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The Machinery of Animal Movement

ONE thing which obviously distinguishes animals in general from other forms of life is a power they have of moving themselves from place to place. Different animals move in different ways – some creep along like a worm, some walk by means of legs, others paddle themselves through the water, or fly through the air. All these movements appear to be very different from each other and different too from the movements of such things as cars, ships, and aeroplanes. In this book I am going to try to tell you how far such impressions are true, and to help you to watch moving animals with increased understanding and pleasure.

If an animal is to move about in an orderly way it must, like a car, be provided with an engine, an efficient steering gear, and brakes; but before we look for these parts in an animal's body we may as well first of all consider just what is required from the engine of a motor car if it is to drive the car forwards. We all know that a car, with its engine switched off, will not start to move over a level surface by itself: to make it move we have to push it with our hands (Fig. 1). We can only push it with our hands if, at the same time, we give an equal and opposite push against the ground with our feet. So far as the car is concerned, if it is to move forward it must be pushed. If it gets no such push the car is an inert object; that is, one which must be forced to overcome its inherent incapability to move by itself. In the language of science we say that a car has *inertia*, and that this inertia is overcome by applying an external force. A force gives the car the energy necessary for movement; it will then go on moving by itself until this energy is taken away from it by another

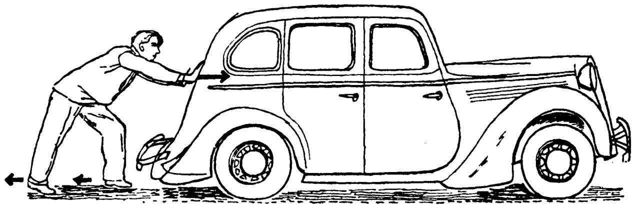

FIG. I. *We can only push a car forward if, at the same time, we give an equal and opposite push against the ground with our feet*

external force acting in a direction opposite to that which set the car in motion; such a force is usually applied to a car in the form of friction between the tyres and the ground. When we get into a stationary car, switch on and start up the engine, and put in the gear, the car moves forwards, but this forward movement still depends on exactly the same essential principle as operates when we push it with our hands; the only difference is that the back wheels and axle replace our feet and hands: the tyres of the back wheels press backwards against the ground and by this means an equal but forward force is applied by the axle to the body of the car. If instead of pressing against the ground the back wheels skid freely, no forward pressure develops against the chassis, and consequently no forward motion is imparted to the car. We can illustrate these facts by placing the hind wheels of a model electrically propelled car on a horizontal surface, so arranged that the surface moves backwards against a spring whenever a backward force is applied to it; the front wheels of the car rest on solid ground (see Fig. 2).

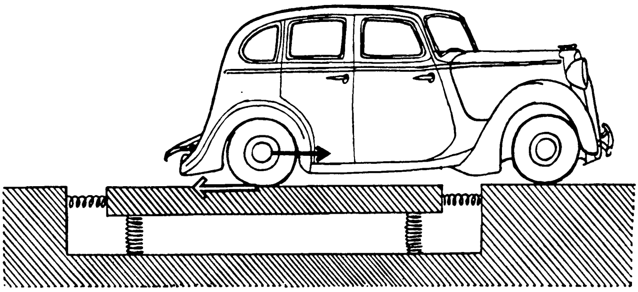

FIG. 2. *The tyres of the back wheels press backwards against the ground and by this means an equal and opposite force is applied by the axle to the body of the car*

As soon as the engine is switched on, the car begins to travel forwards, but, at the same time, the platform moves backwards. The force driving the car forwards is exactly equal to that driving the platform backwards against its restraining spring. Later on we shall do just the same experiment with different kinds of animals and we shall get the same fundamental result: an animal can only propel itself forward by pushing backwards against its surroundings (Figs. 3, 4). An animal on the land must push backwards against the ground; an animal in water must push backwards

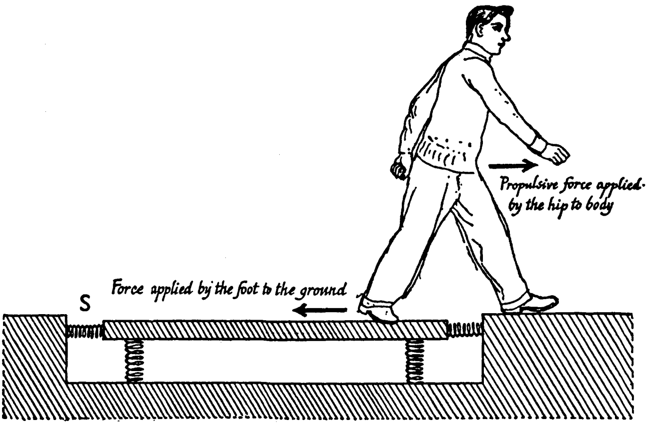

FIG. 3. *A man propels his body forwards by pushing backwards against the ground with his foot. When he steps off a platform mounted on springs, the propulsive force can be measured by observing the extent to which the spring* S *is compressed*

