

## CHAPTER XII.

# THE ANALYSIS OF COMPLETE MACHINES.

“Altes Fundament ehrt man, darf aber nicht das Recht aufgeben, irgendwo einmal wieder von vorne zu gründen.”—Göthe.

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### § 129.

#### **Existing Methods and Treatment.**

Now that by the help of kinematic analysis we have examined the machine as a combination of constructive elements, and also investigated the nature of the latter individually, we have brought ourselves to our final problem—the examination of the machine as a whole. This completed, our work will end as it began, with the machine itself, the dismembering of which, in order that we might better examine it kinematically from every possible point of view, we commenced in our first chapter. It might be supposed that we should by this time have become acquainted with all the essential characteristics of complete machines. We have indeed done so to a certain extent, but only by examining these characteristics singly, as *disjecta membra*, each one apart from its connection with others. It still remains necessary to review them and their mutual relations as a whole, and we shall find that this examination will explain some things as to the nature and use of the machine which have not yet come at all under our consideration.

We must first examine the way in which it has been usual hitherto to treat this subject, in order to see how far it is justified

by facts or can remain useful to us. I alluded in the Introduction to the widely-diffused conception of the nature of complete machines which was specially supported by Poncelet's authority and which has taken such firm root in the French mechanical instruction. This conception is that the complete machine is in general a combination of three parts or groups of parts,—

1. The receiver of energy, or receptor,\*
2. The parts transmitting motion, or communicator,
3. The working parts, or tool.

The part or group of parts constituting the receptor is generally understood to be that upon which the natural force driving the machine acts directly; the tool is the part by means of which the energy received by the machine is directly expended in producing the required change in or in connection with the body to be worked on. As the motions of these two sets of parts are seldom identical, the second group of parts is required to transmit motion from one to the other. The whole conception has something so direct and simple, we might almost say natural, about it as to give a most favourable impression. Poncelet himself spoke of it as well-established—as a matter of which the logical completeness was entirely convincing.† In saying this, too, he rather put in a few words what was previously known, and more or less distinctly recognised, than expressed something entirely new to his time, and now the idea has become to some extent a part of the very foundation on which the study of machinery, in France at least, is based. There is indeed much to be said for its directness, and the ease with which it can be grasped. Its division of its subject into three parts, a beginning, middle and end—two principal parts connected by a third—prepossesses us in its favour by presenting a certain analogy with

\* A few English authors have mentioned this classification, but none except Moseley have, I think, ever used it to any considerable extent. Both words and ideas will be somewhat unfamiliar to English readers, while Prof. Reuleaux's views will not run counter to any preconceived ideas here as they have done on the continent. The controversial part of the following sections would therefore have been unnecessary had they been originally written in English;—the conclusions arrived at are, however, none the less valuable.

† *Traité de Mécanique Industrielle*, Pt. III, § 11. “La science des machines, ainsi envisagée, se compose donc de la science des outils, de la science des moteurs, et de la science des communicateurs ou modificateurs du mouvement . . .”

similar ternary divisions in other regions of investigation. In many cases too it corresponds distinctly with the natural divisions of particular machines. It is necessary nevertheless, or rather I should say for this very reason, to submit these apparently fundamental conceptions to the test of the strictest possible investigation.

If we examine more in detail the usual treatment of the subject, we find that those parts of the machine most closely connected with the receptor, for the best possible utilisation of the driving force, are very generally considered by themselves in groups, forming what is known as prime-movers,—steam-engines, water-wheels, turbines, and so on. By a very similar limitation the group of working parts, or tool, has been taken to be more or less exactly co-extensive with a large class of machines, each one adapted for doing certain particular operations, as spinning, weaving, and printing-machines, machine-tools, &c. Collectively we may call them all tools, by a justifiable use of the word in its most general sense.

But if we look more closely at these familiar extensions of the original idea, we shall find that we are treading on very uncertain ground. For if every complete machine must have some motor in the sense used above, must be driven, that is, by steam, air, water, gas, &c.,—then evidently the lathe and planing machine cannot be complete. Scarcely any of the machines in a factory, indeed, could be considered as complete, none of them would be more than portions of complete machines. The common usage therefore, in which they all receive the name machine, must be entirely inaccurate, for it is quite inconsistent with the technical definition of what the machine really is.

Exactly the same difficulty occurs in the case of prime-movers. A very large number of these, considered by themselves, do not possess any part which can be called a tool, for doing work upon other bodies. They also, therefore, cannot be complete machines. Those engineers who devote themselves to the manufacture of steam-engines, turbines, and so on, are makers not of complete machines but only of parts of them. The only really complete steam-engines must be such machines as steam-hammers or crushers, direct-acting rolling-mill engines and so on. All others, no matter how excellent in design or construction, are incomplete machines in themselves and become complete only when combined with other apparatus.

But all this is in direct contradiction to what our natural idea of completeness in a machine would be were we unhampered by theoretical definitions; while the contrast which it presents to our simple direct idea of the machine makes us to a certain extent question the authority of the theoretical conception upon which (logically or not) this popular idea has based itself.

The doubt thus arising is strengthened by another question. If we look at a spinning-machine, we see the thread passing through certain motions which it could not receive were it not itself a transmitter of motion. Is the thread then here the body to be worked upon, or is it a transmitting part, or is it indeed itself the tool? And where does it begin or end to be any one of the three? Similar uncertainties exist in very many other machines. How is it that the spinning-machine, and with it indeed all other machines connected with the manufacture of textile fabrics, will not fit in to the theory? Is it the fault of the machines, the excellence of which every one knows, or of the theory? Let us take another example, the well-known hydraulic (Montgolfier's) ram. The water lifted by the machine is here a portion of the mass of water which works it. The machine is obviously complete, but which part is the receptor, which the tool, which the transmitter of motion? Does the stream of water represent all three itself? And if so, what are the other parts of the machine? Or has Montgolfier bequeathed to us only a tantalising paradox, a machinal will-o'-the-wisp, instead of an orderly and respectable machine which can give a reason for its own existence?

Thus doubt arises upon doubt, question after question, so soon as we seriously attempt to apply the recognised theoretical classification or subdivision to actual machines. But the question is not one to which one answer is as good as another,—it concerns one of the most important factors in modern civilisation, a branch of human activity affecting almost every one more or less directly; while the most strenuous exertions, intellectual and physical, have been made in order that it might be scientifically mastered. It is therefore not without good reason that we shall now commence the examination of the three popular subdivisions of machines.

## § 130.

**The Tool.**

In commencing with the part of the machine which directly executes the work—the tool—we shall first try to find what portion of a few well-known machines answers to this description. In the lathe, planing-machine, band-saw, etc., this is very easy. The chisel or other cutting tool, the saw-blade and so on, are obviously the pieces directly employed in the work. In the screwing-machine there are generally several pieces, the dies, acting together, and these, together with the frame or stock in which they are placed, may fairly be called the tool, as in practice they actually are. In rolling mills of any kind the two rolls serve as the tool, they share equally in shaping and moving the metal passing between them. In flour mills the stones act as tools, grinding the corn and passing it from them as meal. In the manufacture of wrought iron nails one tool, a compound one, is used to hold the wire, another, also compound, to cut it, a third to form the head, other parts bring forward a new portion of wire, others remove the nail already made.

In the card-making machine, also, several tools act in succession, some to pierce the leather band, others to cut the wire, to bend it, and to insert it in its place in the band, while others act on band and wire together in order to press home the latter. We have, that is to say, a series of tools working in different ways and for different purposes, and so connected that it is very difficult to say where one ends and the next one begins.

We notice here that the unity of the tool, or indeed of the body to be worked upon, does not appear to be a condition of the machine. This fact has to be kept in mind if it be wished to form accurate definitions, and many writers who have endeavoured to carry scientific exactness through all their work, Redtenbacher among them, have been compelled for this reason to use extended descriptions instead of definitions. Before we consider this question let us look into some further examples.

