THE CONCEPTION OF A SHAPE AND THE EVOLUTION OF A DESIGN

by

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1. INTRODUCTION

1.1. A designer makes and manipulates shapes in his environment. To do so, he must conceive and construct these shapes. His activities are constrained by an objective that he keeps in mind, commonly that the shape he designs must fulfil some role in a communication system (it must advertise a product, convey a message, satisfy certain physical requirements or simply be a beautiful shape). The shape itself is any visual or semantic or auditory or tactile form, recognizable as a sign in a given universe of discourse.

1.2. In this paper we consider a Cybernetic view of the designing process. To restrict the field we shall discuss only those systems which can (in principle) be physically realized. Thus, although we are chiefly concerned with design as it occurs in *man*, most of our arguments apply also to *mechanisms* that design. The main contention is that a design, R, can be identified with the shape of a trace left upon a malleable environment, B (such as an image in paint upon a piece of canvas, a set of instructions, like a music score or a choreography), when a *perceptual process*, say

$$\Lambda = [\lambda_1, \rightarrow \lambda_2, \rightarrow \ldots \lambda^*, \rightarrow \lambda^*]$$

which is exteriorized in B, converges as a result of adaptation or learning to a stable form λ^* that satisfies an objective of the form "Maximize $\theta(X)$" (where θ is a functional, determined by a property of B, and $x \in X$ are states of B, specified in a suitable state description). We also insist that Λ is partly localized in a "designer", denoted A, who "learns" and "perceives". But A may be a man, or a group of men, or a mechanism, without restriction.

1.3. It is useful to distinguish between the situations in which *designing* takes place, for example, between members of the list below.

(1) *Extrapolative Design.* The designer, A, is given a principle of induction and a particular exemplar. He is requested to construct further exemplars. To cite a case, A is given the *style* of an advertisement and a particular

placard and is requested to make another placard in a similar style and having other specified features.

(2) *Interpolative Design.* A is asked to bridge the gulf between a pair of shapes. Trivially, perhaps, A is asked to design the missing figure in a cartoon strip; less trivially, he is asked to construct a motion picture script; given a set of situations and ideas.

(3) *Translational Design.* A is provided with a shape, R_0, that is an intelligible sign in a language, L_1, and which conveys a certain message M to a population familiar with L_1. He is required to create R^*, a shape which is a sign in a different language L_2 that conveys M to the L_2 population. Normally, L_1 and L_2 are not spoken languages (though they may be) but the constraints of a cultural or intellectual idiom. A typical identification is R_0 = a road safety poster, successful in an American idiom, L_1 = American idiom (for normal visual display), M = a message exhorting the populace to take care on the road, R^* = another road safety poster, exhibiting M in Britain, L_2 = British idiom (in normal visual display).[1]

(4) *Optimizing Design.* A is offered a list of restrictions like "R shall be a motor car body", "Steel X is more resilient than Steel Y", "The motor car must withstand tropical conditions", "The body must cost less than U". He is at liberty to produce any shape, R, that satisfies all of these restrictions.

1.4. Now distinctions of the kind (1), (2), (3), (4) chiefly effect one, partially separable, component of the designing process Λ, which we shall call the *procedural* aspect P of Λ. P is concerned with explicitly formed designing *algorithms* or computational procedures. Different algorithms are used, for example, in Extrapolative Design and in Interpolation; different kinds of data would assist the designer; if we wanted to help him, by taking some of the job off his hands, we should provide entirely different computing machinery in each case. The procedural aspect of design *can*, incidentally, be rather fully mechanized. The first step in this direction is conventional enough. The designer is provided with *tools*, such as architectual models or simulators, their use being a matter for his own discretion. Hence these tools have precisely the calibre of labour saving devices.

One very advanced labour saving device is a computor which (in the case of visual design) can assist the designer by sketching, on his behalf, from instructions which can either be a preliminary sketch or a sequence of numerical coefficients. The device is able to transform and represent an original sketch, using auxiliary instructions for this purpose (it may enlarge the sketch, rotate or invert it, determine its outline, accentuate certain points of interest, or introduce features such as local curvature). At this stage we have a tool which accepts instructions not only in terms of the design format but also in terms of a metalinguistic description of the format; the kind of description that the designer may think about before he puts his ideas on paper. The computor could, for example, obey instructions to "complete a

figure" or "obtain closure" or approximate a "good form", providing, of course, that "good form" were capable of description in the metalanguage. Or, failing this, we might elaborate the machinery to "learn" what was meant by "good form" by ostensive definition. After being presented with a sequence of exemplars, some of which did and some of which did not have this property, the device would be able to discriminate "good form" objects from others. (Its capability, in this respect, depends entirely upon the degree of consistency and coherence in *our* definition of the property; not *all* properties can be "learned" in this way.)

