Why Animals Run on Legs,

Otherwise, mustangs might be more like Mustangs, impalas more like Impalas,

Our civilization literally runs on wheels. They are the most efficient form of land transport ever invented by human beings. Why, then, have animals not also evolved wheels, contenting themselves instead with inefficient legs? And why do fish swim with tails and fins instead of with the wheel's underwater equivalent, the propeller?

These questions may seem frivolous, until one reflects that nature anticipated and surpassed most other human transport inventions. It is only in modern times that our engineers have succeeded in building workable submarines, gliders, parachutes, and jet-propelled vehicles—modes of locomotion that were evolved and mastered tens of millions of years ago by diving whales and crocodiles, gliding vultures and pterodactyls, plant seeds with natural parachutes, and jet-propelled squid.

Given this string of successes by Nature the engineer, it seems strange that she has failed to crown her achievements by mounting animals on wheels. To appreciate the advantages of wheels, consider the fact that a human being on a bicycle or in a wheelchair uses less energy per mile than the same person on legs, despite the extra weight of the bike or wheelchair. Even paraplegics in wheelchairs are 25 per cent more efficient than healthy human beings are in walking. (In this year's Boston Marathon, the fastest wheelchair athlete took one hour and 47 minutes to complete the course, 22 minutes less than the fastest runner.) In fact, a human being on a bicycle is the most efficient known vehicle, living or inanimate. In calories consumed per mile traversed and per pound of vehicle weight, a cyclist is roughly five times as efficient as an automobile or DC-8 jet plane, 15 times as efficient as a running dog or a flying parrot, and 400 times as efficient as a walking cockroach. Only whales, dolphins, and large fish approach a wheeled human being in efficiency, because swimming is cheaper than land locomotion and because efficiency increases with size.

Until recently, evolutionary biologists contemplating the absence of wheels in nature agreed that the explanation was not undesirability; wheels would be good for animals, just as they are for us. Animals were prevented from evolving wheels, the biologists reasoned, by the following dilemma: Living cells in an animal's body are connected to the heart by blood vessels, and to the brain by nerves. Because a rotating joint is essential to a wheel, a wheel made of living cells would twist its artery, vein, and nerve connections at the first revolution, making living wheels impracticable.

Biologists found apparent exceptions to this reasoning that seemed to support it: the only wheels in nature are animals and plants

Not on Wheels

and rats might travel on retractable roller skates by JARED DIAMOND

that use their whole bodies as wheels, avoiding the dilemma of joints. For example, the pangolin of Southeast Asia, a large and tasty animal, escapes predators by curling into a ball and rolling down steep hills. There are also rolling spiders, somersaulting shrimps, and rolling plants (the tumbleweeds of windy plains).

However, there is a flaw in the argument that the evolution of wheeled animals was thwarted by the insoluble joint problem. The theory fails to explain why animals have not evolved wheels of dead tissue with no need for arteries and nerves. Countless animals, including us, bear external structures without blood supply or nerves—for example, our hair and fingernails, or the scales, claws, and horns of other animals. Why have rats not evolved bony wheels, similar to roller skates? Paws might be more useful than wheels in some situations, but cats' claws are retractable; why not retractable wheels? We thus arrive at the serious biological paradox flippantly termed the RRR dilemma: nature's failure to produce rats with retractable roller skates.

Recently an important contribution to understanding the RRR dilemma was made by Michael LaBarbera, an anatomist at the University of Chicago. If wheels really are such a good idea, LaBarbera noted, it is strange that we twentieth century humans do not make more use of them. Mankind has had wheelchairs since the mid-1600s, roller skates since the mid-1700s, bicycles since the early 1800s. Yet we still prefer legs to wheels as we go about our daily business in houses, in gardens, and on the sidewalk. Yes, civilization runs on wheels, but mainly for long trips, and on prepared roads or tracks. Even recent improvements in skateboards, roller skates, dirt bikes, and dune buggies have chipped away only slightly at our preference for legs. What are the reasons why we, the inventors of the wheel, make such restricted use of it in our transportation? Might it be that the same reasons explain why animals *shouldn't* evolve wheels, and why biologists were wrong in assuming that they should have but *couldn't?*

LaBarbera delved into the technical engineering literature on wheelchair design and the theory of land locomotion. This study revealed three reasons why animals are better off without wheels, and why we use wheels only under special conditions:

First, wheels are efficient only on hard surfaces. (In engineering jargon, "rolling resistance increases with the compliance or softness of the surface.") The heavier the wheeled vehicle, the more inefficient wheels become on a soft surface. For wheeled vehicles on soft surfaces, it helps to use large or wide wheels. This explains the prepared hard surfaces on which most of our wheeled transport runs, the distinctive tires of our dune buggies, and the firm carpets recommended—and often required—in buildings accessible to wheelchair users. The same consideration would also doom roller-skated elephants, and would require large, wide wheels on roller-skated rats.

