Technological Progression:

SOME CRITICAL THRESHOLDS[1]

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INTRODUCTION

This paper examines the progression of two classes of technology: technologies of operations, these being events which take place at work centers; and technologies of systems, these being events which take place at the interfaces between work centers. For both, it will be argued that the capital cost of each successor technology has been greater than for that of its predecessor, while useful life has been shorter, with cost and time respectively increasing and decreasing at exponential rates.

TECHNOLOGIES OF OPERATIONS

Weapons

In 1957, a colleague and friend, Dr. Joseph F. McClosky, presented a paper in which he showed that technological developments in weaponry have been characterized by successively greater capital costs and successively shorter periods of battlefield dominance.[2]

If one may define a weapon as a means of delivering some form of missile against a quarry or foe, and if some historic license may be permitted in confining exemplification to "milestone events," McClosky's thesis may be illustrated by proceding from the first stone conveniently siezed and thrown by aboriginal man, costing nothing and still occasionally useful but by no means dominant, to the pointed and fire-hardened spear, thence to bow and arrow, to cross-bow and catapult, to the smooth-bore muzzle-loaded musket, shaped-cartridge breech-loaded rifle, machine gun and cast steel cannon, manned bomber, guided missile, and finally to the ICBM armed with multiple thermonuclear warheads.[3]

The appearance of each of these required technological capability and capital beyond any of its predecessors, each made its immediate predecessor more quickly obsolete, and was itself more quickly superseded. The multiple-warhead thermonucler ICBM, with coomsday potential, comes close to the ultimate threshold of infinite first cost and infinitesimal "useful" life.

Graphic Arts

The same kind of sequence of cost and time can be recited for the technologies associated with creating and duplicating written and pictorial images upon surfaces of various kinds. Ancient clay tablets were followed by the technology of the scribe, who required parchment or paper upon which to write, ink, reed or quill pen, and a plane surface upon which to work, simple tools and talents were, however, swept into virtual discard[4] by the much more complex technology of Johann Gutenberg, which required an alloy of lead, tin and antimony, die casting of variable width characters of uniform height and rectilinear precision, a system of assembly into words and justification to lines of equal length, a tacky ink to adhere to metal surfaces, and a press to impart the necessary impression.

In the composing room, Gutenberg's movable type superseded perhaps a millenium of scrivening but it was destined to yield to much more complex machines in less than half that interval. Ottmar Mergenthaler's Linotype and Tolbert Lanston's Monotype, both exceedingly complicated mechanisms, appeared respectively in 1885 and 1897 and hand composition forthwith became an adjunct to the keyboarding, justifying, and casting capabilities of these new technologies. Now, less than a century later, these "merchants of alphabets" have rapidly given way to photocomposition, computerized justification, facsimile transmittal, and multifont optical scanning.

Comparable progression also can be recited for the multiplicative operations of printing. Block printing, in which the inked image was transferred to paper or parchment by brushing, was followed by the hand operated platen introduced in the 15th century, and thereafter in increasingly rapid succession by the sheet-fed flat-bed cylinder press, by "perfecting" presses which print on both sides of the paper, by curved plates to make high-speed rotary operation possible, and by the web-fed milticolor colossuses to be found in mass producation pressrooms throughout the world. These processes of image multiplication, possibly because of later beginnings, have obsolesced somewhat less dramatically than those for image making but they were similarly threatened by new techniques of chemical and magnetic deposition and, most of all, by the ubiquitous power of audiovisual transmission, capable of the simultaneous duplication of millions and millions of images throughout the world and, for that matter, into the reaches of outer space.[5]

Other Operation Technologies

Similar scenarios of escalating first costs and diminishing longevity could be presented for other technologies as well: for the spinning of thread and weaving of cloth, for metal cutting, for transportation, for communication, and for computation, to name a few which have been examined in varying degrees of detail. Time and space, however, do not permit such excursions without encroachment upon discussion of the technologies of systems, to which we now turn.[6]

TECHNOLOGIES OF SYSTEMS

The technologies described so far have been capable of only single classes of operations: typesetting, printing, spinning, weaving, metal cutting. Most products--and nearly all transactions as well--require sequences of operations. Cloth is not the result of just spinning and weaving but of a sequence of operations among which spinning and weaving are but two. Books are set in type and printed but these two operations are preceded and succeeded by editing, copy preparation, art work, proofreading, correcting, photoengraving, page make-up, platemaking, lockup, folding, gathering, sewing, and the multiple operations of case binding.

This list may seem long enough, indeed over long, but it is in fact incomplete, and touches only primary manufacturing operations. There are also essential logistical and control sequences: a multiplicity of events which, related one to another and another, comprise <u>inter</u>operation technologies, technologies of <u>systems</u>.

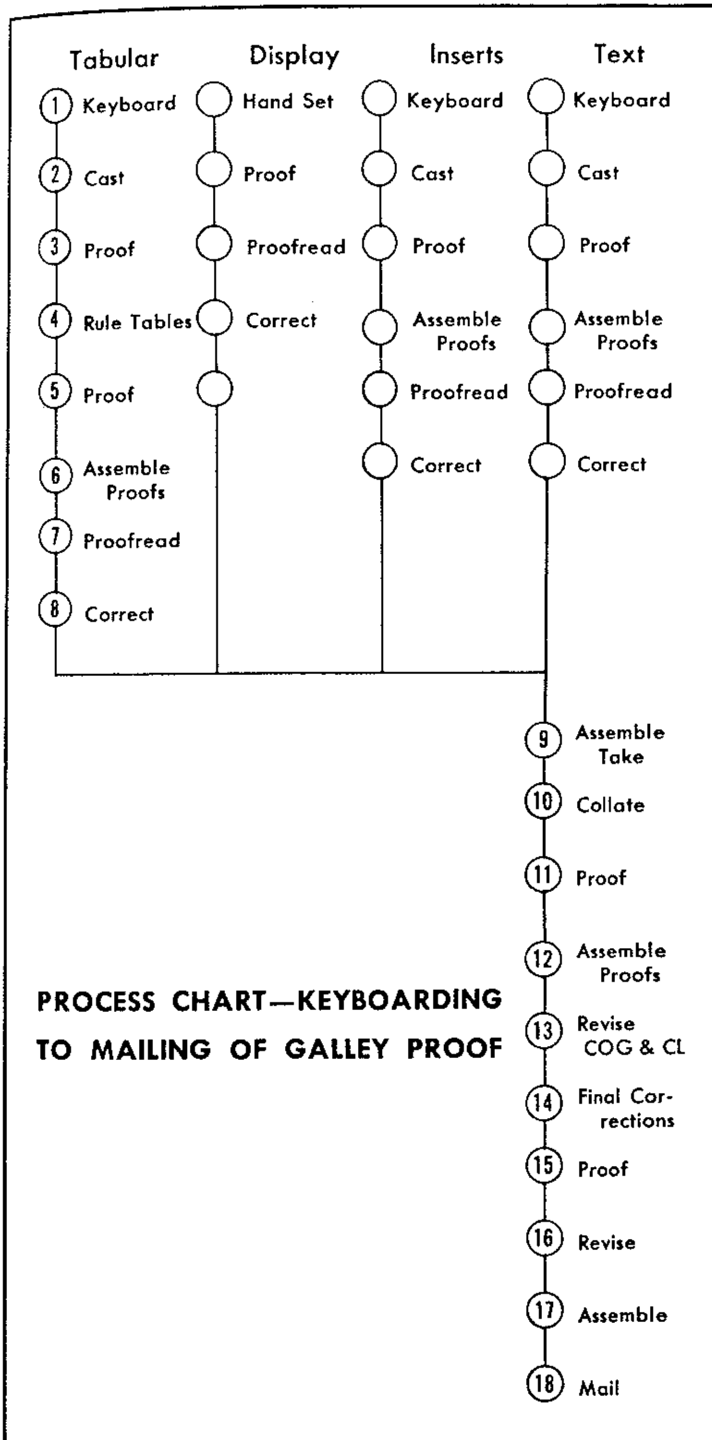
Even in organizations of modest size these interoperation relationships are made complex by sheer weight of numbers, a fact not comprehended, understood, nor appreciated by most people. Automobiles, ships, and aircraft are recognized as products of thousands of component, related operations but few realize that the match they strike and discard has found its way into their hands as a consequence of many hundreds of staffing, supply, production, and control operations. As Allport has pointed out, the Bronx apartment dweller expects to find the morning milk and newspaper at his door but has no comprehension of nor interest in the complex events which put them there.[7]

The Adjacent Operation Interface

The essence of system technology lies at the interfaces between adjacent pairs of sequential operations, in the manner shown by the hold dots of Fig. 1. Each interface or link in the sequential network involves the following components:

- <u>a</u>. Perform Operation No. 1,
- <u>b</u>. Await move to Operation No. 2,
- <u>c</u>. Move to Operation No. 2,

Fig. 1. Process chart showing the operations required to compose and assemble the type for a manuscript containing tables, display (i.e., large sizes of type), inserts (subsidiary matter), and text. The sequence shows 35 component operations between each pair of which is an interface involving the delays and transportations of the kinds detailed in Figs. 2 and 3. (Reproduced from Robert H. Roy: Management of Printing Production, Washington, Printing Industry of America, Inc., 1953, p. 103.)



PROCESS CHART—KEYBOARDING TO MAILING OF GALLEY PROOF

d. Await Operation No. 2,

e. Perform Operation No. 2.

To each of these five steps may be assigned values of time, and, in the case of c, distance.[8] Elements a and c obviously require positive units of time--an operation cannot be carried out in nothing flat. Elements b, c, and d can sometimes have zero time or distance but cannot be negative; usually these values are positive and sometimes both time and distance dimensions are large. As will be shown, the characteristics of elements b, c, and d determine the system technology.