In hoisting machines the hook from which the body hangs as it is lifted has been called the tool. This is perfectly right, according to the definition, for it is clearly the part of the machine which

directly does the work of lifting. But if we suppose the hook removed, and the rope itself tied round the body to be lifted, the machine can work precisely as before. The only difference is one of convenience in securing the load, and this obviously does not affect the question before us. The hook cannot therefore really be the tool of the crane or other hoisting machine, for the total removal of any essential part of a machine must necessarily render it useless. But—it may be suggested—in this case the loop of the rope, the improvised sling, is really the hook, differing from the former one only in material and constructive form, not in kind. Let it be so. But now suppose the load removed entirely and the rope allowed to hang by itself,—it may hang to such a depth that its own weight becomes as great as that of the former load,—and let the crane be set in motion to wind up the empty rope, does it not work precisely as before? There is still a load to be lifted. The wheels, drums, shafts, pawls, cranks, all move precisely as before. But neither hook nor sling exists, the only weight to be raised is that of the rope itself; the body to be lifted has become a link of the kinematic chain. The tool, in the usual meaning of the word, has completely disappeared.

Let us look at another example—the locomotive. The coupling-hooks or other arrangements used for attaching the train to the engine are here usually said to form the tool. But if this be the case is it not extraordinary that such an immense number of different coupling arrangements should exist, all intended to serve the same purpose, and with any one of which any given locomotive might work? In this case would a change of coupling-gear alter the machine as a whole? This must certainly be the case according to the commonly received theory, for the tool is an essential characteristic part of each machine. But in order to look more thoroughly to the bottom of the matter, suppose the locomotive to be running with its tender only, or still better, suppose the case of a tank locomotive carrying also its own fuel and running entirely by itself. If it come to a steep gradient it may have to exert now exactly as much power as it would do on a level if it were drawing the train; the coupling-hooks, however, have now absolutely no connection with its work. They certainly do not form in any sense the tool of the machine. It may be said that the latter is now incomplete because it is not carrying goods or passengers,—but this

is obviously a mere accidental condition, and there is no difficulty in supposing a locomotive built like a Fairlie engine on a frame sufficiently long to afford ample room for both. No part corresponding to the tool can, however, be pointed out; it is only certain that the couplings can no longer in any way represent it. The body to be acted upon, indeed, no longer exists beside or outside the machine, but has become a part of it. The one frame supports both carriage and machine.

There are many other machines in which the conditions are exactly the same as in the locomotive,—as, for example, the steam-boat, where again we can find nothing corresponding to the tool. In small machines we find the same thing;—it is very difficult to say, for instance, what part of the common clock is the tool. If it be the hands, we ask immediately where the body is upon which the hands work. The hands also are not absolutely necessary to the completeness of the clock; they might be replaced by graduated discs turning relatively to some fixed index; or indeed a mere mark made upon a wheel exposed to view might answer all purposes. The hands therefore are not the tool, and it is not possible to name any other part of the clock which fulfils the functions of that organ.

Our investigation thus leads us to the conclusion that the tool does not form an essential part of the machine. In certain machines only do we find it unmistakably recognisable, in some its distinctness is less and in others it does not exist at all.

Looking at the last class of machines—of which we have given examples in the crane, locomotive, steam-boat and clock—collectively, we find that they have in common the object of effecting some alteration in the position of a body or bodies. The first three examples are machines by which loads are moved, vertically, horizontally, or in both directions. Essentially the same thing is true of the clock, but here, for a special purpose, the alterations of position are so arranged that they enable us to measure the time occupied by the process.

The machines first considered, in which the tool really exists, have, on the other hand, the common object of making some alteration in the form of the body or bodies upon which work is done—such as turning, grinding, dividing, uniting, etc., Lathe, planing-machine, screwing-machine and saw change the form of



bodies by removing a portion of them. The nail-making machine and rolling-mill rearrange the molecules or larger portions of bodies worked on, of which at the same time they alter the position. The same is true of the card-making machine. The millstones divide the body into minute pieces, altering its position at the same time. All, however, have one or more tools, and we see that in every case where there has been any indefiniteness about these, it has arisen from the fact that the machine served the double purpose of changing both the form and the position of the bodies worked upon. Apart from this, however, we may now divide machines into two great classes according to the purposes for which they are used, namely :—

I. Machines for altering position, or place-changing machines.

II. Machines for altering form, or form-changing machines.

There is no sharp division line between these two classes, for some form-changes are, as we have seen, necessarily accompanied by changes of position, while some machines, as the corn-mill, seem to belong equally to the two classes. In every case however, those machines which belong wholly or partly to the second class are characterised by the possession of the tool, while this organ is not found in any machine whose object is place-changing alone. The latter are therefore the simpler, and for that reason we have placed them first.

The theory, therefore, which makes the tool an essential part of the machine, is correct only so far as one of these two great subdivisions of machinery is concerned. The tool is not an essential part of the machine; it is accidental to it only, and for this reason cannot form part of the foundation upon which our comprehension of the complete machine is to rest.

### § 131.

#### **Kinematic Nature of the Tool.**

Now that we have found what the tool is not, we must turn to the question of what it is, and endeavour to find the kinematic meaning of this organ in the class of form-changing machines, in



which we have found it to exist, and the general kinematic principles underlying its use.

Let us first look at the action of the tool in some familiar machine, say a common lathe with a slide-rest in which a bar is being turned. The chisel is held fast in the tool-holder of the rest and moves parallel to the axis of the spindle, the bar to be turned is made to revolve along with the mandril in such a way that the portions of its surface to come in contact with the chisel move always towards its edge. The relative motion of the chisel to the bar is the common screw motion, occurring exactly as if the turning tool were a part of a common nut  $S^-$  of which the bar to be turned is the screw spindle  $S^+$ . The chisel and bar have therefore the motion of the pair  $S^-S^+$ . This pair does not exist at the commencement of the work, but as the lathe moves, the chisel (being harder than the piece to be worked on) cuts away those portions of the bar which do not belong to its own enveloping form,  $S^+$ , upon the spindle. That part of the bar, therefore, over which the chisel has passed, has necessarily taken the form of the element  $S^+$ , the chisel itself carrying a small portion of the partner element  $S^-$ . Essentially therefore they form a twisting pair,  $S^-S^+$ , as may be recognised more readily, perhaps, if we suppose the lathe worked backwards, and the chisel passing again over the surface it has already formed. The restraint between the two elements of the pair is not complete in itself (§ 18, &c.), but the lathe is so arranged as to supply the want by chain-closure (§ 43). We may notice that the chisel has carried the profile of the nut  $S^-$  from the beginning, while the bar only received the form  $S^+$  while the turning was progressing. The pairing therefore of the elements into the form  $S^-S^+$  is made as the motion of the machine goes on, and at the end of the operation the two bodies are really formed into such a pair.

We have said that the bar being turned takes the form  $S^+$ . This is visible enough in roughing out work, where a sharp-pointed chisel is used. In finishing or smoothing work, where the chisel edge is made straight and parallel to the axis of the lathe, the bar becomes in external form a cylinder (cf. § 15); but as regards its pairing with the chisel it is still a screw.

We find in the planing and band-sawing machines the same thing as in the lathe—that the tool and the body to be worked on

are combined into a pair of elements, in this case a sliding pair  $P^+P^-$ . In the screwing and tapping machines the pairs  $S^+S^-$  and  $S^-S^+$  respectively are formed in the same way. We see that in every case the body to be worked upon becomes itself a kinematic element or the part or whole of a kinematic link. In the screwing machine this is specially noticeable, for as soon as the screw is started it itself causes the forward motion of the dies. The body to be worked is therefore not something external to the machine but actually forms a part of it. We shall therefore give this body, to which we shall often have to refer, a special name, calling it the work-piece of the machine.

That the work-piece has formed an element in a lower pair is only accidental to the particular machines chosen for illustration. In other cases we find higher pairs exist. In the rolling-mill, for example, the work-piece forms with the rolls the higher pair  $R^+, P^+$ , the work-piece itself forming here a complete link of the chain. In the carding engine the symmetrically placed wires of the cards, compel the fibres of the tangled mass of wool to assume the enveloping forms corresponding to their motion, that is, to lie parallel to each other. In the corn-mill there is a very complex higher pairing, in which force-closure plays an important part, between the grain and the mill-stones.

Our analysis therefore leads us to the following proposition: In form-changing machines the work-piece is a part or the whole of a kinematic link, and is paired or chained with the tool by so arranging the latter that it itself changes the original form of the work-piece into that of the envelope corresponding to the motion in the pair or linkage employed.