The next stage in *P* mechanization is a machine (in place of the environment, *B*) which is co-operative rather than passive. It does not wait for the designer's instruction. Instead, it has certain built-in homeostatic criteria, for example, it aims to achieve "good form" and whenever the designer sketches something, the machine converts it into whatever the machine takes to be "good form".

Now the machine is capable of co-operating most realistically, for the *P* transformation it executes may *suggest* further *ideas* to the designer. Indeed, a machine like this makes *B* into a medium that can embody some active features of the designing process. On the other hand the machine might be a great nuisance. For its co-operative ability depends entirely upon possession of similar criteria of "good form" to those embedded in *A*.

Comparable computing systems are being developed by Marvin Minsky's group at M.I.T. in connection with interpolative design. The same principles could probably be extended to comprehend some kind of extrapolative design, or, at the cost of additional facilities for determining the optimum set of constraints, to comprehend optimizing design. The main difficulty is not elaboration, or coupling between the designer and the machine, but choice of a reasonable and concise set of properties to act as the homeostatic criteria.

But the most we can do in this respect is to provide *ideal* assistance, which might relieve *A* of the whole of *P*. This, however, would not produce a "design", nor would we usurp *A*'s position as designer. Certain underlying processes take place when *A* "designs". These are not "procedural" and, if *A* is a man, they do not enter his consciousness (at least, they only enter it in a very hazy fashion). These underlying "creative" activities do not seem to differ a great deal with the *kind* of design in which *A* indulges.

1.5. We maintained in 1.2 that A was a "perceptual" process (using this word in a rather broad way). On any grounds we could maintain that designing entails perception for *A* must be able to recognize the shapes he deals with. But I wish to make a more potent comment and maintain that perception of any kind (at least in systems capable of genuinely learning about their environment) involves (i) direction towards some objective and (ii) actions that modify either the environment that is perceived or images or concepts of shapes in the environment. If perception is construed in this

manner, Λ *need* be no *more* than perception (to call it "design" is a matter of degree and of certain conventions that chiefly effect the boundary conditions upon Λ and the separable component, *P*, in Λ).

2. PERCEPTION

2.1. A couple of perceptual mechanisms have been seriously considered (Fig. 1 and Fig. 2).

(i) Perceptual filters that represent an image of an input from the environment. The *concept* of a shape that parallels its appearance in the environment is delineated in terms of the *attributes* that the filter selects as *relevant*, for the survival of the perceiving organism, or with reference to some abstract criterion.

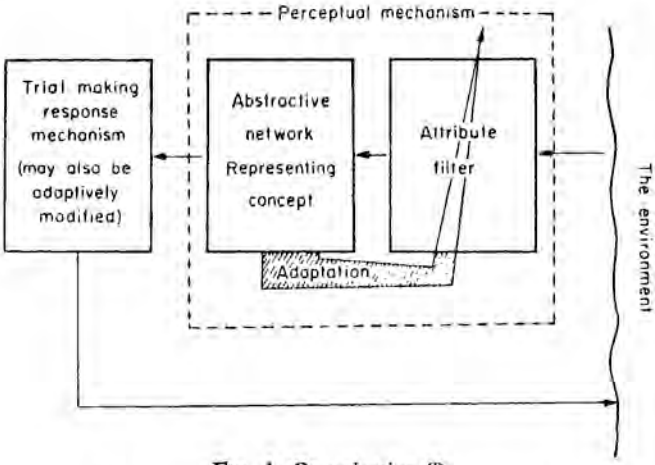

FIG. 1. Organization (i)
Notice that the perceptual mechanism is trivial unless a response mechanism is added.

(ii) Feedback systems mediating a form of homeostasis. The organism perturbs its environment by trials or actions in such a manner that it maintains some relation (between itself and its environment) invariant, notwithstanding the flux of external events. *Concepts* of shapes in the environment have, in this case, the dimensions of whatever actions must be performed to maintain invariance, given the appearance of these shapes as consistent features of events in the environment.

