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# IMPORTANCE OF STABLE EFFORT FOR RESEARCH PRODUCTIVITY

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A common complaint of people who do R&D work in various organizations is that ups and downs in financial support have debilitating effects on the progress of their work. This is heard in industrial laboratories, in universities, and in government laboratories. If it were not so widespread, it might be dismissed as self-serving comment. However, an underlying mechanism is involved that will be discussed here. This mechanism accounts for the universality of the complaint.

Another commonly heard statement is that interruptions associated with committee meetings, administrative chores, and the like, "leave no time to get research done". This response which is partly subjective appears to be stronger than would be expected if the effect were proportional to the relative amounts of time that are involved. That is, the effect appears to be non-linearly related to the cause. it will be argued here that the mechanism underlying this complaint is closely related to that of the first one.

The model that will be described is based on the simple, but non-intuitive, fact that time lost during a slack period cannot be regained simply by increasing effort at a later time by an amount equal to the amount of decrease in effort that has occurred during the slack period. As a result, short and long term fluctuations in research efforts have markedly negative effects on productivity. These effects are permanent unless the slack periods are deliberately counteracted by increased levels of effort that are larger than an amount equal to the foregoing decrease. Conversely, productivity should increase significantly if means can be found to reduce fluctuations in efforts. This is one of the motivations for studying the behavior of the model.

Research work is inherently sequential. It involves overcoming a series of obstacles that must be approached one after the other. This cannot be avoided because a subsequent obstacle does not become well-defined until the preceding one has been overcome. Thus, unlike manufacturing, research work does not lend itself to being speeded up by doing several operations in parallel. And the rate at which it achieves progress depends on the instantaneous effort that is put into it.

<u>Linear Case</u>

We shall begin by defining "effort" as the difference between the total man-months expended in research work, and the non-discretionary man-months associated with administrative tasks. If these are called E, M, and M*, respectively:

$$E = M - M^* \tag{1}$$

where $M^* \leqslant M$.

The research effort that is expended is expected to make progress toward a goal. The goal may be a completed study, an experiment, an invention, a developed prototype, or some other item. Progress will be represented by p; and rate of progress dp/dt by $\phi$. For the first part of the discussion it will be assumed that the rate of progress is proportional to the effort:

$$\phi = AE \tag{2}$$

where A is the proportionality constant.

It is more realistic for $\phi$ to be a non-linear function of E. This will be considered after some discussion of the linear case has been given.

As effort is expended and progress occurs, a result, R will be reached after some time has passed. If the effort is steady, at a level $E_o$, and $\phi = f(E) = AE$, then the time needed to reach R will be: $t_o = R/AE_o$, or $R/\phi_o$.

If the effort is not steady, but fluctuates as indicated in Figure 1 with an amplitude $\epsilon$, the time to reach R becomes:

$$t_1 = \frac{R}{\phi_o}\left[1 - \left(\frac{\epsilon}{\phi_o}\right)^2\right]^{-1} \tag{3}$$

and the average rate of progress is:

$$\langle \Phi \rangle = \frac{R}{t_1} = \Phi_0 \left[ 1 - \left( \frac{\epsilon}{\Phi_0} \right)^2 \right] \tag{4}$$

This expression indicates that if the fluctuations in effort are small compared with the base level they have little effect on $\langle \Phi \rangle$. But it should also be noted that if the fluctuations become large enough, the average rate of progress drops to zero. It has been assumed for simplicity that square-wave fluctuations of constant amplitude and wavelength occur, but this could be generalized to more complex cases. It is apparent that if the effort drops below the nominal $E_0$ for a time, and then simply recovers to the $E_0$ level, the average rate of progress will be still less. The point being made here is that even if the fluctuations in effort are symmetric there still is a loss in the rate of progress. And it can be substantial.

