Information, Work and Meaning

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CONTENTS

INTRODUCTION

We live today in what is called an information economy. The growth in all things computer-related is obvious to all. Shares in companies making information processing products—the "new economy"—have been the stars of Wall Street, London and Frankfurt. At the same time an ever increasing proportion of the workforce in advanced economies has moved into jobs concerned with the handling of information: financial services, tele-centres, advertising and the media.

In the face of this obvious change we want to address some basic questions. What is information? Why is it valuable? What is the relationship between money and information?

In answering these questions we draw upon three areas of study that were until recently quite distinct: classical political economy, thermodynamics and information theory. Classical political economy links the creation of value to work. Thermodynamics, arising from pragmatic studies of the limits to our ability to perform work, became, with the concept of entropy, a cornerstone of our understanding of the physical world. Information theory, originally another pragmatic branch of engineering, has revealed unexpected links between information and entropy.

In the process we will show how concepts derived from thermodynamics have proven themselves to be amazingly fruitful in confirming the hypotheses of the classical economists.

CHAPTER 1

PROBLEMATIZING LABOUR

1.1 WATT ON WORK

Prior to the eighteenth century, muscles—whether of humans, horses or oxen—remained the fundamental energy source for production. Not coincidentally, the concepts of work, power, energy and labour did not exist in anything like their modern form. People were, of course, familiar with machinery prior to the modern age. The Archimedean machines and their derivatives—levers, inclined planes, screws, wheels, pulleys—had been around for millennia to amplify or concentrate muscular effort. Water-power had been in use since at least the first century A.D.,[1] initially as a means of grinding grain; during the middle ages it was applied to a wide variety of industrial processes. But water-power, and its sister wind-power, were still special-purpose technologies, not universal energy sources. Limited by location and specialized use they did not problematize effort as such.

A note on terminology is in order here. The (admittedly not very elegant) verb 'to problematize' derives from the work of the philosopher Louis Althusser[1]. Althusser coined the term *problématique* (problematic) to refer to the field of problems or questions that define an area of scientific enquiry. The term is fairly closely related to Thomas Kuhn's idea of a scientific 'paradigm'. So, to problematize a domain is to transform it into a scientific problem-area, to construct new concepts which permit the posing of precise scientific questions. In the pre-modern era engineers and sea captains would know from experience how many men or horses must be employed, using pulleys and windlasses, to raise a mast or obelisk. Millers knew that the grinding capacity of water mills varied with the available flow in the mill lade. But there was no systematic equation or measure to relate muscular work to water's work, no scientific problematic of effort. That had to wait for James Watt, after whom we name our modern measure of the ability to work.

[1] See Strandh (1979), Ste. Croix (1981, p. 38).

Watt, the best-known pioneer of steam, did not actually invent the steam engine, but he improved its efficiency. As Mathematical Instrument Maker to the University of Glasgow he was called in to repair a model steam engine used by the department of Natural Philosophy (we would now call it Physics). The machine was a small scale version of the Newcomen engine that was already in widespread use for pumping in mines.

The Newcomen engine was an 'atmospheric engine'. It had a single cylinder, the top half of which was open to the atmosphere (Figure 1.1). The lower half of the cylinder was connected via two valves to a boiler and a water reservoir. The piston was connected to a rocking beam the other end of which supported the heavy plunger of a mine pump. The resting condition of the engine was with the piston pulled up by the counter-weight of the pump plunger.

To operate the machine, the boiler valve was opened first, filling the cylinder with steam. This valve was then closed and the water-reservoir valve opened, spraying cold water into the piston. This condensed the steam, resulting in a partial vacuum. Atmospheric pressure on the upper surface of the piston then drove it down, providing the power-stroke. The two phase cycle could then be repeated to obtain regular pumping.

Watt observed that the model engine could only carry out a few strokes before the boiler ran out of steam and it had to rest to 'catch its breath'. He ascertained that this was caused by the incoming steam immediately condensing on the walls of the cylinder, still cool from the previous water spray. His solution was to provide a separate condenser, permanently water cooled, and intermittently connected to the cylinder by a valve mechanism. The cylinder, meanwhile, was provided with a steam-filled outer jacket to keep its inner lining above condensation temperature (Figure 1.1). His 1769 patent was for "A New Method of Lessening the Consumption of Steam and Fuel in Fire Engines".

Watt's later business success was based directly on this gain in thermal efficiency. His engines were not sold outright to users, but were leased. The rental paid was equal to one-third the cost of coal saved through using a Watt engine rather than a Newcomen engine [2](Tann, 1981). This pricing system worked so long as the Newcomen engine provided a basis for comparison, but as Watt's engines became the predominant type, and as they came to be used to power an ever-widening range of machines, some system of rating the working capacity of the engines was needed. Watt needed a standardized scale by which he could rate the power, and thus the rental cost, of different engines. His standardized measure was of course the horsepower: users were charged £5 per horsepower year.

Watt's horse was not a real horse of course, but the abstraction of a horse, a standardized horse. The abstraction is multiple: at once an abstraction from particular horses, an abstraction from the difference between flesh and blood horses

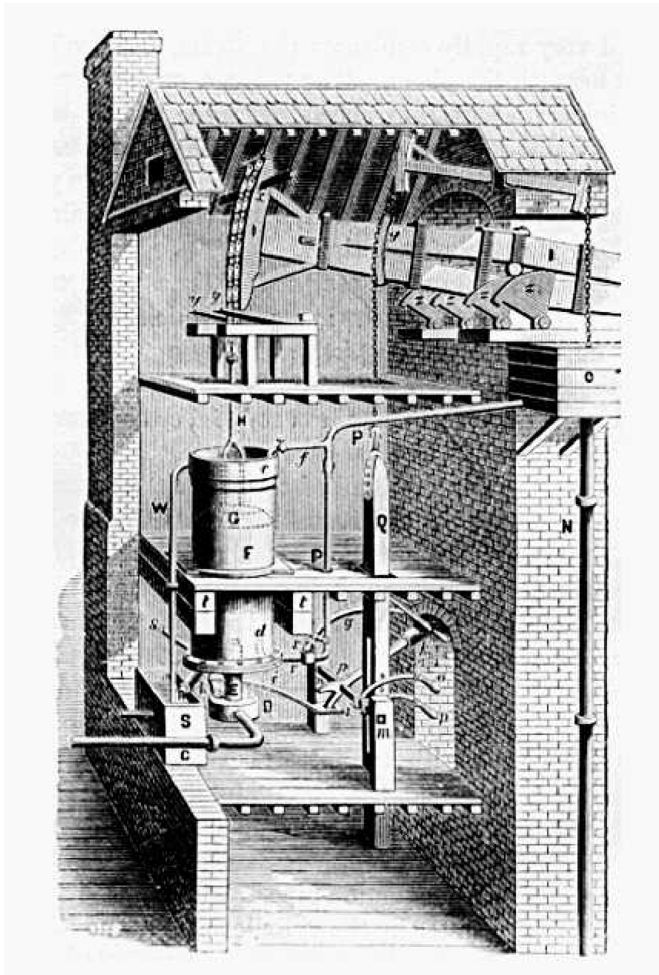

Figure 1.1: The Newcomen engine built by Smeaton (reproduced from Thurston)

and iron ones, and an abstraction from the particular work done. The work done had to be defined in the most abstract terms, as the overcoming of resistance in its canonical form, namely raising weights. One horsepower is 550 ft lb/sec, the ability to raise a load of 1 ton by 15 feet in a minute.

While few real horses could sustain this kind of work, its connection to the task performed by Watt's original engines is clear. The steam engine was a direct replacement for horse-operated pumps in the raising of water from mines. But with the development of mechanisms like Watt's sun and planet gear, which converted linear to rotary motion, steam engines became a general purpose power source. They could replace water wheels in mills, drive factory machines by systems of axles and pulleys, pull loads on tracks. Engine capacity measured in horsepower abstracted from the concrete work that was being performed, transforming it all to **work** in general. Horsepower was the capacity to perform a given amount of work each second. By defining power as work done per second, work in general was itself implicitly defined. All work was equated to lifting. Work in general was defined as the product of resistance overcome, measured in pounds of force, by the distance through which it was overcome.

Mechanical power seemed to hold the prospect of abolishing human drudgery and labour. As Matthew Boulton proudly announced to George II: "Your Majesty, I have at my disposal what the whole world demands; something which will uplift civilization more than ever by relieving man of undignified drudgery. I have steam power."[2] To a world in which human muscle was a prime mover, this equation of work in the engineering sense with human labour was exact. Work on ships, in mines, at the harvest, was work in the most basic physical sense. Men toiled at windlasses to raise anchors, teams pulled on ropes to set sails and hauled loads on their backs to unload cargo. Children dragged coal in carts from drift mines, women carried it up shafts in baskets on their backs. The 'navigators' who built canals did it with no mechanical aid more sophisticated than the wheelbarrow (a combination of lever and wheel, two Archimedean devices).

As horsepower per head of population multiplied, so too did industrial productivity. The power of steam was harnessed, first to raise weights, then to rotate machinery, then to power water-craft, next to trains—and eventually, through the mediation of the electricity grid, to tasks in every shop and home—while human

[2]Compare Antipater of Thessalonika's eulogy on the introduction of the water mill:

> Stop grinding, ye women who toil at the mill
> Sleep on, though the crowing cocks announce the break of day
> Demeter has commanded the water nymphs
> to do the work of your hands
> Jumping one wheel they turn the axle
> Which drives the gears and the heavy millstones

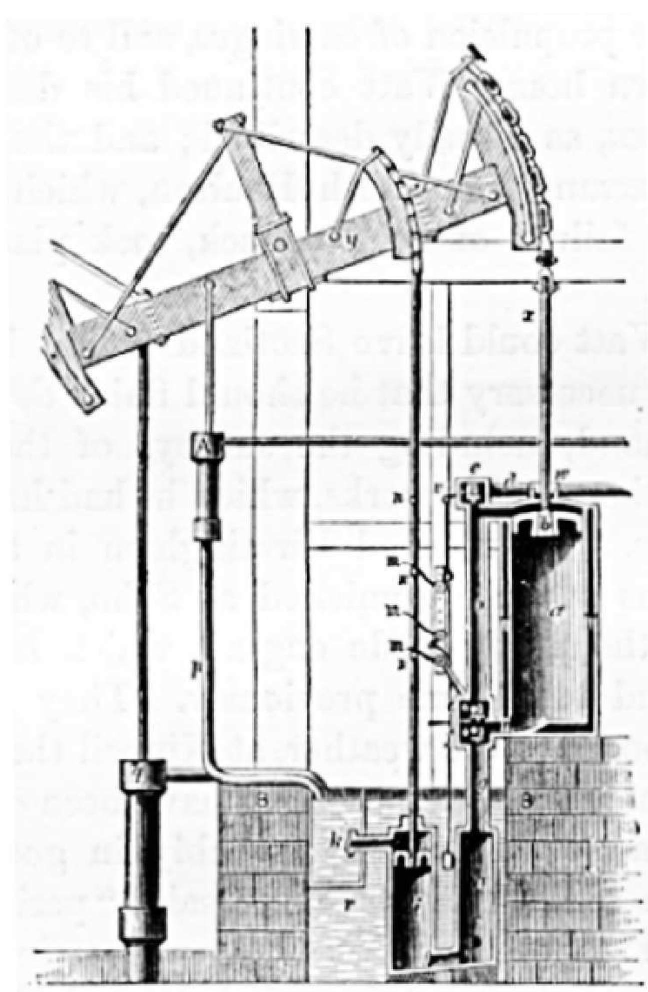

Figure 1.2: Watt's steam engine with separate condenser (reproduced from Thurston)

work shrank as a proportion of the total work performed. More and more work was done by artificial energy, yet the need for people to work remained. A steam locomotive might draw a hundred-ton train, but it needed a driver to control it. Human work became increasingly a matter of supervision, control and feeding of machines. Thus the identification of work with the overcoming of physical resistance in the abstract, and of human labour-power with power in Watt's sense, contained both truth and falsehood. Its truth is shown by the manifest gains flowing from the augmentation of human energy. Its falsity is exposed by the residuum of human activity that expresses itself in the control, minding and direction of machinery.

Indeed, the introduction of powered machinery had the effect of lengthening the working day while making work more intense and remorseless. The cost of powered machinery was such that only men with substantial wealth could afford it. Cheap hand-powered spindles and looms could not compete with steam-powered ones. Domestic spinners and hand-loom weavers had to give up their independence and work for the owners of the new steam powered 'mules' and looms. Steam power brought no increase in leisure for weavers or spinners. The drive to recoup the capital cost of the new machinery brought instead longer working hours and shift-work, to a rhythm dictated by the tireless engine. The fact that the machinery was not owned by those who worked it, meant that it enslaved rather than liberated.

A particular pattern of ownership was the social cause of machine-enforced wage slavery, but that is only half the story. We may ask why the new machine economy needed human labour at all. Why did 'self acting'—or as we would put it now, 'automatic'—machines not displace human labour altogether? A century ago, millions of horses toiled in harness to draw our loads. Where are they now? A remnant of their former race survives as toys of the rich; the rest went early to the knackers. Why has a similar fate not befallen human workers? Why has the race of workers not been killed off, to leave a leisured rich attended by their machines?

Watt's horsepower killed the horse, but the worker survived. There must be some real difference between work as defined by Watt, and work in the sense of human labour.

1.2 Marx: The Architect and the Bee

Karl Marx proposed an argument which seems at first sight to get to the essence of what distinguishes human labour from the work of an animal or a machine, namely purpose.

> An immeasurable interval of time separates the state of things in which a man brings his labour-power to the market for sale as a commodity, from that state at which human labour was still in its first instinctive stage. We pre-suppose labour in a form which stamps it as exclusively human. A spider conducts

> operations that resemble those of a weaver, and a bee puts to shame many an architect in the construction of her cells. But what distinguishes the worst of architects from the best of bees is this, that the architect raises his structure in the imagination before he erects it in reality. At the end of every labour process we get a result that already existed in the imagination of the labourer at its commencement. He not only effects a change of form in the material on which he works, but he also realises a purpose of his own that gives the law to his modus operandi, and to which he must subordinate his will. (Marx, 1970, pp. 177–8)

This suggests that animals, lacking purpose, can be replaced by machines, but that humans are always required, in the end, to give purpose to the machine. We cite Marx's statement because it articulates what is probably a rather widely held view, yet it has several interesting problems. This is an issue where it is difficult to go straight for the 'right answer'. It may be profitable to beat the bushes first, to scare up (and shoot down) various prejudices that can block the road to a scientific understanding.

First, are animals really lacking in purpose? The spider may be so small, and her brain so tiny, that it seems plausible that blind instinct, rather than the conscious prospect of flies, drives her to spin. But it is doubtful that the same applies to mammals. The horse at the plough may not envisage in advance the corn he helps to produce, but then he is a slave, bent to the purpose of the ploughman. Reduced to a source of mechanical power, overcoming the dumb resistance of the soil, he is readily replaced by a John Deere. The same cannot be said of animals in the wild. Does the wolf stalking its prey not intend to eat it? It plans its approach with cunning. Who are we to say that the result—fresh caribou meat—did not "already exist in the imagination" of the wolf at its commencement? We have no basis other than anthropocentric prejudice on which to deny her imagination and foresight.

Turn to Marx's human example, an architect, and his argument looks even shakier. For do architects ever build things themselves? They may occasionally build their own homes, but in general what gives them the status of architects is that they don't get their hands dirty with anything worse than India Ink. Architects draw up plans. Builders build. (In eliding this distinction Marx showed an uncharacteristic blindness to class reality).

An office block, stadium or station has, it is true, some sort of prior existence, but as a plan on paper rather than in the mind of the builders. If by collective labour civilized humans can put up structures more complex than bees, it is because they can read, write and draw. A plan—whether on paper or, as in earlier epochs, scribed on stone—coordinates the individual efforts of many humans into a collective effort.

For building work then, Marx is partially right, the structure is raised *on paper* before it is raised in stone. But he is wrong in saying that it is built in the imagination first, and in implying that the structure is put up by the architect. What is really unique to humans here is, first, the social division of labour between the labour of conception by the architects and the work of execution by the builders, and second, the existence of *materialized plans*: configurations of matter that can control and direct the labour of groups of humans.

While insect societies may have a division of labour between 'castes', for example between worker and soldier termites, they do not have a comparable division between conception and execution, between issuers and followers of orders. Nor do insects have technologies of record and writing. They can communicate with each other. Dancing bees describe to others the whereabouts of flowers. Walking ants leave scent trails for their companions. These messages, like human speech, coordinate labour. Like our tales, they vanish in the telling. But, not restricted to telling tales, we can can make records that persist, communicated over space and time.

Our tales are richer too. The set of messages that can be expressed in our languages is exponentially greater than in the language of bees. Each works by the sequential combination of symbols—words for us, wiggles for bees—but we have many more symbols and can understand much longer sequences. The number of distinct messages that can be communicated by a language is proportional to v^m where v is the number of distinct symbols that can be recognized in the language and m is the maximum message length. If bees have a repertoire of six types of wiggles and can understand 'sentences' of three wiggles in succession then they can send $6^3 = 216$ different messages. A human language with a vocabulary of 3000 words and a maximum sentence length of 20 words could convey about $3.486784401 \times 10^{69} = 348,678,440,100,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000$ distinct sentences. Of course, not all of these would be grammatically correct, and a rather small proportion of those would make any sense, but the number of messages is still astronomically greater than what insects can manage. And we can keep piling on the sentences until the listener loses track.

All this leaves open another interpretation of what Marx had to say. True enough, architects may not build theatres themselves, any more than Hadrian built his wall[3] or Diocletian his baths. But Hadrian caused the wall to be built and Diocletian's architect caused the baths to be built to a specific design. (This use of the word 'built' is of course common in class societies, where real builders get no credit for their creations. Their labour contributes instead to the fame of a ruler or architect.) If the architect creates only a paper version of a theatre, can

[3] It was of course the rank and file legionnaires who built the wall; see Davies (1989).

we say, at any rate, that he creates this drawing in his mind before setting it down on paper? This interpretation of Marx's story of the architect and the bee seems to make sense, but it's not clear that it's a true description of what an architect actually does.

1.2.1 Emergent buildings

Some individuals, autistic infant prodigies or 'idiot savants', do seem to have the ability to hold in their minds almost photographically detailed images of buildings they have seen. Working from memory they are able to draw buildings in astonishing and accurate detail.[4] But it is questionable whether professional architects work this way. Some may, but for others the process of developing a design is intimately tied up with actually drawing it. They start with the broad outlines of a design in their minds. As this is transferred to paper, they get the contexts within which the mind can work to elaborate and fill in details. The details were not in the mind prior to starting work, they emerge through the interaction of mind, pen and paper. Pencils and paper don't just record ideas that exist fully formed, they are part of a production process that generates ideas in the first place.

At any one time our consciousness can focus on only a limited number of items. On the basis of what it is currently conscious of, its context, it can produce responses related to this context. In reverie the context is internal to the brain and the responses are new ideas related to this context. In an activity like drawing a plan or engineering diagram, the context has two parts

(1) an internal state of mind; and

(2) that part of the diagram upon which visual attention is fixated,

and the response is both internal—a new state of mind—and external—a movement of the pencil on the paper.[5] Where in reverie the response, the new idea, slipped all too easily from grasp, paper remembers.[6] Architecture exchanges for the fallibility and limited compass of memory the durability of an effectively infinite supply of A0. One might say that complex architecture rests on paper foundations.

If the idea of the architect as creating buildings spontaneously out of the imagination is dismissed as an almost religious myth, redolent of the Masonic characterization of the deity as the *Great Architect*, what then remains of the antithesis between architect and bee? Well, how do the bees shape their hive? We can be

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[4]It may be worth seeing if we could reproduce some images by such autistic artists

[5]The reader may notice that this argument is a thinly disguised version of Alan Turing's famous argument of 1937.

[6]Cite the passage in Tacitus, I think it is in the Annals, where he says that civilization depends upon Papyrus.

sure there are no drawings of hexagons, made by the 'queen',[7] and executed by her worker daughters. We are talking here of *apis mellifera* not the solitary bumble bee. The labour of the honey bees is collective, like that of workers on a building site, yet although they have no written plans to work from they create a geometrically precise, optimal and elegant structure.

1.2.2 Apian efficiency

Consider the problem to which the honeycomb is the answer: to come up with a structure that is interchangeably capable of storing honey or sheltering bee larvae, is waterproof, is structurally stiff, provides a platform to walk on and which uses the minimum material. Given this design brief it is unlikely that a human engineer could come up with a better structure.

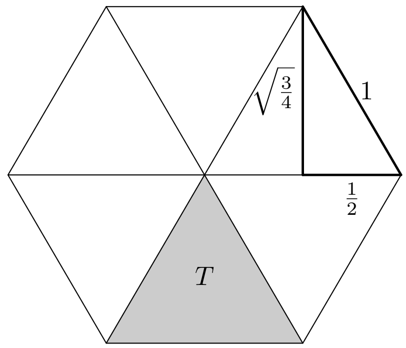
The structure has to be organized as a series of planes to provide access. Within the planes, the combs, the space has to be divided into approximately bee-sized cubicles. These could be triangular, square, or hexagonal (the only three regular tessellations of the plane). Our architects have a predilection for the rectilinear, but the hexagonal form is superior.

Figure 1.3: Tessellation of the plane using hexagons

A tessellation of unit squares has a wall length of 2 per unit area, since a single unit square has four sides of unit length, each shared 50 percent with its neighbours. A tessellation of hexagons of unit area has a wall length of $\frac{2}{\sqrt{3}}$ per unit area, a reduction by a factor of $\sqrt{3}$ (see Digression 1.1). The honeycomb structure used by bees is thus more efficient in its use of wax than a rectilinear arrangement would be.

[7]The breeding female is no more an architect or Caesar than the Pope is the genetic father of his followers. Monarchy and patriarchy project dominance relations onto genetic relations and vice versa. Apian Mother becomes queen, the Vatican monarch, Holy Father.

Digression 1.1 Apian efficiency



(1) A hexagon of unit side is made up of 6 identical equilateral triangles, thus its area is $6T$ where T is the area of an equilateral triangle of unit side.

(2) The area of an equilateral triangle of unit side is $\frac{1}{2}bh$ where b the base $= 1$ and h the height $= \sqrt{\frac{3}{4}}$. So $T = \frac{1}{2}\sqrt{\frac{3}{4}} = \frac{\sqrt{3}}{4}$.

(3) The area of one hexagon is then

$$6\frac{\sqrt{3}}{4} = \frac{3\sqrt{3}}{2}$$

(4) The hexagon's six sides are each shared 50% with a neighbour.

(5) Wall per unit area for a hexagonal tessellation is then $3/\frac{3\sqrt{3}}{2} = 2/\sqrt{3}$ which is better than the wall to area ratio for squares.

The fact that hexagonal lattices minimize boundary lengths per unit area means that they can arise spontaneously, for example in columnar basalts.[8] Here the tension induced in rocks as they cool encourages cracking, preferentially giving rise to six sided columns. We might suspect that the beehive too, gained its structure from a process of spontaneous pattern formation analogous to columnar basalts or packed arrays of soap bubbles. But this doesn't tally with the way the cells are built up, or with the uniformity of their dimensions. In a partially constructed honeycomb the cells are of a constant diameter; those in the middle of the comb are all of uniform height while towards the edge the depth of the cells falls. The bees build the cells up from the base, laying wax down on the upper margins of the cell walls, just as bricks are added to the upper margin of a wall by a bricklayer. The construction process takes advantage of the inherent stability of a hexagonal lattice, allowing the growing cells to form their own scaffolding. But the process also demands that the bees can deposit wax accurately on the growing cell walls, and that they stop building when the cells have reached the right height. That is, it depends on purposeful activity on the part of the bees.

