THE ANIMAL

AS A

MACHINE AND A PRIME MOTOR.

I.

INTRODUCTION.

ENERGY AND ITS TRANSFORMATIONS.

ENERGETICS AND ITS LAWS.

1. **Energy and its Transformations** are the source and the method of all useful work, as of all natural phenomena involving motions of masses or of molecules of whatever kind. All "prime movers" are machines by means of which man diverts energy from natural channels and compels it to do his own work. The water-wheels and windmills simply transfer the energy of the moving fluid to the machinery of the transmission through which it performs useful work; the heat-engines and electric machinery transfer energy, and at the same time convert it from the thermal or the electrical to the dynamic form for application, and thermodynamic or electro-dynamic apparatus thus have two distinct functions.

In some instances we may observe a succession of transformations of energy, as where a steam boiler transforms, and stores for transmission to the engine, energy of chemical affinity; the engine, in turn, transforming it into mechanical energy and transmitting it to a dynamo-electric machine, where it is again transformed, changing into the electrical current, to be sent perhaps miles away to an electro-dynamic machine or motor, where its retransformation into mechanical power occurs, and it is set at the work of driving a mill or other collection of mechanisms. A telephone system illustrates in another way similar transformations and retransformations of mechanical and electric energy, and Mr. Hammer has thus produced a system involving many transformations and including a circuit of a hundred miles.

Nature herself has in these cases usually already performed some such transformations of energy in the reduction of that so collected and applied to the form in which the mechanic and the engineer finds it ready to his hand. The water has been raised from the lakes and the sea, and distributed by the clouds to the elevated sources from which it flows downward in the streams; the winds are the result of differences of temperature and the action of heat energy; the heat of combustion is the representative of an earlier form of energy in which the heat of the sun and of the still cooling earth, and the formation of the coal deposits in early geological periods, played a part. In a general way it has come to be seen that every display of energy, like every new form of matter, is the result of change in some antecedent form, and that neither matter nor energy can be destroyed. This has been admitted from the time of Lavoisier, so far as it affects matter; it has been admitted as applicable to physical energy since the doctrines of the correlation of forces and the persistence of energy became accepted by men of science; and we are gradually progressing towards the establishment of a law of persistence of all existence, whether of matter, of force and energy, or of organic vitality, and perhaps even to its extension until it includes intellectual and soul life.

We see that in the beginning there entered upon an existence of indefinite duration a great universe of matter endowed with its characterizing attributes —the forces. These forces, acting upon a definite quantity of matter with definite intensity, give origin to a fixed amount of actual energy, and become capable of producing another fixed quantity of what is now potential energy. Energy thus brought into existence remains constant in total amount as the quantity of created matter remains constant.

The action of these forces upon this matter has given rise to every phenomenon which has come, or which can come, within the range of scientific inquiry.

2. Forces are Classified, according to their methods of affecting matter, into three great classes:

(1) Those forces with which we are able to make ourselves so readily and thoroughly familiar that we find no difficulty in assigning to each of them its proper place in the scheme of scientific systematization, and which we have found it comparatively easy to distinguish by their peculiar and readily observed effects. These include the familiar physical forces, as gravitation, electrical, chemical, and mechanical forces.

(2) The vital forces—those which are preservative of all life, which produce and promote the growth of or-

ganisms having life, and which are less easily understood, more difficult to study, and far less subject to the modifying power of human action, than are those of the first described class.

(3) The forces of the soul and of the intellect—those most wonderful and most mysterious of all known forms of force—forces of the nature of which we know nothing, and of the effects of which, actual and possible, we have the least comprehension.

By the study of the universe as it now exists, philosophers are led to perceive that its present state is such as would have resulted had the various forms of matter with which we are surrounded, and of which we ourselves are corporeally formed, and had other existences which we suppose to form a part of our universe been, at the beginning, so distributed and so placed in reference to the several kinds of forces that the former, acted freely upon by the latter, should, by a continuity of never-ceasing, ever-progressing change, take those infinite variations of growth, and all that inconceivable variety of shapes, that have supposed to have been, by the process called "evolution," brought into the visible universe.*

Studying the accessible universe, as far as we are permitted, in greater detail, we find that each of the various kinds of forces set at work to modify the position and character of matter has a special part to play, a peculiar work to do; we find that the first class has a

* As early as 1854 Helmholtz showed that the condensation of an infinitely diffused nebulous mass of matter, to form the stellar systems of the universe, by gravitation, was sufficient to furnish all existing heat-energy, and a source of all that mechanical and other transformed energy known now to exist.

sphere of operation which is fully within the reach of our senses; that the second class of forces is also, to a certain extent, familiar to us through a knowledge of their effects: but the last of these several classes of forces existing in nature is, as yet, quite beyond our ken.

Studying these forms of manifestation of force which are divided between the first two classes, we perceive a distinction which is as well defined as is the line separating the two classes of phenomena to which they give rise.

(1) The *physical forces*—and it is intended here to include the mechanical and chemical, as well as the forces which are usually alone treated of in works on physics—are capable of being observed, of being distinguished by certain readily defined qualities, and of being accurately measured quantitatively. The conditions which lead to their active display are capable of being exactly ascertained, and the precise results of their operations under any given set of conditions may usually be accurately predicted. These conditions are subject to certain definite modifications by the power of man, and the changes of effect which will result from such changes of condition may be predicted. The effects which nature produces in certain cases by the action of these forces may be modified by man without entirely defeating the original tendency to bring about a certain change of mode of action of existing energy. These forces, acting alone, never give rise to the more intricate forms seen in nature. Their highest product in the whole morphological range is a crystal of more or less perfect shape, but of a form which is always of some simple geometrical class. These forces do not

exhibit the play of definitely directed energy tending to effect a perfectly well defined, though remote, result. Their effects are the accidental and the incidental, so far as the more wonderful and most intricate of the operations of nature are concerned.

