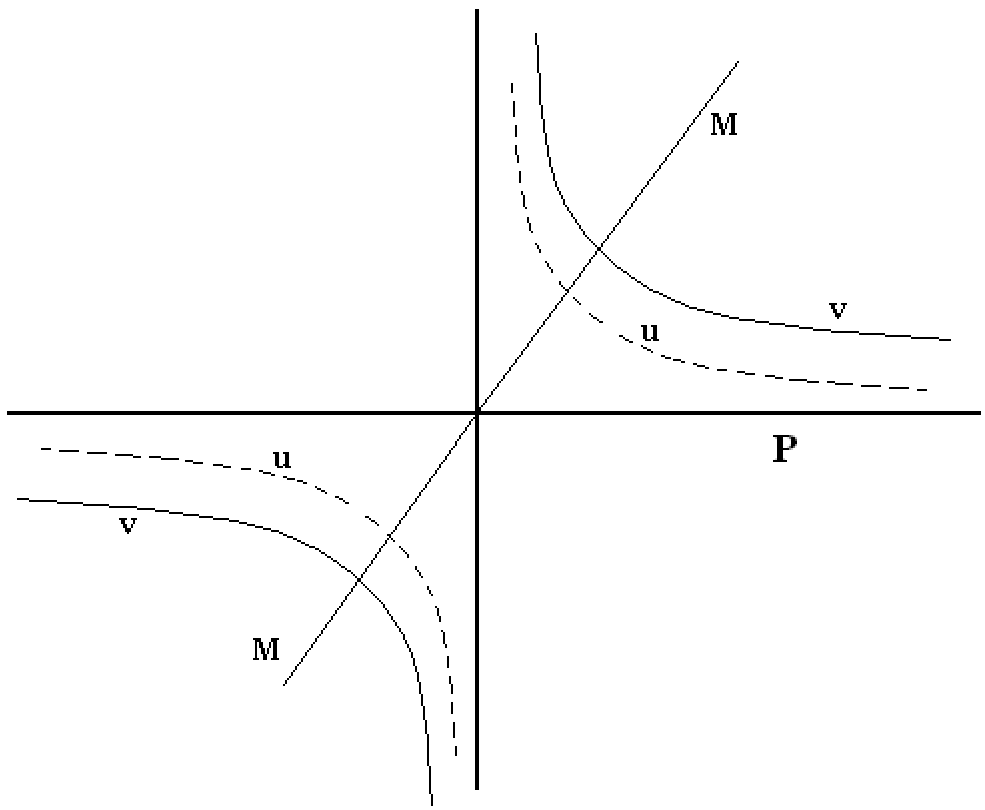


Figure 7.1 M, v and u dependence on pressure. The new statement of the wave-cluster model, Pu = Mv, introduces the variables, M and v, for cluster momentum and velocity. For solutions in osmotic equilibrium, both f and kT are constant and therefore M is linear with respect to P (slope 1/f) while v and u are linear with respect to 1/P (slopes A=fkT and kT respectively).

An intriguing feature that emerges from the model is that cluster momentum increases as cluster size decreases. It is naturally expected that momentum should increase with pressure, and this notion is in line with the extended definition of pressure in the wave-cluster model

$$P = nkT = n M v = f M \qquad 7.5$$

On the other hand, the basic tenet of the model expressed in Equations 4.2 and 4.3 is that the cluster occupies the space of the pressure pixel, u, which decreases with pressure. Unlike the case of a gas molecule, the mass of a cluster as measured by the number of molecules it contains does not determine its momentum, rather it is its number of bonds, N/n, their formation rate and their average energy, b, which do. These parameters adjust to accommodate a value of M which is determined by v and kT, and not by its physical size.

When a wave is reflected off a wall, momentum is transferred by a different mechanism to that operating when hard elastic objects of constant mass strike a wall. Indeed, when anticlusters are reflected, the wall tends to move into the advancing wave and so appears to be pulled rather than pushed by the impact – a behaviour impossible for gases. In the wave-cluster model, pressure is not to be seen as the result of collisions of elastic particles – rather pressure is produced by the rearrangement of the bonds forming the cluster as the wave passes a particular location. Impacts are more forceful between clusters held together by stronger bonds, since more energy is required to break them during the rearrangement. These are the hard clusters. Their bonds are tight since b is low. Indeed, the hardest clusters are the smallest. As we saw in the previous chapter, at maximum pressure all the energy associated with structure, NB, is converted into high-level mechanical energy, NkT. On the other hand, soft clusters are composed of high energy, weak bonds. In the extreme case of zero pressure, there are no defined structures at all. The whole medium is uniform throughout, being on the verge of becoming a single large cluster, or anticluster, and because it is not connected together, it possesses no momentum. The spring analogy is used again here in Figure 7.2 to give a pictorial representation of this concept. It illustrates the intriguing idea that a liquid is a continuous medium in which there may be neighboring regions in different mechanical states, yet which is nevertheless in equilibrium throughout.

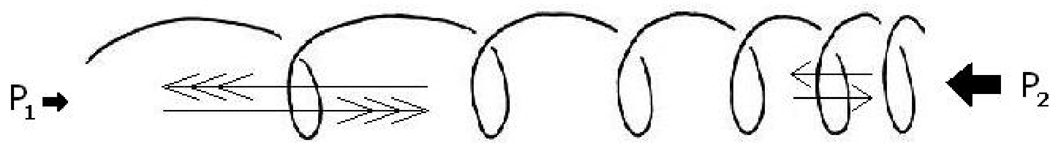


Figure 7.2 Wave velocity and the liquid spring. Pictorial representation of the relation Pv = A. For solutions in osmotic equilibrium, the energy flux through them is the same. The diagram corresponds to a series of solutions in the pressure range from low P_1 on the left to high P_2 on the right (thick arrows). It shows cluster size (wavelength) and the velocity (thin arrow heads) increasing as the pressure decreases to the left. In the classical osmotic plot shown in Figure 4.1, this direction corresponds to solutions of decreasing solute concentration towards the origin on the z-axis.

8. Uncoupling M and v

In the wave-cluster model introduced in the previous chapter, pressure is given by Equation 7.5

$$P = n\,kT = n\,M\,v = f\,M \qquad 7.5$$

This expression is symmetrical with respect to the variables n and M, whereby n carries information about collisions at the macro level and M about bond interactions at the micro level. It applies to all solutions, not only those in osmotic equilibrium that we discussed above.

For example, when a little salt is dissolved in water under normal circumstances, the pressure of one atmosphere does not change. Osmotic pressure then develops in a second step after the solution is put in contact with a reservoir of the solvent, in this case water, through a semipermeable membrane. There are energetic changes on the first step, however – sometimes quite large. The topic of this book concerns only the water-to-water interactions and unfortunately these are too often masked by those larger water-to-solute interactions, which ensue when the solute molecules enter the aqueous environment.

It has been known for more than 100 years that remarkably similar changes occur in solutions, known as the colligative properties. For example, the behaviour of the osmotic and vapour pressures does not depend on the chemical nature of the components of solutions, but only on their concentrations. Thermodynamicists attribute this behaviour to changes in entropic and not energetic factors – or as the journal Chemical Physics Letters told me, to "counting" (see "Background").

It is indeed surprising that the molecular properties of the solutes, such as charged or uncharged, large or small, round or extended, are not involved in colligative behavior. How is it possible that the solvent-to-solvent interactions are separated from the solvent-to-solute interactions in some phenomena, such as osmosis, but not in others, such as release of heat which is quite variable from solution to solution? Or looked at in a different light we might ask: what is it that is common to all solutions, whether they be made of different solutes and even different solvents?

The propagation of the structure wave is possible because of the co-operativity that governs bond formation. The co-operative build-up and break-down of bonds gives rise to moving patterns made of grouped molecules. The introduction of a foreign molecule into the pure population causes disruption to the wave motion, because it redirects the co-operative influences and so interferes with the ability of the patterns to be repeated. Solvent-to-solvent bonds in the immediate vicinity of the foreign molecule can no longer orientate themselves in the optimum directions for the bond-to-bond communication that underpins co-operativity. The reach of its influence is diminished, so the wavelength becomes shorter and clusters smaller.

The structure wave is a form of dynamic tessellation. Readers can find a realistic picture of how this process occurs in Chaplin's models of the formations of molecular networks in water (9). In any pure solvent, the molecules are the identical pieces in the jig-saw, which fit together and make the higher-order pattern. However, in the liquid state there is too much tumbling motion to allow the pattern to spread to the macroscopic extent found in the crystal. On the other hand, co-operativity is still at work and ensures the emergence of long-range, short-lived patterns. With this picture in mind, it can be seen how the introduction of solute molecules disrupt liquid structure, just as introducing a misfitting piece destroys a tessellating pattern. In the extreme picture of a material composed entirely of differently shaped molecules, there would be no higher-order repeatable pattern and hence no structure wave – and of course, no liquid.

Therefore, when a solution forms, there are alterations to the pre-existing patterns created by the solvent-to-solvent bonds. For a stable solution to result, the solvent structure must be able to accommodate these alterations – a condition that is in addition to the solvent-to-solute interactions which, as mentioned above, may be much stronger, especially in the cases of charged ions. The inability of a structure wave to propagate would then explain the lack of solubility of many salts, even though the local water-ion interactions may be favorable, and hence good solubility expected. The energies involved in the structure wave must connect with the macro level, since it transmits pressure. This puts a top-down requirement on the ability of molecules to mix together originating from the higher level, in addition to the neighbour-to-neighbour interactions usually thought to be the only factor responsible for solubility. Put more succinctly, the simultaneous presence of some ions in water produces orientations in the water-to-water bonds that are too irregular to allow repeated tessellating patterns to emerge. In such cases, the dominating influence of the wave propagation prevents the disruptive foreign molecules from entering the liquid medium.

Restricted solvent-to-solvent interactions and smaller clusters in the solutions imply lower wave velocity. On the other hand, because the pressure remains constant, there is no increase in the mechanical energy residing in the spring. Therefore, during the step of making a simple solution, energy must leave the system as the velocity drops, rather than be transferred to the spring. Then, in the second step when the solution is subsequently put in contact with the solvent, the solution spontaneously develops its osmotic pressure. We can summarise the two steps in the following scheme:

$$\begin{array}{ccccc} P_1 & & P_1 & & P_2 \\ n_1\ M_1\ v_1 & \longrightarrow & n_2\ M_1\ v_2 & \longrightarrow & n_2\ M_2\ v_2 \\ (f, kT) & \downarrow & (f, k'T) & & (f, kT) \\ & E & & & \end{array} \qquad 8.1$$

Energy is shown leaving the system in the first step as the solution is made, lowering the energy quantum, kT, while the frequency, f, remains unchanged. Cluster momentum, M_1, is also unchanged because both the frequency and imposed pressure, P_1, did not change. However now the clusters are smaller, and so have hardened to maintain their level of momentum, releasing E as they do so. In the second step, they lose more energy in increasing their momentum to M_2 while retaining their size, but this time it is transferred to the spring on the macro level. Energy now remains within as the pressure rises. As we learnt earlier in Chapter 6, in this step energy is moved upwards.

The proposal that the wave velocity can change independently of momentum implies variability in value of Boltzmann's Constant. The interpretation I put forward earlier (13), that a drop in Boltzmann's Constant reflects a weakening of the spring constant, is supported here. In the first step, the number of clusters increases while there is no change in the pressure they exert. From the analogy with a metal spring described in Chapter 6, "Mechanical or Structural?", we would conclude that, also there, an increased number of turns per unit length, n, is accompanied by a decreased spring constant, if there is no change in the force it exerts. Even stronger support is offered by the colligative property of reduced vapour pressure. The well known experimental fact that a solution produces a lower pressure under its own steam, so to speak, than does the pure solvent, is in line with an interpretation based on weakening of its spring strength by the foreign solute.

We must also consider the possibility that the system follows the alternative route to equilibrium

$$
\begin{array}{ccccc}
P_1 & & P_1 & & P_2 \\
n_1\, M_1\, v_1 & \longrightarrow & n_1\, M_2\, v_2 & \longrightarrow & n_2\, M_2\, v_2 \\
(f,\, kT) & \downarrow & (f\,',\, kT) & & (f,\, kT) \\
 & E & & &
\end{array}
\qquad 8.2
$$

This time it is kT which remains constant while the frequency, f, changes – again as with kT above, first down then up. Energy, E, is again lost from the system in the first step, because the clusters harden, increasing their momentum to M_2 while remaining the same size.

Experimental evidence suggests to me that solutions follow variable paths to equilibrium lying between these two extremes. When water is left to stand undisturbed for long periods of time, it adopts thixotropic behavior (11). I believe this indicates that the physical state of this liquid is indeterminate. Clusters grow in size spontaneously such that large regions, even macroscopic in dimension, become solid. This behavior is dramatically enhanced by the presence of proteins and hydrophilic polymers like DNA. Biochemists know well that experimental systems must be stirred to make sure that homogenous mixing is maintained, in order that their reagents reach all regions and that random collisions needed for their reactions are not obstructed by non-fluid barriers. So in the usual interpretation, agitation ensures that diffusion of reagents is efficient – and this is true. From a structural point of view on the other hand, agitation ensures that pressure continues to be transmitted top-down without interruption to the size of the pressure pixel, so that cluster movement continues to be felt throughout the medium.

In both pathways, Equations 8.1 and 8.2, a given amount of solution is moved upward to higher pressure along the osmotic spring of Figure 8.1 (to the left) in two steps. In both, energy E is released during the first step under undefined conditions, that is, whether M and v, or n and v are uncoupled. This means in turn, that in the overall dissolution process, structural energy stored in b is released in two steps – in the first it is lost, and in the second it is moved into the spring to be expressed on the macro level as P_2. So now it becomes clear that, if this process is carried out in such a way that the solvent passes through a machine executing a cycle, then E could be captured and converted into work, while in a second step the resulting solution is returned to a state of equilibrium with the solvent.

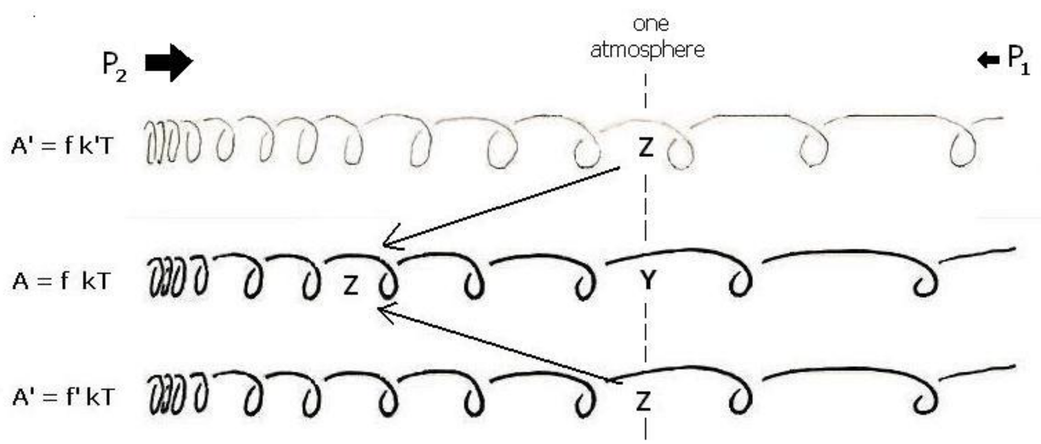


Figure 9.1 Energies of solution. Schematic spring representation of three different osmotic states of solvents and solutions all within the same pressure range from low P_1 to high P_2. A number of molecules of a solute, Z, are first added to pure solvent at intermediate pressure, Y, say one atmosphere, to form solutions at the same pressure. The general effect of the presence of solute molecules is to reduce the velocity of the structure wave. The solution so formed is now in an indeterminate state between the two extremes, whereby either the wavelength is shortened thus squeezing the spring (upper panel), or the frequency is lowered (lower panel). In both these extreme states, there is a decreased energy flux through the medium, $A' < A$. When either solution is next put in osmotic contact with the pure solvent at Y, bond energy is transferred to the mechanical level of the spring increasing its pressure, so that its energy flux is again A, or as depicted in this diagram, it returns to the spring of the solvent (middle panel) but is now located at the new position at higher pressure to the left of Y. This new state corresponds to solutions moving to the left up the isotherms discussed in Chapter 4, “The Osmotic Machine”, see for example Figure 4.2.