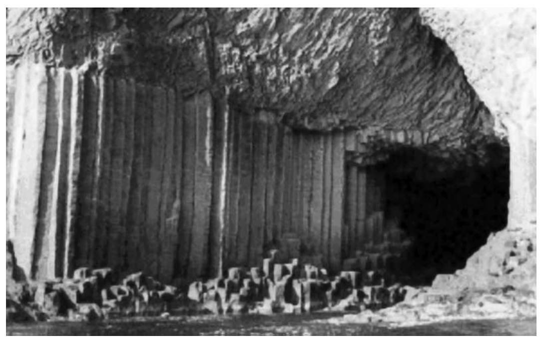


Figure 1.4: Nature is the architect of the hexagonal columns of Fingal's cave (Photo by Andrew Kerr)

A similar process takes place in the human construction of geodesic domes, hexagonal lattices curved through a third dimension. These have an inherent stability that becomes more and more evident as you add struts to them. You build them up in a ring starting at ground level. The structure initially has a fair bit of play in it, but the closer the structure comes to a sphere the more rigid it is. Human dome builders, like bees, exploit the inherent structural properties of hexagonal lattices, but they still need to cut struts to the right length and put them in the cor-

[8]Should we have a photo of the rocks around Fingal's Cave?

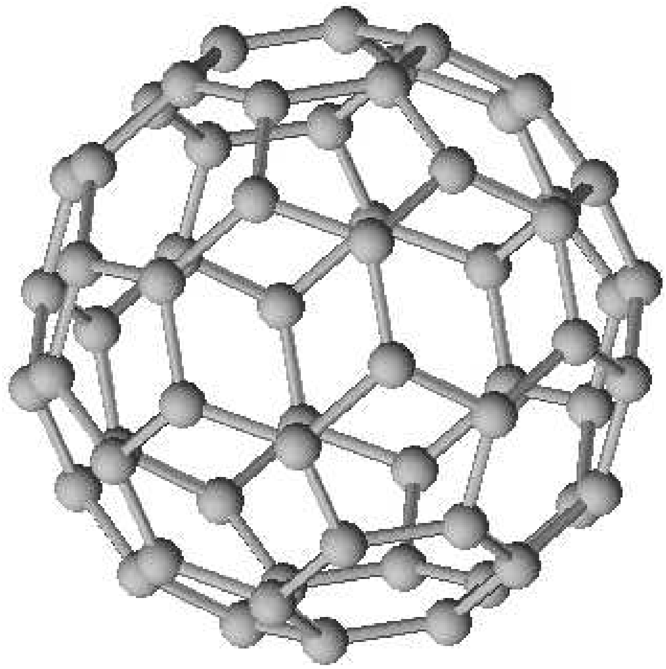


Figure 1.5: C_{60} a spontaneously formed dome structure

rect place. The bees likewise must select the right height for their cell walls and place wax appropriately.

Spontaneous self-assembly of hexagonal structures similar to geodesic domes does occur in nature. The Fullerenes are a family of carbon molecules named after Buckminster Fuller, the inventor of the geodesic dome. The first of these to be discovered, C_{60}, has the form of a perfect icosahedron (see Figure 1.5). Condensed out of the hellish heat of a carbon arc, it depends on thermal vibrations to curve the familiar planar hexagonal lattice of graphite onto itself to form a three dimensional structure. No architect or bee is required. Atomic properties of carbon select the strut length. Thermal motion searches the space of possible configurations; a small fraction of the molecules settle into the local energy minima represented by C_{60} and its sisters.

If the bees can't rely upon spontaneous self-assembly to build their hives, must they have a plan in mind before they start? Since they can't draw, the mind would have to be where they held any plans. While we can't rule this out, it seems unlikely. The requirement is that they can execute a program of work. A bee arriving on the construction site with a load of wax must, in the darkness, find an appropriate place to put it, for which they need a set of rules:

> If the cell is high enough to crawl into, put no more wax on it,
> otherwise if the cell has well formed walls add to their height,
> otherwise if it is a cell base smaller than your own body diameter, expand it,
> otherwise start building the wall up from the base...

No internal representation of a completed comb need be present in the bee's mind. The same rules, simultaneously present in each of a hive full of identical cloned sisters, along with the structural properties of beeswax, produce the comb as an emergent complex structure. The key here is the interaction between behavioral rules and an immediate environment that is changed as the result of the behaviour. The environment, the moulded wax, records the results of past behaviour and conditions future behaviour. But for rules to be converted into behaviours by the bees, the bees must have internal 'states of mind', and be able to change their state of mind in response to what their senses are telling them. A bee that is busy laying down wax is in a different state of mind from one foraging for pollen and their behavioral repertoire differs as a result.

As we have argued above, what an architect does is not so different. Architects produce drawings, not buildings or hives, but producing a drawing is an interactive process in which the architect's internal state of mind, his knowledge of the rules and stylistic conventions of the epoch, produces behaviour that modifies the immediate environment—the paper. The change to the paper creates a new environment, modifying his state of mind and calling into action other learned rules and skills. The drawing is an emergent property of the process, not something that pre-existed as a complete internal representation before the architect put pencil to paper.

1.3 The Demonic challenge

Purposeful labour depends upon the ability to form and follow goals. A goal is a representation of a state of affairs that does not exist plus a motivation to achieve it. Although bees do not have the goal processing capabilities of the human mind, they nonetheless follow simple goals. Goal processing, from simple, reactive programs hard-wired in the neural circuitry of insects, to the much more adaptive and sophisticated rational planning capabilities of humans, is the mechanism that distinguishes the constructive activity of humans and bees from the blind efforts of Watt's engines. An engine transforms energy in one form to another, but it does not act to achieve states of affairs, unlike bees that build or humans that labour.

There is a hidden connection between purposeful labour and work in the engineering sense. Any purposeful activity overcomes physical resistance and involves *work*, measured in watts, for which we must be fueled by calories in our food; the hidden connection comes from the realization that, at least in principle, purposeful labour could itself be a source of fuel.

Recall that Watt's key invention was the separate condenser for steam engines, which saved fuel by preventing wasteful condensation of steam within the cylinder of the engine. In the years after Watt's invention, it came to be realized that the thermal efficiency of steam engines could be improved by maximizing the pressure drop between the boiler and the condenser. A series of inventions followed to take advantage of this principle: Trevithick's high pressure engine, the double and then the triple expansion engine. These had the effect of increasing the amount of effective work that could be extracted from a given amount of heat. But successive gains in efficiency proved harder to come by. The amount of work obtained per calorie of heat could be increased, but not without limit.

It was understood that work could be converted into heat, for instance through friction, and heat could be converted back into work, for instance by a steam engine. But if you convert work into heat, and heat back into work, you always end up with less work than you put in. In converting work into heat, the number of calories of heat obtained per kilowatt hour of work is constant—conversion of work into heat can be done with 100 percent efficiency. The reverse is not true. Heat can never be fully converted into useful work.[9] The practical imperative of improving steam engines gave rise to the theoretical study of the laws governing heat, the laws of thermodynamics.

One of the first formulations of the second law of thermodynamics was that heat will never spontaneously flow from somewhere cold to somewhere hot.[10] This implied that, for instance, there was no chance of transferring the heat wasted in the condenser of a steam engine back to the boiler where it would boil more water. Thermodynamics ruled out perpetual motion machines.

But James Clerk Maxwell, one of the early researchers in thermodynamics, came up with an interesting paradox.

> One of the best established facts of thermodynamics is that it is impossible in a system enclosed in an envelope which permits neither change of volume nor passage of heat, and in which temperature and pressure are everywhere the same, to produce any inequality of temperature or of pressure without the expenditure of work. This is the second law of thermodynamics, and it is undoubtedly true as long as we can deal with bodies only in mass, and have

[9] Carnot was able to show that the efficiency of heat engines depended on the temperature difference between heat source, for example the boiler, and the heat sink, for example a steam engine's condenser.

[10] This formulation was due to Clausius in 1850; see Porter (1946, pp. 8–9).

> no power of perceiving or handling the separate molecules of which they are made up. But if we can conceive of a being whose faculties are so sharpened that he can follow every molecule in its course, such a being would be able to do that which is presently impossible to us. For we have seen that the molecules in a vessel full of air at a uniform temperature are moving with velocities by no means uniform, though the mean velocity of any great number of them, arbitrarily selected, is almost exactly uniform. Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without the expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics. (James Clerk Maxwell, 1875, pp. 328–329)

The configuration of the thought experiment is shown in Figure 1.6. As the experiment runs the gas on one side heats up while that on the other side cools down. The end result is a preponderance of slow molecules in cavity A, fast ones in cavity B. Since heat is nothing more than molecular motion, this means that A has cooled down while B has warmed up. No net heat has been added, it has just re-distributed itself into a form that becomes useful to us. Since B is hotter than A, the temperature differential can be used to power a machine. We can connect B to a boiler and A to a condenser and obtain mechanical effort. An exercise of purposeful labour by the demon outwits the laws of thermodynamics. (Norbert Wiener coined the term 'Maxwell demon' for the tiny 'being' envisaged in the thought experiment.) It seems that the second law of thermodynamics expresses the coarseness of our senses rather than the intractability of nature.

1.4 Entropy

One perspective on the devilment worked by Maxwell's demon is that it has *reduced the entropy* of a closed system. The idea of entropy was introduced by Clausius in 1865 (see Harrison, 1975) with the equation

$$\Delta S = \Delta Q/T \tag{1.1}$$

where ΔS is the change in entropy of a system consequent upon the addition of a quantity of heat ΔQ at absolute temperature T.[11] According to Clausius's equation adding heat to a system always increases its entropy (and subtracting heat always

[11] At this stage the concept of entropy remains firmly linked to the sort of practical considerations, namely steam engine design, that gave rise to thermodynamics. Later, as we shall see, it becomes generalized.

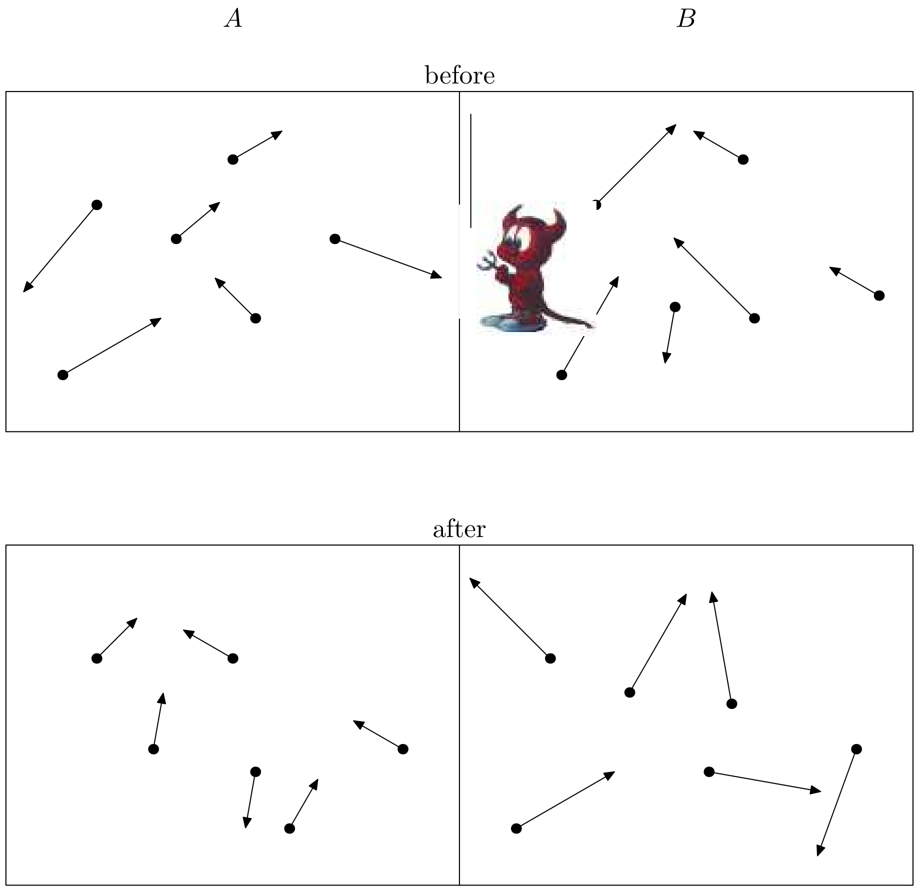


Figure 1.6: Gas initially in equilibrium. Demon opens door only for fast molecules to go from A to B, or slow ones from B to A. Result Slow molecules in A, fast in B. Thus B hotter than A, and can be used to power a machine.

lowers entropy) but the magnitude of the change in entropy is inversely related to the initial temperature of the system. Thus if a certain amount of heat is transferred from a hotter to a cooler region the increase in entropy in the cooler region will be greater than the reduction in entropy in the hotter, and overall entropy rises. Conversely, if heat is transferred from a colder to a hotter region entropy falls. Clausius's concept of entropy as an abstract quantity allowed him to give the second law of thermodynamics its canonical form: the entropy of any closed system tends to increase over time.

Using (1.1) we can readily see that Maxwell's demon violates the second law of thermodynamics. Suppose the demon has been hard at work for some time, so that B is hotter than A, specifically B is at 300° Kelvin and A is at 280° Kelvin. He then transfers ΔQ =1 joule of heat from A to B. In doing so he reduces the entropy of A by $\frac{1}{280}$ joules per degree and increases the entropy of B by $\frac{1}{300}$ joules per degree giving rise to $\Delta S = \frac{1}{300} - \frac{1}{280} = -\frac{1}{4200}$, a net reduction in entropy, contrary to the second law.

Clausius's formulation of entropy did not depend in any way upon the atomic theory of matter. Maxwell's proposed counter-example to the second law was explicitly based on atomism. With Boltzmann, entropy is placed on an explicitly atomistic foundation, in terms of an integral over molecular *phase space*.

$$S = -k \int f(v) \log f(v) dv \tag{1.2}$$

where v denotes volume in six-dimensional phase space, $f(v)$ is the function that counts the number of molecules present in that volume, and k is Boltzmann's constant.

The concept of phase space is a generalization of our normal concept of three-dimensional space to incorporate the notion of motion as well as position. In a three-dimensional coordinate system the position of each molecule can be described by three numbers, measurements along three axes at right angles to one another. We usually label these numbers x, y, z to denote measurements in the horizontal, vertical and depth directions. However each molecule is simultaneously in motion. Its motion can likewise be broken into components of horizontal, vertical and depth-wise motion which we can write as m_x, m_y, m_z, representing motion to the left, up and back respectively. This means that a set of six coordinates can fully describe both the position and motion of a particle.

In Boltzmann's formula, the letter v denotes a range of possible values of these co-ordinates. For example, a volume 1 mm cubed on the spatial axes and 1 mm per second on the motion axes. The function $f(v)$ would then specify how many molecules there were in that cubic millimeter with a range of velocities within 1 mm per second in each direction. Boltzmann's formula relates the entropy of a gas, for instance steam in a piston, to the evenness of its distribution in this six dimensional space: the less even the distribution the lower the entropy. This point is illustrated in simplified manner in Table 1.1. Suppose we have just two cells in phase space, and eight atoms that can be in one cell or the other. The table shows how the entropy depends on the location of the atoms, lowest when all 8 are in one cell, and highest when they are evenly divided between the cells. (Note that the minus sign in Boltzmann's formula is needed to make entropy increase with the evenness of the distribution, consistent with Clausius's earlier formulation.)

Contents of cells 1, 2	$f(1)\log f(1) + f(2)\log f(2)$	Entropy, S
8, 0	8(2.079) + 0 = 16.636	$-16.636k$
7, 1	7(1.946) + 1(0) = 13.621	$-13.621k$
6, 2	6(1.792) + 2(0.693) = 12.137	$-12.137k$
5, 3	5(1.609) + 3(1.099) = 11.343	$-11.343k$
4, 4	4(1.386) + 4(1.386) = 11.090	$-11.090k$

Table 1.1: Boltzmann's entropy: Illustration

Boltzmann also showed that it is possible to reformulate the idea of entropy using the concept of the 'thermodynamic weight' of a state:

$$S = k \log W \tag{1.3}$$

The thermodynamic weight W is the number of physically distinct microscopic states of the system consistent with a given 'macro' state, described by temperature, pressure and volume. This concept is the key to understanding the second law. Recall that the entropy of closed systems tends to increase, that is they move into macro-states of progressively higher thermodynamic weight until they reach equilibrium. States with higher weight are *more probable.* So the second law of thermodynamics basically says that systems evolve into their most probable state.

A simple analogy may be helpful here. Suppose a 'fair' coin is flipped ten times. What is the most likely ratio of heads to tails in the sequence of flips? The obvious answer, 5/5, is correct. Now, what is the most likely specific sequence of heads and tails? Trick question! There are $2^{10} = 1024$ such sequences and they are all equally likely. The sequence featuring 10 heads has probability $\frac{1}{1024}$; so does the sequence with 5 heads followed by 5 tails; so does the sequence of strictly alternating heads and tails, and so on. The reason why a 5/5 ratio of heads to tails is most likely is that there are more specific sequences corresponding to this ratio that there are sequences corresponding to 10/0, or 7/3, or any other ratio. It's easy to

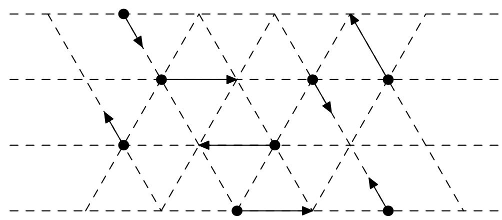


Figure 1.7: The molecules in a lattice gas move along the lines of a triangular grid with fixed velocities

see there is only one sequence corresponding to all heads, and one corresponding to all tails. To count the sequences that give a 5/5 ratio, imagine placing the 5 heads into 10 slots. Head number 1 can go into any of the ten slots; head number 2 can go into any of the remaining 9 slots, and so on, giving $10 \times 9 \times 8 \times 7 \times 6$ possibilities. But this is an over-statement, because we have treated each head as if it were distinct and identifiable. To get the right answer we have to divide by the number of ways 5 items can be assigned to 5 slots, namely $5 \times 4 \times 3 \times 2 \times 1$. This gives 252 possibilities. Thus the 'macro' result, equal numbers of heads and tails, corresponds to 252 out of the 1024 equally likely specific sequences, and has probability $\frac{252}{1024}$. By the same reasoning we can figure that a 6/4 ratio corresponds to 210 possible sequences, a lower 'weight' than the 5/5 ratio.

The number of possible states of a real gas in six-dimensional phase space is hard to visualize, so to explicate the matter further we'll examine a simpler system, namely a two-dimensional *lattice gas* (Frisch et al, 1986). The 'molecules' in such a stylized gas move with constant speed, one step along the lattice per unit time (see Figure 1.7). Where the lines of the lattice meet, molecules can collide according to the rules of Newtonian dynamics, so that matter, energy and momentum are conserved in each collision. The different ways in which collisions occur can be summarized by two simple rules:

(1) If a molecule arrives at an intersection and no molecule is arriving on the diagonally opposite path, then the molecule continues unimpeded.

(2) If two molecules collide head on they bounce off in opposite directions, as shown in Figure 1.8.

Lattice gases are a drastic simplification of real gases, but they are useful tools in analysing real situations. The simple rules governing the behaviour of lattice gases make them ideal models for simulation in computer software or special purpose hardware (Shaw et al, 1996).

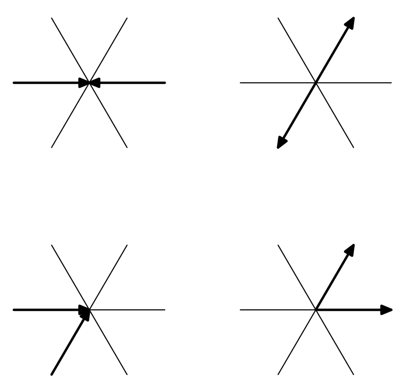


Figure 1.8: Collisions in a lattice gas: 'Molecules' colliding head on bounce off at 60° angles (above). In other cases the collision is indistinguishable from a miss (below). In all cases Newtonian momentum and energy are conserved.

Since the velocity of the molecules in a lattice gas is fixed, the temperature of the gas can't change (this would involve a rise or fall in the molecules' speed). So Maxwell's original example of a being with precise senses, able to sort molecules by speed, is inappropriate. But we can invent another demon to guard the trap-door. Instead of letting only fast molecules through from A to B, this being will keep the door open unless a molecule approaches it from side B. Thus molecules approaching from side A are able to pass into B, but those in B are trapped. The net effect is to raise the pressure on side B relative to A while leaving temperature unchanged.

A lattice gas has only a finite number of lattice links on which molecules can be found, and since the molecules move with a constant velocity, Boltzmann's formula (1.3) simplifies to:

$$S = -kn \sum_i p_i \log p_i \tag{1.4}$$

where p_i is the probability of the node being in state i and n is the number of nodes. The weighted summation over the possible states has the effect of giving us the mean value of $\log p$. Suppose we have a very small pair of chambers, A and B, each of which initially has n nodes, and each containing $3n$ randomly distributed molecules. Then each of the six incoming paths to a node will have a 50 percent chance of having a molecule on it. We have $6n$ incoming paths to our nodes, and each of these has two equally likely states: a particle is or is not arriving at each instant. Each incoming path contributes $k\log 2 = 0.693k$. The total entropy of the chamber is then six time this or:

$$\text{Entropy of A in equilibrium} = 4.158kn.$$

Now suppose that our demon has been operating for some time, letting n particles pass from A to B, so that A now contains $2n$ particles and B contains $4n$ particles. In A, the probability of a molecule coming down any one of the paths is now only $\frac{1}{3}$. We can calculate the current entropy contribution of each incoming path as follows:

Number of particles	probability, p_i	$\log p_i$	entropy, $-kp_i \log p_i$
0	$\frac{2}{3}$	-0.405	$0.27k$
1	$\frac{1}{3}$	-1.098	$0.366k$
total			$0.636k$

The entropy of A after n particles have been transferred by the demon is $3.816kn$ which is less than before he got to work. By symmetry of complementary probabilities the entropy of chamber B will be the same,[12] thus the whole closed system has undergone a reduction in entropy.

This establishes that when an initially dispersed population of particles—the gas molecules in our case—is concentrated, entropy falls.[13] This is because there are a greater number of possible microstates compatible with dispersion than with concentration, and entropy is just the log of the number of microstates.

Consider in this light the work of the bees building their hive. There are two aspects to the work:

(1) The bees first have to gather wax and nectar from flowers dispersed over a wide area and bring it to the hive.

(2) They must then form the wax into cells and place the concentrated nectar in these as honey.

Both processes are entropy-reducing with respect to the wax and the sugar. The number of possible configurations that can be taken on by wax within the few

[12] This will not generally be the case; we have chosen the particle densities so as to ensure this.

[13] This is true on the assumption that the potential, gravitational or electrostatic, of the particles is unchanged by the process of concentration as in our example.

litres volume of a hive is enormously less than the number of possible configurations of the same wax, dispersed among plants growing over tens of thousands of square meters of ground. Similarly the chance that the wax, if randomly thrown together within the hive, should assume the beautifully regular structure of a comb, is vanishingly small. That the wax should be in the hive in the first place, is, in the absence of bees, highly improbable; that it should be in the form of regular hexagons even more so.