The importance of discretionary time can be seen by substituting Equation (1) into (4) which yields:

$$\langle \Phi \rangle = \Phi_0 \left[ 1 - \left\{ \frac{\epsilon}{A(M_0 - M^*)} \right\}^2 \right] \tag{5}$$

This equation demonstrates the interaction that occurs between fluctuations in effort and reductions in discretionary time. If $(M_0 - M^*)$ is small, then the average rate of progress can be quite small even if the fluctuation amplitude, $\epsilon$ is small. As $M^*$ becomes nearly equal to $M_0$, the rate-of-progress approaches zero. This tends to happen all too often in organizations where the appearances of work are allowed to become more important than the work itself.

Non-linear Case

When $\Phi$ depends non-linearly on E, the effect of fluctuations can become much larger. A function that describes the expected features is one that Shockley (1) proposed in his study of the productivities of research workers:

$$\Phi = \Phi_m e^{-\beta/E} \tag{6}$$

Here, $\Phi_m$ is the maximum possible rate-of-progress, and $\beta$ is a parameter that measures the difficulty of making an invention, or accomplishing some other complex result; it is the analog of the activation energy in thermal reaction systems. E is the effort as before. The form of this function is shown graphically in Figure 2.

The reduced rate-of-progress, $\Phi/\Phi_m$ is shown as a function of the ratio of the effort E, to the difficulty parameter $\beta$. The plotted curve indicates that a threshold amount of effort is required before the rate-of-progress becomes significant. A measure of this threshold effort is the point of inflection of the curve (where the third derivative becomes zero). This inflection point lies at $E/\beta = 1/2$.

With this non-linear progress function, if the effort is steady, the rate-of-progress is:

$$\Phi_0 = \Phi_m e^{-\beta/E_0} \tag{7}$$

However, if the effort fluctuates as in Figure 1, the average rate-of-progress becomes:

$$\langle\Phi\rangle = \frac{2\Phi_m}{\left[e^{\beta/(E_0+\epsilon)} + e^{\beta/(E_0-\epsilon)}\right]} \tag{8}$$

and if the fluctuation amplitude is expressed as a fraction of the steady-effort level, and called x, then $x = \epsilon/E_0$, and an expression for the reduced rate-of-progress may be written:

$$\frac{\langle\Phi\rangle}{\Phi_0} = \frac{2}{\left[e^{-\frac{\beta}{E_0}\left(\frac{x}{1+x}\right)} + e^{+\frac{\beta}{E_0}\left(\frac{x}{1-x}\right)}\right]} \tag{9}$$

This is plotted in Figure 3 for a few values of the ratio of the difficulty parameter to the steady-effort level. The plots show that the effect of a given fluctuation amplitude effort becomes increasingly large as the relative difficulty of the task increases. This is consistent with intuition, of course. Notice also that the fluctuation amplitude at which the rate-of-progress becomes negligible decreases rapidly with increasing relative difficulty. Thus, the more difficult it is to achieve a given result, the more important it is to maintain a steady level of effort. In addition it should be a high level.

The relative difficulty can be increased in either of two ways; by increasing the difficulty parameter, or by decreasing the level of steady effort.

Figure 3 also shows the importance of keeping M* small so it does not subtract from $M_0$ any more than is absolutely necessary.

Summary

It is shown that productivity is reduced by fluctuations in effort even if the effort fluctuates symmetrically both above and below a steady level. If the rate-of-progress is proportional to the effort (linear case), small symmetrical fluctuations have only small effects. For a more realistic non-linear dependence, fluctuations can have much larger effects: particularly when difficult tasks are being engaged. These effects are exacerbated by reductions in discretionary time.

## FIGURE CAPTIONS

Figure 1 Square-wave fluctuations in effort as a function of progress.

Figure 2 Normalized rate-of-progress as a function of normalized effort. $\Phi_m$ is the maximum possible rate; and $\beta$ is a parameter that measure the difficulty of achieving a given result (goal).

