Copying life's devices*

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Nature's mechanical contrivances are certainly impressive, but only occasionally have they provided useful models for human technology. Several of the commonly cited successes in biomimetics prove on close examination to be apocryphal. The handful of cases that survive scrutiny suggest that copying nature is the most promising where, (1) we do not attempt slavish imitation, (2) our understanding of the underlying science is weak, or (3) either we want to make something akin to what is common in nature or the natural model happens to be close to what is typical of our own technology.

DAEDALUS fashioned feathered wings like those of birds; his nephew, Talos, made a saw by copying the backbone of a fish. Nature's devices are indeed wondrously diverse and effective; mythology aside, acquiring useful technology by emulating nature's mechanical devices has been a recurrent dream over most of recorded human history. We are dazzled by the structural complexity and functional effectiveness of what we see around us; we suspect that our engineers lack the creativity of our poets and painters; we see nature as 'natural' and by implication admirable and beneficial. And we recognize a host of similarities between the technologies of nature and people – the hollow stems of bamboo and the tubes of our bicycle frames, the water-squirting propulsion of squid and the jet engines of our aircraft, the suckers of octopus and the suction cups with which we stick things to smooth surfaces, to mention just a few.

But does copying nature work? More specifically, where, when, and how have we actually copied nature? One repeatedly runs into assertions of nature's intrinsic superiority and of claims of successful copying, yet the actual history seems to have escaped careful scrutiny. But that history might give some guidance, suggesting what situations are auspicious and what aspects of nature's technology are transferable. It might help us decide where, between the most non-specific inspiration and the most slavish copying, practically and profit are likely to be greatest.

How can we identify cases of successful bioemulation? Mere mechanical commonality can provide only the weakest evidence of copying. After all, the two technologies operate under the same physical laws, within the same environmental climate, and surrounded by the same starting materials. Looking beyond commonality for evidence of copying, though, turns out to be a bit sobering. What is initially most striking is a certain dog that did not bark. If our criteria for copying are even modestly specific, then several of the cases most often trumpeted simple do not make the grade, leaving us with what – given the diversity of both technologies – is a severely limited set of examples. To set a properly skeptical tone, we might first consider three cases that on examination prove almost certainly apocryphal.

Mythology?

John Smeaton, the first great British civil engineer built the third Eddystone lighthouse, off Plymouth, England, in 1759, with the graceful, tapering profile shown in Figure 1. The claim has been repeatedly made that the taper copies that of a large, spreading oak tree; the basis of the claim appears to be a description, written years later, by its builder – 'at the height of one diameter (the trunk) is generally reduced by an elegant (concave) curve, to a diameter less by at least one-third and sometimes to half its original base[1]'. In context, it is clear that Smeaton simply uses the tree in lieu of a picture. Certainly the description falls far short of the specificity needed to build a lighthouse. Furthermore, as Smeaton must have known, the wind-loads on trees and lighthouses are quite different, so the specific taper of a tree is not quite right anyway.

Beginning in 1825, Marc Brunel drove the first tunnel to run underneath a substantial river, beneath the Thames, in London. Brunel is said to have copied the shield he used at the advancing face of the tunnel from the burrowing equipment of the shipworm, *Teredo*, a notorious destroyer of wharf pilings and wooden hulls. Perhaps he knew, cared and even worried about shipworms; but he could not have copied. While the results of a shipworm's boring may be obvious, the activity

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itself cannot be easily observed and was not documented for another century[2]. More importantly shield and shipworm, have virtually nothing in common, as Figure 2 makes it clear. The shipworm (not a true worm but a bivalve mollusc) uses its paired half-shells as rasps, quite unlike the simple digging arrangement permitted by the shield. It does not bore as a rotating augur, as Brunel is said by his biographer, Beamish, to have observed[3]. Furthermore, the crucial role of Brunel's shield was as a pressure barrier, keeping the underpinnings of the Thames from entering the face of the tunnel; the shipworm needs no pressure barrier at all.

For the British exhibition of 1851, Joseph Paxton designed the revolutionary Crystal Palace, incorporating a ridge-and-valley scheme that allowed it to be roofed largely with glass. The design, one hears, was copied from the trussing system beneath the leaves – nearly two meters across – of a giant South American water lily, *Victoria amazonica*. Again, little similarity is apparent when the roof and lily leaf are compared, as in Figure 3. The lily uses an arrangement of large radical and smaller circumferential bracing elements that are impressively large by botanical standards but essentially conventional in design; the novelty of Paxton's roof sufficed for him to patent it. Paxton did have a connection with giant