The second law of thermodynamics specifies that the total entropy in a closed system tends to increase, but the bees and their wax are not a closed system. The bees consume chemical energy in food to move the wax. If we include the entropy increase due to food consumed, the second law is preserved.

1.4.1 Men and horses

Let us return to the question we asked in section 1.1: Why did the introduction of the steam engine, which made redundant the equine workers of the pre-industrial age, not also replace the human workers? We can make a rough analogy between the work done by horses in past human economies and the work done by the bees in transporting wax and nectar from flower to hive. This is in the main sheer effort, work in Watt's sense. Horses bringing bricks to a building site or bees transporting wax are doing similar tasks. What remains, the construction of the hive after the work of transportation is done or the building of the house once the bricks are delivered, is something no horse can do. Construction involves a complex program of actions deploying grasping organs, hands, mandibles, beaks etc., in which the sequence of operations is conditioned by the development of the product being made. Human construction differs from that of a bee or a bird in:

(1) the way in which the program of action comes into being;
(2) the way in which it is transmitted between individuals of the species; and
(3) the form in which it is materialized.

In the social insects the programs of action largely come into being through the evolutionary process of natural selection. They are transmitted between parents and their offspring genetically encoded in DNA, and they are materialized in the form of relatively fixed interactions between components of the nervous system and general physiology. In humans the programs of action are themselves products that can have a representation external to the organism, in speech or some form of notation. Speech and notation act both as a means of transmission between individuals, and as a possible form of materialization of work programs while the work is being carried out—as for example, when one cooks from a recipe or follows a knitting pattern. The ability to make and distribute new work programs distinguishes human labour from that of bees and is the key to cultural evolution.

But even the work of transport requires a program of action, requires guidance if it is to reduce entropy. Transport is not diffusion. It moves concentrated masses of material between particular locations, it does not spread them about willy nilly. Without guidance there is no entropy reduction. A horse, blessed with eyes and a brain as well as big muscles, will partially steer itself, or at least will do better than a bicycle or car in this respect. But teams still needed teamsters, if only to read signposts.

The steam railway locomotive revolutionized land transport in the nineteenth century, quickly replacing horse traction for long overland journeys. Guidance by steel track made steam power the great concentrator, bringing grain across prairies to the metropolis. Railway networks are action programs frozen in steel, their degrees of freedom discrete and finite, encoded in points. Point settings, signaled by telegraph, coordinate the orderly movement of millions of tons according to precise published timetables. Human work did not all lend itself so readily to mechanization.

CHAPTER 2

PROBLEMATIZING INFORMATION

We have suggested that doing purposeful productive labour typically reduces entropy. Such entropy-reducing work requires information in two forms, an action plan or capacity for behaviour, and information coming in from the senses to monitor the implementation of the action plan. Productive labour also involves work in Watt's sense of overcoming physical resistance. As such it consumes energy and produces an entropy increase in the environment that more than compensates for the entropy reduction effected in the object of labour. We have also seen how Maxwell postulated that it should be possible to reduce the entropy of a gas if there existed a being small enough to sort molecules. In this case the being would be using information from its senses, and in its action plan, to produce an entropy reduction in the gas with no corresponding increase elsewhere. Up to now we have not rigorously defined what we mean by information. Once this is done, we shall see the deeply hidden flaw in Maxwell's argument.

2.1 THE SHANNON–WEAVER CONCEPT OF INFORMATION

The philosopher Gaston Bachelard argues that the formation of a science is characterized by what he calls an 'epistemological break', which demarcates the language and ideas of the science from the pre-scientific discourses that appeared to deal with the same subject matter. Appeared to deal with the same subject, but did not really do so. For one of the characteristics of an epistemological break is a change in the *problematic*, which means roughly, the set of questions to which the science provides answers. With the establishment of a science the conceptual terrain shifts both in terms of the answers given and, more importantly, in terms of the questions that researchers regard as relevant.

The epistemological break that established information theory as a science occurred in the middle of the last century and is closely associated with the name of

Claude Shannon. We saw how Watt, seeking to improve the efficiency of steam pumps, contributed not only to an industrial revolution, but to a scientific revolution when he asked questions about the relationship between work and heat. From this problematic were born both a convenient source of power, and our understanding of the laws of thermodynamics. Shannon's revolution also came from asking new questions, and asking them in a very practical engineering context. Shannon was a telephone engineer working for Bell Laboratories and he was concerned with determining the capacity of a telephone or telegraph line to transmit information. Watt formalized the concepts of power and work in an attempt to measure the efficiency of engines. Shannon formalized the concept of information through trying to measure the efficiency of communications equipment. Practice and its problems lead to some of the most interesting truths.

To measure the transmission of information over a telephone line, some definite unit of measurement is needed, otherwise the capacity of lines of different quality cannot be meaningfully compared. According to Shannon the information content of a message is a function of how surprised we are by it. The less probable a message the more information it contains. Suppose that each morning the radio news told us "We are glad to announce that the Prime Minister is fit and well." We would soon get fed up. Who would call this news? It conveys almost no information. "Reports are just reaching us of the assassination of the Prime Minister." That is news. That is information. That is surprising.

A daily bulletin telling us whether or not the Prime Minister was alive would usually tell us nothing, then on one day only would give us some useful information. Leaving aside the circumstances of his death, if an announcement were to be made each morning, there would two possible messages

0 'The P.M. lives'

1 'The P.M. is dead'

If such messages were being sent over the sort of telegraph system that Shannon was concerned with, one could encode them as the presence or absence of a short electrical pulse, as a binary digit or 'bit' in the widely understood sense of the word. Shannon defines a bit more formally as the amount of information required for the receiver of the message to decide between two equally probable outcomes. For example, a sequence of tosses of a fair coin can be encoded in 1 bit per toss, such that heads are 1 and tails 0.

What Shannon says is that if we are sending a stream of 0 or 1 messages affirming or denying some proposition, then unless the truth and falsity of the proposition are equally likely these 0s and 1s contain less than one bit of information each. In that case there will be a more economical way of sending the messages. The trick is not to send a message of equal length regardless of its content, but to devise a system where the more probable message-content gets a shorter code.

Binary Code	Length	Meaning	Probability
0	1	False, False	$\frac{4}{9}$
10	2	False, True	$\frac{2}{9}$
110	3	True, False	$\frac{2}{9}$
111	3	True, True	$\frac{1}{9}$

Table 2.1: A possible code for transmitting messages that are true $\frac{1}{3}$ of the time

For example, suppose the messages are the answer to a question which we know a priori will be true one time in every three messages. Since the two possibilities are not equally likely Shannon says there will be a more efficient way of encoding the stream of messages than simply sending a 0 if the answer is false and a 1 if the answer is true. Consider the code shown in Table 2.1. Instead of sending each message individually we package the messages into pairs, and use between one and three binary digits to encode the 4 possible pairs of messages. Note that the shortest code goes to the most probable message, namely the sequence of two 'False' answers with probability $\frac{2}{3} \times \frac{2}{3} = \frac{4}{9}$. The codes are set up in such a way that they can be uniquely decoded at the receiving end. For instance, suppose the sequence '110100' is received: checking the Table, we can see that this can only be parsed as 110, 10, 0, or True, False, False, True, False, False.

To find the mean number of digits required to encode two messages we multiply the length of the codes for the message-pairs by their respective probabilities:

$$\frac{4}{9} + 2 \times \frac{2}{9} + 3 \times \frac{2}{9} + 3 \times \frac{1}{9} = 1\frac{8}{9} \approx 1.889 \tag{2.1}$$

which is less than two digits.

Shannon came up with a formula which gives the shortest possible encoding for a stream of distinct messages, given the probabilities of their individual occurrences.

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i \tag{2.2}$$

The mean information content of an ensemble of messages is obtained by weighting the log of the probability of each message by the probability of that message. He showed that no encoding of messages in 1s and 0s could be shorter than this. The formula gave him an irreducible minimum of the number of bits needed to transmit a message stream: this minimum was, he said, the real information content of the stream. Using Shannon's formula we can calculate the information content of the data stream encoded in the example above.

$$-\frac{4}{9}\times\log_2\frac{4}{9}-\frac{2}{9}\times\log_2\frac{2}{9}-\frac{2}{9}\times\log_2\frac{2}{9}-\frac{1}{9}\times\log_2\frac{1}{9}\approx 1.837 \qquad (2.3)$$

Since our code used $1\frac{8}{9}\approx 1.889$ bits for each pair of messages, we see that in principle a better code may exist.

In his 1948 article Shannon notes:

> Quantities of the form $H=-\sum_{i=1}^{n} p_i \log p_i$ play a central role in information theory as measures of information, choice and uncertainty. The form of H will be recognized as that of entropy as defined in certain formulations of statistical mechanics where p_i is the probability of a system being in cell i of its phase space. H is then, for example the H in Boltzmann's famous H theorem. We shall call $H=-\sum p_i \log p_i$ the entropy of the set of probabilities $p_1,\ldots,p_n$.

Shannon thus discovers that his measure of information is the same as Boltzmann's measure of entropy and decides that entropy and information are the same thing. Armed with this realization we can go back to the problem left to us by Maxwell. Could a sufficiently tiny entity violate the laws of thermodynamics by systematically sorting molecules?

Physicists have concluded that it is not possible. Leo Szilard, for example, pointed out that to decide which molecules to let through, the demon must measure their speed. He showed that these measurements (which would entail bouncing photons off the molecules) would use up more energy than was gained. Maxwell's demon, to vary the theological metaphor, was a *deus ex machina* (like Newton's God), able to know by immaterial means; Szilard's advance was to emphasize that knowledge or information is physical and can only come about by physical means. Leon Brillouin (1951) extended Szilard's analysis by pointing out that at a uniform temperature, black body radiation in the cavity would be uniform in all directions, preventing the demon from seeing molecules unless he had an additional source of light (and hence energy input).

It is possible, however, to build an automaton that acts as a Maxwell demon for a lattice gas. As we said before such gases can be simulated in software, or in hardware (see Figure 2.1), with each gas cell represented by a rectangular area of silicon and the paths taken by the molecules represented by wires. In such a system the demon himself is an automaton, a logic circuit, as in Figure 2.2. A circuit like this really does work: it transfers virtual gas molecules from chamber A to chamber B. Why does this work in apparent conflict with the laws of thermodynamics?

The behaviour of the demon is summarized in Table 2.2. Notice that while there are 4 possible combinations of input conditions, there are only 3 combinations of output conditions. This implies that we are moving from a system with

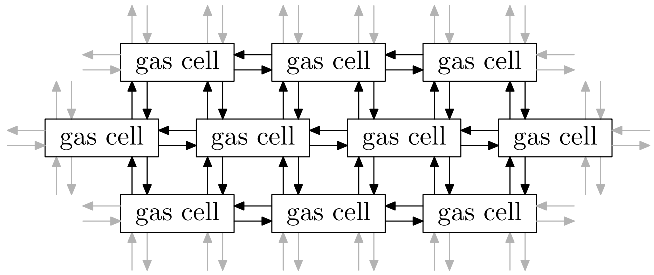


Figure 2.1: A lattice gas can be built in electronic hardware: each gas cell is represented by a rectangular area of silicon and the paths taken by the molecules are represented by wires.

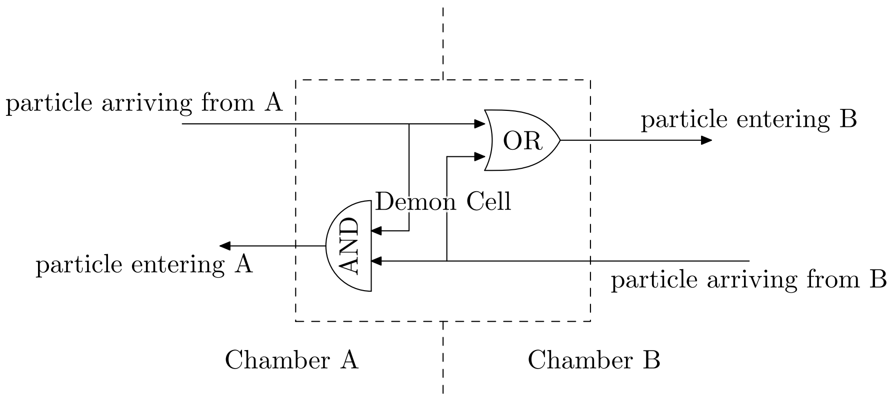


Figure 2.2: In a lattice gas, Maxwell's demon can be implemented with this logic circuit.

input from A	input from B	output to A	output to B	Comment
No	No	No	No	No molecules involved
No	Yes	No	Yes	Door shut, molecule bounces back to B
Yes	No	No	Yes	Molecule goes from A to B
Yes	Yes	Yes	Yes	Molecules bounce off one another

Table 2.2: The action plan of the demon

x	y	x AND y	x OR y
false	false	false	false
false	true	false	true
true	false	false	true
true	true	true	true

Table 2.3: Tabulation of the functions x AND y, x OR y

a higher thermodynamic weight to one with a lower weight, which is what we would expect for an entropy-reducing machine. Just how much it reduces entropy depends on the probabilities of occurrence of incoming particles from each side.

Suppose that the system is in equilibrium and that the probability of occurrence of a particle on the incoming paths on each side is 50 percent in each time interval. In that case each of the 4 possible input configurations in Table 2.2 is equiprobable and has an entropy of 2 bits= $\log_2 4$. Applying Shannon's formula (2.2) to the output configurations we get

$$\frac{1}{4}\log_2 4 + \frac{1}{2}\log_2 2 \frac{1}{4}\log_2 4 = \frac{1}{4}\times 2 + \frac{1}{2}\times 1 + \frac{1}{4}\times 2 = 1\frac{1}{2} \tag{2.4}$$

an entropy reduction of half a bit per time step. The key to how this can happen lies in the nature of the components used, logic gates for the functions AND and OR.

Rolf Landauer (1961) pointed out that any irreversible logic gate must destroy encoded information and in the process must dissipate heat. An irreversible logic gate is one whose inputs can't be determined from an examination of their outputs. Consider gates with two inputs and one output, such as the AND and OR gates whose truth functions are tabulated in Table 2.3. Roughly speaking they take two bits in and generate one bit out, thus destroying information within the system defined by the lines connecting the gates. Landauer argues that the lost information, i.e., the entropy reduction within the logic circuit, results in an increase in the entropy of the environment. Each time a logic circuit of this type operates, the lost internal entropy shows up as waste heat. By applying Shannon's formula (2.2) to the output of the AND gate we get the following:

Output	p_i	$-p_i \log_2 p_i$
false	$\frac{3}{4}$	≈ 0.311
true	$\frac{1}{4}$	0.5
	1	0.811

The output has an entropy of *less* than one bit. Given that 2 bits of information went into the gate, a total of 1.189 bits are lost in processing the inputs. Since the probability structure of OR gates is the same, a similar information loss occurs going through these.

2.1.1 Information engines as heat engines

Boltzmann's constant (see equation 1.2) has the dimension joules per log-state degree Kelvin. Landauer saw that one can use this constant to convert entropy in Shannon's form, measured in log-states, to energy. The equation he established is

$$e = \ln(2)ktb \tag{2.5}$$

e represents the energy-equivalent, t is temperature in degrees Kelvin, b is the number of bits, and k is Boltzmann's constant, which has a value of about 1.38×10^{-23} joules per degree Kelvin. The remaining term in the conversion is the natural log (ln) of 2, to get us from the natural logarithms used by Boltzmann to the base-2 logarithms used in Shannon's information theory.

Using Landauer's equation we can calculate the heat energy, e_{AND}, generated by a single operation of an AND gate, in which 1.189 bits are lost:

$$e_{\text{AND}} = 1.189 \ln(2)kt$$

At room temperature, or roughly 300° Kelvin, this is 3.4×10^{-21} joules each time the gate switches. This is a very, very small quantity of energy which is at present mainly of theoretical interest. What it represents is the theoretical minimal energy cost of operating a two-input irreversible logic gate.

Now look again at the demon cell in Figure 2.2, which has a pair of input logic gates. The process of deciding whether to open or close the trapdoor must consume certain minimum Landauer-energy. The energy consumed by the logical decision to open or close the barrier makes the demon ineffective as a power source.

Watt started out investigating how to convert heat into work efficiently; he was concerned with minimizing the heat wasted from his engines. Since Landauer we have known that information processing, too, must dissipate heat, and that information processing engines are ultimately constrained by the same laws of thermodynamics as steam engines. We can calculate the thermodynamic efficiency of an information processing machine just as we calculate the efficiency of a steam engine. If a processor chip of the year 2000 had roughly 6 million gates and was clocked at 600Mhz, its dissipation of Landauer energy would then be $(600 \times 10^6) \times (6 \times 10^6) \times (3.4 \times 10^{-21}) = 16.3\mu$w, or 16 millionths of a watt. This is insignificant relative to the electrical power consumption of the chip, which would be of the order of 20 watts. It implies a thermodynamic efficiency of only around 0.0001%. As a point of comparison, steam engines prior to Watt had an efficiency of about 0.5%. The steam turbines in modern power stations convert around 40% of the heat used into useful work. Two centuries of development raised the efficiency of steam power by a factor of about 100.

In thermodynamic terms a Pentium processor looks pretty poor compared to an 18th century steam engine: the steam engine was 500 times more efficient! But if compare a Pentium with the Manchester Mk1, the first electronic stored program computer (Lavington, 1980), we get a different perspective. The Pentium has at least a thousand times as many logic gates, has a switching speed a thousand times greater and uses about one hundredth as much electrical power as the venerable valve-based Mk1. In terms of thermal efficiency, this represents an improvement factor of 100,000,000 in fifty years. If improvements in heat engine design from Watt to Parsons powered the first two industrial revolutions, the third has benefited from an exponential growth in efficiency that was sixteen times as rapid.[1]

We know from Carnot's theory that there is little further room for improvement in heat engines. Most of the feasible gains in their efficiency came easily to pioneers like Watt and Trevithick. We're now left with marginal improvements, such as the ceramic rotor blades that allow turbine operating temperatures to creep up. In the case of computers too, efficiency gains will eventually become harder to attain. There is still, to quote Feynman, "plenty of room at the bottom". That is, there is mileage yet in miniaturization. We have room for about a million-fold improvement before computers get to where turbines now are. However, as we take into account the growing speed and complexity of computers, the thermodynamic constraint on data processing will come to be of significance. On the one hand, if the efficiency of switching devices continues to grow at its current rate, they will be at close to 100% in about 30 years. On the other hand, as computers get smaller and faster the job of getting rid of the Landauer-energy, thrown out as waste heat, will get harder. In the 27 years following the invention of the microprocessor the number of gates per chip rose by a factor of some 3000. Processor speeds increased about 600-fold over the same period. Table 2.4 projects this rate of growth into the next century.

From being insignificant now, Landauer heat dissipation becomes prohibitive in about 30 years. A microprocessor putting out several kilowatts, as much as several electric heaters, is not a practical proposition. There is a time limit on the current exponential growth in computing power.

That is not to say that computer technology will stagnate in 40 years. Landauer's equation (2.5) has a free variable in *temperature*. If the computer is supercooled, its heat dissipation falls. But once we're in that game the rate of improve-

[1] Heat engine efficiency improved about ten-fold per century. Information engines have been improving at a factor of about 10^{16} per century.

year	*gates*	*clockspeed*	*landauer watts*
2000	8×10^{6}	600Mhz	16.3μw
2005	3.4×10^{7}	1.9Ghz	230μw
2010	1.5×10^{8}	6.4Ghz	3.24mw
2015	6.4×10^{8}	21Ghz	45.7mw
2020	2.8×10^{9}	68Ghz	643mw
2025	1.2×10^{10}	224Ghz	9.06w
2030	5.1×10^{10}	733Ghz	128w
2035	2.2×10^{11}	2.4Thz	1.80Kw
2040	9.5×10^{11}	7.8Thz	25.4Kw

Table 2.4: Projected Landauer heat dissipation in 21st century computers operating at 300° Kelvin.

ment in computer performance comes to be limited by improvements in refrigeration technology, and these are unlikely to be so dramatic.

2.2 Entropy reductions in action programs

Maxwell's demon cannot exist for real gases, but it can for lattice gases. If the demon really existed, he would reduce the laws of thermodynamics to the status of an anthropocentric projection onto reality. Lattice-gas devils, on the other hand, are not a threat to physics. They reduce the entropy of the gas, but only because they use logic gates with an external source of power. Nonetheless, their structure suggests something important. The demon reduces the entropy of the gas thanks to an action program which has four possible input states and only three possible output states.

We would suggest that this is not accidental: it would seem that *all production processes that produce local reductions in entropy are guided by an entropy-reducing action program*. Consider the bee once again, this time in its capacity as forager. In Maxwell's original proposal, the demon used its refined perception to extract energy from chaos. In reality a bee uses its eyes to enable it to extract energy from flowers. Were bees unable to see or smell flowers, their energy would be expended in aimless wandering followed by starvation. The bee uses information from its senses to achieve what, from its local viewpoint, is a reduction in entropy—the maintenance of homeostasis—albeit at a cost to the rest of the universe. To achieve this it requires a nervous system that performs entropy reduction on the input data coming into its visual receptors. At any given instant the bee's compound eyes are receiving stimuli from the environment. The number of possible different combinations of such stimuli is vastly greater than the number of instantaneous behavioural responses that it has while in flight—the modulation of the beat strength of a small number of thoracic muscles. In selecting one appropriate behavioural response out of a small repertoire, in response to a relatively large quantity of information arriving at its eyes, the bee's nervous system functions in the same sort of way as the AND gate in the demon-automaton of Figure 2.2. Having fewer possible outputs than inputs, it discards information and reduces entropy.

2.3 Alternative views of information

We have come across two approaches to the idea of entropy so far, deriving from classical thermodynamics and Shannon's communication theory respectively. From the 1960s onwards a third version has developed: that of computational complexity. Where classical concepts of entropy derived from mechanical engineering, and Shannon's concept from telecommunications engineering, the latest comes from computer science. The key concepts appear to have been independently developed by Chaitin in the US and Kolmogorov in Russia. Their presentation, while not contradicting what Shannon taught, gives new insights that are particularly helpful when we come to consider the role that information flows play in mass production industries.

2.3.1 The Chaitin–Kolmogorov concept of information

Chaitin's algorithmic information theory defines the information content of a number to be the length of the shortest computer program capable of generating it. This introduction of numbers is a slight shift of terrain. Shannon talked about the information content of *messages*. Whereas numbers as such are not messages, all coded messages are numbers. Consider an electronically transmitted message. It will typically be sent as a series of bits, ones and zeros, which can be considered as a binary number. An information theory defined in terms of numbers no longer needs the support of a priori probabilities. Whereas Shannon's theory depended upon the a priori probability of messages, Chaitin dispenses with this support.

As an example of the algorithmic approach consider the Mandelbrot set picture in Figure 2.3. This image is created by a very simple computer program.[2] Although the image file for the picture is large, about 6 million bits, a program to generate it can be written in a few thousand bits. If one wanted to send the picture to someone who had a computer, it would take fewer bits to send the program than to send the picture itself. This only works if both sender and receiver have computers capable of understanding the same program. Chaitin's definition of information has the disadvantage of seeming to make it dependent upon particular

[2] In fact it uses the formula $z = z^2 + c$ where z is a complex number.