(2) The *vital forces*, on the other hand, effect operations which human power can only touch to impede or to destroy. They have for their mission the creation of strangely complicated and curiously organized structures, in which are stored certain definite amounts of energy, and which are given a power of acquiring and of applying extraneous energy, in probably also definite amount, to the accomplishment of certain tasks. Man may modify their operation and may produce some change in the phenomena which they are appointed to bring about; but it is only by deranging their action. He can mar their work, but cannot directly aid them. That store of vital energy which was created in the infinite past, and which is now passing through one after another of the forms of life, new and old, which are constantly coming into the field of our cognizance, and as constantly disappearing from view, is continually developing organisms of every grade from the simple life-seed, if such exist—from the basic protoplasm—to the human ruler of them all.

Of these two sets of forces, the one is blind and aimless, unintelligent as to the direction of its efforts, indifferent as to its results, and is governed by laws which, under all known conditions, are as simple as they are invariable. The other set appears to act at all times upon a definite, far-reaching plan, and these forces set themselves intelligently about the production of the most elegant and intricate of designs, and the elaboration of the most wonderful and mysterious of organisms. It is only in the structures which are their work that the strange, the incomprehensible phenomena of life are exhibited to the intelligence which vainly endeavors to understand them.*

3. **Energy,** "living Force," ever-living force, as we are now learning to regard it; *vis viva*, as its first discoverer, Leibnitz, called it; the force illustrated in all life and motion, as we now know it; *energy*, as Dr. Young first denominated it: all these expressions for one common quality of every body, substance, or system, in motion either as to its atoms or molecules or as to its mass, denote that mysterious property by which all growth, all life, all changes in physical things or physical substance are brought about and continued. The work of the vegetable kingdom, in the elevation of the simpler, inorganic compositions found in nature to the higher, complex, organic forms in which they find their culmination; those of the animal system which take these complex forms and erect them in a still more complicated animal structure and supply it with the powers of animal life; the work of the living creature in again reducing these complicated structures to the lower and simplest forms, availing itself of their latent energy in the production of all the grandest results of physical and intellectual life: all these are but manifestations in various ways of the ever-living forces, the never-ceasing energies, of the universe.

In its two forms, kinetic and potential, actual and

* The preceding matter is from the vice-president's address before the American Association for the Advancement of Science, R. H. Thurston, 1878.

latent, the sum of which is constant throughout the universe, energy is the source and the basis of all life, of all motion, of all development, of all evolution. It is the mainspring of all physical phenomena; and the science of *Energetics* is the foundation of chemistry, as of physics; of astronomy, as of the mechanics of engineering. Whatever we know of matter, even, is discovered to us by these methods of display of energy in connection with it.

The science of energetics itself is one division of a broader science, that of *Mechanics*,—that great science which bears more or less directly upon every phenomenon of nature and the universe, and which is at the foundation of all the applied sciences, of all the arts of construction, of all the exact sciences of physics and chemistry, of astronomy, and of forces and motions.

4. **Mechanics** thus includes four principal divisionse*

(1) *Statics* treats of the relations of forces acting in any system when no motion results from that action.

(2) *Kinematics* treats of the relations of motions simply, of their composition and resolution, and of their resultant effects.

(3) *Dynamics* or *Kinetics* treats of the motions produced in ponderable bodies by the action of forces.

(4) *Energetics* treats of the measurement, the transfer, and the transformations of energy under the action of forces, and of their result in the variation of the method of its manifestation.

5. **Energetics is defined,** therefore, as that science which treats of all natural phenomena which, through

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*Several pages are here taken mainly from "The Manual of the Steam Engine," vol. 1, by R. H. Thurston; N. Y., J. Wiley & Sons.

the action of force upon matter, result in the production of motion; whether it be a relative motion of atoms, of molecules, or of masses. It is that science "whose subjects are material bodies and physical phenomena." * We may here repeat:

Energetics thus treats of modifications of energy under the action of forces, and of its transformation from one mode of manifestation to another, and from one body to another; and within this broader science is comprehended that latest of the minor sciences—of which the heat-engines and especially the steam-engine illustrate the most important applications—*Thermodynamics.* The science of energetics is simply a wider generalization of principles which have been established one at a time, and by philosophers widely separated, both geographically and historically, by both space and time, and which have been slowly aggregated, to form one after another of the physical sciences, and out of which we are slowly evolving wider generalizations; thus tending toward a condition of scientific knowledge which renders more and more probable the truth of a principle, still broader than this science, even, and which was enunciated before Science had a birthplace or a name; i.e.:

All that exists, whether matter or force, and in whatever form, is indestructible by any finite power.

As already remarked, that matter is indestructible by finite power became admitted as soon as the chemists, led by Lavoisier, began to apply the balance, and were thus able to show that in all chemical change there occurs only a modification of form or of combination

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* Rankine; Proc. Phil. Soc. Glasgow; vol. III. No. 6.

of elements, and no loss of matter ever takes place. The "persistence" of energy was a later discovery, consequent largely upon the experimental determination of the convertibility of heat-energy into other forms and into mechanical work, for which we are indebted to Rumford and Davy, and to the determination of the quantivalence anticipated by Newton, shown and computed approximately by Colding and Mayer, measured with great accuracy by Joule and Rowland.

