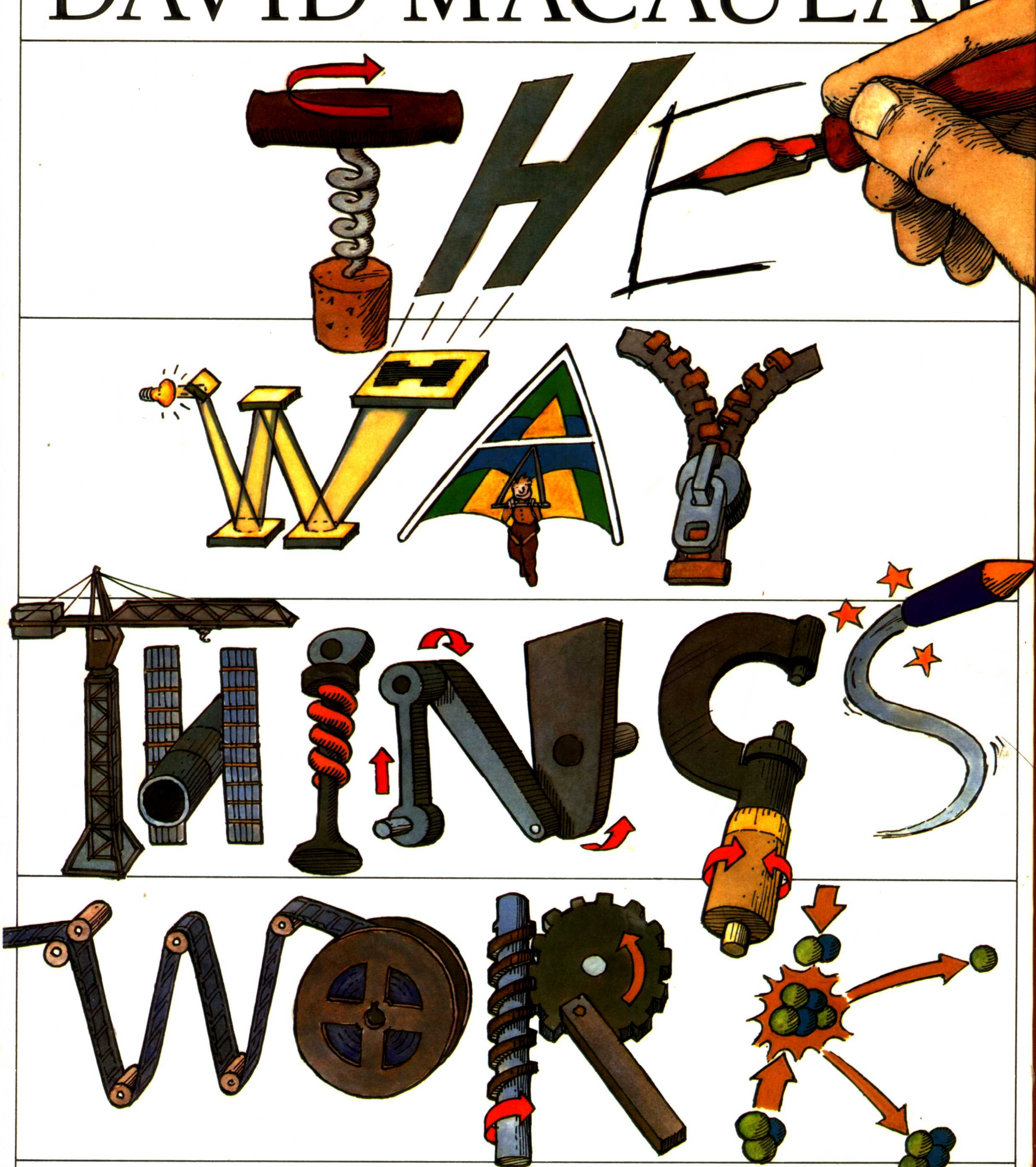
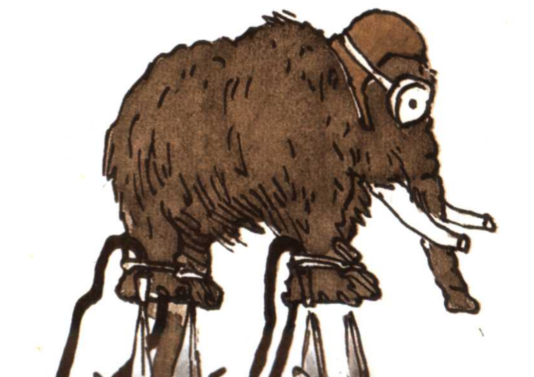
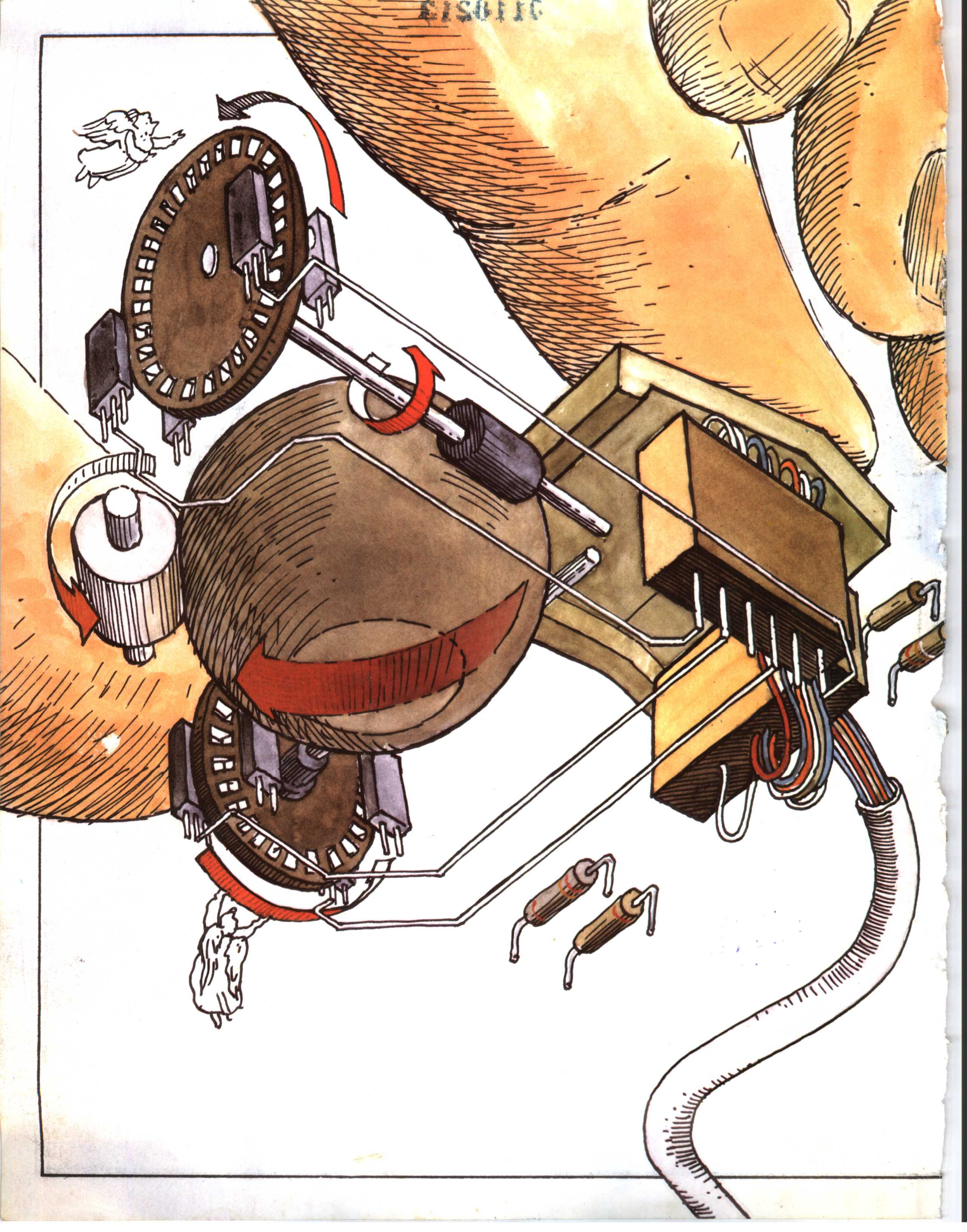
DAVID MACAULAY