This proposition is free from the indistinctness which characterised the older conception of the machine. We see from it, in the first place, that the kinematic chain is not broken at the tool or the working point, but continues through it. It is not the end of the chain, but only a point in it having special importance in reference to the object of the machine. We find here also the answers to several of the questions which came up in § 129. The thread in the spinning-machine, as a link in the kinematic chain, is necessarily a transmitter of force. The spindle, on the upper end of which it first winds and then immediately unwinds itself

forms here a higher pair with the thread, and is itself the tool. Relatively to each other, however, the fibres of the thread act as tools. If we imagine for the sake of simplicity simply a pair of such fibres stretched between the spindle *S* and the draw-frame *D*,



and the spindle to make half a revolution, there is, in the first place, a mere crossing of the two fibres,



but as the turning continues the fibres twist round one another, each fibre acts as a tool in working the other, the screw form of each being simply its envelope relatively to the other. Thus we see that it is not even absolutely necessary that the tool should be harder than the work-piece, and also that occasionally it is not possible to distinguish one from the other. This, however, does not affect our proposition—that the work-piece forms a part, or the whole, of one of the links of the kinematic chain forming the machine.

We notice further that in the work-piece we have a member common to both place- and form-changing machines. We have already noticed that when the so-called tool of the former disappeared, the body on which work was done, the work-piece (where it existed) became a part of the machine. In place-changing machines, therefore, as well as in those which we have been considering in this section, the work-piece is a part or the whole of a kinematic link. In this point the two classes of machines are completely alike.

There follows, lastly, from what we have now found as to the nature of the tool, a proposition which is very important, and which has most numerous applications in mechanical technology. It is the following:—in order that a given form may be given to a body by a machine, we must give to the tool of the latter the envelope of that form. In order to determine this envelope the intended motion of the tool relatively to the work-piece must first be fixed, and as this relative motion may be of many different kinds, not only may the problem admit of several solutions, but as a rule it itself includes numerous other problems. In every case, however, it is a matter of very great importance to

be able to include, in a single definite conception, the whole kinematic relations between the tool and the work-piece.

## § 132.

### The Receptor.

There has been less variety in the common conception of the receptor than in that of the tool, on account of the limited number of bodies which seem suitable for fulfilling the function assigned to it. These bodies are water, wind, steam and some other gases, weights, springs and living agents. By the receptor of any complete machine has hitherto been generally understood that part to which one or other of these bodies directly imparts the energy by which the machine accomplishes its work. It is important that we should acquaint ourselves with the characteristics of the various ways in which this transference of energy is effected in the cases of the bodies mentioned.

Taking first water-wheels and turbines, we find the receptor at once in their buckets. Our earlier investigations (§ 43) have already shown us that the wheel is not used by itself, but that its buckets are kinematically paired with the water and this again with its channel or pipe. The receptor is here, therefore, unquestionably a link in the kinematic chain. In the various forms of hydraulic engines we note exactly the same thing. Here also the water, paired with the piston, enclosed in the cylinder, guided by the valves, forms a link in the kinematic chain; the whole mechanism is one which we have already examined (§ 126) and found to be a ratchet-train. It is, however, impossible to say certainly whether the piston is the receptor, or the cylinder, or both,—or, indeed, whether the valve gear does not also form a part of it along with both.

The wind is utilized as a source of energy under force-closure of the driving organ, in such a way that a kinematic pairing, in this case a higher screw-pairing, occurs between the wind and the sails of the wheel.

Steam and other gases working expansively are commonly used in piston machines, and occasionally in machines arranged somewhat like turbines, always, however, in such a way that they are

kinematically paired or chained with the driving parts. In general this occurs in such a way that it is difficult to point out the receptor in any single piece.

The motors of which we have spoken, water, wind, steam and other gases, are all pressure-organs. Looking generally at the prime movers driven by them so as to classify their leading characteristics, one important fact appears which we must not leave unmentioned. We find two different methods of utilizing the driving energy of the motor, corresponding to two distinct classes of prime-movers. One of these classes, which includes all the machines working with pistons, we have already seen to be ratchet gear, or more fully, reversed ratchet gear. The other class, to which water-wheels, turbines, wind-mills, etc., belong, are characterised by the continuous, or very nearly continuous, motion of their working fluid. This acts no longer periodically or reciprocally, but enters continually at one side and passes away at the other. In water-wheels its action might be imitated by a rack (§ 61), in the wind-mill and in some turbines by a screw, in others by a rope passing down and up round a sheave, etc. The difference between the two classes may be expressed by using names which indicate the principal characteristics of their motion, calling the second running-gear as distinguished from the first, the ratchet-gear. All prime-movers driven by pressure-organs are either ratchet-gear or running-gear.

If we glance again at the chamber-crank and chamber-wheel trains which are described in former chapters, we see that they belong partly to the one and partly to the other class. The chamber-crank machines, both pumps and engines, are partly ratchet-gear and partly running-gear, some of them, indeed, taking a kind of intermediate position between the two classes; the chamber-wheel machines are essentially running-gear. For the purposes of many machines running trains are extremely convenient, because their rotary motion can be so easily and directly utilized. The attempt to design rotary engines and pumps is essentially an endeavour to substitute running-gear for ratchet-gear in machines working with pressure-organs.<sup>68</sup>

The common clock may serve as an illustration of a machine moved by the action of a weight. At first sight it appears scarcely doubtful that the cord or chain from which the weight

is suspended is here the receptor, for it is the part of the machine directly connected with the driving weight. Looking at the question somewhat more closely, however, we see that the case is similar to that of the loaded crane (§ 130). We may suppose, that is, the weight to be removed, but the chain or cord to be lengthened sufficiently to make up the load to its former amount; it alone would then be sufficient to work the clock. The weight, therefore, cannot be the driver, for it no longer exists, while the cord has not altered its nature, and cannot therefore have been the receptor in the former case. It is evident, however, that the cord is a link of the kinematic chain, and is paired with the barrel, on which it is coiled when the clock is wound up. Machines driven by weights have then this in common with the prime-movers just described, that the body transmitting the driving effort to them forms itself a part, a link or an element, of the kinematic chain.

The springs used for driving watches and other small machines are, as we have already seen in § 44, kinematic elements or links. Here again it is very difficult, if not impossible, to say which piece of the machine answers to the common definition of the receptor, but we always see distinctly that the piece through which the driving effort is introduced forms a part of the kinematic chainage of the machine.

While, however, all prime-movers possess this common feature, our investigations show us that from another point of view they divide themselves into two general classes. In all those machines which are driven by pressure-organs a change of form takes place in the latter as it traverses the pipes, ports, valves, buckets, etc.; this may be carried to a very great extent, as in the steam-engine, and may be combined with more or less change of place also. With springs the change of form alone exists. With driving weights, on the other hand, the change of place only remains, the change of form has completely disappeared. We have here exactly the difference which we found before to exist in regard to the object of the machine, or as we may now say, in regard to the treatment of the work-piece. We may therefore again distinguish form-changing and place-changing machines according to the changes undergone by the driving organ in doing its work. This conclusion is not

affected by the fact that the number of such place-changing machines is comparatively very small. The difference between the two classes is intrinsically important, for it removes an apparent want of congruity between prime-movers and other machines, and will further serve to explain some remarkable analogies.

Let us turn now, lastly, to the employment of living agents, that is, of the muscular power of men and animals, to drive machines, looking first at the use of human muscles. The common statement here has been that the receptor is some portion of the machine having a form and motion suitable for receiving the action of the driving body, the hand or arm or foot of the worker. In a common grindstone, for instance, the treadle is considered the receptor, the foot or leg of the workman the motor. Although this is certainly what appears on the surface to be the case, the real constitution of the machine must be stated differently. If the crank-pin were made sufficiently long, the grindstone might be turned by the hand of the workman; or if the workman held one end of a cord attached to the crank-pin he could easily, by periodic pulls or jerks, keep the stone in motion.\* The treadle is not therefore an indispensable part of the machine. All three methods of driving have, however, this in common, that the body of the worker becomes kinematically chained with the machine. Under certain circumstances this chaining may be very complex, in the case before us, however, it admits of tolerably exact determination. In the first place the crank  $a$  with the coupler  $b$ , the treadle  $c$ , and the frame  $d$  (Fig. 356) form a lever-crank  $(C''_4)^d$ . In this mechanism  $c$  is the driving link, so that its special formula runs  $(C''_4)^d_c$ . The workman places his foot on  $c'$ , the prolongation of  $c$ , and (supposing the centre  $1'$  of his hip-joint not to move) his leg forms with the treadle  $c'$  three links, the crank, coupler, and lever, of another lever-crank  $(C''_4)^d$ , to the frame  $d'$  of which the hip of the worker belongs. His knee-joint forms the pair  $2'$  and his ankle joint the pair  $3'$ . The joint  $4$  is common to both the trains of this compound mechanism, as is also the frame  $dd'$  which carries the fixed elements of the pairs  $1, 4$  and  $1'$ . The worker exerts muscular force at  $1'$  and  $2'$ , and indeed at  $3'$  also,

\* As the Kalmuck priest drives the prayer-wheel for example, or the Japanese peasant the reel upon which her silk is wound.--R.



to give the required motion to the machine. His foot thus forms a part of the links'. The special formula of the second mechanism is therefore  $(C_n)_{a=0}$ , and it is to be noticed also that the link  $a$  swings only, and does not rotate. We find then that the worker makes a portion of his own body into a mechanism, which he brings into combination, that is chains kinematically, with the mechanism to be driven.