It is now generally understood that all forms of energy are mutually convertible with a definite quantivalence; and it is not certain that even vital and mental energy do not fall within the same category.

The essentially important, as well as interesting, fact, in this connection, to the engineer as well as to the physicist, it should be noted, is that the laws of energetics apply unqualifiedly to atomic and molecular phenomena, as well as to energies of masses, and to all transformations of energy in either class and of any kind. There is, dynamically, absolutely no distinction, in this respect, between the methods and processes of chemistry, of physics, and of the mechanics of masses. All illustrate phases of one science, and all are energies of matter in motion.

6. Matter, Force, and Energy are the only quantities known to the departments of natural science. The science of *Chemistry* deals with the forms which matter assumes under the action of measurable atomic molecular forces affecting dissimilar kinds of matter; *Physics* is that science which deals with all the other forms of sensible force and their effects. The science of *Energetics* treats of the action of forces producing or modifying energy, whatever the kind of force, whatever the kind of mattera it thus covers the whole range of chemistry and physics.

Matter is that which is capable of directly affecting the senses, and which occupies space. Nothing is known of the ultimate nature of matter, and we are acquainted with it only as it affects the organs of the body. It is usually divided into four classes: solids, liquids, gases, and imponderable matter; the latter meaning that which cannot be assigned a finite specific measure of mass or weight. The luminiferous ether is an example of this last; the other three are familiar forms.

A *Body* is a limited portion of matter.

Force is that which produces, or tends to produce, motion, or change of motion, in bodies; it is measured statically by the weight which will counterpoise it or by comparison with a known standard of force, and dynamically by the velocity which it will give a known freely moving mass in a stated time, i.e., by the "accelerationá" which it is capable of producing.

Work is always performed by the expenditure of energy, and is the product of the resistance overcome by a force, or of the effort exerted by it, into the space through which that action takes place. That resistance may be constant, or variable, and due to an active, opposing force, to resisting pressure, to the inertia of masses, or of molecules compelled to submit to acceleration or retardation; or it may be due to any one of the physical or chemical forces. Thus, if U represents the work done by a force, F, acting through a space, s,

$$U = Fs = Rs; \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and for motion variable only,

$$dU = Fds. \qquad . \quad . \quad . \quad . \quad . \qquad (2)$$

For variable forces,

$$dU = sdF. \qquad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

For forces and motion variable,

$$dU = d(Fs) \qquad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

The Unit of Work is the product of the units of its factors force and space, as the foot-pound, the kilogrammetre, the foot-ton, the gramme-centimetre.

Useful Work is that which is applied to the production of a specified useful effect; *Lost Work* is that which is incidentally wasted, in the endeavor to perform useful work, in overcoming prejudicial resistances, and in doing useless work; this waste occurs usually and principally in overcoming friction of moving parts.

Work of Acceleration is work expended in producing increased velocity in a freely moving body. The effort exerted, and the resistance met, is dependent upon the inertia of the mass, and is measured thus: A body moving freely under the action of gravity, i. e., of a force equal to its own weight, acquires, in this latitude, a velocity of 32.2 feet (9.81 metres), nearly, in one second, and the acceleration, or retardation, of any freely-moving body is proportional to the effort applied, as to the resistance met by it. If f is the actual acceleration, if g measures that produced by gravity, if F is the statical measure of the effort, and W is the weight of the body, we have

$$F : W :: f : g; \quad t : 1 :: v_2 - v_1 : f;$$

$$F = \frac{f}{g} W;$$

$$= \frac{v_2 - v_1}{gt} W; \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

v_1 and v_2 being the initial and final velocities, and t the time of action of the accelerating force.

For variable acceleration,

$$f = \frac{dv}{dt}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$F = \frac{dv}{dt} \cdot \frac{W}{g}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The space, s, is equal to $\frac{v_2 + v_1}{2} t$, and the *work* done is, for uniform acceleration,

$$U = Fs = \frac{v_2 - v_1}{t} \cdot \frac{v_2 + v_1}{2} . t . \frac{W}{g}$$

$$= W \frac{v_2^2 - v_1^2}{2g}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

For variable acceleration,

$$U = d(Fs) = W . d . \frac{v^2}{2g} = W \frac{vdv}{g}. \quad . \quad . \quad (9)$$

Since $\frac{v_2}{2g} = h$, the height due the velocity v, the work is equal to that required to raise the body through the difference of the two heights due the initial and the final velocities, respectively.

Where the motion of the machine or of the part doing work is circular, the space traversed may be measured by the angular motion a, multiplied by the lever-arm, l, and their product, multiplied by the force, R, exerted, gives the measure of the work done. Thus:

$$\left. \begin{aligned} U &= aRl \\ &= 2\pi nRl; \end{aligned} \right\} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

in which last expression n is the number of revolutions made in the unit of time.

These values are equivalent to the product of the angular motion into the moment of the resistance.

Work may also be measured, as in steam, air, gas, or water pressure engines, by the product of the area of piston, A, the mean intensity of pressure upon it, p, the length of stroke of piston, l, and the number of strokes made. Thus,

$$\begin{aligned} U &= Apln \\ &= Aps \\ &= pV, \end{aligned} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

when V is the volume of the working cylinder multiplied by the number of strokes; in other words, the volume traversed by the piston.

Where the force acting, or the resistance, acts obliquely to the path traversed, it is evident that only the component in that path is to be considered.