Only a nominal alteration is needed to convert organization (ii) into a system of scientific inference[1] such as Popper's system.

Trials (or perturbations) are relabelled "tests"; a description of the state of affairs that gives rise to a trial becomes the "hypothesis" to be tested. The

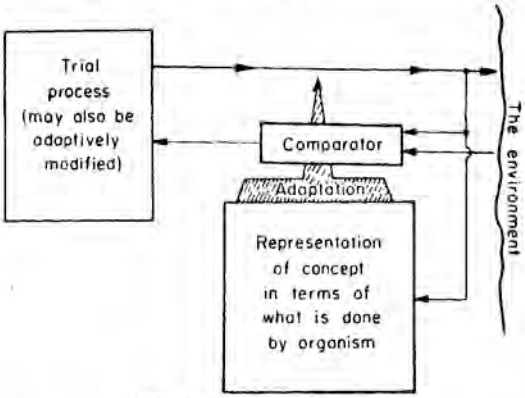

FIG. 2. Organization (ii)
Notice that the comparator in any real and finite organism must include an attribute filter.

test result is "evaluated" using the tenets of homeostatic stability. The whole procedural component, P, of Λ corresponds to the deductive restriction, the scientific discipline, of Popper's system.

Organization (i) can be static (although this is not necessarily the case) and its realization has been discerned in a few animals, by Lettvin,[2] for example, in the retina and colliculus of the frog. Von Foerster[3] and Uttley[4] have, amongst others, built categorizing artefacts which are perceptual filters and their basic principles have been examined in detail.[5] On the other hand organization (ii) (which has, perhaps, a more immediate role in design) is essentially dynamic. Biological manifestations of organization (ii) have been considered by Zopf,[6] MacKay,[7] Napalkov,[8] Mittelstadt[9] and others.

Neither (i) nor (ii) is confined to the lowest level of concept; to the immediate "percept" of the environment. Various levels of Gestalt are derivable by repetition of the same process to form an hierarchy.[10,11] We comment that in Cybernetic terms the classical distinction between Gestalt psychology and a conditioned reflex system is reduced to a matter of degree and a choice of representation. Thus either of the perceptual mechanisms (i) and (ii) can be interpreted as the end product of a conditioning procedure which does (by common consent) involve feedback loops and interactions or as the result of holistic changes (which describe the same mechanism with an accent upon the interaction terms).

2.2. Excepting organisms like the frog, which do not learn with respect to the modalities concerned, we may legitimately doubt the functional separation of organizations (i) and (ii).[12] At any rate, (i) and (ii) define modes of activity rather than identifiable structures and it seems likely that each contributes, in some measure, to any process that resembles our own perception. Certainly it is more convenient, when speaking of the form of a particular concept, to regard it, with Pitts and McCulloch in their classical paper,[13] as

an image of invariants under a group of transformations, derived by averaging over a functional defined on this group. True, it is possible to bring the dynamic features within this "organization (i)" picture, as a change in the function computed by the perceptual filter. But, on the whole, adaptive modification is more conveniently considered in terms of "organization (ii)" as a change in the homeostatic relation and this preference gains a great deal of cogency when we come to deal with changes of attention that modify not only the form of the computed function but also its domain and its range.

In any case, when considering design, we shall be concerned with both aspects of the perceptual process, Λ. So far as the initial conditions and constraints are concerned Λ is most readily construed as an organization like (i). On the other hand, the convergence of Λ, entailing interaction between A and its environment B, is better envisaged as an organization like (ii).

2.3. Although the physical embodiment of Λ is irrelevant for the present purpose, we must deal with an issue that model builders *do* find important, namely, the extent to which any (adaptively modified) perceptual mechanism is *predetermined*. How far is the brain a "tabula rasa"? How far is it a rigid network?