FROM LEVERS TO LASERS, CARS TO COMPUTERS-
A VISUAL GUIDE TO THE WORLD OF MACHINES

THE WAY THINGS WORK





THE WAY THINGS WORK

DAVID
MACAULAY

HOUGHTON MIFFLIN COMPANY
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THE WAY THINGS WORK has taken almost three years to create. It could easily have taken another three years without the help and encouragement of several people. My gratitude, first and foremost, goes to Neil Ardley, who provided all the technical text and who shared his vast knowledge of the subject with tremendous patience and enthusiasm. Another member of the team I would like to thank is David Burnie, whose editorial input, organizational skills and unfailing sense of the book from beginning to end were matched only by the illusion of calmness he maintained as each deadline came and went. Designer Peter Luff both provided a framework which ensured a visual consistency and was also an invaluable critic throughout the making of the pictures. I also wish to thank Christopher Davis who used the old ruse of the after-dinner chat to get me into this whole thing in the first place, and also Linda, Ben and Sam Davis who provided me with a second home during my many meetings in London. Finally, my thanks go to my wife Ruth, who has alternately encouraged and tolerated this project and all its demands. To her, with love, this book is dedicated.

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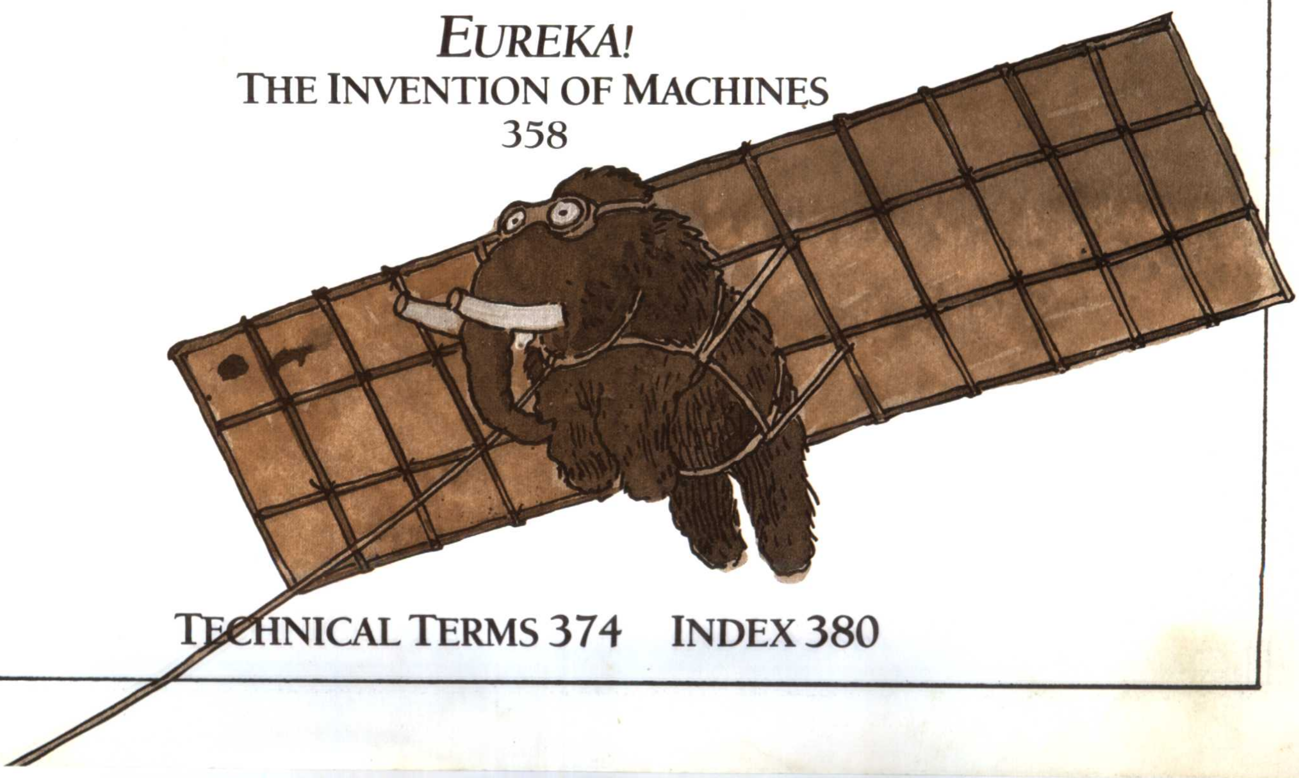
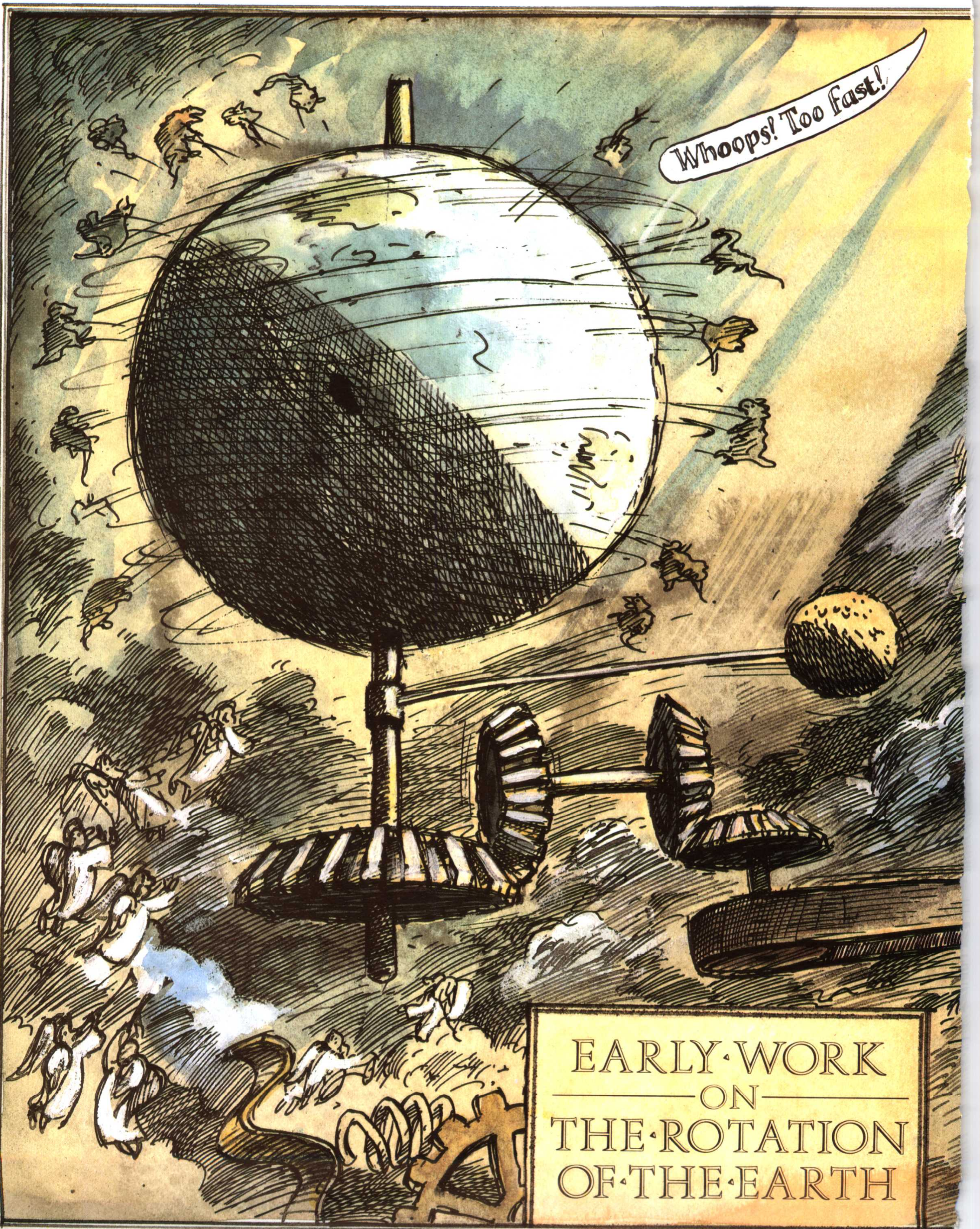
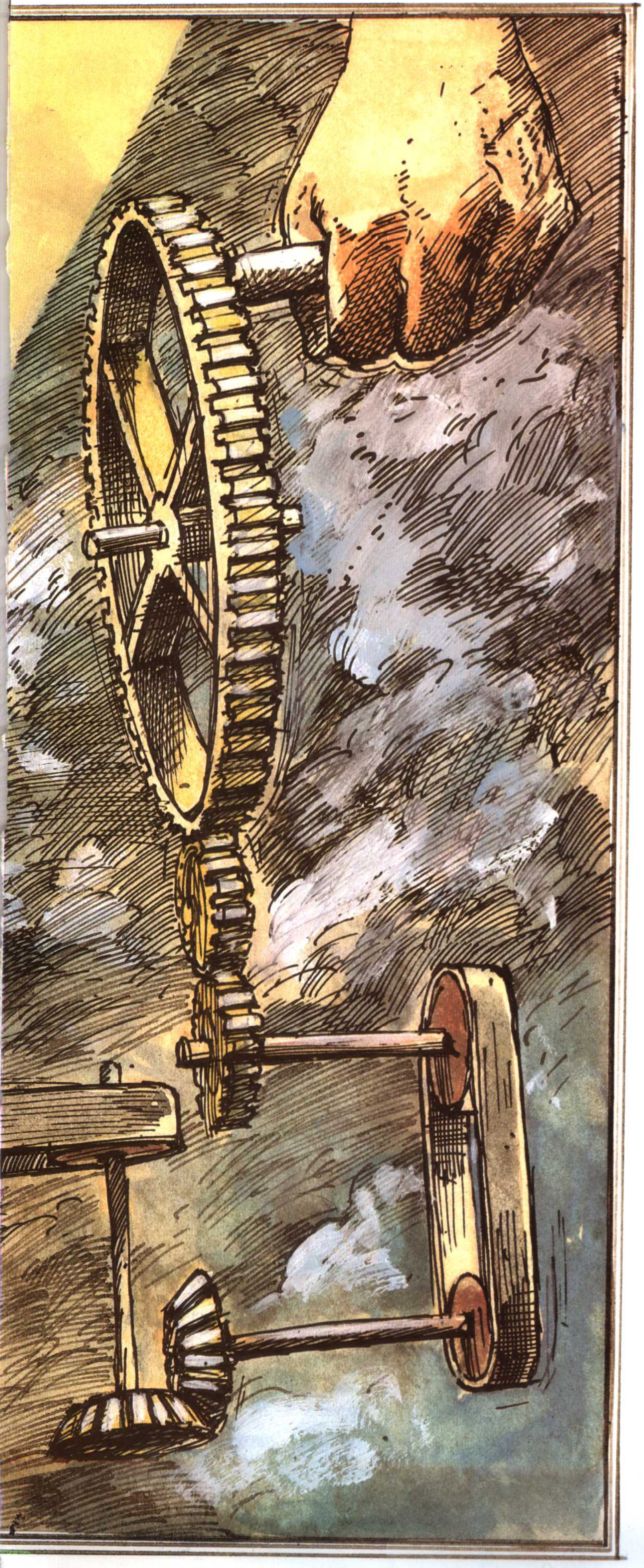