Diagrams exhibiting the amount of work done and the method of its variation are often found useful. In such diagrams the ordinate is usually made proportional to the force acting, or to the resistance, while the abscissas are made to measure the space traversed. The curve then exhibits the relations of these two quantities, and the enclosed area is a measure of the work performed. With a constant resistance, the figure is rectilinear and a parallelogram; with variable velocities and resistances, it has a form characteristic of the methods of operation of the part or of the machine the action of which it illustrates.

Power is defined as the *rate of work*, and is measured by the quantity of work performed in the unit of time, as in foot-pounds or in kilogrammetres, per minute or per second. The unit commonly employed by engineers is the "horse-power," which was defined by Watt as 33,000 foot-pounds per minute, equivalent to 550 per second, or 1,980,000 foot-pounds per hour. This is considered to be very nearly the amount of work performed by the very heavy draught-horses of Great Britain; but it considerably exceeds the power of the average dray-horse of that and other countries, for which 25,000 foot-pounds may be taken as a good average amount.

The metric horse-power, called by the French the *cheval-vapeur*, or *force de cheval*, is about $1\frac{1}{2}$ per cent. less than the British, being 542.47 foot-pounds or 75 kilogrammetres per second, 4500 kilogrammetres per minute, or 270,000 per hour. These quantities are almost invariably employed to measure the power expended and work done by machines.*

* Various nations have a standard "horse-power" derived from Watt's, but, owing to differences in weights and measures, they are not

It is evident that power is also measured by the product of the resistance, or of the effort exerted into the velocity of the motion with which that resistance is overcome or that force exerted. Since $s = vt$,

$$U = Rs = Rvt;$$

and when t becomes unity, the measure of the power, or of the equivalent work done in the unit of time, is

$$U' = Rv,$$

in which the terms are given in units of force and space as above.

The power of a prime mover is usually ascertained by experimentally determining the work done in a given time, the trial usually extending over some hours, and often several days. It is measured in foot-pounds or

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identical; but the differences are usually less than 1½ per cent. The following table, compiled by Mr. Babcock, gives these standards in kilogrammetres per second, and in foot-pounds per second expressed in the foot and pound standards of each country.

STANDARD HORSE-POWER FOR DIFFERENT NATIONS.

COUNTRY.	Kilogrammetres per second.	Baden ft.-pounds per second.	Saxon ft.-pounds per second.	Wurtemberg ft.-pounds per second.	Prussian ft.-pounds per second.	Hanoverian ft.-pounds per second.	English ft.-pounds per second.	Austrian ft.-pounds per second.
France and Baden	75	500	529.68	521.58	477.93	513.53	542.47	423.68
Saxony........	75.045	500.30	530	523.89	478.22	513.84	542.80	423.93
Wurtemberg	75.240	501.36	531.12	525	479.23	514.92	543.95	424.83
Prussia........	75.325	502.17	531.97	525.85	480	515.75	544.82	425.51
Hanover......	75.361	502.41	532.23	526.10	480.23	516	545.08	425.72
England....	76.041	506.94	537.03	530.84	484.56	520.65	550	429.56
Austria	76.119	507.46	537.58	531.39	485.06	521.19	550.57	430

kilogrammetres : the total work so measured is then divided by the time of operation and by the value of the horse-power for the assumed unit of time and the mean value of the power expended thus finally expressed in horse-powers.*

The forces acting in machines are distinguished into *driving* and *resisting forces.* That component of the force, acting to produce motion in any part which lies in the line of motion only, is that which does the work, and this component is distinctly called the "Effort." Similarly, only that component of the resistance which lies in the line of motion is considered in measuring the work of resistance. In either case, if the angle formed between the directions of the motion of the piece and of the driving or the resisting force be called α, the effort is

$$P = R \cos \alpha, \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The other component, acting at right angles to the path of the effort, is

$$Q = R \sin \alpha, \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and has no useful effect, but produces waste of power by introducing lateral pressures and consequent friction.

Energy, which is defined as capacity for performing work, is either *actual* or *potential.*

Actual or *Kinetic Energy* is the energy of an actually moving body, and is measured by the work which it is capable of performing while being brought to rest, under the action of a retarding force ; this work is

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* Custom has not yet settled the proper form of the plural of this word; there is no reason why it should not follow the rule.

equal to the product of its weight, W, into the height, $h = \frac{v^2}{2g}$, through which it must fall under the action of gravity to acquire that velocity, v, with which it is at the instant moving; i.e.,

$$E = U = Wh = W\frac{v^2}{2g}. \quad . \quad . \quad . \quad (14)$$

A change of velocity v_1 to v_2 causes a variation of actual energy, $E_1 - E_2$, and can be effected only by the expenditure of an equal amount of work—

$$E_1 - E_2 = U = W\frac{v_1^2 - v_2^2}{2g} = W(h_1 - h_2). \quad (15)$$

This form of energy appears in every moving part of every machine, and its variations often seriously affect the working of mechanism.

The total actual energy of any system is the algebraic sum of the energies, at the instant, of all its parts; i.e.,

$$E = \Sigma W\frac{v^2}{2g}; \quad . \quad . \quad . \quad . \quad . \quad (16)$$

and when this energy is all reckoned as acquired or expended at any one point, as at the driving-point, the several parts having velocities, each n times that of the driving-point, which latter velocity is then v, the total energy becomes

$$E = \Sigma W\frac{n^2v^2}{2g}.e. \quad . \quad . \quad . \quad . \quad (17)$$

Actual energy is usually reckoned relatively to the earth; but it must often be reckoned relatively to a given moving mass, in which case it measures the work which the moving body is capable of doing upon that mass, when brought by it to its own speed.

