THE MECHANICS OF MACHINERY.

CHAPTER I.

THE MACHINE.

§ 1. WHAT A MACHINE IS.

As our object in the following pages is to study only a certain section of the science of mechanics, that part of the science, namely, which is involved in questions relating to machinery and mechanical combinations of all kinds, it is right that we should commence with a somewhat precise notion of what the limits of our work are to be. The term *machinery* is a large one; it includes many things differing apparently very greatly from each other, and we must first of all find out what are the common points of all these various machines, the characteristics which belong to them as machines. After this has been done, but not before, we shall be able to see what is the actual nature and extent of the problems which lie before us, what ground we shall have to cover, and what matters we may leave untouched, as relating to conditions which do not exist within the limits of our work.

A machine is a thing which has been very often defined, but very seldom, for some reason or other, with anything like real exactness or completeness. According to many definitions, either a hammer or a piece of rope is a machine in itself—a bridge is certainly a machine, or a plank resting against a wall. But, in spite of the definitions, we do not as a matter of fact call any one of these things a machine—if we did the only difficulty would be to find anything in the universe that was *not* a machine. It would be useless, in that case, to make any attempt to study the applications of mechanics to machinery as a special branch of the general science of mechanics. It does not, however, appear difficult to include in a single sentence a complete definition of a machine, a definition, that is, which shall include all mechanical combinations which can by possibility receive that name, and rigidly exclude all others. We shall first give a definition which seems to meet these requirements, and then devote the rest of this chapter to its detailed consideration.

A machine may be defined to be a combination of resistant bodies whose relative motions are completely constrained, and by means of which the natural energies at our disposal may be transformed into any special form of work.

In the first place, then, a machine is a *combination of bodies*—a single body cannot constitute a machine. In each of what are often called the "simple machines," for example—the lever, wheel and axle, etc.,—there are at least two bodies, in some more than two. The mere bar which we call a lever does not in itself constitute a machine, either "simple" or otherwise. All its properties depend upon the existence of a fulcrum about which it can turn, and on the position of this fulcrum. Without this the lever is a mere bar incapable of being of the slightest mechanical use to us, with it, (a proper *form* of fulcrum being here supposed, of which more later on) it forms one of the most important combinations with which we have to deal. Here, therefore, a combination of two bodies can be used to form a machine.

Similarly with the "wheel and axle." Wheel and axle themselves form only one body, so far as our work is concerned. That is to say, whether they are originally made in one, or separately, or in a dozen different pieces, they are fixed together rigidly before they are put to any use, the one cannot be moved without moving the other, and we must therefore treat them as one only. But a wheel fixed to a shaft does not of itself make a machine. Before we can utilise it we must provide rigid bearings for the shaft to turn in, and these bearings (themselves also so connected that they form one piece) form a second body in the machine, just as essential to its working as the former. Here, again, then, a combination of two bodies forms a machine;—we shall see later on that this combination is in fact identical with the former.

We might give further illustrations, but these will suffice. There are no cases in existence in which a machine consists of one body only, and indeed we shall see immediately that we are able to say that no such machine is even theoretically possible.

In nineteen cases out of twenty a machine consists entirely of *rigid* bodies. But this rigidity is not an essential condition. Springs of steel or even of india-rubber, which cannot be said to be rigid—which are, in fact, used simply because they are not rigid—often form part of machines. Fluids also are not unfrequently used under suitable conditions. A column of water enclosed in a tube, for instance, may be used to transmit a pressure from one end of the tube to the other, in which case the water itself becomes in the fullest sense a part of the machine. More frequently than either of these, leather belts or hempen ropes form parts of machines, transmitting motion or force with sufficient accuracy for many practical purposes. Rigidity being thus not necessarily a property of the bodies of which machines consist, the question arises as to what is the essential condition which must be fulfilled by a body in order to make it available as part of a machine. It is that it shall present, or can be made to present, a suitable molecular resistance to change of form or volume, a quality which we have expressed by the use of the word *resistant* instead of *rigid* in our definition. The reason for this necessity for resistance to change of form will be seen better by and by; here, it will suffice merely to illustrate it. We use hempen rope to transmit force (as in tackle) by stretching it over pulleys, and keeping it always in tension. Under these conditions it can transmit pull as well as if it were of iron, and with far greater convenience. If we could so reverse the motion of the apparatus as to put the rope in compression instead of in tension, it would lose its resistance, fail to transmit the pressure, and be entirely useless for our purposes. The case of water is exactly the reverse of this. We can transmit pressure through it, *i.e.*, we can use it in compression, but it is no use as regards pull. We have to enclose the water in a tube, but the tube may be of any form, the fluidity of the water causing it of course to fill up any vessel in which it is placed. The water therefore may change its *form* to a very great extent, but it remains practically unaltered in *volume*, and this resistance to change of volume answers as well for some of our purposes as the resistance offered by a bar of rigid material to the alteration of its length or of its form generally.

