CHAPTER XI.

ANALYSIS OF THE CONSTRUCTIVE ELEMENTS OF MACHINERY.

§ 106.

The Machine as a Combination of Constructive Elements.

HAVING in the foregoing chapters considered the nature of the mechanisms of which machines consist, we must now proceed to examine the separate pieces by the combination of which they are actually constructed. Although this may appear at first sight a return to matters already investigated, it is in reality another step forwards upon the road which we have already marked out for ourselves. For it is to a certain extent more difficult to understand the machine in the form in which it actually stands before us than to comprehend the abstract representations by which, so far, we have replaced its constructive complexity. It was necessary that our general notions as to its essential nature should be made distinct, partly indeed re-made, before we could attempt to systematise the complex forms of its single pieces, or distinguish between their fundamental and accidental properties. This problem is indeed by no means a simple one; we shall not wonder, when we have arrived at its full solution, that it has required such long and careful preparation. It was only when chemical science had reached a very advanced stage that it attempted to decompose materials supposed to be elementary; and similarly it has been necessary that kinematic science should be cleared of many erroneous prejudices before it could attempt to analyse the separate pieces from which the machine is formed in the workshop, and make their nature really intelligible.

Wherever the designing of machinery has been made a systematic study, it has to a certain extent been recognised that the machine consists of only a limited number of different parts occurring in it over and over again. Different writers have given to these different names, such as "details," "elements," "simple-parts," etc.; I myself have for many years called them the "constructive elements," (*bauliche elemente*) of machinery.

The constructive elements have formed the subject of many text-books.[54] In these, however, it has not been proposed that this subdivision should be taken absolutely, or indeed without very considerable limitation. It is not assumed, as in the case of the "simple machines," that all machines are simply combinations of these "elements," but only that the latter occur with special frequency in machine construction. Some idea of this sort has always existed below the surface; the want of exact ideas as to the nature of the machine has, however, prevented its clear enunciation, so that as the art of machine construction has advanced there has been a somewhat suspicious uncertainty as to which and what these "elements" were. Neither a very clear enumeration nor satisfactory definitions of them have been given. Only by instinct, as it were, their number has been more or less distinctly limited; or at least they have in general been treated as if some such limitation did exist.

The following enumeration of constructive elements therefore makes no pretension to absolute completeness. It is simply a list of those parts which different writers on machine design have included under the head of constructive elements, or some equivalent title, and fairly represents the details supposed usually to belong to that class. These are considered to be:—

Screws and screwed joints,
Keys, cutters, gibs, and keyed joints generally,
Rivets and riveted joints,
Plummer blocks, bearings, pedestals,

Pins,
Shafts, axles and spindles,
Couplings,
Framing, bed-plates, brackets &c.
Belts, cords and ropes,
Chains and their connections,
Friction-wheels,
Belt pullies and gear,
Rope pullies and gear,
Toothed-wheels,
Chain-wheels,
Fly-wheels,
Levers,
Cranks,
Connecting-rods, couplers,
Crossheads and guides,
Click and ratchet-wheels and gear,
Brake-wheels and gear,
Pipes and their connections,
Steam and pump cylinders,
Valves,
Pistons and stuffing boxes,
Springs.

In addition to these parts, all of which have very numerous applications, there are others which come into use only in single classes of machinery, spinning and weaving machines, machines for working in metal, etc., but are still employed often enough to have been sometimes included with those above mentioned. By a distinction which appears quite justifiable they have occasionally been called "special" parts as distinct from the above "general" ones. Without giving any illustrations of this second class of constructive elements we shall proceed to consider the first in order. We shall endeavour first to ascertain precisely the kinematic meaning of each, and shall afterwards see how far we can find any general kinematic connection between the whole.

§ 107.

Screws and Screwed Joints.

In the common screw and nut, Fig. 288, we at once recognise the twisting pair (S) or $S^{+}_{=}S^{-}$, and we can do the same in some other applications of the screw where, as in the screw-joint, Fig. 289, the nut and screw are themselves parts of the two elements to be united.

The case of the common screw-joint, of which Fig. 290 gives a familiar illustration, is, however, a different one. Here we have a combination of four pieces, a, b, b_1 and c, the object of the whole being the rigid connection of b_1 with c. We see at once that the screw b is prevented from turning relatively to the piece b_1 by the prismatic form given to its neck (cf. § 19), so that as regards rotation b and b_1 form one piece. If the nut a be turned upon the screw, the head of the bolt is brought up to bear upon the piece b_1. This is brought about by the use of the pair (S), that is to say (as we before expressed it, § 47), by pair-closure. Thus the relative turning of b and b_1 is prevented by suitable restraining profiles, and their relative sliding by pair-closure; the two parts therefore form kinematically, a single piece.

Fig. [illegible]

Fig. [illegible]

Fig. [illegible]

So far as our engraving goes the piece c can turn relatively to b. In the machine itself, however, such a motion is prevented either by the use of a second screw parallel to the first, or by some other means, and the only motion possible to c before the nut is screwed down is translation in the direction of the axis of b. In other words c is paired with $b\,b_1$ by means of a prism parallel to the axis of b; c and $b\,b_1$ form therefore a sliding pair. In reality, therefore, the piece $b\,b_1$ contains two kinematic elements, rigidly connected, a screw S^+ and a prism P^+ parallel to the screw.

The nut a also consists of two kinematic elements, the hollow screw S^- and the plane cone which forms its under surface and rests upon, or more correctly is paired with, c. This surface is not necessarily plane, its general condition is that it must belong to a revolute conaxial with the screw. The pair of revolutes, or turning pair, thus formed by a and c is incomplete, and there pair-closed. This, however, is accidental; essentially the piece a consists of an element S^- having conaxial to it a revolute R, the partner element of which belongs to the piece c.

The last-named piece also consists here of two elements, namely, the above-mentioned prism, paired with that upon $b\,b_1$, and this revolute having its parallel to that of the prism.

The result of our examination is, therefore, that this screw fastening is a kinematic chain of three links, formed from the pairs (S), (R) and (P). If we write its formula in full, disregarding (for the sake of simplicity) the incompleteness of (R) and further replacing (R) by (C) as we know to be possible from § 57, it will run as follows :—

$$\overbrace{C^- \ldots | \ldots S^{-}_{=}}^{a}\ \overbrace{S^+ \ldots \| \ldots P^{-}_{=}}^{b}\ \overbrace{P^+ \ldots \| \ldots C^{+}_{=}}^{c}$$

which we may also write, inverting the lower pairs, and noticing that here there is no difference between | and ||;—

$$\overbrace{C^+ \ldots | \ldots S^{\pm}_{=}}^{a}\ \overbrace{S^- \ldots | \ldots P^{\pm}_{=}}^{b}\ \overbrace{P^- \ldots | \ldots C^{-}_{=}}^{c}$$

and in this we recognise a chain, Fig. 291, which we have already examined. We may use $(S'\,P'\,C')$ for its contracted formula. If we consider the link b as fixed, and a as the driving-link, the special formula of the mechanism is $(S'P'\,C')^{b}_{a}$.

In the applications of the screw-pair to cause rectilinear motion, as in the lathe, or to exert pressure, as in the screw-press, these three links are very distinct, arranged in the first case as $(S'P'C')^{c}_{a}$, in the latter mostly as $(S'P'\,C')^{b}_{a}$. The form of chain shown in Fig. 291 is also very frequently met with in screwed joints, as, for example, in the "tapped bolts" or "set-screws" of Fig. 292. We also find various methods used in joining b and b_1, as, *e.g.*, the key shown in Fig. 293. In screwed joints, however, of whatever form, we always find that the pair $S^{\pm}_{=}S^-$ occurs as part of the chain $(S'\,P'\,C')$.

The action of this chain in different cases varies very much. In the screw-press or the screw-cutting lathe, with which in certain respects the screw-joint might be compared, it is simply used like any other kinematic chain. In the screw-fastening this is also, strictly speaking, the case, but only within such very narrow limits as are allowed by the compressibility of the pieces b and c, beyond these limits it is not used kinematically. When the machine itself is complete, the screw-joint is no longer used as a kinematic chain; it therefore does not appear in the kinematic formula of the machine. It has been employed as a chain for a temporary purpose only, in order, namely, so to connect two or more pieces that they may be treated as a single body, a purpose for which it is often employed also in structures which are not machines. Such a screw fastening, therefore, as is used for a cylinder cover, or to hold down a plummer-block, has not a machinal but a constructive function in the machine. Its object is to make that connection which we indicate in our formula by the dotted line ...., in other words it serves to form the links of a kinematic chain.

FIG. 291.

FIG. 292

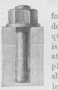


FIG. 293.

Kinematically, therefore, its form is indifferent so long as it does not interfere with the required motions of the links; it is regulated chiefly by considerations of strength. This explains the immense variety of shapes in which screw fastenings occur; the constructive conditions of all are, however, expressed by the formula which we have given above.

We shall have an opportunity of returning to some special forms of screw-joints, safety or locking screws, further on.