Jobbing Operations

In the parlance of manufacturing, the term "jobbing" is applied to those enterprises which produce work to specifications set by their customers, a definition which at once implies that the products to be made will be varied in design, in quantity, in urgency, and--most importantly--in the times required for performance of individual operations. Because of this inherent variability, jobbing is the most complex of system technologies with respect to operational control. Jobbing is also the oldest of system technologies and the least costly in capital requirements. By this means much of the world's work is still done.

To meet varying demands, jobbing establishments usually consist of assemblages of general purpose machines arranged in specialized departments: linotypes, hand composition, proof room, press room, bindery, in a printing plant; molding, foundry, welding, machine shop, assembly, paint shop, in a metal working organization. Factories of this kind are arranged according to the processes performed, like machines and like operations are grouped together and work is moved from department to department in the sequence called for by each order. There are often patterns to these sequences but they are by no means always the same, variation and back-tracking are quite common.

Adverting now to the five-element interoperation sequence described above, departmentalization by process means that the time and distance dimensions for element c, move to the next question, cannot be zero. Both must be positive.

Analogously, under the conditions of operation variability which define jobbing production, the time dimensions for the waiting elements b and d can be zero only if the move from Operation No. 1 to Operation No. 2 is commenced at the instant of completion of Operation No. 1, and if work upon Operation No. 2 is begun precisely at the instant of arrival.

Thus, the jobbing manager, confronted with the variable operational demands of customers' orders, must strike a balance between conflicting values: the costs of delays to work in process on the one hand versus the costs of labor and equipment idleness on the other. Usually the costs of idleness are greater, or appear to be, than the costs of delay, hence every work station or department in a jobbing plant, except in times of slack demand, has beside or within it a reservoir, back-log, or queue of work awaiting processing. Before Operation No. 1 is a back-log of orders awaiting commencement of work, before Operation No. 2 is back-log from Operation No. 1 or elsewhere, Operation No. 3 has its queue as well, and so on to the reservoir of finished work awaiting the final operations of packing and shipping.

In jobbing systems these queues usually are long; not uncommonly the overall time interval between commencement of a customer's order and delivery to him will be divided into fractions of only 5 to 10 per cent for the performance of production operations and 90 to 95 per cent in post- and pre-operation delays. The small portion of a flow process chart shown in Fig. 2, which is a detailed expansion of a portion of the operation process chart shown in Fig. 1, is typical of delay phenomena in jobbing operations.

From this actual example, the situation at adjacent operation interfaces in jobbing production may now be generalized, as shown in Fig. 3. These dimensions of time and distance are representative of <u>all</u> jobbing technological systems, of <u>all</u> of the innumerable operation interfaces in formal organizations of <u>every</u> kind.

<u>Integrated, Balances, and Continuous Systems</u>

The attributes of jobbing systems have been explored not only because much of the world's work is carried on by these means but also because jobbing is the progenitor of all other

Fig. 2. Portion of a flow process chart showing the detailed operation, temporary storage, and transportation requirements for a second correction rework cycle which, if inserted in Fig. 1, would fall between Operations 8 and 9. All of the time intervals are approximate but are reasonably representative of cycle components. Operation times total 4.1 minutes, transportations total 1.7 minutes, inspections (proof revisions) 1.2 minutes, while delays aggregate 154 minutes, or about 95 per cent of total time for the complete cycle. (Reproduced from Roy, p. 134).

Type		First Correction Proof		Second Correction Proof	
Time in Min.	Operation	Time in Min.	Operation	Time in Min.	Operation
		0.6	Revise first corrections		
		27.0	Wait to be moved to composing room		
		0.3	Move to composing room		
		60.0	Wait to be corrected		
0.5	Get type off location, move to frame				
3.5	Correct	3.5	Correct		
0.1	Move to proving rack	0.1	Move to proving rack		
120.0	Wait to be proved	120.0	Wait to be proved		
0.6	Pull proof				
0.5	Return to location	20.0	Wait to be moved to proof room	20.0	Wait to be moved to proof room
	Wait for collation	0.3	Move to proof room	0.3	Move to proof room
		27.0	Wait to be revised	27.0	Wait to be revised
		0.6	Revise	0.6	Revise

LEGEND

- (O) Operation
- (T) Transportation
- (TS) Temporary Storage
- [1] Inspection

Fig. 3. Flow process chart of a typical two-operation interface in jobbing production. Descriptors for the time intervals generalize the kinds of data shown in Fig. 2.

Distance	Time	Symbol	Element Description
----	Extremely Variable	1	Perform Operation No. 1
----	Variable and likely to be large	TS	Await move to Operation No. 2
Variable, occasion- ally large	Variable, occasionally large	T	Move to Operation No. 2
----	Variable and likely to be large	TS	Await Operation No. 2
----	Extremely Variable	2	Perform Operation No. 2

Fig. 4. Distance and time comparisons for operations, temporary storages, and transportations for integrated, balanced, and continuous systems. The symbol means that contiguous operations need not have exactly equal time requirements in balanced systems but must be identically equal in continuous systems.

Integrated Systems		Balanced Systems		Continuous Systems		Symbol	Element Description
Distance	Time	Distance	Time	Distance	Time		
------	Constant T_1 may or may not = T_2, etc.	-------	Constant $T_1 \approx T_2$, etc.	-------	Constant $T_1 \equiv T_2$, etc.	1	Perform Operation No. 1
------	Small	-------	Approaches Zero	-------	In effect, these disappear, becoming part of the successive operations	TS	Await move to Operation No. 2
Small	Small	Approaches Zero	Approaches Zero			T	Move to Operation No. 2
------	Small	-------	Approaches Zero	-------		TS	Await Operation No. 2
-------	Constant T_2 may or may not = T_3, etc.	-------	Constant $T_2 \approx T_3$, etc.		Constant $T_2 \equiv T_3$, etc.	2	Perform Operation No. 2

system technologies which can be identified today. Integrated, balanced, and continuous systems, to be discussed now, have affected operations at the work place but their most profound effects have been at the adjacent operation interface.

In contrast to jobbing systems, integrated, balanced, and continuous system technologies require stability in demand as well as stability in operation, so that systems can be designed to meet the needs of products instead of the whims of individual customers. In these forms of system technology the time and distance dimensions between adjacent pairs of operations exhibit the characteristics shown in Fig. 4.

Integrated Operations

The development of mass markets, the exercise of management decisions to produce for these markets, and more intensive specialization, standardization, and interchangeability have combined to make possible integrated system technologies. These are systems in which personnel, equipment, sequences, and arrangements are selected, designed, and positioned for the execution of particular products or tasks.

It is difficult to say when integrated production was first achieved. Probably some astute jobbing manager observed that many orders, although different in many ways, were alike in some, these following identical paths during parts of the journey through the overall process. Having made this observation, he could then decide that for these invariable sequences work could be rearranged.

The particular operations utilized in this repetitive way could be removed from their several separate departments, where they had been placed according to process, and put cheek-by-jowl in the order required by the fixed sequence. Thus, if most orders, during some part of their passage through a mental working shop, called for a sequence of lathe, shaper, milling machines, and grinder, these machines could be juxtaposed, so that work completed on the first could be put down at the second, then at the third, and so on. By this means the distance and time dimensions for these inter-operation moves could be greatly reduced.

Although the exploitation of partial integration within jobbing technologies may have been the starting point for more complete systems of kind, this remains conjectural. Of greater interest here, perhaps, are two historical examples of integrated systems technologies: Oliver Evans's "Merchant Mill," designed and built in 1784-85 on Red Clay Creek in Newcastle County, Delaware, for the milling of grain into flour;[9] and the integrated rail mill begun in 1866 at Steelton, Pennsylvania, for the production of Bessemer steel rails.[10]

These examples of early integrated systems may serve to give some flavor of origin and development but they are inadequate to portray the dominance of this form of system technology in our society today. Not only are products of every kind manufactured by integrated sequences, there are also integrated systems of other kinds: bank clearing house procedures, travel and hotel reservation systems, and the billing and collection operations of department stores, public utilities, and retail chains of various kinds. These exemplify system technologies in which information is, in effect, the product which flows through the integrated process, more often than not aided by the computer.

Balanced Systems

In some cases the successful development of an integrated technology has been followed by attainment of balance between the component operations. Design of such a balanced system is difficult, requiring measurement of the performance times of each component, according to procedures enunciated by Frederick W. Taylor,[11] followed by grouping the components in such a way that each group requires the same or almost the same time interval.