9. The Osmotic Machine Returns

The operation of the machine shown in Figures 4.3 and 4.4 is here redrawn as the rectangle ABCD in Figure 10.1. This time, the large volumes at the asymptote of the isotherm are not required for the illustration, since the machine contains pure solvent only (that is, $z = 0$) and so does not change its internal pressure with changes in volume. From the cluster model we already have the expression for the work delivered by its cycle

$$w = (n_1 - n_2)\,kT \qquad 5.1$$

where n_1 and n_2 are the cluster concentrations in source at pressure P_1, and sink at pressure P_2. We recall that, if these reservoirs are themselves also composed of the pure solvent, then w is equivalent to a mechanical change that exists in the environment. However, if the second reservoir is R in Figure 4.4, then w arises from osmotic forces and the task still ahead is to identify the underlying source that supplies the energy represented by the change $(n_1 - n_2)$. Cluster concentration is a macroscopic parameter, and so relationships like Equations 5.1 involving changes in n alone do not reveal changes in molecular bonding. However, with help of arguments that we now have from Chapter 7, the work can also be written

$$w = P_1 - P_2 = (M_S f_1 - M_2 f_2) \qquad 9.1$$

where M_S is the value of the cluster momentum in the solvent source on the upper isotherm where the energy flux is f_1kT, and M_2 its value inside the machine after being set in equilibrium on the lower isotherm with flux f_2kT. Since the source and sink reservoirs are at the same pressure P_1, we have $M_S f_1 = M_R f_2$ giving

$$w = (M_R - M_2)\,f_2 \qquad 9.2$$

During the return stroke CD, the softer, larger clusters with momentum M_2 inside the machine cylinder at low pressure are transferred to the sink increasing their momentum to M_R. Consequently the clusters become harder, since they are now held together by tighter bonds. In other words, micro-level energy is released in the transfer, and it is this energy which is available for work. This action manifests itself through the higher tension in the hard clusters in R outside the cylinder pulling on those inside and keeping the internal pressure low.

Because this relationship involves a change in cluster momentum rather than concentration, it turns the focus onto the micro level. With this step we have at last answered the central question posed in Chapter 5 – it is the structural energy stored in bonds which is directly converted into work in the purely osmotic cycle. This conclusion contradicts categorically the century-old explanation based on Free Energy, which continues to be taught in thermodynamic text books (see "Background").

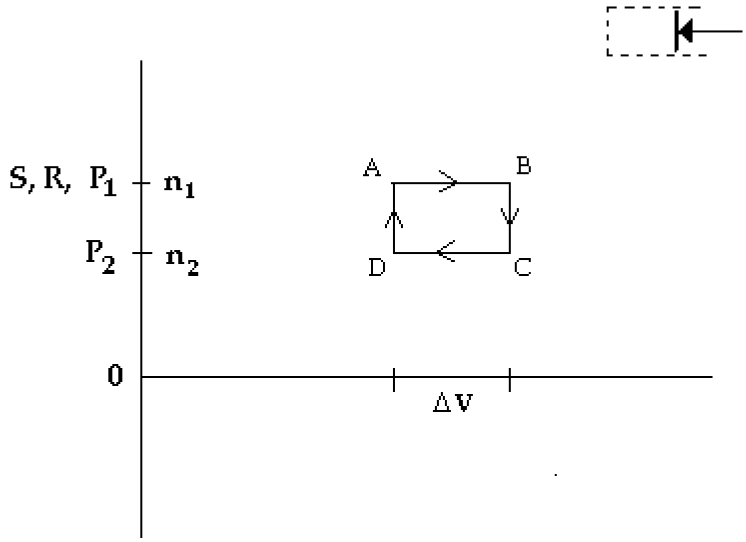


Figure 9.1 Clusters appear. The work cycle ABCD is the same as EFGH shown in Figure 4.4. The machine contains solvent only (so the curved section of the isotherm can be omitted), and expands during the step AB, while in contact with a pure solvent source at $P_1 = n_1kT = M_Sf_1$ (that is, the liquid that enters the cylinder is identical to the liquid already inside). Pressure on the piston is released to $P_2 = n_2kT = M_2f_2$ for the return stroke CD. This step is carried out in contact either with the pure solvent at P_2 in the case of the purely mechanical cycle, or with a solution at P_1 in the reservoir R, in the case of the purely osmotic cycle where the cluster concentration of the expelled volume of solvent, ΔV, returns to the higher starting value, n_1. This is the cluster concentration in the sink reservoir at $P_1 = n_1kT = M_Rf_2 = M_Sf_1$, marked R on the lower isotherm in Figure 4.4, "Osmotic or Mechanical".

thick arrow = pressure

10. Reversing Entropy

During the operation of the osmotic machine depicted in Figure 9.1, (n_1-n_2) quanta of energy kT are collected and transformed by its up-out action into a single energy package on the macro level. In the cycle overall however, there is no change in the number of quanta because the concentration of clusters in both source and sink reservoirs is n_1. During the step BC when pressure is released, energy is moved downwards into structure at the molecular level to be then converted into work in the transfer step CD. By comparison, in the purely mechanical cycle discussed at the outset in Figures 4.1 and 4.2, this downwards relocated energy is not used – in that case instead, the environmental pressures supply the work.

When the machine operates inefficiently, then the area of the cycle is smaller than $w\,\Delta V$. Recalling Clausius' insight illustrated in Figure 3.4, we know that under such circumstances either the number of clusters entering from the source reservoir, x_1, is too small, or x_2 returned to reservoir R is too large, or both.

$$x_1 < n_1\,\Delta V \qquad 10.1$$

$$x_2 > n_1\,\Delta V \qquad 10.2$$

and there is therefore an overall gain in the number of clusters in the two reservoirs since

$$(x_2 - x_1) > 0 \qquad 10.3$$

In fact we know from Chapter 8, that if a volume of solvent, ΔV, dissolves solute, there is an energy loss accompanied by an increase in cluster concentration in the solution over that in the original solvent. In that case no work was done, so all the energy lost, E in Equation 8.1, contributed to the entropy increase. However in the osmotic machine, the process of dissolution is carried out by moving solvent from a source reservoir to a sink while at the same time performing work, and then the additional number of pixels appearing in the environment is reduced. When the work delivered amounts to the maximum possible, $w\Delta V$, there are no additional pixels produced, since then $(x_2-x_1) = 0$. This conclusion is in line with the statistical interpretation of the increase in entropy as being the fragmentation of lost energy due to irreversible changes in the environment.

When the machine operates with its up-in action at negative pressures as illustrated now in Figure 10.1, the opposite numerical result is obtained. For an inefficient cycle, we have again the inequalities

$$x_3 < n_3\,\Delta V \qquad 10.4$$

$$x_4 > n_3\,\Delta V \qquad 10.5$$

$$(x_4 - x_3) > 0 \qquad 10.6$$

Here the concentrations are negative, because the structures are anticlusters. But (x_4-x_3) is again a positive quantity, and so this time there must be an overall decrease in the number of antipixels in the reservoirs.

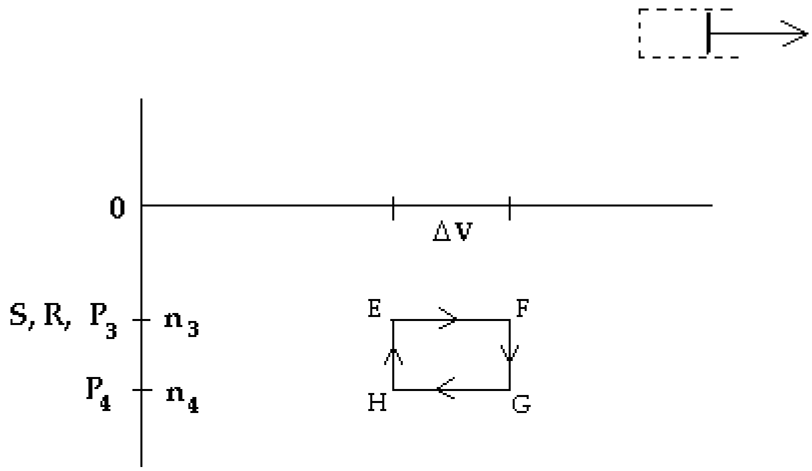


Figure 10.1 Entropy disappears. When the machine operates in the negative pressure regime, the cycle EFGH is obtained in which the expansion step, EF, is carried out in contact with the pure solvent at $P_3 = n_3kT = M_Sf_3 = M_Rf_4$, and the return stroke GH is now the power stroke carried out in contact with the solution reservoir also at P_3, but at the stronger tension $P_4 = n_4kT = M_4f_4$, pulling on the piston from inside the cylinder yielding work $w = (n_3 - n_4)kT = (M_R - M_4)f_4$. This outward flow into reservoir R, against the inward pull P_4, reminds us of the Demon's inverted trick illustrated in TLP Chapter 11, "Cluster as Demon".

thin arrow = tension

This result runs counter to the statistical interpretation of entropy. It tells us that energy is downgraded because quanta fuse together. This result would be no surprise to people working in fields of the information sciences, however. During copying processes, information is lost equally whether bits fracture apart or fuse together. Or again, a typewriter that prints letters on top of one another fails in its function – and likewise, should only a small fraction of the letters that make up the words on this page melt into one another, the text would convey nothing, even though the page would still contain 200 separate patches of ink appearing as words. The poets and antipoets of Chapter 3 have now become technical realities, and the work cycle of the imaginary piston fish introduced early in TLP has now a valid basis.

Clausius and Boltzmann lived in an expanding world (in more ways than one). They were interested in the machines of the industrial age – the age of heat and pressure. There, energy is irrevocably lost as it breaks up and spreads into the environment. In a contracting world of tension on the other hand, energies coalesce through fusing together and concentrating in space. Here, entropy goes in the reverse direction. As we learnt in TLP, biological systems live in both worlds. They rely on processes that store energy and so prevent its dissipation caused by the outward march of entropy. Yet they also rely on processes of division, reproduction and colonisation that spread energy outwards and so prevent its disappearance into a shrinking volume. Biological machinery reveals the double arrow of entropy's drive – to increase and to decrease.

11. The Generalised Isotherm

Returning to the original statement of the cluster model

$$P = n\,kT \qquad 4.2$$

we can now write it in the expanded form

$$P = (z + y)\,kT \qquad 11.1$$

Then identifying

$$P_0 = y\,kT \qquad 11.2$$

as the imposed pressure on the solvent reservoir, we have again van't Hoff's equation

$$P = z\,kT + P_0 \qquad 4.1$$

It has been known for more than 100 years that z can be identified with the concentration of solute molecules, yet despite a detailed theory of phenomena that occur at the event horizon of black holes, we lack an explanation of this simple system still today. The wave-cluster model presented here in Chapter 7 accounts for the increase in clusters in solutions, z, over that in the pure solvent, y, as due to a decrease in wave velocity, producing a more concentrated cluster population. Yet here too, a logical connection between wave velocity and solute concentration is still lacking. We need to establish that localised disruption to the spreading motion of patterns by a misfitting piece diminishes their range without slowing their frequency. The qualitative picture I offered in 1987 (8), that foreign molecules produce nodes, does not answer this question, and so I do not claim that the wave-cluster model has solved the puzzle of osmosis in all its aspects. It solves the counterintuitive nature of the forces at work – but not the letter of van't Hoff's Law.

An attractive possibility is that the wave velocity becomes well defined only after contact with another solution. The structural state of solutions left to stand undisturbed in isolation is indeterminant, so that contact with the second solution could then act as a stimulus forcing structural regularity as osmotic equilibrium between the two is set up. In the contact region, the frequencies, $f = nv$, must become equal, that is, n and v must vary inversely from solution to solution. For example, the velocity in a solution of solute concentration, z, must be reduced compared to that in the pure solvent by the same fraction, z/y, as the cluster concentration has been increased. Such a mechanism would mean there is a causal link between the sizes of molecular networks and the transmission of information, which operates via the drive to keep the energy flux, A, constant. In this picture, it is the influences arriving from neighboring systems that determines cluster dynamics in a mutual way.

In normal usage of van't Hoff's equation written $\Pi = cRT$, the ambient atmospheric pressure, P_0, is not considered to be a variable, since it is the pressure in excess of atmospheric, $\Pi = (P-P_0)$, which is of interest. In expressing the law this way, the variables y and kT in Equation 11.2 remain hidden. However in the wave-cluster model, each of y, k and T can vary independently of the others. A more general cycle of the osmotic machine is illustrated in Figure 11.1, which delivers work

$$W = Z\,(kT - k'T')\ln(V_2/V_1) + (P_1 - P_2)(V_2 - V_1)$$

$$= Z\,(kT - k'T')\ln(V_2/V_1) + (y_1\,kT - y_2\,k'T')(V_2 - V_1) \qquad 11.3$$

This cycle now resembles the usual Carnot cycle, because of variation in kT, which results in a non-zero contribution to the area by the first term zkT. According to the wave-cluster model, this term arises from the drop in wave velocity due to the solutes and leads to positive work if M and v are uncoupled even though T may be constant. If kT remains constant around the cycle, then this term is zero and work can only be obtained from chemical bond differences (osmotic), or pressure differences (mechanical) in the reservoirs. These sources give rise to the second term, $(P_1-P_2)(V_2-V_1)$, and it is the analysis of this term that has been the subject matter of the previous chapters of this book, because it provides us with a clear-cut illustration of the osmotic mechanism.

In Carnot's original cycle, the contribution of this second term is zero, because the asymptotic value of P at large V is taken as zero. Also in that cycle however, there is a finite pressure given by the radiation pressure corresponding to the temperature of the surrounding heat source, which is still present even when the gas molecules have been infinitely diluted. Under those conditions we must consider that a source of infra red photons with an energy flux similar to that of a pressurised gas would exert only a negligible pressure compared to gases, being an order of a million times lower according to Equation 7.4, since gas molecules travel a million times slower than infra red radiation. Put another way: a radiation source exerting a pressure of the order of 1 Pa is needed to heat the gases in the cylinders of a car engine, if these gases are to reach pressures in the range of 1 MPa, that will effectively move the vehicle.

Even though its pressure may be insignificantly small, it is the intensity of the background radiation that determines which gases lie on a particular isotherm, since this quantity is the energy flux, A.

$$A = P_0c = ykTc \qquad 11.4$$

For a gas of molecules with mass, m, at equilibrium with a steady heat source at temperature, T, we have

$$mv^2 = kT = m_0c^2 \qquad 11.5$$

where m_0 is the mass equivalent of a quantum of radiation and c is the speed of light. Then since this gives

$$m = (c^2/v^2)\, m_0 = (n^2/y^2)\, m_0 \qquad 11.6$$

which tells us that the quantity (n^2/y^2) is the number of photons compressed into a molecule of mass m, or in energy terms, the number of kT units packaged into mc^2. So for heavier gases we must move further up the isotherm (to the left) and their concentrations must also increase to keep the frequencies equal, thus maintaining their "osmotic equilibrium".

To paint a simple picture of the model: we imagine a cylinder of vast size in which the vacuum inside is in equilibrium with a radiation source (of intensity A). Initially, particles appear with inertial mass (m) given by Equation 11.5. As compression proceeds, these particles absorb more and more radiation, in turn increasing their momentum and eventually forming atoms. As a result, increasing amounts of energy supplied by the source of background radiation become trapped inside the cylinder in the form of heavier molecules. In the case of liquids on the other hand, we found that this energy is already present internally and becomes expressed as pressure as clusters harden and increase their momentum. But in both cases, energy is transferred from the nano level by being caught in the particles that make up the spring on the macro level.

This analysis reveals a further similarity that photons share with clusters. According to Planck's relation, traditionally written, $E = h\nu$, showing that the energy of a single quantum is proportional to frequency, its momentum is inversely proportional to wavelength since the relation can also be written

$$M\lambda = h \qquad 11.7$$

where λ is the photon wavelength. Expressed in simple terms, this tells us that smaller quanta have higher momentum than large ones.