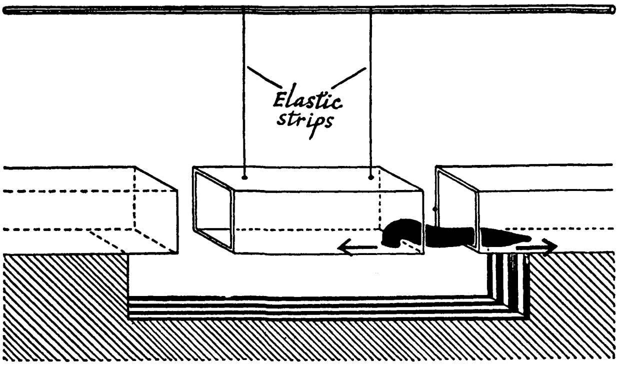

FIG. 4. *A leech pushes its body forward by pressing backwards with the sucker at the hind end of the body. The propulsive force applied to the body can be measured by observing the bending of the elastic strips*

against the water and a flying animal must push backwards against the air. In every case, the force available for moving the animal forwards is exactly equal to that with which the animal pushes backwards against its surroundings.

In cars, ships, and aeroplanes, the backward pressure against the surroundings is exerted by moving parts of various kinds but all called, as a class, 'propellers' – the back wheels of a car, the 'screws' of a steamer or an aeroplane. A 'propeller' of some kind or other exerting a backward force against the surroundings is an essential part of all self-propelling systems, and consequently (as an animal is always a self-mover), we can start our study of animal movements by looking for this all-important part, remembering that the 'propeller' must act against the animal's surroundings – the outside world – and must move relatively to the rest of the animal. Often the 'propellers' can quite easily be identified: the legs of a dog move to and fro on the body, and during their backward movement press against the ground; the wings of a bird move up and down, beat against the air. But sometimes the propellers are less obvious. A snail appears to creep along without changing its shape, but if we look carefully at its under surface, by allowing the snail to creep up or along a sheet of glass, we find that some parts are attached to the glass, whilst other parts are moving. Every animal moving itself must, in fact, obey these two rules – it must be constantly changing its shape, and it must press backwards against the outside world.

When we compare the propellers of animals with those of self-propelling machines made by man, we find one very striking difference. Except the jet propellers of modern aircraft, all the inventions of mankind depend upon rotation; the moving parts operating against the outside world are constantly turning in circles, relative to some other part of the machine. If one part is to rotate about another part in this way, the two parts must be separate from each other. The moving part turns upon an axle or bearing, across which no permanent connexions between the two parts can pass; otherwise they would soon get twisted and broken. In an animal no such arrangement is possible. Every part of the live body is connected to the rest by blood vessels and nerves, and these would quickly be destroyed by continuous twisting. Nature never uses a true wheel; she uses rods or levers, and these can move up and down, or from side to side, but can never make complete revolutions about a stationary axis. Never to be able to make use of a wheel-form seems at first sight a serious disadvantage; but we must remember that a wheel on its axle is really only a series of levers, coming into action one after another. As you see in Fig. 5, a six-spoke wheel rolling along on its rim can be regarded as six legs each ending in a foot; when we turn the axle in the direction of the arrows only one foot is in use at a time, but as soon as the toe of one foot leaves the ground, the heel of the next foot comes into touch with the ground; having pressed against the ground, each spoke turns round on the axis and in due time is ready to come into use again at the right moment. As a propeller, however, it does not matter what a spoke (or leg) is doing after it leaves the ground so long as it is ready to take up its propeller duties again in the right place and at the right time. For example, we can replace six legs arranged in the form of a wheel by two legs each

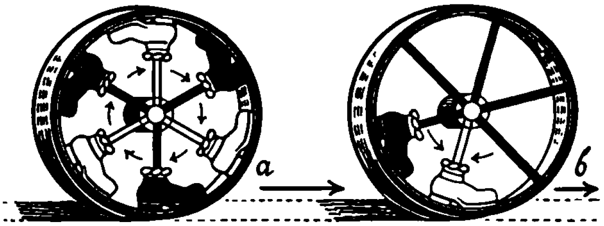

FIG. 5. *A six-spoke wheel rolling along on its rim can be regarded as six legs each ending in a foot. Only one 'foot' of the wheel is in use at a time, but as soon as the toe of one foot leaves the ground, the heel of the next foot comes into contact with the ground. We can replace the rolling wheel with its six spokes by two legs; if each swings forward when it has performed its task as a propeller, it comes into action again at the right moment*

swinging forward again as soon as it has done its duty as a propeller – a motion obviously very similar to that of our own legs. The limb is turning about its upper end, just as each spoke of a wheel turns about the axle – the difference between our legs and the spokes of the wheel is that our leg turns *forwards* about the hip joint when the foot is off the ground, and *backwards* when the foot is on the ground; but the spoke of a wheel moves continuously in one direction in a circle. Mechanically the propulsive effects are the same.