Nevins reports the achievement of this as long ago as 1804 in, curiously enough, the making of biscuits at the British Naval Arsenal at Deptford and, in Cincinnati just after the Civil War, in the slaughtering, dressing, and packing of hogs.[12]

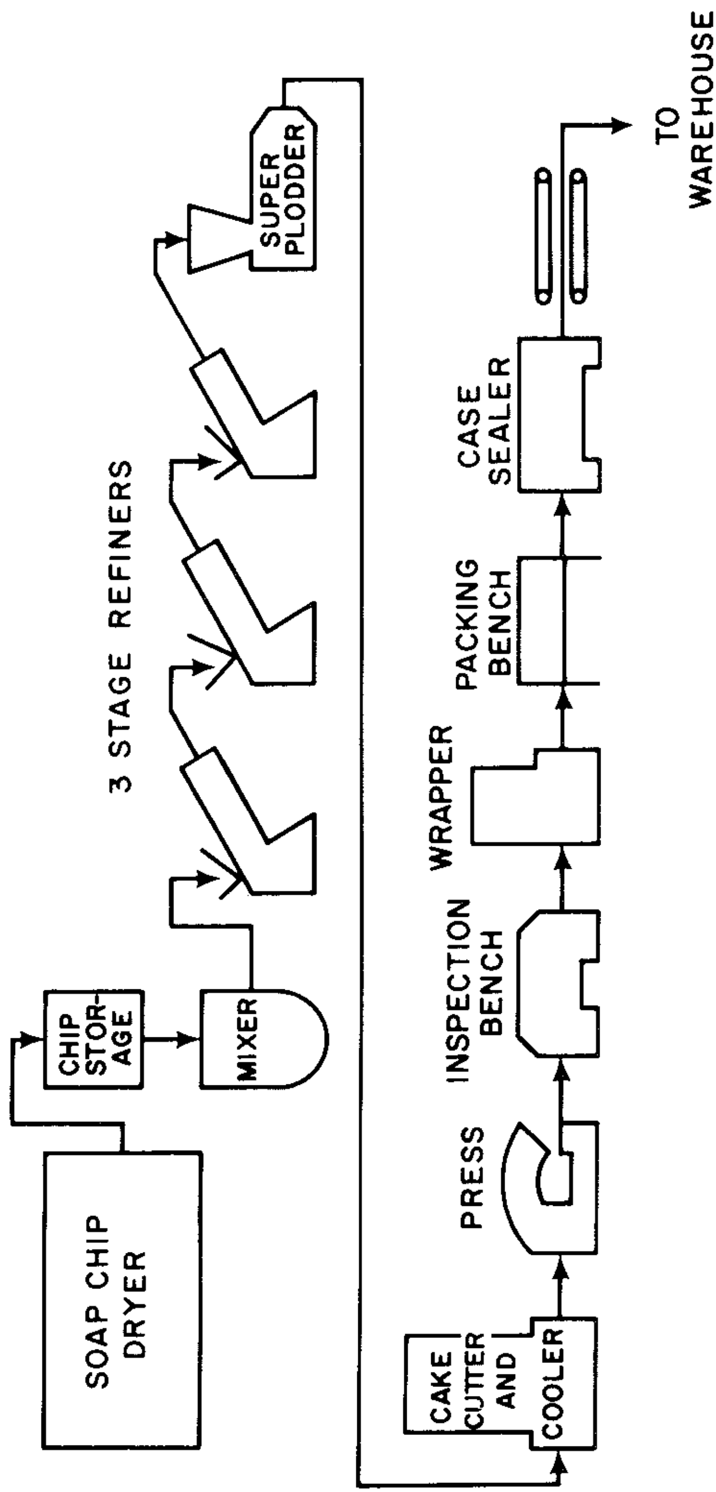
This was a "disassembly" line but most integrated and balanced systems have been the opposite of this--in assemblies of many kinds. The most famous of these, of course, were the moving assembly lines for the Model T Ford development at the Highland Park plant of the Ford Motor Company about 1912.[13]

All of the ingredients to make possible this development were evident: and exploding mass market for a highly successful design, the ultimate in standardization by production of only a single model, and realization of completely interchangeable parts, all combined with resourceful and imaginative management, capable of deciding what to make and how to make it.

Production control in a balanced system technology is of the utmost simplicity in the sense that products once started into the flow can be expected to emerge at the output end, without tracing or expediting during the interim. To gain this advantage--a very great advantage relative to jobbing technologies--the input of work to each station must be constant and assured. Let there by a lack of materials, tools or parts at any single station (or a breakdown) and the entire process will halt, incurring thereby a very costly delay. Indeed, this is the very essence of balanced system technologies: reduction of the delay dimensions at each operation interface to or nearly to zero, an attainment accompanied by the risk of very large and very costly delays to the system as a whole, should any single station fail to perform its appointed task. Because of this, designs for balanced systems are difficult, shake-down periods are always strenuous and sometimes protracted, and operations personnel are subject to the tensions of keeping going, always keeping going. Supervisors of balanced systems must worship at the shrine of continuous operations.

Transfer Machines

Fig. 5. Terminal operations in the manufacture of cake soap. Preceding operations and those through the mixer are batch processes, but all of the succeeding operations until the soap is placed in the warehouse for aging are in balanced sequence. (Courtesy Lever Brothers Company.)

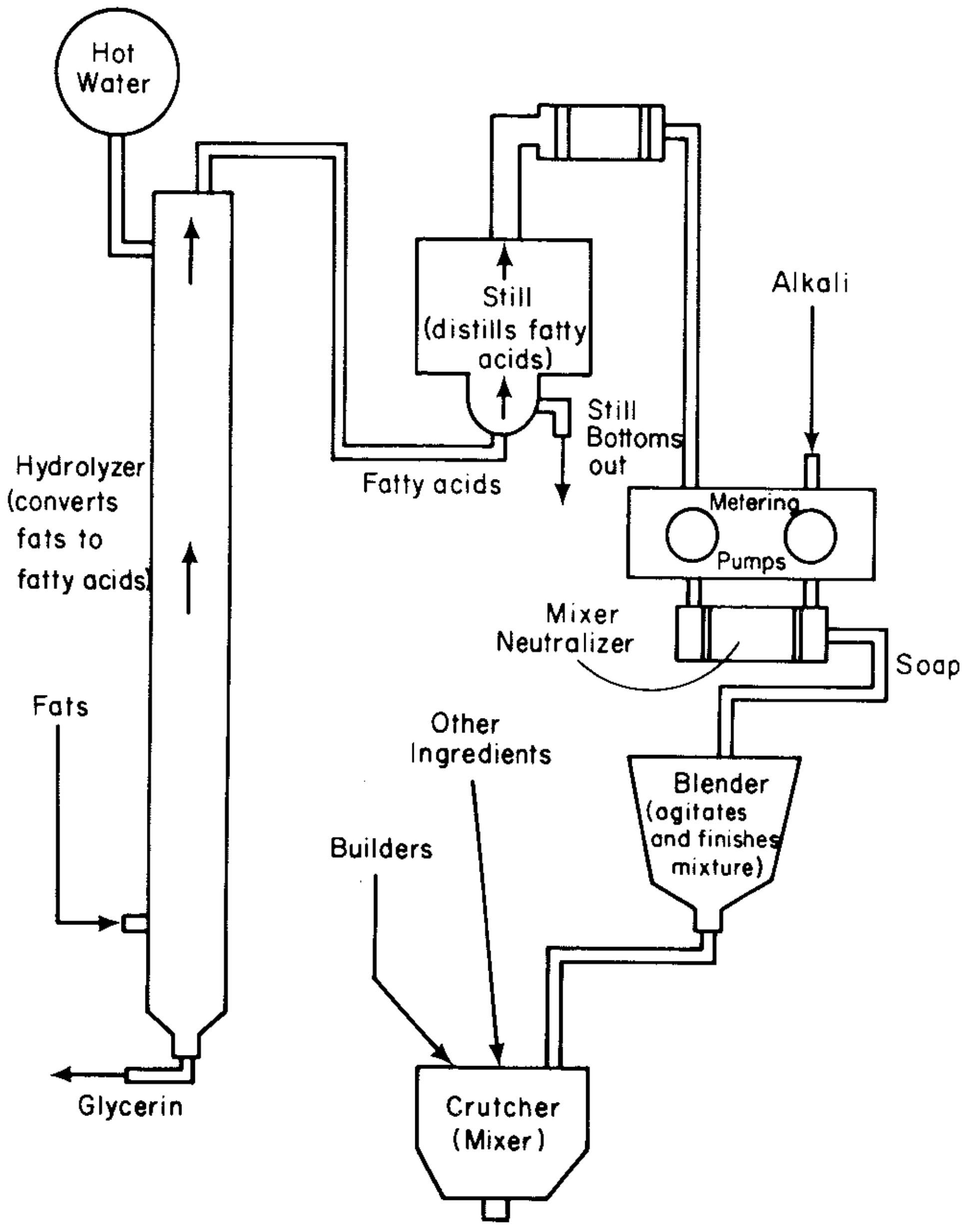

SOAP CHIP DRYER
CHIP STOR-AGE
MIXER
3 STAGE REFINERS
SUPER PLODDER
CAKE CUTTER AND COOLER
PRESS
INSPECTION BENCH
WRAPPER
PACKING BENCH
CASE SEALER
TO WAREHOUSE

The attainment of balance in sequences of operations permits side-by-side placement of adjacent tasks. If part of such an array calls for a succession of machine operations, these may be combined for execution into a single machine, designed to perform the first operation then transfer the work to the second, where performance is followed by transfer to the third, thence to the fourth, and so forward to the end of the sequence. Various parts in automobile manufacturing are produced in this say; bottleing machines perform balanced sequences of cleaning, sterilizing, filling, labeling, and crowning in the same way; so also do the processes of soap making from mixing machines through extrusion, cut-off, plodding die, wrapping, and packing in cartons for storage (Fig. 5). Such machine sequences are, of course, special cases of balanced system technologies.

Continuous Systems

Not so very long ago, soap making, alluded to above, required the storage of the mixed ingredients in large vats to allow time for the necessary chemical reactions to take place. Production planning provided for the vats to be filled and emptied in a rotation which permitted the processing of new batches as needed by subsequent factory operations. This system of batch-by-batch production used considerable storage space (the vats were very large and there were many of them), necessitated substantial in-process inventory, and tied up working capital for the protracted periods of vat storage--a situation analogous to those

Fig. 10. Sequence of operations in the continuous manufacture of soap. The single hydrolyzing column shown at the left has replaced a number of the very large tanks required by the batch process, thereby effecting large reductions in process time, floor space, and working capital. Operations from the mixer on are much the same as those shown in Fig. 5. (Courtesy Proctor and Gamble, Cincinnati, O.)