Different model builders have adopted the different attitudes (but with equal lack of success). Thus, the earliest kinds of "perceptron"[14] were "Random" networks of computing elements. ("Random" in the sense that the connectivity initially assigned to a collection of elements, capable of altering their connections as a function of their activity, was held to be irrelevant.) On the other hand, the majority of other brain models constructed up to 1955 or so were no more than automata.[15] Fashions have changed; and the distinction between "Random" nets and automata has lost its edge (which is amply demonstrated by the relatively structured form of Rosenblatts more recent Perceptrons[16] and the complete absence of strict automata). In this mellower atmosphere it is admitted that *perception* is the property of a system which appears to some extent "Random" or "indeterminate" in the sense (I) that an observer cannot provide a complete description of the perceptual mechanism in a language used to describe its behaviour[17, 18] and (II) that if the mechanism or organism is impelled to provide a description of what it is doing, the algorithms it would recite will not fully account for its behaviour.

Neither (I) nor (II) should suggest a mystique of perception. They reflect an attitude towards behavioural descriptions which comes chiefly from the Cybernetic arguments of Wiener[19] and Ashby[20] which have been discussed in other papers.[21, 22] On the other hand, it is also agreed that perception is not the property of an *unstructured* system. Beer[23] has admirably criticized the concept of such a thing. Further, it can be argued on more practical grounds that even if an unstructured ("tabula rasa" like) brain were contrived, it could never give rise to a process Λ which *converged*. Convergence,

as pointed out by Minsky and Selfridge[24] depends upon ordering properties, regularities and relations to the environment, which permit a coherent strategy to take the place of "Random" trial and retention of those states which lead to some reinforcement. Moreover, in so far as the shapes that are produced by A interacting with B have the status of *signs*, the relation between A and a potential recipient in his universe of discourse is far from haphazard. In fact, A must be similar, in certain crucial respects, to any organism that accepts the shapes he designs.[25] The requirement, however, is "similarity" rather than "identity". As recipients, we are often deluded (say, by chance events). Moreover, we are sometimes willing to accept other than man-made shapes as *signs* or even to call them legitimate designs with a merit of their own (music composed by a computor,[26] paintings made by an ape, or poetry written by sticking a pin to select words from a telephone directory).

2.4. There are adequate grounds for asserting that a learning process (and adaptive perception, like Λ, is a special case of a learning process) is best described in terms of evolution.[27] Hence Λ is a sequence of evolving systems, or "one evolutionary system" or, in the strict sense of the phrase[28] a "self-organizing system".

According to this view, the brain of A (or if A is a mechanism, whatever acts as its brain) is not conceived as a *computor* but a *medium* in which organizations that behave as computing systems are likely to evolve. Unlike a computor, these systems are *not* unchanged by the computation they perform *nor* is their survival guaranteed. Indeed, each organization that survives must *reproduce* itself; it must *compete* with other organizations for a share of the medium in which it is embodied. The medium must be such that some advantage is gained by *correlated* activity or co-operation between subsystems, whereby more elaborate information structures develop. To sustain the evolution there must be imperfect reproduction, or *variation* of structure, and the variants that survive will, on the whole, be those that are able to co-operate. In this respect the evolutionary process is "Random", but there is no lack of strategy. On the contrary, there are likely to be well-defined rules of evolution. These must almost certainly *conserve* successful variants through *recombination* (variants are combined, co-operatively, with parts of previously successful organizations) or some equivalent mechanism. As a result of the co-operative interaction between the evolving subsystems, an hierarchy of "organizations of the original organizations" is constructed. Λ is interpreted as the behaviour of such an "hierarchy building" process.

2.5. As seen by an observer, the indeterminary of Λ is nothing to do with chance events. Rather, it is an uncertainty of location. Due to the evolutionary character of the process, an observer cannot normally locate Λ "in A" or "in B". His image is a large ensemble of evolving subsystems, some "in A" and some "in B", which have close but variable coupling and interaction.

The most specific assertion possible is that Λ is mediated by a system, say Ξ_C, in C where $C \subset (A \cup B)$ or where $C = (A \cup B)$.

2.6. In so far as Λ occurs in the brain of A it leaves a trace which is often called the "engram". In so far as Λ is exteriorized in B, the environment, it leaves a trace R which we call a "design".