A workman applying both hands to a turn as a crank in one case where there is large expenditure of effort, changes the mechanism formed by his limbs to that of the crank in a very complex



Figure 1

manner. He alters at will the action of the force-closure which brings certain joints into, or throws them out of, use, as becomes necessary at each instant.

The motion of the human body in driving a tread-wheel, or still more that of an animal in a "gin," is so complicated in the same way. Always, however, we have the same union, by kinematic chaining, of the living mechanism with that of the machine, while no receptor, in the hitherto accepted sense of the word, can be distinctly recognised. Our investigations, then, lead us to the conclusion: that the receptor does not form an essential part of the complete machine.

## § 133.

**Kinematic Nature of the Complete Machine.**

We have found that the "tool," which has so often been considered an essential member of every machine, occurs only in one half of existing machines. We have seen, too, that the receptor, which has also been considered essential to every machine, is in very many cases quite indeterminate. The prospect that the third member, the communicator, should prove to be essential becomes therefore very small. There are very numerous cases in which it cannot be distinctly identified, although, in some instances, there are large groups of parts which are obviously employed for no other purpose than the transmission of motion. But every link of the kinematic train transmits a greater or less effort from one point of the machine to another; every link may be looked upon as a communicator between the driving force and the resistance; and in most instances it is impossible to say where the function of transmission begins and where it ends, so that we must conclude that the communicator also, as a special subdivision of every machine, must be given up. All three, receptor, communicator, and tool, may exist and may be clearly recognisable in one and the same machine; they are not, however, essential organs of machines in general, they must be reckoned among their accidental members only, for which we shall shortly find another classification.

The fundamental idea to which our investigations have led us, an idea which we have found to be the foundation of, and hidden by, many subsidiary ones, is this: the complete machine is a closed kinematic chain. The driving body and the body on which work is done are equally links or elements in the chain. The laws governing the motion of the motor or driver are the same as those according to which the work-piece is driven and the tool, where it exists, performs its function; they are simply those laws under which the relative motions of any other links or elements take place.

Only one difference appears which tends to impair the simplicity of this conclusion; it is the difference between the form-changing and the place-changing machines. This last remaining distinction deserves somewhat closer examination.

We found that the pairing or chaining of the tool (in the form-changing machines) and the work-piece was such that the former constrained the latter to assume the form of the envelope for its relative motion, the giving of this form being the result aimed at in working the machine. The driver in the form-changing prime-movers passes through an exactly similar process. If we look, however, in this connection at any pair of elements whatever, lower or higher, a pin in its eye, a screw in a nut, a piston in its cylinder, a pair of spur-wheels, we see that in every case form-changes occur in one or the other element, or in both. These changes are of two kinds, viz. (1) temporary changes on account of the unavoidable alterations due to the action of sensible forces even upon the most rigid body, and (2) permanent changes, due to the separation of small portions from the body. In the latter class of changes wear gradually alters the form of the paired elements, and this alteration occurs so that the elements carry the reciprocal envelopes for the motion occurring between them. This law is, however, exactly the same as for the motion between tool and work-piece. In this case we endeavour to carry out the form-change quickly, it is the object of the constrained motion of the machine. In the former case the continuous change interferes with the object of the machine, and we therefore try to limit it in every possible way. In both cases, however, it exists.

The form-changing action which occurs between the tool and the work-piece differs in degree only, and not in kind, from the action taking place between the elements of every other pair in the machine.

We see, therefore, that all complete machines without exception follow the same general laws, and we are now able completely to realise the meaning of the definition of the machine with which we commenced our investigation (§ 1) and which therefore we may conveniently repeat here:—

A machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions.

The “arrangement” of the bodies here mentioned is the kinematic chaining. Motion occurs in the machine when some part of the chain is in a position which cannot be retained under the

influence of the natural force acting upon it. The particular motion then occurring is made determinate by the chaining. In the place-changing machines this motion is used for the purpose of altering the position of the work-piece, in the form-changing machines with the object of altering its shape, the nature of both alterations being fixed by the form of the chain. Both results, the motion of a body in given paths and according to given laws, and the alteration (perhaps simultaneous) of its shape, are forms in which the machine has compelled the natural forces "to do work."

A few general illustrations of this may be in place here.

In the common clock, in which we may suppose the chain increased in weight in the way before mentioned, if the chain be brought into such a position that it begins to uncoil itself from the barrel, every part of the mechanism will at once commence its characteristic motion. In clocks of the common construction motion ceases while the chain is being wound up, the process, that is, of bringing the chain into the "unstable" position just mentioned affects every part of the train. In clocks of a better class means are adopted for removing this defect, such as the use of a weighted lever arranged so as to come into action, and drive the mechanism during the operation of winding up. In other words a second kinematic chain is so placed in reference to the first, that when the latter is not acting on account of the winding process, the former is brought into an unstable position, into a position, that is, suited for driving the mechanism.

In the under-shot water-wheel we allow the pressure organ, water, to act on the wheel as soon as the sluice is opened; the two members of the chain are so formed as to pair at once, and motion occurs through the action of gravity upon the water. In the turbine the water forms a screw pair  $S^+S^-$  with the turbine wheel, it is caused to descend by gravitation, and therefore drives by its motion the element with which it has been paired.

The opening of the stop-valve of a steam-engine allows the column of steam to become a part of the chain (which we have seen to be a ratchet-train, § 126), and to constrain it to perform that particular motion which its form permits. The indefinite length of the driving-link, the steam-column, is obtained by a physical process in the boiler. Similarly in hydraulic machines a meteorologic process furnishes us continually with new portions of the

driving link to replace those which have left the machine. It causes the water to move as it were in a circle, always raising it again after it has passed downwards through the machine.

The hydraulic ram mentioned in § 129 no longer presents any difficulties to us. The water in it is kinematically chained with the other parts, the whole forming, in fact, a ratchet-train. So far as the descending water driven by gravity is concerned this train is reversed, but in respect to the portion of the same water which is raised it is direct. The liquidity of the pressure organ allows it to be thus separated into two streams. It is quite indifferent to us, and in no way affects our definition, that the water here both drives, is driven, and communicates motion. In every case we see that the driving body, the driver or motor, forms itself a link in the kinematic chain, instead of being, as in the old conception of the machine, entirely external to it.

#### § 134.

### **Prime-movers and Direct-actors.**

We have now reached a position which enables us to give an answer to the question formerly raised (§ 129), whether the steam-engine, the water-wheel and turbine, the lathe and planing-machine, the loom, the crane, and so on, could or could not each by itself be considered a complete machine.

In regard to the three first we can at once say that they are complete machines; they are moreover place-changing machines, giving to certain of their parts, by suitable kinematic chaining, a determinate motion which may be utilized for any desired end. A steam-engine, for example, may be employed to drive machinery of the most different kinds without in the least altering its own mode of action. The various uses to which portable engines are put gives us a familiar illustration of the way in which advantage is taken of this fact in practice. One prime-mover may always be substituted for another without any alteration in the machines driven by it, if only the effort applied to the shaft and the speed at which it is driven remain unaltered. In other words, the machine fulfils its end in these cases if it give to one link of the chain a uniform rotation, or cause its points to undergo changes

of position along circular paths. In treating prime-movers as complete machines, then, popular usage has done not merely what is practically convenient but also what is in theory perfectly correct.