Hot Water
Still (distills fatty acids)
Alkali
Still Bottoms out
Hydrolyzer (converts fats to fatty acids)
Fatty acids
Metering Pumps
Mixer Neutralizer
Soap
Fats
Other Ingredients
Blender (agitates and finishes mixture)
Builders
Glycerin
Crutcher (Mixer)

ascribed to jobbing operation technologies.

More recently, development of hydrolyzing columns has made it possible to change from batch production to continuous operations (Fig. 6). The chemical reaction which formerly required a relatively long time interval now is completed in a continuous progression, and the end product of the column proceeds without delay to subsequent operations, where continuity also has been realized.

Continuous operations have been most successful in the chemical industry where liquids, gases, and solids can more easily be handled as continuous streams rather than as the discrete units of other production systems. The difference, however, is nominal. For the production of discrete objects, integrated and balanced technologies reduce or eliminate the distance and time dimensions at operation interfaces. Continuous systems do this too, but in a significantly different way: operations are carried out while the product moves through the system. Inter-operation delays disappear altogether and transportation becames a part of the continuous system itself. Such systems have done most to pave the way for automation and cybernation.

Automated and Cybernetic Systems

Each of the four system technologies descirbed so far has been made possible by the development of its predecessors. Mass markets, specialization, standardization, and interchangeability have been necessary for conversion from jobbing to integrated systems; intergration has been prerequisite to balance, and balance prerequisite to achievement of continuity. For the newest technologies, automated and cybernetic systems, the pattern of direct descent has been continued, but at the same time, broken. These technologies bring powerful new forces to bear upon control, forces which are applicable to all of the antecedent forms.

Control

When the manager of a jobbing system arrays the capacities of his work centers upon a chart and shows demands upon the system in their orders of priority, he is engaging in measurement. When he provides for reports of progress, he utilizes the principle of feedback, extracting information about the state of the system which can be compared with the predictions shown on the chart. Based upon this comparison he may then take such corrective action as he deems necessary, and again utilize feedback to check results. These four ingredients: measuring, comparing, correcting, and checking, comprise the essence of all control.[14]

In jobbing systems human intervention is required at every operational step: for decisions about how commitments should be made, when prediction versus performance errors are sufficient to warrant correction, what the corrective action should be, and whether or not, once supplied, it has been sufficient.

Integrated systems simplify the control process in two ways:

(1) there is much less to measure, compare, correct, and check because fewer different things are done; and (2) part of the control process has been embodied in the design of the integrated system itself. To a degree, control has been programmed.

The transfer of elements of control from management during the operational stage to programmed control at the design stage is intensified in balanced systems, where continuity of flow is determined by setting the system in motion. Corrective measures requiring managerial action still are necessary, to remedy imbalances, interruptions, and stoppages, but the human role in controlling on-going operations is diminished.

Continuous technologies would seem to be simply more of the same thing: very careful design of a system capable of performing a sequence of continuous operations, with human intervention needed only to monitor and correct departures from the predicted flow. While this is conceptually so, it is only part of the truth, for continuous systems have grown too complex for control by the human senses: our mental and motor responses are not acute enough or quick enough to make the corrections called for by the information fed back. Present day chemical processes, for example, are much too delicate to be controlled by the human senses.

Automated Systems

In automated systems the trends described above are made complete. Operational control is transferred in toto[15] from men to machines; the performance of an automated system is programmed--by men of course--during design of the system, so that no human intervention is required once the system has been set in motion and logistically sustained.

The machines, devices, and instruments which exercise the four essentials of control in automated systems are tools in the sense that they embody and extend human capabilities, just as Gutenberg's press, Hargreaves' jenny, and Watt's steam engine embodied the skill, intelligence, and power of the printer, spinster, and worker, However, between these earlier tools and the control devices of automation there are directional and dimensional differences--and the differences are very great.

The directional differences are away from embodiment and extension of man's motor capabilities and toward the transfer and extension--refinement would be a better word--of man's mental capabilities. Because motor and mental processes are interactive (to lift a finger requires both), the difference has not been from black to white but one of content and degree. Most technological developments of the past have transferred man's skill to machines, and most of that skill has involved motor abilities: strength, dexterity, movement. There have been intelligence components too (a page of type contains the intelligence as well as the skill of the compositor) but they have been subordinate. In automated systems, the intelligence component has been dominant.

The dimensional differences between earlier systems technologies and those of automation have derived from fortuitous combinations of ideas about feedback, control, and information, taking expression in such devices as servomechanisms and analog and digital computers, reinforced--indeed, made possible--by the electron tube and transistor. The creation of earlier system technologies largely depended upon mechanical, technical, and engineering ingenuity; automated and cybernetic systems depend much more upon requisite combinations of mathematics, science, and engineering science, combined, of course, with ingenuity and creativity.

Cybernetic Systems

It would be exceedingly difficult, if not impossible, to draw a distinct line between automated and cybernetic system technologies. The automatists themselves do not agree upon a single definition and among the cyberneticians the situation is even worse, each writer upon the subject tending to expound upon what the new science is, not always--in fact, not often--in complete agreement with his colleagues.[16]

Again, for contextual--and quite inexpert-- reasons the points of departure taken here will be related to the capability of cybernetic systems to do different as well as same things, to adapt to the vagaries of chance as well as to foreseen differences, and to exercise control under such conditions automatically. This is a very large order, so large as to at once explain the extensive preoccupation that all cyberneticians have with biological mechanisms of communication and control: the nervous system and the brain.

Information

Central to the extension of automated control to different processes are: (1) analytical and quantitative understanding of information and (2) the development of machines capable of handling information per se. The first of these refers to the concepts of communication and information theory as enunciated by Shannon, Weaver and other;[17] the second to analog and digital computers, which to at least one author[18] had better be named "information machines," computation being but one of their powerful capabilities.

These additional ingredients, information theory and information machines, point the way from automation to cybernetics. The route is more maze than path but in a fashion it can be traced.

Consider, for example, a balanced system designed for the production of some metal object, and assume that in the balanced production sequence there is a special-purpose machine designed to shape the object by performing, over and over, an invariable weries of operations, without human participation. As specified, this part of the process can be said to be automated.

Suppose, however, that it becomes desirable or necessary for this part of the process to perform different tasks instead of or in addition to its regular invariable sequence. This can be done by reversion to general purpose machines and procedures, or it can be done by designing and procuring a special-purpose automated machine for each different need. The first of these possibilities sacrifices automation, the second requires inordinately large investment.

A much better possibility involves the concept of a physical analog or model, which the machine can be contrived to obey, to work upon the metal in such a way that the finished product will be like the analog. Then, by changing the analog as may be desired, the process can be made to do different things, and to do them automatically.

A second step toward cybernetic technology may also be exemplified by developments in metal working. At M.I.T. a milling machine has been made to do different things automatically by programming its activities for a digital computer. Programs are written to specify how the milling cutter shall shape the product. As long as the program remains the same, so will the product remain the same; correspondingly, to change the configuration of the product, it is only necessary to provide a suitable new program.[19]

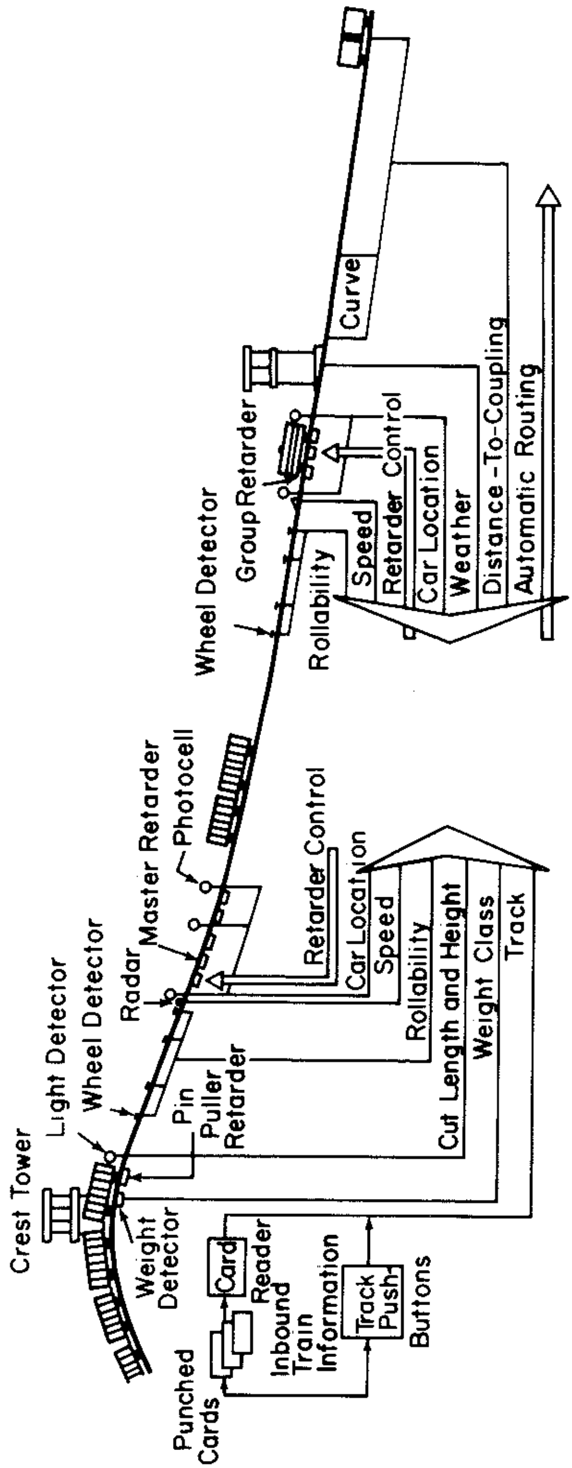
Assuming continuity of maintainance, power, and raw materials, such a machine may be provided with programs of any feasible kinds and diversities, thus bringing automatic control to bear upon what traditionally and inherently has been jobbing technology.