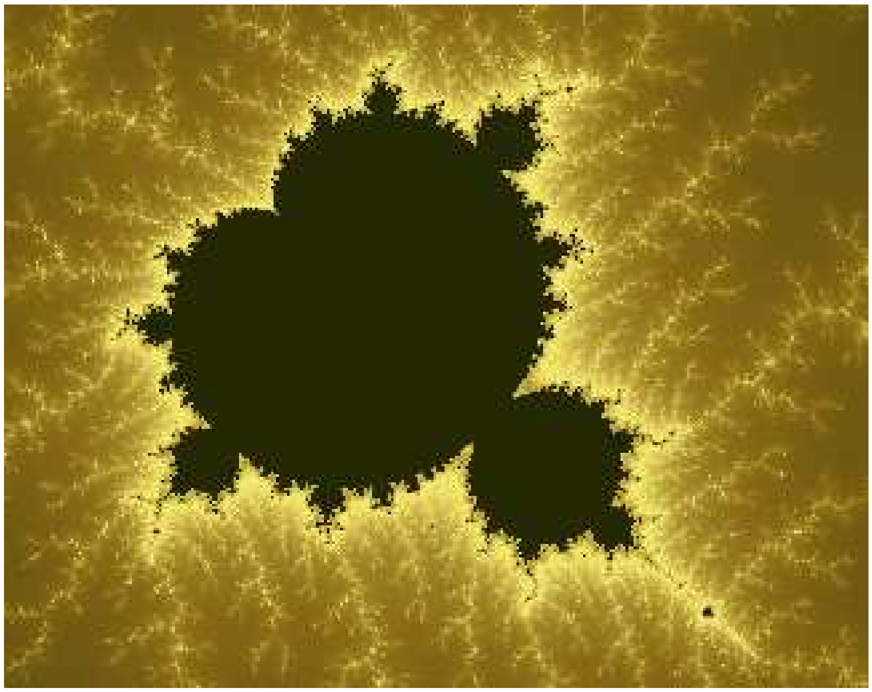


Figure 2.3: The Mandelbrot set, a complex image generated from a tiny amount of information.

brand of computer used. One could not assume that the length of a program to generate the picture would be the same on an Apple as on an IBM.

In principle one could chose any particular computer and fix on it as the standard of measure. Alternatively one could use an abstract computer, much as Watt used an abstract horse. Chaitin follows Watt, using a *gedankenapparat,* the Universal Turing Machine, as his canonical computer. Thus he defines the information content of a sequence S as the shortest Turing machine tape that would cause the machine to halt with the sequence S on its output tape.[3]

Randomness and pi

An unsettling result from information theory is that random sequences of digits contain more information than anything else. According to common sense, information is the very opposite of randomness. We feel that information should be associated with order, but Shannon's identification of information and entropy amounts to equating information with *dis*order. To illustrate this let's compare a long random number with π. We know from Shannon that 1 million tosses of a fair coin generates 1 million bits of information. On the other hand, from Chaitin we know that π to a precision of a million bits contains much less than 1 million bits, since the program to compute π can be encoded using much fewer bits. Thus π must contain less information than a random sequence of the same length.

But what do we mean by random? And how can we tell if a number is random? The answer now generally accepted was provided by Andrei Kolmogorov, who defined a random number as *a number for which there exists no formula shorter than itself.* By Chaitin's definition of information a random number is thus incompressible: a random number of n bits must contain n bits of real information.

A fully compressed data sequence is indistinguishable from a random sequence of 0s and 1s. This not only follows directly from Kolmogorov and Chaitin's results but also from Shannon, from whom we have the result that for each bit of the stream to have maximal information it must mimic the tossing of a fair coin: be unpredictable, random.

We have a paradox: one million digits of π are more valuable and more useful than one million random bits. But they contain less information. They are more valuable because they are harder to come by. They are more useful because a

[3]There is, in principle, no algorithm for determining the shortest Turing Machine tape for a sequence. $3 \div 7$ is a rule of arithmetic, an algorithm that generates the sequence 0.428571428571. So this sequence is presumably less random than 0.328571428771 (we changed two digits). But we can never be sure. This is a consequence of Gödel's theorem, which showed we cannot prove completeness of a consistent set of arithmetic axioms. There will be true statements that cannot be proven. If there existed a general procedure to derive the minimal Turing machine program for any sequence, then we would have a procedure to derive any true proposition from a smaller set of axioms, contra Gödel.

host of other formulae use π. They contain less information because each and every digit of π was determined, before we started calculating it, by π's formula. Thus in a sense the entire expansion of π is redundant if we have its formula. Valuable objects are generally redundant. We thus have three concepts that we must distinguish with respect to sequences: their information content, their value, and their utility.

Concept	*Meaning*
Information	Length of program to compute the sequence.
Value	Cycles it takes to compute the sequence.
Utility	The uses to which the sequence can be put.

The *value* of a sequence is measured by how hard we must work to get it. π is valuable because it is so costly to calculate. We can measure the cost by the number of machine cycles a computer would have to go through to generate it.[4] As with information content, this definition is dependent upon what we take as our standard computer. A more advanced computer can perform a given calculation in fewer clock cycles than a more primitive one. For theoretical purposes any Universal computer will do. Information theorists typically use machine cycles of the Universal Turing Machine (UTM) for their standard of work. We will follow them in defining the information content of a sequence in terms of the length of the UTM program that generates it, and the value of a sequence in terms of the UTM cycles to compute it.

Now the UTM is an imaginary machine, a thought experiment, living in the platonist ideal world of the mathematician. Its toils are imaginary, consuming neither seconds nor ergs; its effort is measured in abstract cycles. But any physical computer existing in our material world runs in real time, and needs a power supply. Valuable numbers—tomorrow's temperature for example—whose computation requires large number of cycles on the Met Office super computers, take real time and energy to produce. The time depends on clock speed, and the energy depends on the computer's thermodynamic efficiency.[5] If we abstract from changes in computer technology, information value in UTM cycles is an indication of the thermodynamic cost of producing information. It measures how much the entropy of the rest of the universe must rise to produce the information.[6]

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[4]We are identifying the value of a sequence with what Bennett calls its logical depth. The homology with Adam Smith's definition of value should be evident.

[5]The UTM plays, for computational complexity theory, the role of Marx's "labour of average skill and intensity" in the economic theory of value. Improvements in computer technology are analogous to changes in the skill of the worker.

[6]This is what Norretranders calls *exformation*.

Having traced the conceptual thread of entropy from Boltzmann through Shannon to Chaitin, it is worth taking stock and asking ourselves if Chaitin's definition of entropy still makes sense in terms of Boltzmann's definition. To do this we need to move from numbers to their physical representation. A material system can represent a range of numbers if it has sufficient well-defined states to encode the range. Will a physical system in a state whose number has, according to Chaitin, a low entropy, have a low entropy according to classical statistical mechanics?[7]

What we will give is not a proof, but at least a plausible argument that this will be true. As a *gedanken* experiment we will consider a picture of the Mandelbrot set rendered on digital paper. Digital paper is a proposed display medium made of thin films of white plastic. In the upper layer of the plastic there is a mass of small bubbles of oil, in the middle of each of which floats a tiny ball. One side of the ball is white and the other black. Embedded within the ball is a magnetized ferrite crystal with its North pole pointing towards the black end.[8] If the paper is embedded in an appropriate magnetic field all of the balls can be forced to rotate to have their white half uppermost, making the paper appear white. Applying a South magnetic pole to a spot on the paper will leave a black mark where the balls have rotated to expose their dark half. When it is passed through an appropriate magnetic printer, patterns can be drawn. A sheet of digital paper with a Mandelbrot set image on it nicely straddles the boundary between an industrial product and a number or information structure.

According to algorithmic information theory, the Mandelbrot set image represents a relatively low entropy state, since the length of the program to compute it contains fewer bits than the image. Does it also represent a low entropy state in statistical mechanics?

The second law of thermodynamics states that the entropy of a closed system is non-decreasing. So we would expect that a picture of the Mandelbrot state drawn on digital paper would tend to change into some other picture whose state would represent a higher entropy level. In fact there are good physical reasons why this will take place. If a local area is all white or all black, the magnetic poles are aligned as shown in the top of Figure 2.4. In this configuration the like poles tend to repel one another, and over time some of the poles will tend to flip to the configuration shown in the bottom half of the diagram.

The rate at which this occurs depends upon the temperature, the viscosity of the fluid in which the balls are suspended, and so on, but in the long run entropy will take hold. The image will gradually degrade to a higher entropy state, both in thermodynamic terms and in algorithmic terms. The program necessary to produce

[7] We need this step if we are to apply Chaitin's theory to labour processes that produce real physical commodities. We need an epicurean not a platonist theory.

[8] We are giving a somewhat stylized account of digital paper for the purposes of this argument.

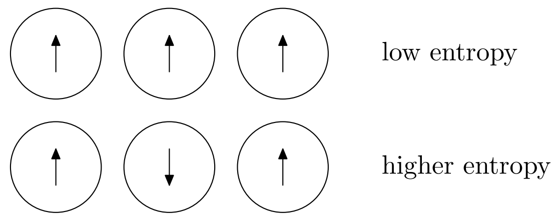

Figure 2.4: Configurations of parallel poles are unstable and tend to evolve towards the anti-parallel configuration.

the degraded picture is bound to be longer than the program that produced the pristine one. Hence thermodynamic and algorithmic entropy measure the same scale.

The example we have given is stylized but the thermodynamic degradation of digital information is not hypothetical. Magnetic tape libraries have a finite life because of just this sort of flipping of the magnetized domains on which the information is stored.

2.4 Randomness and compressibility

You may find at this point that reason in you rebels at the idea that information content and randomness are equivalent. But this is what information theory teaches us, so it is worth considering and trying to resolve several apparent paradoxes that arise from information theory.

Kolmogorov identifies the randomness of a number with its incompressibility (via his "no shorter formula" proposition). There seems to be a contradiction—or at least a strong tension—between this conception of randomness as a property *of a number* and the "ordinary" conception of randomness as a property of a *mechanism for generating numbers*. (As in the statisticians' talk of a "random variable" as a variable whose values are determined by the outcome of a "random experiment".)

2.4.1 Random numbers contain non-random ones

To expose the tension, consider a random number generator (RNG). Suppose it's a true quantum RNG, set to produce a series of uniformly distributed ten-digit numbers. The standard definition of randomness would be that every ten-digit number is produced with equal probability (and the drawings are independent, so the equal probability condition holds not only in terms of marginal probability but regardless of conditioning information). Thus if we leave our RNG running for a while, it's bound to produce numbers such as 1111111111 and 0123456789. But these are not "random numbers" on the Kolmogorov definition. The paradox is then that the output of a random number generator (i.e. a device that generates numbers at random) is bound to include nonrandom numbers.

In these examples we have non-random sub-sequences of the output of the RNG. This is not a valid objection, as we have to take the entire output of the RNG up to some large number of digits, in order to obtain these sub sequences that appear non-random. So these short subsequences are not produced by the random number generator, but, strictly speaking, by a Turing machine program that is a prefix to the random number generator, and which searches for patterns like 1111111111111 in the output of the RNG. The Algorithmic Information Theory approach to this would be to add the information content of the program which generated the sequence to the program which selected for the "non-random" sub sequences.

2.4.2 Randomness of a number as opposed to of a generator.

In standard statistical parlance it doesn't really make sense to talk of a random *number* as such, as opposed to a random *variable* or a random number *generator* (where the adjective "random" attaches to the generator, i.e. it's a random generator of numbers rather than a generator of random numbers). Kolmogorov defines "random number", in a way that seems to conflict with the standard view.

But this is just a divergence between what we commonly understand as a number in statistics and how a number is defined in computational complexity theory. By number the Algorithmic Information Theory just means a sequence of digits. Since any sub-sequence of digits is also a number, formalisations in terms of numbers also provide for formalisation in terms of finite sequences of numbers. Thus a sufficiently large number can be treated as a generator of smaller numbers.

2.5 INFORMATION AND RANDOMNESS

To get at the second paradox we will report a little experiment. We have an ASCII file of the first eleven chapters of Ricardo's *Principles*: it's 262899 bytes. We ran the bzip2 compressor on it and the resulting file was 61193 bytes, a bit less than quarter of the size. Suppose for the sake of argument that bzip2[9] is a perfect byte-stream compressor: in that case the 61193 bytes represent the incompressible content of the Ricardo chapters. They measure the true information content of the larger file, which contains a good deal of redundancy. That idea seems fair enough.

[9] A publicly available data compression program.

The second part of the experiment was to generate another file of 262899 bytes of printable ASCII characters (the same length as Ricardo), this time using a random number generator[10], and running `bzip2` on the resulting file produced a compression to slightly over 80 percent of the original size.

The first question is why we get any compression at all on the "random" ASCII files?

Our bytes are printable characters. These are drawn from a subset of the possible byte values[11], and as such all, the possible byte values are not equiprobable. Thus the stream is compressible.

The next question concerns the information content of the various files. Suppose we have already accepted the idea that the 61193 bytes of bzipped Ricardo represent the irreducible information content of the original Ricardo file. Then by the same token it seems the 218200 (or so) bytes of bzipped rubbish from the random number generator represent the true information content of the (pseudo-)random byte stream. The rubbish contains almost four times as much information as the Ricardo. This is very hard to swallow.

The point here is that standard data compression programs use certain fixed algorithms to compress files. In this case an algorithm known as Lempel-Ziv[12] is used. Lempel-Ziv does not know how to obtain the maximum compression of the stream—which would be an encoding of the random number generating program. One can not make a general purpose compressor that will obtain the maximum possible compression of a stream. One can only produce programs that do a good job on a large variety of cases.

We make the distinction between information as such and utility, and in those terms it's clear that the Ricardo is of much greater utility than the rubbish. Even so, intuition rebels at the idea that the rubbish carries *any* information. We have a conception of "useless information" alright, but it seems doubtful that a random byte stream satisfies the ordinary definition of useless information. In ordinary language information has to be *about* something; and it's useless if it's about something that is of no interest. For me, the weekly guide to Cable TV programming may contain useless information. It's of no more interest to me than a random byte stream. Nonetheless, I recognize that it does contain (quite a lot of) information; it is certainly about something.

In classical political economy use-value is neither the measure nor the determinant of value, but nonetheless it's a *necessary condition* of value. If a product has no use-value for anyone then it has no value either, regardless of how much labour time was required for its production. Can we say that the utility of a message is

[10]the `rand()` function in the GNU C library

[11]There are 256= 2^8 possible values for 8 bit bytes.

[12]Ziv 78.

not the measure of its information content, but if a "message" is of no potential use to anyone (is not about anything) then it carries no information, regardless of its incompressible length?

No. Information exists even if it is not useful. Take the case of hieroglyphs prior to the discovery of the Rosetta stone.[13] They were meaningless until that was discovered, useless in other words. Once it was discovered they became useful historical documents. Their information content was not created *ex-nihilo* by Champollion, but must have been there all along. Similarly, the works of Ricardo in Chinese contain no information to me, are of no use to me, but they still contain information.

In the end, whether information is useful to us concerns our selfish thermodynamic concerns. Does it enable us to change the world in a way that saves us work or produces us energy. This is an anthropospective projection. It is not a property of the information it is a property of the user of the information, which is cast back onto the information itself. Information theory in its epistemological break, had to divest itself of anthropospective views, just as astronomy and biology had to.

The "digital paper" example suggests one further paradox on the issue here. Let's go back to the ASCII Ricardo. Its incompressible length was (according to bzip2) 61193 bytes. Now suppose the hard drive is exposed to radiation that results in random bit-flipping, which changes some of the bytes in the Ricardo file. At some later point we try compressing the file again. We find that it won't compress as well as before. Its information content has increased due to the random mutation of bytes! Meanwhile, of course, its value as representation of what Ricardo said is eroding. Is it possible to make any sense of this?

Yes. The degraded work contains more information since to reconstruct it one would need to know the trajectories of the cosmic rays which degraded the stored copy, plus the original copy. We may not be interested in the paths of these cosmic rays,[14] but it is additional information, provided to us courtesy of the Second Law.

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[13]The inscription on the Rosetta Stone, is a decree for King Ptolemy V Epiphanes dating from March 196 BC. It is repeated in hieroglyphs, demotic and Greek. By using the Greek section as a 'key' scholars realised that hieroglyphs were not ideograms, but that they represented a language. Jean-Franois Champollion (AD 1790-1832), realised in 1822 that they represented a language which was the ancestor of Coptic.

[14]In other circumstances, archeological dating for example, such radiation damage gives us useful information.

CHAPTER 3

LABOUR PRODUCTIVITY

> Those who possess rank in a manufacturing country, can scarcely be excused if they are entirely ignorant of principles, whose development has produced its greatness. The possessors of wealth can scarcely be indifferent to processes which, nearly or remotely have been the fertile source of their possessions. Those who enjoy leisure can scarcely find a more interesting and instructive pursuit than the examination of the workshops of their own country, which contain within them a rich mine of knowledge, too generally neglected by the wealthier classes.
>
> (Charles Babbage, *Economy of Machinery*, Preface.)

3.1 RAISING PRODUCTION IN GENERAL

In this chapter we are looking at the means by which labour productivity increases over time. The level of our analysis here remains essentially technical. We are looking at productivity in physical terms rather than in value terms. We are not yet, interested in how many Euros' or dollars' worth of output each worker produces per hour. Instead we are looking at physical production, tons of steel, meters of rope, numbers of cars etc.

This concentration on physical productivity means that our focus is not only limited to technical considerations, its is also narrow, looking at one industry at a time. We can not yet look at the economy in general since, by abstracting from prices or other means of valuation we have deprived ourselves of any scale by which we could measure the national product. The total product of the economy comprises a hetrogenous mixture of goods[1] For the moment we will consider one

[1] Technically speaking, it is a *vector*, a list of numbers:[x tons of steel,y cars, z barrels of oil, ...]. Vectors are a means of describing positions in multi-dimensional space. To get an unambigous measure of changes in production you need a scale to measure the changes, a *scalar* quantitity like \$$w$.

product at a time, and the natural units of that product will provide us with our scale.

We are primarily interested in the flow of product per unit time, things like 17 million tons of steel per year, 15 meters of cloth per hour. As a secondary question we are interested in product flow per unit time per worker since this is the dimension along which the wealth of society in general increases[2].

There are 3 fundamental ways in which the flow through any production process can be increased.

(1) Accelerating the production cycle.
(2) Parallelising production.
(3) Eliminating wasted effort.

These basic methods apply whether the production process is human or animal, mechanical or biological, carried out by men, bees or robots. Examination of them will provide the main substance of the chapter.

3.1.1 Entropy analysis

Before going onto the 3 methods of increasing productivity, we shall extend our analysis of information and entropy to look at the changes in entropy that take place in during industrial production.

We have already looked at digital paper as a gedanken experiment. We showed that if you wrote text on it, although this text represented information, it contained much less information than the paper potentially could. If we transfer what we have learned from this example to ordinary paper and the process of producing a book we see that the production process encompasses two opposite phases.

(1) The production of the paper. This is an entropy *reducing* process. The blank sheets of paper oviously have low information content with respect to human language, but they also constitute a low entropy state with respect to the raw material. In a sheet of paper the cellulose fibres are constrained in:

    (a) Orientation, since they must lie in a plane rather than being free to take up any angle. This implies a reduction in the volume of state space that the fibres occupy, and thus from Boltzman, a corresponding reduction in entropy.
    (b) Position, the fibres are constrained to exist within a small volume a few hundredths of a millimeter thick. This restriction in physical space obviously entails a smaller entropy, as shown in our discussions of Maxwell's daemon.

[2] Abstracting for now from the division of this wealth between the different classes in society.

(2) The writing of the text, whether by hand, as in the distant past, or by a printing press. This is an entropy *increasing* process. We can see this in two ways:

   (a) Consider the text to be printed as binary data, encoded using ASCII[3] or UNICODE[4]. Clearly the book contains this information, since by sending the book in the post to someone we can enable them to recreate the relevant binary file. Thus by the equivalence of information and entropy, we have increased the entropy of the book relative to the blank sheets of paper.

   (b) Consider the fact that whilst all blank sheets are alike, printed sheets can be different. The number of possible different pages that can be printed is so huge as to dwarf the concept of astronomically large [5]. Since entropy is logarithimcally related to the number of possible states, the increase in the number of possible states implies a rise in entropy.

It may be objected that whilst there are a vast number of possible pages that could be printed, we are only interested in printing a particular page. This is true, but it is the particularity of the page that constitutes the added information and thus the added entropy.

First a low entropy material is created, following on from that its entropy is increased in a controlled way. Initially *natural* information is removed. Subsequently *anthropic* or human created information is added. The natural information removed is irrelevant to our concerns, that added, is dictated by them. The first processs, pulping wood, bleaching it, forming it into sheets, drying it, has to use energy to produce the reduction in entropy— thermodynamics gives any local reduction in entropy, its energy price.

The second process, increasing entropy, could in principle be done at no energy cost[6]. In practice our technologies are not that efficient. Still, the power consumption of a printworks remains lower than that of a paper mill.

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[3]American Standard Code for Information Interchange, a code which uses 7 bits to represent each letter or symbol, it is restricted to the characters appearing on US typewriters

[4]A newer 16bit code that can represent every letter or glyph used in any of the world's languages, including ideographic scripts like those of China and Japan.

[5]If we allow 40 lines of 60 characters, with these characters drawn from a lexicon of all of the worlds languages we have of the order of some 10^{10000} possible printed pages, , the volume of the universe in terms of the Plank dimension 10^{-35}m the quantum of space, is of the order of 10^{210}

[6]The controled-not gate proposed for quantum computing is in principle a mechanism by which a process analogous to the printing of information onto blank paper can take place in a reversible and thus non energy consuming way.[DiVincenso95].

Considerable research is currently underway to develop nano-technologies that use self-assembly of microstructures. In this case the increase in entropy that occurs as the structures aquire form and information occurs directly by thermondynamic means, albeit starting off from precisely controlled compositions and temperatures[Witesides 95].

3.1.2 Replicated parts

Consider two books by two different authors, each 200 pages long, printed with the same size of letters. Each has roughly the same amount of information added to the paper in the printing process, but in each case the information is different. On the other hand two copies of a book have the same information added. The added information is what on the one hand differentiates books, and on the other makes replication possible.

It is easy to see the relevance of information theory to the printing industry. Its product, after all, contains information in the everyday as well as the technical sense of that word. Does it provide insights into how other production processes function?

Consider the process of producing cloth. The starting material is wool or cotton fibres in a random tangled state. This is first carded to bring the fibres into rough alignment, and then simultaneously twisted and drawn to spin them into yarn. In the yarn both the volume and orientation are sharply reduced. Energy is used to reduce the entropy of the cotton. The weaving of the cotton then increase the entropy by allowing two possible orientations of the fibres at right angles to one another, more, if we take into account the differences in possible weave.

In the case of man made fibres the extrusion and drawing processes that preceed spinning are designed to align the polymer molecules with the axis of the fibres, again this is clearly an entropy reducing process.

Other industries that use thin, initially flat materials clearly have a lot in common with printing. The manufacture of car body parts from sheet steel, or the garment industry, share the pattern of producing a low entropy raw material and adding information to it. In pressed steel construction, added information is encoded in the shape of the dies used to form the car doors, roof panels etc. We can quantify it using Chaitin's algorithmic information theory, as proportional to the length of the numerically controlled machine tool tape that is used to direct the carving of the die. In the making up of garments from bolts of cloth, the added information comes in the form of the patterns used to cut the cloth.