Figure 3 Effect on the effort fluctuation amplitude on the average rate-of-progress. $\Phi_o$ is the rate-of-progress when the effort is steady (zero fluctuations) at the level, $E_o$.

Acknowledgment

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## REFERENCES

(1) W. Shockley, Proc. of IRE, 45, 279 (1957).

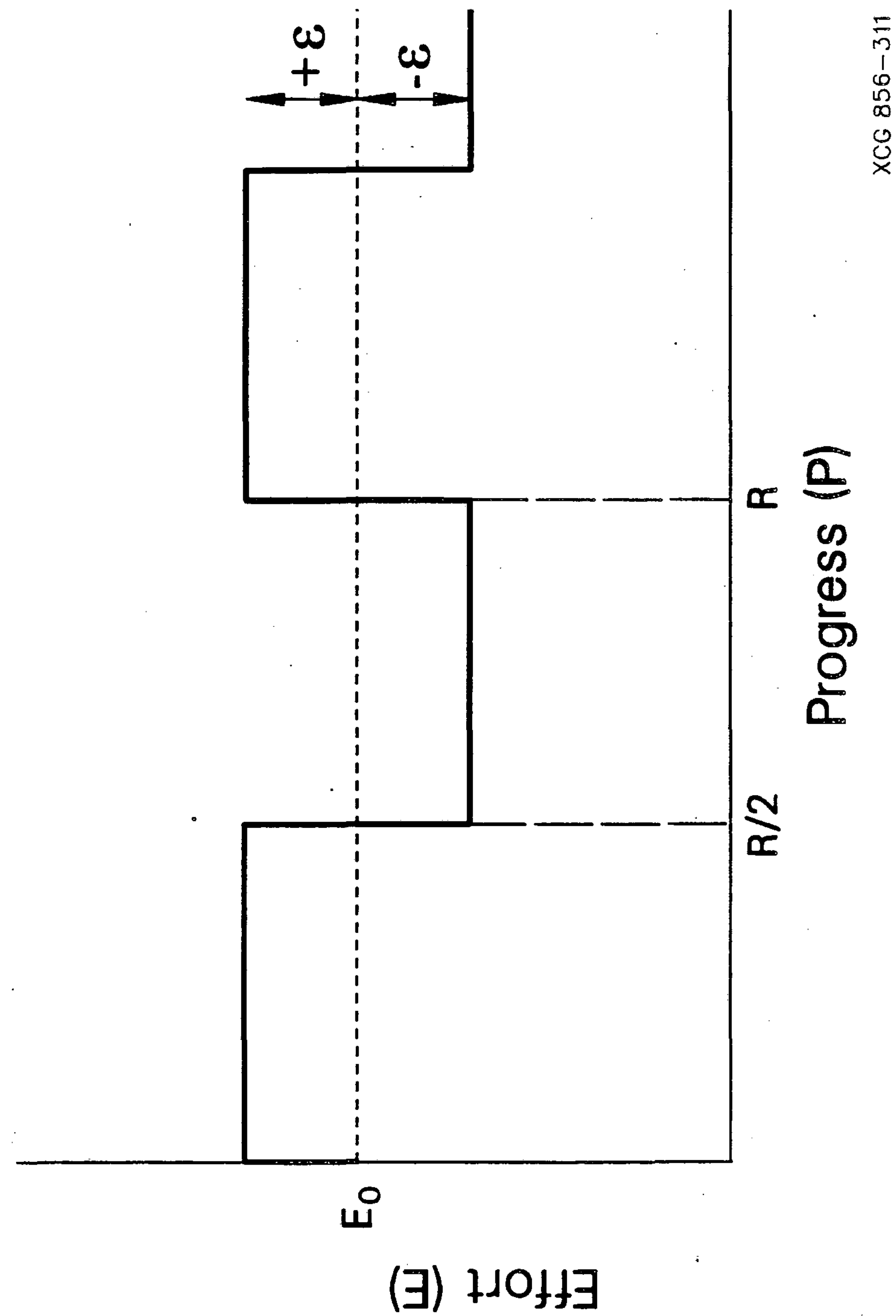


Figure 1

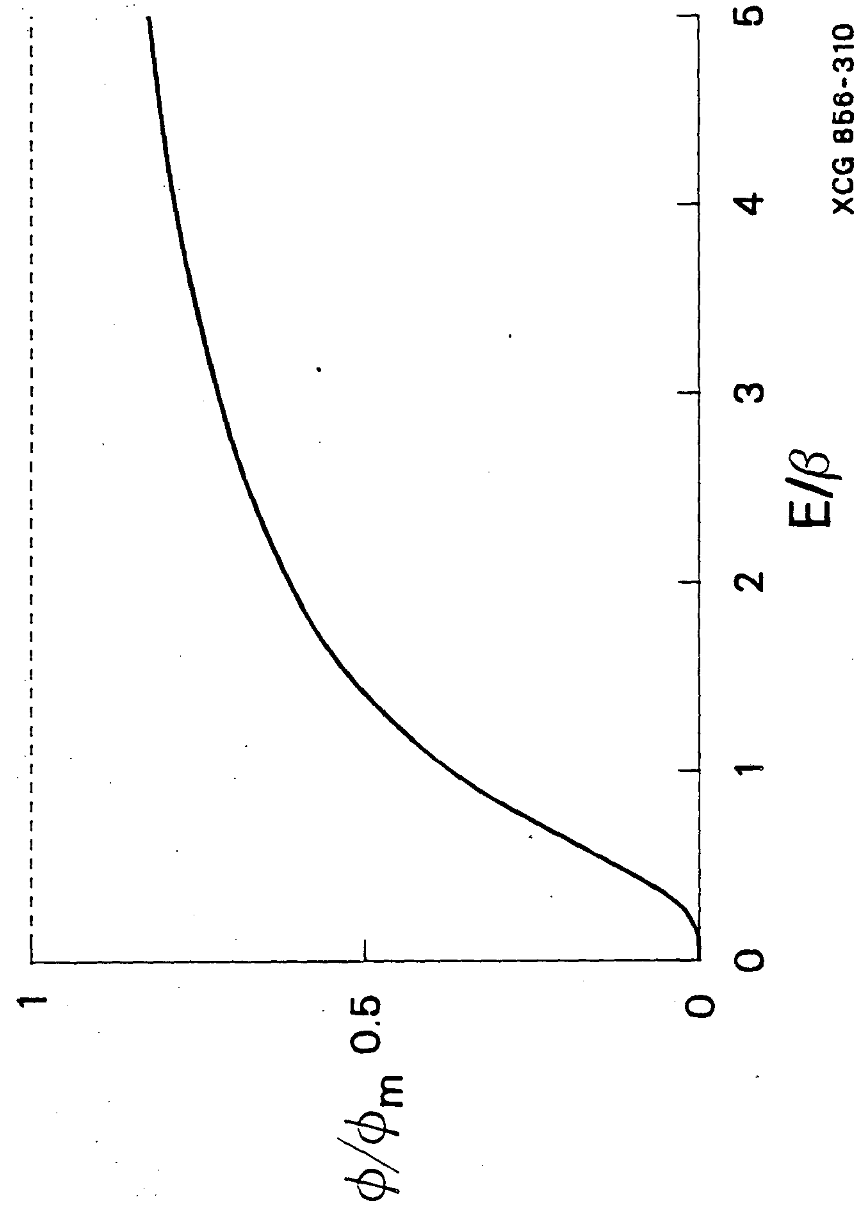


Figure 2