The question whether the lathe, planing-machine, spinning-machine, etc., are complete machines does not appear quite so easy to answer. We may suppose each of them to be arranged so as to be driven by a belt,—for this purpose they only require to be furnished with suitable belt-pulleys. We may then certainly say, if the belt have always the tension necessary to prevent slipping, that they are complete. It is quite indifferent, so far as regards the chaining and the action of the machine, whether the belt be endless or not, whether it be moved by a weight or by muscular force (as in Berthelot's knotted belt Fig. 357,\* or Borgnis' "flexible ladder" Fig. 358), or be driven from the shaft of an engine. In each case the belt is as truly the driver of the machine as the steam is of the steam-engine. Just as in that case it is indifferent whether the steam be received direct from the boiler or whether the engine be worked by the exhaust steam from another engine (as has been sometimes the case), so here it is indifferent by what means the belt be set in motion, it is and must in all cases be the driver of the machine.

In mining and tunnelling operations we often find prime-movers worked by air which has been compressed by a hydraulic air-pump, (as in the Mont-Cénis tunnel) or by a pump driven by steam. As prime-movers they are, however, complete, as long as the requisite quantity of driving air is supplied them. Their driver is the column of air in the pipes, and is itself set in motion by another prime-mover. This air-column between the two machines is, however, in precisely the same position as the belt between a steam-engine shaft and a lathe, loom, or any other machine driven from it. Our investigations have already shown us (§ 44) that the cases are not merely analogous but essentially identical. But whether the driven machine be itself a prime-mover or be a machine directly employed in mechanical work is obviously beside the question. The machines considered

\* Three or more men work beside each other on as many ropes, the pulleys of all being placed on the same shaft *a*. Borgnis, *Mécanique appliquée, Composition des Machines*.

are therefore, taken along with their driving organs, complete machines.

This is equally true of pumps (which are only place-changing machines), of looms, shaping-machines, sawing-machines (which are both form and place-changing machines), and so on; in short, for all machines arranged so as to be driven by a prime-mover,



Fig. 211.

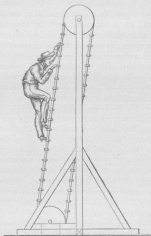


Fig. 212.

whatever the nature of the latter be. Such machines we may call collectively direct-actors. By practical machine-makers they have long been considered complete machines, in opposition to the conceptions of the theorists, so that here again we find the popular view to be fully justified upon strictly theoretical grounds.



We have still to consider those direct-actors which are driven by animal power. We saw above that in these machines the body of the man or animal combined with the mechanism in a kinematic chaining sometimes of great complexity. The special complication, however, lies always in the organic part of the chain, the links of which receive the necessary constraint by the action of forces commanded by the will. If we bear in mind that in the example given—the grindstone worked by the foot—and equally in the hand-pump, in the tread-wheel, the horse-gin, etc., the mechanism driven by muscular energy forms in itself a closed kinematic chain, we see that the relation of the organic driving parts to the inorganic machine is precisely that of the prime-mover to the direct-actor driven by it. The man or animal is to be regarded as a prime-mover, of which the parts—hands, arms, feet—move so as to drive in the required manner the given artificial machine. The locomotive has often enough been called a steam-horse,—we may reverse the comparison and call the gin-horse, Fig. 359, the locomotive of the machine which it drives. Its direct work is simply that of moving against a certain resistance. A man working in a tread-wheel, or clambering Borgnis' endless ladder is in exactly the same position, his work is that of continually raising the weight of his own body. The assistance given by the living agents to the process is purely physical in each case, and not intellectual; it is not in the least degree necessary that they should know the object of the machine in order to do their work. This work is precisely that which would be performed by an inorganic prime-mover in driving the same mechanism.

So far, therefore, as machines driven by muscular power are themselves closed kinematic chains, they may be regarded as complete machines, and do not in themselves differ from machines driven by any other than muscular force.

This brings us to another important question, which certainly has a right to a place in any complete treatment of the theory of machines, although it has never yet found one. It is the question of the share taken by living agents, and especially by men, in the executive portion of the machine's action. If the application of animal power to machines be considered at all in the study of

machines, as it continually is when that power acts the part of a prime-mover, it is not consistent to leave unnoticed the share taken by the same agency in modifying the work produced by the machine,—in taking, that is, the part of a direct-actor. This subject is one to which we have been brought by a method of treatment differing entirely from the old one, under which it found no place. Here I can only enter into it so far as is necessary to enable us to come to some definite conclusion as to the completeness of those machines in which human agency is employed in the handling of the work-piece.

In some machines the co-operation of the hand of the worker in the operations to be performed is, from their nature, essential. In the spinning-wheel, for instance, which is one of these, the

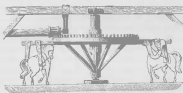


FIG. 356.

spinner has herself to regulate and carry out an important part of the form-change which the fibres undergo. Her hand becomes in this way an organ of the machine, in which it forms part of a very complex chaining controlled by the worker's will. A process takes place here, therefore, which corresponds entirely to that described above as occurring, for instance, in the grindstone. The spinning-wheel is driven by the worker's foot also, so that human agency has a twofold action in it. The grinder in Fig. 356 is doubly connected to the machine at which he works in the same way and for the same purposes.

With the sewing-machine the case is precisely similar. In some machines the one hand of the worker drives the mechanism while the other guides the work, in others both hands, often acting in a very complex manner, are required for the latter purpose.

The needle-grinder works at his stone as a part of a machine to which he does not himself give motion. He holds the needles between his fingers and thumb, moving them to and fro, and making them roll on his fingers at the same time in such a way that each needle receives its conoidal point as the envelope to its motion relatively to the grindstone. In modern factories this machinal work of the grinder is to a great extent done away with. The required motion of the needles is obtained by the use of a special mechanism and by giving a special form to the grindstone itself. For some purposes, too, sewing-machines are made entirely self-acting, being driven by power and having their work mechanically guided, and after long years of study the spinner has found her representative in the spinning-machine. None the less, however, must we regard the grindstone, sewing-machine and spinning-wheel as in themselves complete machines. It is possible to do definite work in all three without the direct intervention of man. The grindstone can polish pieces of cylinders, the sewing-machine can stitch straight strips of material, the spinning-wheel can twist and wind up the loose fibres presented to it. The man adds his own action as that of a machine controlled by will to that of the given mechanism; the living and the lifeless direct-actors together produce, necessarily, a far greater variety of work than was possible for the latter alone.

### § 135.

#### **The Principal Subdivisions of Complete Machines. Descriptive Analysis.**

Our examination in the preceding sections of the receptor, communicator and tool has shown us that it is no longer possible to regard these as representing the parts into which complete machines commonly divide themselves. We have found that each of them is absent from some series of cases, so that neither forms a general characteristic of the machine; and in the end our investigations carried us back once more to the closed kinematic chain, which alone we found to belong to every machine. It cannot be denied that when we stand before the machine itself this abstract idea seems bare and unsatisfactory,

and does not promise to be of much practical assistance in the work of the machine designer. But in every possible case, however complex, it is of the greatest importance to be able to lay hold clearly of the general underlying principle, and thus to recognise the cause of the non-success of certain combinations which have rested on a defiance of this principle, a destruction of the closure of the chain. The natural wish remains, however, to go beyond this general principle, and to determine at least the more important lines along which the development and application of the principle take place. The three old subdivisions have certainly been of some assistance in this respect, and it was in no way our intention in criticising them to oppose such a desire. But before we could meet it, it was necessary thoroughly to clear the ground, and obtain a rigid, logical basis upon which we could rest when we turned to more detailed matters. Now, however, that we have attained such a position, we may proceed to examine the distinguishing characteristics of certain parts, or groups of parts, which seem to serve very definite functions, within the machine itself.

Our investigation has shown, in the first place, that two parts appear distinctly as forming portions of the great majority of machines, which hitherto have been generally considered to be external to them—the driver and the work-piece. In the steam-engine we recognise the former at once in the driving column of steam;—the latter is less distinct, it may sometimes be the fly-wheel shaft, sometimes a toothed-wheel upon it, sometimes a belt. With the lathe the case is reversed, the work-piece we see directly, the driver is not so obvious. In general the driver is most easily recognised in the prime-mover, the work-piece in the direct-actor. This shows itself very distinctly in the names of the different machines, as steam-engine, gas-engine, water-wheel, &c., among the prime-movers, paper-machine, rivet-machine, &c. among the direct-actors. Thus in name, at least, if not in theory, driver and work-piece have been considered as parts of the machine.