All of these involve the replication of standard products, dependent on the existence of materialised information in the form of patterns and dies. If steam powered the industrial revolution, the technologies of replication were the key to mass production. The classic example of the importance of accurate replication

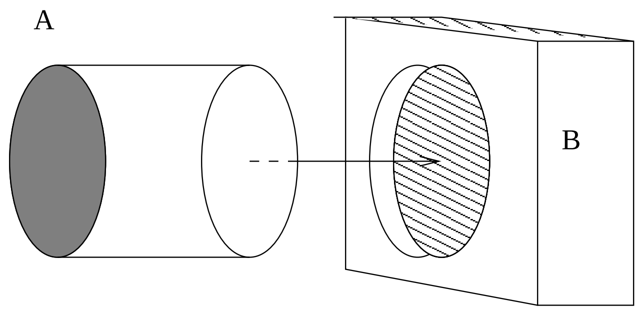

Figure 3.1: When inserting axle A into bearing B we want to minimise the conditional information $H(B|A)$, between B and A.

was in the production of the Colt revolver in the mid 19th century. Prior to Colt extablishing his factory the gun trade was dominated by handicraft manufacturing techniques. The different parts of a gun's mechanism were individually made by a gunsmith so that they fitted accurately together. Whilst the components of an individual fowling piece might fit together beautifully, if the hammer were removed from one gun, it would be unlikely to fit accurately into another. Mass production required the use of replicated interchangable parts. For parts to be interchangeable they must be made to very precise tolerances. This improvement in accuracy of production involves the parts having a lower entropy, occupying a smaller volume of phase space, than the old hand made parts. Again by the equivalence of information and entropy this means that the standardised parts embody less information than the hand made ones. This makes sense; for example it may have been possible to identify the maker of a hand made gun, whereas this would be impossible with a standardised Colt.

In the 19th century, prior to the introduction of numerically controlled machine tools, replictated parts had to be comprised of circular and planar elements which could be produced on lathes or milling machines. The limited information content of these can be seen when you consider that in turning a smooth bore gun barrel one only has to specify the inner and outer radii and its length. If an axle and a bearing are being produced separately to fit together, then one wants the uncertainlty in the surface of the bearing, given the surface of the axle to be reduced below a certain limit.

Information theory analyses this in terms of *conditional entropy*. The Chaitin formulation of this is as follows: the conditional entropy of a character sequence B dependent upon a sequence A, which we write as $H(B|A)$, is given by the lengrh

```
00000000000000000000    00 000 000 000 000 00 000 00
00000000000000000000    00 000 000 000 000 00 000 00
00000000000000000000    00 000 000 000 000 00 000 00
00000000000000000111    11 110 000 000 000 00 000 00
00000000000000111111    11 111 110 000 000 00 000 00
00000000000011111111    11 111 111 100 000 00 000 00
00000000001111111111    11 111 111 111 000 00 000 00
00000000011111111111    11 111 111 111 100 00 000 00
00000000111111111111    11 111 111 111 110 00 000 00
00000001111111111111    11 111 111 111 111 00 000 00
00000011111111111111    11 111 111 111 111 10 000 00
00000011111111111111    11 111 111 111 111 10 000 00
00000111111111111111    11 111 111 111 111 11 000 00
00000111111111111111    11 111 111 111 111 11 000 00
00001111111111111111    11 111 111 111 111 11 100 00
00001111111111111111    11 111 111 111 111 11 100 00
00001111111111111111    11 111 111 111 111 11 100 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00011111111111111111    11 111 111 111 111 11 110 00
00001111111111111111    11 111 111 111 111 11 100 00
00001111111111111111    11 111 111 111 111 11 100 00
00001111111111111111    11 111 111 111 111 11 100 00
00000111111111111111    11 111 111 111 111 11 000 00
00000111111111111111    11 111 111 111 111 11 000 00
00000011111111111111    11 111 111 111 111 10 000 00
00000011111111111111    11 111 111 111 111 10 000 00
00000001111111111111    11 111 111 111 111 00 000 00
00000000111111111111    11 111 111 111 110 00 000 00
00000000011111111111    11 111 111 111 100 00 000 00
00000000001111111111    11 111 111 111 000 00 000 00
00000000000011111111    11 111 111 100 000 00 000 00
00000000000000111111    11 111 110 000 000 00 000 00
00000000000000000111    11 110 000 000 000 00 000 00
00000000000000000000    00 000 000 000 000 00 000 00
00000000000000000000    00 000 000 000 000 00 000 00
00000000000000000000    00 000 000 000 000 00 000 00
```

Figure 3.2: A slice through the axle.

of the shortest prefix Turing machine programme that when fed with the program for *A* will generate *B*.

How can we apply this concept to our previous mechanical example?

Well let *A* stand for an ecoding of our axle and *B* an encoding of our bearing(Fig. 3.1). We divide space up into cells of a fixed size, let us say a $\frac{1}{10}$th of a millimeter on edge. If the space is occupied by metal we denote this with a 1 otherwise we denote it by a 0. We can then use arrays of characters like those in Fig. 3.2, to represent slices through the axle.

According to the Chaitin view, the information content of the cross section through the axle is given not by this array of 1s and 0s but by the shortest program to generate it. Here is an example of a short program that will print out the pattern in Fig. 3.2:

```
program circ ;
const
    b: array [boolean ] of char =( '1' , '0' );
    c =20;
    r =18;
var
    a: array [-c ..c ,-c ..c ] of boolean ;
begin
    a← √(ι0² + ι1²) < r;
    write(b_a);
end .
```

We can not guarantee to have found the shortest such program[7]. Indeed Chaitin shows that in the general case one can never prove that a given program is the shortest to produce a particular output. But the program is considerably shorter than the pattern that it produces, and with the alteration of the definition of two variables *c* and *r* it will generate arbitrary sized circular patterns of 1s in a field of 0s.

Clearly if the bearing exactly fitted the axle the expanded encoding for a slice through the bearing would be an array similar to Fig 3.2 but with 1s and 0s swapped round. This can be produced by a trivial change to the program circ, the additon of a single statement. Indeed all that is required is that the line:

write($b_{\textbf{not}a}$);

replaces the line:

write(b_a);

[7]The program is in Vector Pascal which is fairly concise, see Cockshott and Renfrew 2004.

```
00000011111111111111     11 111 111 111 111 10 000 00
00000011111111111111     11 111 111 111 111 10 000 00
00000001111111111111     11 111 111 111 111 00 000 00
00000000111111111111     11 111 111 111 110 00 000 00
00000000011111111111     11 111 111 111 100 00 000 00
00000000000111111111     11 111 111 110 000 00 000 00
00000000000011111111     11 111 111 100 000 00 000 00
00000000000000011110     11 111 100 000 000 00 000 00
00000000000000000000     11 100 000 000 000 00 000 00
00000000000000000000     10 000 000 000 000 00 000 00
00000000000000000000     00 000 000 000 000 00 000 00
```

Figure 3.3: Part of a pin with a fault on its circumference.

in the program. This must come close to minimising the conditional entropy of the two parts.

Suppose that the parts were less than perfectly made, so that there were roughnesses on the surface of the axle. Fig. 3.3 shows a cross section through a pin A' that should be circular, but has a step on it, generated perhaps by improper turning.

Suppose we have our perfectly formed circular hole B, then as before the conditional entropy $H(B|A')$ of the hole and the imperfect pin is much greater than before. Working in the domain of generator programs we would need to add the following lines to the generator of A' to make the bitmap for B:

$a_{r,1} \leftarrow$ *false*;
$a_{r,2} \leftarrow$ *false*;
$a_{r+1,0} \leftarrow$ *false*;
$a_{r,0} \leftarrow$ *false*;
$a_{r-1,-1} \leftarrow$ *true*;
write($b_{\mathbf{not}a}$);

This obviously contains extra information, required to correct the bitmap of A' to generate that of B. In pre-industrial production, the extras steps in the generator program would translate into additional steps of filing and grinding to make parts fit. The aim of standardised production is to arrive at a situation where independently made parts, derived from a common technical specification, fit together because the conditional information of the mating parts is minimal.

3.2 Accelerated Production

The most obvious way in which production can be increased is by accelerating the production process itself, by making people and machines work longer and faster.

3.2.1 Longer days

If the working day is increased from 8 hours to 12, and if the same tempo of work is maintained, then output per worker will rise by a half. The effect, over a 24 hour day is analgous to increasing the average intensity of labour. Similarly if a machine is used for 12 hours a day rather than for 8, we have the same effect as if the machine ran 50% faster.

From the standpoint of society as a whole, however, there are real differences. If machines are scarce, an economy can increase its output by using them on a 24 hour shift system. But if a system of three shifts each of 8 hours is used, then three times as many workers are required. Total production will rise threefold, but output per worker remains the same[8]. If on the other hand, the working day is extended to 12 hours, and two shifts are worked, both total output and output per worker go up. This fact encourages employers to lengthen the working day whenever the labour supply is limited. Further, since daily wages rarely rise in proportion to hours, longer hours mean more profit. But the scope for extending the working day is still relatively limited - perhaps 16-18 hours under the most exploitative conditions; less than a doubling of the pre-industrial working day.

These are small gains compared to those available from technology. No free workers would willingly work such hours. It is rather the fate of slaves; either bonded labourers or wage slaves without access to free trades unions. The working day is ever the inverse reflection of workers' liberty. As workers gain political rights and influence, the working day comes down and other ways have to be found to increase productivity.

3.2.2 Studied movements, intensified labours

Today we think of mass production interms of the mechanised production line introduced by Henry Ford at the start of the last century. But mass production started much earlier. In the 18th century, before steam or water power were generally applied, mass production took place in manufactories[9]. In a manufactory, the work was done with hand tools[10], by groups of workers using a division of labour.

It is a common enough observation that a person's speed improves with practice. Through practice, sequences of muscle movements cease to be under con-

[8] The labour required to produce one unit of output may fall slightly, since the depreciation of the machines may not rise proportionately with their intensity of use.

[9] *manu*factory, from manus, the latin for hand.

[10] 'The difference between a tool and a machine is not capable of very precise distinction; nor is it necessary, in a popular explanation of those terms, to limit very strictly their acceptation. A tool is usually more simple than a machine; it is generally used with the hand, whilst a machine is frequently moved by animal or steam power. The simpler machines are often merely one or more tools placed in a frame, and acted on by a moving power.' *Charles Babbage* Economy of Machinery and Manufactures, 1832, Chap 1.

scious control and become reflexes. We no longer have to think about them. We do them automatically and we do them fast. Early manufacturing based itself upon this principle. Each worker had a simple repetitious task, performed largely under reflex control. Production was accelerated both by the increased speed that came from practice, and by eliminating the 'lost time' which would otherwise be spent changing from one task to another. The combination of faster movements and the elimination of wasted time could lead to remarkable improvements in productivity[11]; but the drawbacks of this form of production are obvious. People are, for the duration of the working day, used as automatons, their minds and imaginations rendered redundant. We use the present tense advisedly, plenty of consumer goods in our shopping-malls today come from third world manufacturies where children work as machines.

3.2.3 Mechanical sequencing and power

Nearly all human productive activity involves movements by the hands or limbs. The fingers must move in a precise sequence of motions to manipulate the tool and produce the desired effect on the product. The speed with which this can be done depends on:

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[11] 'To take an example, therefore, from a very trifling manufacture; but one in which the division of labour has been very often taken notice of, the trade of the pin-maker; a workman not educated to this business (which the division of labour has rendered a distinct trade), nor acquainted with the use of the machinery employed in it (to the invention of which the same division of labour has probably given occasion), could scarce, perhaps, with his utmost industry, make one pin in a day, and certainly could not make twenty. But in the way in which this business is now carried on, not only the whole work is a peculiar trade, but it is divided into a number of branches, of which the greater part are likewise peculiar trades. One man draws out the wire, another straights it, a third cuts it, a fourth points it, a fifth grinds it at the top for receiving, the head; to make the head requires two or three distinct operations; to put it on is a peculiar business, to whiten the pins is another; it is even a trade by itself to put them into the paper; and the important business of making a pin is, in this manner, divided into about eighteen distinct operations, which, in some manufactories, are all performed by distinct hands, though in others the same man will sometimes perform two or three of them. I have seen a small manufactory of this kind where ten men only were employed, and where some of them consequently performed two or three distinct operations. But though they were very poor, and therefore but indifferently accommodated with the necessary machinery, they could, when they exerted themselves, make among them about twelve pounds of pins in a day. There are in a pound upwards of four thousand pins of a middling size. Those ten persons, therefore, could make among them upwards of forty-eight thousand pins in a day. Each person, therefore, making a tenth part of forty-eight thousand pins, might be considered as making four thousand eight hundred pins in a day. But if they had all wrought separately and independently, and without any of them having been educated to this peculiar business, they certainly could not each of them have made twenty, perhaps not one pin in a day; that is, certainly, not the two hundred and fortieth, perhaps not the four thousand eight hundredth part of what they are at present capable of performing, in consequence of a proper division and combination of their different operations.' *Adam Smith*, The Wealth of Nations, Chap 1

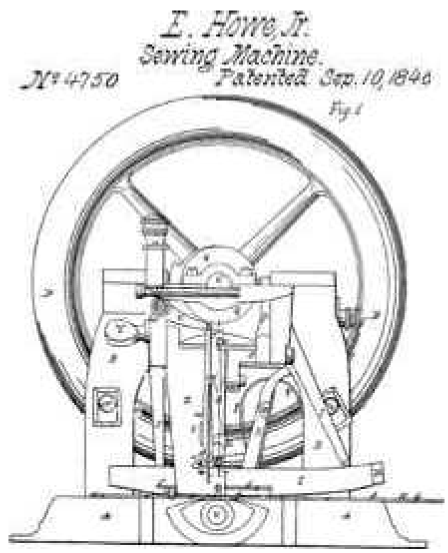


Figure 3.4: The lockstich sewing machine of Elias Howe.

(1) A flow of information, supplied by the brain in the form of nervous impulses, sent in the correct sequence to the hand.

(2) The flow of energy, supplied by hand and arm muscles which accelerate the hands plus tools whilst overcoming mechanical resistence.

There is a limit to how fast even the most practiced hand can move, a limit to how fast a seamstress or tailor could sew. This is imposed both by the brains inability to provide the nervous impulses faster than a certain rate, and by the speed with which the fingers can be moved. A whole class of industrial appliances accelerated production by first providing a self acting mechanism to supply the information input, and then providing an external source of power, allowing a previously manual production process to be accelerated.

The classic example of this was the sewing machine. The first functional sewing machine was invented by French tailor Barthelemy Thimonnier in 1830. He was almost killed by other enraged French tailors who burnt down his sewing machine factory because they feared unemployment. In 1834, Walter Hunt built America's first sewing machine. He later lost interest in patenting his sewing machine because he believed the invention would cause unemployment. Sewing machines did not go into mass production until the 1850's. The first commercially successful sewing machine was the one designed by Isaac Singer. The Singer machine used the Lock-stitch mechanism patented earlier by Howe (Fig, 3.4). It therefore differed from a tailor in using two threads instead of one. The upper needle simply moved up and down whilst the cloth was dragged past it. Meanwhile a shuttle containing a second reel of thread was rotated through the loops created in the first thread. Singer's machine could be operated either by a treadle or by a crank. It was a huge success and Singer and Howe both became multi-millionaires.

The key to its success was the fact that it greatly increased the productivity of sewing cloth together. The number of stitches a person could do per hour increased by an order of magnitude.

The speed of stitching could be made much higher for two reasons. First, the much stronger muscles of the leg replaced those of the hand in moving the needle. Second, the sequence of needle movements was no longer generated by the human nervous system translated in finger movements. Dexterity gave way to rotary action as cams, cranks and levers sequenced the thread movements to generate the lock stitch. The cams could operate far faster than the nimblest fingers, turning every tailor into a Rumplestiltskin.

Training can accelerate manual skills immensely, as the control of our muscles is transfered from conscious to reflex action. But such acceleration meets its limits, set both by the reflex speed of our nervous system and ability of our hand muscles to accelerate and decelerate our fingers. A machine with an external power source is freed from these limits. The sequence of movements to be made is now encoded in the mechanical linkages. Rotate the drive shaft faster and the sequence speeds up. The ultimate limit now becomes either friction or the strength of steel exposed to sudden acceleration and deceleration. This can be a couple of orders of magnitude above the limits of human dexterity.

The automatic control mechanism of the treadle sewing machine allows muscluar effort of the foot to produce an embodied information structure in the twists and loops of the stitches It is worth noting here, that once we deal with a repeated process like stitching, that the algorithmic and thermodynamic conceptions of entropy diverge. If an automaton is to produce a repeated pattern $P = c^n$, containing n repetitions of a basic cell c, then we would expect the algorithmic information to be bounded by $H(c) + H(n)$. It will be bounded by the information content of the basic cell plus the information content of the number n, But since an integral number can always be expressed in binary, the information content of n must be bounded by the number binary digits in n. Thus on algorithmic grounds we would expect $H(P) \leq H(c) + \log_2 n$ When analysing the thermodynamics of production this formula does not necessarily hold.

Thermodynamic analysis of production is more complex. Doing one hundred stitches clearly involves about one hundred times more physical work than doing one. Some of that work will be dissipated in frictional heat - a clear entropy increase. Another part goes into bending and twisting thread both in the stitches and in the cloth being worked on. This increase in thread entropy absorbs another portion of the work. Thus the thermodynamic entropy increase varies as $nh(s)$ where $h(s)$ is the increase in the entropy of the the thread involved in doing a single stitch[12].

3.3 Parallelising production

The sewing machine greatly increased the productivity of tailors, but it did not augur in a social revolution. An individual tailor could still afford to work on their own since the price of sewing machines was within their reach. The sewing machine in fact became a staple of domestic equipment, allowing women to clothe their families more cheaply. It was compatible with the continued self sufficiency of the farm household.

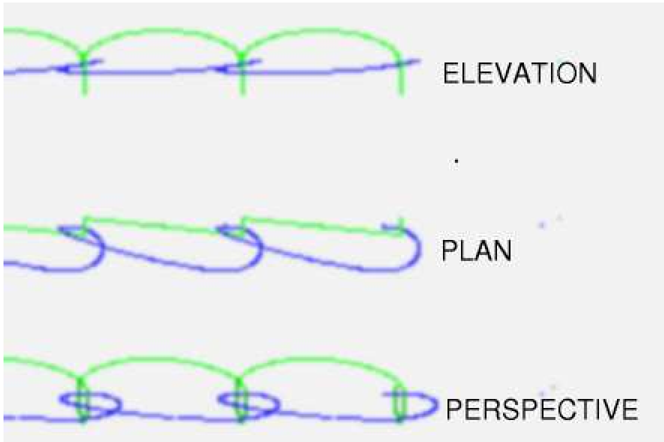
3.3.1 More people

Today most work done by sewing machines is done in factories. Millions of women are employed in Asia sewing garments for western chain stores. In these factories productivity will be somewhat higher than in domestic production but not enormously so. Such productivity gains as there are, stem from the mechanisms analysed by Smith over 200 years ago: the division of labour and the repeated execution of the same task. But these gains are not huge. What has happened to transform the sewing machine from a tool of family independence to an instrument of exploitation?

It is a combination of two factors.

First the big difference in wealth between the already industrialised nations of Europe, North America, Australia and Japan means that there is a huge demand in these countries for cheaply made clothes. Since the goods are being exported across the world, the trade inevitably falls into the hands of capitalist middlemen. These, through their contacts and wealth are in a position to supply material to, and sell on the products made by individual seamstresses. With the passage of time it becomes advantageous to them to bring the workers under one roof and make the seamstresses direct employees. In so doing they gain better control over the labour process, can impose stricter work discipline, and save the costs of distributing cloth to lots of home-workers.

[12] For macroscopic products the thermodynamic entropy changes are much larger than the algorithmic entropy changes. For sophisticated nanosystems which may be built in the future evolving along conservative lines, like Feynmann's proposed quantum simulator (Feyman 1982) the thermodynamic and algorithmic entropies of repeated patterns may be equivalent.



procedure *sew* ;
begin

$\theta \leftarrow \frac{2\times\pi\times\iota_0}{c}$;

$s \leftarrow 2 \times r \times (\frac{\iota_0}{c})$;

$$x1 \leftarrow \begin{cases} r+s & \text{if } \iota_0 \textbf{ mod } c < h \\ s - r\times(\cos(\theta)) & \text{otherwise} \end{cases};$$

$y1 \leftarrow 0.5 \times r \times \sin(\theta + \pi)$;

$z1 \leftarrow 0.125 \times r \times \cos(\theta)$;

$x2 \leftarrow x1 + r \times (- 0.2 + 0.45 \times \sin(\theta))$;

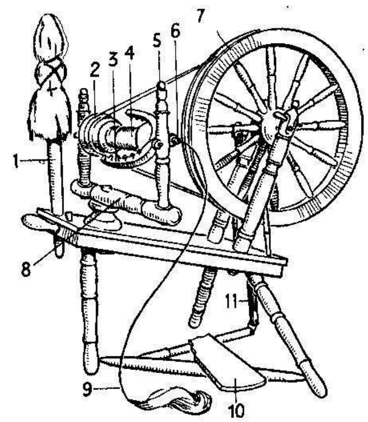
$y2 \leftarrow - 2 + 0.1 \times r \times \sin\theta$;

$z2 \leftarrow r \times (- 0.35 + 0.35 \times \cos\theta)$;

end ;

Figure 3.5: The Lock-stich presented in plan, elevation and perspective views, along with a generating action program. Note that all steps of the action program are generated by sine and cosine functions driven by θ which models the angular rotation of the sewing machines drive wheel. The computer algorithm has to specify 6 degrees of freedom, 3 for each thread. This is to ensure that our modeled thread does not intersect itself. A practical sewing machine will work by controling 4 degrees of freedom: a) The movement of the cloth, modeled in the algorithm above by s. b) The vertical movement of the needle, modeled by $y1$. c) Circular movement of the lower thread, modeled by $x2, z2$.

spinn'ing *n.* ~*-jenny*, spinning-machine with several spindles; ~*-wheel*, simple spinning-apparatus in which spindle is driven by wheel worked by hand or foot.



SPINNING WHEEL

1. Distaff. 2. Flier or spindle whorl. 3. Hackle. 4. Bobbin. 5. Maiden. 6. Spindle. 7. Wheel. 8. Mother-of-all. 9. Yarn. 10. Treadle. 11. Footman

Figure 3.6: Treadle spinning wheel.

A second cause is the dominance of distribution in the developed capitalist world by big chain stores selling branded goods. These big companies can place contracts for large numbers of identical garments, with local manufacturers. They require cheap standardised garments produced either in sweatshops or by home-workers subject to the control of subcontractors.

The employers can exploit the machinists because the employers are rich and well connected, whereas the machinists are poor. The employers dont exert the control due to any particularly superior technology, but due to their social position. But they have this position because their role in an international capitalist trade network. And this network in turn depends upon the prior industrial development of richer nations going back two centuries.

3.3.2 More spindles

It was not sewing machines that drove the birth of the industrial revolution but spindles. Immediately prior to industrialisation yarn in Europe was produced by domestic treadle spinning wheels. Although, made as it is of wood, the spinning wheel looks a much more primitive machine than Singer's sewing machine, in many ways they were very similar devices.

They were both driven by foot power. Both were, in a sense, single threaded. The spinning wheel allows the twisting and drawing out of a single strand of thread. Both involve a modicum of hand control, guiding the cloth in one case, drawing out the yarn in the other. Like the early sewing machines the spinning wheel was essentially a domestic instrument of production. No factory system based on spinning wheels ever established itself. The mechanisation of spinning took what was essentially a much more adventurous course than Singer did. Comptons Mule, Fig. 3.7, multiplied the number of spindles and also replaced the hand actions of the spinner with a sequence of mechanical movements.

The spindles were mounted on a moving carriage. The sequence of actions emulate those done by a hand spinner.