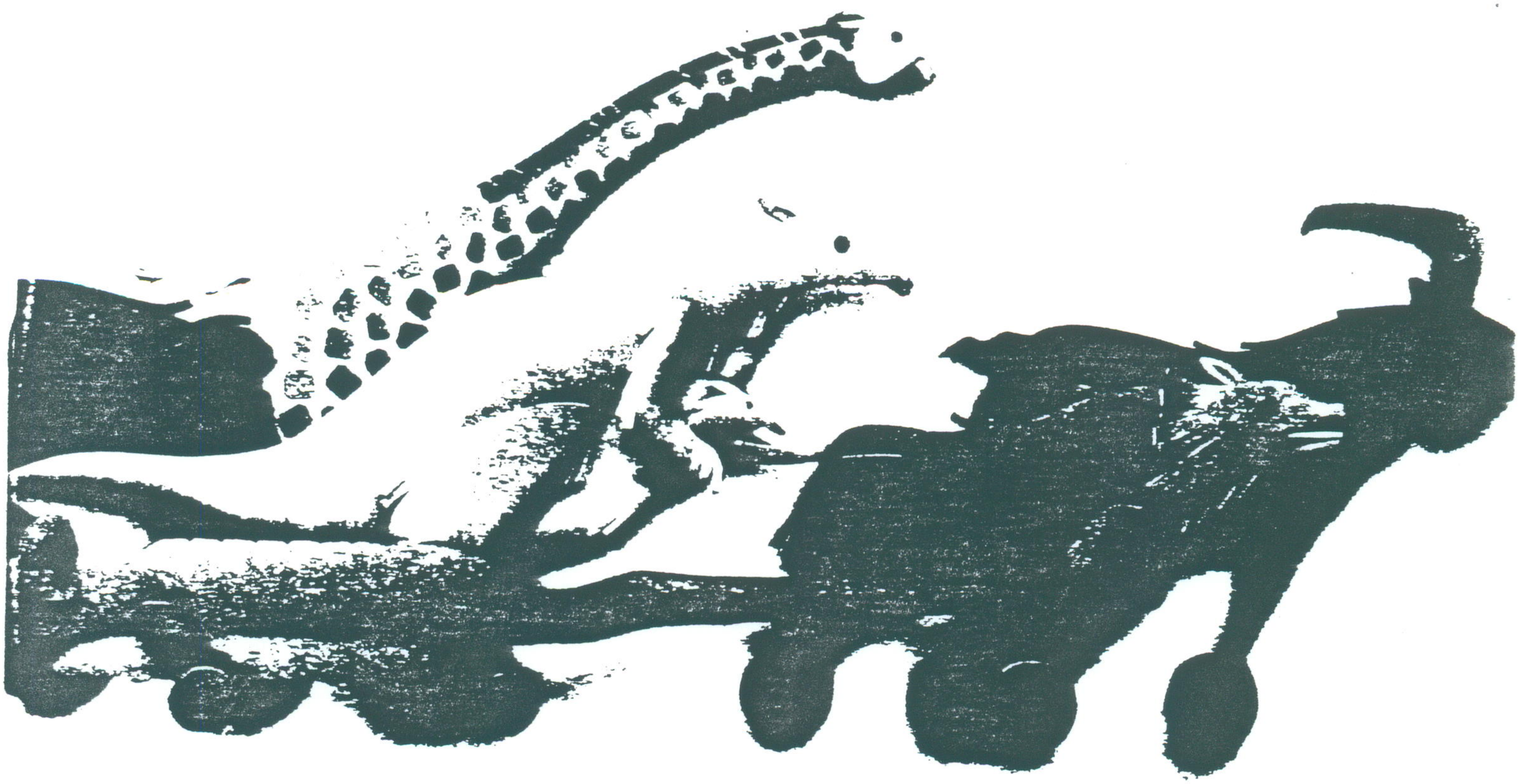
"Man has covered the earth's surface with a new type of habitat, concrete,

The second limitation on wheeled vehicles and animals comes from vertical obstructions. We are all familiar with the difficulties in riding bicycles and pushing wheelchairs up over curbs: the problem of riding over vertical obstructions on the surface of the moon was a major consideration for NASA in designing the powered cart used by astronauts. It turns out that a wheeled vehicle with a rigid chassis cannot surmount a curb higher than half the wheel radius. Even non-rigid vehicles that can shift their centers of gravity, as can most animals, cannot surmount curbs higher than the wheel radius itself. But natural terrains have far more low vertical obstacles, like pebbles and blades of grass, than high ones. This consideration would doom roller-skated ants: a field that seemed smooth to us would be an obstacle course of lofty curbs to an ant. With legs, of course, one just climbs over curbs and even over walls.

