

A paper clip appears to be among the simplest of objects. In its most common form, it consists of a four-inch-long piece of wire shaped by three bends into a thing that is both pleasing to look at and easy to use. It comes fully assembled, and no batteries are required for its operation. No one expects instructions to come with a box of paper clips, and we tend not to think very much about how they are made and used. We take paper clips, as we do a lot of familiar artifacts, for granted, and seldom give them a second thought. They seem to be just too simple and ubiquitous to be very interesting or instructive. However, sometimes the simplest of things can hold as much mystery and provide as many lessons about the nature of engineering as the most complex.

When an object is simple and small enough to hold in our hand and turn about at will, we can inspect it to our heart's content to see for ourselves how it is made and how it works. If the artifact is inexpensive enough, we can each have an adequate supply to break open or test or experiment with in any way that might help us understand how the object is made and how it works. If the principles on which the object functions are conceptually simple and clearly visible, then we can explore questions of how we ourselves might engineer an improved version. Finally, the artifact can serve as a gripping metaphor for engineering itself.

Pick up a box of paper clips and examine it. The box is likely to have a minimum of information printed on it: The brand name (perhaps ACCO, which seems to be just another anonymous acronym, or Noesting, which seems to be an unpronounceable nonsense word); a name describing the kind of paper clips (perhaps Gem or Perfect Gem or Nifty or Peerless or Ideal—certainly something positive-sounding); the quantity in the package (usually a nice round number, like 100, but does anyone ever really count the number of paper clips in the box?); a catalog or stock number (so the supply can be replenished); possibly the address of the

manufacturer (so the purchasing department knows where to reorder or locate a supplier, or complain about the product); most likely that ubiquitous UPC (universal product code) barcode that enables checkout counters to be automated; and, more likely a factor in selling the box than almost anything else printed on it, a picture of the kind of paper clips inside.

One thing that is *not* likely to be on a box of paper clips is instructions for use. We are all expected to know how to use these clever little objects, as readily as we know how to open the box and remove a clip, but we might be hard pressed to explain in words alone how to attach a single paper clip to a group of papers.

Let's open a box of paper clips and take one out, an action we are likely to perform without looking, letting our fingers select a clip from the top of the pile. We seldom, if ever, stop to admire or marvel at the paper clip. If our other hand holds the papers to be fastened, we may glance at the paper clip to see if it is oriented properly to slide onto the papers; if it is not, we will manipulate it around in our fingers without a thought. As we bring the clip to the papers, we will unconsciously notice the loops that must be slid one on each side of the papers. Experience will have taught us that a standard paper clip will not just slide automatically onto the papers, however; we must open the clip, most commonly by a rather subtle action of pressing the end of the longer loop against one side of the paper (which one of our fingers backs up and stiffens), while at the same time flexing the clip just enough so that it can be slid down on the papers with its smaller loop on the other side. This all takes place so quickly and automatically that the complex small motor skills required are usually overlooked, yet this action of applying the paper clip is central to its use—and to our appreciation of it as a piece of engineering.

THE SPRINGINESS OF MATERIALS

The paper clip works because its loops can be spread apart just enough to get it around some papers and, when released, can spring back to grab the papers and hold them. This springing action, more than its shape per se, is what makes the paper clip work. Springiness, and its limits, are also critical for paper clips to be made in the first place. To appreciate this, open a paper clip a bit wider than needed to get the loops around some papers. There will be a point at which the clip will be bent out of shape and will not return to the flat pattern that it had when fresh out of the box. When this happens, the clip's elastic limit is said to have been

Petrosky, H. (1998). Paper clips and design. In H. Petrosky, *Invention by design: How engineers get from thought to thing* (pp. 8-42). Cambridge, MA: Harvard University Press.

exceeded (or the wire is said to have been plastically deformed), and it is extremely difficult to restore the clip to the shape it had in the box. Needless to say, the clip is also no longer as effective in holding papers or in lying flat upon them.