A third example, and a third step toward cybernation, is afforded by the railway classification yard constructed and operated by the Penn Central Railroad at Selkirk, N.Y.[20] There the digital computer not only directs the switching of individual cars to make up outbound trains suitably arranged for various destinations but receives feedback information on weight, height, length, and width as each car passes over the "hump," to determine its rolling characteristics and insure coupling without damage to contents (Fig. 7). Again, the program has been designed to meet the exigencies of differences, again, it has made possible the automatic control of a traditional jobbing type of operation.

This example has been described as a third step toward cybernation because of the more sophisticated program required to control operation of the classification yard. Earlier, in what has been described as a first step, control is determined by the analogs provided to guide the machine; in the second step, movement of the milling cutter is determined by the successive instructions of its program. The key word is determined; in these control programs nothing is left to chance.

But in this third case the switching of successive cars is not determined in advance; instead trains and the cars which compose them are accepted however they may come, in all of their endless variety of shapes, sizes, weights, heights, lengths, cargoes, and destinations. To handle this complex heterogeneity

Fig. 7. Schematic elevation of a cybernetic railway classification yard. (Reproduced by permission from the Baltimore *Evening Sun*, November 11, 1968, p. C 14).


Crest Tower
Light Detector
Wheel Detector
Radar
Master Retarder
Photocell
Wheel Detector
Group Retarder
Weight Detector
Pin Puller Retarder
Retarder Control
Car Location
Speed
Rollability
Cut Length and Height
Weight Class
Track
Rollability
Speed
Retarder Control
Car Location
Weather
Distance-To-Coupling
Automatic Routing
Curve
Punched Cards
Card Reader
Inbound Train Information
Track Push-Buttons

the control program must anticipate and provide for all foreseeable contingencies, avoiding errors of omission as well as commission.

Once this degree of comprehensive foresight has been achieved, the yard will operate as an automated system, according to some, and as a cybernetic system, according to others. Such differences of opinion as there may be about nomenclature will be related to what happens when an unforeseen, unprogrammed event occurs, when over the hump there passes a car of such unique attributes as to have escaped the programmer's attention. As matters stand, the system would be likely to require human intervention to switch the maverick car and restore automatic control. However, if the system were truly cybernetic, it would also be adaptive, would be capable of "learning" from its own mistakes. Under these conditions, passage over the hump of the unique car would "teach" the system how to handle such a car whenever one arrived.

Imparting to a technological system its own intelligence, so to speak, is a very large order yet the concept lies within the ambitions of cyberneticians, who already have created devices imitative of biological processes: a homeostat so contrived as to restore stability whenever disturbed by outside forces;[21] Machina speculatrix, mobile, light seeking, obstacle-avoiding, tortoise-like machines remarkably life-like in their behavior;[22] maze running devices capable of learning just the

System Technology	Control	Variety
Jobbing	Human	Extensive
Integrated	Embodied partly in design of the system, augmented by considerable human intervention.	Much less extensive
Balanced	Embodied largely in design of the system, augmented by much less human intervention.	Limited
Continuous	Embodied in design of the system, with the human role reduced to monitoring.	Very limited
Automated	Embodied in design of the system with control by analogs and servomechanisms, no human intervention.	Less limited
Cybernetic	Adaptive control embodied in design of the system, no human intervention.	Extensive

Fig. 8. Progressive characteristics of technological systems.

right turns to avoid dead ends and blind alleys.[23] These and other machines like them already have been built; others remain in the realm of speculation but are logically possible.[24] Achievement of adaptive control over enormously complex probabilistic systems, stated as a kind of ultimate cybernetic goal by Stafford Beer,[25] may lie just beyond the horizon. When and if that goal is achieved, we shall have come full circle, through all of the steps summarized in Fig. 8.

Operation and System Unity

In previous narrative the technologies of operations and the technologies of systems have been discussed separately, the first concerned with activities at work centers, the second with flow between work centers. For jobbing systems such separate treatment has been meaningful; the work done on a composing machine and a printing press, or on a spinning machine and a loom, and the flow of work between such work centers, can be clearly distinguished and properly discussed as separate topics.

However, commencing with the first step toward integration, and increasingly with progression to balanced, continuous, automated, and cybernetic systems, the separation of operations from flow has become increasingly unrealistic. Insofar as operational capability is concerned, a balanced, continuous, automated, or cybernetic system cannot be dissected into its component parts; each and all are necessary, the aggregation becomes both the system and the operation. They are one and the same.

COST AND LONGEVITY

Earlier discussion of the technologies of operations emphasized order-of-magnitude increases in the capital cost of new technologies, accompanied by ever-diminishing life expectancies. These trends are also discernible for successive system technologies but for them the developmental time scale has been enormously compressed. One cannot point to an integrated system in classical times, nor during the Renaissance. Such systems may have existed during the Industrial Revolution but this seems doubtful. In any case, integrated systems have not flourished until the nineteenth and twentieth centuries, when they have developed space, followed in very rapid succession by balanced, continuous, and automated systems, with cybernation just around the corner. In particular, the introduction of feedback and servomechanism controls and their linkages with computers have brought and are continuing to bring about changes that appear to be much more abrupt than those ascribed to the technologies of operations. Indeed, the birth of each new technological system simultaneously seems to be accompanied by conception of a still better way. The threat of instant obsolescence, like the threat of instant annihilation already mentioned, is not altogether fanciful.

Escalating system costs have been alluded to in discussion of the technologies of operations and just above this trend has been reinforced by discussion of the essential unity of the two technological forms in their more advanced states. An automated factory, or transportation system, or communications network cannot be evolved piecemeal but must be created in the whole cloth, and associated costs are increasingly large.

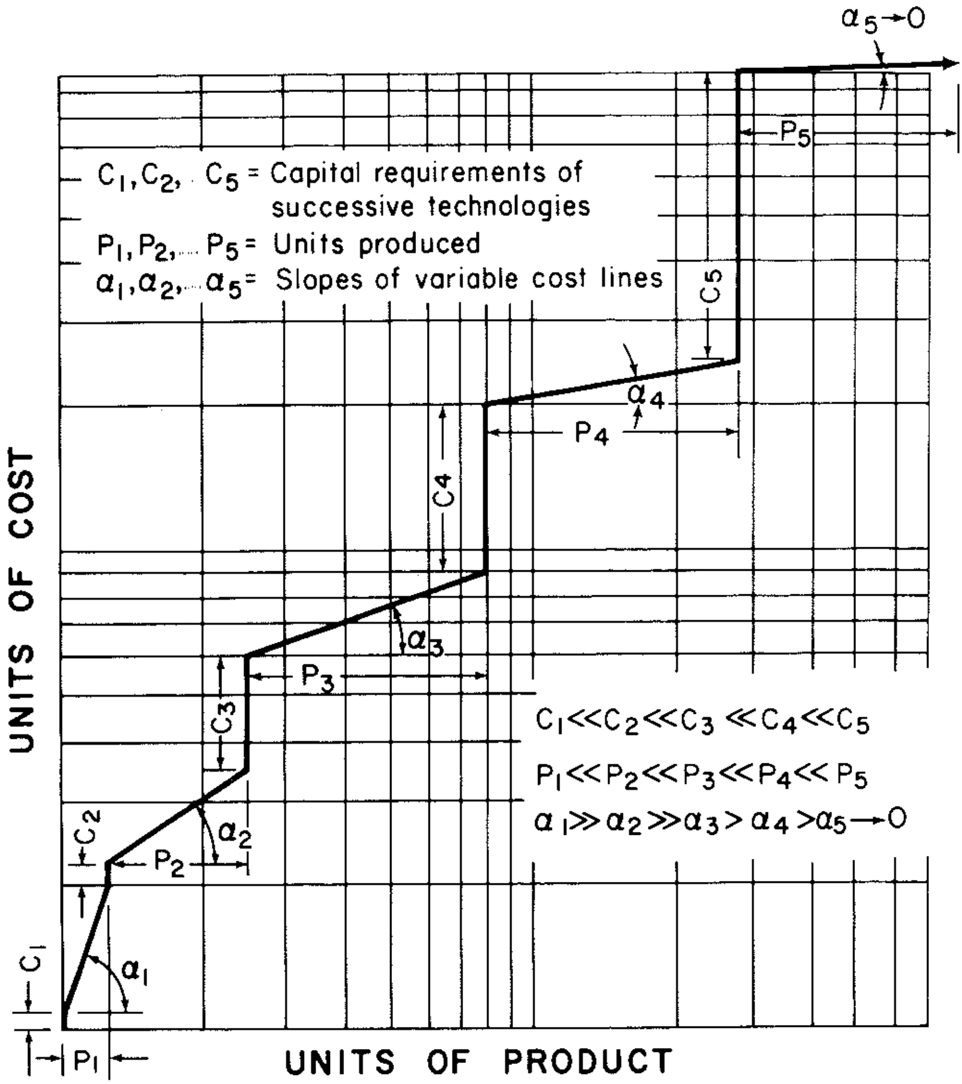
TECHNOLOGY AND MANAGEMENT

The dominant result of technological change has been increased material benefits at lower costs, and this has created an apparently irresistible force toward continued innovation. Despite changes in the nature and intensity of competition and the imposition of controls by government, the force remains inexorable.

Complicating the continued thrust toward change are new dimensions of cost and time, remarkably different from those faced by predecessor managers, dimensions which approach the ultimate levels of infinitely large costs for new technologies accompanied by the threat of infinitessimally short life expectancies.