EARLY·WORK ON THE·ROTATION OF·THE·EARTH

PART 1

THE MECHANICS OF MOVEMENT



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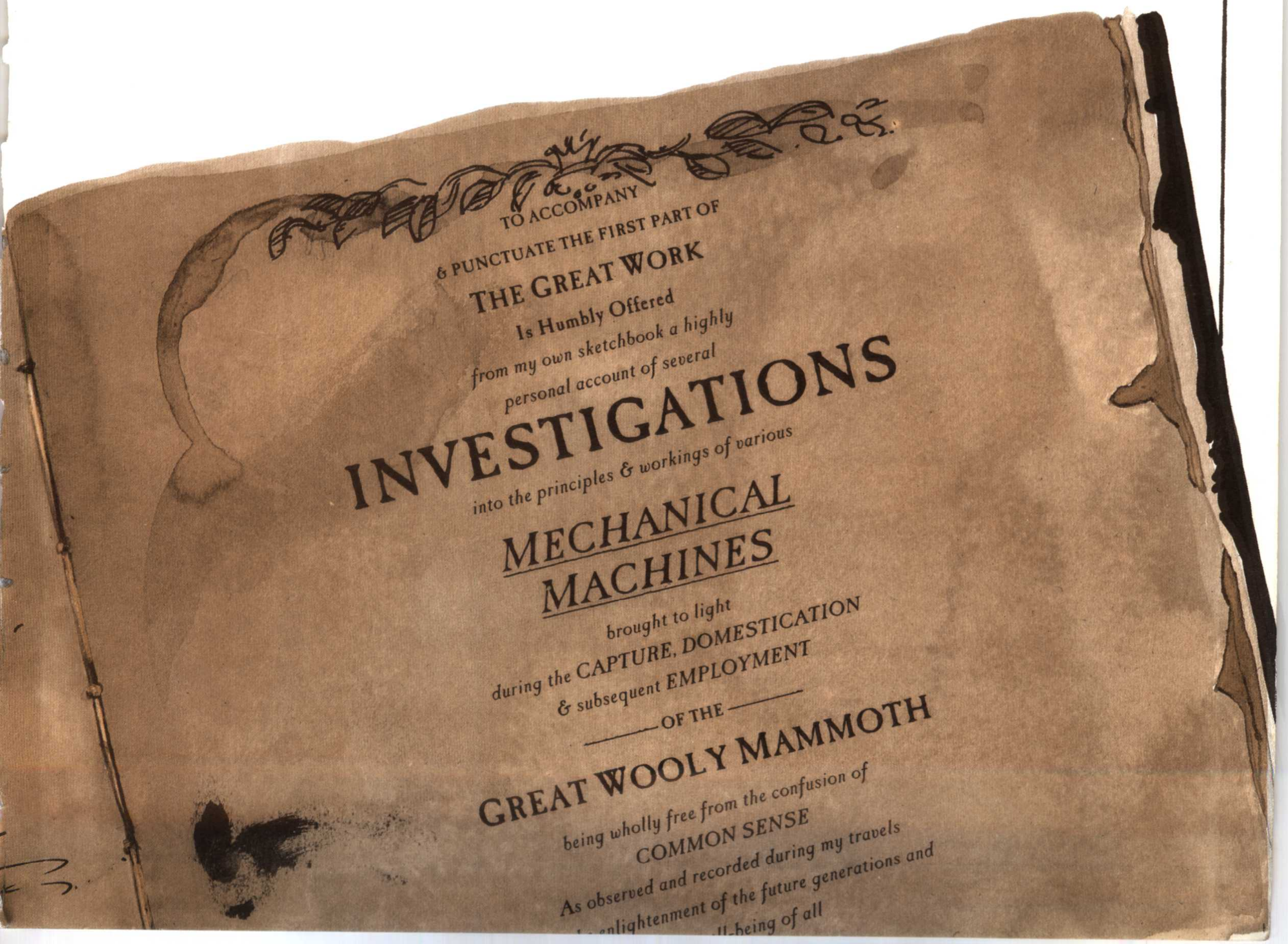


TO ACCOMPANY
& PUNCTUATE THE FIRST PART OF
THE GREAT WORK
Is Humbly Offered
from my own sketchbook a highly
personal account of several
INVESTIGATIONS
into the principles & workings of various
MECHANICAL MACHINES
brought to light
during the CAPTURE, DOMESTICATION
& subsequent EMPLOYMENT
OF THE
GREAT WOOLY MAMMOTH
being wholly free from the confusion of
COMMON SENSE
As observed and recorded during my travels

INTRODUCTION

TO ANY MACHINE, work is a matter of principle, because everything a machine does is in accordance with a set of principles or scientific laws. To see the way a machine works, you can take the covers off and look inside. But to understand what goes on, you need to get to know the principles that govern its actions.

The machines in this and the following parts of *The Way Things Work* are therefore grouped by their principles rather than by their uses. This produces some interesting neighbors: the plow rubs shoulders with the zipper, for example, and the hydroelectric power station with the dentist's drill. They may look very different, be vastly different in scale, and have different purposes, but when seen in terms of principles, they work in the same way.

MACHINERY IN MOTION

Mechanical machines work with parts that move. These parts include levers, gears, belts, wheels, cams, cranks and springs, and they are often interconnected in complex linkages, some large enough to move mountains and others almost invisible. Their movement can be so fast that it disappears in a blur of spinning axles and whirling gears, or it can be so slow that nothing seems to be moving at all.