The relative motions of the resistant bodies which together constitute a machine are said, in our definition, to be *constrained*. This point requires a little more extended remark than the preceding ones, for it forms in reality the chief characteristic by which problems belonging to the mechanics of machinery can be distinguished from those of general mechanics. It is this, practically, which enables us to separate from the latter, and treat by themselves, all the mechanical questions which arise in engineering work, and specially it enables us (as will be seen further on) to apply to the solution of these questions graphic methods, simple straight-edge-and-compass solutions, which from a practical point of view have in most cases many advantages over algebraic calculations.

The special feature, then, by which the problems belonging to our branch of mechanics are to be distinguished among those of the science in general, is this:—in the general case the bodies whose motions come into consideration are *free*, in all the cases with which we have to do they are *constrained*. Where a body is *free*, the direction in which it moves depends entirely upon the direction of the force which sets it in motion, and can be altered at any moment by an alteration in the direction of that force or, what is the same thing, by the action of other disturbing forces. Where a body is *constrained*, on the other hand, the direction of motion is absolutely independent of the direction of the force which causes motion in the first instance, and can neither be changed by any change in its direction nor by the appearance of disturbing forces. In the first case the motion of a body during any interval of time is only known if we know completely all the forces which will influence it, intentionally or accidentally, during that interval. If a machine had to be treated in this way these forces would include knocks and jars as innumerable as they are irregular, even a hand pressure on any of its parts would have to be taken into account, and the whole problem would become a totally impossible one. In the second case however, to which the machine fortunately belongs, the direction of motion of every part at every instant is determined completely by its construction. The only possible alternatives are motion in the right direction or no motion at all. As long as the machine is in motion, every part of it is compelled to move in a pre-arranged path, and these paths can only be changed by force if that force be sufficient to distort or destroy the machine. **So long therefore as the machine remains uninjured, we can say that all its motions are, as to their directions, completely independent either of the direction or the magnitude of the external forces which cause them.**

We say that the direction of motion is independent of the direction of the force causing motion. But of course, in machinery as well as in the rest of the universe, the motion of a body is actually determined by the *whole* of the forces acting upon it. In every case we must virtually apply the same method to get rid of disturbing forces—viz.: balance them; but the method of balancing is very different in the two cases of free and constrained motion. In general the resultant of all the forces acting on any body is oblique to the direction in which we wish it to move; such a resultant may be resolved into two components, one in the direction of motion wished, the other at right angles to it. If the latter be balanced, we shall have done all that is necessary to ensure the body moving in the right direction. In the case of a body moving freely this balancing of the disturbing forces must take place from moment to moment as the latter come into action. If a body be falling to the ground, for instance, and in its motion meet with some disturbing force in the shape of a side push, then in order that its path may not be altered it must be arranged that another push, exactly equal and opposite to the first, shall begin and end precisely at the same instants with it. Any such arrangement for balancing disturbing forces, although theoretically possible, is of course practically out of the question—a totally different plan is used in machinery. *There* we provide for the complete balancing of all disturbing forces by so connecting the moving bodies that any departure from the desired motion could occur only if the *form* of the connections could be changed, and we further make these connections of material such as cannot change its form easily under the forces acting upon it. The disturbing forces, then, are balanced as they occur simply by the resistance of the material of the machine to change of form;—this molecular resistance is usually called **stress**, a word which we shall have frequent occasion to use. We may sum up all this by saying that **the constrained motion characteristic of the bodies which form parts of machines, is obtained by so connecting them that all forces tending to disturb their motion are balanced as they occur by stresses in the bodies themselves.**

It is often said, and to a certain extent quite truly, that the motions of the different parts of a machine are rendered constrained by the geometric *form* (pin and eye, slot, screw, &c.) of the connections between them. When, for instance, we require a body to revolve about a particular axis, we make some portion of it in the form of a cylinder having the same axis (Fig. 1), and cause this cylinder to work in bearings made to fit it accurately—the cylinder being