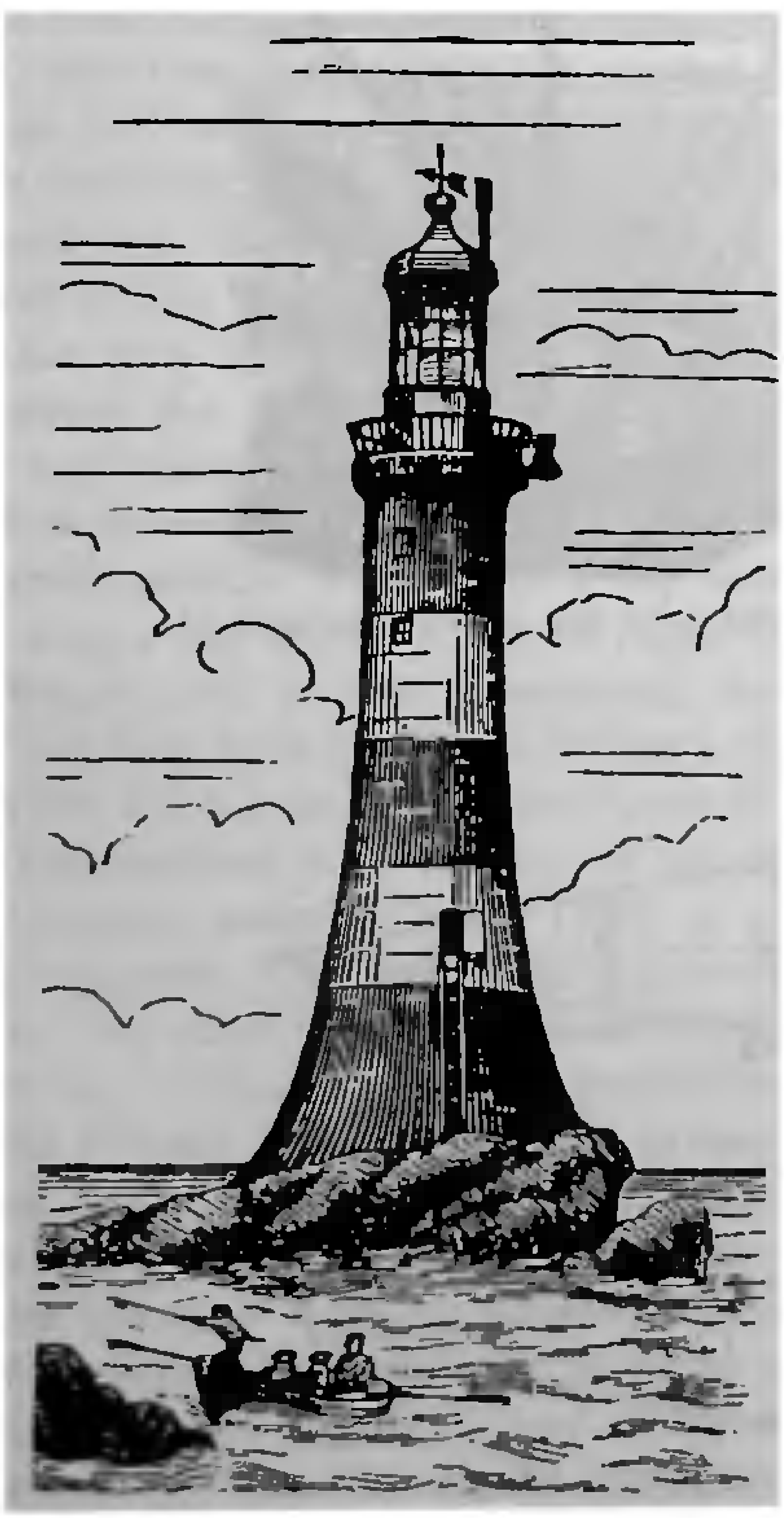

Figure 1. John Smeaton's third Eddystone lighthouse of 1759.

water lilies. Earlier he had built a small building to house the first such lilies to be raised in England, and, largely for esthetic reasons, built it with a roof that copied the lily leaves themselves. The legend seems to rest on a casual comment in a speech that Paxton gave about the Crystal Palace in the fall of 1850, while it was under construction[4]. In it he displayed a lily leaf simply to illustrate what trussing was all about – how many real trussing systems could be held up in front of an audience?

Lighthouse, tunnelling shield, and Crystal Palace are splendid achievements of outstanding engineers. Beyond mere factual misrepresentation, we ought to be offended at the implicit disparagement of their accomplishments. One might ask why these particular legends – all British and from the late 18th to the mid 19th century – got their firm footholds in the biomimetic mythology? Perhaps they reflect an anti-technocratic and bucolic romanticism reactive to the excesses of the industrial revolution – 'the dark, Satanic mills' of the poet, William Blake.

Some successes

But skepticism does not mean denial. Successful cases of copying do exist, and impressive ones at that. Among mechanical devices at least six share sufficient specificity and applicability to deserve our attention. Each has taken its place in contemporary, commercial technology as something well beyond mere proof-of-concept prototype.

A body that travels through air or water experiences least resistance (drag) if it is rounded in the front and tapers to a point in the rear, with the now familiar shape we call 'streamlined'. Around 1809, George Cayley, interested both in making better boats and in the possibility of human flight, tackled the problem of making low-drag bodies. He was frustrated in his attempts to understand what determined a body's drag ('... this subject is of so dark a nature as to be more usefully investigated by experiment than by reasoning'). So he turned to animals that seemed to move through water with ease – to trout and dolphin in particular ('... the only way that presents itself is to copy nature'). He measured the girths of each at a series of points from the nose to the tail and divided each girth by three; those data then served as diameters for round bodies of satisfyingly low drag. Indeed, modern streamlined bodies are only marginally better than Cayley's. Figure 4 comes from his notes on the matter[5].

A wing whose surface arches upward from front to back (a 'cambered airfoil') gets much more lift relative to its drag than does a flat one. In the 1880s Horatio Phillips, in England, took the first systematic look at such curved airfoils, putting models in a wind tunnel