§ 108.

Keys, Cutters, &c., and Keyed Joints.

We have already seen (§ 64) that the key * is not a kinematic element in our sense of the word, but that it consists of two prismatic elements, and in its most common application forms a link of a three-linked kinematic chain. This chain, represented by Fig. 294, has the formula:

$$\overset{a}{\overline{P^{+} \ldots \angle \ldots (P)}} \; \overset{b}{\overline{\ldots \angle \ldots (P)}} \; \overset{c}{\overline{\ldots \angle \ldots P^{-}}}$$

* I use the word universally employed in this connection by engineers, instead of wedge.

for which we have used the contracted expression $(P_3^{\perp})$. The keyed joints occurring in machines have indeed always this form, neglecting the occasional force- or pair-closure of incomplete pairs.

The familiar case of the keying of a wheel upon a shaft, Fig. 295, shows all three links, *a*, *b* and *c*. The prism pairs 1 and

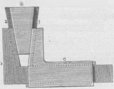


FIG. 294.

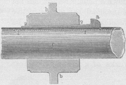


FIG. 295.

2 can be at once recognised, each one incomplete in itself but closed by the other. The pair 3 is omitted, but the wheel, which is to be moved by the key only in a direction perpendicular to the axis of *c*, is prevented by force-closure from moving in any other direction.

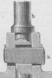


FIG. 296.

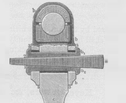


FIG. 297.

In the case of a round bar keyed into a socket, Fig. 296, we find all three links and all three pairs. The pairs 1 and 2 are at the under and upper surfaces of the key, and the pair 3 appears in the cylindric surfaces of *b* and *c* as well as the sides of the openings in *c* through which the key passes. It is these which make the cylinder into a prism pair. In a "gib and cutter" joint such as is shown in Fig. 297, the pair 3 is complete, but 1 and 2 are incomplete. The gibs b_1 and b_2 are kinematically parts of the rod c and the strap b respectively.

Keyed joints are therefore in general, as we see from these examples, three-linked kinematic chains, which however, like those considered in the last section, have not a kinematic function in the machine, but serve simply to form links. We do, however, frequently find the chain (P_{5}^{c}) used in the machine just as the screw-joint chain $(S'P'C')$ is also used, for effecting motion or exerting pressure, but in these cases it is a mechanism, and does not fall to be considered under the head of constructive elements.

§ 109

Rivets and Riveting, Forced or Strained Joints.

A single rivet joining two plates (Fig. 298) might be regarded as a cylinder-pair $C_{-}^{+}C^{-}$, the rivet being supposed to be fixed to one of the plates. The latter would then form the elements of a turning pair, and their relative motion would be simple rotation. Rivets are in practice sometimes used in this way, as for instance in flat-linked chains; but such constructions generally come under the head of pins rather than of rivets, and will therefore be considered in the next section. By

FIG. 298

a riveted fastening we rather understand one in which more than one rivet is used, and in which no relative motion whatever is permitted to the pieces riveted together. The rivets receive their form by hammering while in a more or less plastic condition, and do not in themselves possess the fundamental characteristics of kinematic elements. As constructive elements they serve, like screws and keys, for the formation of kinematic links. They are most frequently used (as my readers know) in boilers and reservoirs of different kinds, in the formation, that is, of the vessels V^- used for the enclosure of a liquid or gaseous pressure organs.

A very important part of the action of rivets in pressing together the bodies which they unite is due to the shrinkage or contraction of the rivet as it cools. The same phenomenon is utilized largely in other forms of fastening, and especially in the process of "shrinking" rings of metal over bodies which it is desired to strengthen or unite. The rings are put on their place hot, and of course exert an enormous pressure when they contract in cooling. The same result has of late years been obtained by pressure merely, without previous heating, and in many very important cases this is superseding the older process, in fixing railway carriage wheels on their axles for instance, and in securing the cranks and crank-pins of locomotives, etc. Looked at as a whole the two processes lie very near each other, the latter might almost be called cold riveting. We shall therefore not look at them as distinct, but shall include them both under the name of forced or strained joints.

Kinematically, strained joints represent fastenings of a kind which may be regarded as cylinder or prism pairs, (C) or (P), in which the elements are so closely pressed together that as regards the action of any ordinary forces they form one body only, and which therefore serve for the formation of kinematic links. This close union of the elements is effected essentially by the friction produced by the straining pressure. We shall have occasion once more to return to this point.

§ 110.

Pins, Axles, Shafts, Spindles.

A pin considered kinematically forms one element of the pair $C\underline{+}C^-$; it is the element C^+, or more strictly R^+ if we use the more general symbol (R) instead of (C). The pin and its bearing, the combinations of elements $R\underline{+}R^-$, may be considered the most common pair of elements; it occurs in almost every kinematic chain, in large and small dimensions, under light and under heavy pressures, moving slowly and moving rapidly. We shall return to the element R^- in § 112.

Axles are pins joined conaxially; that is, kinematic links of the form $C^+ \ldots | \ldots C^+$. The word axle is used specially in those cases where the forces to be resisted tend chiefly to bend the link.

Shafts are also links of the form $C^+ \ldots | \ldots C^+$. They are therefore kinematically identical with the axles, but the name shaft is used specially in those cases where torsion is the force chiefly acting.

[The word spindle is in many parts of this country used for small shafts].

The kinematic position of these three familiar constructive elements in the machine is therefore very distinct.

§ 111

Couplings.

Under the name of couplings are included a number of constructions by which the motion of one shaft can be transmitted to another. Their kinematic position is not quite such a simple matter as that of the pieces hitherto considered, on account of the very different arrangements which have received and are known by the name of coupling. Toothed-wheels, friction-wheels and wheel-gear generally, although used for the purpose of transmitting the rotation of one shaft to another, do not receive the name of coupling, but frequently enough couplings are trains containing several links. We may perhaps define a shaft coupling as an apparatus which transmits from one shaft to another equal numbers of revolutions in equal times and in similar directions without the use of wheel-gearing. The definition is certainly not a very sharp one, but it seems entirely to cover what is usually meant by a coupling.

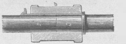


Fig. 299.

Couplings may be divided into fixed, moveable, and loose, the latter being in most cases known as clutches. We shall here consider the first two classes only, returning to the last in § 123.

Fixed couplings join two shafts in such a way that they may be treated as a single body. They are fastened with screws, or with keys, or with both ; indeed there is nothing in principle to prevent their being fastened by rivets. Fig. 299 shows what is known as a muff-coupling, in which the three links and pairs of the chain (P_3^L) will easily be recognized. The flange-coupling, Fig. 300 is a combination of two keyed fastenings with a multiple screw-joint. Other fixed couplings show still further combinations. Their real function in every case is the formation of kinematic links, these links having the form $C^{+} \ldots | \ldots C^{+}$

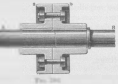


Fig. 300.

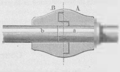


Fig. 301.

Moveable couplings subdivide themselves into those which are moveable axially, radially, and angularly. Sharp's claw coupling, Fig. 301, is an illustration of the first kind. It is formed as a prism pair $P^{+}_{=}P^{-}$, for the claws of the piece A and B are prismatic, and are so formed that a relative motion can take place between them only in the direction of the axis of the shafts a and b. We may suppose the pieces A and B to be connected to a and b by key fastenings.*

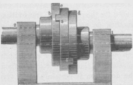


Fig. 302.

Oldham's coupling, Fig. 302, is one which is moveable radially. We have already examined this mechanism fully (§ 72), and have found it to be a turning cross-block, having the special formula $(C''_{2} P^{\perp}_{2})^{a}_{b}$.

The universal joint, Fig. 303, is an example of a coupling having angular motion. We have in our earlier investigations repeatedly spoken of this train, and in § 62 pointed out that it was a conic turning cross-block $(C^{\perp}_{3} C^{\angle})^{a}_{b}$. It must not be forgotten that the link $C^{-} \ldots \angle \ldots C^{-}$ is omitted from our figure, as is usually the case in representations of the joint.

These examples are sufficient to show that in the moveable

* This coupling is not intended for use as a clutch, but for allowing a or b to move axially without disturbing the transmission of rotation

couplings we have partly pairs of elements and partly complete mechanisms or portions of them, and that it is possible for the

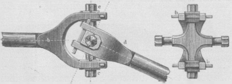


Fig. 303.

individual links of the latter themselves to consist of several pieces united by screwed or keyed joints.

§ 112.

Plummer Blocks, Bedplates, Brackets and Framing.

The plummer-block or pedestal makes, along with the spindle or shaft C^{+}, the pair of elements $C^{\pm}_{-}C$; it is therefore itself the single kinematic element C^{-}. In its actual construction many varieties of screwed and keyed joints and other such auxiliary mechanisms are used, partly to unite the separate pieces of which it consists (*i.e.* to form links), and partly to facilitate lubrication and cleaning. In neither case therefore do they appear in its (principal) kinematic formula.

