Summary

Automata may make use of several methods of information and data reduction before classification or perception of the input stimulus pattern. Some methods may involve retaining as much information as possible throughout the process until the final classification is accomplished. Suggested here is a concept of pre-organization of information by "property filtration" which reduces the information as near the source within the automata as is feasible with respect to the over-all system compatibility. "Property filtration" is explained and illustrated by describing two practical and several theoretical property filters. The results of this work to date indicate that this approach to data reduction and pattern identification may greatly simplify the ultimate construction of adaptive automata, if such property filters are used as functional input units.

1. Introduction

Any automaton worthy of being considered a member of the general species will surely consist of an aggregate of functional units, each unit functionally supporting and perhaps augmenting the operation of all of the other units and of the automaton in general. To direct the total activity of all the units and in general to control the operation of the automaton, either an external control entity or some internal control entity will be used. This control unit may be either a single unit or may be a combination of units—in any case, however, this may be called a control center. This control center will place some value judgment upon each unit's operating ability and necessity, the judgment being solely determined upon the merits as to whether the well-being of the automaton as a whole is maintained. To enable the control center to make these judgments and control decisions, information from the various units of the automaton and from its environment must be presented to the control center in some acceptable form. In all but the trivial instances, the information as utilized by the control center will not be of the same form or of the same complexity as that arriving at the automaton from the environment. That is, some transformation and reduction of the stimulus information will be necessary before the control center can digest the information and make an appropriate decision. Thus an automaton will contain units whose various functions are transduction, encoding, transmission, decoding, perception, as well as general data reduction of the information present both in the environment and in transit in the automaton.

Figure 1. Simple Automaton

Figure 1 illustrates a conceptually simple automaton. The information from the environment must first be processed by a stimulus transducer—i.e., a sensory element—after which it undergoes various transformations and reductions so as to be in suitable form for perception and control center assimilation. Upon assimilation of the information by the control center working in conjunction with the perception unit, a decision as to appropriate action, if any, is made by the control center and the units of the automaton are instructed to act in some manner conducive to the goal of the automaton. Ultimately, the output of the automaton will appear as some action or information in its environment, so a final transduction must be made. Therefore, after the control center makes a decision, its decision information must be transformed in some...
manner and then finally a transduction to the environment occurs.

For simple automata with limited special purpose behavior, the scheme shown in Figure 1 seems to be adequate. When the automata requirements are more complex, the question of reliability and economy of data processing may dictate some additional units being placed at various places along the information path. For example, it is more expedient to transfer through to the perception unit nearest the control center as much of the information as possible with the contention that more reliability of stimulus classification can then be made or is it more expedient to reduce and classify the stimulus data as near to the afferent stimulus transducer as possible and perhaps depend upon several different parallel information paths to the perception unit near the control center for reliability of classification? Taking a hint from the functioning of various biological organisms, the author believes the latter method to be most expedient. In fact, perhaps in addition to parallel information transmission paths between stimulus transducer unit and perception unit, different information about events in the environment should be obtained through different sensory modes. This means that instead of only redundancy of information in the coding process, redundancy of source and form of information may be desirable. The result would be redundancy of function as well as redundancy of information through coding.

Once the concept of reducing information as near its source in the automaton as possible is accepted, the concept of "property filtering" as conceived at the University of Illinois Biological Computer Laboratory seems applicable. Property filtering as used here is to be understood as information processing networks arranged in parallel computation channels which extract from the set of input data present certain particular subsets of data which characterize the input data in some manner. The properties which filter through the computational networks and are eventually transmitted to the perception unit near the control center are those properties which are pertinent to the operational goals of the automaton. Perhaps initially the property filters of an automaton would be structurally determined by the designer of the automaton, but it is not inconceivable that the property filter networks could be constructed using any of several different types of "synthetic neurons" as designed by many different laboratories, the resultant filters being adaptive with respect to time and function. To better illustrate the concept of property filtering some practical and theoretical filters will now be described.

2. The Numa-Rete

The numa-rete is a very clever form of property filter which was conceived and constructed by P. Weston of the University of Illinois Biological Computer Laboratory. The purpose of this filter is to determine the "n-ness" of its environment which consists of dark objects on a light field, the "n-ness" being the number of such objects which appear simultaneously upon the sensory layer--i.e., retina--of the device. Simply, the "numa-rete" counts the number of distinct dark shadows which are present on its retina when an interrogation button is activated, the count appearing on a numerical display panel.