While this is an egregious exaggeration, it contains more than a kernel of truth. Hitherto, as has been shown for both the technologies of operations and the technologies of systems, progress has been characterized by the substitution of capital for labor. Substitutions of this kind still take place--indeed, they continue to epitomize technological change--but now, in automated and cybernetic systems, there is no labor left for which to substitute; this component has approached the limit of

Fig. 9. Sequence of fixed and variable cost lines portraying technological progression. Logarithmic scales have been used and variable costs shown as straight lines simply to emphasize that the quantities c and p associated with each step are very much greater than for preceding steps.



C1,C2, C5 = Capital requirements of successive technologies
P1,P2,... P5 = Units produced
α1,α2,...α5 = Slopes of variable cost lines
C1<<C2<<C3<<C4<<C5
P1<<P2<<P3<<P4<<P5
α1>>α2>>α3>α4>α5→O
α5→O
UNITS OF COST
UNITS OF PRODUCT

zero.

To consider these statements in a managerial context, we may examine a sequence of technological decisions by means of fixed and variable cost lines, using the equation $C = F + VN$ to plot the fixed cost of tools (F), the variable cost per unit produced (V), and the number to be produced (N), with the product and sum of these representing total cost (C). By ordering the successive steps and emphasizing visual effect more than mathematical nicety, Fig. 9 shows the sequence.

Several things may be noted: each successive fixed cost line has been made longer than its predecessor, not only linearly but by arbitrary imposition of the logarithmic scale to emphasize that the sequence is positively exponential: each successive capital cost is very much larger than the last. Analogously, the units of product derived from each technology are very much larger than the yield from its predecessor; again the positive exponential sequence is portrayed by longer lines and logarithmic scale.

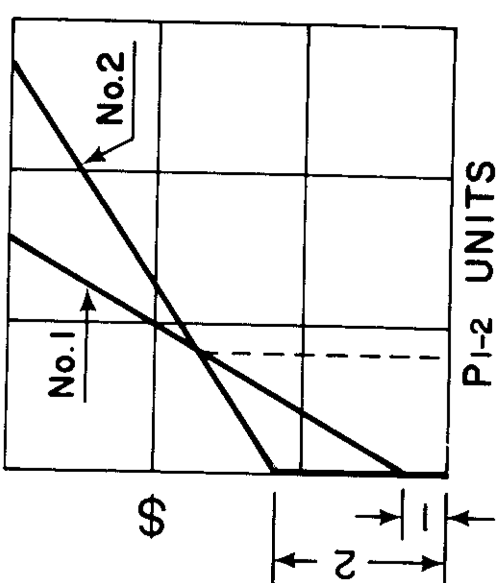
The converse of these positive exponential differences is suggested by the slopes of the variable cost lines, which have been made progressively to diminish, approaching zero as a limit. The lengths of the vertical cost lines are measures of capital intensity, the slopes of the variable cost lines of labor intensity, with the last line for technology No. 5 approaching zero as shown.

Of what consequence is this to management?

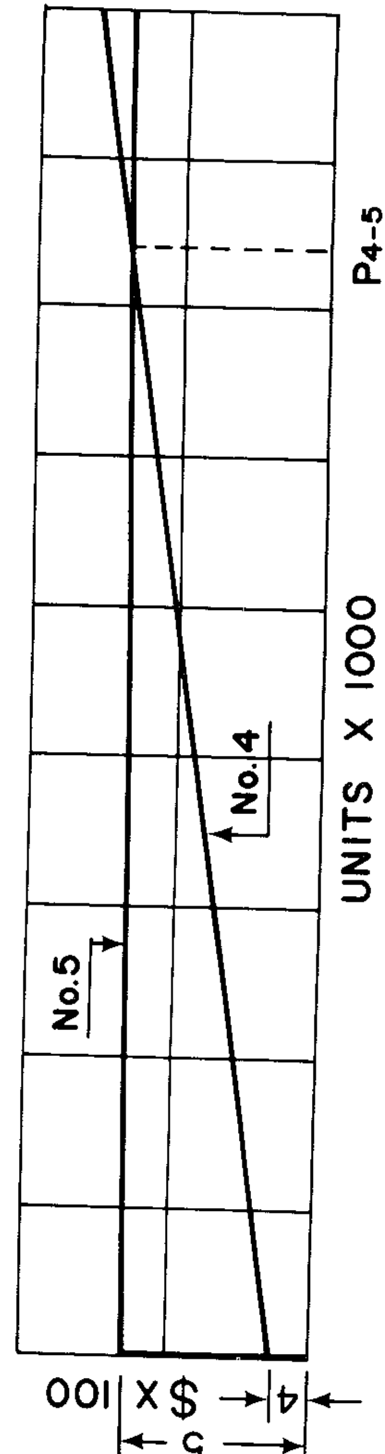
To consider this we may first compare the rudimentary, labor-intensive technologies 1 and 2 with the more sophisticated, capital-intensive technologies 4 and 5, superimposing each pair upon adjacent graphs of fixed and variable cost lines (Fig. 10). In the situation depicted by the upper portion of the figure the manager has an easy decision to make. The slopes of the two variable cost lines differ markedly, the break-even point is sharply demarked, and the amounts of capital to be risked are small, which ever of the two methods is chosen. The decision is a "comfortable" one.

In contrast, the lower portion portrays technologies both of which demand much more substantial investment in tools, although the amount required by No. 5 is very much larger than for No. 4. Here the slopes of the variable cost lines differ by much less and the break-even point is at a very much larger number of units. Furthermore, the break-even point is not so clearly demarked, indeed the intersection cannot be called a point in the mathematical sense that a point is dimensionless. And any change in the slope of either variable cost line will shift the break-even point by a very large number of units. The manager's choice between alternative technologies is now fraught with much greater risk, is much less comfortable. The manager's discomfort is also aggravated, as will be shown, by the diminishing life expectancy of each contemplated new technology

Fig. 10. Comparisons between "adjacent" technologies. The upper figure compares rudimentary technologies 1 and 2, the lower figure the more sophisticated technologies 4 and 5, these numbers referring to the subscripts of Fig. 9. Here the scales are not logarithmic but linear, with those in the lower part arbitrarily multiplied by factors of 100 and 1000. Although only visual effect is sought and no specific numerical values are intended, the equations represented by the four lines are not unrealisitc for the kind of technological progression described.



No.1
No.2
P_{1-2} UNITS
$
1
2



No.4
No.5
P_{4-5}
UNITS X 1000
$ X 100
4
5

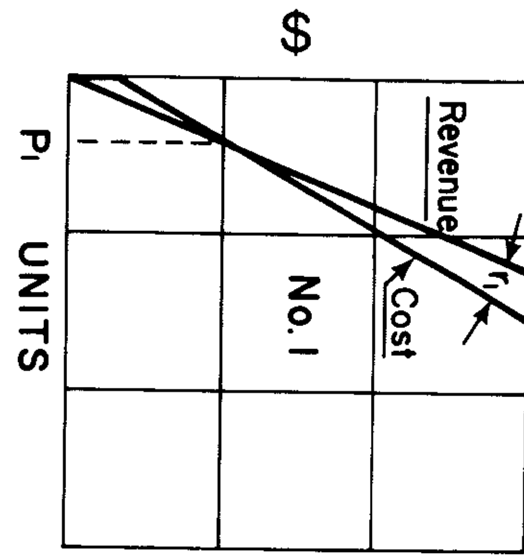
and by the fact that the numbers may involve millions, tens of millions, or hundreds of millions of dollars and units of production.

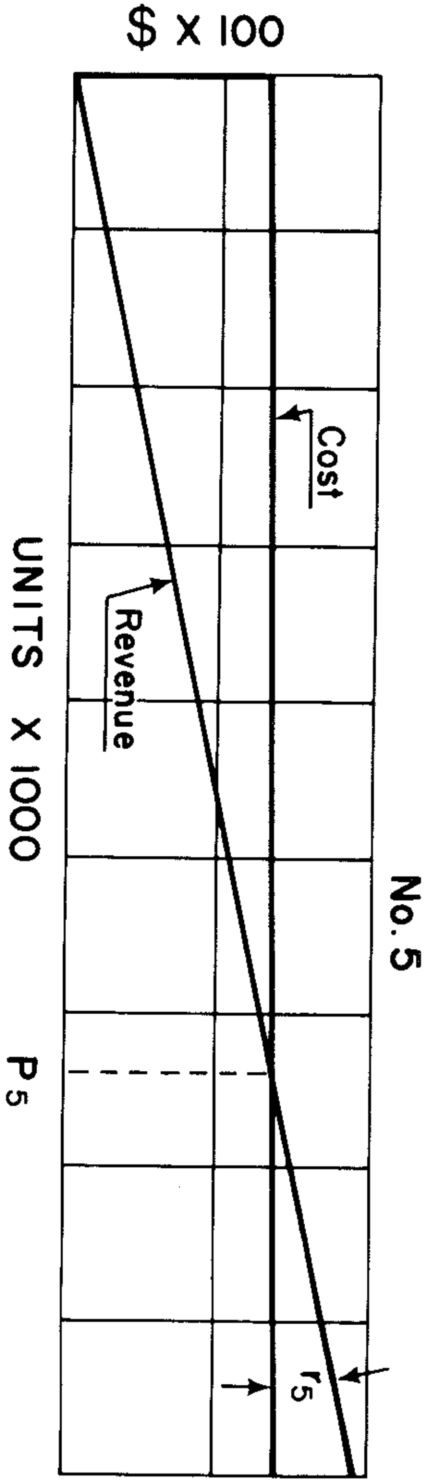
Managerial stress is likely to be worse, however, than has been indicated. So far it has been implied that quantities to be made are specified, in the manner of jobbing manufacture. More often the manager must not only compare and decide among feasible technologies but must consider probable market and price as well. These variables, themselves interactive, further complicate an increasingly complicated problem.