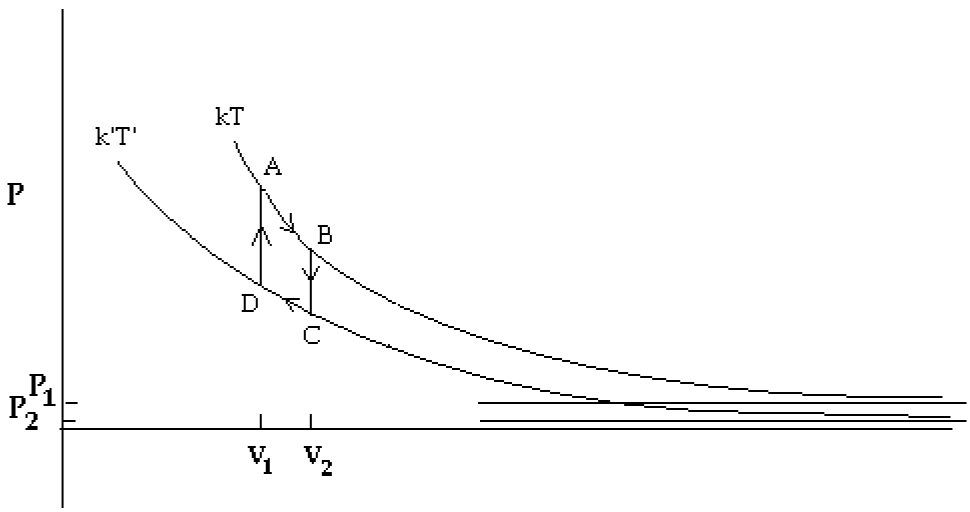


Figure 11.1 The generalized machine cycle. All the work cycles performed at positive pressures presented in the previous chapters are particular examples of the general cycle, ABCD, shown here. When the pressures of the source and sink, P_1 and P_2, are negligibly small compared to the pressure regime in which the machine is operating, then the cycle is equivalent to Carnot's heat machine for a gas operating between temperatures, T and T'. In that case however, there is also in principle a contribution to the work given by the area of the rectangular cycle obtained at large volumes, which arises from the black-body radiation corresponding to these temperatures.

This conclusion lends support to the counterintuitive concept that emerged in Chapter 7, “Hard and Soft Clusters”, that is, that smaller clusters possess higher momentum. In Planck’s relation, wavelength and momentum also vary inversely. I do not know today’s orthodox explanation of this property of quantum size, but if the analogy with the cluster model holds, where bond strength inside the cluster is the decisive factor, then a parallel interpretation would invoke a strengthening in the coherence of the vacuum as wavelengths shorten. Readers who are interested in this interpretation can find more detail in Appendix 2, “Photons and Pixels”.

With a background radiation pressure suggested above of 1 Pa exerted by quanta of 10^{-20} J (corresponding to a temperature of about 400 Celcius) the equilibrium pressure of carbon dioxide (molar mass = 44 Da) would be of the order of 1 MPa, or 10 atmospheres, while that for hydrogen (molar mass = 2 Da) would be just 2 atmospheres. Or considered from a different perspective, for a body of hydrogen to be also at the pressure of 10 atmospheres, it needs to lie on a high isotherm in equilibrium with more intense radiation exerting a pressure of approximately 5 Pa.

We conclude then, that van’t Hoff’s equation is a special case of an extended form of an expression which has its roots in Boyle’s Law. But as I’ve often mentioned in these two books, Equation 4.1 has been applied for more than a century without an understanding of the osmotic mechanism it describes, and as a consequence of this failure it has been sidelined to obscure avenues of biological research ignored by the physical sciences. Yet in its general form, Equation 11.1 describes the behaviour not only of liquids, but of radiation and gases as well.

12. The Muscle Machine

The osmotic machine of the previous chapters is a classical piston machine. In its basic version, it is an up-out-push device that collects energy from water and integrates it into a single macro quantum of energy represented by one outward thrust of the piston. Although cells use pressure for tasks such as moving their cytoplasm around, they do not, of course, contain such anthropomorphic apparatus. However its twin version, the up-in-pull machine, is familiar to everyone – the muscle. Muscle contraction pervades the entire animal kingdom, and as far as I know, there is not a single muscle that actively extends. Again it is not the anthropomorphic piston-in-a-cylinder device, but nevertheless the mechanical units of muscle cells do collect energy from molecular stores and convert it into macro-level work. It is instructive to compare these two machines – nature's and ours.

In man-made devices based on piston action, molecular energies of hot gases are collected by the restriction imposed by the walls of the cylinder, which prevent expansion sideways. Sideways collisions of the molecules with the walls of the cylinder are very wasteful in general, because they transfer energy to the material of the cylinder keeping it hot. The heat that enters the machine during the power stroke would, in an efficient machine, all be used to push the piston – not to keep the surroundings hot.

In an improved design, all the molecular springs could be fixed in position end-to-end forming an array of micropistons in parallel alignment with the direction of the piston stroke. This would prevent energy leaking out of the system sideways. In the muscle cell, the basic contractile units are organised precisely in this way as shown schematically in Figure 12.1. Each of these units is a micro-level "cylinder" called the sarcomer, and biologists know its internal structure in fine detail.

You could say that the sarcomer rightly deserves the name "micromachine", being just a few micrometers in size. A cell from the type of muscle familiar to most of us is a long thin tube, say a few centimetres long but less than one millimetre across. In this cell, there are about one million sarcomers, all aligned head-to-tail so that their pulling action is lengthwise along the cell. When all these sarcomers contract together, the cell shortens, and since tension, not pressure, is the driving force of contraction, their inward movement toward one another must be the power stroke. With a piston on both ends of each piston shaft, it can be seen how a microscopic contraction of each machine would lead to a shortening of the assembly overall. This massive battery of tiny contractile units is the basis of mobility across the whole animal kingdom.

Extending the analogy a little further, we imagine that each tiny machine contracts like the osmotic machine cycling under tension in the negative regime represented in Figure 10.1. Inside that macro-sized machine, energy was stored in the anticlusters of the pure solvent. During the return stroke, GH, P_4 was negative and Q_4 positive, that is, energy on the scale smaller than the pixel size was stored in molecular motion. Work was delivered as this macro-sized piston was pulled by the tension inside, P_4, while water was expelled through the membrane walls by micro-level pressure, Q_4, pushing the molecules out from within – another example of the Demon's inverted trick.

In Figure 12.2, we next take a look at a more realistic picture of nature's machine than our fanciful muscle composed of a battery of micropistons – there are no pistons in the sarcomer, and nature's cylinders are not surrounded by a membrane as is the osmotic machine. There is no need for containment, because the clusters are held in position by a parallel array of hundreds of rod-shaped protein structures, called the thick and thin filaments, which are packed into every sarcomer. This internal organisation is a lower-level spatial order than the grid of pistons depicted in Figure 12.1 – we are now down at the molecular level. Then, spaced at regular intervals throughout this deeper grid are the proteins which can release the energy previously stored in the cell's fuel molecule, ATP. Because they project outwards from the thicker rods towards the thinner through the intervening layer of water, cell biologists have named these structures "crossbridges". It is at these locations that the energy is released from ATP and transferred to the clusters.

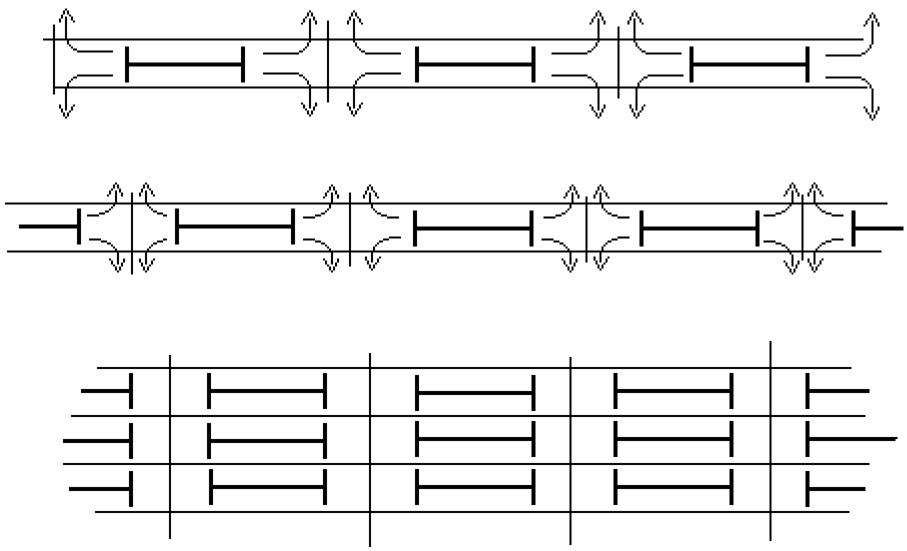
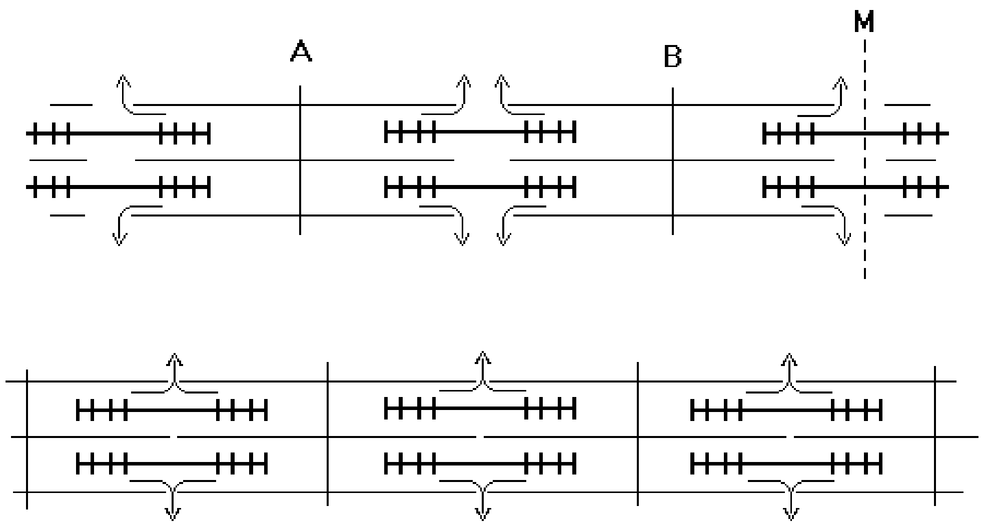


Figure 12.1 Assembly of pistons. The top panel shows a row of double-headed pistons in cylinders assembled end-to-end. The pistons shafts do not change length as they move closer together, shown in the middle panel, so the medium inside the cylinders must flow out of the machines (curved arrows). The bottom panel is a schematic representation of a cross-section through a three-dimensional battery of machines aligned end-to-end and side-to-side. The whole assembly is shown in a contracted state as compared to the top panel, which occurs without a shortening of the piston shafts themselves.



<u>Figure 12.2 Assembly of sarcomers.</u> In striated muscle each machine unit, A to B, stretches a length of 1-2 micrometers. Known as the sarcomer, it contains a side-by-side parallel array of protein filaments numbering in the hundreds. These proteins adopt rod-like forms which enable them to assemble into structures drawn here as interdigitating straight lines in a highly representative oversimplification of the biological tissue. The crossbridges are shown projecting from each end of the thick filament shafts. Biologists have found that even when these filaments are isolated from one another out of muscle, they nevertheless can still adopt the elongated rod form as they do in their natural state in the sarcomer. The cross-bridges are sites where the chemical reaction of the triphosphate compound, ATP, takes place, releasing energy that fuels the contractile force. The watery medium surrounding the protein components (cytoplasm) is shown exiting at the middle of the sarcomers (curved arrows), at the location where biologists know that there are gaps in the wall filaments here (called the M-lines), which run laterally through hundreds of aligned sarcomers across the entire muscle cell and which do not alter their register as lengthwise contraction proceeds. The medium carries with it the spent fuel, the diphosphate compound called, ADP. Enzymes which regenerate ATP from ADP are known to be located in the region of the M-line. In the return stroke, the passive muscle cell is stretched back to its starting length, while the refuelled cytoplasmic medium returns into the region of the crossbridges.

The clusters are already organised in their spatial arrangement by the protein filaments which have well delineated parallel orientation. By way of example here, the degree of alignment displayed by these extensive protein assemblies in the flight muscles of insects is so ordered, that this tissue is often referred to as being crystalline. This means in turn that water exits from the sarcomeric space where macro tension is operative, in a predetermined direction and not simply through pores lacking spatial order as we imagine exists in the membrane surrounding the cylinder depicted in Figure 12.1. In recent years, an increasing amount of data has emerged showing that sarcomers contract in a series of steps of equal size (12). These results are in line with the cluster model, since they imply that water is ejected from the machine in packages rather than as a continuous flow of individual molecules.

The fact that the sarcomer shortens in steps offers strong support for the cluster model on other grounds as well. For instance, since the number of parallel filaments in a single sarcomer is in the hundreds, the fact that it shortens as a unit, reveals a high level of synchronisation in the release of energy from the ATP stores and its conversion to mechanical work coupled with quantised movement of the liquid medium. It has been long known that the filaments keep their register by moving together as shortening proceeds – indeed the German biologist, Krause, saw the striations of light and dark bands in the light microscope in the 1860s. Later investigations established that the distinctive longitudinal and lateral patterns of striations observable in the microscope by early investigators are due to the alignment of the interdigitating filaments within the sarcomers. It would not be possible for these patterns to persist after repeated contraction-relaxation (shortening-extending) cycles if sarcomeric elements moved independently, because their alignment would disappear. Thus the striations visible on the macro level do not represent an average arrangement resulting from the statistical motion of filaments on the micro level, but on the contrary, from an ordered arrangement that survives the repeated alterations in sarcomer length that occur during the use of each and every muscle.

The picture that emerges from the fact that the filaments move as one is that, rather than a battery of tiny pistons, the sarcomer can be viewed as a single integrated piston machine. As we saw in Chapter 3, “Four Machines”, the direction of the force delivered by piston action in our man-made machines is set by the rigid walls of the cylinder – here in nature’s machine it is set by the head-to-tail connections of the parallel rods constructing a network on the macro level. In Figure 12.3, tension develops in the sarcomer overall in the longitudinal direction when pressure is exerted on water molecules on the micro level within the anticlusters in the neighborhood of the crossbridges. Water is thus pushed out of the region under tension by a mechanism reminiscent of the counterintuitive flow out of Pfeffer’s apparatus illustrated in TLP Figure 10.3, “The Puzzle of Osmosis Returns”. Since the time of the pioneering experiments by the renowned biologist Szent-Gyorgyi more than 50 years ago, biochemists have known that a crude random mixture of the filaments isolated from living tissue with no high-level ordered alignment turns from a sticky gel into a fluid solution when ATP is added to it. This fundamental observation demonstrates how the watery medium surrounding a jumble of muscle protein switches from tension to pressure as the chemical energy is released, even in the absence of the organization which captures these forces and produces energy-for-us.

This wealth of detailed knowledge from the molecular level tells us that the muscle cell is a bottom-up machine. To produce large-scale contraction, cells gather energy at the intermediate mesoscopic level of the pixels and transfer it coherently up to the macro level converting it into work. In furthering our endeavor to understand the process fully, our task now is to examine the level below – how is the chemical energy transferred downwards by the pixel machine and then stored at the molecular level, as, for example, happens in the synthesis of ATP?