Every material that engineers work with, whether it be timber, iron, concrete, or the steel wire of paper clips, has a characteristic springiness to it (not unlike the springiness of a rubber band), and the spring manifests itself in everything made of these materials. This behavior of materials was no doubt observed long before Aristotle's time, but it was a particular topic of discussion in that Greek philosopher's circle. In a collection of "mechanical problems" compiled in the fourth century B.C., the question was asked, "Why are pieces of timber weaker the longer they are, and why do they bend more easily when raised?" We have certainly all observed this behavior of long pieces of most everything: two by fours, spaghetti, pencil leads, plastic rulers, yardsticks, and so on. Anything slender can be bowed easily, and the longer the easier, yet if not broken or plastically deformed it will regain its straightness when put down. This is spring action, and it was not fully understood until about 2000 years after Aristotle's time.

Even the great Galileo did not fully recognize that all bodies have a certain springiness, and, as we shall see in Chapter 3, this led him to make some fundamental errors in his seminal work on strength of materials, published in 1638. It remained for Robert Hooke, a contemporary of Newton, to articulate the essential elements of elasticity. Hooke was an early advocate of the microscope and so was inclined to look closely at natural and artificial objects and to see things that other scientists overlooked. (Among the first observations Hooke reported in his *Micrographia*, published in 1665, related to the details of simple objects, such as the point of a needle or the edge of a razor.)

There was fierce competition among seventeenth-century scientists over priority of discovery of everything from calculus and natural laws to clever new devices, and so publishing a discovery in a cryptic manner established that one had made the discovery without having to reveal the details of it until the busy scientist or inventor had the time or inclination to do so in the way one would now, in the form of a scientific paper or a patent application. Although Hooke discovered the nature of spring force as early as 1660, he did not publish his observation about the elasticity or springiness of materials until 1678, and then in the form of an anagram.

The customary language of the time was Latin, and anagrams then did

not have to spell out something apposite as they are expected to today (for example, THEY SEE is an good modern anagram of THE EYES). Thus, Hooke's anagram was presented with the letters in alphabetical order, as follows: *ceiinossttuv*. When he was ready to articulate his principle, he rearranged the letters to spell out, *Ut tensio sic vis*, which is commonly translated by the phrase, "As the extension so the force."

What Hooke had discovered was that, up to a limit, each object stretches in proportion to the force applied to it. Conversely, the more we stretch something elastic, the more resistance it offers to being further stretched. Thus if we pull a rubber band with twice as much force, it stretches twice as far. If we hold a very long piece of spaghetti by one end, it sags in a gentle but barely perceptible curve. Here the weight of the spaghetti itself is the force doing the pulling, and the stretching results from the bending that occurs. If the piece of spaghetti were too long, it could break, as it will if we cause it to vibrate, which adds the force of inertia to that of gravity and causes curving and bending beyond the Hookean, or elastic, limit. When the spaghetti or its broken parts are put back on the table, they are straight again, with the table providing support.

These springing phenomena are manifestations of Hooke's Law, and they (along with many other phenomena of materials and structures) affect the behavior of airplane wings and bridges and skyscrapers and paper clips and virtually everything mechanical and structural that engineers design. Heavy wire cables that support elevators in skyscrapers have a springiness that is exaggerated by the extreme length of the cable, and the bounce it produces can be unsettling to passengers if not properly taken into account in designing the elevator system.