We must also consider that mechanism in the machine which connects the required change of place or form, or both, in the driver with the similar changes in the work-piece, as forming one of its essential parts or groups of parts. We distinguish for instance the piston-engine from the steam re-action-wheel, the bucket-wheel from the turbine, the shingling-hammer

from the shingling rolls, and so on. We shall call the mechanism which plays this striking part in every machine its main or leading train. The names we have just cited show that in practice special importance has already attached to the mental separation of this train from the whole machine; indeed the establishment of the foregoing generalisation leads directly to this special distinction.

It is in the design of the leading train of a machine that we meet with those requirements which the old theory has attempted to satisfy by receptor and tool. If either or both of these exist at all they will form part of the main train, and can be treated by themselves if it be wished. I believe I may say that the practical mechanic has very seldom troubled himself about the exact determination of the receptor, while the whole construction of what we have called the main train flashes at once before him so soon as the name of the machine is pronounced. This makes it the more necessary that we should endeavour to ascertain theoretically what is included in this idea.

In our common direct-acting engine the leading-train is a ratchet-train, formed from piston and chamber with valves, and the slider-crank train  $(C''P\perp)_c^d$ . In a wharf crane of the usual kind the main-train is running-gear (p. 498) formed of the chain, barrel and spur-gearing; in a heckling machine it may be a pair of heckling rollers with their driving mechanism; in the spinning-machine it is the draw-frame and spindles and their driving mechanisms, and so on.

There are many machines in which we find, as in the one last mentioned, that the main-train consists of several parts, or that several main-trains are united, each acting at its own proper time. In some cases this action is periodic, and frequently also, where the leading train is single only, we find a periodic sequence of single changes of motion occurring, governed by special mechanisms. These mechanisms may be considered as forming a group by themselves. In many pressure-organ machines they are represented by the valve-gear, but as they occur in many other cases where there are no valves, we shall include them generally under the name of the director or directing-gear of the machine. The director is therefore the apparatus by which the motions of the machine are caused to succeed each other in their required order.

In the steam-engine above mentioned the directing-gear is simply the familiar mechanism by which the slide-valve is opened and closed at the right instant; in a planing machine driven by a rack the directing-gear determines the periodic reciprocation of the table; in the self-acting spinning machine the gear is a train of no little complexity, comprehending, as Stamm first showed theoretically,\* four different motions in succession, which he called *Sortie*, *Torsion*, *Depointage* and *Renvidage* respectively.

Within the directing-gear there is often an arrangement made to provide for bringing fresh portions of the material which forms the work-piece regularly under the action of the machine. In the carding engine a band of cloth with two feed-rollers is used for this purpose; in the cotton-preparing machine, combs or spiked rollers serve to supply the machine with raw cotton; in the mill feed-rollers are sometimes used to convey the grain regularly to the stones; in the needle-grinding machine a toothed-wheel gives the requisite feed to the needle-frame. In many machines, also, a similar arrangement exists for the purpose of bringing continually into action fresh portions of the driver. All these mechanisms we may include under the one head of feed or supply gear. The arrangements for moving the tool in planing-machines, lathes, drills, &c., as well as those for feeding boilers are examples of them.

For a purpose exactly opposite to that of the supply there is often another special arrangement added to the machine, an apparatus, namely, to remove the finished work-piece from the direct-actor. We may call this the delivery-gear; as examples of it we have the delivery tables in brick-making machines, the delivery drum (or in recent machines a more complicated arrangement) from which the prepared fleece is passed out of the carding-engine, the mechanism for shooting out the finished rivets from the die of the rivet-making machine, and so on. Supply and delivery form as it were the entrance and exit doors of the machine. Through the one the raw material enters the mechanism, through the other the finished manufacture leaves it. It is in connection with direct-actors chiefly that the construction of delivery-gear has been very fully developed.

Along with the director we find in very many complete machines a second mechanism, having special characteristics of its own,

\* Stamm, *Traité théorique . . . des Métiers à filer Automates*, &c., Paris, 1861.

and employed to control the passage of the driver or the work-piece through the machine, to regulate, that is, the quantity of the material of either of them employed per unit of time according to the requirements of each instant. We may call this the regulating-gear or regulator. While the director determines the sequence of the motions in the machine, the regulator determines their quantity. The various governors of prime-movers of course belong to this class of mechanisms; they regulate the motion or supply of the driving-organ and consequently the speed of the whole machine. In the Cornish engine the cataract is the regulator, in the working-gear of clocks escapements of various kinds fulfil the same function. There is also regulating-gear in very many direct-actors, as in the regulators of looms and paper-making machines. Escape-valves placed upon air, steam or gas-pipes also regulate the supply of the fluid by preventing its pressure ever increasing beyond a certain fixed amount.

It is sometimes required, most often in direct-actors, that the regulator should be able entirely to stop the action of the driver; as, for instance, when there is danger of any great irregularity occurring in the work produced by the machine. Regulating-gear acting in this particular way we may call stop-gear; it is made in very many forms. As illustrations of it we may mention;—the arrangements in the loom, which bring the machine to a stand if the weft thread does not pass; those which stop it if any one of its numerous threads break; the arrangements for shutting off the water from a hydraulic lift when the right height has been reached, and so on.

The regulator and the director are often very closely connected; in modern steam-engines, for example, the former (the governor) acts directly upon the latter (the valve-gear), and by means of it controls the motion of the driver (steam); it is always possible, however, to consider the two separately. When both of them or other sub-mechanisms exist special parts frequently (although not always) become necessary simply for the purpose of transmitting motion. This we may call the transmitting-gear, or more shortly the gearing of the machine. Gearing is also frequently inserted between a prime-mover and the direct-actors which it drives.



In complete machines then, apart from other secondary mechanisms, which can generally be placed without any forcing in one or other of the subdivisions which we have considered, we frequently find that besides their

#### Driver and Work-piece,

- (a) the main-train, in which receptor and tool may exist,
- (b) the director, with its subdivisions supply and delivery,
- (c) the regulator, with its subdivision stop-gear,
- (d) the gearing or transmitting-gear,

can be distinguished each as a distinct and separable mechanism. Their separation, which places before us the general purpose of the combination of mechanisms forming the machine, we may call the descriptive analysis of the machine.

The separation of machines into the two classes of form-changing and place-changing is often useful in considering their purpose as a whole, especially in those cases where the change affects the work-piece,—where it concerns the driver (§ 132) it is of less practical importance. It may therefore well find a place wherever machines are systematically treated. It must always be remembered, however, that the distinction is not an essential one, but strictly speaking a difference of degree only and not of kind. This fact makes it sometimes doubtful whether a machine belongs to the one or to the other class. In every case, however, it is according to the nature of its main-train that the machine is classed—an additional reason for examining the characteristics of this mechanism separately.

In the form of analysis which we have indicated in this section, we have rather developed and systematised a method not unfrequently made use of by practical men, and given it distinct form, than introduced a completely new idea. We often find machines explained from a point of view very nearly resembling ours. It appears to me altogether very desirable that this descriptive analysis should form the first part of the description of a machine. The complete or abstract analysis, examining its mechanisms in detail, can be added afterwards. In many cases this may be unnecessary; as, for instance, where the particular mechanisms have already been studied by themselves. Two things must always here be borne in mind;—first, that machines do not invariably divide themselves

into the separate trains we have enumerated, so that the existence of these is not necessary that a machine may be complete,—and, secondly, that (as already said) there may sometimes be employed in the machines arrangements for special purposes which do not fall exactly under any of the subdivisions spoken of.

### § 136.

## Examples of the Descriptive Analysis of Complete Machines.

It will be useful to give here a few examples of descriptive analysis, in order to show more distinctly by particular instances what the nature of the problem is, and how far its results extend. Let us first take a few prime-movers.