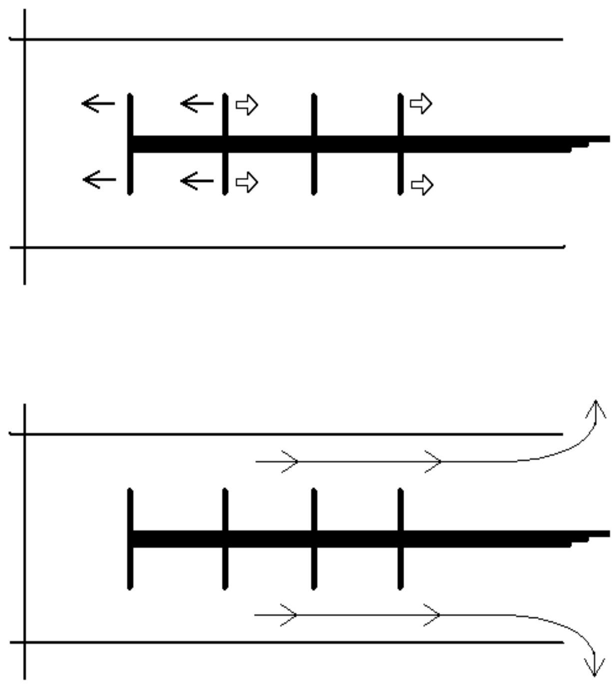


Figure 12.3 The muscle machine. In each half of the contractile unit, the force of contraction is generated. The protein that constitutes the cross-bridges changes its physical state when it reacts with ATP, which results in it experiencing asymmetric forces at its contact surfaces with water – macro tension pulling towards the end (to the left), and micro pressure pushing towards the middle (to the right). These forces arise from the water structure switching between clusters and anticlusters in response to the changes in the protein structure due to the interaction with ATP. Readers can find an extensive description of this model for force generation proposed in the final chapter of TLP where the mechanical forces experienced by the protein involved in DNA replication are depicted. For contraction to proceed, some watery medium must exit from the region at the end of the shaft (curved arrows), either by flowing laterally directly out of this region (see figure 12.1), or as indicated here, by first flowing longitudinally to the M-line before leaving the sarcomeric space (see figure 12.2).

empty thick arrows = pressure
full thin arrows = tension
curved arrows = direction of water flow

13. Energy Moves Down

Can energy move down? Can it be concentrated and relocated onto lower hierarchical levels as exemplified by the phosphate bond in ATP? Those readers convinced by the traditional picture in which the drive of entropy is basic to nature, would automatically see downward transfers in a different light, as an on-going process of dispersion – energy naturally fragments into smaller pieces as it spreads out. So when a drinking glass falls to the floor and breaks into small pieces, a pulse of large-scale gravitational energy is transformed into the scattering motion of the fragments. In contrast, when a rubber ball hits the floor this energy is retained and reused as it bounces back. Recalling the discussion on the action of springs in Chapter 3, "Four Machines", this non-entropic event is the result of a machine cycle, and this idea underlies a major claim of these books to explain liquid behavior – the movement up and down between structure and spring. It is now a deeper problem that confronts us – can it be moved down into specific locations quantum by quantum, for this is the claim of enzyme action?

Planet Earth is covered with material composed of high-energy molecules. From a zoom out perspective, this stark distinction to its sister planets, the dead planets with their coverage of low-energy molecules, justifies the oft used title – The Living Planet. This observation makes it clear that downward transfer is central to the overall problem of life and its origin. To the more chemically trained readers, the production of energized molecules is not problematic at all. It's well known that during collisions between particles one of them can absorb some of the energy of collision. Those readers will recognize such terms as excited, or activated, or inverted, or stimulated, to describe this energized state. But this is an uncontrollable chaotic way of achieving such a state – and once again it is of course, the entropic way – and once again we can be sure, that the material of our biosphere was not produced this way.

Of the four machines illustrated in Figure 3.6, we recall that classes 3) and 4) direct energy downwards. Machines with ordered internal structure can deliver large-scale quanta into yet smaller pixels located in single chemical bonds of solutes rather than the collective bonds of a solvent cluster. The task now is to examine what principles can be used to analyse the operation of these machine types. For example, can Carnot's insight be applied again to help us understand these cases as it was for the machines based on piston action? Figure 4.3 is reproduced here to remind us of the up-out action described by his basic cycle. In analysing the present problem however, a change in machine volume is not desirable, since the movement of a piston results in mechanical work appearing on a higher level. So the companion cycle shown in Figure 13.1 shows instead the pressure changes as a function of the concentration of solute molecules inside the machine. Now we can specify that volume changes moving solvent in and out of the cylinder are avoided – a condition that excludes the performance of mechanical steps. However changes do still occur, and these offer the possibility of supplying energy for a different type of work, which is not delivered by movement of the piston.

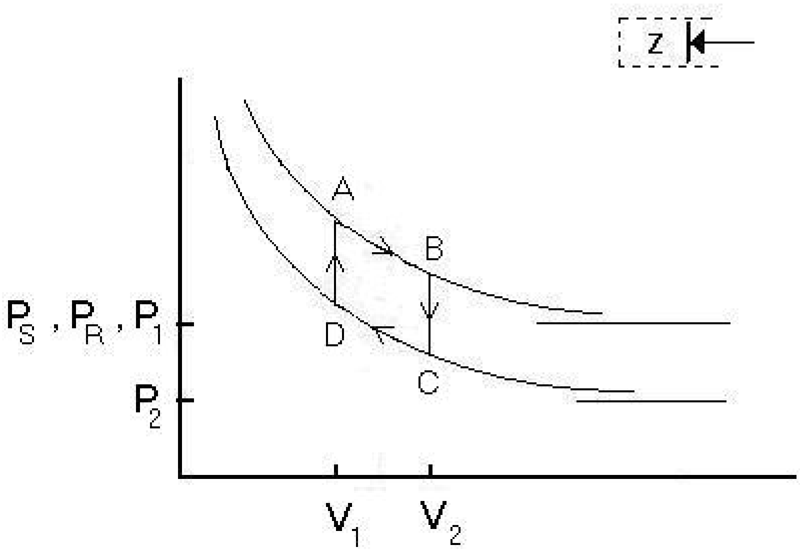


Figure 4.3 Work cycle of the general osmotic machine The cycle ABCD is performed while the machine is in contact with the solvent source S, at an external imposed pressure $P_S = P_1$ for the step AB, and with the solution sink also at $P_R = P_1$ for the step CD. During step BC the internal pressure is released, so that it comes into equilibrium with the sink reservoir, R. P_2 is the pressure that would be exerted by the solvent alone if it had been set in equilibrium with that sink. This pressure is lower than that at C, because the machine contains a solution of Z solute molecules and not pure solvent. Recalling the description in Chapter 4, the pressures inside the machine at B and C would approach P_1 and P_2 at large volumes as the concentration of Z approaches zero.

thick arrow = pressure on the piston

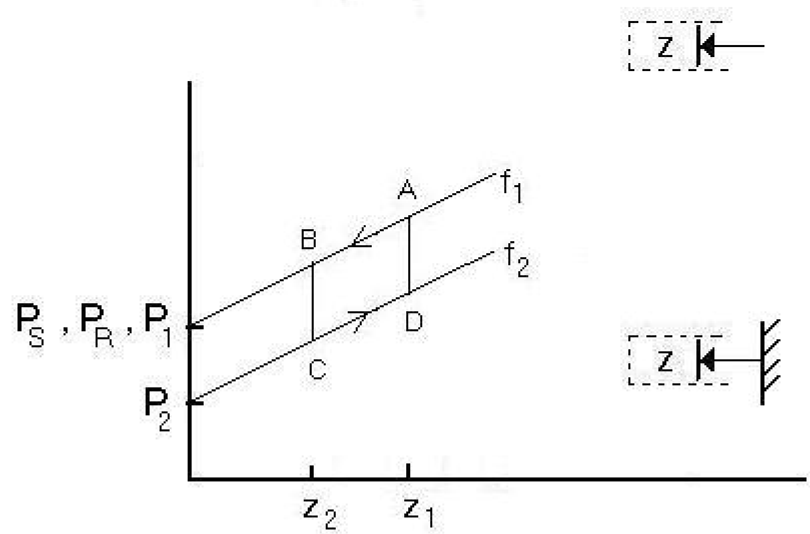
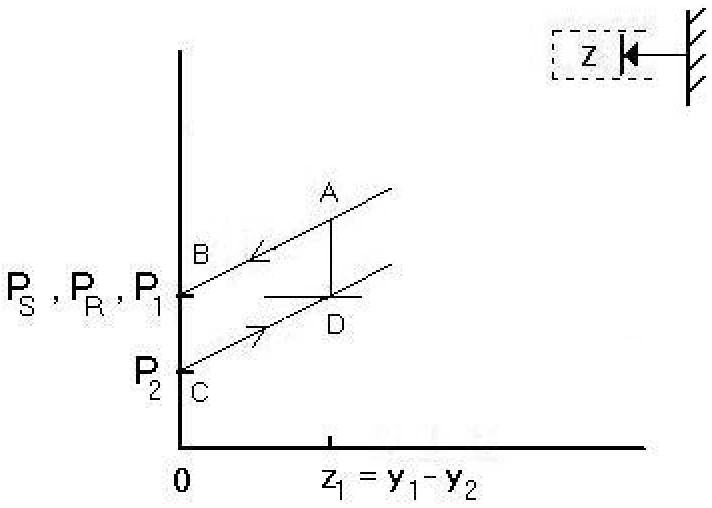


Figure 13.1 Work cycle dependence on solute concentration By plotting the same cycle against solute concentration, z, rather than volume, V, a different interpretation becomes apparent. Since $z=Z/V$, it may change because of changes in either V or Z (or both). As a result we can now picture the machine expanding down the step AB as usual illustrated in the previous diagram, or assume decreasing values of z while V is held constant. In this representation the variables z_1 and z_2 correspond to volumes V_1 and V_2.

thick arrow = pressure on the piston, or
thick arrow = pressure but movement of the piston blocked



<u>Figure 13.2 Simplified cycle at constant volume</u> In this special case the cylinder of the machine contains unit volume of the sink solution with solute concentration z_1. During AB, all the solute is removed giving $z=0$, so that solvent alone remains at B. Then solute is returned during CD, so that the machine contains the original sink solution again at D. The pressure on the piston at B and D is therefore the pressure on the reservoirs (usually atmospheric), and y_1 and y_2 are the cluster concentrations in pure solvent at pressures P_1 and P_2.

thick arrow = pressure but movement of the piston blocked

What energetic changes occur along the step AB? We already know that osmotic energy is released when solutes dissolve in solvent to form a solution. It's source is the structural bonds that hold the liquid molecules of the solvent together. The source is not is not the solute molecules themselves, not the solute-solvent interactions. It is the strengthening cohesion of the solvent medium. In Chapter 8, "Uncoupling M and v", we saw how the liquid spring operates to direct this energy upwards. Now we are faced with the opposite process in which it acts downwards to remove solute molecules back out of the liquid environment.

With the fall in cluster concentration from $n_1 = z_1+y_1$ at A, to $n_2 = z_2+y_1$ at B, they grow in size, meaning there is a corresponding increase in the wavelength of the structure wave. This change provides us with a clue to the destination of osmotic energy flow, since it in turn means there is concomitant disappearance of nodes. The pressure drop does not require energy input, since it results from transfer from spring to structure. However, the removal of foreign does require input, because it is accompanied by further softening of the clusters to produce the pure solvent. This portion of the energy is derived from the source S, which provides energy by propagation of the structure waves through the cylinder walls. Examples are presented in the diagrams of the following chapter, though for the moment we need only suppose that the disappearance of nodes coincides with extending the network of interconnecting bonds, while clusters fuse together. That these bonds form along the downward direction of the isotherm AB, means that during their formation they are accepting energy derived from the solvent source S, producing larger, softer clusters.

To pursue this line of argument a little further, let's identify the contents of the machine at A, illustrated in Figure 13.2, to be unit volume of the same solution as in the sink reservoir, R. There are therefore Z solute molecules inside the machine with concentration $z_1 = y_1\text{-}y_2$, which are removed by the step AB, yielding the pure solvent at B where $z_2 = 0$. Such a cycle represents the reverse process of the cycles represented in Chapters 4 and 10, which describe how physical upward-directed work is achieved by transfer of pure solvent from source S, to sink R, during the return stroke CD, yielding the overall result

$$w = P_1 - P_2 = z_1kT \qquad 9.1$$

Interested readers can find further technical discussion in Appendix 3, where related cycles are described.

For the case of the parallel scenario in the negative pressure regime, Figure 13.3 shows the cycle delivering physical work from volume changes under tension, and its corresponding representation in terms of changes in concentration of solute molecules, Z, in Figure 13.4. In this operation mode, the power stroke is the return stroke GH, while the machine is in contact with the sink, R. It is the propagation of anticlusters that underlies the structure wave in the medium under tension, we have then in this case, an increase in wavelength accompanying the increase in concentration of foreign molecules along GH, according to the picture of anticluster dynamics developed in TLP Chapter 10, "Pixel and Antipixel".

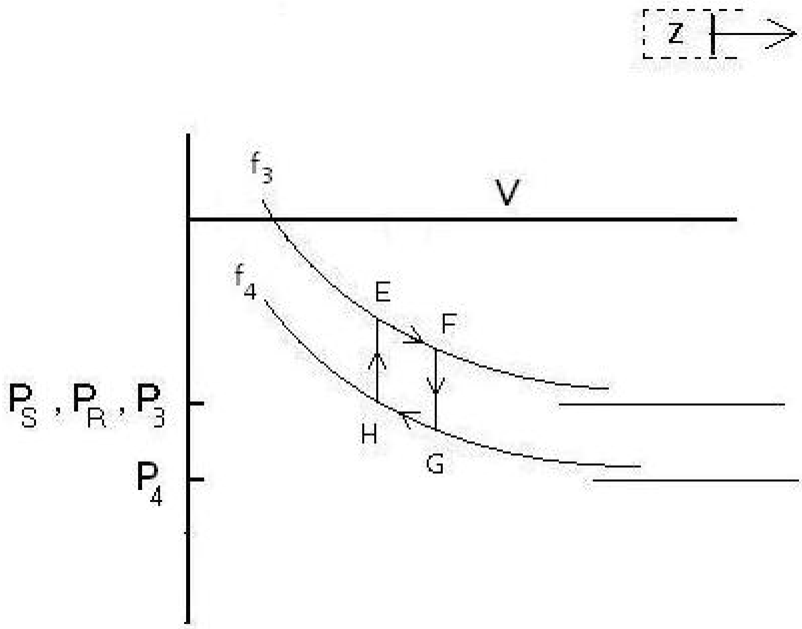


Figure 13.3 Mechanical work delivered under tension The cycle EFGH is performed while in contact with the solvent source at an external imposed tension $P_S = P_3$ for the step EF, and with the solution sink at the same tension $P_R = P_3$ for the step GH. During step FG, the tension is increased so that it comes into equilibrium with the sink reservoir. P_4 is the tension that would be exerted by the solvent source if it had been set in equilibrium with the sink. This is a higher tension than at G, but if the machine expanded to large volumes, the tension at F and G would approach the corresponding asymptotic values P_3 and P_4.

thin arrow = tension pulling on the piston

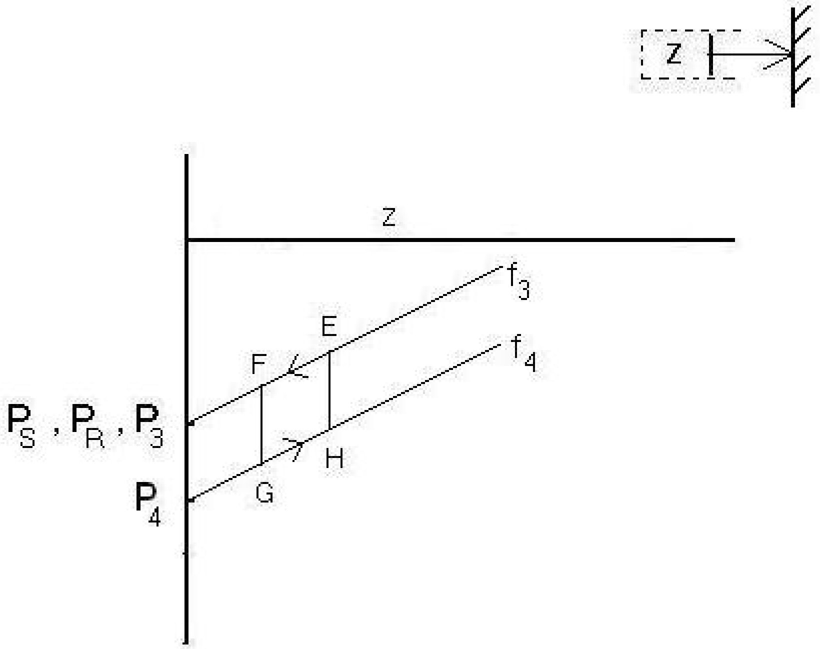


Figure 13.4 Chemical work delivered under tension Chemical work corresponding to the mechanical work delivered by operating in the negative pressure regime shown in the previous diagram, is obtained by replotting the cycle against z, in the same way that Figure 13.1 corresponds to Figure 4.3.

thin arrow = tension but movement of the piston blocked

So calculation of the work performed in the positive and negative regimes yields opposite results. The step AB produces the same effect on the structure wave as does the removal of solutes, while along GH the changes indicate their introduction. Consequently, during AB energy is injected into bonds that form, while during GH it is injected into bonds that break. In the expanding world familiar to us, stable bodies linked by strong bonds tend to form spontaneously releasing energy as they do so, while delicate bodies naturally split apart also releasing energy as their bonds fracture. This picture corresponds to the entropy-driven processes we are accustomed to and take for granted – all the chemistry I practised during my career, inorganic, organic and biological was carried out in that environment. To synthesize high-energy unstable products in the test tubes of our laboratories, reactive agents or high temperatures have to be used in the starting mixture and the yield of the desired product is low. This is the traditional way of providing the required energy to reactions occurring in statistical environments under atmospheric pressure. But in contrast, the energized products of the biological world comprise an enormous class of surprisingly delicate molecules synthesized by enzymes operating in an organized environment. Those machines deliver their successful outcomes without the need for the extreme reaction conditions employed in our chemical technologies.