A degree of elasticity can be very helpful in the operation of even the simplest of objects. If a straight pin, for example, did not have sufficient flexibility to allow it to bend a bit as it was threaded through a piece of fabric, the pin would tend to be more difficult to use and would not work as well. Furthermore, if it did not have enough spring and tended to stay crooked or plastically deformed whenever so slightly bent, it would not be so easily reusable. Although primarily intended to hold clothing together before buttons were commonplace, straight pins, like all technological artifacts, also came to be cleverly adapted for other uses. One important use was to attach papers together, long before anything like a modern paper clip was developed. To this day one can find pins used in this manner in third-world countries and in banking and brokerage businesses that cannot tolerate the risk of a paper clip slipping off documents

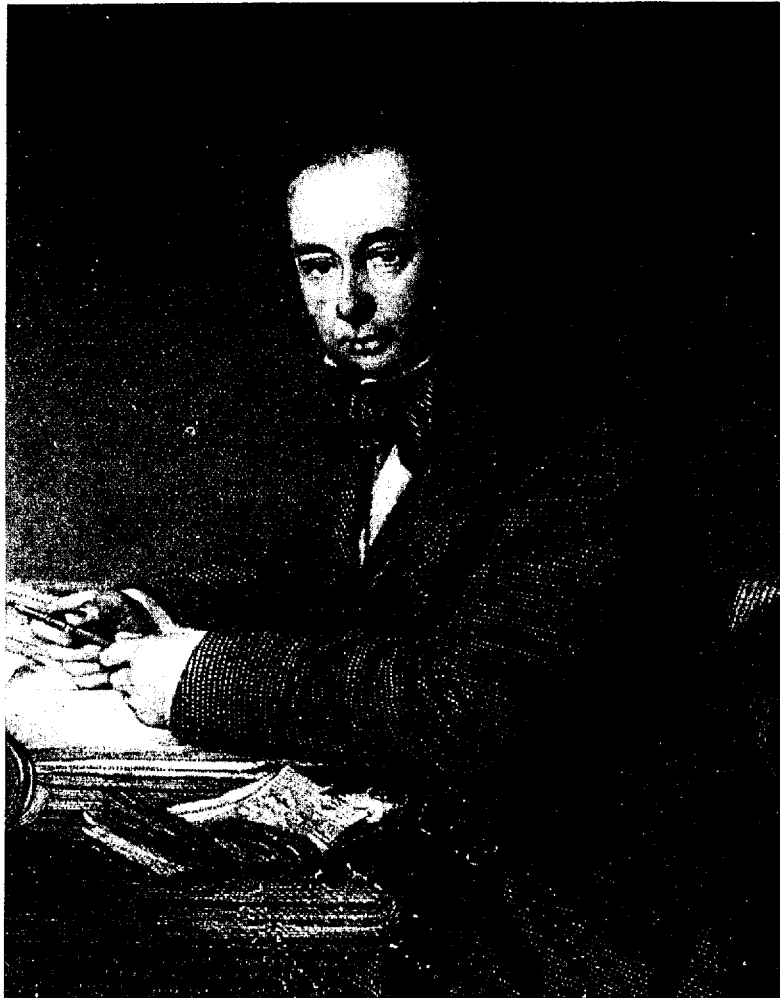


FIGURE 2.1 A mid-nineteenth century portrait of the British engineer Isambard Kingdom Brunel, holding a pencil, with a wooden paper clip in the foreground

or the extra time it would take to remove staples. Before the metal paper clip, clothespins and other wooden clamplike devices were also used to fasten larger piles of papers together (as in Fig. 2.1), and in the mid-nineteenth century the term “paper clip” more often than not meant a rather large metal clamp much like the kind that is found on clipboards today. But well into the twentieth century the straight pin remained a most common means of keeping a few sheets of paper together.

FORMING WIRE INTO PAPER CLIPS

The kinds of wire used for centuries for making pins was also suitable for making paper clips, but the idea of a bent wire paper clip is more obvious in retrospect than in prospect. Bending wire into clever shapes is a very old concept, and even the Romans had such devices as safety pins. But before the advent of wire-working machinery in the mid- to late-nineteenth century, the process for making even a single pin or needle was rather long and tedious. In his famous book on the wealth of nations, the eighteenth-century Scottish economist Adam Smith used pin making as a prime example of division of labor and its economic benefits. Each step in the process was performed by a separate individual, and collectively they could make 4800 pins per day. Smith estimated that if an individual uninitiated to the techniques did all the steps on a single pin, the output might not even approach 20 pins per day. The famous French encyclopedia edited by Denis Diderot described pin and needle making in the late eighteenth century and illustrated parts of the process (Fig. 2.2). It was not hard to see the advantages of designing machinery to perform automatically all the tedious steps of pin making, but it was not until the 1830s that the American inventor John Howe succeeded in developing an effective pin-making machine (Fig. 2.3). Such a machine has been on