Potential Energy is the capacity for doing work possessed by a body in virtue of its position, of its condition, or of its intrinsic properties. Thus, a weight suspended at a given height possesses the potential energy, in consequence of its position, $E = Wh$, and may do work to that amount while descending through the height, h, under the action of gravity. A bent bow or coiled spring has potential energy, which becomes actual in the impulsion of the arrow or is expended in the work of the mechanism driven by the spring. A mass of gunpowder or other explosive has potential energy in virtue of the unstable equilibrium of the chemical forces affecting its molecules. Food has potential energy in proportion to the amount of vital and muscular energy derivable by its consumption and utilization in the human or animal system. These potential energies are not measured by the observed actual energies derived from these substances in any case, but are the maximum quantities possibly obtainable by any perfect system of development and utilization. In practical application, more or less waste is always to be anticipated.

Every instance of disappearance of actual energy involves the performance of work, and the production of potential or of some new form of actual energy in precisely equal amount. A stone thrown vertically upward loses kinetic energy as it rises, in precisely the amount—resistance of the air being neglected—by which it gains potential energy. A falling mass striking the earth surrenders the actual energy acquired by loss of potential energy during its fall, and the equivalent of the quantity so surrendered is found in the work done upon the soil ; it finally passes away as the equivalent energy of heat motion produced by friction and impact. The potential chemical energy of the explosive is the equivalent of the kinetic energy of the flying projectile, and the latter has its equivalent in the work done at the instant of striking and coming to rest, and in the heat produced by the final change of mass-motion into molecular or heat motion.

Work may be defined as that operation which results in a change in the method of manifestation of energy, and Energy as that which is transferred or transformed, when work is done. The motion of a projectile is the transfer of energy from one place to another. It is generated at the point of departure, stored as actual or kinetic energy, transferred to the point of destination, and there restored and applied to the production of work.

Acceleration and retardation of masses in motiont can only be produced by doing work upon them, or by causing them to do work, and thus, by the communication of energy to them or by its absorption from them, in precisely the amount which measures the variation of their actual energy as so produced. Every body which is increasing in velocity of motion thus receives and stores energy ; every mass undergoing retardation must perform work, and thus must restore energy previously communicated to it. In every machine which works continuously, and in which parts are alternately accelerated and retarded, energy is stored at one period and restored at another, in precisely equal amounts.

Work done upon any machine may thus be expended partly in doing the useful work of the system, and partly in storing energy; and the same machine may do work at another instant partly by expending the energy received by it, and partly by expending stored energy previously accumulated.

Storage or restoration of energy thus always occurs when change of speed takes place. It is evident, since the storage or restoration of energy implies variation of speed, that the condition of uniform speed is that the work done upon the machine shall at each instant be precisely equal to that done by it upon other bodies, The work applied must be equal to that of resistance met at the driving-point. Thus,

$$\Sigma Pv = \Sigma Rv'; \int Pdv = \int Rdv'; \quad . \quad . \quad (18)$$

and the effort at each point in the machine will be equal to the resistance, and will vary inversely as the velocity of the point to which it is applied; i.e.,

$$\frac{P}{P'} = \frac{v'}{v}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

In the starting of every machine, energy is stored during the whole period of acceleration up to maximum speed, and this energy is restored and expended while the machine is coming to rest again. This latter quantity of energy is usually expended in overcoming friction.

The useful and the lost work of a machine are, together, equal to the total amount of energy expended upon the machine, i.e., to the work done upon it by its "driver." The *Useful Work* is that which the machine is designed to perform; the *Lost Work* is that which is absorbed by the friction and other prejudicial resistances of the mechanism, and which thus wastes energy which might otherwise be usefully applied. These two quantities, together, constitute the *Total Work* or the *Gross Work* of a machine, or of a train of mechanism. In every case some energy is wasted, and the work done by the machine is by that amount less than the work performed in driving it. In badly proportioned machines the lost work is often partly expended in the deformation and destruction of the members of the construction; in well-designed and properly worked machinery loss occurs wholly through friction. In machines acting upon fluids this work is usually partly wasted in the production of fluid friction—i.e., of currents and eddies; thus producing new forms of actual energy in ways which are not advantageous; even this waste energy is finally converted, like the preceding form, by molecular friction, into heat, and is dissipated in that form of molecular energy. Thus all wasted work is lost by conversion from the energy of mass-motion into molecular energy, and ultimately disappears as heat.

The Efficiency of Mechanism is measured by the quantity obtained by dividing the amount of useful work performed, by the gross work of the piece or of the system. It is always, therefore, a fraction, and is less than unity; which latter quantity constitutes a limit which may be approached more and more nearly as the wastes of energy and work are reduced, but can never be quite reached. If the mean useful resistance be R, and the space through which it is overcome be s', and if the mean effort driving the machine be P, and the space through which it acts be s, the total and the *net* or *use-*

ful work will be, respectively, Ps, Rs'; the *lost work* will be $Ps - Rs'$, and the

$$\text{Efficiency} = \frac{Rs'}{Ps} < 1. \quad . \quad . \quad . \quad . \quad (20)$$

Counter-efficiency, C, is the reciprocal of the effiency; i.e.,

$$C = \frac{Ps}{Rs'}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

The efficiency and the counter-efficiency of a machine, or of any train of mechanism, are the products of the efficiencies or of the counter-efficiencies of the several elements constituting the train transmitting energy from the point at which it is received to that at which the work is done, i.e., from the "driving" to the "working" point.