Expressing the work in terms of momentum gives a view of the picture from the micro level. The extended form of Equation 9.1

$$w = P_1 - P_2 = (M_S f_1 - M_2 f_2) = (M_R - M_2) f_2 \qquad 9.1$$

reminds us that the energy converted into work is equivalent to that released by clusters as they change from soft M_2, to hard M_R, up the lower isotherm, f_2, under the chosen special conditions of unit volume, constant kT, and P_R=P_S. Under more general conditions we have to know the particular chemical reactions causing removal of solute molecules from the solution. However, the fact that work can be expressed in terms of momentum means that energy absorbed from the source is transferred to chemical work via structural changes. On the other hand, energy absorbed in the negative regime down the step EF, is first transferred into the spring of the cluster wave as the tension increases from E to F and on to G. Again, as seen in Figure 10.1, energy for the work, $w=(M_R-M_4)f_4$, derives from the difference in negative momentum as the clusters change from hard M_4 to softer M_R. In the type of system discussed in this present chapter, the contents of the machine are not transferred into the reservoir R, but are chemically converted into the same solution as in R by an increase in solute content. In this environment of high tension, the osmotic energy is then used to break bonds during the work step GH.

The simple scheme in Figure 13.5 summarizes the conclusions drawn from these qualitative analyses of the making-breaking dynamics of molecular interactions. When energy is absorbed through random entropic events, bonds break under pressure but form under tension. To oppose these spontaneous tendencies machines are needed. So the picture painted here is a further development of the general concept of the four machines described in Chapter 3. The upward energy transfer of classes 1) and 2) were dealt with by the familiar piston machines in Chapters 9 and 10. Now in addition, we have the linking together and splitting apart of entities on the micro level resulting from the inward and outward drives of classes 3) and 4) exerted from above on the meso level of clusters. That a quantum of energy is gathered out of the structure wave and transferred from that level to the specific location of a bond making- or breaking-event, justifies classifying these non-random absorption steps as examples of natural work.

Entropic environment	Make high-energy bonds	Break low-energy bonds
Pressure	machine action	random event
Tension	random event	machine action

Figure 13.5 Dynamics that move energy down Chemical bonds make and break under a variety of environmental circumstances. We inhabit a world of pressure in which energy spontaneously fractures and spreads. Under tension, energy spontaneously coalesces and concentrates. Machines are needed for energy to remain trapped at the site of reaction and be incorporated into high-energy products. In this chapter, we discuss cycles which use osmotic energy to make high-energy bonds (Figure 13.1) and break low-energy bonds (Figure 13.3). To make low-energy bonds or break high-energy bonds, energy is emitted from the site of the reaction. However, these are instances of spontaneous energy loss and so are not of interest in our discussion of chemical work.

14. The Enzyme Machine

As far as I know there is no theory of molecular machines. For physicists the reason is clear – they are impossible. As we learnt in TLP Chapter 7, "The Demon", they were barred from science more than 50 years ago. Yet today, biochemical literature of the highest rank is replete with diagrams of molecular machines. This position adopted by the biochemists is an ambivalent one, since on the one hand, their models show enzymes operating as mechanisms in an orderly way, yet on the other, biochemical texts teach that the action of enzymes follow the rules of Michaelis-Menton kinetics, that is to say in non-technical language, the rules of random motion. In this latter role, enzymes behave as a vast collection of participants engaged in a series of chance encounters played out in the cell, and it is this chaotic movement which results in them catalysing those vital biochemical reactions which underpin life.

Catalysts are well known to chemistry because of their widespread use in industry. They speed up reactions that are too slow or even blocked for some reason and cannot proceed. In short, this highly technical knowledge can be summed up for us in an easy way by the statement: catalysts help reacting molecules release energy faster than they normally would. But this is not at all what biology is about. The biosphere is not supplied with ready-made molecules whose energy it releases at accelerated rates – on the contrary, it makes high-energy molecules and stores them! According to the overall scenario we met in Chapter 1, the enzymes within the green leaves of plants pump sunlight into low-energy carbon dioxide and synthesise energy-rich carbohydrates.

Let us look a little deeper into the action of catalysts. It is well known they do not break the thermodynamic law of Free Energy, or put in less technical language, they cannot supply the energy that makes a natural reaction run backwards – they aid the progress of natural reactions only. Yet they do supply some energy, called the Activation Energy, and it is this extra energy which stimulates unreactive molecules into doing their job. But with this explanation we can already feel the thin edge of the wedge pushing open the door to let the Demon in to take up his role of directing the course of events. For if catalysts can supply this special Activation Energy, then why not the forbidden Free Energy? Indeed, catalysts must be able to supply large amounts of energy, since the Activation Energy needed to help some reactions proceed is well in excess of the Free Energy. So there is a hidden assumption here: somehow catalysts are able to distinguish between these two forms of energy, for they never make the mistake of supplying energy to the needs of the forbidden Free Energy rather than the allowed Activation Energy.

There are even more consequences flowing from accepting the statistical interpretation of enzyme behavior. With random motion as a basic plank, the spirit of this theory is opposite to that implied in the published models of how enzymes work, since it assumes that material moves about the cell by diffusion. The consequence alluded to here is, once again, the question of how do enzymes and their metabolites get to the right place at the right time without a mechanism to direct their movement? A bare-bones model to which all such statistical processes can be reduced, was presented in Figure 2.1 as a game of dice, in which the odds of winning, we recall, were calculated to be one in 62 billion. In an updated version redrawn here in Figure 14.1, the Demon has been replaced by separate protein molecules, which take on the role of controlling the chemical reactions we call metabolism.

It's known that in the subcellular world, reactions are carried out such that each step occurs in the right place at the right time. In every metabolic pathway, the initial reactant is converted into the final product with a surety that leaves no room for chance. The reaction steps do not proceed back and forth in any order at random, they proceed from beginning to end in a predetermined sequence. Additionally, the metabolites do not leave the enzyme complex at any of the intermediate stages and diffuse away into the surroundings, for otherwise the cell's interior would become choked with metabolic debris. This behavior resembles that of a system with inbuilt design – a behavior expected by the engineer and computer technologist, whose opinions we will seek again in the next chapter. Biological pathways do not obey the laws of statistical mechanics – they obey programs.

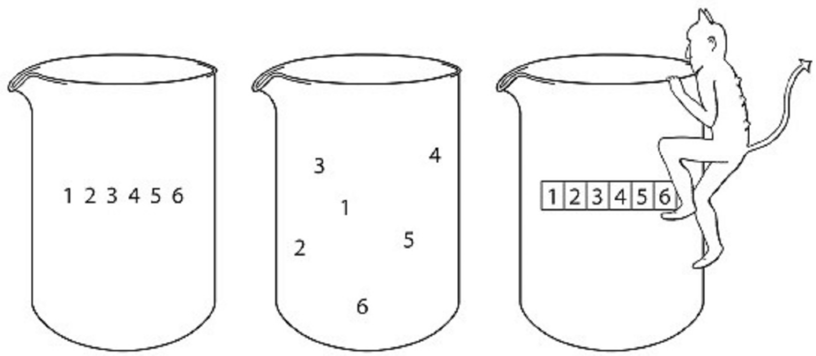


Figure 14.1 Mechanism or no mechanism. We learnt in Figure 2.1 that the probability that a metabolite molecule would follow the straight path shown on the left as a result of diffusion processes is equal to one in 62 billion, with other words, the same chance as tracing out any average path like the one shown in the middle. In the right-hand beaker the locations are predetermined, because the space in which the biological reaction occurs is subdivided into volumes of definite size occupied by the enzymes which catalyse the steps. Thus each chemical step occurs in its own box and the product is moved into the next one along the sequence. Since the metabolites which enter the pathway at step 1 all pass through to be released as products after step 6, the chance of this sequence occurring equals one. Although the model is artificial, it demonstrates dramatically the difference between mechanism and no mechanism

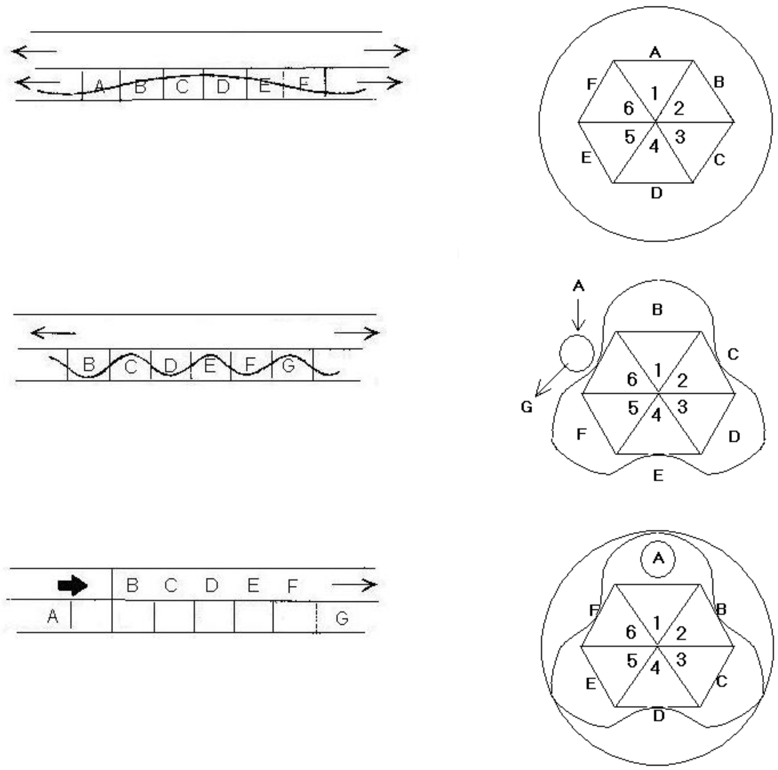


Figure 14.2 Working pixels. The 6 ordered locations of the previous diagram are now seen as 6 pixellated domains defining the space and position of enzymes molecules in a supermachine. A model of its action has already been presented in TLP Figure 12.2, "The Cell's Six Cylinder Engine", where we saw the stepwise processing of the starting metabolite, A, through to the end product, G, without the disruptive effect of diffusion preventing reliable function. An essential part of that machine was a layer of cytoplasmic medium which moved stepwise linearly relative to the sequence of enzyme molecules. However, that mode of action requires additional displacement of the medium in neighbouring regions, which must also come under the control of the machine. Panels 1, 2, 4 of that diagram are reproduced here on the left.

The panels on the right are a schematic representation of the machine in a circular conformation. The medium of the outer ring of the complex holds the molecular forms A,……F, of the metabolite, so that each can interact with (bind to the surface of) the corresponding protein molecule. After the catalytic step converting each into the next member of the sequence, the circular form of the structure wave undergoes the transition to the shorter wavelength form. In the following steps, the end product, G, is removed, the outer ring of the water layer rotates relative to the inner protein core and a new starting metabolite molecule, A, enters the vacated position. This new arrangement stimulates the wave to revert back to the long wavelength state corresponding to a gel under tension.

Biochemists have discovered many enzyme complexes whose functions are known to be cyclic, and whose stepwise mechanism is known in great detail (for example see Boyer (13)).

Because enzymes are links in a sequence, they rely on the correct and efficient function of the other members – those downstream need the products of their neighbors upstream. They are interdependent, so to achieve the correct spatial and temporal sequence, the enzyme complex must function as a coherent whole. The structural units of this horizontal ladder are shown as equally sized boxes in Figure 14.2. Biochemists know that large protein supermachines are subdivided into smaller domains, and that these smaller units are roughly the same size independently of their function. I believe that this strong signal of pixellation in the protein world is indicative of an underlying principle governing biological organization at this hierarchical level. This concept is discussed at length in TLP Chapter 12, "The Protein Pixel".

For the supermachine complex to function in an orchestrated way, the catalytic steps and the transport of their products have to be synchronized. In an oversimplified picture, we can imagine that the individual enzyme units carry out their reactions simultaneously, the products are then released, displaced one unit along the sequence and rebound to the next enzyme site simultaneously, as though the metabolic products are displaced together as a block like items along an assembly line. Recalling the model presented in TLP, the chemical and mechanical steps are coupled with harmonic transitions in the wave motion, where changes in wavelength and shape act as triggers of the pressure-tension switch. Although this oversimplified mechanism is of course highly speculative, the illustration in Figure 14.2 highlights two clear requirements which the switch must be able to fulfill for any such assembly line to function: firstly, the various reactions in the chain must be co-ordinated as a whole, meaning that there must be top-down and bottom-up controls, and secondly, the complex must itself carry out the physical displacement of metabolites to prevent their escape through chaotic diffusion which would interfere with its smooth running.

In Figure 14.3, attention is paid to the immediate site of the switch that operates between levels. It shows a node at the interface between neighboring pixels, composed of water or protein, which occurs when the surfaces are repulsive and so exert pressure on one another. Concomitant with the transition to an antinode, the surfaces become attractive and tension is now exerted across the space of this contact zone. The bonding and antibonding orbitals of electrons in simple molecules are an illustrative parallel to these two forms of the structure wave. They emphasize the quantum principle underlying the model and introduce the idea that we are dealing with energetic states of biological matter – that is to say, with a holistic quality of the material and not just short-range forces across the interface. So even though local chemical and mechanical events trigger switches between bonding and antibonding states of proteins, the wave links them to the global state which extends over the whole assembly. This model is not an alternative to the present-day theory of protein interactions, it is an extension of it. X-ray crystallographic data have located thousands of short-range atom-to-atom interactions across protein interfaces with high precision. In the model presented here, these interactions are not seen solely as individual bonds but as belonging to the larger network throughout the whole space of the assembly, so that all are contributing to the higher-level interaction.

Reversing this line of thought, we imagine an energized wave moving the energy of its vibrations downwards into chemical bonds. This time, the wave directs atomic events. We have arrived at the down-in machine, which is necessary for a model of living matter if we are to explain the phenomenon of energy capture and storage. Returning for a moment to the previous chapter, we recall that the physical principles underlying the operation of this type of machine reveal that the drive comes from above, because energy must be concentrated down into smaller packages occupying the level below the pixel size. This means in turn that, in those regions of the cell where the machines that synthesizes ATP are located, osmotic forces use harmonic transitions in the structure wave to guide energy down to the molecular level of chemical bonds. In line with this proposal, the results of some recent studies show that the state of water in mitochondria and chloroplasts undergoes coherent oscillations, which resonate over the whole of these subcellular structures when they are actively synthesizing ATP (14).