To show this, rudimentary technology No. 1 may be contrasted with advanced technology No. 5 by adding a sales revenue line to each cost diagram (Fig. 11). In each of these graphs a measure of the risk associated with the decision is provided by the difference between the slopes of the respective sales and variable cost lines, represented by the angles r_1 and r_5. In the upper diagram, which depicts the earlier technology, the slopes differ but little and this will be true for any sales line because the variable cost line for any simplistic technology is steep. The chance of large loss or large gain, represented by the spaces between the lines, is not very great; should the market forecast of break-even quantity p_1 be in error, the consequences will not be dire.

In contrast, technology No. 5 shows a near-zero slope for the variable cost line; the difference in slope between this

Fig. 11. Contrast, with sales revenue lines added, between technologies 1 and 5. Again, visual effect has been the objective and no specific numbers are intended, although the lines conform reasonable well with possible actual events.


$
Revenue
Cost
r1
No. 1
P1
UNITS


$ X 100
Cost
Revenue
r5
No. 5
P5
UNITS X 1000

line and the sales line--again <u>any</u> sales line--approaches a maximum. Since the variable cost line cannot have negative slope, the difference between marginal revenue and marginal cost also has approached a maximum. Prediction of break-even point P_5 assumes greater and greater importance as the marginal cost of production approaches zero; risk of loss and chance of gain are now extremely sensitive to market demand, sales volume above P_5 has become imperative, a force more conducive to the growth of large scale organizations than either political philosophy or human ambition.

The lion's share of greater difficulty derives from the magnitudes of the values involved: a decision to invest hundreds of thousands is easier and more comfortable to make than a decision to venture hundreds or thousands of millions; an anticipated useful life of one year gives the decision maker much more stress than a ten-year expectancy. There is, besides, a compound effect: each datum interacts with the other to aggravate the degree of difficulty.

In addition, the neat, easily quantified linear relationships which prevailed for variable costs have been replaced by relationships which are much more elusive and intractable. As a consequence, managers seeking a rationalize decisions involving greater magnitudes are turning more and more to sophisticated quantitative methods which have come to pay near-dominant roles in decision making, at the same time permitting the practitioners of such methods to move into positions of power. Cost-benefit analysis and "computerized management" are often derogated but they provide--or seem to provide--the rational means by which managers can make the momentous decisions thrust upon them by the forces of technological change.

THE RATE OF CHANGE OF RATE OF CHANGE

Elton Mayo has said that man must learn to respond to technological change by becoming adaptive.[26] Perhaps so. But man is not a perfectly elastic, adaptable creature and the logical consequence of the rate of change of rate of change, the second derivative, may be arrival at intolerable thresholds. If and when this happens the now almost universal quest for more change may be succeeded by a quest for stability.

There are at least a few signs that the shift will come.

The present generation of young people, who in America have had no perception of economic adversity, seems disenchanted with the pursuit of affluence; in spirit they are more akin to Thoreau than to Horatio Alger. There is increasing awareness that we shall only compound traffic problems by more cars, more superhighways, more parking lots. Scholars and teachers in schools, colleges, and universities are beginning to sense that the knowledge explosion leads to intellectual obsolescence as well as learning. One distinguished critic has pointed out that in science loyalty to humanity must transcend loyalty to truth.[27] Population control--the essence of stability--is recognized as a worldwide necessity.

These are only faint signs which as yet do not illuminate technological change per se. But perhaps they presage a future in which the god of everlarger Gross National Product will be recognized as only an idol.

ADDENDUM

Empirical Models

To provide emphasis to the managerial meaning of the historical progression of technology, empirical--or more specifically cut-and-try--models have been devised. Admittedly, these are conjectural but the shapes of the two curves and their accompanying scales do provide visual support to the argument and the data do have a reasonable measure of verisimilitude (Fig. 12).

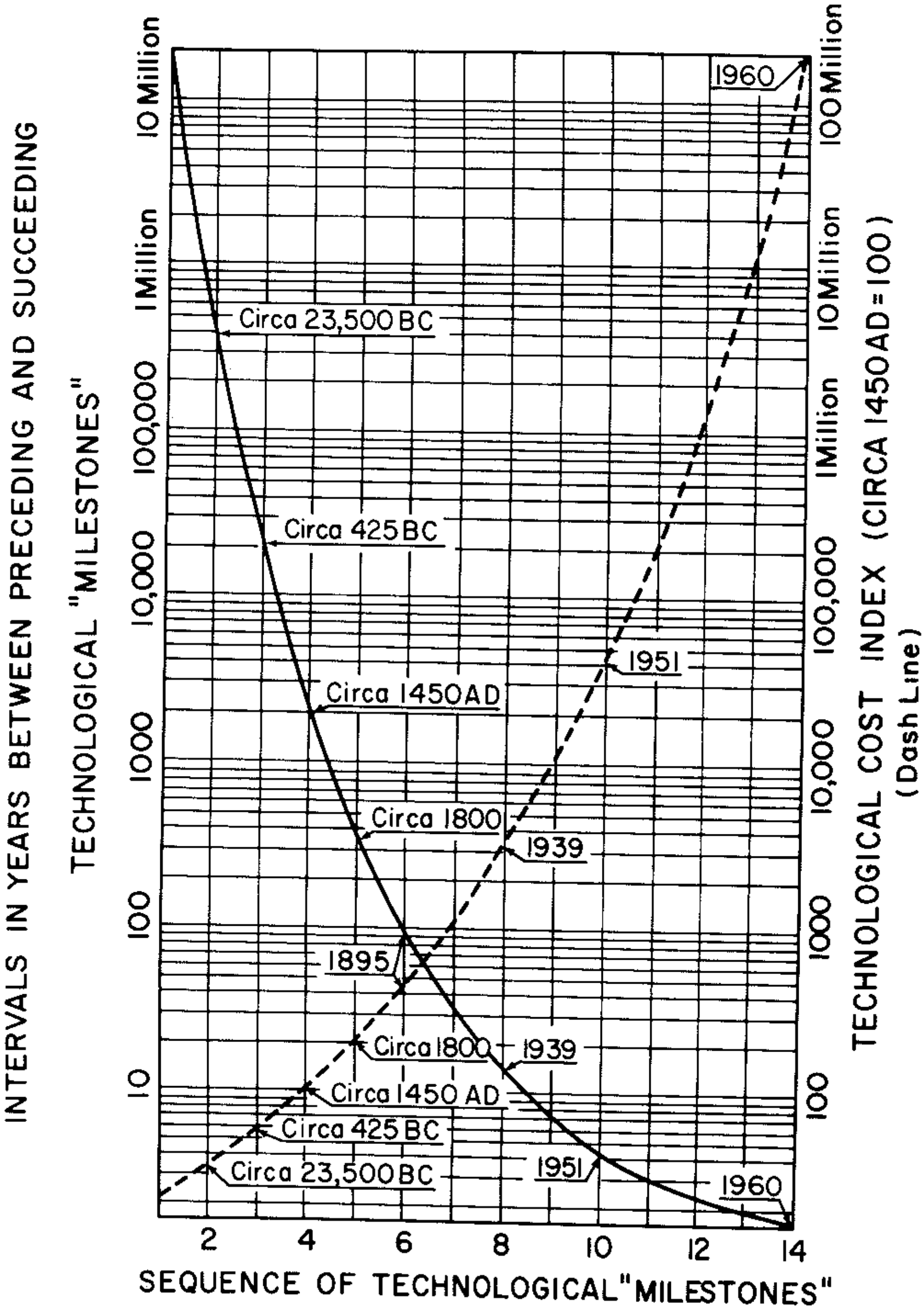
The curve which shows periods of technological dominance (the solid line at the left, related to the scale in years at the left) has been derived by assuming, as already stated, that the decline in life expectancy of each successor technology is related to its predecessor's period of dominance according to some exponent, that is

$$(t_2 - t_1)^{1/x} = (t_3 - t_2),$$

$$(t_3 - t_2)^{1/x} = (t_4 - t_3), \text{ etc.}$$

Where t_1, t_2, t_3, etc. are the times of origin of each successive technology. The remainders within each set of parentheses then become predecessor technological life spans, i.e., historical life spans, T_1, T_2, etc. and the equations simplfy to:

Fig. 12. Empirical representation of technological evolution. The solid line at the left and its related ordinate scale at the left show exponentially decreasing life spans for successive technologies. The dash line at the right and its related ordinate scale at the right show index numbers for the increasing capital cost of each successive technology.


INTERVALS IN YEARS BETWEEN PRECEDING AND SUCCEEDING
TECHNOLOGICAL "MILESTONES"
10 Million
1 Million
100,000
10,000
1000
100
10
Circa 23,500 BC
Circa 425 BC
Circa 1450 AD
Circa 1800
1895
Circa 1800
1939
Circa 1450 AD
Circa 425 BC
Circa 23,500 BC
1951
1960
1960
1951
1939
100 Million
10 Million
1 Million
100,000
10,000
1000
100
TECHNOLOGICAL COST INDEX (CIRCA 1450 AD = 100)
(Dash Line)
2
4
6
8
10
12
14
SEQUENCE OF TECHNOLOGICAL "MILESTONES"

$$I_1^{\ 1/x} = T_2$$

$$T_2^{\ 1/x} = T_3, \text{ etc.}$$

Using a few of the dates provided by the histories previously recounted (e.g., the Classical period, circa 400 B.C.; the Renaissance, circa 1450; and the Industrial Revolution, circa 1800), a cut-and-try procedure has yielded an exponent of about 1/1.3 as best satisfying intuitive appraisal. The curve shown has been plotted upon this assumption, that is, that I_n 1/1.3 = T_n + 1

In much the same way, assuming that capital cost requirements increase analogously (e.g., $C_n^y = C_n + 1$), the positive exponent y = 1.15 has been found to satisfy one's sense of rightness. The dash line at the right of Fig. 12 and its accompanying scale of index numbers portrays this relationship ($C_n^{1.15} = C_n + 1$), using an arbitrary assumption that the index for the year 1450 = 100.