In the bed-plate which carries the plummer-blocks we have simply the fixed link or frame of a kinematic chain, arranged so that the elements C^{-} or C^{+} may be connected to it by suitable fastenings, or made in one piece with it. Fig. 304 shows a bed-plate for the two parallel shafts A and B. If we imagine the two plummer-blocks to be in their places we have in the whole simply the constructive form of the frame $C^{-} \ldots \| \ldots C^{-}$, Fig. 305

A bed-plate for two shafts at right angles to each other, Fig. 306, such as is frequently required for turbines, is (with its two plummer-blocks) equivalent kinematically to the frame, $C^{-} \ldots \perp \ldots C^{-}$ in

Fig. 307, ort bearing in mind the invertibility of the lower pairs, to the piece C^+. $\perp$.. C^+ in Fig.t308. Brasses, tscrews, cover, bolts and so on serve only to complete constructively the element C^- and tot secure it to the floor ort building. Thet compound bed-plate

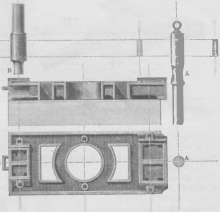


Fig. 309.

Fig. 309 may be represented (always supposing the addition of the plummer blocks) by the four elements C of the frame shown in Fig. 310.

Fig. 310.

In the design of any machinetit is very advantageous to begin by representing in this way the simple kinematic forms which form the basis of the framing, bed-plates, brackets and structures which connectthem,beforeaproceedingwiththeadesign.a Thisawillagreatly help the designer in realising his problem in an abstract form, and

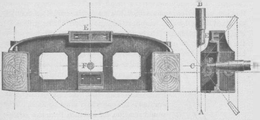


FIG. 306.

FIG. 307.

FIG. 308.

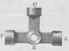


FIG 310.

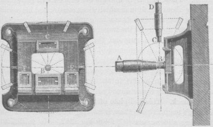


FIG. 309.

the result will be shown in the increased simplicity and excellence of his work. Theafirst step inathisadirectionais generally to grasp firmly and carry with us the apparently elementaryanotion that the fixed part of the machine is really a portion of its kinematic linkage. Itais onlyatooeasyto forget that the masonry, timber, flooring, and so on, upon which the pedestals, guides or framing areafixed,have by that very factabecome a link of the kinematic chain of aamachine. I have alreadyaremarked (§ 58) how often the fixed link is omitted from engravings. Unquestionably this omission has arisen from indistinctness as to its nature, and itreacts in a similaradirectionauponathoseaforwhose usetheaengravingahasabeenamade. Thereais nothing whatever to help the latter to realisea thea facta thata thea importanta link omittedistheone whichamustbeafixed. Who wouldaimagine,aforinstance,fromthe accompanyingafigureaof anaoscillatingaengine,ataken from a modernkinematic text-book, that the bearings A and B mustbearigidlyconnected? Theyareaapparently quitewithoutaconnection of any kind. Theaexample I have givenais, however,aonlyoneaamongmany. We cannot be surprised, therefore, that this connection has oftenbeen carried out incompletely in actual machine construction. Those engineers who are old enough will remember the noisemadeaboutthea forminwhich Penn constructed hisaoscillating marine engines, simply because he employed cross-shaped frames to give special rigidity to theaframeofhis machine. Andyet Penn did nothing more than carry out the simple requirement which we recognised at the verybeginningaofour investigations, as belonging toathatlinkof theakinematic chain

Fig. 311

Weasee an exactlyasimilarimprovementanowabeingcarriedaout in the horizontal steam-engine, in the introduction (in America first) of a straightaheavyframeadirectlyconnecting theacylinderaandthe plummer-block. Thisbed-plateaof the Corliss and Allen engine, ofaTangye'senginesaandothersis nothing else thanthe frame d of our turningaslider-crank $(C_3'' P^{\perp})^d$ Fig. 312. It is difficult to believeathatthisspecialform of construction has been soarecently introduced that the "improvement" embodied in it is still more or less a subject of remark while it seemed to develop itself as aamatterofacourse from our first propositions. But theawayin which these matters have hitherto been looked at has made many things appear simple and self-explanatory which in reality are complex and require proof, while others have been considered specially remarkable which are only conclusions directly deducible from definite propositions. In the latter circumstance we can recognise the power we possess in having at our command an exact logical system.

Many other examples could be mentioned, which show, like those cited, the want of a distinct perception of the function of

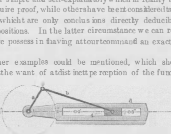


Fig. 312.

those parts of machines and structures of which we have been speaking. Redtenbacher's attempt to treat those machines in which the frames are in one piece as a class by themselves seems to have been due to the same cause.* We have seen that the right treatment of the problem is very simple and intelligible, and does not indicate the existence of any such separation—it will not, therefore, be well to perpetuate it.

§ 113.

Ropes, Belts, and Chains.

We have already found (§ 41) that ropes, belts and chains are kinematic elements. They are the tension-organs $T_{\pm}$, T_p and T_r. If they are so used that by the help of hooks, screws, rivets, etc., they are either made endless (that is, returning upon themselves), or are united with other bodies, they represent links of certain kinematic chains which we shall consider in the next paragraph. The flat-link chains are essentially combinations of numerous kinematic links each of the form $C^+ \ldots \| \ldots C^-$, the closure of the whole being effected by the insertion of a frame between the chain-wheels.

* Redtenbacher gave these the name of *Möbel-maschinen*.

§ 114

Friction-wheels; Belt and Rope-gearing.

Friction-wheels are kinematic elements in force-closed pairs. Two corresponding wheels, such as those of Fig. 313, arranged so as to work in gear with each other, form a higher pair of elements of the form R^+, R^+ or R^+, R^-.

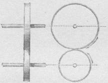


Fig. 313.

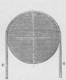


Fig. 314.

A pulley which guides a cord or belt, or by its rotation sets such an organ into motion, forms with it the pair $R^+, T^\pm$, as in Fig. 314. Two such pairs (which are, as we know, force-closed), when suitably united, give us the belt- or rope-train (as the case may be) shown in

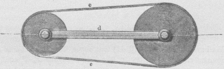


Fig. 315.

Fig. 315, if the shafts of the pullies and the connecting frame be added (cf. § 44). The single rope-wheel or belt-pulley or drum forms with its shaft a link of the chain represented in the figure, the "endless" tension organ being itself another link.

§ 115

Toothed-wheels, Chain-wheels.

Toothed wheels are links of the chain $(R_z C''_2)$, of which an example is furnished by the spur-train of Fig. 316. The framing carrying the plummer-blocks takes the place (§ 112) of the straight

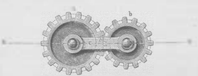


Fig. 316.

Fig. 317.

link c. If a toothed wheel be geared with a chain we obtain the pair R_z, $T\frac{+}{z}$ (Fig. 323). A suitable combination of such pairs gives us chain-wheel gearing.

§ 116.

Flywheels.

We have already had an opportunity (§145) of examining the kinematic meaning of fly-wheels. They are heavy bodies formed as revolutes, and attached to links of the form $C^{+} \ldots | \ldots C^{+}$ in order either to carry the machine over its dead points by their momentum, or to make its motion more uniform. They do not demand any special symbolic indication as links or elements, for our notation is not concerned with the masses of the parts it represents.

§ 117.

Levers, Cranks, Connecting-rods.

Levers, whether simple or compound, are kinematic links furnished with pins about which they can swing (see p. 284). The simple lever is one like the link c of the chain (C''_4), of which the formula is $C^+ \ldots \| \ldots C^+$. The compound lever is a compound link formed from the simple one, such, for example, as is represented by the formula

$$C^+ \ldots \| . \begin{cases} \ldots C^+ \\ \ldots C^+ \end{cases}.$$

The crank is also a link of the form $C^+ \ldots \| \ldots C^+$, but is so arranged that it can turn completely round its pin or shaft; it corresponds exactly, that is, to the link a of the chain (C''_4) or $(C''_3 P^{\perp})$. The connecting-rod, lastly, is also a link formed of two cylindric elements, generally in the form $C^- \ldots \| \ldots C^-$. It corresponds to the coupler b in the trains $(C_4)^d$ and $(C''_3 P^{\perp})^d$. In its kinematic form, therefore, it does not differ from the bedplate Fig. 304 in § 12.

We have here, therefore, a series of links before us, which while they are constructively very different, are kinematically precisely similar, and owe their different characteristics entirely to their position in the chain. The compound lever, too, is exactly similar to the compound bedplate (§ 112) in which the element C is used in precisely the same relative positions.

§ 118.

Crossheads and Guides.