(1) The carriage moves out drawing the as yet unspun yarn through rollers that impede its progress. As this is done the spindles impart a twist onto the yarn. This emulates the first action of the hand spinner as they move their hand away from the spindle stretching the yarn.
(2) Next the carriage stops and the spindles start winding the thread onto the bobbins. Simultaneously the carriage moves back to the starting position as the thread is drawn in.
(3) The cycle repeats.

The mule was, in the terminology of the day, *self acting*. We would now say it was *automated*. It carried out its basic sequence of operations so long as power was supplied. Human invervention was restricted to loading and unloading bobbins, and connecting broken threads. Whilst the fact that the mule was water or steam powered meant that it could spin each individual thread faster, this was not critical. The really important thing was the parallelism. Combined with self action this allowed the number of threads spun by each worker to grow enormously. The system illustrated in figure 3.7 illustrates an 8 fold multiplication of productivity but later mules increased the level of parallelism to the order of 100 fold.

3.3.3 From Samian ware to UV lithography the development of printing like technologies

Pottery casting We will now look at a quite different method of raising productivity one which has a long history and is transforming society even now. One of

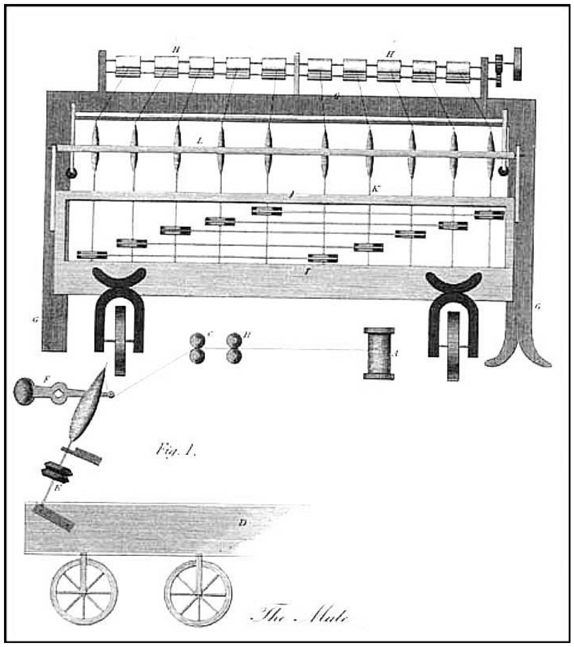


Figure 3.7: Compton's Mule. Note the multiplicity of spindles and the moving frame which substituted for the stretching movement of the hand spinner's arms.

the early mass production industries was the Roman Samian ware industry which flourished from .. to .. It produced ochre coloured pottery kitchenware vessels with raised designs as illustrated in Figure **??**. These were unlike earlier pottery styles in that large numbers of identical pieces were produced. The key to this was the use of casting.

Pottery vessels went through two earlier stages of development. In the first phase pots were made by hand shaping the clay prior to firing. Next came the invention of the potters wheel. This, perhaps the earliest rotary production tool, accelerated the production of circular vessels. The rotation of the wheel meant that the potter had only to specify two parameters for each vertical position on the pot: its inner and outer radii. The 'specification' was done by where they placed their thumb and forefinger relative to the axis of the wheel. The wheel enabled pots to be made with a reduced algorithmic information content. The pots were more even and their production was easier. The potters wheel was the progenitor of a whole class of rotary tools: lathes, drills etc.

The next development dispensed with the wheel and introduced moulds. Clay was pressed into a pre-shaped mould and took on the entire shape in a single operation. With the wheel shaping was still a sequential process. A one dimensional path, a spiral was traced out in the frame of reference of the pot by the potter's grip. With casting the shaping became a parallel two dimensional process. The mould is a two dimensional surface with information encoded as raised and lowered details. Consider what this implies:

(1) The shape is impressed onto the whole surface simultaneously. Of course this is only approximately true with the mold for a curved vessel, but we can conceptualise this as a process in which an approximately flat die comes into contact with a roughly flat sheet of clay, imposing detail right accross the surface. The archetypical model becomes more realistic with subsequent examples of this sort of production.

(2) Whereas the wheel accelerated production by reducing the algorithmic information in the product, moulding did not have this disadvantage. It allowed arbitrary and detailed artistic patterns to be embossed on the piece. The product of the wheel must be a solid of revolution, and arguably, much of the beauty of hand turned pottery stems from this constraint. Moulding allowed decoration to run riot. Samian ware seems to have an almost Victorian love of fancy detail.

(3) No two pots turned on the wheel are the same, but the Samian ware industry was able to churn out masses of identical bowls. Moulding allowed standardised mass production. This was helped by the fact that moulding can be recursive. Pottery moulds were a negative image of the final pot, with raised areas on the pot being depressions on the mould. But if the mould was ceramic, it could be made by first pushing a positive pattern piece into an unformed mould which was then baked. Suppose that a mould could be used 100 times before it became too damaged. Suppose further that the master used to make the mould coul be used 100 times, then this two step process could turn out 10,000 copies of the original pattern piece.

It is worth returning to the paradox relating algorithmic to thermodynamic entropy in production that was mentioned in section 3.2.3. There we said that the algorithmic information in repeated production grows by a law of the form $H(P) \leq H(c) + \log n$ where P is the total product made up of n repetitions of c. If we look at the process of reproduction as a whole there are two terms the first given by the complexity of the original and a second logarithmic term given by the number of repetitions.

In the case of the Samian ware pottery there is the original work of producing the master or pattern piece which corresponds to $H(c)$, but then the number of copies that could be made grows exponentially with the number of successive steps of copying: if the master is used directly to produce the pots then L pots can be made, where L is the lifetime of the master. If the master produces moulds which in turn produce the pots then L^2 pots can be made, etc. Invert the relationship and we find that the number of successive steps of copying will be related to the number of pots produced n as $\log_L(n)$, a relationship suggested by the predictions of information theory.

Cast iron moulding The application of mass production to iron working required a similar path. The crucial step here was the ability to cast iron.

> The transition from the *stckofen* to the blast furnace was gradual. In the taller furnaces the iron ore remained exposed to the reducing action of charcoal for a longer period, and this, combined with higher temperatures from the water-driven blast, generally, but not always; caused some of the iron to melt and trickle from the bottom of the furnace, where it solidified. This iron, having absorbed enough carbon to transform it into cast iron, which is brittle and unworkable in the forge, was an annoyance to the smelter whose object was to produce low carbon wrought iron. As yet he had no use for cast iron and returned it to the furnace to be remelted. In the early part of the fourteenth century, a new term began to appear among iron smelters*flssofen*, that is, a flow oven, clearly indicating that it was capable of producing molten iron.
>
> It was also known in German as a hochofen and in French as a *haut fourneau*. The increasing appearance of molten iron running from the furnace presented the smelter with a problem. We are left to conjecture what may have passed through his mind. In the proportion that iron flowed from his furnace, the quantity of wrought iron which he obtained was lessened.
>
> At the same time, the return of the solidified iron to the furnace for remelting interfered with his operations as a producer of wrought iron. Bronze was then being cast in many forms. Among the chief, if not the chief, cast bronze products were church bells. The iron smelter was certainly familiar with the bronze foundry industry. What could have been more natural than for the producer of cast iron and the bronze foundryman to have been brought together? The circumstances under which this may have occurred are obscure, but it appears most likely that church bells were the first cast iron products extensively produced, followed by a much greater demand for cast iron cannon and cannon balls. (Fisher 1962, p27)

Prior to the development of the blast furnace iron objects required repeated hammering to forge a shape out of the bloom. The resulting wrought iron was tough but expensive to produce. Its use was limited to tools and weapons. Once iron could be heated enough to cast it, one could make shapes that would be hard to produce by hammering - for example cooking pots or cast iron stoves. These could be mass produced from a single pattern wooden pattern from which sand-moulds could be taken[13]. This allowed the mass production of iron utensiles for applications where high tensile strength was not essential. Iron stoves, pipes and cookware became available for domestic use. Cast iron pillars could be used to support the large working areas of mills. Cast iron members operating in compressive mode could be used for bridges. As with Samian ware we see an exuberance in decorative detail made possible by the new technology.

The development of the Bessemer process then allowed the same sand mould technology to be applied to steel production so that even parts used in tension could be cast. The mass production of car engines for example, would have been impossible without castings.

Again we have a technology that utilises the parallel formation of a product enabling a huge extension of production.

Plastic mouldings In the 20th century one saw a recapitulation of history as plastic moulding became available. As with cast iron, this enabled the mass production of domestic utensiles. The significant differences were that plastics were lighter, and could be made to higher dimensional accuracy than cast iron. If one considers products from vacuum cleaners to buckles, we see a progressive replacement of cast or pressed metal parts by cast plastic ones. Aside from the gain in weight, manufacturing costs are reduced by replacing a sequence of metal forming steps by the parallel forming of the product in a mould.

---

[13] *Of casting iron and other metals.* Patterns of wood of metal made from drawings are the originals from which the moulds for casting are made: so that, in fact, the casting itself is a copy of the mould; and the mould is a copy of the pattern. In castings of iron and metals for the coarser purposes, and, if they are afterwards to be worked. even for the finer machines, the exact resemblance amongst the things produced, which takes place in many of the arts to which we have alluded, is not effected in the first instance, nor is this necessary. As the metals shrink in cooling, the pattern is made larger than the intended copy; and in extricating it from the sand in which it is moulded, some little difference will occur in the size of the cavity which it leaves. In smaller works. where accuracy is more requisite, and where few or no after operations are to be performed, a mould of metal is employed which has been formed with considerable care. Thus, in casting bullets, which ought to be perfectly spherical and smooth, an iron instrument is used, in which a cavity has been cut and carefully ground; and, in order to obviate the contraction in cooling, a jet is left which may supply the deficiency of metal arising from that cause, and which is afterwards cut off. The leaden toys for children are cast in brass moulds which open, and in which have been graved or chiselled the figures intended to be produced.

Charles Babbage *Economy of Machinery and Manufactures*, 1832, Chapter 11, section 106.

Printing press The casting of pottery vessels was not the first use of impressions. The use of seals as a certificate of authenticity in correspondance certainly predated it. Sumerian cultures used cylinder seals that could be rolled onto wet clay tablets. Roman administrative authorities used circular stamps looking very like modern postmarks to mark government property. The stamping of coins is another similar example. The purpose in these cases was to have a mark that was unique and easy to apply. The information on the mark could be easily replicated but the master stamp or seal was difficult to replicate. A particular information structure then authenticates an object or claim on an object.

These are specialised activities though, not involving mass production. That changes with the development of the printing press and moveable type. Printing replaces the serial production of the scribe with parallel processing. An entire folio of several pages is formed with a single impression. Here we have the clearest, the archetypical, example of this class of production process. Information, encoded in the physical structure of the array of type is simultaneously transfered accross an entire plane surface onto a receiving medium, the paper. It is clear that what we have transfered is information: we can read it. The transfer is done by a physical movement of the press at right angles to the paper.

But in printing, making marks on paper is the final step in the process of information copying. What made the printing press revolutionary in Europe was the moveable type[14]. One could in principle have carved an entire page of a book as a single block using etching or engraving, as was done with the earlier Chinese wood block printing. This would have speeded up the making of prints, but the work of engraving the master plate would still have been considerable. The use of pre-cast type reduces the labour required to make the master. The information in a page of type comes at two conceptual levels. The semantic level is given by the sequence of words, further decomposed, in Europe, to a sequence of letters from a small fixed alphabet. The shape of these letters comprises a second level of information. In hand written text each letter 'B', 'W' etc will be different. In printed text they are all identical 'BBBB...B' etc. The type used in each B is cast from the same mould. This means that the information in a page of printed text is much less than that in a page written by hand. The cheapness of printing stemmed from the following :

[14]Printing from moveable types. This is the most important in its influence of all the arts of copying. It possesses a singular peculiarity, in the immense subdivision of the parts that form the pattern. After that pattern has furnished thousands of copies, the same individual elements may be arranged again and again in other forms, and thus supply multitudes of originals, from each of which thousands of their copied impressions may flow. It also possesses this advantage, that woodcuts may be used along with the letterpress, and impressions taken from both at the same operation. Charles Babbage *Economy of Machinery and Manufactures*, 1832, Chapter 11, section 93.

(1) Each folio off the press was identical to the preceding one. This means that in algorithmic terms we are exploiting the logarithmic term of the repeated production cost. In labour time it makes use of the fact that repeated copies cost only the labour required to load a sheet of paper and operate the press through one cycle.

(2) The fact that individual letters do not have to be carved reduces typesetting to the choice of appropriate letters.

Taken together these represented a huge change in the productivity of information copying. They were a material precondition for generalised literacy and the eventual development of industrial civilisation.

The process of parallel transfer of information to the product initiated with ceramic casting creates an independent existence for the information source. With seals this independent existence was harnessed to certify the validity of documents. Only the holder of a particular seal could validate a document. But the invention of moveable type transformed this relationship. The particular configuration of type used in an edition of a book became incidental as the type themselves were reusable. The printers plates are of little value in themselves. The information that is being impressed on the page is only secondarily the particular shapes of the letters used. A change in typeface alters all of these but leaves the book substantially unaltered. It becomes clear that what is being transfered is an information structure that has multiple possible representations. The book is an abstract identity surviving its impressions, defined purely as a sequence of characters.

We have a 3 stage evolution of the relationship between labour and information in the product here:

(1) In handicraft work, the information is impressed on the product by the bodily movement of the artisan and has no idenpendent existence.

(2) In pattern or mould based production, the handicraft work is captured once in a pattern or mould from which multiple copies are made. The pattern piece is then an independently existing encoding of the information, whose possesion implies social power. This is either overt in the case of the holder of a seal of office, or implicit in the iron-master's ownership of a store-room of pattern pieces for standard products. The pattern pieces embody much more labour than the individual products they inform and their monopolisation gives market power to their owner.

(3) In printing the information structure becomes abstracted from the impressing apparatus and potentially mobile. Printer with a copy of a book can turn have it typeset and turn off an impression at will. All that is required is the labour of typesetting which is typically less than the labour of authorship. Printing breaks the link between material possesion and ability to reproduce.

> If the labour of writing was to be recompensated in a society of independent commodity producers, the sequence of words itself had to be made an item of property. Hence the printing press in combination with bourgeois social relations gives rise to the law of copyright. Information becomes property independent of its material embodyment.

It is notable that whereas in the case of authorship, the direct producer of the information ususally ends up owning it, this has not been the case for pattern-making, the author owned his copyright, the iron-master owned the patterns, not the pattern maker. Whence the difference?

There appear to have been a number of contributory factors here. The ponderous nature of the patterns made them analogous to other products of direct labour which, in bourgois right, always belong to the employer. A pattern used in sand casting was apparently no different from any other piece of exact carpentry. The pattern-maker might be the more skilled worker and paid better than a moulder, but he was still an employee working at his masters' direction. Next we have to consider that in the casting of machine parts, the pattern would often be an embodiment of information already recorded as technical drawings by an engineer. But this can not have been decisive since the original designs would not necessarily be the property of the iron-master, but might belong to the customers to whom he was contracted to produce parts.

Prior to this one has to ask why the pattern-maker ends up as a wage labourer surrendering his right to the information he produces whereas the author typically remained an independent agent. The decisive factor has to be the extent to which the process of producing information structures can be carried out independently. An author can write 'on his own account', since there is little need for collective input to his production. The work of the pattern-maker forms part of an industrial division of labour. The function of any system of property law is to ensure the reproduction of the agencies of production, be these agencies individuals, firms or the state.

In a commodity producing society, non-state agents of production can only survive by the sale of their product. If that product is an information structure, the agency that bears the cost of making it, will tend to own it. They can then survive by selling either the information itself, or the use of the information. This is a sufficient cause for their survival, whether it is a necessary cause is another matter.

Photography versus painting Printing technology gave us the mass production of images.

Picture prints could be cheaply turned out provided that a human artist had made the master copy. This might be an etching or a lithograph but in either case the information on the page went via human eye, brain and hand. This meant making the master was an inherently serial process. The camera changes this.

Photography, literally translated means drawing with light, but this is an understatement[15]. It is printing with photons. Instead of a metal plate comming down on the paper at centimers per second, wavefronts of light traveling at 300,000 kilometers a second impose their image on the film. As in printing, they work on the whole frame simultaneously.

With photography all humanist mysticism relating information to concious agency is evaporated. With photography the creative subject vanishes. The image is a work of nature. The photographer, where he is even present, has his role reduced to selecting the vital instant at which nature can do its work. With photography Landauer's aphorism that 'information is physical' is literally made manifest. Photography was our first technology to encounter the limits that nature places on the handling and transmission of information. Consider some of its contraints.

Photon quantisation Although the light waves that impinge on the film approach at the ultimate speed c, this does not produce the acceleration in process that one might anticipate. To form an image we need photons to interact with tiny crystals of silver iodide and seed their photo-decomposition. Where struck by photons the crystals break down to leave black colloidal silver.

An individual tiny crystal makes a binary choice, it is either hit by a photon and decomposes or it does not. If struck it evolves to a black dot, if not, it will be dissolved away in the developing process. But we do not want our picture to be just black and white. We want shades of grey. Suppose we want to have 100 shades of grey available. Then we need 100 crystals in each small area that we can resolve. Suppose we have crystals that are $\frac{1}{10}$mm across. Then 100 crystals will fit into each square millimeter of film.

When we take a picture we exploit that probabalistic nature of the photo-decomposition process. If an exposure caused all crystals to absorb photons then we would get a totally black surface. If it was so short that no photons hit any crystals the film would be left white. To get an acceptable grey to black range, we need to have an exposure such that, given the ambient light levels, we would expect that, on a randomly chosen part of the film, about 50% of the crystals will have decomposed. The longer we have the shutter open the more likely it is that we will have enough photons arrive at the surface. Because the arrival of photons is a random process the actual number of crystals triggered will vary. An area with

[15]True photo*graphy* had to await the laser printer, whose hair thin beam, like the engraver's stylus, forms its image stroke at time

100 crystals ‘should’ have half its crystals black, but sometimes has 40 sometimes 60 etc. This gives the film a grainy, noisy look.

We can remove the graininess by using smaller crystals. As you increase the number of crystals in each small area the percentage of them that will turn black at a given light level becomes more predictable.

The noise introduced by photon quantisation is refered to as ”shot noise”. The degree of uncertainty induced by the quatised nature of light is proportional to the square root of the number of photons arriving on a sensor.

Number of crystals	expected brightness error
10	16%
100	4.6%
1000	1.5%

As the number of crystals rises the error in our estimates of the light level falls. This is visually apparent as a smoother less grainy image. Having smaller crystals enables us to capture more information about the light falling on each small area of film. But this gain in information about light levels comes at a cost. It makes the film slower. Smaller crystals have a lower probability of absorbing a photon, so we have to open the shutter for longer to capture our picture. Gaining more information about intensity means that we are restricted to photographing static scenes.

We are up against the fact that information is not only physical, it is physically quantised. The information available about a scene is encoded in the trajectories of photons arriving from it. There are only a finite number of these available. The numbers of photons arriving sets limits on how much we can know about the scene. A fast film allows us to image rapidly moving objects, but the cost is a coarse and grainy image. An alternative is to supplement the supply of photons. In film studios where they want to capture motion and have high quality images, they have to use intense artificial lighting.

λ is the letter conventionally used to represent the wavelength of light or other electromagnetic radiation. Visible light has a $\lambda \approx 0.5\mu = \frac{1}{2{,}000{,}000}$th of a meter. λ determines the smallest details that we can in principle represent by photography. You can not use photography to form a pattern of light and dark whose smallest features are smaller than light waves. This is mainly of relevance in microscopy or the manufacture of microscopic components. But as microman-ufacture has become the governing technology of our age, this constraint weighs more and more heavily upon us.

Let us concentrate for now on photography at conventional scales. We are still faced with constraints imposed by the wave-length of light. The problem arises from diffraction. The wave nature of light imposes a relationship between the resolving power of a lens and its apperture. If you take a picture of a star , something which is effectively a point source of light, with an ordinary camera what you actually see is not a point but little fuzzy circle. The angular size of this circle of confusion is roughly given by the ratio of the wavelength of light to the aperture of the camera. If one has a tiny camera with an aperture of the order of a millimeter, you cant expect to be able to resolve more than few hundred distint points accross your image. As the aperture of your lens goes up, so does the resolving power so that the number of pixels you can have in your image rise in proportion to the area of your lens. The constraint on the production of pictures is then set by the amount of information actually passing through space as light.

Sound recording Sound recording involves copying in two senses. In the first sense a musician plays a piece, this is recorded and subsequently people can listen to a 'copy' of that performance. These copies are separated from the original in time.

The second sense involves making distinct copies of the recording - multiple disks, copies of the tape. These copies can then be separated in space allowing people to simulaneously listen to the performance in many different places.

The first sense of copying is inherently sequential. The performance has to be done from begining to end and recorded as it takes place, and the act ov listening is also sequential. The second sense can be either parallel or sequential.

The production of records whether the old analogue ones or the modern CDs is a special example of a casting processs. A master disk on which a negative image of the tracks has been cut is used to press out the disks from hot soft plastic. As such it is a parallel process. The entire recording is transfered to the disk in a single step. When music is recorded onto tapes on the other hand the copying process is inherently sequential. Such parallelism as there is, is due to having large numbers of tape recorders operating at the same time.

The transition from Edisons original cylindrical phonograph to disc recording was driven by the need to economise on copying. A cylinder could not be pressed out but had to be cut sequentially. The cheapness of disk pressing is what created a mass market for sound recording. With the record industry it at first appears that what is involved is merely the mass production of a material object, and in this context the efficiency of the productive process was vital. But the internet has revealed what should always have been clear: records were merely an intermediary to the copying of performances. People were being forced to buy the material object to get the information it contained. All products contain information, added during production, but for some products - initially books, then records and now software, their use value is their information.

Radio/tv Radio and television take the technologies of sound recording and photography and add to these the principle of broadcasting. Here the product - radio waves, is a direct physical, though immaterial embodiment of information. Once released, broadcast information is available to anyone within reach of the transmitter. The number of copies of a broadcast musical performance that are heard is limited only by the number of recievers within range. The marginal labour embodied in each heard performance tends to zero as the number of listners goes up. To produce say a live musical broadcast there is a certain fixed cost: the time of the musician, the time of the technicians operating the broadcasting equipment, the depreciation on the equipment. These costs are essentially unrelated to the number of listeners. The only component of the cost of broadcasting that relates to the number of listeners is the power used by the transmitter. This tends to be a relatively small part of the total cost.

From its inception therefore, broadcasting was an implicitly 'communist' medium, where performances are given away free to listeners. This free distribution meant that the labour required to run the broadcasting system had to be in a sense directly social labour. The BBC provides a model of this where what is essentially a special tax, the Radio License was levied to provide the service. The private sector equivalent, broadcasting funded by advertising, essentially taxes the sellers of mass produced goods to meet broadcasting costs. Once radio and TV advertising is introduced, manufacturers of consumer goods are forced to finance TV, or loose out to competitors who do.

The free nature of broadcasting prefigures the general transition of the mode of material production to one favourable to communism. As production becomes more and more dominated by the principle of copying information - a principle that has been in development ever since pottery casting - the underlying cause of commodity production and market mechanisms comes to be increasingly undermined. Commodity forms of production can only be sustained by increasingly elaborate and 'unnatural' legal constructs that enforce property rights over information.