Friction is the principal cause, and usually the only cause, of loss of energy and waste of work in machinery. A given amount of energy being expended upon the driving-point in any machine, that amount will, in accordance with the principle of the persistence of energy, be transmitted from piece to piece, from element to element, of the machine or train of mechanism, without diminution, if no permanent distortion takes place and no friction occurs between the several elements of the train, or between those parts and the frame or adjacent objects. Temporary distortion, within the limit of perfect elasticity, causes no waste of energy; permanent distortion, however, causes a loss of energy equal to the total work performed in producing it. But permanent distortion is due to deficiency of strength and defective elasticity, and is never permitted in well-designed machinery properly operated; and hence the important principlea

In engineering, the principles of pure mechanism, of theoretical mechanics, and pure theory in the science of energetics, or of thermodynamics, are to be studied as introductory to a science of application in which all actions and all calculations are to be considered with reference to the modifications produced by the wastes of energy and the alteration of the magnitudes and other properties of forces consequent upon the occurrence of friction.

7. **The Laws of Energetics,** the basis of the science which it has been proposed to call by that name, area

(1) *The Law of Persistence, or of Conservation of Energy*:—Existing energy can never be annihilated; and the total energy, actual and potential, of any isolated system can never change.

This is evidently a corollary of that grander law, asserting the indestructibility of all the work of creation, which has already been enunciated.

(2) *The Law of Dissipation, or of Degradation of Energy*:—All energy tends to diffuse itself throughout space, with a continual loss of intensity, with what seems, now, to be the inevitable result of complete and uniform dispersion throughout the universe, and, consequently, entire loss of availability.

It is only by differences in the intensity of energy, and the consequent tendency to forcible dispersion, that it is possible to make it available in the production of work.

(3) *The Law of Transformation of Energy*:—Energy may be transformed from one condition to another, or from any one kind or state to any other; changing

from mass-energy to molecular energy of any kind, or from one form of molecular energy to another, with a definite quantivalence.

These laws lead to the conclusion that, in any isolated system of bodies, or in any isolated mass, the total of all energy present is always the same ; though it may be transformed in various ways, and to an extent only limited by the special conditions affecting the system. They lead to the conclusion that energy of higher intensity than the mean must occupy a limited space, and will continually tend to dissipate itself by dissemination through a greater volume, affecting larger and larger quanties of matter, with proportional reduction of intensity, until the whole system is occupied by the originally existing energy, at a finally uniform and minimum intensity. Energy confined within a limited space thus continually tends to expand, and to break through its boundaries, and, if not freed from this constraint, it produces a pressure upon the surrounding surfaces, which, e.g., is exhibited as tension of enclosed vapors and gases. Freed from confinement, it tends to indefinitely expand.

Either form of energy may produce either other form under suitable conditions.

Rankine's statement of the "General Law of the Transformation of Energy" is as follows:*

"The effect of the whole actual energy present in a substance, in causing transformation of energy, is the sum of the effects of all its parts."

The *axiom*, as Rankine calls it, that "any kind of energy may be made the means of performing any kind

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* Proc. Phil. Soc. of Glasgow ; vol. III. No. 5 ; 1853.

of workä' is derived by "induction from experiment and observation," and confirmed by all experience.

The Sources of Energy are: (1) Potential: (*a*) fuel; (*b*) food; (*c*) head of water; (*d*) chemical forces. (2) Actual: (*a*) air in motion; (*b*) gravity in waterfallsą (*c*) tides.

8. "**Newton's Laws**" follow directly from the general law of persistence of energy, a corollary to which may be stated thus: Change of energy can only be produced by the action of force, and by doing work. *Newton's Laws* are:

(1) A free body tends to continue in the state in which it, at any instant, exists, either of rest or of uniform rectilinear motion.

(2) All change of motion in a body free to move is proportional to the force impressed, and is in the direction of that force.

(3) The reaction of the body acted upon by the impressed force is equal, and directly opposed, to that force.

Inertia is that property, observed in all bodies, in consequence of the existence of which they are capable of exhibiting the action of these laws. The laws of Newton themselves are all easily verified by experiment. The "Atwood Machine," illustrated in nearly all works on physics, is constructed for this special purpose.

While Newton's laws are readily verified by experiment, the more general laws of energetics are accepted simply as being in accordance with universal experience. The generally accepted theory of the constitution of matter being assumed as a premise, however, the general laws of energy are all easily deducible from Newton's laws. Thus, the first law is but a differently worded statement of Newton's three laws combined.

To assert that every moving body tends to persist in its rate of motion, exerting an effort always equal to the retarding or accelerating force, and exerting such effort in the line of action of such force, is to assert that its energy can only be altered by the performance of an equivalent amount of work, and an equal amount of energy of opposite sign ; and this latter assertion is a declaration of the indestructibility of energy. To assert that all bodies, whether masses or molecules, when in motion tend to move in rectilinear paths, is to assert a tendency to unlimited dissipation of energy through space. To assert that all matter in motion is subject to Newton's laws is to assert the laws of universal conservation of energy, and of the quantivalence of all transformations, as stated in the third general law. Whenever it becomes established that any phenomenon, as the transfer of heat, of light, of electricity, or of sound, is a mode of motion affecting bodies of whatever class, Newton's laws bring that phenomenon within the scope of the general laws of energy. Every phenomenon, molecular or other, which involves relative motion of masses, vibrations of parts, or pulsations in fluid media, is now well understood to be subject to these laws.

9. **Algebraic Expressions** of the transformability of the energies are now readily deduced. If in any isolated system a certain quantity of energy exists, homogeneous in character and heterogeneously distributed; and if, by any process, other and various forms of energy appear in that system, these latter must be the result of transformations of parts of the initial stock of energy by conversion into the new

forms. But every such change must be effected by a perfectly definite and exact quantivalence.

