A New Auxanometer.¹

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With two Figures in the Text.

HAVING regard to the slow rate of growth usually obtained under laboratory conditions, and the small magnifications effected by existing auxanometers, an endeavour has been made to design an instrument which will record the growth of the plant on a much larger scale, that is with a much higher 'magnification' than has, as far as the author is aware, ever been attempted hitherto, and which will at the same time allow of the observation extending, if necessary, over a period of at least three or four days. Although the form of apparatus to be described can claim no advantage over its predecessors in the matter of simplicity, the manipulation should present no difficulty after the first setting up, and the care necessary will not seem disproportionate when the fact is taken into consideration that the instrument is capable of magnifying the growth to such an extent that its representative length on the recording graph may be varied at will from 20 to 100 times the actual increase in length of the plant.

An experimental instrument fitted with everything except the compensating gear for the stretching of the fibres has shown itself capable of giving smooth curves on the recording sheet for periods of two days with a magnification of fifty, and has been checked by a Ganong auxanometer working on the same plant; but as, owing to the present conditions, only a rough working model has so far been constructed, the present account must be looked upon as merely preliminary.

The chief features in the new instrument are as follows:

1. The magnification is not produced by concentric pulleys of different radii arranged as in Ganong's instrument, nor by a lever as in Farmer's, but by employing a differential pulley, the plant being (indirectly) connected by

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a fibre to the hook which usually carries the load, while the inking pen is attached to the thread on which the 'work' is done.

2. The inking mechanism, to avoid friction, does not travel on a vertical wire as in Ganong's instrument, but runs horizontally on a mono-rail, two-wheeled trolley.

3. The pen on the trolley travels over a rotating drum which is actuated by a large falling weight and made to revolve once in twelve hours by a clock mechanism; and

4. The particular arrangement of pulleys over which the fibres pass forms a complete compensating mechanism for general expansions and contractions in the fibres, so that no error is introduced by variations in the relative humidity of the surrounding atmosphere.

FIG. 1.

Fig. 1 is a diagrammatic representation of the instrument, showing only the essential features without the compensating gear for changes in length of the fibres. A fibre attached to the tip of the plant round a cotton-wool pad passes over the two pulleys A and B, and down to the hook which carries the pulley C. The pulley C is in the loop of a thread Q R, of which the end R passes round one of the grooves of larger radius of the differential pulley E, while the end Q passes round a groove of smaller radius in the opposite direction. Each end passes about one turn round its own groove and is then affixed to the rim of the pulley. Round that groove on E which has the largest radius passes a fibre U, one end of which is affixed to the pulley, while the other is attached to the trolley F. The

latter runs on two grooved wheels on the single rail K, and carries a glass pen L (see inset, Fig. 1), the point of which rests on the drum G. G revolves once in 12 hours and possesses clips, which are not shown in the figure, for affixing graph paper. As the plant grows the pulley C drops by the same amount as the plant apex rises. Suppose the plant apex rises and the pulley C falls a distance d , then if the thread R passes round a groove on E of radius r_1 , Q round a groove of radius r_2 , and U round a groove of radius R, it can be easily shown that the trolley F and pen L

move along the drum a distance $\frac{2 d R}{r_1 - r_2}$. For, if the pulley E turn through one complete revolution, F moves a distance $2 \pi R$ (to the left, say), the thread R descends a distance $2 \pi r_1$, and the thread Q ascends a distance $2 \pi r_2$. C descends a distance equal to half the difference between the distances moved by the threads Q and R, $= \frac{1}{2} \{2 \pi r_1 - 2 \pi r_2\} = \pi (r_1 - r_2)$. The magnification or ratio

distance moved by F / distance moved by C $= \frac{2 \pi R}{\pi (r_1 - r_2)} = \frac{2 R}{r_1 - r_2}$, so that if the plant grow a distance d the pen moves a distance $\frac{2 d R}{r_1 - r_2}$. When the plant

grows it allows the differential pulley to turn so that the trolley F carrying the pen may move over the drum. The movement is produced by a small hanging weight N, and communicated to the trolley by means of the fibre S which passes over the pulley M. In order that there may be no undue strain on the plant, the weight N is such that it only just exceeds the value of the limiting friction of the trolley and pulleys. With the same object the weight D is provided to counterbalance the weight of C.

As the pen moves along and the drum G revolves, a spiral line is traced out, the pitch of the spiral representing the twelve hours' growth multiplied by $\frac{2 R}{r_1 - r_2}$. The pulley E is made with five separate grooves

of radii 5 cm., 4.9 cm., 4.8 cm., 4.6 cm., and 4.0 cm. (see inset to Fig. 1), so that any desired magnification may be obtained by using appropriate pairs or threes of the grooves. Any of the fibres may be affixed to any of the grooves on E, the end of each fibre being provided with a little hook which fits into a notch on the circumference and so facilitates the operation of altering the magnification. At T is a clock-work mechanism for rotating the drum. It is actuated by a heavy weight (not shown) hanging on the end of a flexible brass wire which passes round a drum at H. The weight is wound up by the handle P. The pulleys throughout are mounted on needle or 'frictionless' bearings.