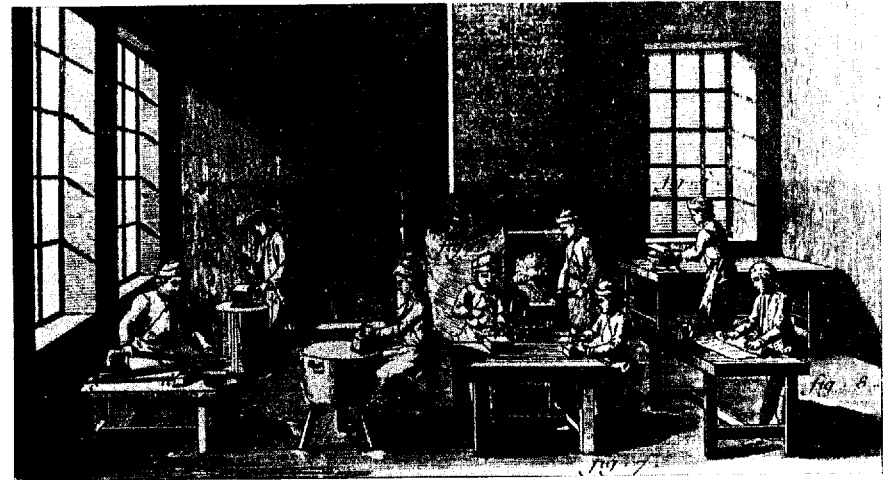


FIGURE 2.2 The very labor-intensive activity of needle making in the eighteenth century, suggesting also the division of labor involved in pin making at the time

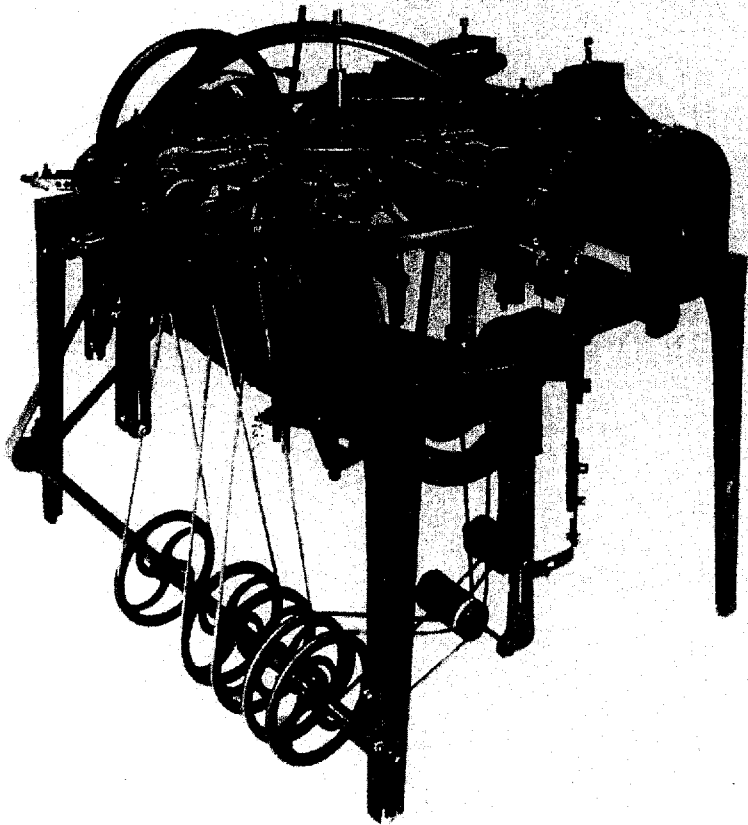


FIGURE 2.3 A pin-making machine, patented by John Howe in the mid-nineteenth century

display in the National Museum of American History of the Smithsonian Institution, along with a videotape showing pins being made by it.