Assuming this ratio of values of customary units reduced to a system of equivalents, it becomes at once practicable to measure all these energies in the same units; as, for example, when Joule measures either heat or mechanical energy, taking $J = 778$ foot-pounds, as the equivalent of a British thermal unit, or $J =$ about 427 *kilogrammetres*, as the equivalent of one calorie or metric thermal unit; the thermal unit being defined as the quantity of heat or energy-equivalent demanded to raise the temperature of unit weight of water one degree from the temperature of maximum density.

Taking either kind of unit in thus measuring, we shall have the initial stock of the one kind of energy altered by the quantity which, in the same units, measures the aggregate several quantities of energy resulting from the change; and

$$dE = \frac{dE}{dT}dT + \frac{dE}{dU}dU + \frac{dE}{dV}dV +, \text{etc.}; \quad . \quad (1)$$

where E, T, U, V, etc., are the symbols representing the several energies, initial and other.

If T measure heat-energy, and U be taken as potential energy of the molecular kind, V the potential energy of an elastic fluid varying in volume, W the work of some mechanism or a dynamic process, the total variation of the initial energy E, will be equal to the total of all the new energies and the new work, in proportions which become known as soon as the partial coefficients $\frac{dE}{dT}$, etc., are determined.

If two energies only, as thermal and mechanical, are affected, and if the original stock were simply heat-energy, we should have a change, dE, in the initial stock of heat-energy, which would be the precise equivalent of the sum of the two changes taking place, simultaneously, in the initial store and in the temperature, T, of the system, and in work by the change of volume, V, against a pressure of, say, the intensity p. Then, obviously,

$$dE = \frac{dE}{dT}dT + \frac{dE}{dV}dV; \quad . \quad . \quad . \quad . \quad (1)$$

and, since $\left(\frac{dE}{dT}\right)_v$ measures the specific heat, K_v, for constant volume, and as $\left(\frac{dE}{dV}\right)_T$ must measure the intensity of pressure producing, or resisting, the change of volume,

$$dE = K_v dT + p dV. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If but one kind of transformation occurs, as by conversion of any original form of energy, E, into work, a process illustrated in every purely thermodynamic, thermo-electric, or electro-dynamic operation,

$$dE = p dV; \text{ or, } dE = R dS. \quad . \quad . \quad . \quad (3)$$

Whatever the method of transformation of actual energy, it is simply a process of transfer of the energy of motion from one kind of matter to another, or from a mass to a collection of molecules, with, usually, modification of the mode of motion, as from rectilinear to vibratory, or from motion in an orbit of one form to movement in a path of different character.

10. The Object of all Mechanism is to produce a certain definite motion of some part or parts—the position and form and the methods of connection of which are known and fixed—against any resistance that may be met with in the course of such movement. Every machine and every train of mechanism is therefore a contrivance by means of which energy or power available at one point, usually in definite amount and acting in a definite direction and with definite velocity, is transferred to other points, there to do work of definite amount, and there to overcome known resistances with known velocities.

The object of the engineer in designing mechanism is to effect this transfer of energy and these transformations at the least cost and with least "running expense," and hence with maximum efficiency of apparatus. It is often important to secure minimum volume and weight of machine, as well as maximum effectiveness in operation.

The work of a machine is measured by the magnitude of the resistance encountered and the velocity with which it is overcome. The nature of the work, aside from its simple kinetic character, is as widely variable as are the details of human industry.

Prime Movers are those machines which receive energy directly from natural sources, and transmit it to other machines which are fitted for doing the various kinds of useful work. Thus, the steam-engine derives its power from the heat-energy liberated by the combustion of fuel; water-wheels utilize the energy of flowing streams; windmills render available the power of currents of air; the voltaic battery develops the energy of chemical action in its cells; and, through the movement of electro-dynamic mechanism, this energy is communicated to other machinery, and thus caused to do work.

Machinery of Transmission is used in the transformation of energy supplied by the prime mover into available form, for the performance of special kinds of work, or for simple transmission of power from the prime mover to machines doing that work.

11. The Sources of Energy, applied by man, through the prime movers, to the economic purposes of life, are six in number:

(1) The potential energy of fuel, coming of the storage, in early geological periods, of the actual energy of the heat, light, and chemical forces of the sun's rays, and the energy of the dispersing internal heat of the earth, gathered up by the vegetation, and, in case of the mineral oils, possibly, by the animal life, of those primitive ages, reduced to this potential form and stored in the depths of the earth for use in modern times. Very possibly a still earlier history of this energy may be traced in the gradual transformation of the potential dynamic energy of a chaotic universe, infinitely dispersed, into the heat-energy of collision of particle with particle, and of globe with globe, as the existing systems of worlds took form. The potential energy of fuel is converted by combustion into active form.

(2) The dynamic, the kinetic, energy of falling water, transferred through water-wheels without transformation, to do useful work.

This has a similar origin to the preceding; the water being raised from the seas, lakes, and streams to the clouds by the action of the heat of the sun, thus carried to the higher portions of the land, again to return in the streams to the sea-level.

(3) The kinetic energy of the air-currents, as utilized by windmills, which convert it to useful purposes precisely as the water-wheel intercepts the energy of falling water with a similar end.

The primary source of this energy is again the heat of the sun, which produces a convection of air-currents similar dynamically, in method and result, to those of water in the ocean or over or on the land.

(4) The energy of the tides, the rise and fall of which constitute a source of power less easy of utilization than that of streams, and for this reason, rarely applied to the production of power.