Instead of using only two levers swinging alternatively backwards and forwards, we can arrange a series of legs one behind the other and coming into action one after another. This is, in fact, one of Nature's commonest arrangements, especially for animals with large numbers of legs. Each foot touches the ground a moment before the one just ahead of it, the legs move rather as the keys of a piano move when a finger is drawn along them. Fig. 6 shows the pattern of leg movement in a large millipede from South Africa. This animal has about four hundred legs, and these give the impression of 'playing scales' on the ground as the animal walks along. We are asked from

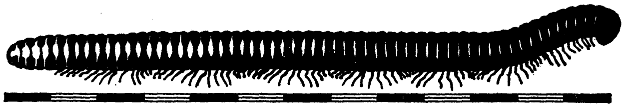

FIG. 6. *A large South African millipede has about four hundred legs. Each foot touches the ground a moment before the one just ahead of it, and the legs move as the keys of a piano move when a finger is drawn along them*

time to time, 'Which leg does a centipede (or millipede!) move first?' The answer is that all legs start together just as the spokes of a wheel do: but the legs of the centipede are kept in the right position in relation to each other by a very complex piece of nervous 'machinery', whereas the spokes of a wheel are fixed together by a mechanical axle. We can sum up the whole situation by saying that engineers use levers fixed together to form rigid revolving wheels; Nature gets the same mechanical results by moving her levers up and down or from side to side. Or, if we like, we can say that a man propels himself by two spokes, a dog by four, an insect by six, a spider by eight, and a centipede by a very large number!

In this book we shall be dealing almost always with the movements of fairly large, common animals, and we shall find it fairly easy to regard the bones as levers and the muscles as active engines. It is worth remembering, however, that such animals as this are the *latest* of Nature's designs. In the early stages of her experiments Nature worked on a much smaller scale; long periods of time passed before the principle of rigid levers, driven by muscular engines, was adopted. The principle of muscular levers was preceded by two other much less successful designs.

If you look carefully at the surface of the mud at the bottom of a shallow muddy pond, you may sometimes see very small white spots, which, examined under the microscope, turn out to be little irregularly-shaped creatures called *Amoebae*. These animals have no proper limbs, but move along by squeezing out blunt processes from the surface of the body. One of these processes attaches itself to the surface of the mud and the rest of the body flows either towards or away from it; then a new process of 'pseudopodium' forms, and the cycle is repeated. An amoeba is a very small animal – about one-twentieth of the size of a pin's head – and it moves along at a rate of not usually more than half an inch an hour, or one foot in a day. Movement of this kind – amoeboid movement – has not been developed as a means of propulsion for larger animals. But Nature has not forgotten it altogether; it plays a very important part in the life of such animals; by amoeboid movement the white cells of our blood can flow around and swallow up foreign particles which may

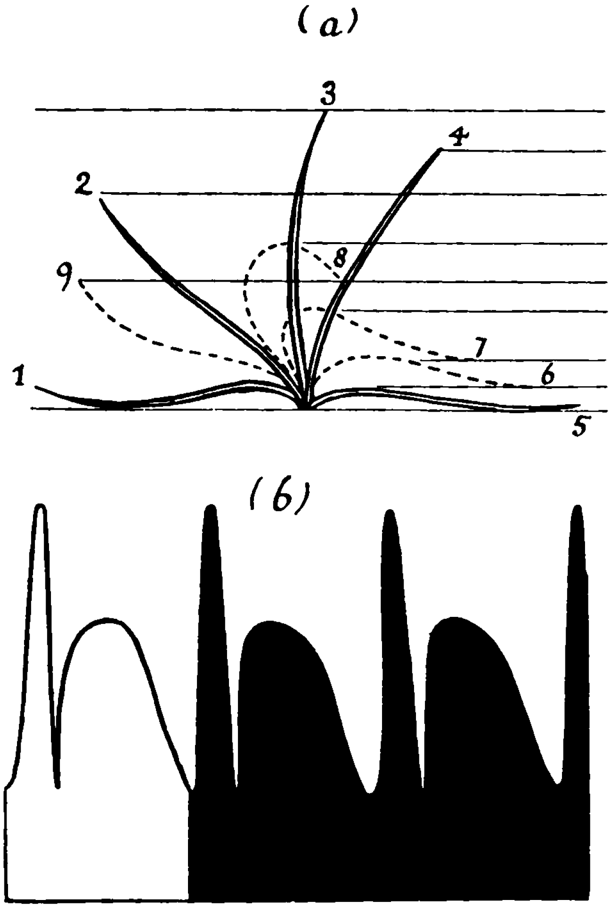

FIG. 7. *Cilia sweep backwards like the pliant lash of a whip, but forwards like a stiff rod. Thousands of cilia work in relays creating an impression of waves passing over the surface of the body, like waves passing over a field of corn in a gust of wind. In Fig. 7a a single cilium is beating in the plane of the paper; the*