The operation and construction of the numa-rete can be understood by referring to Figure 2. The sensory layer of the device is a planar square array of photo cells upon which the shadows or the objects themselves are placed. The computation layer consists of a similar square array of active elements, each connected to a photo cell in the sensory layer in an absolutely inhibitory manner in a one to one fashion. These active elements are threshold components which may be considered as non-adaptive synthetic neurons. Each active element is connected in a mutually excitatory manner along rows and columns of the computation layer to each of its four immediate neighbors. Completing the connections to each active element is an interrogator interconnection scanner connection and an output connection. Figure 3 shows the connections to a typical active element and the relative weights of each of its connections, including the threshold value of 0 = 1/2.

The control and display unit completes the numa-rete. Its purpose is to sequentially interrogate each active element in the computation layer in a manner to be described soon, sum the resulting activity to determine the total object count, and present the result on the numerical display panel.

The operation of the numa-rete is as follows. A number of distinct shadows are cast upon the retina, each shadow’s placement and size being within the resolution limits of the device. The operator then presses the interrogation button which sets all the active elements to one bistable state and also starts the interrogation scanner. The active element array is scanned sequentially, element by element, along rows until the scanning pulse interrogates an active element whose corresponding photo cell is in shadow. Since this element is not absolutely inhibited by its photo cell, it is triggered to its other bistable state. This results in any of its neighbors whose corresponding photo cells are also in shadow being triggered to their other bistable state. Neighbors whose photo cells are not in shadow are left unchanged. Therefore all active elements whose photo cells are under the same shadow are forced to change state, regardless of their position in the array. The result of all these active elements changing
Typical active element connections in the numa-rete
(Numbers in cell indicate relative weights of connections)
state is an output pulse to the summing unit.
In the meantime, the interrogation scanner continues its interrogation of the active elements. Since an active element which has been triggered previously cannot be triggered again until it is reset, only the active elements which are under a different shadow from all previous shadows can be triggered by the interrogation pulse. Therefore, after the scanner has completed interrogating the entire array, the number of output pulses is equal to the number of disconnected shadows appearing on the retina.

The numa-rete has no limitations with respect to shape or position of shadows on its retina other than the obvious ones of size and minimum distance between shadows as determined by the size and placement of the photo cells in the retina. Its operation does depend, however, upon a sequential method of interrogation. For some purposes this might be undesirable and so in an attempt to eliminate this restriction so that parallel operation of the output count could be performed, the method to be described next was devised.

3. Topological Counter

Consider a property filter which would instantaneously determine the total number of disconnected activity classes present at any instant upon some lamina structure; for example, if the lamina is a retina then the property filter would detect the total number of distinct objects focused upon the retina. L. Lofgren of the University of Illinois Biological Computer Laboratory has suggested a unique way to perform this count. This method makes use of the well-known circuit topology equation which relates the number of meshes, nodes, branches, and separate circuits of a network. Reinterpreting the terms mesh, branch, node, and circuit in terms of active elements and various combinations of these active elements within a lamina, the equation in question can be used to determine the number of separate classes of active elements in the afferent lamina in question. Thus:

\[ C = M + N - B \] (1)

where:

\[ C \] = the number of classes of connected active elements in a specific afferent lamina,
\[ M \] = the number of particular combinations of active elements, each combination corresponding to an elementary network mesh,
\[ B \] = the number of particular combinations of active elements, each combination corresponding to an elementary network branch,
\[ N \] = the number of active elements, each element corresponding to an elementary network node.

Figure 4 illustrates the simplest arrangement of elements and the various combinations of active elements in a lamina which correspond to a node, a branch, and a mesh for use in Equation (1). That is, a node is an active element, a branch is a combination of any two adjacent active elements, and a mesh is a combination of any three triangularly adjacent active elements.

Other than the obvious resolution limitations of size and distance between distinct objects when the lamina in question is a retina, there is one serious fault with this system when used to determine the total number of distinct objects present. These objects must all be "holeless"—i.e., be simply connected—otherwise the total class number, \( C \), is reduced by the quantity, \((m - 1)\), for each \(m\)-ordered multiply connected object on the retina. However, when the topological counter is used in conjunction with the numa-rete, this disadvantage becomes an advantage as will be shown later.

As an example of the hardware requirements for such a system, consider a lamina with a structural arrangement like Figure 4 containing \((n + 1)\) rows, each row containing \((n + 1)\) nodes. The resulting maximum total numbers of meshes, nodes, and branches which may occur are:

\[ M_{\text{max}} = 2n^2 \] (2)
\[ N_{\text{max}} = n^2 + 2n + 1 \] (3)
\[ B_{\text{max}} = 3n^2 + 2n \] (4)

Thus it is quite apparent that the number of mesh, node, and branch detectors for parallel computation of all possible lamina stimulus becomes quite large for even a moderately small lamina.