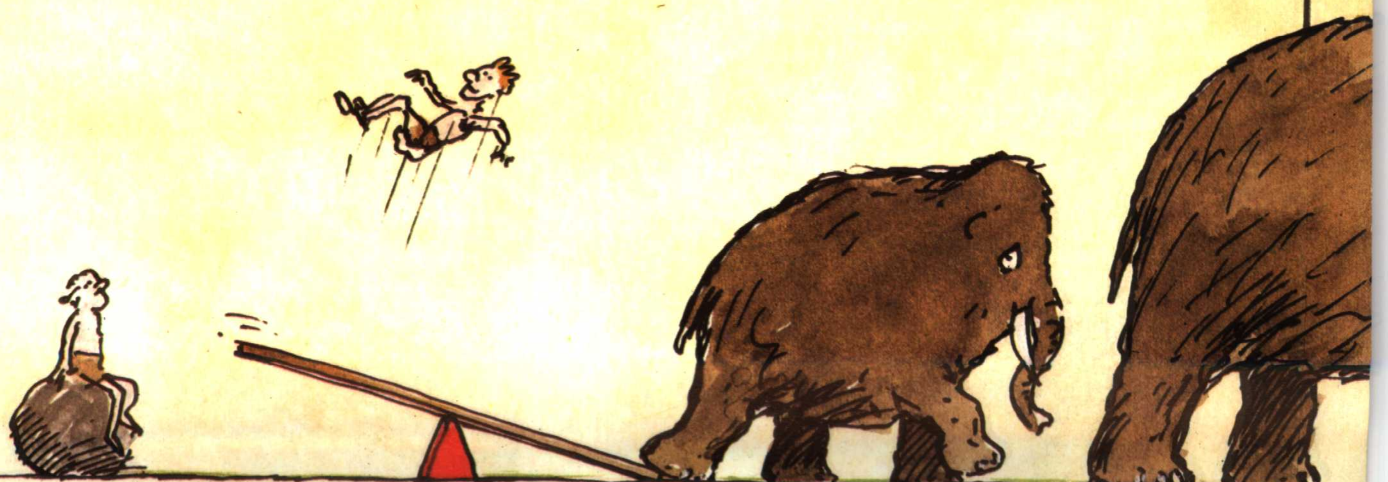
But whatever their nature, all machines that use mechanical parts are built with the same single aim: to ensure that exactly the right amount of force produces just the right amount of movement precisely where it is needed.

MOVEMENT AND FORCE

Many mechanical machines exist to convert one form of movement into another. This movement may be in a straight line (in which case it is often backward-and-forward, as in the shuttling of a piston-rod) or it may be in a circle. Many machines convert linear movement into circular or rotary movement and vice-versa, often because the power source driving the machine moves in one way and the machine in another. But whether direction is altered or not, the mechanical parts move to change the force applied into one – either larger or smaller – that is appropriate for the task to be tackled.

Mechanical machines all deal with forces. In one way they are just like people when it comes to getting them on the move: it always takes some effort. Movement does not simply occur of its own accord, even when you drop something. It needs a driving force – the push of a motor, the pull of muscles or gravity, for example. In a machine, this driving force must then be conveyed to the right place in the right amount.

There is a lot of ingenuity involved in transmitting force from one place to another, and ensuring that it arrives in just the right quantity. When you squeeze and twist the handles of a can opener, the blade cuts easily through the lid of the can. This device makes light work of something that would otherwise be impossible. It does this not by giving you strength that you have not got, but by converting the force that your wrist produces into the most useful form for the job – in this case, by increasing it – and applying it where it is needed.



HOLDING MATTER TOGETHER

Every object on Earth is held together and in place by three basic kinds of force; virtually all machines make use of only two of them.

The first kind of force is gravity, which pulls any two pieces of matter together. Gravity may seem to be a very strong force, but in fact it is by far the weakest of the three. Its effects are noticeable only because it depends on the masses of the two pieces of matter involved, and because one of these pieces of matter – the whole Earth – is enormous.

The second force is the electrical force that exists between atoms. This is responsible for electricity, a subject explored in Part 4 of this book. Electrical force binds the atoms which make up all materials, and it holds them together with tremendous strength. Movement in machines is transmitted – unless the parts break – only because the atoms and molecules (groups of atoms) in these parts are held together by electrical force. So all mechanical machines use this force indirectly. In addition, some machines, such as springs and friction devices, use it directly, both to produce movement and to prevent it.

The third force is the nuclear force that binds particles in the nuclei of atoms. This force is the strongest of all, and is released only by machines that produce nuclear power.

THE CONSERVATION OF ENERGY

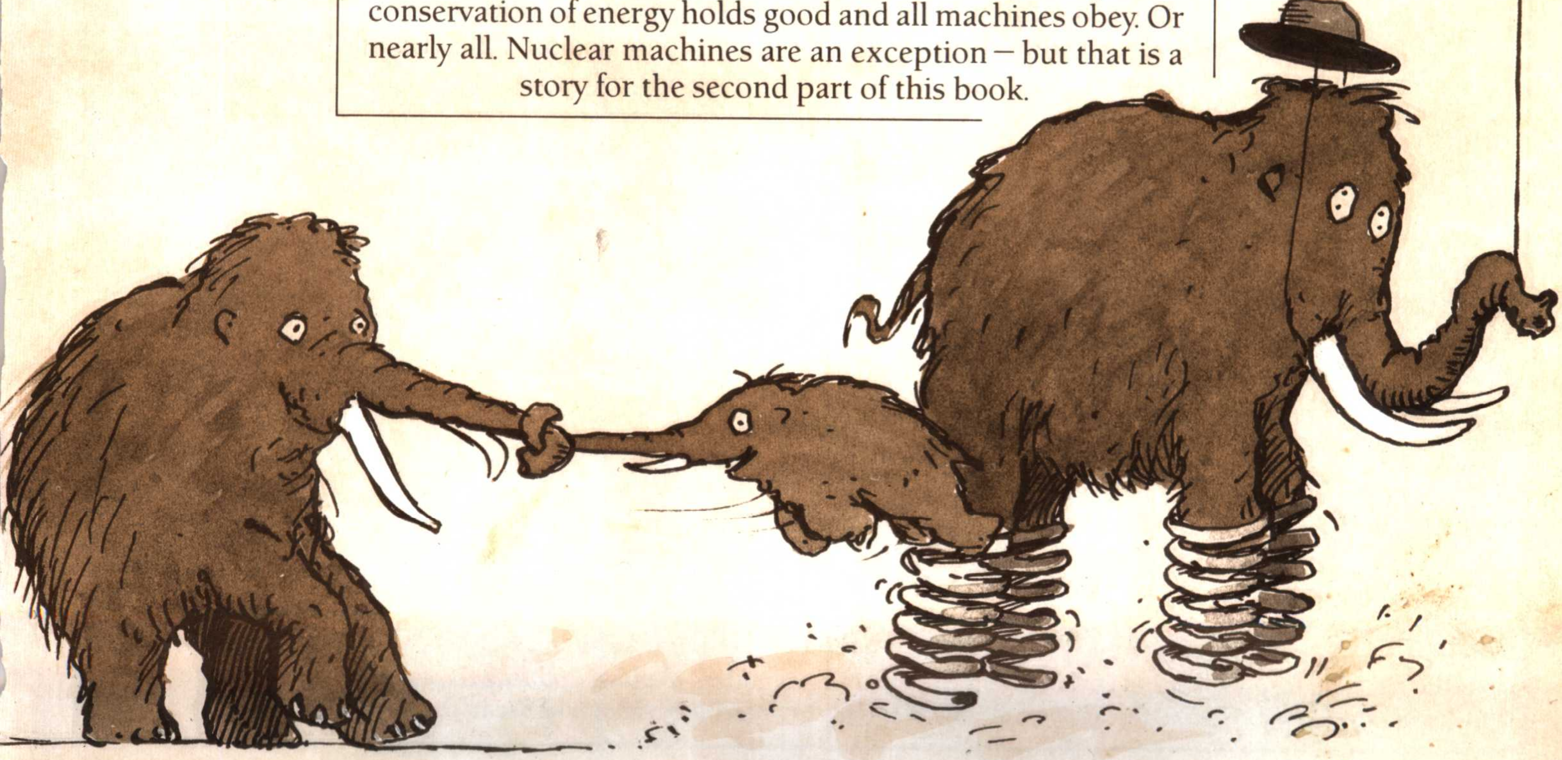
Underlying the actions of all machines is one principle which encompasses all the others – the principle of conservation of energy. This is not about saving energy, but about what happens to energy when it is used. It holds that