The common crosshead is simply the link c, the "block," of the chain $(C''_3 P^{\perp})$. It has the formula $C \ldots \perp \ldots P$. The guides in which it works are formed in many different ways. They constitute the element of the pair 4 which is carried by the frame d in the train $(C''_3 P^{\perp})^d$, Fig. 318, and generally have the form P^-, although sometimes they are also made P^+. This prism is shown in the slide-bars $D\,D$ of Fig. 319, where also C is the crosshead,—the block c of Fig. 318. As a matter of history the crosshead has passed through an unusually large number of changes of form, which show of what careful study it has been the subject. The

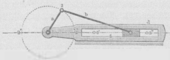


FIG. 318.

production of an exact rectilinear motion in a given mechanism—a matter which at first sight appears so simple—is a problem which for a long period remained without a practical solution.*

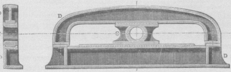


FIG. 319.

We have now seen that the crank, the connecting-rod, the crosshead, the guide bars (including with them the crank shaft bearing), and the lever are in fact all the links of the crank trains $(C''_3P^{\perp})^d$ and $(C''_4)^d$.

§ 119.

Click Wheels † and Gear.

The exact treatment of click- or catch-gear leads to very complex and many-sided problems. We cannot attempt to treat these

* Cf. end of § 3.

† For the purposes of Prof. Reuleaux's work it has been necessary to distinguish between two classes of ratchet gear, that, namely, in which the pawl or click acts merely to prevent mot[illegible], and that in which it is used to d[illegible]ve the wheel or [illegible] I propose to call the first class click-gear, and to use the common name of ratchet-[illegible] only [illegible] portan[illegible]

exhaustively, but must here content ourselves by looking at a few of the more important cases which occur.

Among the numerous forms in which click-gear is used the most common is that of a toothed wheel provided with a click or pawl, Figs. 320 and 321. The train consists, in both the cases shown, of three links—viz. the wheel $a = C \ldots | \ldots C_z$, the click $b = Z \ldots | \ldots C$, and the frame $c = C \ldots \| \ldots C$; we shall suppose this

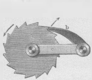


Fig. 320.

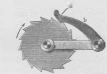


Fig. 321.

last to be the fixed link. The tooth Z, the working end of the pawl, lies force-closed (as we have already pointed out, p. 180) in the spaces of the wheel a, the catch being held down either by a spring or by its own weight. It must also be remarked that b is kinematically paired with a only for one direction of rotation, left-handed rotation in Fig. 320 and right-handed in Fig. 321. If any turning commence in the opposite direction the wheel is at once held fast by the click, so that the whole mechanism becomes equivalent to a single piece.

At first sight it might appear that the difference between the two trains was constructive only, the pawl being formed to resist pressure in the first case and tension in the second. If, however, the direction of the arrows shown upon the figures be noticed, it will be seen that in the first case the turning of the wheel and click, if the former be set in motion, takes place in opposite directions, while in the second case it occurs in similar directions. Between the pressure or push-click and the wheel there is thus the same relation as between externally toothed wheels, between the tension or pull-click and the wheel the same as between an annular-wheel and a spur-wheel. We may therefore use the symbol Z^+ for the tooth of the pressure-click, and Z^- for that of the tension-click.

A second property of the gear which must be indicated by our notation is the single action of the click-wheel. We may show this by substituting a semi-colon for the comma between C_z and Z. With the addition of the sign for force-closure the pair will therefore be written $C_z ; \frac{Z^+}{f}$ or $C_z ; \frac{Z^-}{f}$. The point may be taken to denote the immoveability of the chain in one direction, the comma showing that it is moveable in the other.

Placing the chain on c, its complete formula will be therefore

$$\overbrace{C^+ \ldots \| \ldots C_z ;}^{a}\ \overbrace{Z \ldots \| \ldots C^\pm}^{b}\ \overbrace{C^- \ldots \| \ldots C^{\pm}_{=}}^{c}.$$

The form symbol for Z has been here omitted in order to make the expression more general. The sign for forceclosure is also omitted; it can usually be dispensed with—the unusual nature of the pair being sufficiently pointed out by the semicolon. The latter, indeed, makes it possible for us to use a single element symbol only for the pair $C_z ; Z$, for we shall indicate it quite sufficiently if we take $C_z ; Z, = (C_z ;)$. This contracted form is also justified by the analogy of (C_z) for the spur-wheel pair C_z, C_z —for we may consider the pawl $C \ldots \| \ldots Z$ essentially as a piece of a spur-wheel, carrying a single tooth.

The rack click-gear of Fig. 322, with fixed frame, would have for its extended formula:

$$\overbrace{P^+ \ldots \| \ldots P_z ;}^{a}\ \overbrace{Z^+ \ldots \| \ldots C^\pm}^{b}\ \overbrace{C^- \ldots \perp \ldots P^{\pm}_{=}}^{c}$$

for which the contracted form would be $(C\,P\,P_z ;)^c$.

There is another class of click-gear which differs in one very important particular from that which we have been considering;—an example of it is shown in Fig. 323. Here we have click-wheel, pawl and frame exactly as above, but here the pawl so grips the teeth of the wheel as to make its motion in either direction impossible. The click b is therefore, as it were, a combination of those of Figs. 320 and 321, for it acts as a pressure-click against motion in the one direction and as a tension-click against motion in the other. While, therefore, the click-trains just considered were single-acting, the one now before us is double-acting; we may call them free and fast click-trains respectively.

We must find a new symbol of relation to enable us to express this double action of the fast click. The tooth may, in the first place, be indicated by $Z\pm$, and further, following out the same reason for which we chose the semicolon above, we may here use the colon for the sign of pairing. We shall therefore indicate the pair of elements consisting of a click-wheel and double acting pawl by $C_s : Z\pm$, or by the contracted symbol $(C_s:)$. The fast click train of Fig. 323 will therefore be $(C''_3C_s:)^c$

Fig. 323.

This train differs very greatly from the free click train $(C''_3C_s;)^c$. In the latter nothing whatever prevents the free turning of the wheel a in the proper direction; the pawl is lifted by the motion of the wheel itself, and drops again immediately by force-closure. If it be desired that turning should take place in the opposite direction, some special means must be provided for lifting the pawl b, and so throwing the whole train "out of gear." With $(C''_3C_s:)^c$ on the other hand, motion cannot occur in either direction unless the click be first thrown out of gear. If any fast click be thrown out of gear, and then, motion being commenced, be again brought under the action of the closing force (Fig. 324), the rotation lasts only until the next space comes under the tooth of the pawl. The latter then falls instantaneously, and wheel, pawl, and frame become equivalent to a single piece only. With the free click-train (Fig. 325), on the other hand, the pawl falls gradually under the same circumstances (the wheel, Fig. 325, turning to the right), and reaches the bottom of the space even before the moment of closure. It intercepts the wheel teeth therefore with greater safety than in the other case.

Fig. 325.

If after any loaded click train—a train, that is, whose click-piece a is subjected to the action of some continued forward force—be set in motion, its click does not come under the action of the closing force, the wheel a will continue to turn, and will turn the quicker the greater the load be. This motion may be called the reversal of a click train. It is well suited for such a purpose as bringing into action at a given moment mechanical energy which has been stored up in any part of a machine. Click-trains used for this purpose may be called curb-gear; they are employed in many forms, of which an extremely familiar one is the common gun-lock. In this the two "bents" of the tumbler are the teeth of the click-piece or curb, which are released by

Fig. 214.

Fig. 215.

pulling the trigger. Long ago, in the cross-bow of the middle ages and the catapults and ballistas of the ancients, the principle of the curb-gear was used in mechanisms by which stored-up energy was brought suddenly into action (§ 48). In important modern machinery it serves the same purpose; in the self-acting spinning machine, for example, both free and fast click-trains are used as curb-gear, the special object here being the effecting of a required change of motion at a given instant.*

§ 120.

Reversed Motion in Free Click-trains.

The applications of both forms of click-gear are—as our examples have shown—extremely numerous and important, more important, indeed, than they appear to be at first sight. This makes it necessary to examine somewhat more closely the mechanisms formed from them, several of which will throw considerable light

*Click-trains have not unfrequently been turned into chamber-gear, generally in the form $(C_2^{\prime\prime}C_z\,;)_a^c\,,-(V\pm)_l=b,c.$ This is the formula, for instance, for Watt's well-known rotary engine, in which the revolving piston is simply a one-toothed click wheel. This was patented by Watt in 1782, and afterwards by Routledge in 1818, (see Farey, *Steam-Engine*, p. 672, Pl. XV.), but naturally enough it was unsuccessful, the higher pairing C_z ; Z could never be steam-tight, and was alone sufficient to destroy its efficiency upon the nature of particular classes of constructive elements. We must therefore somewhat overstep the usual limits assigned to the constructive elements themselves.

We have already pointed out that click-trains are employed both for direct and reversed motion. We shall first examine shortly the nature of the reversed motion of the click-piece and the corresponding relative motions of the pawl or click.