2.7. The distinction between an adaptive process and genuine evolution is more than nominal. Considered in terms of mechanism, an adaptive process is adequately specified as a sequence of changes in the parameter, ϕ, of a system Ξ_C with states $x \in X$ that represents the physical embodiment of the designing process, Λ. More exactly, we suppose that a system of the form

$$\Xi_C = F; \quad X \to X$$

is transformed, as a result of the design process Λ, into $T(\Xi_C)$. Let i, j, be different values of ϕ. In the case of adaptation, the transformation T has the form

$$[\Xi_C = F_i; \quad X \to X] \to [T(\Xi_C) = F_j; \quad X \to X]$$

Adaptation is maintained if ϕ assumes a sequence of values, including the values i and j and converging to a value ϕ^* such that the entire sequence, $[\phi]$ is selected to maximize $\theta(X)$. In this case

$$\Lambda = F_{[\phi]} \quad \text{and} \quad \lambda^* = F_{\phi^*} \quad \text{and}$$
$$F_{\phi^*}(x) = \lambda^*(x) = x, \quad \text{for all } x \in R.$$

On the other hand, evolution involves a different transformation of Ξ_C, say T^*, such that Λ entails

$$[\Xi_C = F_i; \quad X_0 \to X_0] \to [T^*(\Xi_C) = G_j; \quad (X_0 \cup Y) \to (X_0 \cup Y)]$$

Typically, if X_0 is a subset of X, $Y = X_0 \otimes X_0$ or, alternatively, $y \in Y$ may be a set of states of C defined in terms of attributes different to those used in determining $x \in X$ states. In mechanical terms this comes about because a reproductive process is involved in evolution. Thus Ξ_C must be reproduced with controlled variation. To avoid Rosen's Paradox[29] (that an "automaton" or system cannot reproduce itself because the range of a characteristic mapping such as X, in $F; X \to X$, cannot include F) we must invoke an "automaton" or system of higher logical *order* than the original (in this case the system characterized by G) such that the G system will, in a certain sense, "accept $F; X \to X$ as an input" and "reproduce it as an output".

On the other hand, the distinction between adaptation and the evolutionary process can be readily interpreted in terms of design, as such. Rosen's Paradox is the mechanical analogue of Russell's "Vicious Circle" Paradox[30,31] that a function cannot have its name as a member of its range. Russell's Paradox is resolved by the more explicit introduction of "Logical Order" and of "Logical Type". In the present case, the relations entailed by the

computation of G characterized systems are of higher logical order than those entailed by F characterized systems. Consequently, statements referring to these different levels in the evolving hierarchy are of different logical *type*.

Commonly G determined aspects of design appear "creative" with reference to the "procedural" aspects mediated by F systems. If $Y = X_0 \otimes X_0$ novel *relations* are "created" between existing objects; if Y is a novel set of objects adjoined to the original universe of discourse, *these* are "created". All in all, we identify the distinction between the "creative" and procedural" aspects of the design process with a distinction of type; and comment that the need to make this distinction, which is so manifest in the case of design, is present whenever we discuss the behaviour of evolving organizations.

3. CONCEPTS OF SHAPE AND A SPECIAL EXPERIMENTAL DEVICE

3.1. We have characterized the design of a shape, in a Cybernetic sense, by a distinction involving logical type and the mechanism of evolution. It is not difficult to identify this abstraction with real life design jobs, at an introspective level.

So far as I am concerned, for example, the act of painting a picture involves organization (ii) almost exclusively. The physical medium is sufficiently plastic (as I use it) to admit a conception of the job in terms of what can be *done* (within technical and other limits). The final image evolves in stages of increasing organization. At any stage procedural decisions stem from "creative" processes that often appear in consciousness as insightful interpretations of splashes of paint or badly delineated objects which, when they were produced at an earlier and less organized stage, had no unambiguous connotation. A flavour of organization (i) only appears when the picture is nearly complete or when the work involves a visual cliché. On the other hand, designing a circuit is predominantly a matter of organization (i). The juxtaposition of components to form trial arrangements, which does form part of the design process, is subservient to a search for one amongst a number of predetermined percepts which, when discovered, will yield the point of view that elucidates the design problem or even solves it. The whole business is conceived in terms of appearances, rather than actions.

Individual differences are so great that comments of this kind have very doubtful value. Certain generalizations may be legitimate. Translational design, for example, emphasizes the construction of a logical hierarchy of metalanguages. Optimizing design is apt to be conducted as an organization (ii) process initially (until some familiar "hill" is found in the parameter space) after which (as the designer, acting like an optimizing controller, climbs the "hill") it becomes chiefly an organization (i).