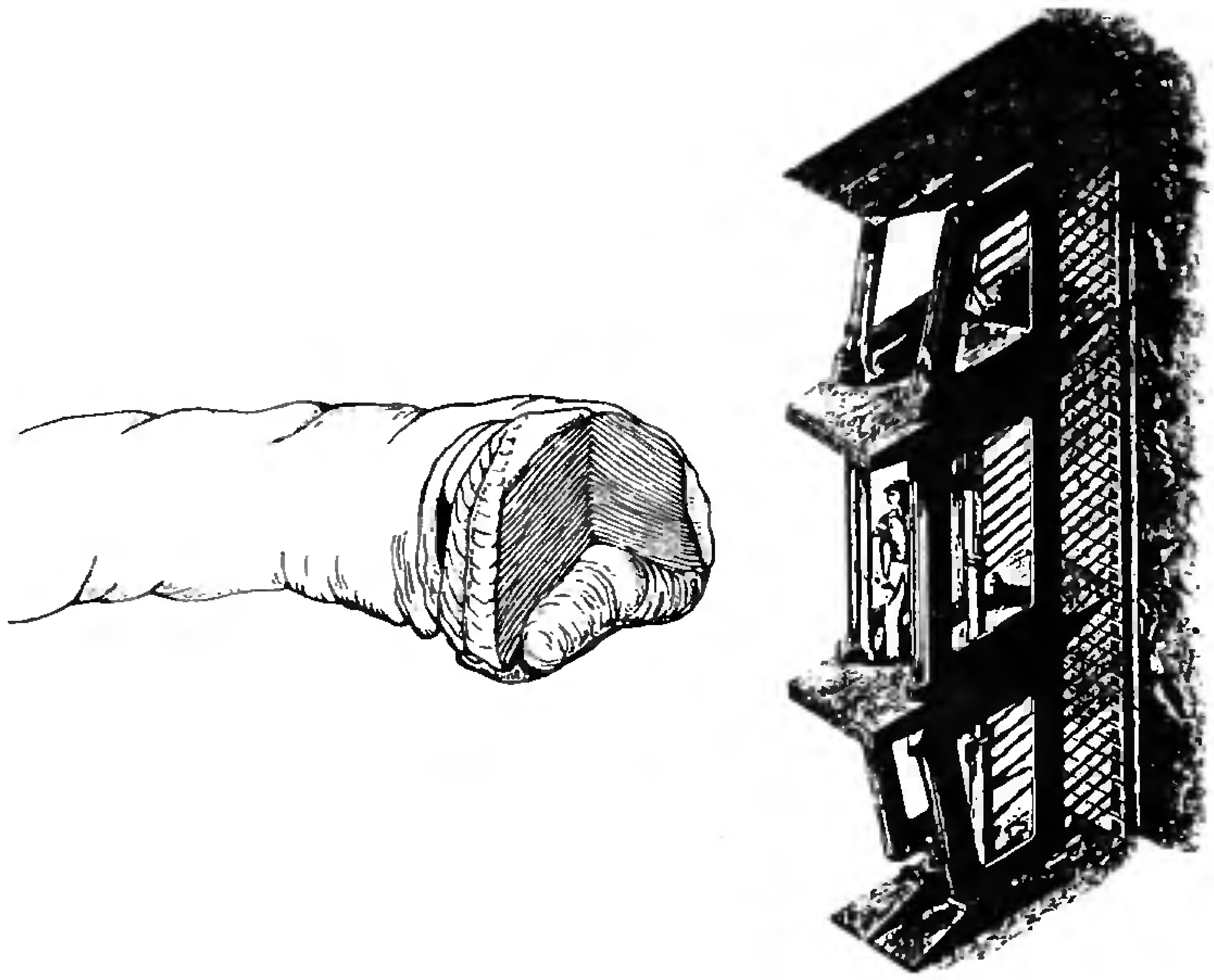

Figure 2. (Left) Front end of a shipworm, with its rasping half-shells; (right) one section (top to bottom) of Brunel's tunnelling shield.

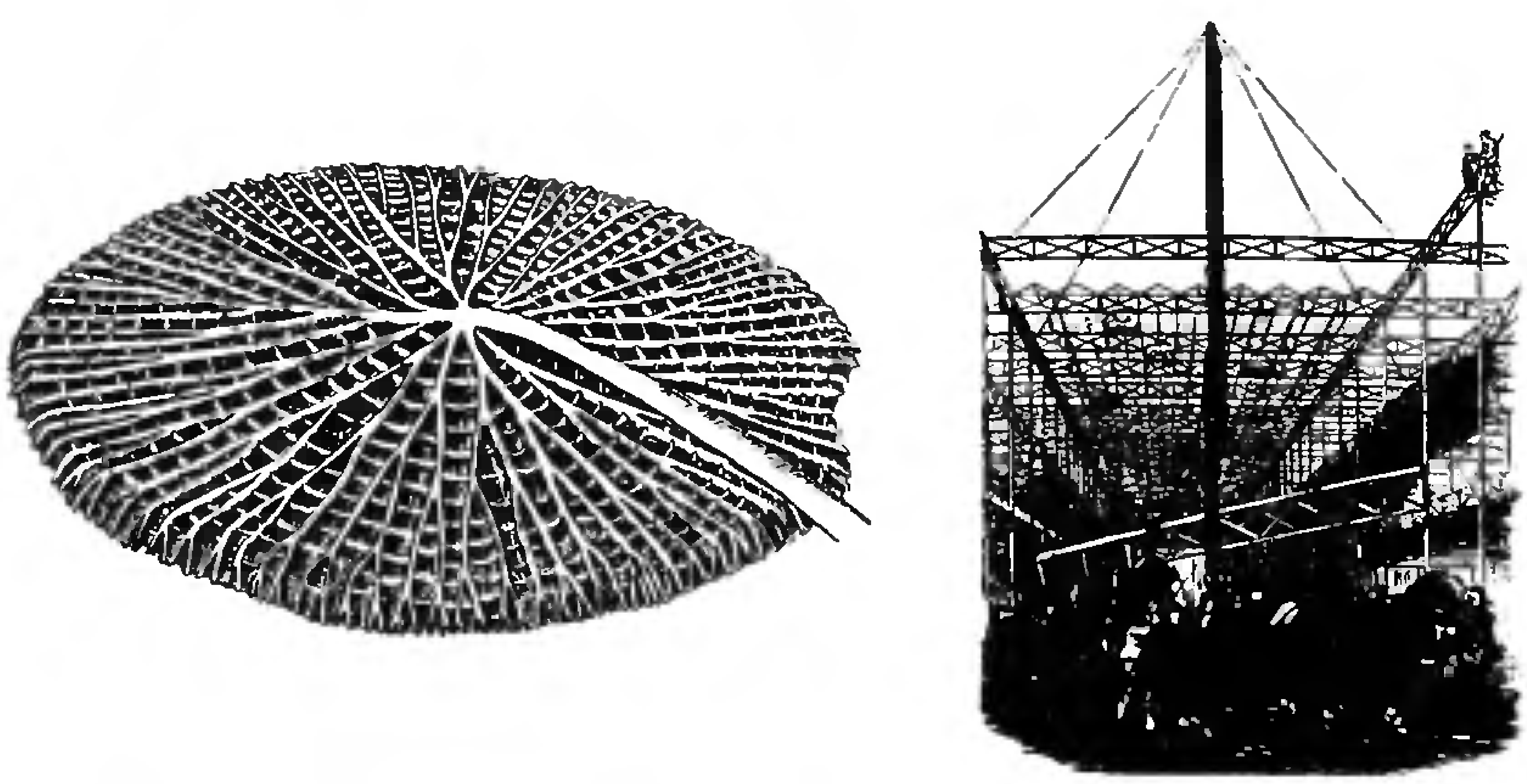

Figure 3. (Left) Underside of a floating leaf of the giant Amazonian water lily; (right) installation of the ridge and valley roofing system of Paxton's Crystal Palace.