In the apparatus in its simplest form as described above, it will be noted that any stretching of the fibres due to changes in humidity in the atmosphere all acts in the same direction, namely to make the growth appear *too much*, and as the magnification is large, and there is great length

of fibre, the error introduced would be serious in accurate work. In order to compensate for the variability in the lengths of the fibres the arrangement employed is that seen in Fig. 2. In this figure it will be observed there is no longer a single continuous fibre from the plant apex to the pulley C as in Fig. 1, but there are three distinct fibres X_1X_2 , Y, and Z. The fibres X_2 and Y when they reach the pulley A pass round it a few turns and then become attached to its rim. Similarly the fibres Z and X_1 pass round the pulley B a few turns and are then also attached. In each case the two fibres run round the pulley in the same groove and in the same direction, but the pulleys A and B, instead of being simple, as in Fig. 1, are now double, each possessing two distinct grooves of the same radius and side by

side (see inset, Fig. 2). In the second groove of each pulley there is attached a fibre running in the opposite direction to the other two, which when it leaves the pulley hangs down and carries a small weight. The weights V, V' carried on these fibres are exactly equal, and their function, which will be more fully understood later, is to maintain a tension in X_1X_2 . The reason that v and v' run in separate grooves on the pulleys A and B is to avoid friction with the other fibres, and to prevent the possibility of those which are being wound on to the pulleys becoming superposed on those which are leaving. The grooves are figured, for the sake of clearness (in Fig. 2), as if they were of different radii, but this is not actually so, their

FIG. 2.

radii being, as already stated, exactly equal. As in Fig. 1, the pulley C is counterbalanced by the weight D, and, when the plant grows, is allowed to fall by the same distance as the stem apex rises. Now that the nature of the pulleys and connexions is understood it will be readily seen from the figure that stretching in the fibres Y and Z will tend to make the reading *too large*, while stretching in the fibre X_1X_2 will tend to make the reading *too small*. Also stretching in Q R, which in this respect acts like a single fibre of length x (see Fig. 2), tends to make the reading *too large*. For compensation, therefore, the length of X_1X_2 must be made equal to the sum of the lengths x , Y, and Z. As the growth of the plant and fall

of C are small compared with the length of x , this relation holds sensibly true throughout the experiment.

If the only possible source of error were that introduced by stretching of the threads consequent upon changes in the relative humidity of the atmosphere, this condition would be sufficient in itself to ensure compensation; but as the fibres are also liable to stretch as a result of the tensions to which they are subjected, complete compensation will only be obtained if the average of the tensions in the fibres Z , Y , and $(Q+R)$ taken together be made equal to the tension in the fibre X_1X_2 . This condition is secured by giving appropriate values to the weights v , v' and w (Fig. 2), and these values are determined as follows:

Suppose the tension maintained in the fibre U by the weight $N = t$. Then the tension in Z will be equal to the weight of $C + \frac{2tR}{r_1 - r_2}$, and the tension in $Q = \text{tension in } R = \frac{tR}{r_1 - r_2}$.

As $v = v'$, the tension in X is only due to the weights v , v' , and we have

$$\left. \begin{aligned} T_Y &= W \\ T_X &= v' \\ T_Z &= C + \frac{2tR}{r_1 - r_2} \\ T_{(Q+R)} &= \frac{2tR}{r_1 - r_2} \end{aligned} \right\} \begin{aligned} &\text{where } C \text{ represents the mass of the pulley } C, \text{ and} \\ &T_X, T_Y, \&c., \text{ represent the respective tensions in the} \\ &\text{fibres } X, Y, \&c. \text{ For equilibrium a weight } w_3 \text{ is} \\ &\text{provided, equal to } \frac{2tR}{r_1 - r_2}. \end{aligned}$$

For compensation (see above),

$$T_X = \frac{T_Y + T_Z + T_{(Q+R)}}{3}$$

$$\text{i. e. } v' = \left\{ W + C + \frac{2tR}{r_1 - r_2} + \frac{2tR}{r_1 - r_2} \right\} / 3.$$

$$= \left\{ W + \frac{4tR}{r_1 - r_2} + C \right\} / 3, \text{ or collecting the constant quantities,}$$

R, r_1, r_2, t , and C to one side of the equation, we get

$$3v' - W = \frac{4tR}{r_1 - r_2} + C.$$

With the exception of the value of t , which can be found by preliminary experiment in a manner to be described later, all the quantities on the right-hand side of this equation can be easily found by direct measurement or weighing, so that for perfect compensation a weight w is placed in the scale-pan, which satisfies the above equation using the given values of v and v' . If the tension produced in Y be found insufficient, or great enough to harm the growing point, the weights v and v' may be altered and the corresponding value for w again found from the equation and placed in the scale-pan. The value of v is of the order five to ten grammes,

and w may be anything from about 1.5 grm. down to 0.5 grm. or less, according to the nature of the plant on which the experiment is conducted.