However, we need to replace remarks of this sort by an objective account of the shape of a designer's developing concepts of shape. At the moment

very little can be said for certain. In the rest of this paper I shall do no more than indicate some of the difficulties and suggest the bones of an experimental method capable of yielding objective data.

3.2. Since A, the brain, is inaccessible to precise measurement, an objective account depends upon exteriorization of the design process. The designer must be persuaded to use B rather than A for the conduct of Λ or, phrased in terms of mechanism, the evolution of Ξ_C must take place in the medium afforded by B. Formally, if η is a set measure, we aim, as experimenters, to maximize an index of exteriorization like

$$\mu = \eta(B \cap C)/\eta(C) = \eta(B \cap C)/\eta[(B \cap C) \cup (A \cap C)]$$

An immediate requirement is that B has characteristics that fit it for a medium in which Ξ_C can evolve (in precisely the sense that a brain is such a medium). In fact, the environments used for design do have reasonable characteristics in this respect (they are "malleable" as in Section 1.2) but, talking now in designer-like terms, it is not absurd to suppose that a form of B ideally fitted, as in Section 1.4, to procedural manipulations would maximize μ. A designer does not need too much encouragement to make use of any facilities that are provided, since his brain is far from an ideal medium (it is particularly limited in memory capacity and has deficient computational facilities). Moreover, we know, by definition in Section 1.2, that *some* exteriorization must occur in design. Hence $\eta(B \cap C) > 0$. So, on these grounds, the experimenter should carry out the recommendations of Section 1.4 and measure what use is made of the computing system he provides as B. Something very like this is done, of course, when setting up a problem solving experiment[32] where the same difficulty is encountered in a slightly different guise.

The objection to this course is partial and well known. In fact it is possible, at a given stage in the evolution of Λ, to exteriorize the component P of Λ. But, again by definition in Section 1.2, we must satisfy $\eta(A \cap C) > 0$. Hence, in order to preserve the essential participation of A, we need to maintain an informational matching between whatever aspect of Ξ_C is embodied in the medium of A and whatever goes on in B. Now a man learns; further, P is not really separable from Λ (it is only a convenience to place creativity in a separate compartment from procedure, as we pointed out before); hence the ideal P requirements change as the designer learns or Ξ_C evolves. Whilst it may be possible to adequately exteriorize rather simple problem solving, where the P criteria are fairly rigid, it does not seem possible to adequately exteriorize Λ in any *passive* environment when Λ defines a really interesting design process. The requirements of informational matching can only be met by an active form of environment with characteristics that *adapt* to suit the changing procedural demands of A.

There appear to be a couple of alternatives. One, which is applicable if A

is a group of people rather than one man, is considered by Lewis in his paper at this meeting. The other, which we shall discuss here, is to determine the form of environment by an adaptive process that uses a feedback connection, measuring *A* behaviour, in order to maximize the coupling between information structures mediated in *A* and in *B*.

3.3. Ideally we should provide a structure like Selfridge's evolutionary paradigm, "Pandemonium", as a device that controls and selects amongst a population of computing systems such as those suggested in Section 1.4, the "Pandemonium"[33] receiving its reinforcing feedback from *A* behaviour. This idea is not impracticable but has not yet been realized. However, we have experimented with similar arrangements[34] and the one which comes closest to the design problem was a device for exteriorizing certain aspects of the evolutionary process that takes place when a musical performer *improvises* either to suit his own taste or the whims of an audience (improvised performance would be *design*, if the results of improvisation were retained). The system concerned was called "Musicolour" and was devised, built, and used in various manifestations by T. R. McKinnon Wood and me, about 1954.

The arrangement resembled the "Colour Music" system recently demonstrated in London by Professor Lerner of the U.S.S.R. Academy of Sciences. As in Fig. 3 the performer plays on a musical instrument, the sound from which is amplified and fed to an adaptive machine. We may regard the