you can only get as much energy out of a machine as you put into it in the first place – no more and no less.

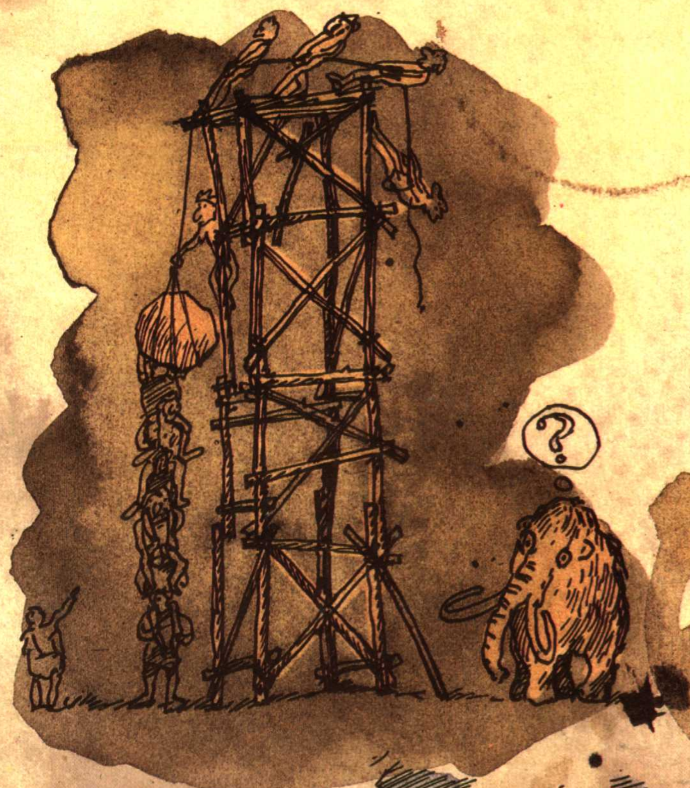
As a motor or muscles move to supply force to a machine, they give it energy; more force or more movement provides more energy. Movement is a particular form of energy called kinetic energy. It is produced by converting other forms of energy, such as the potential energy stored in a spring, the heat energy in a gasoline engine, the electric energy in an electric motor, or the chemical energy in muscles.

When a machine transmits force and applies it, it can only expend the same amount of energy as that put into it to get things moving. If the force the machine applies is to be greater, then the movement produced must be correspondingly smaller, and vice-versa. Overall, the total energy always remains the same. The principle of conservation of energy governs all actions. Springs may store energy, and friction will convert energy to heat, but when everything is taken into account, no energy is created and none destroyed.

If the principle of conservation of energy were suddenly to be dropped from the rule-book that governs machines, then nothing would work. If energy were destroyed as machines worked then, no matter how powerful those machines might be, they would slow down and stop. And if the workings of machines created energy, then all machines would get faster and faster in an energy build-up of titanic proportions. Either way, the world would end – with a whimper in one case and a bang in the other. But the principle of conservation of energy holds good and all machines obey. Or nearly all. Nuclear machines are an exception – but that is a story for the second part of this book.



THE INCLINED PLANE



ON CAPTURING A MAMMOTH

In the spring of that year, I was invited to the land of the much sought-after wooly mammoth, a land dotted by the now familiar high wooden towers of the mammoth captors. In ancient times the mammoth had been hunted simply for its meat. But its subsequent usefulness in industry and growing popularity as a pet had brought about the development of a more sophisticated and less terminal means of apprehension.

Each unsuspecting beast was lured to the base of a tower from which a boulder of reasonable dimensions was then dropped from a humanitarian height onto its thick skull. Once stunned, a mammoth could easily be lead to the paddock where an ice pack and fresh swamp grass would quickly overcome hurt feelings and innate distrust.

THE PRINCIPLE OF THE INCLINED PLANE

The laws of physics decree that raising an object, such as a mammoth-stunning boulder, to a particular height requires a certain amount of work. Those same laws also decree that no way can ever be found to reduce that amount. The ramp makes life easier not by altering the amount of work that is needed, but by altering the *way* in which the work is done.

Work has two aspects to it: the effort that you put in, and the distance over which you maintain the effort. If the effort increases, the distance must decrease, and vice versa.

This is easiest to understand by looking at two extremes. Climbing a hill by the steepest route requires the most effort, but the distance that you have to cover is shortest. Climbing up the gentlest slope requires the least effort, but the distance is greatest. The work you do is the same in either case, and equals the effort (the force you exert) multiplied by the distance over which you maintain the effort.