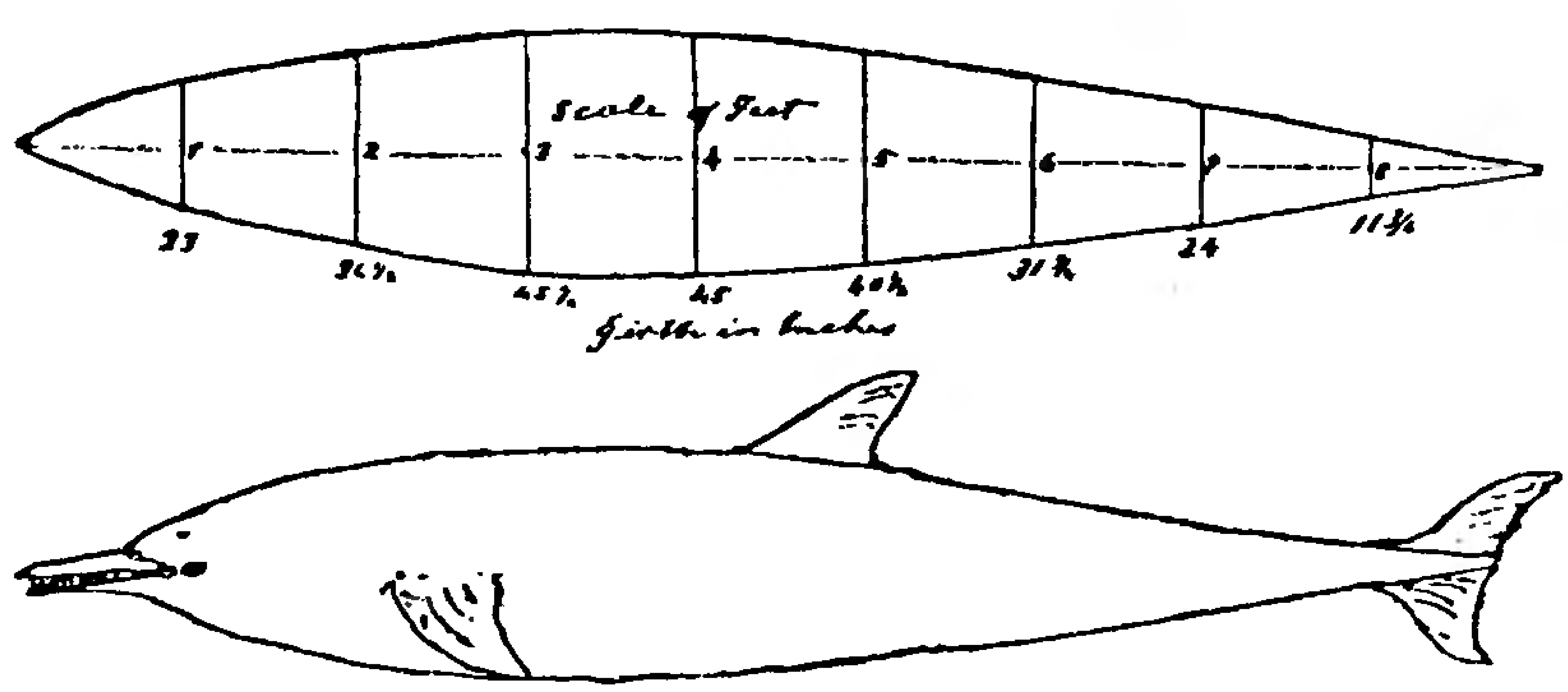

Figure 4. George Cayley's drawing of a dolphin and his streamlined abstract version with the lengths and girths.

(itself a novelty at the time) and looking for shapes that maximized that lift-to-drag ratio. Simultaneously with his models, he tested the wing of a rook, which was similarly arched upward along its length. The rook's wing, like the models, did better than a flat plat tilted at the optimal angle; from the context it appears likely that the bird wing provided the crucial hint that camber improved performance[6]. At about the same time, Otto Lilienthal, in Germany, did a more intensive study of bird wings, carefully making and testing models that reproduced their cross-sectional shapes. He gave the resulting book the explicitly bioemulatory title of *Bird Flight as the Basis for Aviation*[7]. Incidentally, instead of using a wind tunnel, he got his data by swinging the models around on a whirling arm – which apparently introduced some systematic errors that the Wright brothers discovered the hard way. Neither Phillips nor Lilienthal understood why camber helped. Both thought the hollow beneath the wing was more important than the arch above, but no matter – their work led to the cambered wings of all our subsonic aircraft. In fact, a wing gets lift in a marvelously subtle manner, and several decades elapsed before our present explanation was generally accepted.

The record is quite clear – despite a great many attempts, successful airplanes (beyond streamlining and cambered wings) were not made by copying birds. But birds did contribute one specific feature. The Wright brothers, who took the problem of control more seriously than their contemporaries, decided to turn their craft, not primarily with a rudder, but by twisting each wing lengthwise. They got the idea from birds, and a letter from Wilbur Wright to Octave Chanute, written in 1899 (when they first began making gliders), is quite explicit about the avian origin of their wing-twisting scheme, explaining how the buzzards they watched managed to control themselves[8]. The present analogue of that arrangement is the aileron – a flap near the outer end of a wing's rear edge that can be raised or lowered. Orville Wright, late in life, downplayed the idea that they got any help from birds, but Wilbur's letter shows that the birds did at least provide assistance at one point.

While papermaking is an old art, the use of our most common starting material, wood fiber, is a relatively recent development. Up through the eighteenth century, most paper was made from cotton and linen rag, and the supply of rag increasingly limited production as commerce and literacy were augmenting demand. Around 1719, the great French entomologist and polymath René-Antoine Réaumur suggested that paper might be made from wood, as were the nests of paper wasps of the North American genus *Polistes*. If wasps could macerate wood and glue the fibers into sheets, why could not humans do likewise? During the subsequent century, a number of people in various European countries attempted to produce such paper, and reasonable evidence links Réaumur and his wasps with their efforts. The German, Jacob Christian Schäffer, for one, made paper in the 1750s from a wide variety of plant material that used only a small amount of rag. Drawings of adult, larva, and nest of a paper wasp appear in his subsequent book on papermaking. Full success, that is, paper using no other fiber, was achieved, finally, by Matthias Koops, in London in 1800. Koops demonstrated his achievement by publishing a book on the history of papermaking, mentioning Réaumur as a predecessor[9]. His paper was good acid-free stuff – copies of the book show little sign of having spent two centuries on the shelf – but Koops himself went broke in the endeavour.

The same Réaumur had another suggestion that also ultimately proved practical, although in this instance his role (and that of Robert Hooke, who had the same idea even earlier) is less clear. Silkworms extrude through a fine orifice a viscous liquid that immediately solidifies into silk. Perhaps a textile fiber might be manufactured by some analogous extrusion process. During the 19th century the possibility was explored by a number of people – Louis Schwabe, in England, extruded glass fiber as early as 1841, and Georges Audemars, in Switzerland, patented an extruded 'artificial silk' in 1855. Hilaire de Chardonnet later (with great labour and expense) developed a practical process for making an extruded artificial silk, initially the dangerously flammable cellulose nitrate[10]. But if Réaumur's contribution is uncertain, the silkworm's footprints are unmistakable. Schwabe, Audemars and Chardonnet were all involved in the natural silk industry, and the early extruders looked very much like the equivalent piece of insect anatomy, as shown in Figure 5. Even more telling is the name given to the extruder, 'spinneret'. The name derives from the process of spinning, as done with spinning wheels by humans to make long threads out of short fibers. It was (and still is) inappropriately applied