If the click-piece a be a wheel, its reversed rotation gives to the pawl $C \ldots \| \ldots Z$ also a motion of rotation, the conditions of which depend upon the particular form used for the back of the teeth of a. This may be considered, in the most general case, as a portion of the curved profile of a disc or cam a, Fig. 326. The motion given by this profile to the pawl will be an oscillation about the axis of the pair connecting it to the frame c. If the radius of the pawl be made infinite it becomes a block b (Fig. 327), which, with suitable force-closure, is caused to slide to and fro in a straight line by the cam a. Here we have, as before, a chain of three links; its formula is

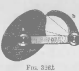


FIG. 326.

$$\overbrace{C^{+} \ldots \| \ldots C}^{a},\ \overbrace{\frac{Z}{f} \ldots \perp \ldots P^{\pm}}^{b}\ \overbrace{P^{-} \ldots \perp \ldots C^{=}}^{c}$$

By placing this chain upon the link c we obtain a very numerous series of mechanisms, which we may call slider-cam trains. There are various ways in which the force-closure of Z may be replaced by pair-closure. One of these is the addition to the end of the block or pawl which is paired with the cam of a cylindric pin—an element, that is, of which the profile is a curve equidistant to the end-point,—and the pairing of this pin with a groove in the cam a, formed by drawing equidistants to the original profile, Fig. 328 (cf. § 35). The force-closure of the pawl or block b is therefore not an essential feature in the cam train, but only a separable and accidental property of it. We were therefore fully justified in the omission from our formula, in the last section, of the sign for force-closure. We must not go further into this question here; it is one which must receive extended treatment under Applied Kinematics. It was only necessary to point out that the click-wheel with its sharp teeth belongs strictly to the class of slider-cam trains,[55] which on their

FIG. 321.

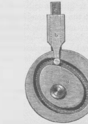


FIG. [illegible]

part also become, under certain circumstances, spur-wheel trains. We must now turn to some compound mechanisms which are formed from click-gear.*

§ 121.

Ratchet-trains.†

The common forms of ratchet-gear play apparently a somewhat subordinate part in machinery, for which perhaps their force-closed motion may account. None the less do they require our most careful attention, for reasons which I shall show further on, and we must therefore here make ourselves familiar with their principal characteristics.

* The slider-cam train—which we might indicate by the contracted formula $(CC_{z}P)$—has, like the chain $(C_{z}^{m} C_{z};)$, been frequently used as chamber-gear, not unfrequently with a force-closed sliding-block. It will be sufficient to mention, merely as illustrations of the form taken by the chain when chambered, the engines of Davies (Burn, *Steam-Engine*, p. 128), Scheutz (D. K. Clark, *Exhibited Machinery of* 1862, p. 318), or Sudlow (*Engineering*, Ap. 10, 1874, p. 267). The higher pairing in these machines again renders any attempt to form them into satisfactory steam-engines quite useless.

† See note p. 455

A piece of a machine is said to receive a ratchet motion if it be moved always in the same direction but with an intermittent instead of a continuous motion. The special mechanism by which this motion is given is called a ratchet-train. Such a train requires that the link receiving the intermittent forward motion should be prevented during the longer or shorter pauses that occur from moving backwards,—and for this purpose click-gear is very often employed. A complete ratchet-train is therefore frequently, although not always, a combination of ratchet-gear and click-gear.

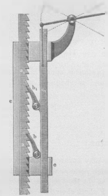


Fig. 328.

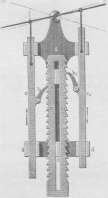


Fig. 329.

The click or other gear thus coming into use we shall call retaining-gear.

A form of ratchet-train which often occurs is sketched in Fig. 329, the object here being the lifting of the rod $a\,a_1$. The rack click-train (CPP_s;), which we have already examined, is here used as retaining-gear; and the ratchet work consists of an exactly similar chain placed upon a, whose rack a_1 is made one with that of the retaining-gear, and which moves relatively to the fixed frame c. When c_1 is moved downwards the rack $a\,a_1$ is held by the retaining-gear, while the pawl b_1 of the ratchet-train slips over the tops of its teeth; when it is lifted, on the other hand, b_1, c_1, and a_1 behave as a single piece, while b allows the rack to move upwards.

If, retaining the same relative motion of c and c_1 as before, we make half of it into absolute motion, we obtain the double-acting ratchet-train which is represented by Fig. 330. Here the two racks a and a_1 are formed upon opposite sides of the same rod, and guided by an internal prism pair. The pawl rods, c and c_1, are moved by couplers from an equal armed lever above them, in the same way as before. (In practice, where the double-acting ratchet-train occurs not unfrequently, the pawls are generally placed directly upon the working lever, so as to dispense with the couplers and rods.) No retaining-gear is now used, the two sets of ratchet-gear acting alternately. It is to be noticed that the pawls here, although they have only half the stroke of those in Fig. 329, pass over the same distance on the rack in each downward motion as in the former case, supposing the whole travel of the rack to be the same, per period, as in the single-acting ratchet-train.

The "levers of Lagarousse" (Fig. 331) form another double-acting ratchet-train. Here one block carries both a pull- and a push-click, and these act alternately on the ratchet-wheel a. For each upward or downward motion of c, the number of teeth over which the one pawl slips corresponds to twice the distance through which the other (acting) pawl moves the wheel forward. This peculiarity of the motion should be remembered, as we shall have to return to it again.

We notice here that free click-gear is very suitable for use in ratchet work. This is specially the case in one important class of ratchet-trains, the escapements of clocks or watches. These act generally in the manner described in the foregoing section, by the alternate engagement and disengagement of a click with a click-wheel, the latter being continuously driven by some external force in one direction. The engagement and disengagement are caused to take place at intervals of time as nearly uniform as possible, so that the escapement may regulate the motion of the clockwork by compelling its wheels to move through equal angles in equal times.

Graham's well-known anchor escapement (Fig. 333) may serve us for an example of this. In it two free click-trains are united in such a way that the two clicks b_1 and b_2, the one being a pull- and the other a push-click, form parts of the same piece, here called

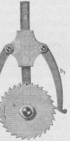


Fig. [illegible]

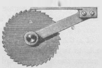


Fig. [illegible]

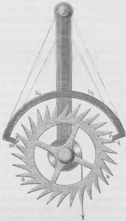


Fig. [illegible]

an anchor. The motion of the pendulum causes the regular alternate lifting and engagement of the clicks. If the click b_1 be lifted, b_2 falls into one of the spaces and arrests the motion of the escape-wheel, upon which the driving force acts continually in the same direction. As the anchor swings back, b_2 is disengaged and the escape-wheel is held by b_1. Each time the wheel moves through a distance corresponding to half the pitch. Each tooth of the wheel, as it slips past the ends q or m of the anchor, exerts some outward pressure upon it, and slightly accelerates the motion of the pendulum. This, however, is merely an accidental feature of the escapement, used to adapt it to particular purposes; there are many escapements, especially modern ones, in which it does not exist. In some escapements of specially delicate construction, such as the chronometer escapement, a single click only is used, and is lifted and engaged once in each complete vibration (double swing) of the pendulum, allowing one tooth of the escape-wheel to pass it at a time. In Wheatstone's chronoscope, as improved by Hipp, an escapement of this kind, which acts with extraordinary rapidity, is used (Fig. 333). It is so constructed that it can make 1000 complete vibrations per second. In each of these the escape-wheel moves one tooth forward and is again arrested at the next. We thus see that in the most delicate machines which have been constructed this click-gear, which at first sight appears so rude an appliance as scarcely to be suited for any approach to machinal exactness of motion, is extensively utilized.

Fig. 334 is an example of a ratchet-train with a fast pawl. If the wheel a is to be moved it is necessary first to raise or disengage the pawl b. This is effected by means of a tooth d_1, which forms one piece with the revolving ratchet-tooth d, and lifts the pawl by coming in contact with the face b_1. So soon as this occurs the ratchet d enters one of the spaces of the wheel a, and drives it one tooth forward. At the end of this motion, however, the pawl again drops, the tooth d_1 having passed the projecting piece b_1. As soon therefore as the ratchet motion has occurred the click-train is again fixed. The ratchet $d\,d'$ may revolve in either direction, so that the wheel may be caused to move either forwards or backwards.

If the radius of the wheel a be made infinite, it becomes, as we know (cf. §§ 69 and 71) a straight rack. We should therefore obtain,—if the ratchet $d\,d_1$ were suitably formed,—a train in which a rack could be moved backwards and forwards by ratchet-gear and held during its pauses by a fast pawl.

Without going here into other forms of this kind of ratchet-gear, I must briefly look at one application of the train which occurs with special frequency. This is its application in locks,—where from the common door or box-lock to the most complex "patent safetya'aapparatus,— weafindathisatrainaeverywhereaapplied intheamotion of the bolt bythe key.

Thecornmondoor-latch, in theafirstaplace, showsaitself ataonce to be a free click-train under our definition. Both the common liftinglatch and the ordinaryaspring-bolt or "sneck," form,awith the lock-box or frame, the doorframe and the door itself,click-trains, which belong to the class shown in Figs 320 and 321. They differ from these only so far that after the bolt or latch has fallenintoagearby theclosingof the door,the socket of the bolt onatheaoneahand,aanda thea frame ofatheadooraonatheaother,aprevent anyafurtheramotion ofathe dooraon its hinges, so that theafree click has become a fast one.