All stretching of the fibres is now compensated for except that of the fibre U , which connects the trolley and differential pulley. Stretching here is far less serious than elsewhere as it is not magnified by the instrument. It will be seen that, supposing the instrument be magnifying the growth a hundred times, even if the fibre stretch as much as the plant grows (which it is very unlikely to do) the error will only be one per cent., and is therefore scarcely worth correcting for. With lower magnifications and any very accurate work, however, the error may be completely eliminated by using a control fibre. A fibre 10 cm. long attached to a trolley of its own running on a rail by the side of the first may be fixed to a special hook on the stand carrying the differential pulley and be subjected by similar means to the same tension as the first fibre. The expansions and contractions of the control fibre are recorded at one end of the drum, and if they amount to anything appreciable, the correction for the particular length of the fibre U which has run out from E at any moment may be calculated and added or subtracted from the recorded reading as the case may be. In order to facilitate the determination of the length of U a scale of centimetres is provided beside the rail K , the zero-mark being perpendicularly below the bearings of E . When only a twelve hours' observation is taken and the travel of the trolley is large, the paper on the drum, when unfolded, will reveal two graphs which may be added together algebraically to give the correct curve.

Before an experiment, when no plant is connected with Y and the scale-pan w is empty, small weights are gradually added to a light scale-pan hanging at N , until the weight is found which will *just* set the experimental trolley and differential pulley, &c., in motion. Let the weight found = w_1 . Next the weight is found which sets the trolley in motion when disconnected from the differential pulley. Let this weight = w_2 . Then, when the whole apparatus is fitted up for an experiment, and the weight in the scale-pan at N is w_n , the tension in the fibre U is given by the equation $t = (w_n + w_1) - (w_n + w_2)$, where w_n is the weight of the scale-pan at N .

$$\text{i. e. } t = w_1 - w_2.$$

This is the value of t which should be substituted in the expression

$$3V' - W = \frac{4tR}{r_1 - r_2} + C,$$

when finding the correct value of w which ensures compensation in the fibres Q , R , X_1X_2 , Y , and Z (Fig. 2). With a given value for the weights V and V' , therefore, the complete working equation for w is as follows:

$$W = 3V' - \left\{ \frac{4R(w_1 - w_2)}{r_1 - r_2} + C \right\}.$$

This, and the equation for the magnification, namely

$$M = \frac{2R}{r_1 - r_2},$$

are the only equations needed in the practical work.

A brief outline will now be given of the method of manipulation of the instrument. The chief points in the preparation for an experiment may be enumerated as follows:

1. Weigh the pulley C.
2. Connect the fibres Q, R, and U with grooves on E which give the desired magnification.
3. Place the plant in position and measure the distance Y from its apex to the pulley A.
4. Find the sum of the lengths x and Z by measuring from the centre of E to the centre of B, and subtracting the length of the mounting of C.
5. Calculate $x + Y + Z$, and move the pulley O until $X_1 + X_2 = x + Y + Z$. (During these operations, pulleys which have loose threads on them may be clamped, if necessary, by special provisions to prevent them being turned by unbalanced weights.)
6. Attach the weights v and v' .
7. Find the weight w_1 with the trolley detached.
8. Find the weight w_2 which turns all the pulleys when the trolley is attached to E. The value of w_2 may be incorrect for two reasons: (a) the friction of the pulleys A and B will be less than during the experiment, as the weights w and w_3 are not yet in place, and (b) because the friction of the pen L on the drum will be greater than during the experiment as the drum is at rest instead of in motion. As the weights w and w_3 are very small compared with the other weights producing friction in A and B, namely, v , v' , C, and D, the difference in friction values due to their absence will be practically negligible, and the speed of revolution of the drum being also very small, the two errors may be taken as counterbalancing one another. If they do not counterbalance, the calculated value of w will be too small (assuming the errors due to friction in A and B to be the most serious), and w may be increased by a few milligrammes at the beginning of the experiment. This will overcome the friction of A and O, and so restore the slight tension in the thread Y.
9. Calculate the value of t and the tension in Z due to t alone (i.e. $\frac{2tR}{r_1 - r_2}$). Counterbalance this tension by a suitable weight placed in the scale-pan at w_3 . Also use the equation to find w . If the value found be suitable, place the weight in the scale-pan; if unsuitable, repeat the operation with a different value for v and v' .
10. Attach Y to the growing point.
11. Adjust O very slightly until F is at the correct end of the drum.

12. Set the drum in motion.

At this point the whole system is in equilibrium, for in the cases of A and B the moments are equal in the two directions and the tension in Z has been arranged to counterbalance exactly the tension in U. When the plant grows the tension in the fibre Y is released so that the moments of the forces tending to turn A to the right become greater than those tending to turn it to the left. A therefore turns to the right and increases the tension in X_2 . This increases the tension in X_1 and turns the pulley B to the right, allowing C to fall. The tension in Q R falls so that E revolves to the right as a result of the tension in U. The length of U is therefore increased so that the trolley F moves over the drum. When the trolley reaches the end of its travel it automatically stops the clockwork so that further rotation causes no unnecessary lines on the graph, and the record may be removed at the operator's convenience.

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