A breast-wheel used for driving a manufactory has for its main-train a mechanism of the formula  $(C'C_{\lambda} V_{\lambda})^c_b$ ,—as we found from § 62,—that is, a toothed-wheel having a liquid pressure-organ—guided (in the breast) by a portion of the frame which carries the wheel,—in place of a rack. The motion is continuous, the main-train is therefore a running train. The driver is the pressure-organ, water. Neither director nor supply exists; the work of the supply gear is performed in a physical or meteorological operation which furnishes continually fresh portions of driving material without any action of the part of the machine. A regulator may exist, as a governor acting on the sluice-valve.

Jonval turbine.—The main-train here also is running gear,—it is a screw-train with the place of the nut taken by the water which forms the driver of the machine. There is no director,—a regulator may be arranged as in the water-wheel. Stop-gear may be employed, as for instance in the turbines at Schaffhausen, where in case of one of the driving ropes breaking the regulator suddenly allows a sluice-valve to fall.

Steam-engine.—Let us examine a high-pressure engine such as is shown in outline in Fig. 360. Here, besides, the main-train we have both a director and regulator. The steam is the driver, the work-piece being the fly-wheel shaft.  $A$  is the main-train (in the form of a cylinder with suitable ports and piston, cross-head, connecting-rod, crank, shaft and frame),—a reversed and double-acting

ratchet-train (§ 126), formed from the train  $(C_2^*P^1)_2^2$  with the addition of a slide-valve. Steam is the ratchet, the piston the click-frame (the links  $a$  and  $c$  respectively in Figs. 352—355).  $B$ , the valve-gear, is the director, and consists of a train  $(C_2^*P^1)_2^2$  formed by the eccentric, eccentric-rod, slide-rod and frame. It drives the slide-valve, which is itself a combination of four separate valves, representing the ratchet-pawls—in the Corlius and

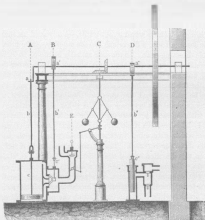


FIG. 350.

similar engines the four valves appear separately.  $C$  is the regulator, consisting of a common centrifugal governor (the kinematic constitution of which we must here leave unexamined), with a throttle-valve and gearing.

The feed-pump requires special notice. It might be considered as a machine by itself, for which the engine was the prime-mover, but if we assume that the engine has a boiler for itself alone we may treat the pump as forming a part of the engine. It would

then form that subdivision of the directing-gear which we have called the supply. The feeding apparatus is here a direct and single-acting ratchet train, consisting of the chain  $(C''P\perp)_a^d$  with suction and delivery-valves as ratchet- and click-pawls. These are raised and dropped at the right instants by the fluid ratchet, the water. The whole arrangement forms therefore a second ratchet train which differs from the leading train in being single-acting and in requiring no director. The latter peculiarity, however, we may neglect, for we could if we chose use a slide-valve worked by an eccentric instead of the automatic valves. In this case we should have in our machine two ratchet-trains,—a reversed ratchet-train for the leading train, a direct one for the supply,—both fitted with suitable directing-gear. In the case actually before us there are the additional differences that the one is single- and the other double-acting, and also that the pressure-organ is gaseous in the one and liquid in the other. These differences, however, we may suppose also to be removed, and the question then presents itself, why is the one ratchet-train reversed and the other direct, although both work with the same pressure-organ, the water passing through the boiler? This resolves itself into the general question of the conditions which determine whether a ratchet-train with directing gear be direct or reversed. The answer is, that it is direct if the effort in this direction exceed the resistance—reversed in the opposite case. The main train (the piston and its connections) receives from the column of steam a reversed motion (considered as a ratchet-train), because the effort of the steam exceeds the resistance at the crank; while the train constituting the pump is a direct one, because here the driving effort at the crank (the eccentric  $a''$ ) is greater than the resistance at the plunger.\* If at any time the mean resistance at the crank-pin becomes greater than the mean effort on the piston, the machine runs backwards, and the ratchet-train as such becomes a direct one, forcing first steam and then air drawn through the exhaust pipe through what had been the supply pipe. We have illustrations of this every day in the working of the locomotive.

The fact that the directing gear of the ratchet-train, as we have seen, possesses the property of acting either forwards or backwards

\* I hope to be able to treat this interesting question, and others directly connected with it, elsewhere more fully. —R.

according to the relation between the forces acting on the mechanism, allows the ratchet-gear to have that motion which running-gear has of itself. The director, that is to say, removes the monokinetic (cf. § 41) properties of the ratchet-train and so removes the difference existing between it and running-trains.

In order to stop the machine the steam-column is broken by means of the stop-valve *E*. This valve, with its box and fittings, forms a mechanism by itself, arranged to be worked by hand. It is the stop-gear of the engine, and so forms a part of the regulator. Taking the steam-engine as a whole then,—apart from keys, cocks and so on,—we find it to consist of a main-train, a director, a train for feed or supply, a self-acting and a hand-regulator,—five mechanisms in all.

Passing now to the direct-actors, let us take first a common wharf-crane with revolving platform. Such a machine has two leading-trains which can be worked by hand, independently of one another—the chain-drum with its pulleys and spur-gearing for raising the load, and another wheel-train for turning the platform. No director exists, but a regulator is provided in the brake by which weights can be lowered slowly. There is also a click-train used as stop-gear, for preventing any unintended descent of the load. It forms a part of the regulator, but is self-acting, in connection always with the first mentioned main-train.

A common clock with going and striking gear has also two main trains, one for moving the hands and the other for working the striking apparatus. As a rule each train has its own driver in the form of a weighted cord or sometimes a weighted loose pulley; they stand, however, in close kinematic connection. The going-gear is a compound spur-wheel train. Its motion is determined by a regulator, represented by the escapement and pendulum. We have already seen (§ 121) that escapements are ratchet-trains acting by the periodic disengagement of the clicks. The striking-wheel with its lever-train forms the director of the machine. For each twelfth of a revolution of the hour-wheel this directing gear may cause the hammer (for example) to strike once for the half-hour and to make one of a series of strikings (in arithmetical progression) for the hour. It is driven by the going-train, and its immediate action on the striking-train is the disengaging of a click which allows the hammer-train to work. In order that the latter may act uniformly,

a special regulator, in the form of a fly, is attached to the striking gear. The weight drums are connected to their spindles by running clicks, so that they may be moved backwards by hand in order to bring the weights once more into such a position that they can drive the machine. In reality these clicks are simply auxiliary mechanisms for the purpose of supplying the machine anew with its driving organ. There is lastly a lever which can be moved by hand so as to throw the striking-train in or out of gear; this lever with its connections form a directing-train moveable by hand. Summing up the different mechanisms which together form such a clock as we have described, we find them to be eight in number,—two main-trains, a self-acting director, a hand-director, two supply-trains worked by hand, and two regulating-trains;—five of them are automatic and the others arranged for being moved by hand.

A saw-frame, which we may suppose to be driven by a belt from some prime-mover, has its main-train in the crank and connecting-rod mechanism  $(C''_3P^1)_{\frac{d}{2}9}$  which drives the frame. The tool (the saw-blade) forms part of the block  $c$ ; the work-piece is the block or tree-trunk being sawn. The tool forms upon this its envelope, the saw-cut,—removing for this purpose those portions of material which are presented to it at each stroke. The motion of the work-piece by which this is done is effected by a ratchet-train driven from the crank-shaft and moving forward periodically the frame or table upon which the log rests. This train therefore forms the supply. The only regulator is the stop-gear, which enables the workman to place the driving-belt upon a loose pulley.

In the Jacquard loom there are two main-trains, the mechanisms for working the beam and the shuttle; the Jacquard mechanism itself forms a very complex directing-gear. There is also a supply-gear for moving the chain forward and a regulator (already mentioned) for the tension of the warp, and lastly one or more stopping arrangements.

The hydraulic ram, which we have had occasion to mention several times, forms a very easy subject for descriptive analysis. The head water  $HAB$ , Fig. 361, is the driver, while the prolongation,  $DE$ , of the same column, forms the work-piece, both being enclosed in suitable vessels. The main-train is a ratchet-train having two pawls in the valves  $K$  and  $D$ . There is no director, the air-vessel  $R$  forms a regulator.

The special feature of the ram, that the work-piece forms a portion of the driver, is to be found also in some other machines, as, for example, in the Chinese scoop-wheel mentioned in § 48 and other wheels resembling it, such as the *Noria* (§ 49), where the machine consists of a main-train (running-gear), having neither director nor regulator. The chains forming the basis of these machines have the wheel in one end, the wheel, the water and the piece forming the frame for the one end and the handle for the other.