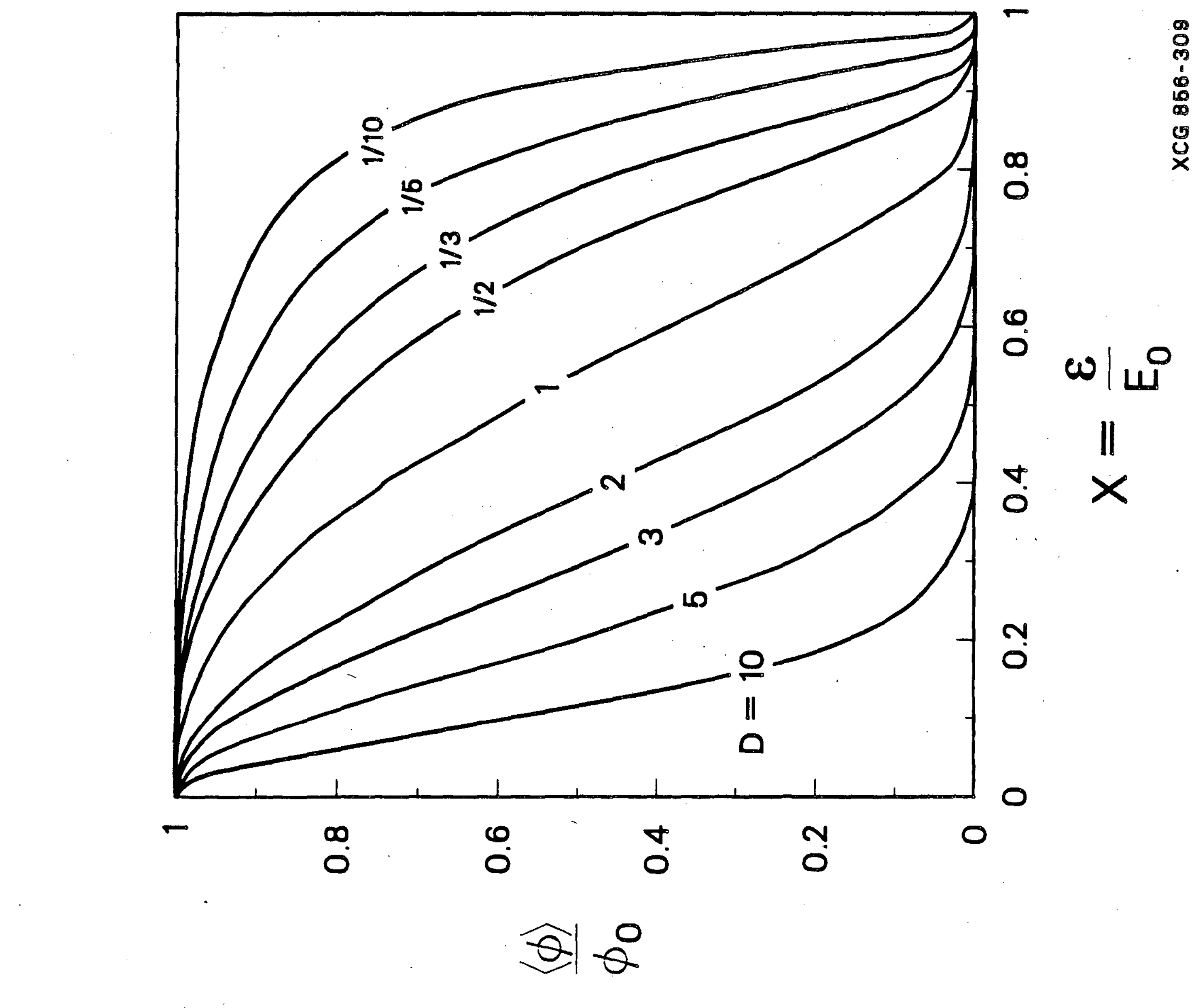
D = 10
5
3
2
1
1/2
1/3
1/5
1/10
0
0.2
0.4
0.6
0.8
1
$X = \frac{\varepsilon}{E_0}$
$\frac{\langle\phi\rangle}{\phi_0}$
XCG 856-309

Figure 3

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