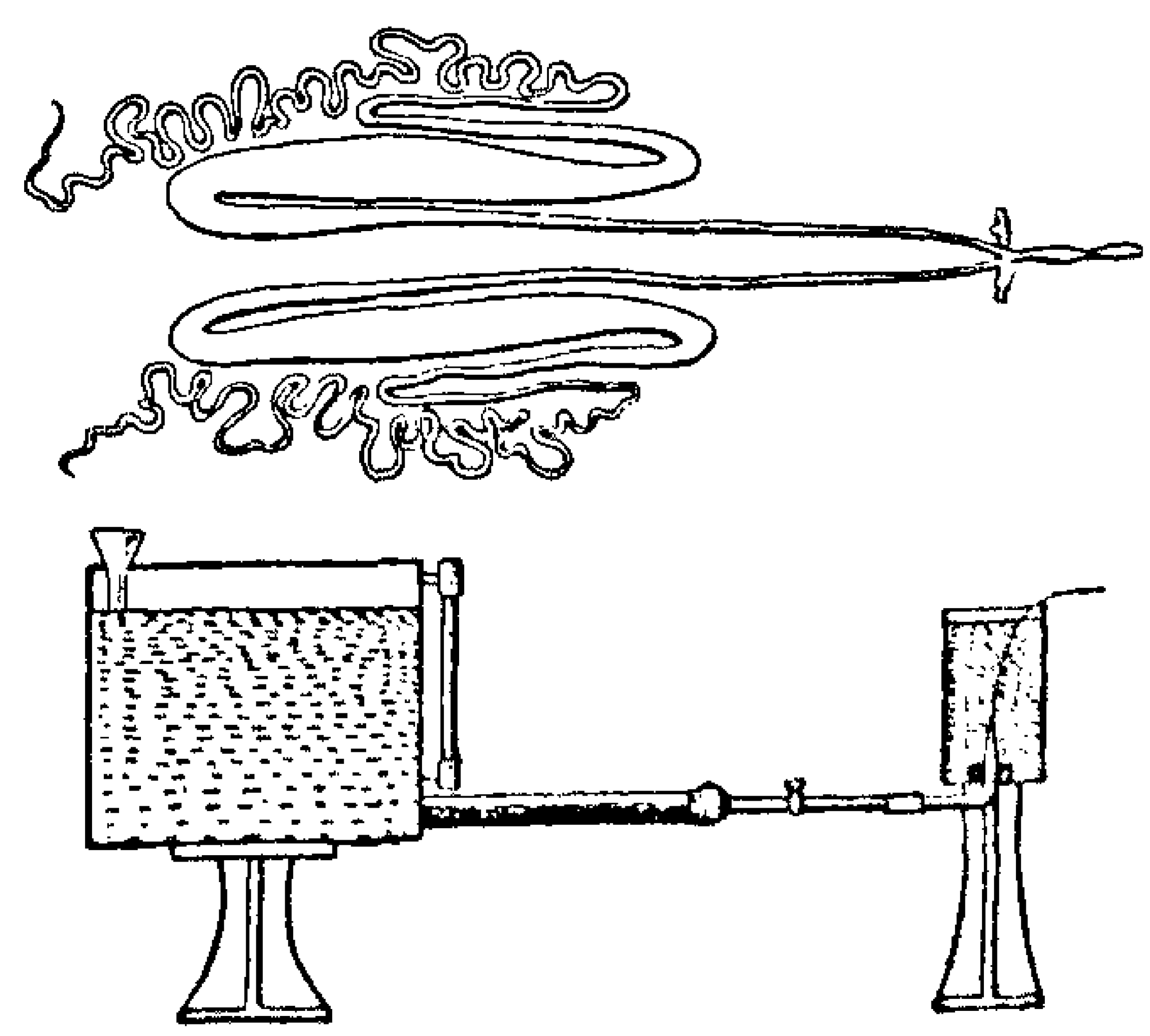

Figure 5. (Top) Silk gland and extruder of a silkworm; (bottom) an early tapered spinneret.

to the silkworm's extruder, which does not rotate in any proper sense at all. It is even less appropriate for the extruder of artificial fibers – these are, in fact, spun into thread, but at a later stage in the process. Without the silkworm as antecedent, such a name would never have been chosen.

Finally, Alexander Graham Bell considered how one might transmit voices instead of mere telegraph signals over electrically-conductive wires. He was not the only one trying to achieve telephony – one contemporary scheme used sets of tuned reeds to break a complex sound into discrete frequencies for separate transmission; the sound would then be reconstituted by a mixing process at the receiving end. But Bell, by his own admission more familiar with auditory physiology than with electricity, had the key insight that broke the logjam. He recognized the eardrum as a single transducer that handled all frequencies at once. He also noted that its thin membrane could move the (relatively) more massive auditory bones of the middle ear ('... if a membrane as thin as paper could control the vibrations of bones that were, compared to it, of immense size and weight, why should not a larger and thicker membrane be able to vibrate a piece of iron in front of an electromagnet?')[11]. He hit on that basic idea of creating a ear-like microphone, as seen in Figure 6, one that managed all frequencies, in 1876; his initial patent (possibly the most profitable in all of American history) simply reversed the arrangement for the earpiece, with a signal in the coil driving the magnet and diaphragm. His microphone lasted as a commercial item for only a few years – Thomas Edison's carbon microphone proved more sensitive. But the reversed version survives in the earphones we still use.

Dividing devices into major and minor may be an uncertain business, but three further cases seem to involve more task-specific things, designs of much narrower applicability and – in that sense at least – of less importance to us.

Barbed wire continues the ancient and widespread practice of planting thorny hedges to confine livestock. Good evidence points to an origin as a copy of plant thorns, of the thorns of one plant in particular. Osage orange was used in the American mid-west as such a hedge during the 19th century, and the first barbed wire was developed, manufactured, and sold there. Michael Kelly, who received the first patent, in 1868, called his enterprise the Thorn Wire Hedge Company – drawing attention to the familiar antecedent must have saved a lot of explaining – and his version looked very much like plant thorns[12]. Two people in Illinois began large-scale production (and large-scale patent litigation); both Joseph Glidden and Jacob Haish had previously been in the business of selling seeds and seedlings of Osage orange. As commercialization progressed the barbs of barbed wire diverged from their antecedent thorns, as in Figure 7. For obvious reasons, the ease of manufacture mattered more than the fidelity to nature.

Modern chain saws use cutters of a design unlike that of any other kind of saw, a design based on a natural analogue. The chain of the chain saw was invented in 1943 by Joseph Cox, who was a machinist working as a logger. At the time, despite the invention of various motorized saws, long (up to five meters), human-powered, cross-cut saws still dominated commercial logging. Cox examined the way the mandibles – the side-to-side jaws – of the grub of a timber-mining beetle cut tunnels through fresh wood. He then devised cutters, as in Figure 8, based on those mandibles[13,14]. His cutters moved in the different pattern than those of the beetle – they were pulled along by the chain and cutting alternately on opposite sides of the groove rather than pushing forward and closing inward in tandem. Here again, precise emulation did not translate into practicality.