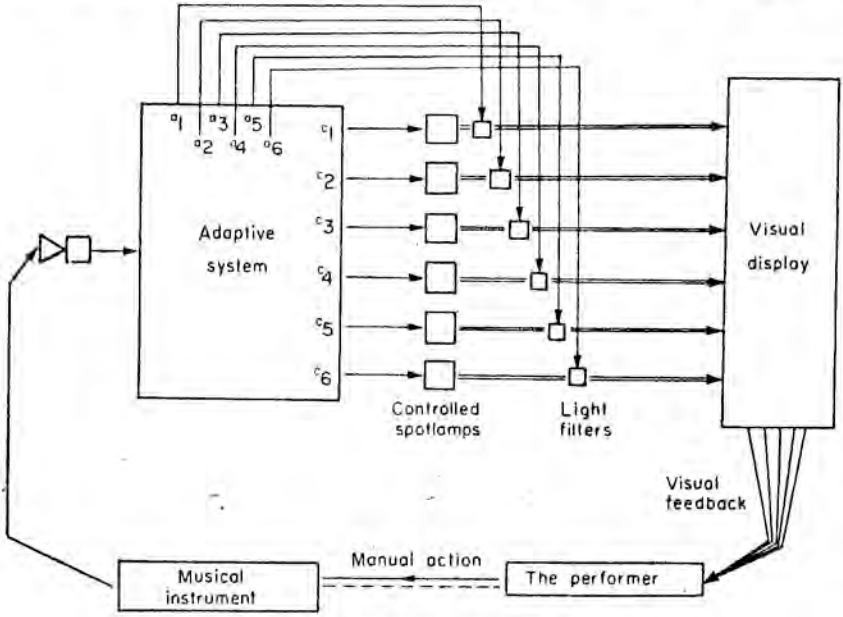

FIG. 3. Projection apparatus.

performer as making selections from an auditory alphabet to form auditory words. The adaptive machine, using some rule, makes selections from a visual alphabet to form visual words. The mechanism illustrated uses a set of controlled spotlamps and a set of controlled optical filters, which may change the colour of the lamp or the form of a projected image. The optical filters are controlled by outputs $a_1, a_2, a_3, a_4, a_5, a_6$, which will later be identified with the parameters of feature-detecting servomechanisms in the adaptive machine. The spotlamps that project through these filters to form a visual display are controlled by rapidly changing outputs $c_1, c_2, c_3, c_4, c_5, c_6$ which will later be identified with the outputs of adaptive trigger circuits associated with the state of these servomechanisms.

At least in principle, this much is common to Professor Lerner's "Colour Music" system and our "Musicolour". However, in the present case, the rule adopted by the adaptive machine is changed in such a way that the information transfer around the feedback loop involving the performer, A, and the machine and display, B, is maximized, thus maximizing μ and the coupling between systems in A and in B.

It is convenient to look at the system Ξ_C, which evolves in the performance, as made up of subsystems $\xi \in \Xi_C$ some of which can be identified with servomechanisms, available in B and able to assist the performer, and some of which are organizations that evolve in the performer's brain. These systems are able to adapt and maximize θ (the measure of Section 1.2 which, in this case, we identify with a suitable index of information transfer around the feedback loop). Now the ξ may exist independently or in co-operative aggregates with members that are coupled together. If a pair of subsystems, such as ξ_i and ξ_j co-operate, we express the fact by "$\xi_i \cup \xi_j$". To secure the co-operative pre-requisite of evolution in the medium of B (its existence being assumed in A) the measure θ, taken conditionally upon the activity of any subsystem, must be superadditive. Thus, for any i, j, we have, by design

$$\theta(\xi_i \cup \xi_j, X) > \theta(\xi_i, X) + \theta(\xi_j, X)$$

The subset of $\xi \in \Xi_C$ realized in B could, for example, be interpreted as the "Demons" in a "Pandemonium", when this condition is satisfied. On the other hand, in the present system they are realized by servomechanisms in the adaptive machine of Fig. 3 concerned with altering specific rules of "auditory" language to "visual" language translation.

The mechanical details are shown in Fig. 4. The amplified sound from the performer's instrument is fed to a bank of m variable "band pass" filters. In practical systems $24 \geqslant m \geqslant 6$ and we show $m = 6$ in Fig. 4. The kth filter, denoted VF_k, $k = 1, 2, \ldots, m$, "listens" to a specific feature of the sound input at a given instant. In the simplest case this "feature" is a specific band of frequencies although more elaborate feature specifications have been used. The particular feature, selected at a given instant by VF_k, depends upon the

position of a selector, which is servo adjusted (as the parameter of VF_k). Any selector can assume any of v positions.