Printed circuits/ics The dominant technology of the first decade of the 21st century is digital electronics. This technology has seen sustained rates of growth of productivity that outstrip anything seen in past generations. At the heart of this growth has been the progressive refinement of copying technologies. The ket component of contemporary digital technology is the NMOS transitor. This is the basic element, which repeated millions of times over, builds our computers, cell phones etc. A transistor is basically an electrically controlled switch. Figure **??** illustrates a cross section through a transistor. It comprises 3 electrical contacts, the source, the gate and the drain. When the switch is on, current flows from the source to the drain. When it is off, current can not flow, since current flowing from the source is impeded by having to pass from the N-type silicon aroung the source to the surrounding P-type semi-conductor. To turn the switch on a positive charge is applied to the gate. This creates repells positive charge carriers from below the gate, creating a temporary N-type channel under the gate linking the source to the drain. The components occupy a thin layer in the surface of a silicon chip. The key to their manufacture is to lay out and interconnect large numbers of these transistors on a chip.

Figure 3.8 shows the fabrication steps involved in making NMOS semi-conductor chips. Reading left to right and top to bottom these are:

(1) Start with a polished wafer of P-doped silicon.

(2) Oxidise the wafer to form a SiO_2 layer about half a micron thick by heating the wafer to about 1000°C in an oxygen atmosphere.

(3) After oxidising, a layer of photoresist is spread on the wafer. This is done by rapidly spinning the wafer so that drops of photoresist spread out to a uniform layer before drying.

(4) Next use photolithography to define the source and drain areas of the transistors (one transistor is shown). This involves shining UV light through a shadow mask ensuring that only some areas of the photo resist are exposed to the light. The exposed area undergoes chemical changes allowing it to be washed away by a developing fluid. After this step the information structure on the mask has been transfered to a pattern of holes and lands in the photoresist. The photo resist is then baked so that it can resist acid which will be used to etch holes in the oxide layer.

(5) Expose the wafer to HydroFluoric acid to disolve the the oxide wherever there are holes in the resist. The acid does not disolve pure silicon so the etching stops once it is through the oxide layer.

(6) The photo-resist has been dissolved by an organic solvent leaving a pattern of holes and lands in the oxide layer that matches the pattern on the original mask. (We are now at the right end of the second row in Figure 3.8.)

(7) The silicon under the holes is now doped to N-type (black in the diagram) by diffusing phosphorous into it. This step forms the source and drain of the transistors.

(8) The oxidation of step 3 is repeated to grow a fresh layer of SiO_2.

(9) A new layer of photoresist is spun on. We are now at the end of the third row of the diagram.

(10) The photoresist is exposed under a new mask and a hole is etched through the oxide to expose the area of the silicon that will become the gate of the transistor. We are now at the end of the fourth row of the diagram.

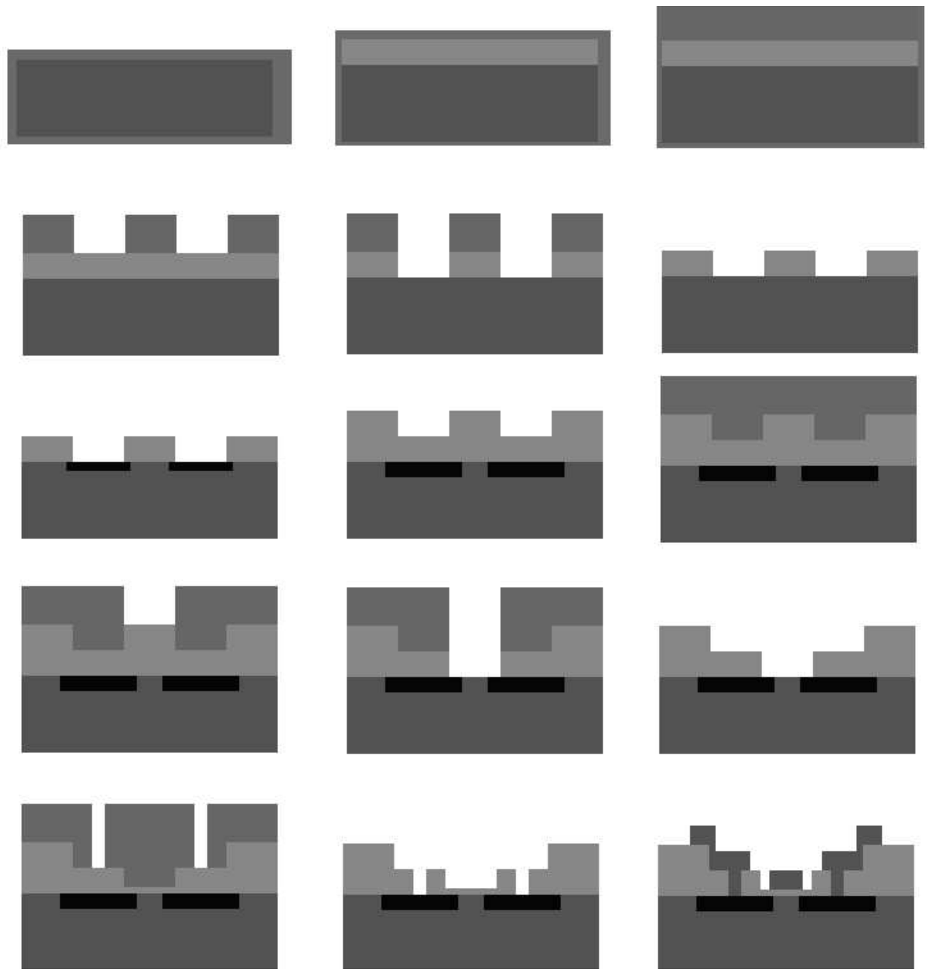


Figure 3.8: NMOS fabrication steps

(11) A short further oxidation step is used to place a very thin insulating layer (a few hundred angstrom) accross the top of the gate area. This has to be thin to allow sufficiently strong electric fields through from the gate to switch the transitor. we dont show this step in the diagram, but the resultant oxide layer can be seen in subsequent images.

(12) Another sequence of photoresist coating, UV exposure and etching is used to cut contacts through the oxide down to the source and drain. We are now at the middle of row five.

(13) The wafer is coated with aluminium. This forms the wires on the surface of the chip. The wafer subjected to yet another round ot photo resist coating, exposure and etching to cut the uniform aluminium layer into a networkof wires joining the chips. This yields the final circuit.

It is evident that the crucial repeated step in this manufacturing process is photolithography. It is this that is used to transfer patterns from a mask to the chip. The ability to project a clear image of a very small feature onto the wafer is limited by the wavelength of the light that is used and the ability of the reduction lens system to capture enough diffraction orders off of the illuminated mask. Current state-of-the-art photolithography tools use Deep Ultraviolet (DUV) light with wavelengths of 248 and 193 nm, which allow minimum feature sizes on the order of 130-90 nm. Future tools are under development which will use 157 nm wavelength DUV in a manner similar to current exposure systems. Additionally, Extreme Ultraviolet (EUV) radiation systems are currently under development which will use 13nm wavelengths, approaching the regime of x-rays, and should allow feature sizes below 45 nm.

The number of transistors that can be produced per square centimeter of silicon obvious varies inversely as the square of the feature size. If you half the feature size you can produce, then the number of transistors you can make goes up four times. Productivity gains have also come through increasing the sizes of the wafers used, allowing more transistors to be printed with each processing cycle.

The production of IC's shows very clearly how manufacturing moves towards being a process of copying information. In making a new Processor Chip, the big costs are :

(1) The work of creating the original design for the chip - this is typically a Computer Aided Design file or set of files which is transfered to the master masks used in chip production.

Each generation of chips uses smaller transistors. This means that the number of transistors used in this years model is likely to be twice as many as was used in the previous model released two years earlier. In consequence the labour of design grows over time just as the cost of producing the individual components falls.

(2) The capital cost of setting up the IC fabrication line. This tends to rise from generation to generation since the equipment used must be increasingly precise, the standards of cleanliness in the production facilities become more stringent, and the imaging equipment becomes more and more esoteric.

The combined effects of these opposing movements means that whilst there has been a rapid exponential growth in the number of transistors produced, with a doubling time of the order of two years, the number of firms able to bear the development costs of new products falls. This has led to an increasingly monopoloised system of manufacture. One company, Intel, has ended up dominating the world production of CPU chips, with only marginal competition from a few smaller firms.

Pcr and genomics The 1950s saw both the birth of the electronic computer industry and the discovery of the structure of DNA. It became clear that living organisms could be seen as self replicating information structures. The reproduction of cells had as a precondition the copying of genetic information. The biotechnology industry rests fundamentally upon these insights. But since the invention of the Polymerase Chain Reaction(PCR), a copying technology has become a key part of the industrial process for biotechnology.

PCR is a technique for copying DNA. A polymerase enzyme from a thermophilic bactrium is placed in a solution of DNA bases and an initial starter quantity of DNA. The temperature of the solution is then cycled up an down. Each time the solution is warmed up, the double strands of DNA disassociate. As it is cooled, the polymerase enzyme builds up a complementary strand of bases on each single strand. This regenerates a complete double stranded molecule of DNA. Thus each cycle doubles the number of molecules, each of which is a copy of the original starter molecule. Here in the PCR process we seen the full industrial application of the principle discussed in sections 3.2.3 and 3.3.3 whereby the algorithmic information in repeated production grows by a law of the form $H(P) \leq H(c) + \log n$ where P is the total product made up of n repetitions of c. If one wants to make n copies of a DNA molecule containing c bases by automated DNA synthesis followed by the PCR, then there will be two phases. In the first phase a small number, in principle as few as 1, copies are made of the DNA using an automated synthesis machine. The number of steps to be followed here will be of the order c. Next the PCR is used to repeatedly double the number of DNA molecules we have. This phase will have to be repeated of the order of $\log_2 n$ times.

With the PCR we see that the regulation of the productivity of an industrial process follows directly from the laws of algorithmic information theory.

3.4 BABBAGE AND THE BIRTH OF DIGITAL TECHNOLOGY

We have emphasised the role of copying as a key factor in the growth of labour productivity over the centuries. The importance of this was first recognised by Charles Babbage.

> The two last-mentioned sources of excellence in the work produced by machinery depend on a principle which pervades a very large portion of all manufactures, and is one upon which the cheapness of the articles produced seems greatly to depend. The principle alluded to is that of copying, taken in its most extensive sense. Almost unlimited pains are, in some instances, bestowed on the original, from which a series of copies is to be produced; and the larger the number of these copies, the more care and pains can the manufacturer afford to lavish upon the original. It may thus happen, that the instrument or tool actually producing the work, shall cost five or even ten thousand times the price of each individual specimen of its power.
>
> As the system of copying is of so much importance, and of such extensive use in the arts, it will be convenient to classify a considerable number of those processes in which it is employed. The following enumeration however is not offered as a complete list; and the explanations are restricted to the shortest possible detail which is consistent with a due regard to making the subject intelligible.
>
> Operations of copying are effected under the following circumstances:

by printing from cavities	by stamping
by printing from surface	by punching
by casting	with elongation
by moulding	with altered dimensions

> Charles Babbage *Economy of Machinery and Manufactures*, 1832, Chapter 11.

Babbage was driven to write *Economy of Machinery and Manufactures* because of the efforts he had put in to develop his pioneering computing machines. For these he required the reliable production of highly accurate gears and other parts, and, given the technologies available at the time this was a real struggle. He had to visit and become familiar with a multitude of manufacturing activities, and then he "was insensibly led to apply to them those principles of generalization to which my other pursuits had naturally given rise". The modes of thought that he had obtained as a mathematician and the first computer designer allowed him to see the key underlying principles at work in manufacturing production.

His analysis of industrial production was immensely influential economically and politically. The two leading economists of the mid 19th century, Karl Marx and J. S. Mill drew heavily on Babbage for their analysis of industry. Marx's distinction between manufacture and machine industry derives essentially from Babbage. Babbage's emphasis on copying technologies, tended however, to be

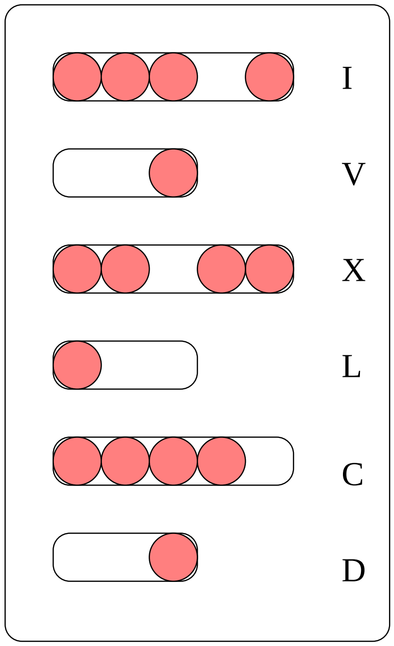


Figure 3.9: A Roman abacus showing the number DLXXVI or in our notation 576.

filtered out in these his followers. One of the precepts of this present book, it should now be clear, is that concepts deriving from computing and information technology are key to understanding industrial production. We will now go on to look at the development of the modern computer in the work of Babbage and Turing.

3.4.1 Tables

The way in which we do calculations is culturally and historically determined. At school we learnt arithmetic, but a particular kind of arithmetic. We learned to do arithmetic with a decimal number system derived from India via Arabia. We probably also learned an alternative way of writing numbers, Roman notation. We may have wondered how on earth the Romans did arithmetic with their numbers, since they seem so ill adapted to the kind of arithmetic we learned at school. The answer is that the Romans used pocket calculators.

Figure 3.9 shows a schematic diagram of a Roman pocket abacus, a number of which have been retrieved in archaelogical digs. Looking at them one realises that Roman numberals were a notation perfectly suited to recording the results of caculations using their abacii. They did not have to use their numberals to do computations, since these could all be done on the abacus. In fact, it was not till the middle ages that the idea of doing calculations using nothing but pen and ink was introduced to Europe. Up until then the term *arithmetic* refered to doing calculations with an abacus or a reckoning table. Reckoning tables were inscribed with lines upon which coins of different denominations were placed and moved about in a similar way to the beads of an abacus.

To work with a reckoning table or abacus you need to be able to count and also to understand the rules for shifting beads and for carrying. If I was to add IIII to the DLXXVI shown in Figure 3.9 I would move beads in the top row accross

abacus	my head
DLXXVI	IIII
DLXXVII	III
DLXXVIII	II
DLXXVIIII	I

I have now moved all the I beads accross to the right and still have I to add. To do this I have to carry which I do by shifting the I beads back to the left and attempt to move the V bead to the right.

It is already to the right, so I carry again, shifting the V to the left and moving one of the X beads to the right. This gives the answer

DLXXX = 580

Now compare this to the way you were taught to do arithmetic at school. We want

```
 576
   4  +
 ------
 580
```

We added 4+6 and got 10, so we wrote down 0 in the rightmost place of the bottom line, then we carried the 1, added it to 7 to get 8, and added 0 to 5 to get 5. To do this I needed to have memorised my addition tables for all the digits from 0 to 9.

0	1	2	3	4	5	6	7	8	9
1	2	3	4	5	6	7	8	9	10
2	3	4	5	6	7	8	9	10	11
3	4	5	6	7	8	9	10	11	12
4	5	6	7	8	9	10	11	12	13
5	6	7	8	9	10	11	12	13	14
6	7	8	9	10	11	12	13	14	15
7	8	9	10	11	12	13	14	15	16
8	9	10	11	12	13	14	15	16	17
9	10	11	12	13	14	15	16	17	18

Note that each entry in that table could be computed using your fingers, or using an abacus, but that by memorising the table you may speed up the process[16]. If you learnt this table and similar subtraction, multiplication and division tables then using the rules of long addition, long multiplication etc, you were equipped to do calculations on numbers of arbitrary length. When it was introduced, this system was called not arithmetic but *algorithmics*, from the name of the Arabic author of a popular maths book of the period. To be useful, algorithmics depended on the memorisation of tables, which in turn implies a certain amount of time as a child rote learning the tables. Algorithmic calculation presupposed a certain social investment in education.

For the normal tasks of commercial calculation adding, subtracting and multiplying were enough. But with the development of oceanic navigation more sophisticated maths was required. Provided that one had an accurate estimate of the time, and an observation of the elevation of the sun, it was in principle possible to determine where you were. Dava Sobel's book *Longitude* describes the long struggle to develop the accurate naval chronometers needed for the estimate of the current Greenwich time. Even with a chronometer the calculations were very elaborate and were only became practicable with to the printing of tables for trigonometric function, logarithms and ephemera.

> These tables are connected with the various sciences, with almost every department of the useful arts, with commerce in all its relations; but above all, with Astronomy and Navigation. So important have they been considered, that in many instances large sums have been appropriated by the most enlightened nations in the production of them; and yet so numerous and insurmoutable have been the difficulties in attending the attainment of this end, that after all, even navigators, putting aside every other department of art and science, have, until very recently, been scantily and imperfectly supplied with the tables indespensibly necessary to determine their position at sea. (Lardner, D., *Babbage's calculating engines*)

These tables stored up the results of long and complex calculations, in a similar way to times tables we learnt at school. But the preparation of trignometric tables was an altogether more difficult task.

3.4.2 Babbage and the division of mental labour

Babbage described how, influenced by reading Adam Smith on the division of labour[17] and charged by the Government of France with the construction of a new

[16]Only may, since a skilled user of an abacus may be able to do it faster

[17]Having one day noticed, in the shop of a seller of old books a copy of the first English edition 1776, of Smith's "Treatise on the Wealth of Nations", I decided to acquire it, and on opening the book at random, I came across the chapter where the author had written about the division of labour; citing, as an example of the great advantages of this method, the manufacture of pins. I conceived all of a

and more complete collection of mathematical tables, a M.de Prony developed a systematic industrial approach to calculation.

> The ancient methods of computing tables were altogether inapplicable to such a proceeding. M. Prony, therefore, wishing to avail himself of all the talent of his country in devising new methods, formed the first section of those who were to take part in this enterprise out of five or six of the most eminent mathematicians in France.
>
> First section. The duty of this first section was to investigate, amongst the various analytical expressions which could be found for the same function, that which was most readily adapted to simple numerical calculation by many individuals employed at the same time. This section had little or nothing to do with the actual numerical work. When its labours were concluded, the formulae on the use of which it had decided, were delivered to the second section.
>
> Second section. This section consisted of seven or eight persons of considerable acquaintance with mathematics: and their duty was to convert into numbers the formulae put into their hands by the first section an operation of great labour; and then to deliver out these formulae to the members of the third section, and receive from them the finished calculations. The members of this second section had certain means of verifying the calculations without the necessity of repeating, or even of examining, the whole of the work done by the third section.
>
> Third section. The members of this section, whose number varied from sixty to eighty, received certain numbers from the second section, and, using nothing more than simple addition and subtraction, they returned to that section the tables in a finished state. It is remarkable that nine-tenths of this class had no knowledge of arithmetic beyond the two first rules which they were thus called upon to exercise, and that these persons were usually found more correct in their calculations, than those who possessed a more extensive knowledge of the subject.
>
> 245. When it is stated that the tables thus computed occupy seventeen large folio volumes, some idea may perhaps be formed of the labour. From that part executed by the third class, which may almost be termed mechanical, requiring the least knowledge and by far the greatest exertions, the first class were entirely exempt. Such labour can always be purchased at an easy rate. The duties of the second class, although requiring considerable skill in arithmetical operations, were yet in some measure relieved by the higher interest naturally felt in those more difficult operations. The exertions of the first class are not likely to require, upon another occasion, so much skill and labour as they did upon the first attempt to introduce such a method; but when the completion

---

sudden the idea of applying the same method to the immense job with which I had been burdened(de Prony 1824)

> of a calculating engine shall have produced a substitute for the whole of the third section of computers, the attention of analysts will naturally be directed to simplifying its application, by a new discussion of the methods of converting analytical formulae into numbers. (Babbage, *Economy of Machinery and Manufactures*, sections 244 and 245.)

The mass of the work was done by people who had now knowledge of mathematics other than the 'first two rules of arithmetic', addition and subtraction. How was it possible to reduce the calculation of complicated trigonometric functions to simple steps of addition or subtraction?

The key to this is the recognition of two steps:

(1) A trignonometric function can be approximated to arbitray degree of accuracy over a short portion of its range by an appropriate polynomial. That is to say if we have some trig function of x we can approximate it by an expression of the form:

$$a_0 + a_1x + a_2x^2 + a_3x^3 + \ldots + a_nx^n$$

where the a_i terms are constant and n is the maximum degree of our polynomical approximation.

(2) It so happens that tables of such functions can be computed using repeated additions using what was termed 'the method of differences'.

Trignometric require quite long polynomials to give a reasonable approximation so to illustrate how the method of differences works we will use a simpler example invented by Babbage himself: calculating the number of cannonballs in a pile. In some old castles in Britain you still see rows of cannons ranged on the battlements with triangular piles of cannonballs by their side. We can construct a table listing the number of balls in such triangular piles:

Length of pile edge	Number of Cannon balls
1	1
2	4
3	10
4	20
etc	etc

Let us assume that this sequence can be represented by a polynomial and since the cannon balls fill a volume in space we can safely assume that the polynomial

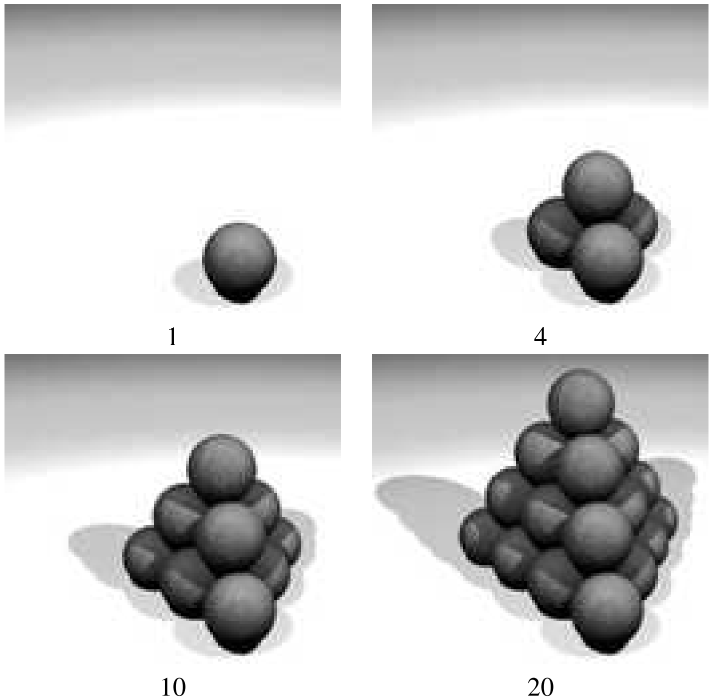


Table 3.1: Table of differences for piles of cannon balls

Layers	Balls	1st difference	2nd difference	3rd difference
1	1	3	3	1
2	4	6	4	1
3	10	10	5	1
4	20	15	6	1
5	35	21	7	1

will be a cubic[18], but the interesting thing comes if we analyse the table itself in the way shown in Table 3.1. Here we have tabulated the original information followed by the 1st, 2nd and 3rd difference terms. The 1st difference is computed by subtracting the current entry in the table from its successor, giving the sequence 3,6,10,... If we think about it the 1st differences are the number of balls in each successive triangular layer of the pyramid of cannonballs as we work down from the top.

The 2nd difference is obtained by subtracting successive terms of the 1st difference from one another giving the sequence, 3,4,5,... This is the number of balls in the edges of successive horizontal layers of the pile.

The 3rd difference is always 1 and this corresponds to the fact that as we go down the pile each layer has edges that are one ball longer than the last.

If we look at the first row in Table 3.1 :1, 3. 3. 1 this now contains sufficient information for us to reconstruct the whole table up to an arbitrary number of layers of balls.