Velcro, the hook-and-eye soft fastening material, perhaps the best known case of copying nature, was invented about 1948 by Georges deMestral, a Swiss

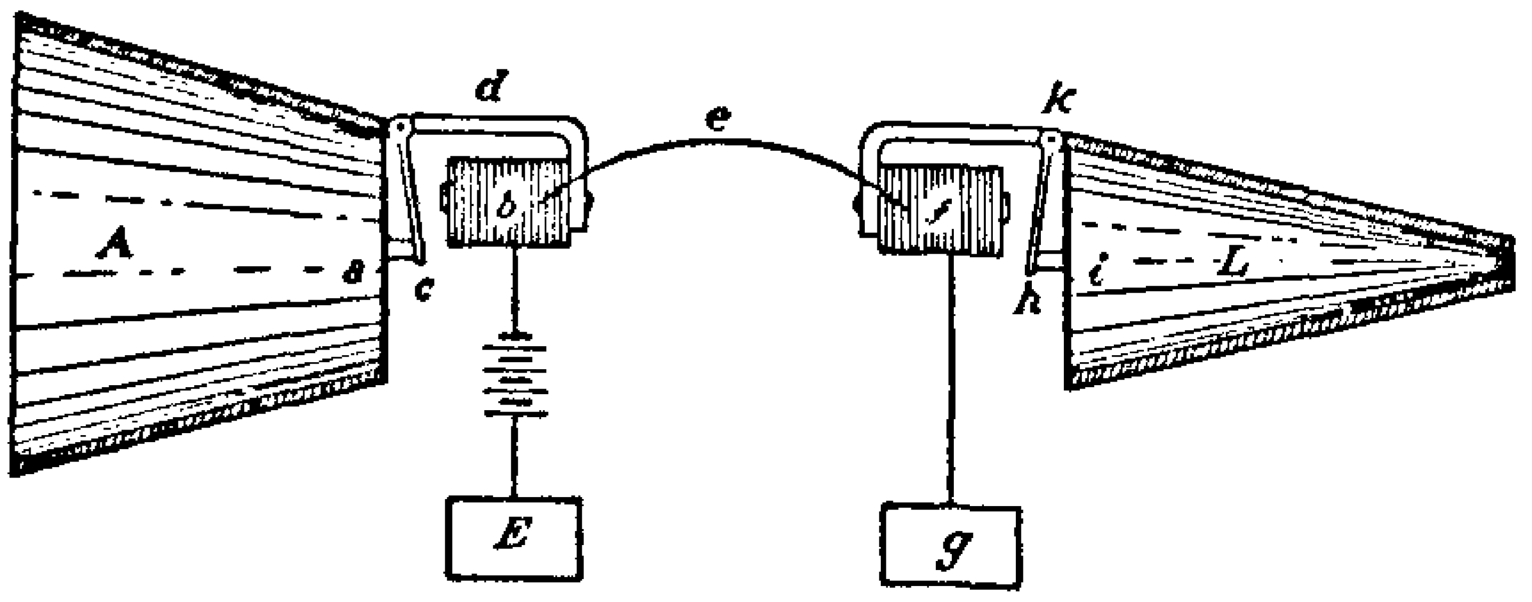

Figure 6. Key drawing from Bell's patent, US number 174,465, with the mouthpiece (microphone) on the left and the earpiece (speaker) on the right.

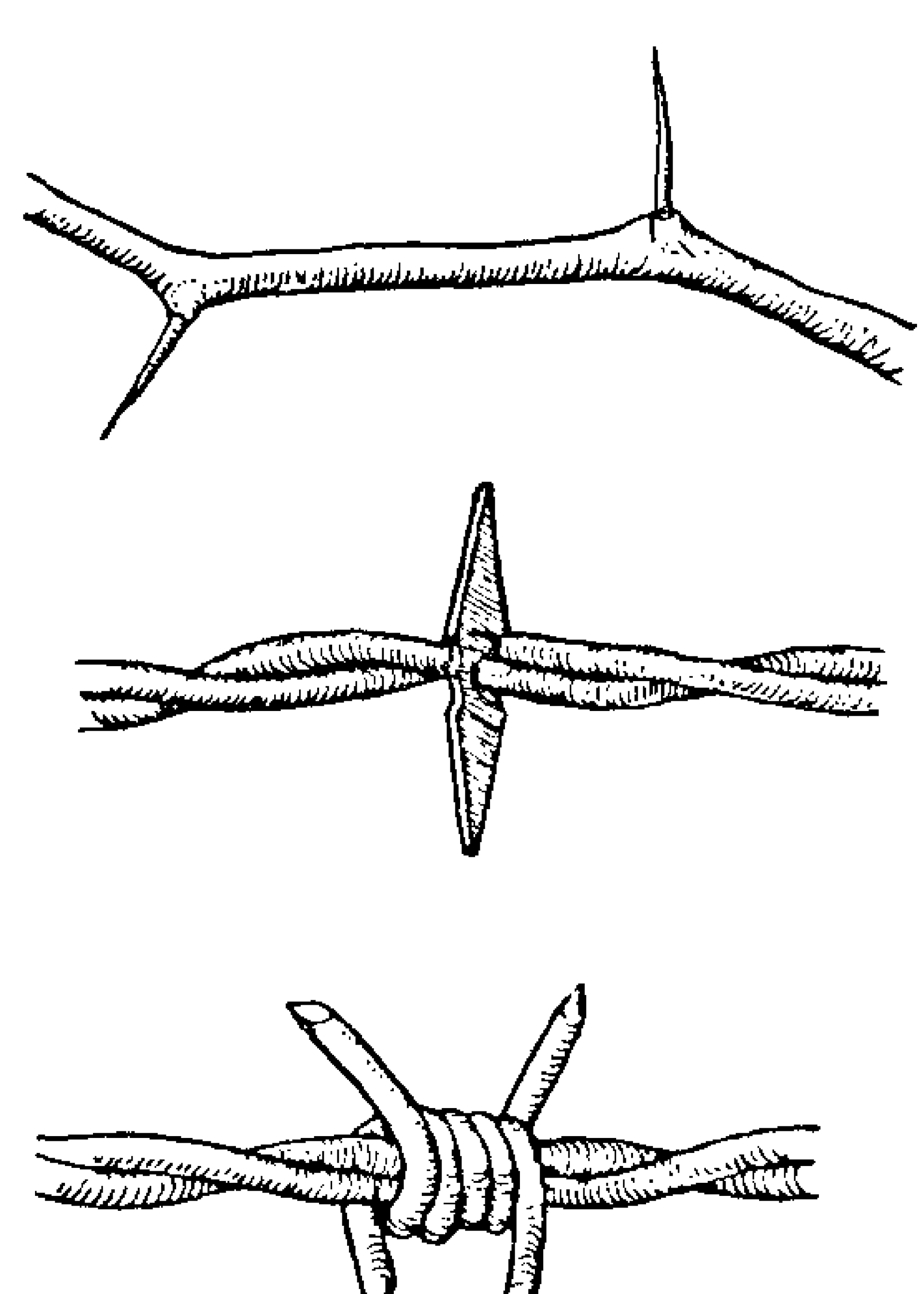

Figure 7. (Top) Branch with thorns of an Osage orange; (middle) Kelly's thorny fence of 1868; (bottom) piece of modern barbed wire.