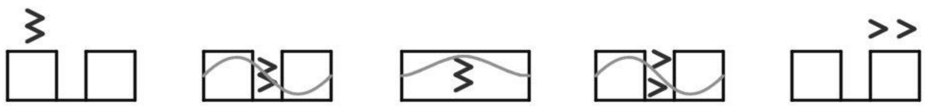


Figure 14.3 The pixel switch. The metabolite molecule (zig-zag line) binds at the interface between two protein molecules of pixel size of an enzyme complex introducing new forces that result in attractive interactions across this interface. Initially the structure wave oscillates with a node located at the binding site. A tight protein-metabolite complex forms as shown by the full wave in the middle panel. This results when the capture of the metabolite releases bond energy of attraction which is transferred up to the pixels – that is, from spring to structure. Now the two proteins have fused into a single high-energy pixel with an antinode at the binding site. After catalysis, the next panel illustrates the new molecular force across the interface which becomes repulsive again. In the last panel the metabolite products (v shapes) are released ready for the next step, which is a displacement step. In terms of the structure wave, there is an harmonic transition as the two protein molecules fuse which doubles the wavelength, followed by the reverse transition which halves the wavelength back to the initial value corresponding to the two smaller separate molecules. This sequence of events illustrates an antibonding-bonding-antibonding transition between two protein pixels.

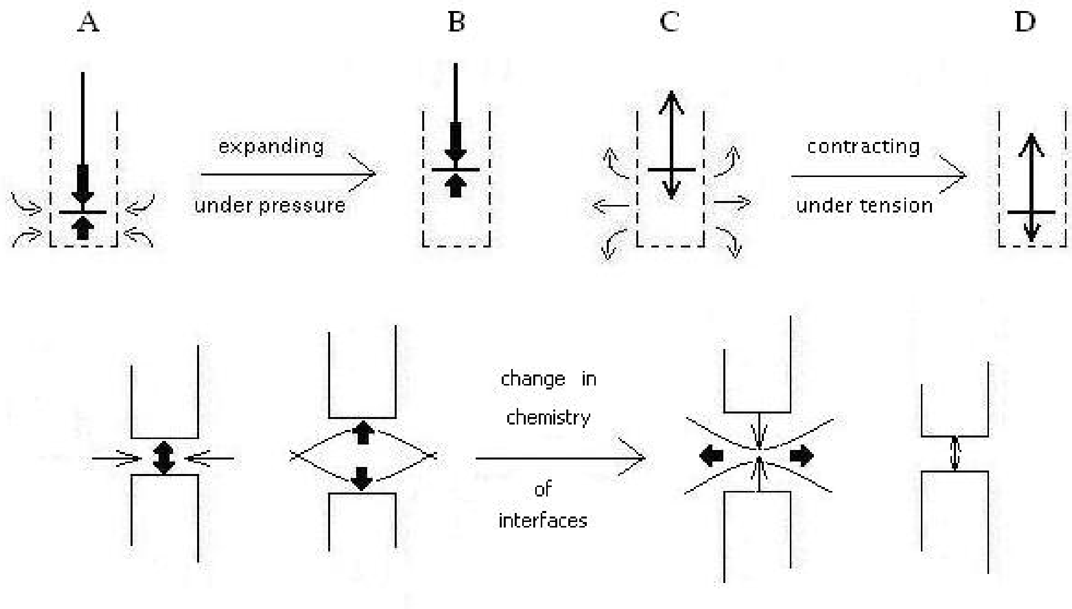


Figure 14.4 The Pixel Pump. The upper panel shows the macroscopic piston machine action corresponding to the cycle illustrated graphically in Figure 4.6. The expansion A to B is under pressure with the solute concentration in the surrounding reservoir lower than inside the machine, while the contraction C to D is under tension with the external concentration now higher than the internal. In this cycle, the change in the macro level circumstances in the surrounding solutions occurring in the step B to C functions as the switch.

In the lower panel, a single cluster cycles through the same steps. Shown in cross-section between two interfaces, say the ends of two protein filaments, it pulls laterally on surrounding medium while exerting vertical pressure against its boundaries at the interfaces. In this case, the switch to an anticluster now occurs because of a chemical reaction changing the nature of the interfaces. An example here is the reaction we discussed above in Chapter 12, of muscle protein with the metabolite ATP pumped to the crossbridges in the incoming medium. The spent fuel product ADP is then removed from the site with the exiting anticluster.

thick arrows = pressure
thin arrows = tension
curved arrows = direction of medium flow

Biochemists accept top-down mechanisms quite naturally – even unquestioningly. The speculative models presented in the diagrams are based broadly on models you find in the biochemical literature. Some enzymes make new chemical bonds, others break bonds, while still others pump salts or move energy-laden electronic charges along predetermined conducting chains. For many of them the mechanism of action is known, that is to say, the resultant chemical changes are known. For some it is known in fine detail. Nevertheless, as detailed as this information is, it answers the question: what happens? as opposed to: how does it happen? and for this reason we need to clarify the concept of mechanism further. As far as I am aware, there is not a single published enzyme mechanism that offers us information on the underlying question: when atoms move, which forces move them? – except, of course, for the claim that random motion moves atoms.

As well as transferring energy between levels, transitions in the structure wave can produce alternating patterns of opposing forces, which offers a possible mechanism for the second requirement for a working model of enzyme function – that of displacing the medium in order to move metabolites along pathways. In Figure 4.6 we saw how the osmotic machine can both actively imbibe and expel a volume of solvent in one cycle of its operation, in which the reservoir solutions are changed from one containing low solute while the piston pushes, to high solute while it pulls. Figure 14.4 shows a combination of outward- and inward-directed action achieving just this result, that is, in one turn of the cycle the machine effects the transfer of water from a low to a high salt environment without the need for an input of energy. Osmotic flow is generally thought to be smooth and continuous, as solvent water flows through membrane pores of the cylinder walls, but the forces at work are seen more clearly when we zoom in down to the size of a single cluster. At its edges, a cluster exerts pressure while being internally under tension, whereas the reverse applies to an anticluster. In this case, the site of the switch is located at the boundary of the cluster where it makes contact with permanent structures such as protein rods and lipid bilayers acting as walls. An important feature of the atoms comprising the walls making contact with the cluster is their built-in geometric patterns, reminiscent of the atomic order found in mineral crystals. When metabolites arriving with the displaced medium interact chemically with such sites, then the forces at the boundaries can alternate between repulsive and attractive, and so stimulate the pressure-tension switch. Since the region involved is the space occupied by a single cluster – a pixel of structural energy – then this change inverts a cluster into an anticluster and the medium now tends to flow laterally outwards because it is internally under pressure. Viewed from this perspective, we see how a sequence of steps coupling molecular reactions with mechanical displacements on the meso level, represents the action of a pixel-sized quantum pump.

In the main, the four machines of Chapter 3 have so far been described separately as non-living objects in isolation. But now the discussion of supermachines shows that an understanding of living systems will require combining all four in varying arrangements even for the simplest pathways within a single celled organism. This means that following a chain of events like that of our introductory scenario connecting speaker to listener, will reveal a multilayered construction in which the supermachines of metabolism occupy a low level in the hierarchy. And at an even lower level, the metabolite molecules themselves will come into focus, because of their double role as a material part of two neighboring machines in the sequence. Returning to the arguments developed in the opening chapters we recall another double role – that of information being the read-out of one machine and the read-in to the next. So the metabolite can be regarded as the vector carrying information – it switches one enzyme off, but the next one on.

In the next chapter we will investigate the role of information as the link and open up for discussion once again the fundamental proposal that life is a network of interconnected machinery. Let's focus once more on our present activity as a pertinent example. The printed black marks you, the reader, are now scanning is a recorded text which, loosely said, connects the final stage of the printing process with the retinas of your eyes. Most readers would no doubt respond, quite rightly, that this is not a very significant observation. But let's turn now to the significant observation, which, again loosely said, is that this text projects the ideas of the author into the mind of the reader. It reminds us that every act, mental as well as physical, executed by a human being involves zillions of enzymes – energy is pixellated a vast number of times inwards, cascading down through many layers to the bottom stratum of water molecules, and then integrated again a vast number of times outwards, coalescing in the reverse direction up to the highest level of the whole body resulting in mental activity. Transferred between each level, biological information must have an exit and an entry – like two sides to the one coin, it must be simultaneously output and input.

15. The Missing Bit

Let us pick up immediately on the concluding note of the previous chapter. Investigating how enzymes perform their tasks has taught us that the ability to transmit messages from one to another is essential. Applied to computers, those machines on the information end of the spectrum, this is of course a tautology – everybody knows that number-crunching needs input. But what of machines on the opposite end – the energy machines?

In our man-made motor, the message is in the repetitious signal generated by the rhythm of the piston. The other machine parts further down the line need the cyclic pattern delivered by the piston shaft to ensure smooth running of the whole, in spite of the fact that this may appear like an absurdly low level of information to IT workers. In Babbage's Engine in contrast, there is an enormous variety of possible arrangements available to the machine parts without any malfunction, so we think of it as a computer, not a motor. Hence for all machines to function, information is an essential ingredient.

Armed with this knowledge, we can now return to the original problem set out at the beginning of the book – the nature of information in the biological world. At one extreme we have the position taken by those people under the spell of the successes of the IT industry, that the code is everything while the message is nothing. This appraisal of the content of communication, which we might call "mathematical information", is supposedly firmly grounded on unassailable mathematical deduction. Readers can find this attitude expressed in very strong terms by Yockey (15). At the other, we have the approach taken in applied biological fields like modern medicine, where the theory that diseases are caused by defective genes is accepted as dogma. For example, a project to identify all the cancer-causing genes in the human genome is underway at the Cold Spring Harbor Institute headed by Watson (of Watson and Crick fame). This project, it is claimed, will lead to the eradication of that terrible scourge. We might call the object of such studies "message science" since for these researchers the message is all and the code is irrelevant. This attitude is certainly easy to understand, when we remember that those patients waiting for the result of a DNA test that detects faulty genes, accept without question the undeniable power of this new technology.

As I'm fond of mentioning, it is surely no coincidence that both fields have delivered their spectacular successes as they gathered momentum along side one another over the last 50 years. Are these parallel advances an indication of an underlying mutualism? Direct support of each other does not seem to be the explanation however, since, while it is true that computing know-how has been vital for progress in molecular biology, research in IT does not rely on any understanding of biology. Yet the achievements in IT can be heralded as nothing short of breathtaking. And it is not only the accelerating rate of progress given by Moore's Law (that computing speeds double every 18 months) which convinces me of that – it is the way in which microprocessing devices have penetrated every aspect of our lives. Today, individuals carry out their daily activities under the control of computer programs, of which they are unaware yet upon which they have become totally dependent. This extensive technical know-how and the benefits of its application have been developed independently, not only of biology, but more surprisingly of our scientific concepts, like mass, time, space and so on – concepts regarded as basic by us all. I have taught IT students who do not know (nor care) what an electron is. As a result, the ever-accelerating field of the information sciences has now, after half a century, become disconnected from the main body of traditional science and exists as though floating above it. There are even claims that information theory is not related to physics at all. Readers will find these remarks reminiscent of how I described the present state of the biological sciences at the beginning of the story in the introductory chapters of TLP. And I'm sure that most readers think as I do, that this parallel is no coincidence – or in other words, there is a connection between the two, which until now has remained invisible to us. The pursuit of both these new fields of study, computing and biology, is at bottom the action of molecular machines, which were neither predicted nor explained by the physical sciences. The historical background for this failure was discussed in Chapter 3, "Four Machines", where their top-down action was introduced as a class of machine. And here at the closing stages, there is now further clarification of the puzzle of why the connection has remained so elusive: computing engineers are interested in programming, that is to say, in mathematical information, while molecular biologists are interested in biochemical reactions, that is to say, in message information. Or put another way: the former are not interested in the pixellation of energy – the take their energy supply for granted, while the latter are not interested in the mechanisms of processing – they take enzyme function for granted.

To put the problem in more concrete terms, let's ask of both disciplines: what does a sequence of the letters A, T, C and G along the DNA of a gene mean? In mathematical information, these letters are taken in groups of 3 and the answer becomes clear, since this combinational process reveals an alphabet to be translated into another alphabet, which in turn is to be translated into another alphabet and so on – biology is code-cracking. Some workers in the field of theoretical genetics claim that Watson and Crick discovered a coding principle, not a biological principle. To the biochemist however, the letters of the code mean protein. And then to the practical geneticist they mean characteristics of the whole organism, its physiology, susceptibility to disease and so on. From an interdisciplinary perspective these various meanings are all valid, and this fact simply illustrates that DNA occupies a rung on many intersecting ladders, be they in the mental, physical, botanical or zoological worlds. That such a variety of meanings can be ascribed to a sequence of symbols highlights the confusion surrounding the concept of information. How can it have so many meanings? An answer to this question cannot be found by experiment, since it relies on the deeper issue of the way in which we understand conceptual problems in science, and this in turn means that we are now confronted by the bottom line: what is the meaning of meaning?

As hinted in the introductory remarks on information offered in Chapter 1, we all have a similar idea of what has meaning for us in our practical day-to-day lives. When information fits a mental picture we already possess, its meaning is clear. In this interpretation, the code is not an important aspect at all – "a tree falls in the forest" has to be said in English code for this phrase to have meaning for English speakers only. For people who cannot decode English, it must be said in their language. The meaning is not in the code. Further, when a phrase has valuable information for us, then we experience the natural feeling that we are receiving "an important message" – a message that helps us complete the picture rather than just fit the picture. It is the missing piece of a jig-saw of which we have the other pieces already in place. Thus it helps mould the future, because it brings into being a new entity which until then could not take form. It is the missing bit. This role of filling a key slot in a bigger picture is perhaps the main way in which we experience what information is. However in pursuing this explanation, the argument has moved up a notch from the biological into the philosophical realm where the meaning of meaning belongs. Since we know next to nothing of the level of the mind, further argument along these lines would necessarily become speculative, so let's retreat a little. Let's now step down a few rungs, through the brain, of which we also know so little, to a nerve cell – an entity investigated in great detail by biologists.

A nerve cell is in either a resting or an active state – quiescent or firing off an electrical impulse to a neighboring cell. In its quiet state however, it is not really resting but internally very active, because its subcellular machinery is busy maintaining the cell in a state of expectation. Expecting what? Every living cell awaits a message from outside. For some cells, for instance the simplest of nerve cells, this message is the smallest message possible – just one bit. It is delivered in the form of just one molecule, which is an object one million times smaller than the cell itself. The molecule attaches to an enzyme on the cell's surface, which triggers a cascade of internal activity involving an enormous number of other enzymes in the chain of activity ending in the electrical impulse. Thus from an outside perspective, the cell itself behaves like a single particle, just as a light does when switched on and off. Yet now we see that this particle is composed of many parts. In reality, it is the outward expression of a vast complex of layered activities occurring on deeper levels awaiting the arrival of messages from above.

It is often claimed that the brain, or even life itself, can be likened to a computer – a popular view promoted by enthusiasts of artificial intelligence who include many of the adherents of mathematical information. Such a model necessarily lacks the depth of any living organism – be it just a single cell. Computer switches are based on a single electrical mechanism, the transistor. They do not contain yet smaller machines cyclically synthesizing individual energized molecules or transporting electrons one-by-one through nano-sized tunnels. In the case of the brain on the other hand, there is no activity without cellular activity. But then there is no cellular activity without protein activity, and again there is no protein activity without water activity, and as we will see in the following chapter, further down there is no water activity without coherent activity of subatomic particles, although, just as with the brain itself at the opposite end of the ladder of Figure 1.1, we know little of this fine-grained world at the level of quantum chemistry. In contrast to the single-level computer, the multitude of machines occupying all these levels of the biological organ function in concert to give rise to the mind.