The output of VF_k is rectified and averaged and indicates the predominance, at the instant concerned, of the selected feature in the sound input. This signal is applied to an adaptive trigger circuit M_k. This circuit has the characteristic that if the signal amplitude exceeds a threshold value, M_k is "ON", if not, M_k is "OFF". However, if M_k is "ON" a process is instituted

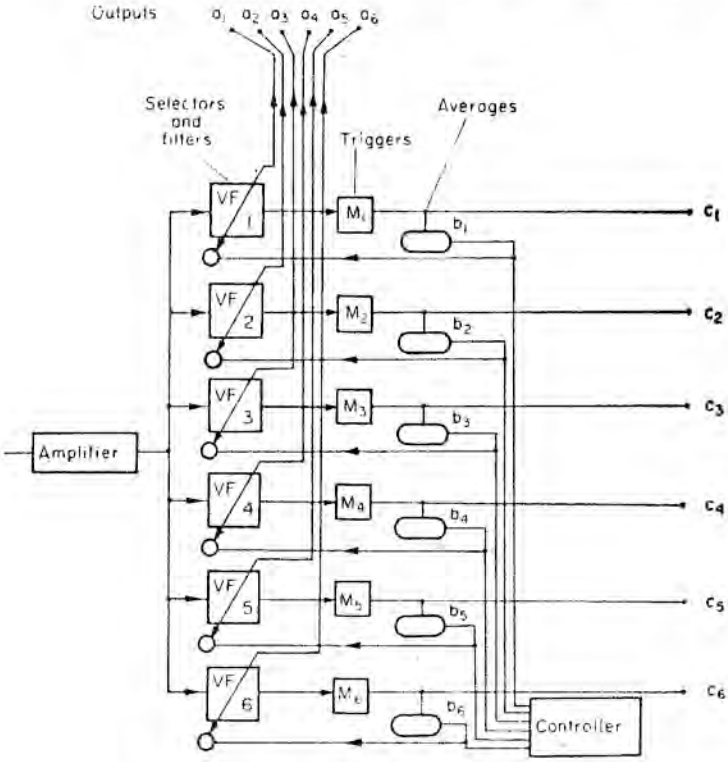

FIG. 4.

that increases its threshold value, so that, in order to retain M_k "ON", the input signal must be maintained and increased in amplitude.

The number of transitions from "ON" to "OFF" is averaged (over all m of the M_k) and is used to indicate the information transfer, θ. The selector servomechanisms, adjusting the features listened to by each VF_k are programmed to maximize θ. Hence the adaptive machine aims for a θ maximizing rule. In order to realize this programme it is necessary to provide at least $(v.m)^2 + m + 1$ analogue "Memory" registers, that retain the gain in θ achieved by assuming various possible states.

The performer interacts with the adaptive machine and "trains" it to assume a translation rule which he *approves* (to perform the auditory to visual translation that meets his requirements, to be the sort of design tool he needs) by variations upon his performance which can be quite generally specified (as variations in pitch, in amplitude, in rhythm or in transient characteristics; there is no one feature determining an interaction language).

3.4. Using this system, it was possible to show that a close coupled interaction between the performer and the adaptive machine could be established under many different conditions, reliably and repeatably. The reality of the stable state was tested by injecting disturbances into the system, without the performer's knowledge. In the conduct of these investigations it was found that the stability of the coupled system (estimated by the magnitude of disturbance needed to render it instable) increased (at least for an hour or so) as the performance got under way. Hence, on grounds of stability, a system of this kind is a practicable tool for the objective investigation of design.

Next, there was some peripheral confirmation of the evolutionary hypothesis. The modes of interaction between the performer and the machine, whereby the performer "trained" the machine, became more elaborate as the coupling persisted and there was some evidence of discrete levels in an hierarchy of organization. Finally, the performer's almost invariable comment that he was co-operating with the system (often "having a conversation with the device") tallied rather well with an objective account of system stability. It also seemed possible to make more detailed predictions, from the objective data, about what the performer's impressions would be. Hence, on grounds of potentially available information, a system of this kind should be considered further as a tool for investigating design.

In conclusion, recall that such a system can also be viewed as an "aid to the designer" (simply by removing the constraints introduced by the experimenter in order to give him specific data). In fact, the present system was chiefly used, as an aid to a performer, in this fashion and, minimally altered, could be applied in connection with many kinds of designing.

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