Explication

Both of the ordinate scales are logarithmic and may be read directly. The scale at the left shows intervals between preceding and succeeding technologies, that is, the number of years that the preceding technology has survived before the advent of its successor. Thus, the scale reading for the point designated as circa 1450 is 2000; this means that the technologies which preceded (e.g., manuscript writing, the distaff and spindle, the catapult) those introduced about 1450 (e.g., printing, the spinning wheel and flyer, the hand gun) had characterized society for about 2000 years. Analogously, the reading for circa 1895 is about 90 years, the period of dominance of predecessor technologies introduced at the time of the Industrial Revolution.

To assess the impact upon management, consideration of more recent times is much more important. For example, the model shows about 14 years as the life span for the technology preceding 1939; by 1951 the reading declines to about 4 years, and by 1960, which has arbitraily been taken as a base, to about 1.6 years.

Earlier the assertion was made that the curves have requisite verisi-militude, an assertion which may be challenged by the smallness of the numbers for more recent times. Indeed, if the data are interpreted to specify the life spans of plant and equipment, they are not credible but this is not the intention. Electronic switching, for example, is now a reality in telephony, superseding cross-bar equipment, but this does <u>not</u> say that all cross-bar installations have at once been abandoned. At this moment multifont optical scanning is in not-quite-feasible status; its perfection, when realized, may ultimately presage the demise of the linotype but the transition will require the passage of time.

Precisely this same emphasis upon broad interpretation of the word technology must be applied also to the cost model, where each technology costs more than its predecessor. The assumption of an index number of 100 for circa 1450 says, in effect, that the technology which cost 100 units then has been supplanted by the technology of 1960 at a cost two million times as great. When thought of in terms of individual units of plant and equipment, this is patently ridiculous; when applied to whole technologies--the meaning intended--the data become more credible. Such technologies as the computer networks which now are permeating the economy, the prospective supersonic transport and the ground installations it will require, satellite communication, and space travel give the credence that is intended.

Finally, each model represents what may be described as a self-aggravating phenomenon based upon conjecture. Self-aggravating phenomena (traffic snarls, epidemics, etc.) always tend to become self-correcting at some threshold, and this may --indeed will--become the case here, by changes in the exponents toward levels more conducive to stability.

FOOTNOTES

1. This paper has been excerpted and condensed from chapters of a manuscript in preparation by the author. Presentation has been much more abridged than future publication may, it is hoped, permit.

2. Joseph F. McClosky: A Historical Approach to the Direction and Control of the Research and Development Function. Operations Research Society of America, 12th National Meeting, Pittsburg, 1957.

3. A major source for many of the technological "milestones" cited here has been Charles Singer, E.J. Holmyard, A.R. Hall, and Trevor I. Williams (Eds.): A History of Technology, London, Oxford University Press, 1854. For weapons technology papers used from these volumes have been: Kenneth P. Oakley: Skill as a Human Possession, vol. 1, pp. 1-37, and A.R. Hall: Military Technology, vol. 11, Other sources have been Melvin Kranzberg and Carroll W. Pursell (Eds.): Technology in Western Civilization, New York, Oxford University Press, 1967; J.F.C. Fuller: Armament and History, New York, Charles Scribner's Sons, 1945; Jac Weller: Weapons and Tactics: Hastings to Berlin, London, Nicholas Vane, 1966; Liddell Hart: A History of the World War, 1914-1918, Boston, Little, Brown & Co., 1935; and William Manchester: The Arms of Krupp, Boston, Little, Brown & Co., 1968.

4. D.B. Updike: Printing Types, Their History, Forms and Use, Cambridge, Harvard UniversityPress, 1937, vol. 1, ch.1.

5. Sources for discussion of the graphic arts have been Michael Clapham: Printing, in A History of Technology, vol. III; S.H. Hooke: Recording and Writing, ibid., vol. I; and Thomas F. Carter: The Invention of Printing in China, New York, Columbia University Press, 1925.

6. A similar progression of technological developments for spinning and weaving can be recounted from R. Patterson: Spinning and Weaving, in A History of Technology, vol. II; Julia de L. Mann: The Textile Industry: Machinery for Cotton, Flax, Wool, 1760-1850, ibid., vol. IV; and D.A. Farnie: The Textile Industry: Woven Fabrics, ibid., vol. V.

7. Gordon W. Allport: "The Psychology of Participation," Psychological Review, LIII, May 1945. Reprinted in Schuyler Dean Hoslett (Ed.): Human Factors in Management, Parkville, Mo., Park College Press, 1946, p. 257.

FOOTNOTES

8. In most cases it is the work itself which is moved to the next operation but when the product is large, as in the case of construction or shipbuilding, it remains stationary and the workers move. The discussion is applicable to both situations.

9. Greville and Dorothy Bathe: Oliver Evans, Philadelphia, The Historical Society of Pennsylvania, 1935, p. 11 et seq.

10. Elting E. Morison: Men, Machines, and Modern Times, Cambridge, The M.I.T. Press, 1966, ch. 7.

11. Frederick W. Taylor: The Principles of Scientific Management, New York, Harper & Bros., 1919.

12. Nevins and Hill: Ford: The Times, the Man, the Company, p. 467.

13. Ibid., ch. xviii.

14. Gordon S. Brown and Donald P. Campbell: Control Systems, published in Automatic Control, New York, Simon & Schuster, 1955, p. 27.

15. While conceptually correct, "in toto" is an exaggeration. Totally automated systems capable of self-regulation, self repair, and self-supply, without a vestige of human intervention, do not exist. Like perfect competition, perfect vacuums, and perfect gases, the concept is useful.

16. "At one extreme, there is the original definition, 'the science of control and communication in the animal and the machine,' advanced by Norbert Wiener. At the other extreme is Louis Couffignal's proposal, put forward as an expansion in 1956, 'la Cybernitique est l'art d'assurer l'efficacite 'de l'action.' The gap between science and art is filled by a continuum of interpretations. Thus, Stafford Beer looks upon cybernetics as the science of proper control within any assembly that is treated as an organic whole. . . . Ashby, on the other hand, gives emphasis to abstracting a controllable system from the flux of the real world." Quoted from Gordon Pask: An Approach to Cybernetics, London, Hutchinson, 1961. See also Michael J. Apter: Cybernetics and Development, Oxford, Pergamon Press, 1966, ch. 1.

17. Cláude E. Shannon and Warren Weaver: A Mathematical Theory of Communication, Urbana, University of Illinois Press, 1949.

FOOTNOTES

18. Louis N. Ridenour: Information Machines, published in Automatic Control, p. 111.

19. Andrew Bluemle: Automation, New York, World Publishing Co., 1963, p. 92.

20. The Baltimore Evening Sun, November 11, 1968, p. C 14.

21. A machine constructed by W. Ross Ashby ". . . to imitate the biological phenomena described by Dr. Cannon . . . Made up of a series of groups of components that are freely supplied with energy, Homeostat is constructed so that when any attempted changes are imposed from the outsied--in this case, the changes would cause movement of indicators (needles on a dial) connected to the components--the various parts of the mechanism interact with one another in a very complex feedback pattern. This pattern continues until the change is negated or neutralized and the needles return to the point indicating stability. . ." (Quoted from Corinne Jacker: Man, Memory, and Machines: An Introduction to Cybernetics, New York, The Macmillan Co., 1964, pp. 61.62.

22. ". . . The device usually regarded as the prototype toy of this kind is Grey Walter's 'tortoise' which he calls Machina speculatrix . . . having a tricycle undercarriage driven by an electric motor . . . Machina speculatrix has just two cells, one visual and one tactile. The visual apparatus is infact a photoelectric cell, rotating on top of the device and looking for light. The machine runs about in a random way; . . when an adequate light signal impinges on its receptor the organism steers itself toward the light. The secons and tactile cell is simply and electrical contact which operates when the organism touches some impeding object. This operation causes the photocell to stop working in the way so far described and makes it work instead like an oscillator. . . (so that) the tortoise makes brief retiring and advancing movements. . . M. speculatrix is capable of remarkably life-like behavior. It searches a room in an enquiring manner, . . . and when it has seized on a suitable goal (in the form of a light) makes for it. Encountering an obstacle, a combination of its two sensory inputs causes (it) to skirt round. . . retreating temporarily. . . then advancing under the light stimulus, and so on." (Quoted from Stafford Beer: Cybernetics and Management, London, The English Universities Press, Ltd., 1959, pp. 115,116. See also W. Grey Walter: An Imitation of Life, in Automatic Control, pp. 121-131.

FOOTNOTES

23. Corinne Jacker: Man, Memory, and Machines, pp. 70,71.

24. Two such conceptions, a "Turing Machine" and machines capable of reproducing themselves, are described in John G. Kemeny: Man Viewed as a Machine, in Automatic Control, pp. 132-146.

25. Stafford Beer: Cybernetics and Management, ch. II.

26. Elton Mayo: The Social Problems of an Industrial Civiliaztion, Cambridge, Graduate School of Business Administration, Harvard University, 1945.

27. Archibald MacLeish: "The Great American Frustration," Saturday Review, July 13, 1968, pp. 13-16.

28. Dr. Rodger D. Parket, Associate Professor of Public Health Administration in Teh Johns Hopkins University School of Hygiene and Public Health, gave valuable assistance in the development of these models.