With respect to how the actual calculation of \( C \) in Equation (1) can be performed, several different methods may be used. If analog methods are used, then severe restrictions are placed upon the tolerances of the components if the lamina is only reasonably large. Therefore, threshold devices and standard computer techniques may be indicated, if only for the required accuracy. Certainly, synthetic neurons can be used as the threshold devices.6

Regardless of what methods are used, the final system will have some correspondences to that shown in Figure 5 where a parallel computation method is illustrated for a \(16 \times 16\) node stimulus lamina. Again the laminae structure possible is visible as it was also in the numa-rete, emphasizing the property filter technique of lamina computation.

As mentioned previously, the numa-rete uses basically a sequential method for its computations.
Fig. 4
Typical simple node arrangement for topological counter

Fig. 5
Topological counter with a 16 x 16 node retina
whereas the topological counter just described uses basically a parallel technique. However, the latter could conceivably make use of a modified sequential technique which would be a compromise between the two methods and which might relieve some of the hardware limitations on the topological counter.

4. Theoretical Property Filters

The two property filters, or more properly property detectors in their present use, which have been described are practical solutions to the problem of reducing and classifying information which may be present as afferent stimuli in some lamina. Other reductions and classifications are certainly possible, among them being the ones studied theoretically by A. Inselberg, L. Lofgren, and H. Von Foerster of the University of Illinois Biological Computer Laboratory. A brief description of some of their theoretical property filters follows.

Figure 6. Simple Property Filter

In Figure 6 are illustrated three infinitely extending one-dimensional arrays of elements. Assume layer i is composed of light sensitive elements which can activate the elements in layer j through the connections shown. Assume also that the elements in layer j can each perform some logical functional operation upon the outputs of the particular associated elements in layer i. If, for example, element B and all elements in layer i to the right of element B are excited as illustrated but element A and all elements to the left of element A are not excited, and if each element of layer j or performs the logical operation of exclusive "or" on its inputs, then only those elements in layer j which are at the stimulus edge will produce an output. Thus only the element \( \nu \), in layer j with output \( AB \lor \overline{AB} \), will have any output activity for the illustrated instance, all other elements in layer j being inactive. Similarly, a right edge of stimulus would activate the corresponding element in layer j and so the laminae structure considered extracts the property of "edgeness" or contour from the stimulus activity.

If each of the 16 possible logical operations of the elements of layer j upon their inputs are investigated, it will be found that both positive and negative edge detectors, positive and negative right and left edge detectors, positive and negative replicas, and various other characteristics of the original stimulus activity results. In principle, then, various properties of the stimulus can be extracted as a result of these logical operations performed upon the response of one lamina by elements of a succeeding lamina.

This action of one lamina upon another lamina suggests the general concept of some "action-function" between n-dimensional laminae. In fact, if only one lamina is involved, the concept of some "interaction-function" is suggested. The "action-function" would specify how much output activity of any element in lamina i would be passed on to the input of any element in lamina \( i + n \), where \( n > 0 \). For \( n = 0 \), the "action-function" would become an "interaction-function" which would specify how much output activity of any element in lamina i would be passed on to the input of any other element in the same lamina i. If \( n < 0 \), the "action-function" becomes a "feedback-function" which would specify how much output activity of any element in lamina i would be passed on to a preceding lamina. Only "action- and interaction-functions" have thus far been considered.

There is also no conceptual difficulty if the elements are allowed to become indefinitely small and indefinitely close to each other, resulting in a continuum n-dimensional lamina. The resulting stimulus density \( \sigma(p) \) and the response density \( \rho(p) \) at any point p in the n-dimensional continuum can be defined as follows:

\[
\sigma(p) = \lim_\Delta V \to 0 \frac{\Delta S(p)}{\Delta V^i} \tag{5}
\]

\[
\rho(p) = \lim_\Delta V^i \to 0 \frac{\Delta S(p)}{\Delta V^i} \tag{6}
\]

where:

- \( S(p) \) = the stimulus or excitation input at point p on some lamina,
- \( R(p) \) = the response or activity output at point p on some lamina,
Therefore for an n-dimensional continuum lamina structure a response density function is:

\[ \rho_j(p) = \int \rho_j(q) F(q, p) ds(q) + \int \rho_i(r) G(r, p) ds(r) \] (7)

where:

- \( \rho_j(q) \) = the response density at point q in lamina j.
- \( F(q, p) \) = the action-function between point q in lamina j and point p in lamina i.
- \( ds(q) \) = differential n-dimensional volume element in lamina j.
- \( \rho_i(r) \) = the response density at point r in lamina i.
- \( G(r, p) \) = the interaction-function between point r in lamina i and point p in the same lamina.
- \( ds(r) \) = differential n-dimensional volume element in lamina i.