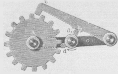


Fig. [illegible]

A bolt moved by a key is almost invariably a click-rack *a* of the form $P \ldots a \ldots P_x:$, the tumbler is a fixing pawl *b*, which isamade in several pieces in the better classes of locks for security's sake. The key is the ratchet and lifting tooth dd_1, the frame of the lock the fixed link *c*. Besides this the bolt *a* forms with the lock frame and the door a special

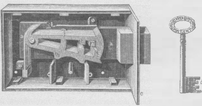


Fig. [illegible]

fast click-train. Inathose locks in which moreathan oneaturnaof the key is required to withdraw,aor to shoot the bolt,the racka*a* has more than one ratchetand click-tooth. In order toaprevent any unauthorized opening of the lock, the link of the train which lifts the click and moves the bolt, *i.e.*, the key,—is made separate from the lock itself. The key in many cases serves only to lift the click out of gear, a separate ratchet, connected with a handle, being used to move the rack. Complex forms are given to the key and the tumbler in order to render it impossible, or at least very difficult, to move the bolt by any other key than that specially made for the lock.

The accompanying sketch of a Chubb-lock (Fig. 335), in which the different parts are marked with the letters used for corresponding parts in former figures, may make this matter somewhat clearer. The action of other safety locks, those of Bramah, Hobbs, Yale, &c., are so far the same. The art of lock-making indeed, which has been the parent of so many remarkable and ingenious inventions, has worked in its latest and most refined productions strictly in the spirit of kinematic science,—it has followed its laws throughout with the greatest precision.

§ 122.

Brakes and Brake gear.

Brake drums or wheels are links of kinematic chains,—made usually of the form $C' \ldots | \ldots R$,—which serve to control or entirely to stop the motion of the links connected with them, by friction produced upon their surfaces. The blocks or band pressed upon the latter and the mechanisms connected with them form with the drum a complete brake. Brakes are applied both to pieces which move in straight, and to those which move in curved paths.

One fact about brakes which requires to be noticed is that the blocks, slipper or band, form with the drum or rod a pair of kinematic elements so long as the gear is in motion. If a drum be used we have the pair (R), if the block acts on a bar or rail, the pair (P), and so on. Those brakes therefore which are employed completely to stop a motion, are used to p r e v e n t t h e a c t i o n o f a p a i r o f e l e m e n t s, and this is done by uniting the partnerelements in such a way that kinematically theytmay form a single piece only. Under some circumstances brakes act in exactly the same way as click-gear; there is, however, this difference between them that in the case of the brake the two elements are combined by making the motion of the pair gradually more and more difficult, the union of the two elements occurring when this difficulty becomes a maximum.

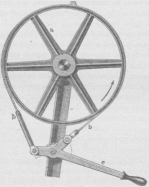


FIG. 336.

Brakes have the further resemblance to click-trains that one class of them act equally well for motion in either direction, as in the fast click-train, while those of another class, like the free click-trains, are either single-acting, or act differently in the different directions, as *e.g.*, in the case of the band-brake in Fig. 336. In the following section we shall be able to investigate more generally these points of similarity.

§ 123.

Engaging and Disengaging Gear.

Among the constructive elements which we have considered there have been several specially arranged and used so as to stop the action of a part of the machine when required, or to set it again free to move. Such arrangements are known as engaging and disengaging gear. It is obviously important that we should have a distinct general idea of the alterations thus occurring in the kinematic chain, in order thoroughly to understand the means by which those alterations are effected. We shall examine some examples of the methods commonly used.

One method very frequently adopted is the separation of the elements of an existing pair, so that the pairing between them may be dissolved. Friction wheels, moved a small distance away from each other, belt-trains in which the belt can be loosened

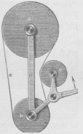


Fig. 337.

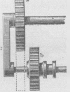


Fig. 338.

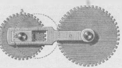


Fig. 339.

by moving a tightening pulley (Fig. 337), or by throwing it off one or both of the drums, spur-wheels which can be moved out of gear either axially (Fig. 338) or radially (Fig. 339) are all examples of this method. When the pairing is dissolved, the motion of the driven link necessarily ceases, no matter whether or not that of the driving-link continues. Engagement, or "throwing into gear," is simply the re-union or re-pairing of the separated elements.

Loose couplings (p. 445) or clutches are another form of disengaging gear. The most common form of this is the claw clutch or crab, the three most important varieties of which are shown in Figs. 340 to 342. The piece a is fixed to the shaft A, while b can slide upon B; the two shafts are then coupled if the clutch teeth be in gear, as shown. These teeth, it will be seen, are formed exactly as those of click-work. The two pieces a and b in fact, form parts of a click-train, a fast-train in the first example and a free-train in the second (§ 119), while in the third case the clutch acts as a free-click if the teeth be engaged to half their depth only, and as a fast click if they be in full gear. These claw clutches are therefore clicks which are thrown out of or into gear when the driven piece is to be stopped or to be again set in motion. The

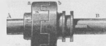


Fig. 340.

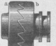


Fig. 341.

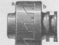


Fig. 342.

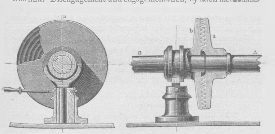
difference between them and the click-trains before described is that here the link formerly fixed is itself in motion. The relative motions in the train, however, are exactly as before.

Such couplings as those of Pouyer-Quertier and Uhlhorn* are in principle similar to these,—but in them the driven piece, that corresponding to b in Fig. 341, receives its motion from a second prime mover, and if it be stopped its teeth disengage themselves automatically from those of a, which then slide freely under them.

In Friction couplings, of which one is represented in Fig. 343, some arrangement (such as that shown) is employed to press b so closely against a, that the friction between them is greater than the resistance to the motion of b, which therefore moves as one piece with the driving shaft A. The coupling is disengaged by the removal of the pressure. Apart from the special purpose for which it is used we have here simply a brake, and this is true also of other friction couplings.

* These are better known in Germany than with us. They are used where one shaft is driven by two separate prime movers, and are so constructed that the stopping of one of these does not interfere with the continued motion of the shaft, driven then by the other only. Both forms of coupling are illustrated in Reuleaux's *Constructeur*, 3rd Ed. p. 277, &c. (*Kraftmaschinenkupplungen*).

We thus see that these loose couplings, looked at as mechanisms, are click-trains or brakes, but that instead of combining a moving with a stationary piece, they are used to unite two moving pieces. As to their action in the mechanism as a whole we notice that when the parts to be coupled are engaged, or put in gear with each other, they become kinematically one piece only. The shafts A and B become in this way a single shaft C ... | ... C, while before they are coupled each one separately forms such a shaft. The engagement therefore forms A and B into one link of a chain, while the disengagement again separates the parts or elements of this link. Disengagement and engagement then, by such methods as



[illegible]

have been described, are respectively the separation and re-union of the elements of a link of a kinematic chain.

The various couplings used in this way may be subdivided according to the manner in which the parts of the link move, or are compelled to cease motion, after their separation; as may also the couplings before described. It is the province of Applied Kinematics to examine all these matters, here we must be content with the establishment of the general principles of their construction. I need only further mention that many of the contrivances used to prevent the loosening of nuts or keys are click-trains of the kind here described.

§ 124.

Recapitulation of the Methods used for Stopping and Setting in Motion.

We have seen that disengagement and engagement may be used either in a pair or in a link of a kinematic chain. Its object is in each case to bring to rest, or to set in motion again, some portion of the mechanism. Remembering at the same time that click-trains and brakes often serve the same purpose in connection with the whole mechanism, it will be useful for us to recapitulate here the principles upon which the different methods used for stopping and setting in motion mechanisms or parts of them are founded.

We have already noticed that click and brake act upon the elements of a pair in such a way as to unite them into one body. Such a union of an element with its partner we may call the fixing of a pair. Remembering this, we see that the stoppage of a mechanism or of a portion of one is effected

(*a*) by fixing a pair of elements in the kinematic chain (as in click-gear or brakes);
(*b*) by disuniting a pair of elements in the kinematic chain (as in disengaging toothed wheels, throwing off belts, lifting a "gab," etc.);
(*c*) by dividing a link in the kinematic chain (as in claw-couplings,—in throwing off pump-rods by removing a key, etc.),—

while the original motion again becomes possible if the chain be restored to its normal constrained condition. We shall see immediately that this classification applies equally to pressure-organs; it covers therefore the whole ground which we are examining. A general examination of the ways in which it is possible to make a kinematic chain immoveable and moveable at will, without destroying any of its parts, makes it evident that in the classification given above we have exhausted all the means available for this purpose.

§ 125.

Pipes, Steam- and Pump-cylinders, Pistons, and Stuffing-boxes.