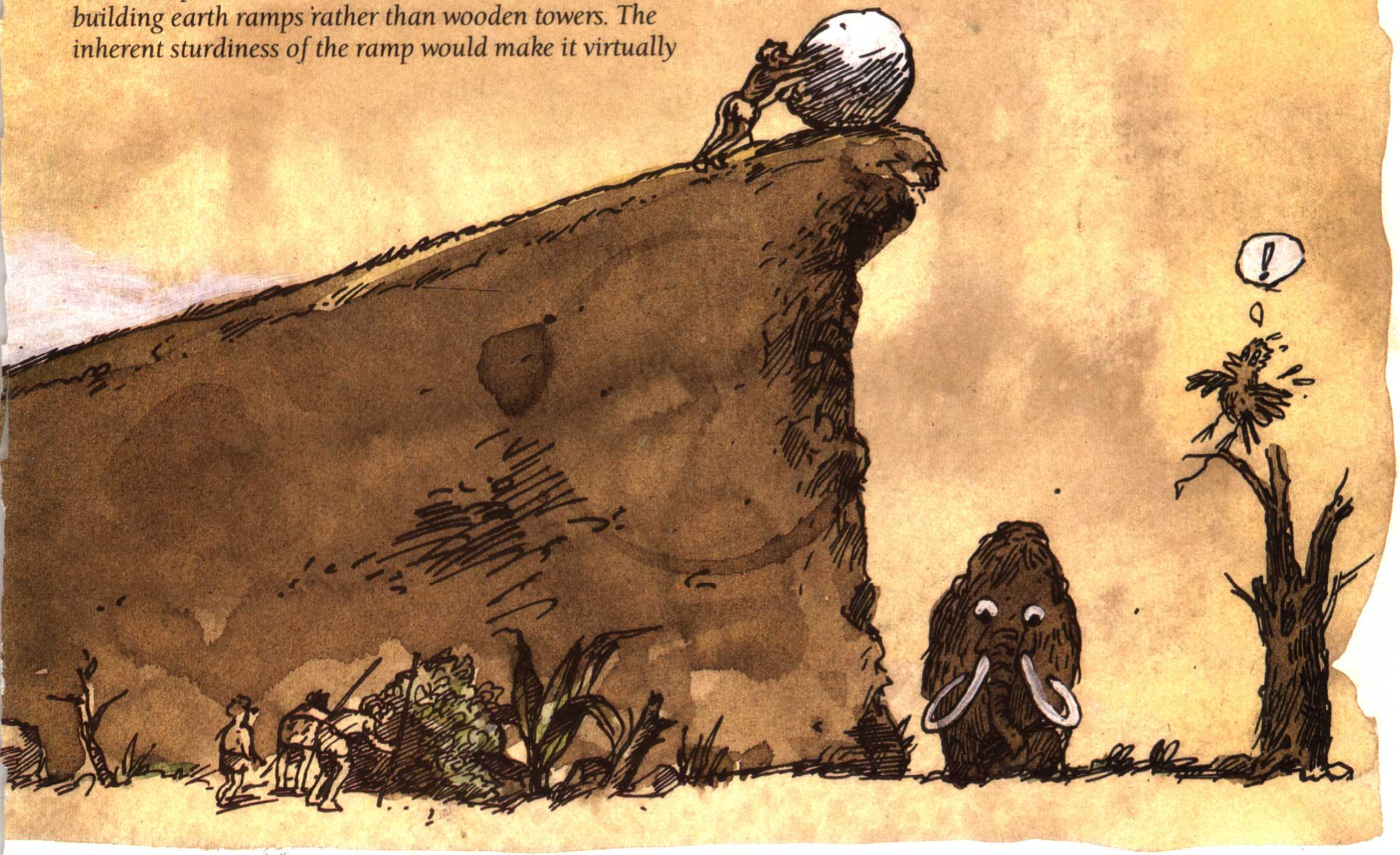
So what you gain in effort, you pay in distance. This is a basic rule that is obeyed by many mechanical devices, and it is the reason why the ramp works: it reduces the effort needed to raise an object by increasing the distance that it moves.

The ramp is an example of an inclined plane. The principle behind the inclined plane was made use of in ancient times. Ramps enabled the Egyptians to build their pyramids and temples. Since then, the inclined plane has been put to work in a whole host of devices from locks and cutters to plows and zippers, as well as in all the many machines that make use of the screw.

While the process was more or less successful, it had a couple of major drawbacks. The biggest problem was that of simply getting a heavy boulder to the right height. This required an almost Herculean effort, and Hercules was not due to be born for several centuries yet. The second problem was that the mammoth, once hit, would invariably crash into the tower, either hurling his captors to the ground, or at least seriously damaging the structure.

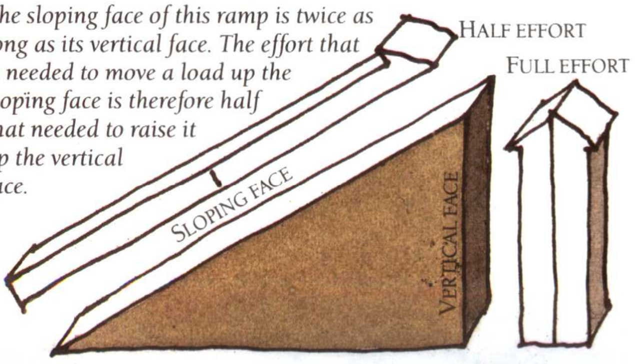
After making a few calculations, I informed my hosts that both problems could be solved simultaneously by building earth ramps rather than wooden towers. The inherent sturdiness of the ramp would make it virtually indestructible should a mammoth fall against it. And now, rather than trying to hoist the boulder straight up, it could be rolled gradually to the required height, therefore needing far less effort.

At first, the simplicity of my solution was greeted with understandable scepticism. "What do we do with the towers?" they asked. I made a few more calculations and then suggested commercial and retail development on the lower levels and luxury apartments above.



How Effort and Distance are Linked

The sloping face of this ramp is twice as long as its vertical face. The effort that is needed to move a load up the sloping face is therefore half that needed to raise it up the vertical face.



The Wedge

In most of the machines that make use of the inclined plane, it appears in the form of a wedge. A door wedge is a simple application; you push the sharp end of the wedge under the door and it moves in to jam the door open.