And so a consequence of the holistic approach is that it excludes the possibility of artificial intelligence – that well publicised and eagerly awaited product of IT research. At a recent meeting of the American Association for the Advancement of Science, Larry Page, of Page and Brin, the inventors of the internet program "Google", assured listeners that the solution to the problem of consciousness is just around the corner, since artificial intelligence is simply a matter of sufficiently powerful computational capability. The idea that life is like a computer, has led to the claim that our present understanding of information theory has already opened the way to building a robot endowed with human, and even superhuman, intelligence. But there is a world of difference between having been created and having evolved. Our brains fill the three-dimensional space of the cranium, and their major constituent is water – the material we inherit from our very beginnings. As recently suggested by Marc Henry, the high degree of versatility shown by water molecules in building its structural networks could be the molecular basis for mental phenomena (16). Energetic conversions pass simultaneously up and down through layers existing in this space from the levels of subatomic particles to that of abstract thought. Artificial intelligence, on the other hand, is forecast to emerge from pulses of electricity travelling around one-dimensional circuits, and this in turn means that mental phenomena must be the result of events occurring on the single level of the electric current. But if it is true that our thoughts are the products of the evolved nervous system, then the possibility that they can also be produced by the circuitry inside robot brains does not exist, for otherwise we must conclude that the multilayered activity of the animal brain is purely to supply electric current – the plug in the wall behind the computer – and that it is this current in turn which then produces our thoughts and feelings by non-biological means.

So now we look back on Figure 1.1 with new eyes. The levels are not spatially separated like rungs of a real ladder, but are superimposed on top of one another. The machinery of each level exists in the same space and at the same time as that of the others, and consequently, the downward and upward flows occur throughout this same space, like pulses cycling alternatively inwards then outwards within the same body. Descending large-scale energy quanta are pixellated down to atomic sized quanta and then integrated again as they ascend to the level of the organism – be it in a swimming bacterium or the thinking brain.

Scientists are often accused of taking the feeling and spirit out of human creativity, so I am aware that this description seems to paint a mechanical picture of the way our highest achievements are realized. Some readers may even feel that following the logic of such ideas would, in the end, render human life lifeless. For instance, that our feelings are just chemicals may be a common notion among scientists – many readers will be familiar with the determinist stance presented in Crick's (of Watson and Crick fame) popular book "The astonishing hypothesis" (17) in which this idea is expounded in full. But even much earlier, the great physicist, Planck, father of the quantum, taught that the movements of the atoms in the brain obey the laws of thermodynamics. We might like to think otherwise, but according to his thoroughly reductionist position, our thoughts are determined by the random motion of elementary particles. Not surprisingly, this cold world-view is anathema to our artistic brethren.

Readers may further find it impossible to accept the idea that "meaning" is closely related to a "machine part", since the notion seems to imply an insensitive lack of interest in the mysteries of human creativity. Such a concept naturally sounds very materialistic, or even outright mechanical, especially when we come to discuss spiritual experiences, like the inner feelings of pleasure that accompany the appreciation of artistic endeavors. However the explanation does offer a solution to the problem posed by the meaning of meaning, because it tells us that the secret is in the message, not the formalism. Information must be acceptable to its target, which is distant and distinct from its source. So it is the target which decides on the question of meaning. Messages have the power of switches, because they prevent randomization of energy by ensuring that steps proceed only after the message has arrived, in other words, only in a prescribed sequence. Meaning can be equated with the holistic activity set in motion on a new level, up or down, as a consequence of the arrival of a message. As with any chain of command, translating code is of course necessary along the way, because the mathematical information passes through a variety of materials each of which propagates signals according to its own physical laws. In Figure 2.2, "A Horizontal Ladder", we saw the need for machines at the interfaces between levels, which function to decode and encode in order to ensure smooth transmission. The thoughts of the speaker can reach the mind of the listener via a different chain, up and down different ladders, and through different media – paper, tapes, screens – none of which involves vibrating air. Clearly then, the coding mechanism depends on the transmission medium and not the information transmitted.

In Chapter 3, the speaker who had no audience made sound waves but no sound, now we see additionally that his words had no meaning. In this example, "meaning" refers to a high-level sophisticated quality we automatically associate with human understanding stimulated in the mind of a listener, but the principle applies to the simplest of communication steps. Consider the example in which the structure wave travelling through water strikes the glass wall of its container. Here, there is also no transfer of information. But when it makes osmotic contact with a second body of water, then it is "heard" by the clusters it encounters there and stimulates them to alter their state. In this case, the line of communication is just one step long. The transfer across it is accomplished by the simplest pixel machines, water clusters, which alter their states according to the incoming information on the structure wave.

Identifying and analysing the role of machines has helped a clearer picture of information to emerge. We are at last finally able to discern at least three distinct meanings among the vague suggestions outlined in the introductory chapters. Let's now re-consider the concepts "mathematical information", "messages" and "meanings", bearing in mind the earlier confusion encountered in using the term "information" to mean any of these taken singly, or indeed mixed together without any particular emphasis on the proportions in the mix.

"Mathematical information" belongs wholly to the field of IT. Perhaps a more descriptive title for this class might be "code". I use the term "mathematical" loosely to indicate that its elements are abstract and their interrelationships are governed by theory of probability as demonstrated by Shannon, and rules of switching historically associated with the names of Boole, Turing and vonNeumann. Notably, as stressed earlier herein, understanding and using code does not require a great deal of scientific knowledge.

On the other hand, a "message" has a physical existence. At bottom, it is a pulse of energy, but the form it takes is crucial also. The energy of the chemical bond in ATP for instance, is the same as that in ADP and in several other phosphate compounds present in the cell, yet for a machine called an ATPase, like those we have encountered in the previous chapters, only ATP carries information. The other compounds carry an equal quantum of energy, but their physical form prevents them from playing the role of the missing bit which stimulates the receiver to respond.

But for "meaning", a message is not enough. We have all experienced the state of confusion in our minds when we feel the need to offer the comment "yes, I got your telephone message, but I don't know what it means". Although I'm obviously referring to a sophisticated human scenario, the relationship between "message" and "meaning" applies to lower levels also. Let's consider the more clinical rendition of that comment rephrased with the words "yes, my inner ear and auditory nerve were stimulated, but that did not lead to a response in my cerebral cortex". The code arrived and the message was delivered, but there the chain of events come to and end. "Meaning" emerges when changes in the receiver triggers a follow-on response in a larger assembly of machines to which the receiver belongs. "Meaning" refers to hierarchical organization, not to rules of code. To be able to act as one, the assembly must be already primed into a state of expectancy by the arrival of other messages. So for "meaning" to ensue, the message must be received by an integrated structure which is already rich in information. That is why, along the chain of communication depicted in Figure 3.2, there are additional injections into the flux of information, I, by the machinery of the nervous system of the listener, that is, on the receiver end of the line.

What then can we say of the original supposition that something called "information content" must remain constant during its journey from speaker to listener? In more direct language the question runs: how much of the content of the speaker's ideas is transmitted across the critical connecting step – the vibrating air? We have at last reached the stage where we can offer an answer: surprisingly little! Sound waves carry code only. They are not even messages until they interact with an eardrum. In this analysis, the thoughts of the speaker have been stripped down to their bare minimum – propagating humps and dips in the pressure of the intervening air. So can we now also accept the reductionist position of mathematical information that, in the last analysis, life equals code? Can we go even a step further and agree with Turing's insight, that all reality can be reduced to a series of dots and dashes? The story told in these pages brings some new perspectives on this claim. If you are interested in code and not interested in meaning, then yes, all can be reduced to code. But if on the other hand you are interested in meaning, then no, code is not enough.

In that "information molecule" DNA, the triplet "AAA" is the genetic code for the amino acid, lysine. But there are other codes too. "UUU", which the biochemists call the anticodon, is one, so is "lys" and so is "K". All these codes are written in letters of the Latin alphabet and, in stark contrast to genes, did not exist 100 years ago. Indeed, the genetic code is just 50 years old, and began to emerge after Nirenberg and co-workers took the first steps to crack it around 1960. The aim of information science in this field has been to discover the mathematical interrelationships between these codes, which means establishing the rules of encoding and decoding – a pursuit which can be followed without special reference to biology. In their practice, IT researchers invent representational descriptions written in Latin or binary (or some other code) with the purpose of simulating what natural switches do. Biologists, in contrast, are interested in those switches.

16. Information Comes Alive

The concluding chapter of TLP presented proposals for two top-down machines – one that operated at the dawn of evolution and the other that operates today in the sophisticated environs of the cell. Although we had not yet developed the top-down classification, it was clear that the proposals were attempts to answer the question of the synthesis of biologically relevant molecules, that is to say, of lower-level objects possessing energy and information. There, Figure 13.1, "Early Machines of Life", showed the synthesis of basic carbohydrate chemicals – the precursors of proteins – in the prebiotic era of the young Earth by early non-living mechanisms. That model laid the ground for an explanation of the issue introduced at the outset with the illustration of the Grand Canyon between the sciences, from where we recall the proposition: "the upper protein is alive, the lower one is dead". Biological protein is the higher-level product of copying processes that followed coded instructions imprinted in pre-existing matter, whereas physical protein is produced by random chemistry. The latter is therefore devoid of a history – it has a past, but no story. In physical protein there are no traces of the hierarchical sequences: code, message, meaning, code, message, meaning, code……. Like the lucky pilots it possesses no memory to call on, or expressed in other words, there is no sense of becoming – at one point it was not, then at the next it was. In contrast, discussion of the osmotic machine revealed how basic energetic steps, which in TLP were carried out by demon-like actions of water clusters, were directed by pre-existing order and thus avoided randomization. Its operation was made possible through incorporating the patterns of atoms on crystal surfaces as essential machine parts. We now see that the influence of such surfaces was a message from the older mineral world projected onto the burgeoning prebiotic era – they were creating a future.

The concept of flux through levels places greater importance on neither one of upward- or downward-directed transmission – they are given equal weight. The familiar picture in contrast, is very different. DNA, or a similar information-laden molecule appeared spontaneously in the primordial soup and life developed upward and outward from there. Furthermore, the extended explanation based on natural selection dismisses any notion of downward-fed information being involved in this expansion. On the other hand, in the pixel model water clusters synthesized energy-rich molecules under the organizing influence of mineral surfaces. This means that the pixel machines occupy an intermediate level rather than the bottom rung of the ladder of evolution, because the simple molecules they produced occupy a position below water clusters, and well below proteins and cells, in the natural hierarchy. Or put another way, the first steps on the way to living matter were performed by downward-directed machinery, as we shall now see.

At its present stage, Earth possesses a dazzling array of chemical molecules, all of which have been synthesized by the living. As far as I am aware, there is no vitamin B to be found on Mars, and before it was produced here on Earth, it did not exist anywhere in our galaxy (in all probability). Yet, as wondrous as this enormous variety may seem from one perspective, it nevertheless represents a collection of dead molecules populating the lowest rungs of the ladder of life. They possess unexpected qualities though. They are energized, complex in their structures and carry a message – just think of estrogen and testosterone – and so could not have been the spontaneous outcomes of a chaotic environment. They were produced by downward-directed evolution.

For the more technical readers, we can proceed one step deeper. Students of physics prefer to identify molecules as electron clouds rather than groupings of atoms. Such clouds are quantum entities belonging to the realm of the fundamental building blocks of the Universe. Like the clouds in the sky, we can imagine them as vaporous shapes made of nothing more than electrical space. The electron clouds of the early period had basic shapes – spheres, ellipsoids, dumbbells and pyramids. From the creative powers of the pixel machines however, came more delicate larger structures with fragile complicated shapes composed of zigzags, waves, pipes, donuts, spirals and more, which would readily disintegrate back into the basic shapes of the stable first clouds without the protection of the new environment that began to emerge with the first signs of life. The molecule called cyanocobalamin, by the chemists, or vitamin B, by the biologists, is a star-shaped ultra-thin, nano-sized disc resembling a sheet of intricate filigree, to the physicists. The production of such complex quantum particles on the bottom rung required more than the rich primordial soup – they could only have been generated by newly evolved chemistry directed from above.

Although vitamin B was of course not needed for early life, the basic carbohydrates were – or stated more accurately, were needed at that stage which predated living protein. Yet they also had to be synthesized from above, since their production requires input of energy and information. So these building blocks of proteins must have themselves been created by already existing machines. In this scenario, the first steps of evolution were top-down, that is, in the opposite direction to the one we have become accustomed to accept in the familiar picture of evolution's course.

Scientists, and especially biologists, use the term "evolution" in the narrow sense to describe the history of living forms, and in the main, this is how the term is used in these books also. However, now at the concluding stage, it has become clear that living forms are simply the most recent developments in the continuous evolution of energy forms, which spans a much longer period reaching further back into the history of our planet. Living matter developed from non-living in a natural way and did not appear suddenly following a disjunction between the two marked by the chance synthesis of the first biological molecule on the northern edge of the chaotic abyss. Projecting this line of thought into the future we can safely forecast that a more advanced form of matter – let's say, "mental matter" or "psychic matter", depending on whether your inclination is for Latin or Greek – will develop in a natural way from living matter. Indeed, I feel that many readers would claim they sense the emergence of fleeting forms of its building blocks already in our time.

Taking center-stage in this present work is the proposal that energy conversion can occur in a predictable way as a result of machine action. The point of departure is the notion that natural events are the outcomes of two fundamental tendencies – expanding and contracting energies. The first goes hand-in-hand with fragmentation, that is to say, with on-going division of larger quanta into smaller, as is described by the Second Law of Thermodynamics. The second goes hand-in-hand with coalescence, the fusion of many into a single quantum. These tendencies lie behind the two drives, outward and inward, responsible for evolutionary change. That the drives oppose one another has prevented all the available energy from being dissipated away in every direction, on the one hand, or all collapsing together into a single entity, on the other.

These drives are not sufficient for evolutionary change however, because the type of world they predict would be nothing more than a huge mix resembling chaos in motion. Images of dissipative structures come to mind, like swirling vortices appearing and disappearing, and rising columns of bubbles exploding and imploding in a boiling ocean. But when energy passes through regions which offer resistance to the flow, then we have a machine, and the fusion and fragmentation processes can be controlled. In other words, machines ensure that the spontaneous processes are rendered non-random – fusion becomes integration and fragmentation becomes pixellation. Through integration energy moves up a rung of the hierarchical ladder, while through pixellation it moves down. Following these principles we are on track to answering the question raised at the end of Chapter 1, which highlighted the mystery of how energy is continually re-organizing itself as it moves about the world rather than flowing forever down a one-way street towards an inevitable, featureless end.

Integration can be likened to construction. We recall from Chapter 2, Davies' picture of an explosion under a pile of bricks producing a house, as an analogy for the random-event theory of the origin of life. But as we all know, rather than gamble with such risky techniques, builders prefer to construct houses by placing each brick in the right place at the right time. And similarly, pixellation can be likened to what happens to the operator's muscular effort used in turning the handle of Babbage's Engine, or in the more modern version, when the electric current from the plug in the wall is split into a myriad of minuscule impulses as it passes through a computer. Here, fragmentation is an orderly process of subdivision. Allowing an electric current to dissipate through a tangled circuit will never display a circle on a screen or print out the value of pi, just as when a lightning bolt flashes to the ground there is a lot of fragmentation, but no calculation.

Putting finally the main theme into narrower focus: the twin processes of integration and pixellation are the non-random versions of the more general twin processes of fusion and fragmentation. They lay the basis for categorizing energy transfer as movements either up or down the ladder of the hierarchy of quantum sizes. Combination with the two drives, expansion and contraction, leads to the four modes for energy conversion proposed in Chapter 3. Two of these, the bottom-up machines, were described in technical detail in Chapter 4 guided by Carnot's insight into cyclic action. In Chapters 13 and 14 these analyses were extended to the top-down versions presenting for the first time the mode of operation of these machine types in natural systems already well known to biochemists.

In Part 3, "The Living Matrix", this theme will be developed even further to investigate the constant re-organization of energy in the wider world beyond biology. In that early epoch before the emergence of biotic forms, the environmental conditions suitable for the birth of machines must have been very limited. However, all was not chaos – the primitive order imprinted in crystalline minerals, probably the clay silicates, projected itself into the flickering structure of neighboring water, and stimulated the pixel machines into action. Perhaps we can trace the messages back even further to forms of matter that predate those crystals, but the flexibility of the pixel machines with their ability to switch between inward and outward action, allowed energy to be moulded into new bigger and smaller forms destined to become the building blocks of life.