The final limitation on wheels is the problem of turning in a space cluttered with obstacles, such as trees and boulders, or in a small space. This second consideration is uppermost in the minds of road designers in mountainous terrain. How tight a switchback can a bus negotiate? The answer is complicated, and depends on the length and width of the bus's wheel base, as well as on the size, number, and positions of its wheels. Without even doing these calculations, one has only to picture a dense forest to realize that rats with retractable roller skates would have their roller skates retracted most of the time.

All three of these limitations to the use of wheels on land disappear in the sea or air. Then why are there no propeller-driven fish or birds? Nature actually has produced a tiny but true propeller: the flagellum, or thread-like tail, by which a bacterium moves. That flagella spin like propellers was proved by an elegant experiment in which a living bacterium's flagellum was glued to glass, whereupon the bacterium could be seen to spin about its fixed flagellum!

We are so accustomed to propeller-driven boats that we unconsciously equate the propeller in water, like the wheel on land, with efficiency. The bacterial flagella seem to confirm this prejudice. But fluid mechanics theory shows that reality is more complicated. For tiny objects like bacteria, rotating flagella are indeed as efficient a means of propulsion as can be designed. But the superiority of the propeller disappears for larger objects. Efficiencies at converting input power to thrust are only about 60 per cent for a typical oil tanker's propellers, 80 per cent for airplane propellers at high speed, and 88 per cent for the ingenious propeller built for the man-powered aircraft *Gossamer Albatross*. Much higher propulsion efficiencies can be achieved with a flexible foil or paddle that oscillates from side to side, like the fins and



offering unfilled niches to the animal that can evolve to exploit them."

tail of a fish. The theoretical efficiency of such a foil is 96 to 98 per cent, and large fish actually achieve 96 per cent.

Thus the puzzle becomes reversed. It is no longer a mystery why fish lack propellers: fish are much better off as they are. Instead, the mystery is why ship designers have been unable to perfect oscillating flexible foils like a fish's tail and fins.

The paradox about the failure of land animals to evolve wheels also comes full circle. Just as land animals are better off without wheels, there are also two famous cases of human civilizations that reached this same conclusion for themselves. When Europeans discovered the Aztecs, Incas, and other civilizations of American Indians, they were astonished at the complete absence of wheeled transport—even from places where llamas were used as beasts of burden. For a long time we thought that Indians had simply never thought of the wheel, until archaeologists discovered pre-Columbian Mexican ceramics in the form of wheeled animals, possibly used as toys. Evidently, some Indians were able to build wheeled vehicles but found them not worthwhile for serious use.

The other case is more dramatic, because it involves civilizations that abandoned an already entrenched system of wheeled transport. Before the time of Christ, horse-drawn military chariots and ox-drawn carts were ubiquitous in the empires of Assyria, Persia, Carthage, and Rome. Thereafter, the invention of the North Arabian camel saddle permitted the pack camel to replace wheeled transport for about 1,500 years in virtually all of North Africa and the Middle East, from Morocco to Afghanistan! Modern European tourists who are charmed by the narrow, winding streets of old North African and Middle Eastern cities rarely realize that they are witnessing monuments to this triumph of the camel over the wheel. The explanation is that the pack camel was more cost-efficient than a wagon drawn by ox, horse, or by the camel itself—without even taking into account the expense of building and maintaining roads for wagons. Wheels continued to be used in North Africa and the Middle East for irrigation, pottery making, and milling.

What about the evolutionary future of wheeled animals? There is no doubt as to the advantages of wheels on hard, smooth road surfaces without obstacles—especially when someone else pays the costs of building and maintaining the roads. Man has covered the earth's surface with a new type of habitat, concrete, offering unfilled niches to the animal that can evolve to exploit them. Some biologists, advocates of an evolutionary theory named the theory of punctuated equilibrium, believe that evolution usually proceeds in rapid spurts. According to this theory, when new niches become available, new species quickly evolve to occupy them, then persist unchanged for long times. If these theorists are correct, then in a few thousand years we may actually be sharing our highways with rats that have retractable roller skates. ■