Where the nature of a prime-mover is already known by analysis it is often possible to include it as a whole in the descriptive analysis without impairing the distinctness of the description. In a paddle-steamer, for instance, we may call the engine with its

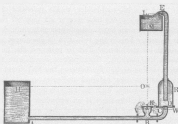


FIG. 191

paddle-wheels paired with the water the dead-end train; the rudder and its gearing form here a mechanism for guiding the motion of the whole, that is, a director; a self-acting regulator is seldom applied, there is commonly only one arrangement to which can be worked by hand as a stop-gear. The steam-engine itself has its own director and supply, as we have already seen.

The illustrations we have given are sufficient to show how our analysis can be used, and what results it gives. In most of the machines described it would have been useless to apply the old subdivision into receptor, communicator and tool. Any attempt to apply it to (say) the steam-engine, the clock or the loom shows at once that it is absolutely of no help to us. Indeed there has



never been any serious attempt made to analyse by it machines having any degree of complexity.

The view which our analyses have given us of the action of the hand in the operation of the machine is remarkable. We see that it occasionally takes part in the directing and regulating gear, and less frequently in the main-train itself,—and also that as each machine develops into more perfect forms both its director and its regulator are made automatic. Looked at historically, from Humphrey Potter, who invented a primitive form of self-acting valve-gear to save himself the trouble of working the valves of Newcomen's engine, to the engineer of an American river steamer, whose business it is to control three polished levers in an elegantly-furnished cabin; from the turner of sixty years ago, whose hand was his tool-holder, to his successor of to-day whose machines, once set, can take five or six cuts off the work-piece simultaneously; we have one phenomenon only, developed in different degrees. This is the reduction of the direct action of the worker with his machine, or, if it be preferred, the increase of automatism in the machine. This process began with the very origin of the machine itself. For between the first timid attempt of man to constrain two external bodies to execute some determinate relative motion, and the most complex production of modern machine-industry, there is an unbroken connection; the lines of development are faintly marked, but are continually increasing in distinctness, while they have always followed and still follow the same fundamental laws.

Those machines must therefore be considered the most nearly perfect or complete in which (as already mentioned in Chap. VI.) human agency is required only to start the machinal process and to cause it to cease. In general the progress in this direction is quite visible, while in some cases existing machines appear to have already arrived fairly within sight of this ultimate perfection.

### § 137.

## **The Relation of Machinery to Social Life.<sup>57</sup>**

From the general point of view to which our special investigations have once more brought us, one question seems so promi-

ment that it is hardly possible to avoid glancing at it. We have traced the growth of the machine from the primitive fire-drill to the Jacquard loom, and have seen to some extent the direction which its future development is likely to take. The growth of the machine has been simultaneous with that of the race; what has been the influence of the former upon the latter? The question is altogether of too wide and too general a nature to be treated here; it may be interesting, however, just to look at a few of the matters suggested by it which seem to be most directly connected with our investigations.

The present form of the industry of civilised nations dates from the introduction of the steam-engine. The ancients certainly carried on important and lucrative manufactures, but the methods of production were then essentially different from those with which we are familiar. They were in general based upon home-industry, each worker doing his own share of the whole at his own house, as is still the case among semi-civilised peoples. The germ of the modern factory appeared when the home-worker took assistants to work along with him. In the middle ages this system had already attained considerable proportions; and since the close of the last century, it has grown with increasing rapidity, until we now have huge factories, full of busy workmen and workwomen, in every part of the country. It is the steam-engine which supplies the driving energy in these factories; had we been still dependent upon the older motors—upon muscular force, or wind, or falling water—they would never have existed. It is easy to see how this prime-mover, once introduced, brought with it the rapid growth of machinery in general. Its influence made itself felt in both directions in which, as we have seen, the machine naturally grows (cf. § 51). It increased, on the one side, the force at our command; not only did it react upon itself, so that engines were made larger and more powerful, but the older hydraulic prime-movers also received new development from the ease with which they could now be constructed. It increased, on the other hand, the attainable variety of motions by removing all difficulties as to want of sufficient power for their execution. In this way it has become the parent of an immense number of direct-actors, and we owe to it, in very great measure, both the advantages and the drawbacks of our modern industrial life.

In the great majority of cases the change from the old to the new industry has taken the form of a concentration of isolated workers and work-places. This is naturally noticed most of all in connection with those productions which possessed an importance before the time of the steam-engine which they have since retained, and in none more than in textile industry. Here the results of the change cannot be said to be in every respect advantageous. The home-worker, the small master, has all but disappeared. This in itself may be in many instances a cause for regret. But with him has also disappeared much of his individual skill. The work in the factory does not call for the possession nor allow of the employment of that personal skill which was required and shown by the old home and hand-worker, and the skill therefore no longer exists, at least in these industries. The breaking up of home life, too, which is involved in the factory-system is a matter having many possible drawbacks; it has already called for public attention more than once, and may do so still more pressingly in the future.

It is in connection with the future of these industries that the construction of small, cheap prime-movers becomes a matter of special importance. The direct-actors are every day being made better and less expensive,—but it is at the same time found that the prime-mover works the more economically the larger it is. For factories, therefore, one huge, expensive but economical engine drives an immense number of small direct-actors, and in this way only can the goods be made cheaply enough for the market. I believe that in many places and circumstances it would be an advantage if the home-industry could be placed in a position to compete with the factory-work. This can only be brought about when it becomes possible for the workman who has a little money at his disposal to buy a small and cheap prime-mover which is at the same time economical, to drive the two or three direct-actors which he may be able to possess. It is in this direction that I look for a future for the gas-engine, which has lately been brought into practical shape, and perhaps also for small hydraulic motors and hot-air engines.

But there are many industries,—the manufacture of engines and machinery for instance,—in which the drawbacks I have mentioned do not appear, or appear in a less distinct form, while in others

the influence of the introduction of machinery has been almost altogether good. This is the case especially in those industries where the work in its own nature is disagreeable, unhealthy or even degrading. In mining operations, for instance, we can look forward with unmixed pleasure to the substitution of machine labour for much of the work of the colliers, and to the consequent amelioration of the sad social conditions so often associated with their work.

It is remarkable, also, that the place-changing machines, as distinguished from the form-changing machines, have had an influence upon social life which is almost entirely favourable. Railways, steamers, cranes have only to be named to make this recognised. The work of those connected with them may be hard, but it is as a rule healthy, while it demands every day more and not less skill and knowledge on the part of the workman. Of the good which the State as a whole derives from them it is unnecessary to speak.

There is one other characteristic of modern industry as affected by the growth of the machine to which I may direct attention. This is the substitution for manufacture of what I have elsewhere called *machinofacture*.\* The two differ essentially in degree only, but the difference is so marked as to thrust itself upon our notice. This *machinofacture* appears especially in those cases where many machines have to be made from the same model, or from a limited number of forms in different combinations. In gun-making or in waggon-making, for instance, it has done extraordinary things, and in many other departments, locomotive building among them, it is making rapid progress. We have to thank it, too, for the spread everywhere of cheap and well-made sewing-machines. Reacting upon its source, the growth of *machinofacture* is accompanied by an increase in a variety and capacity of direct-actors, that is, especially, in the varieties of constrained motion at our command.

The wonderfully quick development of *machinofacture* which has taken place within the last few years must be ascribed in great measure to the particular direction in which the ideas of inventors have turned, and especially to the fact that they have given up the attempt to copy the operations of the hand or of nature in

\* *Offizielle Bericht über die Pariser Welt-ausstellung, 1867. p. 401, et seq.*

the machine, and have tried to make the latter solve each problem in its own way, a way often very different from that of nature. Attempts were made for many years to construct a sewing-machine which should produce work exactly the same as hand-stitching, but they always resulted in failure. As soon as this idea was completely discarded, and a new form of stitch specially adapted for the machine was looked for, the spell was broken, and very shortly the sewing-machine appeared. It is the rolling-mill, which works in a way so greatly differing from the time-honoured operations of the smithy, that has been the special means of developing the manufacture of malleable iron. The attempt to imitate nature in the machine rests upon an altogether mistaken idea, and it was when this was entirely thrown overboard that machine development received the impetus under which it is still making such rapid progress.