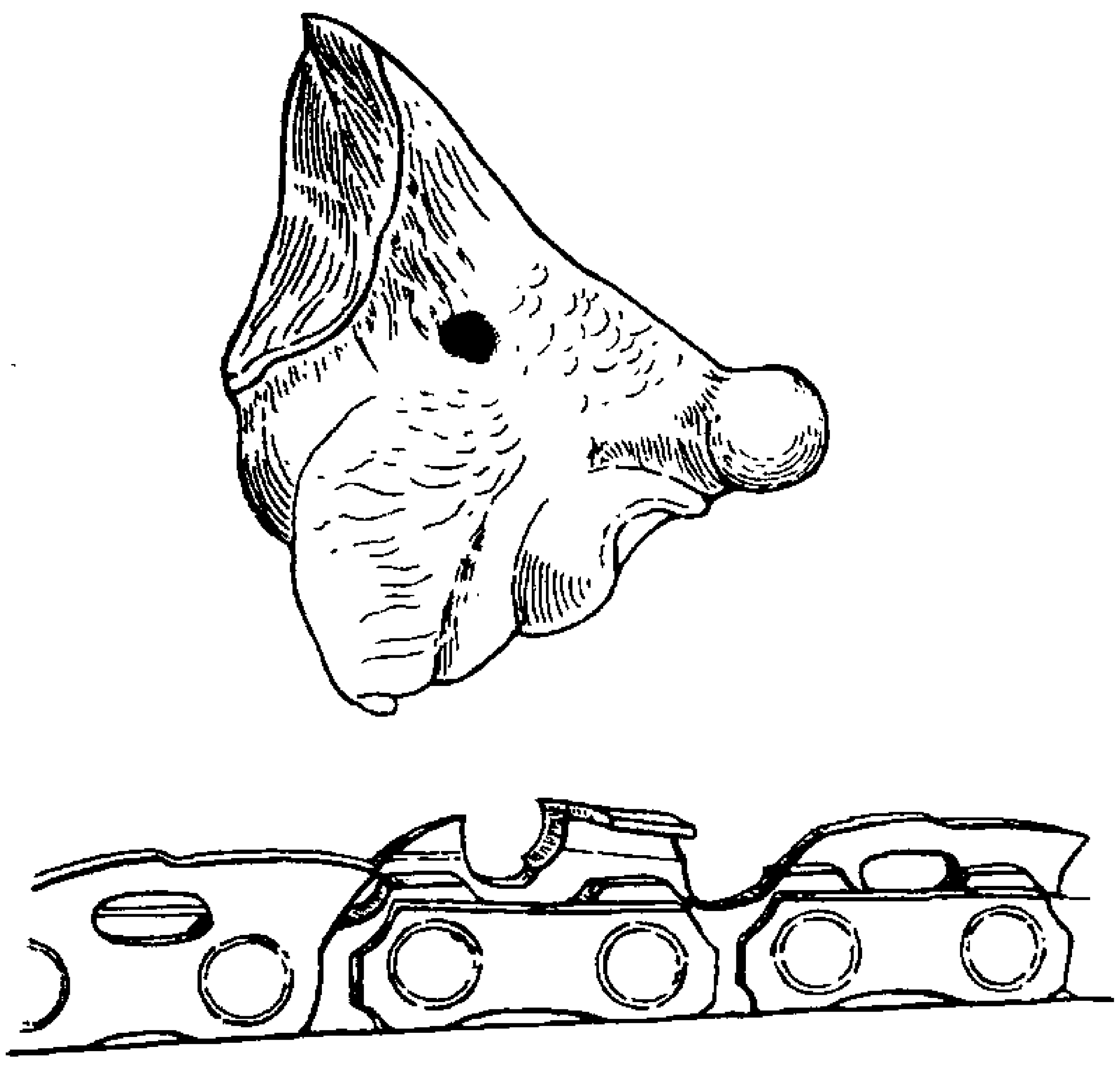

Figure 8. (Top) One mandible (jaw) of a timber beetle; (bottom) section of a saw chain with cutter (left) and depth feeler (right).