Pipes are, as we have already seen in § 41, the indispensable partner-elements of pressure-organs; the connections between them serve to form the links of the kinematic chain in which they occur. In the cylinders of steam-engines and pumps we have the vessel V^- containing the pressure-organ; they are therefore single elements, paired with their pistons or plungers V^+. Piston-rods and stuffing-boxes are partly paired with pressure-organs and partly occur as simple sliding-pairs $P^{\pm}_{=}P^-$. In the tubes therefore we have necessary, and in the four other constructive elements most familiar, forms of pieces which are used as links or as single elements in chains containing pressure-organs. They include, essentially, the chambers of rotary engines and pumps, the channels or races of water-wheels, the housing of turbines, and so on.

§ 126.

Valves.

Valves appear to be the most difficult of all the constructive elements to define kinematically. Their forms are so extremely numerous and varied that they seem to correspond more or less completely with a great number of different cases, without belonging entirely to any one of them. There are clacks, lifting-valves, piston-valves, tapered, cylindric and flat cocks,—the slide-valves of steam-engines, lifting and sliding equilibrium-valves, automatic valves and those which are not self-acting; there is the throttle-valve, the shutters and sluices for water-wheels and turbines, and many others. All these are valves; they serve, that is, to divide the capacity of a vessel containing a pressure-organ in some required manner. They do this in so many ways however, that is, they differ so greatly kinematically, that it appears at first as if it would be impossible to treat them all kinematically as one class. So far as I know, indeed, no attempt has been hitherto made to do this, which remarkable omission we probably owe to the fact that the pressure-organ machines have been almost entirely left without kinematic treatment of any kind. I have elsewhere* attempted a classification of valves according to their constructive characteristics which may be of service to us so far as it goes. It is as follows:

1. Valves which slide, including
   a. Cocks and disc-valves,
   b. Slide-valves;
2. Valves which lift, including
   (*a*). Clacks, hinged-valves,
   (*b*). Direct lift-valves.

I gave as the essential difference between the two classes that the fluid pressure upon the sliding-valves had no tendency either to open or to close them, while in the lifting-valves it did both, according to the direction in which it acted. The latter, therefore, can be used as self-acting valves, while the former cannot.

There is a good deal to be said for this classification, which does reach to some extent below the surface. It is, however, by no means exhaustive. It is founded on an examination of its subject from without and not from within, and so fails when it is carried to extreme cases, in reference, for instance, to those lifting valves which are completely balanced, and which therefore do not possess the property above named as that characteristic of lifting-valves in general. The division also stands so far upon the same ground as those of the old descriptive school that it does not fully explain its own definitions, and especially that it gives no indication of the position of the valves among kinematic arrangements. Now that we have familiarised ourselves with kinematic ideas by a series of analytical exercises, it is possible to give a definition which really goes to the root of the matter. It is this:—Valves and their connections form the click-trains, and under certain circumstances the brakes, of the pressure-organs.

Among these valve-trains also both free and fast clicks exist. The self-acting lifting valves are free clicks, that is, they permit motion past them in one direction and not in the other. The sliding-valves and the balanced-valves above alluded to are fast

* *Constructionslehre für den Maschinenbau*, p. 846, *et seq.*; *Constructeur*, 3rd Ed. p. 583.

clicks, which must be placed in and removed from their fixing position by external means.

The common pump-clack, Fig. 344, corresponds to the free click-train with the common pawl, Fig. 345. The valve *b* is the pawl, which prevents the click-rack *a*, the water, from moving downwards. The tube *c*, which carries also the joint for the valve, corresponds to the frame *c* of the click-train. It is merely accidental that the hinge of the valve is made of a flectional element, leather; valves with a cylinder pair joints are of course quite usual. The fluidity of the pressure organ which forms the click-rod makes the click teeth unnecessary. The cock, Fig. 346, corresponds to a fast-click, such, for example, as that in Fig. 323. The train as shown in Fig. 347, which is used in Thomas's calculating machine, is also exactly analogous to the cock. *a* is the click-piece (here a wheel turning about a fixed centre) corresponding to the water in Fig. 346; if *b* be turned through a certain angle it interposes no obstacle to the

Fig. 344.

motion of *a*, in the position shown it prevents it from turning in either direction. The frame *c* contains two elements, one for carrying *a*, the other for carrying *b*, exactly as in Fig. 346. The sluice-valve used in water or steam-pipes, Fig. 349, corresponds to the fast click in Fig. 349;—*a* click rod, *b* valve or click, *c* frame carrying both. Balanced valves of all kinds represent clicks so arranged that the fluid pressure affects their engagement and disengagement to the smallest possible extent. The reader can find a multitude of other analogies,—for we have here an actual correspondence to deal with, and not a mere fanciful parallel.

Fig. 345.

If a valve be opened only a small distance, so that the pressure organ encounters a great resistance in passing through it, the click-train acts as a brake. These two classes of mechanisms, therefore, pass here one into the other, exactly as we have already found (§ 122) to be the case with trains composed of rigid elements only

The analogy between fluid click-trains and those consisting solely of rigid bodies exists equally in those cases where the trains are employed in complete mechanisms or machines. The mechanism Fig. 350, which represents simply a common lift pump corresponds to the ratchet-train of Fig. 351, which we have already examined. The pump-barrel c, represents the frame c of

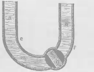


FIG. 350.

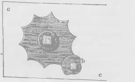


FIG. 351.

theratchet-gear, the suction-valve the lower pawl b, the bucket-valve the ratchet-pawl b_1, tthe prismo-cylindric arrangement of bucket and barrel correspondstto the prism pairing between the bar c_1 and the frame c.

The double acting ratchet-traint Figt 352, which we already know, exactly representsthe Stoltzpump, Fig. 353. The pump and

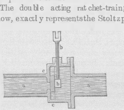


FIG. 352.

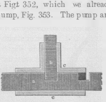


FIG. 353.

the ratchet-train correspond part for part; the two buckets c and c_1 with their rods, are the two bars c and c_1; the valves b and b_1 are the ratchet pawls, the pump-barrels and frame d correspond to the guides and frametd of the ratchet-train. The passing of the one click over twice as many teeth astcorrespond to the distance through which the rack is lifted has also its parallel in the pump,—the water moving relatively to the descending piston with twice as great a velocity as it is raised by the other. It is not necessary that the pumps should be placed side by side in this arrangement; in some cases they are arranged with the two barrels one above the other and conaxial, one pump being driven from above and one from below.*

The double-acting ratchet-train of Lagarousse, shown once more in Fig. 354, is represented by a double-acting Vose pump, Fig. 355.

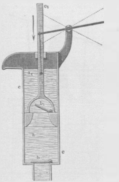


FIG. 354.

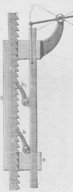


FIG. 355.

The analogy can again be followed out through every detail; here again we find, too, that the velocity of the one piston relatively to the water is always twice as great as its velocity relatively to the frame, just as in the case of the clicks b and b_1 and the wheel a.

In a similar way we find in pumps of other constructions a complete analogy with ratchet-trains. The differences are simply those permitted or rendered necessary by the fluidity of the

* Cf. König's *Pumpen*, p. 52. In Prunier's pumps at the Vienna Exhibition, the two barrels are conaxial and the rod of the upper plunger is made hollow, that of the lower one passing through it. They are thus both worked from above. See *Record of Vienna Univ. Ex.* (Maw and Dredge) Pl. lxvii

pressure-organ. In other words, piston-pumps with valves are fluid ratchet-trains.

The view which this proposition affords us of the different systems of pump construction appears to me to be extremely instructive, and greatly to simplify the whole matter. It is interesting to notice that both free ratchet-gear and piston and valve pumps were known and had attained some degree of completeness before the introduction of the steam-engine; both click and ratchet pawls and lifting valves are force-closed arrangements,

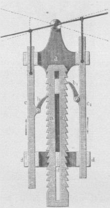


Fig. [illegible]

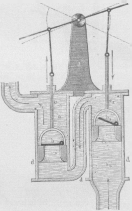


Fig. [illegible]

and so came earlier in the natural course of machine development. We can observe also a distinct tendency making itself felt among modern engineers to supersede the force-closed motion of the valves by a constrained motion—as in pumps with slide valves, etc.*

* Cf. for instance, Hänel's suction valves in Scholl's *Führer des Maschinisten*, 8th Ed. p. 419.

Hydraulic and steam engines (in their usual forms) have in general the same arrangement as that of piston and valve pumps or fluid ratchet-trains, and are made both single and double-acting. When in motion, the difference between them is simply that in the former the pressure-organ is no longer driven, but is itself the driving link of the mechanism. The valves therefore can no longer be self-acting—but must move with chain-closure. The

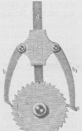


Fig. 352.

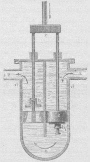


Fig. 353.

general relation of their motion to that of the piston is, however, the same as in the case of the pump-valves. In order that this motion may be brought about without any great expenditure of energy, fast-clicks are used, that is, balanced lifting-valves, or (especially in the steam-engine) slides, to which the required motion is given by means of suitable valve-gear. We may therefore say: the common steam-engines, hydraulic engines, etc., are reversed fluid ratchet-trains.* We shall return to this question further on.