Paper clips could certainly be made by hand, just as pins had been for so long, but since pins served the purpose there was no pressing need to make such specialized objects as paper clips. With the development of the Industrial Revolution and the concomitant need to handle more and more volumes of paper as businesses expanded first nationally and then internationally, extremely specialized devices such as paper clips could

be sold in such quantities as to make their manufacture worthwhile, if it could be done effectively.

Imagine how paper clips might be made by hand. They would most likely start much as a pin did, with a piece of wire pulled off a spool and straightened and cut to the appropriate length, say about four inches. This wire would have its spring, of course, but the fact that there was a limit to the spring would make the forming of a paper clip possible. As the wire was bent beyond the elastic limit, it would retain the bent shape. With the experience gained of trial and error, one could learn how to bend the wire, perhaps with the help of some pointed pliers, just far enough beyond the limit so that when the wire was released it would spring back to just the right shape. One could, after a while, develop a facility in doing this bending, and one could devise arrangements of pegs or jigs around which or in which to work the wire. In this way more paper clips could be made and, incidentally, made more quickly, and one might be able to make them inexpensively enough to sell for prices competitive with the pins they would displace in the office. Since pin making had become automated by the time wire paper clips were conceived, it essentially meant that paper clip making also had to be automated to produce a competitive product.

But paper clips could not have replaced straight pins on the basis of competitive price alone, and this brings us to one of the central technological ideas of invention and innovation and the roles that engineers play. A new artifact will displace an existing one only if there is a clear advantage that the new holds over the old. The most direct and successful means of establishing an advantage is to point out the shortcomings and failings of existing technology and to show how the new device serves to remove objections to the old. Nothing is perfect, and even the most traditional and established ways of doing things leave something to be desired. If a new artifact can be shown to overcome one or more incontrovertible disadvantages of an old, then there is likely to be some artifactual succession or evolutionary displacement. Generally speaking, however, the very fact that long-existing artifacts have become so familiar also means that people have adapted to any inconveniences or problems associated with their use. In fact, it is at first often only the inventor or engineer, effectively acting as technological critic, who even sees anything wrong with things as they are. But, once articulated, the problems that just one critic clearly points out will be immediately obvious to everyone.

If a new invention removes those problems, then it has a chance of succeeding.

The problems that late-nineteenth-century inventors found with the straight pin as paper fastener were several. It was difficult to thread through more than a few sheets of paper; it left holes in the paper; its point could prick one's finger; it could catch extraneous papers; it bulked up piles of paper. A flat paper clip that slid on and off a group of papers could be readily seen to do the job better by removing, or at least reducing, many if not all of these objections. Thus it was that early paper clips could displace pins in office use. But, as with many new products, early versions of the paper clip themselves soon came under criticism by other inventors. Early paper clips were generally not as easy to attach as subsequently conceived versions; early paper clips slipped off too easily; early paper clips got tangled together; etc., etc.

Whenever an inventor got an idea for a "new, improved" paper clip, its advantages were argued in contrast to the relative disadvantages of the old. A plethora of paper clip patents was issued around the turn of the century, but very few of the designs touted so successfully in the patent applications have survived. This is not surprising, since as each new artifact comes on the scene it becomes an object of criticism, especially by inventors who can imagine how this or that shortcoming (which, at first, only they see) can be removed, perhaps just by giving this or that leg of a paper clip a slightly different bend, turn, or twist. Not every inventor would choose to patent a new paper clip design, however, for various reasons. Some chose not to patent because the cost of the patent application seemed too high, others did not believe that the patent system was the best way to encourage invention, others felt they could maintain a better competitive advantage by keeping a trade secret than by revealing a new process in a patent application in exchange for the right to sue infringers.