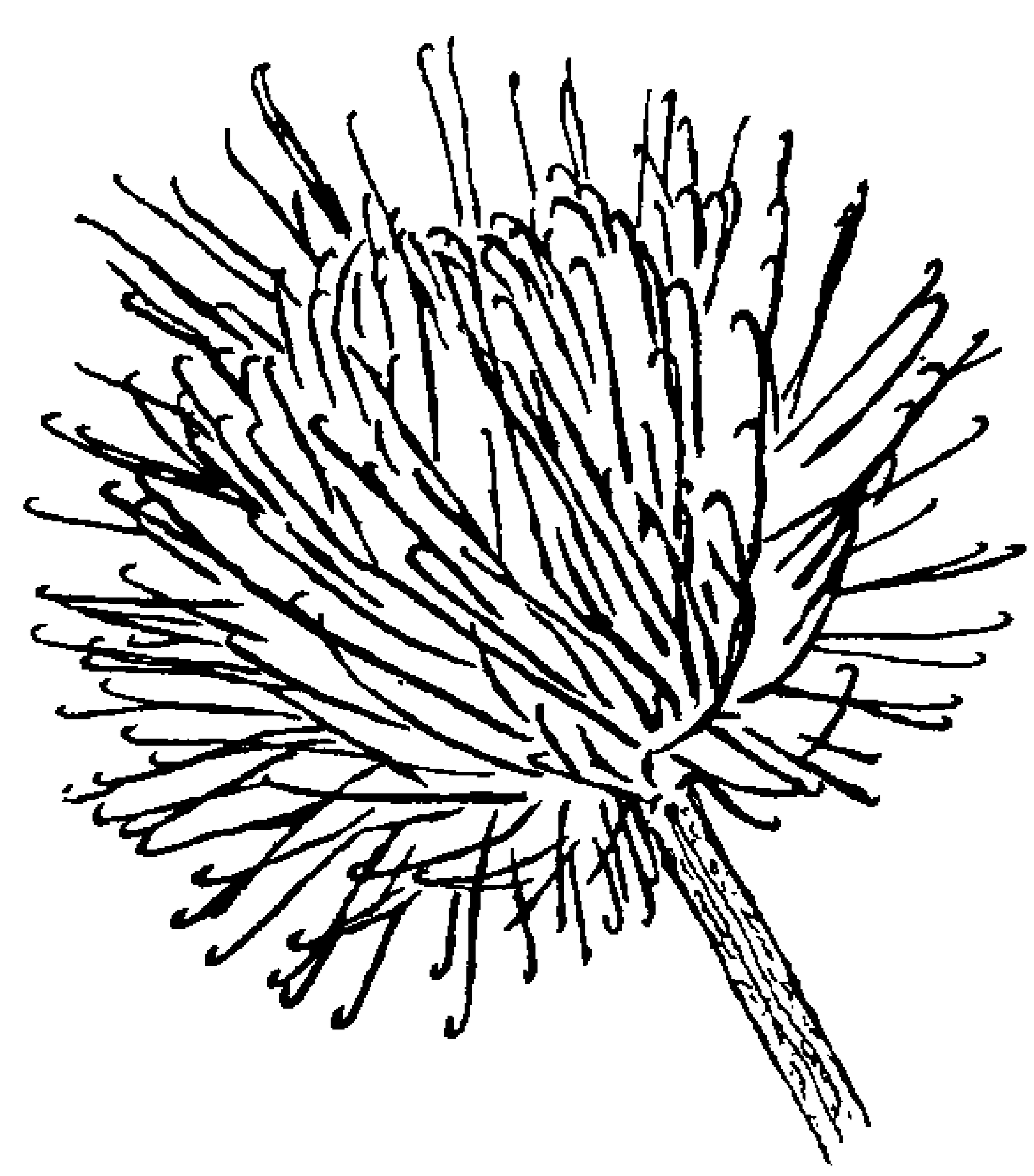

Figure 9. The hooked burs of a plant, *Arctium minus* (courtesy of the Duke University Herbarium).

engineer. He began by taking a close look at some plant burs (of burdock, specifically, as in Figure 9) that stuck to his trousers and his dog after a hike. In a sense, the time was ripe – nylon, then fairly new, was one of the few materials from which hooks analogous to those of the burs could be made. But manufacturing the material economically and in quantity proved far from easy, and the burs, of course, gave no hint of a solution. In a sense, deMestal was not fully successful – the human version requires a mating surface with eyes for its hooks while the plants are less fastidious about their substrates[15].

Lessons

What can we conclude from these nine success? First, slavish imitation is not likely to be productive. Cayley did not make a model fish but used girth measurements to extract the key feature. Phillips' best airfoils gave greater lift-to-drag ratios than his rook's wing. Neither barbed wire, chain saw cutter, Velcro, nor the original telephone mouthpiece is an especially close copy, either structurally or functionally. Practicality seems to lie somewhere between general inspiration and exact emulation. In particular, nature's devices reflect her functional imperatives, her materials, and her methods of manufacture. While her purposes may sometimes be reasonably close to our intended use, her materials usually differ in important ways, and her production methods always remain far distant from our own.

Second, both the chance of success and the generality of the resulting device seem inversely related to how well we understand the underlying science. Before the present century, fluid mechanics was a murky business. Streamlined bodies, cambered airfoils, and ailerons could not be easily derived from theory. As Cayley took pains to emphasize, copying was the best one could do under the circumstances. The behaviour and management of electrical signals with complex waveforms were almost unknown, so the eardrum allowed technology to leap ahead of science. Papermaking and fiber extrusion involve complex combinations of solid mechanics, fluid mechanics, and chemistry – since such complexity does not bother natural selection, nature could provide useful hints both of what is possible and of how to proceed. By contrast, barbed wire, chain saw teeth, and Velcro, however useful represent specific tricks rather than general technological breakthroughs.

A third point emerges from the remarkable difference between the two technologies. Nature's is typically tiny, wet, non-metallic, non-wheeled, flexible, and so forth; human technology is mainly the opposite – large, dry, metallic, wheeled, and stiff. Where one technology operates in what is normally the domain of the other, emulation is at its most auspicious. Thorns and mandibles are especially stiff as natural structures go, so perhaps they are preadapted to serve as models for devices characteristic of human technology. Velcro is relatively flexible for a device made by humans; perhaps it is the kind of thing we are likely to derive from nature.

This last point suggests a future for bioemulation considerably brighter than its history implies. We are moving toward ever smaller components in our various contrivances, in effect getting closer to nature's miniature world – after all, an average animal is only a millimeter or so in length. We are developing a great array of flexible materials to supplement or supplant stiff metals and brittle ceramics. We are exploring the use of composite materials – fancy progeny of fiberglass – a world in which nature (perhaps for lack of metals) is an experienced and versatile player. And with improvements in small actuators and complex controls, devices made of muscles, tendons, bones and nerves are increasingly attractive as models. In short, as the characteristics of our technology draw closer to those of nature's, nature may provide us with evermore guidance.

The histories of both science and technology are full of cases in which someone with an unusual background or outlook – an outsider – solved a long-standing problem by taking a fresh look at it. Perhaps the most potent outcome of a careful look at nature's technology is to provide an analogously fresh perspective on our own, to allow some useful distance from immediate problems, to bring into view possibilities that might otherwise escape our notice, to do something even more valuable than providing models for specific items that we might make.

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International interactions in science – The Indian experience*

M. Vijayan

Historical perspective

Modern science is essentially European in origin although it owes a great deal to the contributions of earlier civilizations. Science in India, as it is being practised today, arose through contacts with the West[1]. We are aware of our ancient scientific traditions. But the scientific enterprise in modern India has no direct connection with those traditions. The main springs of those traditions had dried up or were in the process of drying up when Europeans, particularly the British, came to India with their commercial and colonial agenda. Of course, promoting education and science in India was not part of that agenda. But they used them to the extent necessary to promote their interests. It is not an accident that geological survey was the major scientific enterprise undertaken by the British authorities in India. Naturally, it was important to have an accurate picture of the land mass of this country to exploit it. The scientific survey of India which began in 1761 led to the establishment of the Geological Survey of India in 1951. India is a land of monsoon and the British established the India Meteorological Department in 1875. India is rich in plant resources and the exploitation of these resources was of considerable importance. Thus the Royal Botanical Garden at Calcutta was established in 1787 and the Botanical Survey of India in 1890. In the meantime, the

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