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Appendix 1

The Spring Analogy

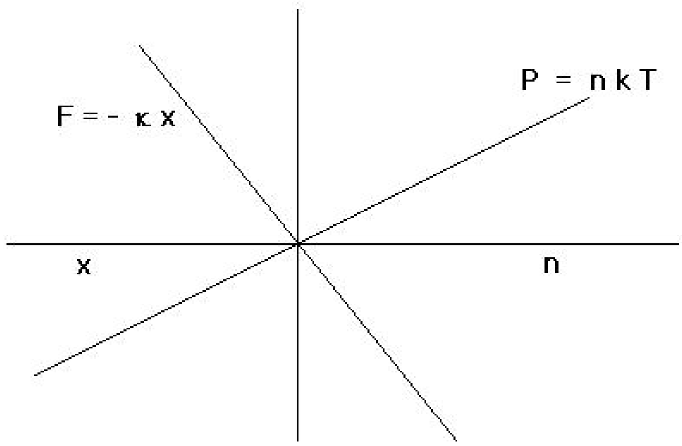
In this Appendix we look at the analogy a little closer. From Chapter 6, “Mechanical or Structural”, we have

$$F = -\kappa x$$

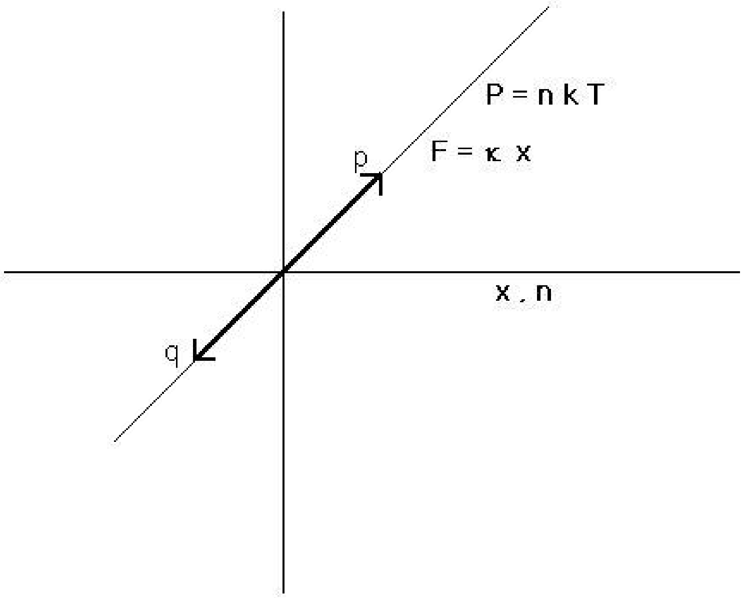
for a spring, where κ is the spring constant and x the extension, and

$$P = nkT$$

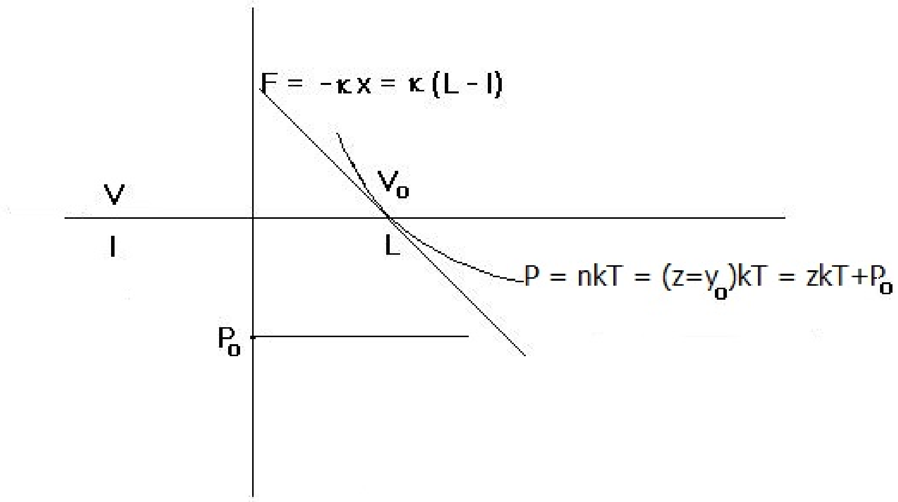
for a liquid. These simple relations are shown below in Figure 1.



If instead of length extension, we chose x to represent the concentration of turns in the spring, then the plots would co-inside, since the concentration increases as the extension decreases – just as we see when a spring is squeezed – and conversely when it is stretched. Then we have Figure 2.



There is still a difference in the behavior of the two systems, because in liquids the cluster concentration changes without a change in physical size. In liquids, pressure is simply a Newtonian reaction to an externally imposed stress, analogous to a solid surface supporting a weight placed on it. However, for solutions in osmotic equilibrium, we can have size changes producing changes in cluster concentration, as is achieved by moving the piston in the osmotic machine. In this case, the systems are analogous, with compression concentrating turns in springs and clusters, and with extension diluting them both. From Figure 3 we see that the fractional extension of the spring, l/L, is analogous to the fractional concentration of clusters in the solution, z/y_0.



Taking the analogy further, we can consider the possibility of structural oscillations in liquids. Since simple harmonic motion is the well known natural behavior of strings, it leads directly to the speculation of a parallel phenomenon in liquids. When springs are loaded with energy through a compression or extension, they automatically set up a free oscillation between the points p and q in Figure 2. Liquids in contrast, do not need an initial impulse of energy supplied from outside to start an oscillating motion, because their bonds act co-operatively to absorb and release energy as its physical state swings between pressure and tension. The comparison between mechanical and structural oscillations is summarized in the table below.

	solid spring	liquid
pressure	energy in stressed bonds of compressed turns = macro potential energy	kinetic energy in cluster momentum = low energy in tight bonds
neutral point	macro kinetic energy = low energy in stable bonds	potential energy in broken bonds b = B
tension	energy in stressed bonds of stretched turns = macro potential energy	kinetic energy in anticluster momentum = low energy in tight bonds

If we consider systems in osmotic equilibrium, on the other hand, then interaction with an external source must occur. In this case, we can imagine alternating expansion-contraction piston action to occur, similar to that of spring, or, as discussed in Chapter 13 “Energy Moves Down”, reciprocal movement of solutes in and out of the oscillating region of the solution.

Appendix 2

Photons and Pixels

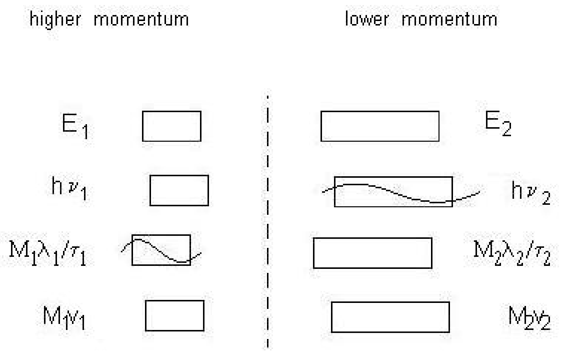
In the wave-cluster model, pressure is caused by pixels of energy colliding with boundaries, whether photons of radiation, gas molecules, or liquid clusters. In all three cases, macro mechanical pressure can be modelled by the compression of a spring. I do not know whether photons collide with one another, however, since they reflect off boundary walls they can obviously be compressed. This process is mediated through the atomic oscillators identified by Planck as the basis of his derivation of the distribution in photon energies emitted by bodies when they come to thermal equilibrium with their surroundings. In Equation 11.4, the reservoir of background radiation is assumed to be a supply of photons of concentration y. Since the oscillators are fixed in position, say in the walls of a container kept at constant temperature, they cannot be incorporated into the model of compressed pixels in which pixel volume, u, changes. This restriction can be overcome if we allow the pixel length instead to vary, as illustrated in the Figure below. Then a close parallel becomes apparent after comparing Planck's relation for photons

$$E = Mc = h\nu \qquad M\lambda = E\tau = h$$

with the similar one for pixels

$$E = Mv = kT \qquad M\lambda = kT\tau$$

In the wave-cluster model, the quantum kT is carried by a cluster of pixel size, u, within a liquid body where the total volume is occupied by pixels, since the molecules are in the compact liquid state. On the other hand, under conditions forcing clusters to adopt anisotropic shapes with a predetermined cross-section area, their volume would be proportional to their length, and then the parallel to photons would be even closer.



Quatum homology between photons and pixels When solid bodies come to thermal equilibrium they exchange quanta of energy shown schematically here as rectangular prisms emitted from a hotter body on the left and a cooler body on the right. The rectangles represent photons of radiation with energy, E_1 and E_2, where $E_1 > E_2$. For black-body radiation, the energies are given by Planck's famous distribution of quantum sizes after they have come to equilibrium. As they move towards one another, they pass through a plane positioned in space between the surfaces of the emitting bodies. Since the spatial positions of the oscillators (atoms) which absorb and emit these photons are fixed in the walls of the bodies, we can imagine that it is the wavelengths that determine photon size as they travel through the intervening space between the oscillators. Turning to the wave-cluster model, this picture translates into one in which pixel volumes are proportional to the length, λ, of the rectangles, whereby this now represents the wavelength of the structure wave.

Appendix 3

Machines Performing Chemical Work

To calculate physical work we start with the classical function, PdV. But to calculate chemical work, we are interested in the function, Pdn, under conditions where the volume does not change, dV=0. We have already met Pdn in Chapter 6, "Mechanical or Structural", as the starting point for explaining internal energy changes in a liquid body caused by direct imposition of pressure alone. Under such conditions, there is a shift in energy between the spring (momentum carried by the structure wave) and structure (strength of cluster internal bonding). In the present problem, we are interested in the input of additional energy from external energy-rich osmotic sources, which cause changes in chemical bonds of solute as well as solvent molecules. In this case, the spring constant, F, now refers to the spring in bonds between atoms on the nano level below, rather then to the spring in pressure on the macro level above. The force function to be integrated is then Fndn, or more precisely F(z+y)dz, where the focus now turns to the changing concentration of solutes, z, while y refers to the unchanging solvent cluster concentration in the reservoirs. Using the work cycle shown as a function of z illustrated in Figure 13.1 gives

$$\text{stored chemical energy} = (P_1 - P_2)(z_1 - z_2)$$

for kT held constant around the cycle. Dividing by the amount of solute removed from the machine, $(z_1 - z_2)$, gives the work performed

$$w = P_1 - P_2 \qquad 4.7$$

Simplifying the example even further, we can consider the case of the machine containing just unit volume of the reservoir solution, R. Then the cycle becomes that illustrated in Figure 13.2, and we obtain again

$$w = P_1 - P_2 = z_1 kT \qquad 9.1$$

We now have three identical results for three variations of the same system under the same basic conditions including, unit volume, $P_R = P_S$, and constant kT:

1) physical work done by transfer of pure solvent from source, S, to sink, R, (Figures 4.3 and 9.1)

2) energy shift from structure to spring with cluster concentration change from y_2 to y_1, by increasing pressure from lower to upper isotherm without changing volume or solute concentration.

3) chemical work done to remove Z solute molecules from unit volume of solution (Figure 13.2).

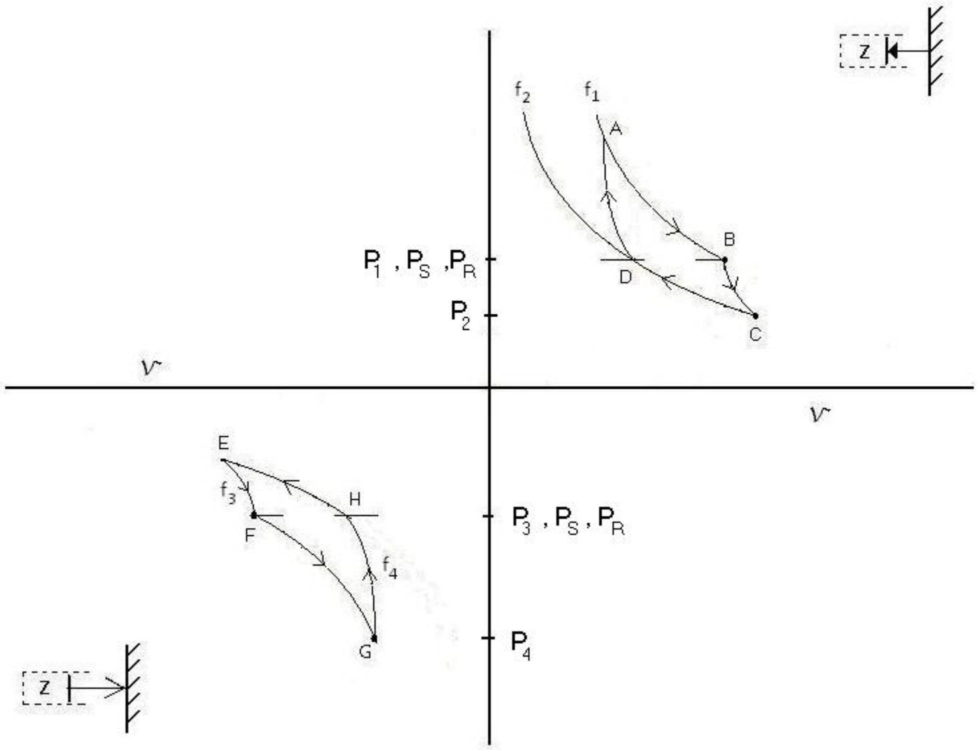
The second variation occurs during the vertical steps, for example, DA and HE, in Figures 13.1 and 13.3. The change is internal occurring without contact with the surroundings. Variations 1) and 3) occur during steps, AB and EF, down isotherms in contact with reservoirs. Since these steps are associated with work performance, we can conclude that contact with external reservoirs must be needed to fuel them by an inflow of energy. This follows because the simple pressure changes alone from A to B and E to F, are explained by purely internal shifts. However, plots of the cycles themselves do not show such a flow, just as the classical Carnot cycle does not show flow of heat – it is inferred.

A clearer indication of flow is given by plotting the cycle in terms of wave velocity as shown in the Figure below. In this plot, we have a familiar hyperbolic dependence of pressure from the relation

$$Pv = A \qquad 7.4$$

Where A represents energy flux between systems in osmotic equilibrium. This type of plot illustrates the direction of flow because of the fact that higher values of A mean higher rates of delivering energy. Now we see the reason why the upper isotherms in the P,V diagrams from Chapter 4 onwards correspond to the source S, and the lower to the sink R, whether in the positive or negative pressure regime.

When two systems are in contact, osmotic energy flows between them. If the flow passes through a machine, it can be directed upwards into mechanical work (Equation 4.3) by a change in volume, or downwards in to chemical work (Equation 14.1) by a change in solute concentration, each achieved via an intermediary structure-spring switch in level (steps BC, FG).



Work cycles at constant volume In this diagram pressure is plotted against wave velocity. In this case, steps AB and EF follow the isotherm for contact with the source, given by $Pv=f_1kT=A_1$, and steps CD and GH for contact with the sink, given by $Pv=f_2kT=A_2$, with $A_1>A_2$. These cycles correspond to those shown in Figures 13.1 and 13.3. Chemical reactions remove solutes Z from the solution inside the cylinder along AB and EF, and introduce Z along CD and GH. If the reactions go to completion, the concentration $z=Z/V$ reaches zero as in the corresponding cycle in Figure 14.2, and there is then solvent only in the cylinder at B, C, F and G. This stipulation is not necessary for any work cycle, it is introduced for discussional purposes only. The dots at B and C mark the ends of isotherms in the positive regime where the wave velocity for the pure solvent reaches maximum. In contrast, the dots at F and G correspond to minimum velocities, because as the solutions approach the state of the pure solvent, the tension increases and the speed of the structure wave carrying anticlusters decreases.

thick arrow = pressure but movement of the piston blocked

thin arrow = tension but movement of the piston blocked