THE GEM PAPER CLIP

For whatever reason, the most successful paper clip design, and the one that has become virtually synonymous with "paper clip," was never patented. Indeed, the concept of what has come to be known as the Gem clip clearly existed in the late nineteenth century because a patent was issued to William Middlebrook, of Waterbury, Connecticut, for a machine (Fig. 2.4) for making paper clips, and the patent drawings clearly show a fully formed Gem as the *raison d'être* of the machine. Middlebrook's 1899

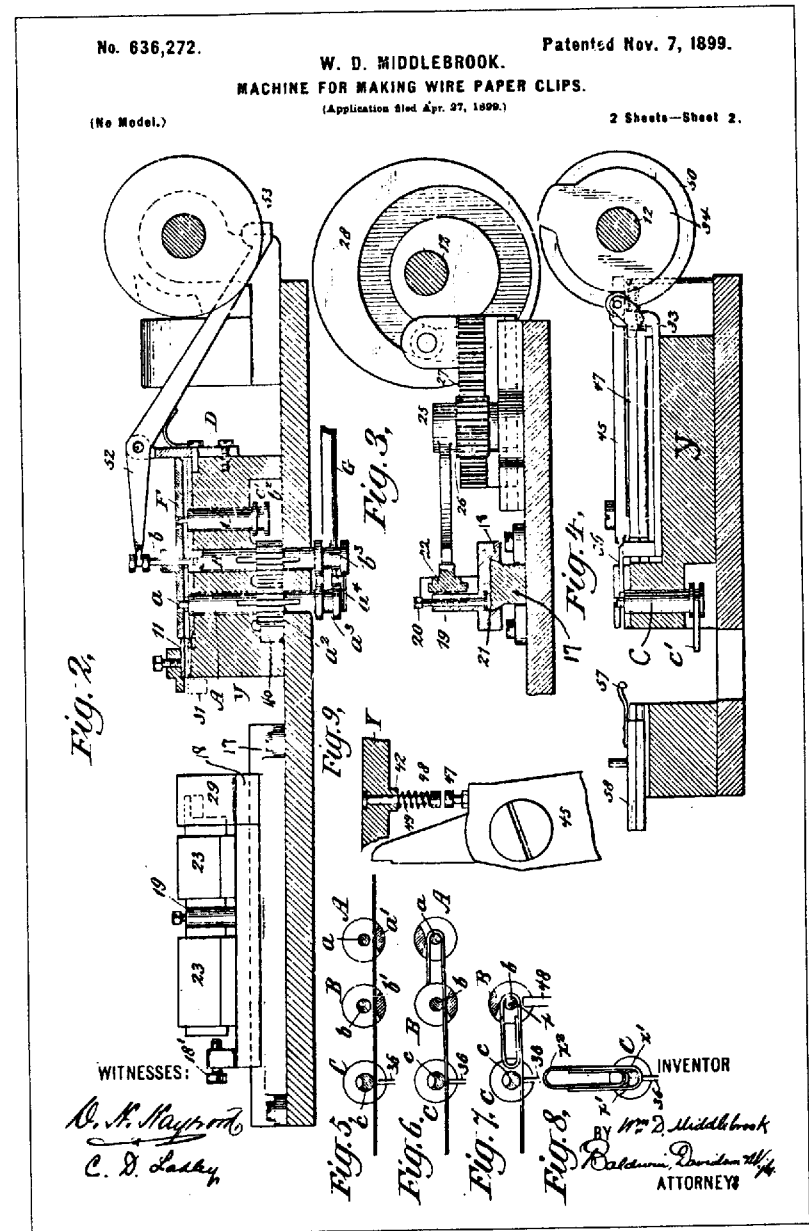


FIGURE 2.4 William Middlebrook's patent for a machine for making paper clips