Let us follow the method of M. Prony and employ a division of labour.

> The folio-sheets that were distributed amongst them were each drawn with and divided into 100 intervals, 50 on the recto side and the remainder on the verso. The top line of numbers, on one side of the folio sheets only, was as I have mentioned previously, provided by the workers of the second section. The ninety-nine remaining lines were then filled in by means of purely mechanical operations carried out by the 3rd section, each of whom was performing 900 to 1000 additions or subtractions per day, nearly all of whom not having the least theoretical notion on the work which they were doing.
>
> All the calculations were done twice: expedite means of verification, but very rigorous, were prepared in advance; and I noticed that the sheets the most exempt from error were in particular, furnished by those who had the most limited intelligence, an existence, so to speak, 'automatique' [of routine][19].
>
> (M. de Prony, 1824)

[18]Let us write this as $balls(x) = ax + bx^2 + cx^3$, then since we know the results for the first few values of x we can write this as:

x	balls	Equation
1	1	$= a + b + c$
2	4	$= 2a + 4b + 8c$
3	10	$= 3a + 9b + 27c$

We can then solve this set of equations for a, b, c to get $balls(x) = \frac{x}{3} + \frac{x^2}{2} + \frac{x^3}{6}$

[19]Note how de Prony preferred to use people with the minimum possible level of skill to do the bulk of the work. Such people were obviously cheaper to employ, but also had the advantage that their lack of knowlege made it easier to reduce them to the roles of automatons. Employers today are begining to take a similar attitude towards the computing graduates they employ, saying that their technical training in mathematics and computing should be drastically reduced to about a third of their univesity education. The rest of the time should be spent on business studies, which would presumably give them the appropriate indoctrination in the values of big business.

Assume that three clerks sit at a long desk. The rightmost is given the task of producing a 100 line table to be formed by adding the constant 3rd difference to the intial 2nd difference. They thus produce the sequence:

3

4

5

...

103

When they finish they hand this table to the middle clerk and then start work on their next table of 100 numbers.

The middle clerk has the task of forming a new table of 100 numbers by adding the numbers from the rightmost clerk to a running total that starts with the initial 1st difference. Their table looks like: 3

$3+3=6$

$4+6=10$

$5+10=15$

etc

Finally the leftmost clerk takes a table from the middle clerk and adds 1st differnces to the starting value of the entire table. They produce a table looking like

1

$3+1=4$

$6+4=10$

$10+10=20$

$15+20=35$

etc

Now after a delay equal to the time for the first two clerks to complete their first tables, the third clerk is now working at full speed doing simple additions to turn out the final table. Each page of the table represents the accumulated work of 3 clerks who work in parallel on the arithmetic forming a sort of pipeline of numbers.

It will be evident that by dint of repeated application of the same rule, the clerks become very rapid at their job. By employing a longer desk, like a longer pipeline, the method of differences could be applied to higher order polynomials. For instance one might use the polynomial $1-\frac{x^2}{2}+\frac{x^4}{24}-\frac{x^6}{720}$ to approximate $\cos(x)$ when preparing a table. This would require 6 clerks per desk. Multiple desks in a room would have clerks working on different ranges of the cosine table.

Figure 3.10: Babbage's first difference engine. Appeared as frontispiece from his book *Passages from the Life of a Philospher* 1864

3.4.3 Babages machines

It will be appreciated that there is a significant possibility of error with this sort of manual calculation. If a small error is made in one of the higher order differences it propagates both down that table and through all of the tables calculated using that table. Errors would be more serious if the higher the order of the difference in which they occured. If one could afford to have all of the calculations done twice this significantly reduces the likelihood of error, but it is not impossible that certain operations are more likely to generate a mistake than others. In this case two clerks working independently are liable to make the same mistake, and the resulting error would go undetected.

In his later years, Babbage recalled that whilst labouring with Herschel to correct such mistakes in tables of Logarithms, he exclaimed 'I wish that these tables could be computed by steam!', and then set his mind to solving exactly this problem. The ground had already been prepared by Adam Smith and de Prony. Adam Smith through his enunciation of the principle of the division of labour, and de Prony by his application of it to the preparation of tables. The division of labour is a prelude to mechanisation both because it reduces the basic operations of production to their simplest from and thus minimises the difficult of mechanisation:

> The division of labour suggests the contrivance of tools and machinery to execute its processes. When each processes, by which any article is produced, is the sole occupation of one individual, his whole attention being devoted to a very limited and simple operation, improvements in the form of his tools, or in the mode of using them, are much more likely to occur to his mind, than if it were distracted by a greater variety of circumstances. Such an improvement in the tool is generally the first step towards a machine. (Babbage,*Economy of Machinery*, Sec. 225).

To this end he developed his Difference engine, the prototype of which is shown in Figure 3.10. The first prototype could handle 3rd order differences, and operates as a proof of concept. Having established the principle, he then set about raising money for a much larger machine suitable for the industrial production of tables. This machine was to to be able to compute 7th order differences to a very high precision - over 30 digits. This compares very favourably with our electronic computers whose default accuracy was for long 10 digits, and is now approaching 20 digits with the availability of 64bit processors. It was to be equipped with a printer to ensure that results of calculations were transfered to paper without the possibility of human error intervening.

The project to build the second difference engine eventually foundered. A combination of factors, Babbages poor relations with his chief engineer, Babbages insistence on continually improving the design, and above all, the great difficulty he had in obtaining precisely and repeatably engineered components, contributed to this failure. The basic soundness of the design was, however, demonstrated in the 1990s when the Science Museum in London used Babbages original drawings to have the machine constructed, and it was found to work just as designed.

The principle of their operation can be explained by looking at Figure 3.10. This shows the small prototype machine that Babbage constructed between 1828 and 1833. Suppose we were to set the machine to calculate the number of cannonballs in piles as described previously. Each of the difference terms shown at the top of Table 3.1 would be entered into one of the columns of the machine by rotating the digit wheels. Then the handle would be turned. With each rotation of the handle, the 1st difference would be added to the total. The 2nd difference is then added to the first difference and then the 3rd difference to the 2nd. It thus emulated in machinery the division of labour devloped by de Prony. In the process the possibility of human error is removed. As a final insurance against error, the machine set the result in type and printed it.

The difference engine was the first machine capable of calculating and tabulating mathematical functions. But it was restricted to a small class of functions, those that could be approximated by polynomials. To do this it used two basic principles - storage of numbers, and addition. It turns out that subtraction could be performed by a subtle trick. Suppose I have a decimal adding machine that can handle two digits. That is, it could represent numbers from 0 to 99. Suppose I want to subtract 3 from 25 using this machine. How could I do it?

By adding 97, since $25+97 = 122$, since the machine can only represent 2 digits it will show the answer as 22. But this is the same result we would get by doing $25-3 = 22$.

But there are 4 basic arithmetic operations $+,-,\times,\div$. Babbage, having seen that he could mechanise repeated additions and subtractions, sought to produce a machine that could handle a much wider range of calculations. This led him to his analytical engine which prefigured the modern computer. Its key components were

(1) A set of number registers to store decimal numbers. These were similar to those of the difference engine. Babbage refered to these registers as $V_1, V_2, \ldots$ indicating that they were used to hold variables.

(2) A component which Babbage, copying the industrial terminology of his day, termed the *mill*. This was capable of performing the four basic operations of arithmetic on two numbers.

(3) An instruction store made up of punched cards. Each card specified three variable registers and an arithmetic operation. For instance it might specify a calculation such as:

$$V_4 = V_1 + V3$$

(4) A set of data cards which held numbers to be loaded into the registers.

(5) A printer to produce the results.

Babbage realised that were such a machine to be contructed, it would be capable of mechanising any calculation that a human mathematician might attempt. Technical and financial difficulties prevented it from being built, but already at the dawn of the industrial age, the essential principles of the modern computer had been laid down. Implementation had to await the work of another great mathematician Alan Turing.

3.5 SPECIAL PURPOSE VERSUS GENERAL PURPOSE MACHINES *Greg*

3.5.1 RUR

CHAPTER 4

INFORMATION AND COMMUNICATION

Much of the previous discussion has hinged upon information as patterns of difference. What is most interesting about such patterns is that they can carry messages: as we shall see, patterns within information may be structured in different ways to reflect different meanings. In particular, two entities may communicate provided they are able to transmit patterns of information between each other, and to interpret each other's patterns consistently

"The medium is the message." — Marshall McLuhan

For communication to take place, patterned information must be embodied in a form that enables it to be transmitted. Embodying information is relatively straight forward, requiring a medium within which it is possible to discriminate differences.

For example, consider two people talking face to face. The speaker's voice sets up patterns of vibrations in the air between them and the listener. The vibrations pass through the air and enter the listener's ears, eventually enabling them to hear what was said. The communication can take place because vibrating air molecules can embody patterns in information.

If the people were talking by telephone, then speakers voice would, via the air, vibrate the microphone in their handset. In turn, this would set up variations in the electricity in the wire connecting their phone to the exchange. That wire is, courtesy of the telephone system, connected to the wire to the loudspeaker in the listener's handset. The loudspeaker vibrates the air, enabling the listener to hear what was said by the speaker. Here, while electricity is an additional medium for communication, the electric variations carry the same meanings as the vibrating air. This ability to embody information patterns in electricity lies at the bottom of the profound revolution in machine aided communication and information processing, that started in the mid 19th century with the telegraph.

If our telephonists were using a digital telephone system, then the vibrating electricity from the speaker's microphone would be converted by electronic circuits to digital patterns of electric 'on's and 'off's for transmission. Eventually they would be converted back to vibrating electricity to drive the listener's earpiece. These digital patterns contain the same meanings as the continuous patterns in the electricity or air, but are much better suited for manipulation by electronic means, especially computers. For example, its much easier to detect when something's gone wrong with digital transmissions and to correct them. That's why the record manufacturers feared CD's, and the video manufacturers feared DVD: digitally structured information can be copied perfectly, and manufacturers' recordings are no longer superior to home copies.

"Between thought and expression, there lies a lifetime." — Lou Reed

When two entities interact by sending patterned information through a medium, they take it in turns to transmit and receive information. For their communication to be effective, the receiver must be able to understand the transmitter's message. That is, there must be consistency between the meanings that the transmitter generates and that the receiver interprets. Curiously, such consistency is not a property of the information itself: the same pattern of information may be interpreted as having different meanings in different contexts.

Consider, for example, the pattern "111". This might be interpreted as "three" in Roman numerals $(1+1+1)$, or as "one hundred and eleven" in Arabic numerals $(1 \times 100 + 1 \times 10 \times 1 \times 1)$, or as "seven" in binary digits $(1 \times 4 + 1 \times 2 + 1 \times 1)$. Here, the same pattern of information bears different meanings in different languages.

Consider for example, Dr Seuss' immortal refrain "Yes I like green eggs and ham". We can show that this has different meanings by placing brackets to indicate how the salient words are associated with each other. The more obvious meanings are "Yes I like green (eggs and ham)" i.e. "I like both my eggs and ham to be green", and "Yes I like (green eggs) and ham" i.e. "I like my eggs to be green and I like ham in general". A less obvious though equally valid alternative is "Yes I (like green eggs) and ham" i.e. "I like my eggs to be green and I'm a bad actor". That is, we can discern different structures with different meanings within the same pattern of information, even in the same language.

Nonetheless, entities communicate most effectively when they use the same language. In general, a language defines a class of information structures that bear meanings. Its usual to distinguish between the alphabet, symbols, syntax and semantics.

The alphabet consists of the base units of embodiment in the medium, for examples phonemes in speech, letters in writing or 'on's and 'off's in digital communication. These base units don't have any necessary meanings themselves. Rather, they provide a first level of structure to apparently raw information.

The symbols are the base units of meaning, for examples words in human languages. While symbols carry meanings, once again they don't have necessary meanings. For example, in Scots "mind" means "remember", as in "Should auld acquaintance be forgot and never brought to mind". In other dialects of English, "to mind" means to object to. Hence the old joke:

> Scots person: Do you mind my face?
> English person: No, you look fine.

The syntax defines sequences of symbols which correspond to a further level of rules for structuring information. Thus, its usual to view many written human languages as composed of phrases, clauses, sentences and paragraphs.

Finally, the semantics describe what the well formed symbol sequences mean. As yet, we have little idea about how to define the semantics of human languages well enough for them to be understood by computers. Nonetheless, we all imbibe semantics as we learn our native tongue. We will return to this problem later on.

Human beings are raised in cultures that seethe with language. Children are immersed in language from the moment they are born: all around them people engage in social transactions using language. The sooner children acquire language they sooner they can take part in effective interaction. More to the point, languages carry ideologies. In learning language children become socialised, that is they imbibe memes that both reproduce and challenge societies.

It is striking how hard people with different languages find communication, even when their cultures are very similar. Although they share the same potential meanings they lack a common means of expressing them. Apparently trivial activities, like buying train tickets, involve astonishingly rich powers of expressiveness.

Contrariwise, people from different cultures but with a common language can communicate unfamiliar, culturally specific meanings. This was the dream behind Esperanto, an attempt to devise an international language. Of course, Esperanto bares the hallmarks of its time, having been invented in 1887. For example, male and female genders are distinguished in contexts in which they are irrelevant. Nonetheless, Esperanto was motivated by the lofty ideal to break down barriers between cultures. However, its failure to compete with, let alone displace, its contemporaries shows how firmly language is rooted in the societies in which it evolves.

While it is not clear whether or not there are linguistic universals that are shared across all human languages, it is likely that human brains are equipped to acquire arbitrary languages. Babies will learn the language they are brought up in and young children from one culture very quickly learn the language of another. Indeed, it is common for immigrant children to mediate between their parents and the host community, on first arrival in a new society. However, this linguistic plasticity is quickly lost. Generally, adults find it much harder to learn new languages. It seems that our brains come to depend on the first language that we acquire, as a high level way to structure accounts of reality.

No one knows how human languages originated. Animals certainly communicate using languages, but they are not able to generate and interpret rich ranges of meanings compared with humans. Most species have limited repertoires of behaviours and very restricted learning capabilities. One implication is that animal brains are not able to represent and process information in such a way as to enable them to change the world as well as interpret it.

This is somewhat unfair. Animals necessarily change their worlds simply by living in them. For example, the eat/shit cycle is central to the reproduction of the natural environment. But most change is localised to animals' habitats, if we conveniently overlook the impact the world's cow population has on global warming, and most animals cannot live outside of relatively constrained habitats. Animal brains and bodies seem best adapted to enabling them to survive in the presence of the sort of slow predictable change experienced in any one locale on our planet as it gently wobbles its way round the sun.

In contrast, human beings survive all over the globe, displacing and exterminating other species, as well as each other, as they spread. Human language is one of the fundamental tools that has helped us to become the dominant species on this peculiar planet of ours. It enables us to make models of our circumstances such that we can predict the effects of our behaviours and modify them to achieve diverse aims.

Of course animals also make models of their environments but much animal modelling is hardwired. For example, hares' coats change from brown to white as autumn turns to winter and from white back to brown again as spring approaches. But this is driven by the temperature and the length of daylight rather than some fiendish harey plan to escape detection amongst the snows.

Unlike hares, chimpanzees seem to have rich inner existences. They have highly structured societies, held together by well understood social rules that are passed from parents to children. Chimpanzees can learn to use rudimentary tools, for example using sticks to winkle honey out of hives, and such tool use is again passed on through the generations.

"If lions could speak, we wouldn't understand them." — Witgenstein

Alas, all attempts to teach chimpanzees human language so far have failed to progress beyond a simple vocabulary based, Paulo Freire fashion, on everyday experiences. Chimpanzees can learn symbols for food and places, and for colour and quantity, and can learn to use them to interact with humans. However, chimps are poor at learning grammar and rarely produce novel word sequences, instead repeating sequences that they know will elicit appropriate responses in their keepers. It is as if chimpanzee brains cannot form and manipulate information structures of adequate complexity to see how things might be different and to make them so.

Chimpanzees are far more bound to their hard wiring than we are. For example, chimps can be taught that if they nominate either of two quantities of food, it will be given to another chimp leaving them with the remaining plate. When pictures of food are used, chimps always point to the smaller quantity and receive the larger. But when real food in closed glass jars is used, chimps cannot stop themselves reaching for the larger quantity, even though they loose it as soom as they do this. In the wild, if you don't eat when you can then something else will instead. This response has become deeply ingrained as a powerful survival mechanism in most animals' psyches, and cannot be displaced by a little local learning.

We share 98 percent of our DNA with chimpanzees. The other 2 percent is why they use tools and we make them. Chimp brains are well adapted for living in unchanging forests, or in circuses and research laboratories. But their limited ability to manipulate information structures is why they don't hold human tea parties in their zoos.

Human information structures like natural language have helped make us masters of our own dung heaps. They have also enabled us to transmit descriptions of our knowledge of our circumstances to other people. Our information structures can be embodied in artefacts, like cave paintings and scrolls and books and floppy disks, that long outlast us as individuals. But that knowledge is only useful to others if it can be discerned from the information structures that carry it.

Consider the Rosetta stone, mentioned in the previous chapter, containing inscriptions in hieroglyphic, demotic and Greek alphabets. Because Greek was already understood, and it was assumed that all three inscriptions bore the same meanings, it was possible to decipher the hieroglyphic and demotic inscriptions. This assumption of consistency might be wrong. The demotic might actually be a cry for help from the unfortunate slave that carved the stone. However, there are sufficient structural similarities between the inscriptions, and with other inscriptions using the same alphabets, to give confidence that they do all represent the same message.

Consider, for example, the strange fate of the Pioneer 10 space craft, launched from the USA in March 1972. In 1997, Pioneer 10 was 10.10 billion kilometres from earth and is still heading out across the cosmos. On its side is a gold plaque showing, amongst other things: the behaviour of a hydrogen atom, the most common element in the universe; the location of our planet relative to the centre of the galaxy; a waving human man next to a smaller human woman. The intention was to persuade passing aliens that there was intelligent life on earth. Perhaps this symbolism is reasonable. We have no idea what information structures aliens will use, so our own are probably as good as any. But the aliens may utterly misconstrue our message of goodwill. Perhaps they will think its junk mail, advertising vacations in a hydrogen rich atmosphere. In truth, they may have no common point of reference whatsoever with our graphical information structures.

"If you want to know the taste of a pear, you must change it by eating it yourself." — Mao Tse-Tung

But it isn't just explicit messages that bear meanings. All information structures have meanings for the entities that interpret them. And manipulation of information structures is fundamental to extracting meanings from them. Our aliens will undoubtedly find out more about us by taking the space craft to bits and working out how it functions, that is by interpreting our artefacts themselves as information structures that reflect something about their origins. Similarly, in understanding language, brains and computers tear internal representations of messages to pieces, to identify and interpret their information structures.

Consider a URL in the HTML language used for communication between people and computers:

`http://www.klingon.planet/~whorf/fun/fighting.jpg`

First of all, this URL is made up of a sequence of letters: 'h', 't', 't', 'p', ':' and so on. These are the letters we type to enter the URL into a computer. We know which keys to use because they have similar, if not the same, letters on them. These letters are also close to the lowest level representations that computers use to communicate.

Within the letter sequence, different letters mark different regions of the URL. In HTML, as in most human languages, symbols are made up of sequences of a fixed set of alphabetic letters. Thus, we and the computer can distinguish the words "http", "www", "klingon" and so on, as being bearers of basic meanings.

The punctuation marks structure the symbol sequences and help us an or a computer elucidate the URLs meanings. The '://' marks the separation between the type of message and the start of its main content. The first word, "http" tells us, and computers, that the rest of the words specify a WWW location. If the first word were "emailto" then we would know that the rest of the words describe an email address. This first word effectively tells us the dialect of HTML in which the rest of the URL is written.

The sequence separated by '.'s up to the first '/' is the main address of the WWW location. Curiously its read from right to left rather than left to right. It tells us to look for a specific locale, often associated with an individual organisation, called "klingon", amongst a number of systems associated with the common domain “planet”. The “www” tells us to start from a standard place in that system’s files, in order to move to the fine detail of the location.

The international standard for WWW locations and email addresses is to write from most specific to most general, as it has been for hundreds of years with top to bottom addresses on envelopes. However, from the point of view of finding an address it would be easiest to start with the most general locale and then home in. Both human and artificial languages suffer from the vagueries of the contexts in which they evolve. Indeed, early UUCP email addresses used to be from most general to most specific from left to rught.

Next, the ‘˜ before “whorf” tells us to look in a standard directory (also called “www”) at the top level in the files belonging to the user whose login is “whorf”. The next ‘/’ marks the start of the name of a subdirectory in whorf’s “www” file. Here, that directory is called “fun”. The next ‘/’ marks the start of the name of a file in that subdirectory called “fighting.jpg”. The “.jpg” tells us that this file contains a picture, in yet another encoding.

Our understanding of English, and of American TV, helps us deduce that we may have been told to look at a picture of Mr Whorf, from the planet Klingon, fighting. On the other hand, the URL tells a computer to send a set of information structures from its memory to a display screen or printer. Computers don’t yet watch Star Trek and the computer is unable to be even indifferent to our crude representations of alternative ways of being.

Unlike Mao Tse-Tung’s pear, information structures need not necessarily be destroyed in the process of being understood. Even though an individual embodiment of an information structure may be taken to pieces in the process of understanding it, an identical copy may still embody the original information structure. Thus, if our aliens chance upon Pioneer 10’s companion, Pioneer 11, they will find exactly the same gold plaque on its side. And if they broke something in examining Pioneer 10, they can always start again with Pioneer 11. As with the Rosetta stone, they aliens may find reassurance in the duplication of information structures.

We might say that an information structure bears meaning for another information structure when the interactions between the structures cause the second one to change. Computers are information structures and not just in the basic sense of being a particular configuration of atoms. Computers have memories which at any one time can hold a very large number of different patterns of ”1”s and ”0”s. Those patterns will in turn determine how the computer will behave. The microprocessor in the computer inspects the patterns in the memory, one after another, treating them as instructions in a language which is understood by all other microprocessors of the same family. These instructions typically specify that other patterns should be manipulated. We can characterise the state of a computer in terms of all the patterns in its memory and the position of the pattern it is currently inspecting. If we can take a copy of this state then, in principle, we can load it into another computer which will then behave exactly like the first computer.

When two computers pass each other information they change each other's internal states. Human beings are also information structures with internal states in brains, consisting of links between neurones, electric potentials between synapses where two neurones meet and chemical balances establishing the electric potentials within the neurones themeselves. When human beings interact they also change each other's internal states. Suppose your neighbour has a pet rabbit. There will be some component of their brain state that determines how the presence of the rabbit affects their behaviours. For example they will routinely feed the rabbit and clean its hutch. When you tell your neighbour that their rabbit has been eaten by your cat, you have changed fundamentally their conception of their rabbit, and hence their subsequent behaviours. For example, they now need to learn not to feed the rabbit. These changes are ultimately mediated by changes in their brain states.

Brain states are fabulously complicated and characterising a person's brain state as a sequence of symbol patterns is well nigh impossible. This effectively precludes the possibility of cloning truly identical individuals. It may be possible to clone genetically and physically identical individuals, but in the absence of a precise characterisation, they cannot be loaded with the same brain state. Computers are much simpler and the same program running on two computers with the same configurations will display consistent behaviour.

If we can give a precise characterisation of an information structure then we can measure its meaning in terms of the minimum amount of work necessary to generate or interpret it. There are profound mathematical results which say that it is impossible to make a precise measurement of the meaning of an arbitrary information structure. However we can make crude measurements which divide meanings up into broad classes.

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