The origin of this energy is in the force of gravitation as it acts upon the ocean, changing its level through the attractions of the sun and the moon. This is seen to be essentially different from the other cases.

(5) The energy of electricity, originally exhibited either in the form of molecular energy resulting from chemical action, or produced by transformation directly from the dynamic form. In this latter case, the machine transforming it is an intermediate or a secondary, instead of a prime, motor. In the former case the origin is potential, in the latter kinetic.

(6) The energy of muscular action, the power of animals, derived from the chemical forces acting in the production of vegetation and transformed for use in the animal system, through either thermo-electric or thermodynamic processes, or perhaps through the action of both, each having its appropriate task.

In the animal system, the vegetable matter employed as food is converted by the natural forces of digestion and nutrition into available form for use by the nervous and muscular systems of the body, by means of intermediate processes which are as yet obscure. It is only certain that they cannot all be thermodynamic processes; it seems probable that they are, in some cases, at least, related to the electrical methods of transformation. In some instances, as in the carnivora, the final conversion results from a double transformation,

Thus substantially all utilized natural energy is derived, directly or indirectly, from the sun.

According to Sir William Thomson, "the mechanical value of a cubic mile of sunlight is 12,050 foot-pounds, equivalent to the work of one horse-power for a third of a minute. This result may give some idea of the actual amount of mechanical energy of the luminiferous motions and forces within our own atmosphere. Merely to commence the illumination of three cubic miles requires an amount of work equal to that of a horse-power for a minute; the same amount of energy exists in that space as long as light continues to traverse it; and, if the source of light be suddenly stopped, must be emitted from it before the illumination ceases." *

The same authority says: "Taking the estimate 2781 thermal units centigrade, or 3,869,000 foot-pounds,

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* The mechanical value of sunlight in any space near the sun's surface must be greater than in an equal space at the earth's distance, in the ratio of the square of the earth's distance to the square of the sun's radius, that is, in the ratio of 46,400 to 1, nearly. The mechanical value of a cubic foot of sunlight near the sun must, therefore, be about .0038 of a foot-pound, and that of a cubic mile 560,000,000 foot-pounds. Similarly we find 15,000 horse-power for a minute as the amount of work required to generate the energy existing in a cubic mile of light near the sun.—*Thomson.*

as the rate per second of emission of energy from a square foot of the sun's surface, equivalent to 7000 horse-power,* we find that more than 0.42 of a pound of coal per second, or 1500 lbs. per hour, would be required to produce heat at the same rate. Now if all the fires of the whole Baltic fleet were heaped up and kept in full combustion over one or two square yards of surface, and if the surface of the globe all round had every square yard so occupied, where could a sufficient supply of air come from to sustain the combustion ?—yet such is the condition we must suppose the sun to be in, according to the hypothesis now under consideration, at least if one of the combining elements be oxygen or any other gas drawn from the surrounding atmosphere."

12. **The Forms of Motor,** the special machines through which these transfers and transformations are effected, are the followinga

(1) *The animal body* is a vital machine, of extra-ordinary complexity, self-constructing and self-repairing, and is automatic in its many and usually mysterious internal processes.

This machine is directed by conscious intelligence and will, and, when usefully applied to the production of work, is guided by the mysterious action of the mind. It effects conversions of energy through the processes of chemical action peculiar to the animal system.

(2) *The heat-engines,* including steam-, air-, gas-, and vapor-engines of various less familiar kinds.

In these machines, the potential energy of fuel is, by combustion, converted into the active form, and stored

* This is sixty-seven times the rate at which energy is emitted from the incandescent electric lamp at the temperature which gives 240 candles per horse-power.

in a gaseous or vaporous fluid, the variations of temperature, pressure, and volume of which result in the production, more or less efficiently, of mechanical power in readily applicable form.

The heat-engines do by far the greater part of the work of the world, and the steam-engine the main portion of that performed by thermodynamic operations.

Solar engines, so-called, are heat-engines in which the direct heat energy of the sun, instead of the stored heat energy of a combustible, is utilized through the action of a working fluid, as with other forms of machine of this class.

(3) *The water-wheels*, including the various classes of so-called vertical wheels, and the turbines; in which latter, the water, instead of entering “buckets,” to be again poured out of them, passes continuously through channels, without reversal of motion.

These machines effect no transformations of energy; but simply turn it out of its natural course into an artificial channel of application. It is kinetic, as found, and remains kinetic until transformed in the course of its application to its intended purpose.

(4) *Tidal machines* are simply floats, rising and falling with the tides; or they are vertical water-wheels, working in tidal currents in precisely the same manner as those operated by ordinary running streams. They transfer, but do not transform, energy.

(5) *Windmills* are pneumatic turbines, especially fitted to take up the energy of moving air, and to transfer it, without transformation, to machinery of transmission, through which it is conveyed to its point of application.

(6) Electrical engines, electro-dynamic machines, dynamos and motors, as they are variously called, are

apparatus for transformation, converting the molecular energy of electricity into the mechanical form in such manner as permits its useful employment.

These machines, reversed, change the energy of mechanical power into the electrical form, and both directions of transformation in well-designed machinery result in a very efficient conversion of energy. As a rule, it is found much more satisfactory to derive the energy, initially, from a prime mover, by conversion into the electrical form, than to obtain it directly from the voltaic battery. Water-power or the combustion of fuel is vastly less costly than the combustion of zinc and the saturation of acids with its salts.

The purpose of this discussion is to describe, briefly and exactly, the characteristics of the animals as motors, to describe their methods of action and their sources of gain and loss of energy, and to present the principles of energy-production and transformation illustrated by them.