Using this formalized approach to property filtration, Von Foerster, et al., derive some interesting results for various choices of \( F(q, p) \) and \( G(r, p) \). For example, if a one-dimensional lamina is excited by a stimulus function, \( U(p) \), that can be expanded in a Fourier series with respect to distance along the lamina and if the interaction-function, \( G(r, p) \), is chosen as a normal statistical distribution with respect to distance--note that there is no action-function here since only one lamina is being considered--then it can be shown that the lamina in question will perform a "sharpening" of the stimulus function distribution. That is, the higher order terms in the Fourier series expansion are enhanced.

Another interesting example involves two two-dimensional laminae with an action-function, \( F(q, p) \), defined as a normal statistical distribution with respect to distance from corresponding points--note that there is no interaction-function here. The result of this analysis, as might be suspected by analogy to the first simple illustrative example, is a contour filter for all two-dimensional response functions of activity from the first lamina, provided the response function can be expanded in a polynomial with which contains any distance, \( x \), to a degree no greater than one. This condition can easily be satisfied.

Perhaps the most interesting examples of action- and interaction-functions among laminae are those which involve anisotropy of the functions involved. These result in property filters which may allow certain characteristic information about the geometry or the topology of the lamina activity to be extracted. Of immediate interest are action-functions of the form:

\[ F(q, p) = F_4(r, \varphi) = \epsilon \cos 2\varphi \] (8)

where:

- \( F_4(r, \varphi) = F(q, p) \) expressed in polar coordinates.
- \( r \) = the radial distance from the point p in question to the point corresponding to q in the previous lamina.
- \( \varphi \) = the angle between the radius, \( r \), and some reference line in the lamina in question.
- \( \epsilon \) = arbitrary constant.

If action-functions of this form operate upon the response of some lamina, and if that response is a straight line contour of activity only, then the response of the analyzing lamina will be a function only of the normal distance from the point in question to the straight line contour and of the angle of inclination of the contour with respect to the arbitrarily selected reference line.

The action-functions defined by Equation (8) have certain lines of symmetry with respect to the angle of the radius, r. If more than one anisotropic laminae operate upon the same response function and if the lines of symmetry of each of these laminae are rotated relative to each other, interesting results are obtained when the responses of these computation laminae are summed. In particular, if three parallel anisotropic computation laminae, each differing from the other only in the \( \varphi \) of Equation (8), this difference being \( \pi/3 \), and the responses of these computation laminae are summed, the result is zero at every point provided the input stimulus is a straight line contour of infinite length. Such a system might be called a "straight line filter".

5. Conclusions

The numa-rete, the topological counter, and the theoretical property filters just described suggest ways in which the afferent stimulus information from an environment can be reduced and classified into responses appropriate to different requirements. Separately, they indeed detect certain limited properties, but in combination, they may be even more useful. For example, the numa-rete and the topological
counter operating in parallel can classify an object or character as to its order of connectivity and the numa-rete and the straight line filter in cooperation may be able to dichotomize a group of characters as to whether they are composed of only straight lines or whether they contain curves as well as straight lines.

These concepts lead into the over-all larger property detection area, that of the detection and use of gross object characterizations such as multiple-connectivity ("holeness"), "straight lineliness", "angleness", "intersectness", etc. If such property filters as are needed to detect these more gross characteristics of patterns can be designed and constructed, then the way seems open to pattern detection and identification in terms of neighborhood properties only.

TABLE 1

<table>
<thead>
<tr>
<th>Properties</th>
<th>Printed Digits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>&quot;single holeness&quot;</td>
<td>x   x   x   x   x</td>
</tr>
<tr>
<td>&quot;straight lineliness&quot;</td>
<td>x   x   x   x   x</td>
</tr>
<tr>
<td>&quot;curveness&quot;</td>
<td>x   x   x   x   x</td>
</tr>
<tr>
<td>&quot;smoothness&quot;</td>
<td>x   x   x   x   x</td>
</tr>
<tr>
<td>&quot;single intersectness&quot;</td>
<td>x   x   x   x   x</td>
</tr>
</tbody>
</table>

Table 1 illustrates a simple tentative characterization of printed digits by this scheme where the "properties" to be filtered are listed at the left for the corresponding digits across the top. It will be noticed that such characterizations will be independent of size, translation, and rotation, but not entirely from distortion. To make these independent of distortion, topological properties such as the connectivity should be chosen, if possible.

It should be emphasized that the particular characterization illustrated by Table 1 is not yet possible since all the required property filters are not designed and indeed may not be technically possible. However, the concept of property filtering using methods other than standard statistical methods seems to offer some promising possibilities.

Acknowledgment

The author wishes to emphasize that the present article is, in part, a summary of work on data preorganization being done at the Biological Computer Laboratory of the University of Illinois by not only himself, but also by A. Inselberg, L. Lofgren, P. Weston, and G. Zopf, under the direction of H. Von Foerster. The work is sponsored by the Information Systems Branch of the Office of Naval Research.

References


From the collection of the Computer History Museum (www.computerhistory.org)