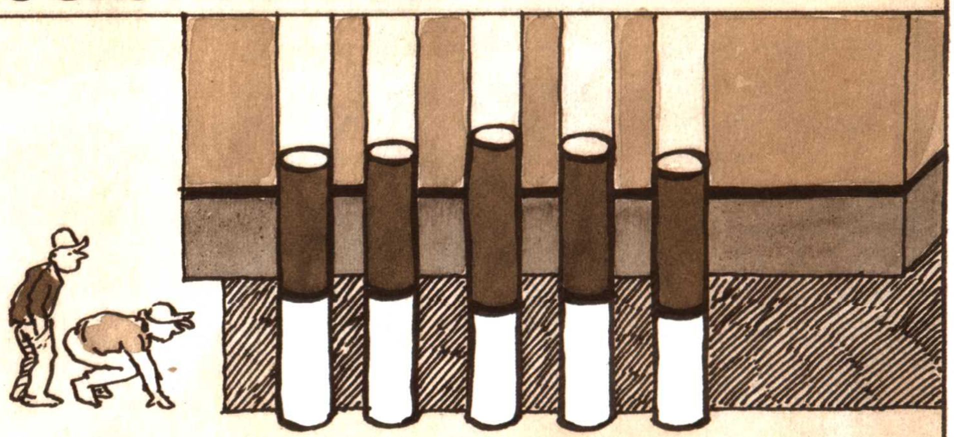
The wedge acts as a moving inclined plane. Instead of having an object move up an inclined plane, the plane itself can move to raise the object. As the plane moves a greater distance than the object, it raises the object with a greater force. The door wedge works in this way. As it jams under the door, the wedge raises the door slightly and exerts a strong force on it. The door in turn forces the wedge hard against the floor, and friction (see pp. 86-7) with the floor makes the wedge grip the floor so that it holds the door open.

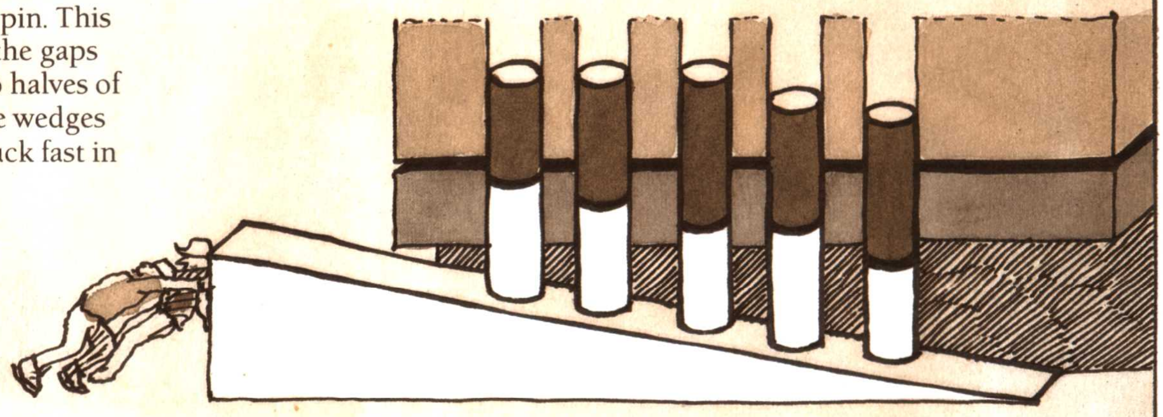
LOCKS AND KEYS

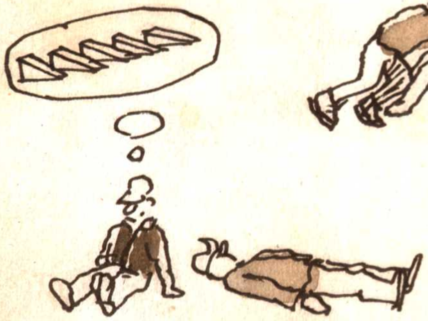
Here's a puzzle not unconnected with locks: how to separate two blocks held together by five two-part pins. The gap in each pin is at a different height. In order to separate the blocks, the pins must be raised so that the gaps line up.

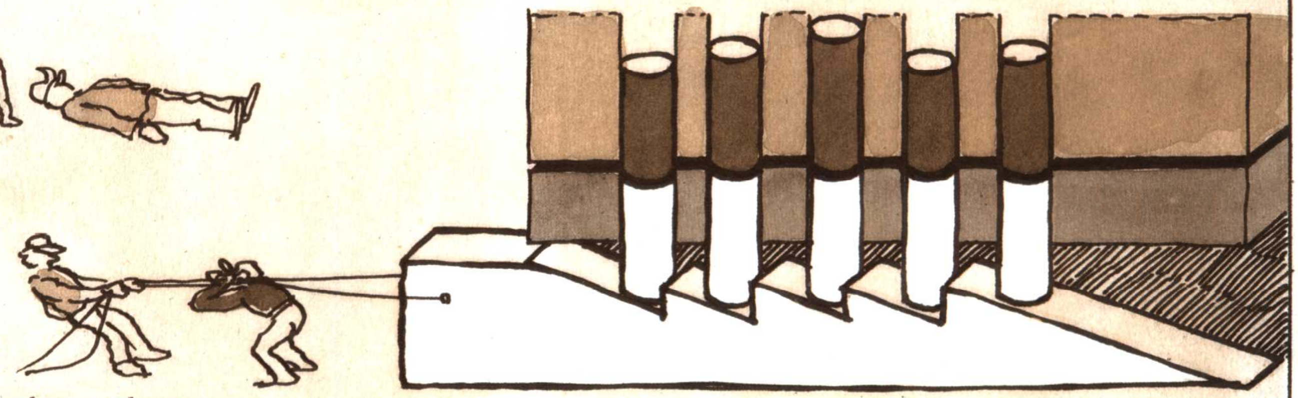
Knowing the principle of the inclined plane, we insert a wedge. It pushes up the pins easily enough, but by the wrong distances.

More thought suggests five wedges – one for each pin. This raises the pins so that the gaps line up, freeing the two halves of the block. However, the wedges themselves are now stuck fast in the lower half.









The key to the puzzle is just that – a key – because the block is a simplified cylinder lock. The serrated edge of the key acts as a series of wedges that raises the pins to free the lock. Because the serrations on the key are double-sided, the key can be removed after use. The springs will then push the pins firmly back into position, closing the lock.