* This r[illegible]on of the action [illegible]ily be seen in F[illegible] 353, for instance, by supposing the fluid [illegible] move in the opp[illegible] to that shown by the a[illegible]s,—the valves being moved at the right time by some separate mechanisms. In the correspond[illegible] train of Fig. 352, the same thing would occur if the bar a moved down instead of up. It will be noticed that it does not follow in either case that the [illegible] driver.

§ 127.

Springs as Constructive Elements.

We have already examined the function of springs in kinematic chains. We found (§ 42) that they were flectional kinematic elements, and might be arranged so as to work under every kind of force-closure, while the tension- and pressure-organs could be used with one force-closure only. Along with the parts attached to or connected with them springs become kinematic links. It follows unquestionably from our earlier examination of the matter that they should be reckoned among the constructive elements.

§ 128.

General Conclusions from the Foregoing Analysis.

The foregoing analysis of the constructive elements of machines has given us some not unimportant results. It has shown us, in the first place, that the parts generally included under this common designation are kinematically of very various descriptions. In part they are really kinematic elements (pins, bearing-blocks, tubes, pistons, stuffing-boxes, cords, belts, chains, springs), in part links of kinematic chains (shafts, axles, frames, levers, cranks, connecting-rods, cross-heads, steam-cylinders, &c.), in part complete pairs of elements (friction-wheels, toothed-wheels);—some too are portions of kinematic chains (belt-gear, click-gear, brakes, moveable couplings and disengaging-gear, valves, &c.), and a few complete kinematic chains (screwed and keyed joints). Looking at them as a whole we may draw the general conclusion that the "constructive elements" are really those pairs of elements and kinematic links which are most frequently used. For some of those which are complete chains in themselves, such as the screwed and keyed joints, are not used constructively to obtain the motions of the chains which they represent, but simply as fastenings, that is, for link-formation; and the belt and cord-gear occurs as a part of a chain, simply because flectional elements can only be used in closed chains under chain-closure. Some moveable couplings, brake-gear, click-gear, &c., are more complex, and seem more distinctly to be complete kinematic chains. These, however, occur so frequently as subordinate parts of larger chains that relatively to the latter they appear elementary, and their appearance among the constructive elements may be justified upon this ground.

The question now presents itself whether we cannot, from the point of view now reached, find some rational classification for the constructive elements, based upon their real kinematic nature. This can certainly be done, and the matter is of sufficient importance to merit a short examination here.

It must be quite understood, in the first place, that no absolutely rigid systematic treatment is here possible. The classification must be based throughout on judicious compromise; we must be content to give and take, that we may accommodate ourselves to the exigencies of the numerous practical questions which refuse to remain within the bounds of a rigid system. This, however, does not of itself involve any error, for it is a consequence of the real nature of the problem before us (p. 437), and in no way interferes with our firm grasp of the scientific kinematic basis upon which the whole matter rests.

We shall in the first place make a more distinct separation than has hitherto been usual between the rigid and the flectional elements. We may begin with the former, placing first the most simple cases which occur. For this purpose, however, we must remember that the simplest things are not always those having fewest parts, and that a combination, therefore, is not to be rejected simply because it contains more than a single element, or a pair of elements. For our purposes those combinations in which no motion occurs—the immoveable fastenings used for forming links—may be considered simpler than the moveable pairs of elements; we may therefore place them first in our list. Next to them come the kinematic elements, pairs and links which give us simple moveable connections. Within these pieces themselves also the immoveable fastenings very frequently occur.

Arranged in this way the following will then be the first series of constructive elements:—

I. Rigid Elements.

a. Joints (for forming links).

- Rivets and riveted joints,
- Keys and keyed joints,
- Strained joints,
- Screws and screwed joints, passing into

b. Elements in pairs or in links.

- Screw and nut (used for their motions),
- Pins,
- Bearing-blocks,
- Shafts and axles,
- Fixed couplings,
- Levers (simple),
- Cranks,
- Levers (compound),
- Connecting-rods,
- Crossheads and guides,
- Friction-wheels,
- Toothed-wheels,
- Fly-wheels.

Whether moveable couplings and clutches should not be treated along with fixed couplings may be questioned, for we have already seen that in general, when their parts are in gear, they simply form parts of rigid links. It must be remembered, however, that these higher couplings contain in themselves numerous subordinate parts, levers, clicks, brake-blocks and so on, and present on this account greater difficulties to the student than the others. For the same reason they require, to a considerable extent, a special treatment dependent upon the nature of their details, and we are therefore justified in placing them rather among the complete mechanisms than here. Let us now go on to the second class of constructive elements, and their simplest arrangement in chains.

II. Flectional Elements.

a. Tension organs by themselves and used with chain-closure.

- Belts
- Cords
- Chains

and their arrangement in gearing.

b. Partners of pressure-organs.

- Pipes,
- Pistons and plungers,
- Steam-cylinders and pumpbarrels and chambers,
- Stuffing-boxes,
- Valves.

c. Springs.

- Tension-springs,
- Pressure-springs,
- Bending-springs,
- Twisting-springs.

We have here another doubtful point, whether, namely, the valves should be included under II. *b*, or whether they should be placed in Class III. along with the click-trains formed from rigid elements, to which, as we have seen, they completely correspond. They fall along with pistons and stuffing-boxes (which also strictly speaking belong to click- and ratchet-trains) so naturally, however, and have been so often treated along with them, that the arrangement adopted will be on the whole the most convenient. The case is one of those in which logical completeness must be sacrificed to considerations of expediency.

Springs are obviously in their right place among the constructive elements in II. *c* above. The calculations connected with them fall to a very great extent, however, into the studies of elasticity and the strength of materials. Whether they be treated there or along with the constructive elements must depend upon the circumstances of each particular case.

We may conclude our list of constructive elements with the few which are more or less nearly complete chains, but which almost always occur in machinery as what may be called elementary groups of parts, and which for that reason may be conveniently treated along with the parts more strictly included under the name of constructive elements.

III. Trains.

- Click-gear in its simplest forms,
- Brakes,
- Moveable couplings and clutches.

These form a kind of transition from the constructive elements to the complete machine. It will be remembered, however, that these three classes of trains are not the only ones occurring among the constructive elements. We had, for example, the screw-train $(S'P'C')^c$ among the rigid elements, while in the chain, rope and belt-trains of Class II. we had other complete mechanisms. We know too that the clutches are click- and brake-trains (cf. § 123) while the moveable couplings are mechanisms formed from lower pairs of elements.

Our investigation of the constructive elements from a kinematic point of view has led us rather to a rearrangement of them than to any alteration in their number. It has furnished us, however, with explanations on some points by which, I believe, the treatment of the whole matter will be greatly facilitated.

The analysis has in several cases thrown a new and unexpected light upon very well known and apparently very thoroughly understood constructive elements. This has been specially the case in regard to valves and the machines fitted with them,—pumps, blowing-machines, steam-engines, etc. The conclusions which we reached showed for the first time the close connection existing between many of the characteristics of these machines, and have thus greatly aided their comprehension. They enabled us to define relationships which before had not been proved, even where they had been recognised. In this way we have succeeded in effecting a real simplification of the subject, the advantages of which will be felt specially in the problems of Applied Kinematics.

In reference to locks, too, our analysis has given us an explanation of which the want has often been felt. It has shown us that their kinematic principles are exceedingly simple, and that their treatment falls fairly within the limits of Applied Kinematics. Those arrangements which we have called curb-trains also (the special properties of which have not hitherto been distinctly recognised), and the escapements, we have been able to bring into their proper position among other mechanisms, and to examine from a general point of view instead of from the special one commonly adopted. The same is true also in the case of water-wheels, steam-engines and other complete machines, the more detailed examination of which we shall take up in the next chapter.

Our investigations have, lastly, furnished us with a most important theoretic result connected with the general nature of the closure of a kinematic chain or pair of elements. They have shown us that in every description of kinematic chain, from the most complex to the simplest, we have to distinguish three kinds of closure, namely:

1. Normal constrained closure,
2. Unconstrained closure,
3. Fixed closure.

In all three cases the conditions are fulfilled that the chain returns upon itself, and that proper pairing occurs between each link and its neighbour.

Under constrained closure all the relative motions of the links are perfectly determinate.

Under unconstrained closure these relative motions are made indeterminate by the addition of links to the chain.

Under fixed closure the motions of the links are entirely prevented.

All these kinds of closure are used in practice. The first and most important occurs in every machine, and forms a characteristic feature of it. The second we find in disengaging apparatus, where the action of a portion of the machine is stopped or reversed. The last kind of closure is used both for this purpose and with the object of preventing motions taking place within any single link, or, in other words, for making separate pieces into one link. The common constrained closure lies between the two other cases, and this is sometimes an assistance to us in finding out among the possible closed arrangements of links in any chain the important special case of constrained connection.

The apparent work of the machine designer consists in utilising these three methods of closure in different ways and for different objects. In reality, however, they are to him only means which he employs to solve the problem placed before him in the complete machine. We must now proceed to examine the general propositions which present themselves in connection with this subject.