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CODING FOR RECORDING AND RECALL OF INFORMATION

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Abstract—To explore the potential fruitfulness of the mathematical theory of communication for information science, we examine the question of how to encode a message at the time it is encountered so that it will come to mind at the time it is needed or can be used. After describing some examples of this problem, we propose a prototype computer program and an experiment, and use these to analyze ways of extending or replacing the classical model of communication theory to include multi-channel, multiway networks with store-and-forward memories. Coding is discussed in the context of associational structures. The general purpose nature of information, and the analogy between "energy as an invariant of motion" and "information as an invariant of thinking" is suggested. It is unlikely that the classical mathematical theory of communication will have great potential applicability to information science without major modification, though some of its concepts have already exerted their influence. A central problem of information science on which to test its applicability is how to find representation mappings (encodings) so that increasingly effective plans and acts can be selected, using meaningful, action-oriented maps that stress use of human effort and time in attending to organized cumulative knowledge that can be brought to bear on human needs at strategic times.

1. INTRODUCTION

When a person needs an item of information he has encountered before and fails to use it, it is primarily because he fails to think of it and only secondarily because he fails to retrieve it after thinking of it[1]. When encountering new items, is there anything a person can do to ensure that he will think of it when an occasion to use it arises? In addition, what can he do at the time of first encounter to make it easier to recall or retrieve when it is thought of?

If a person is working on a problem over a longer period, perhaps on a research paper or preparing his tax returns, then his mind is prepared to see the relevance of certain items of information that he encounters during that time, which he would otherwise not notice. He may use these items at encounter time or else encode them at encounter time so that he will readily think of them when he anticipates using them. It is the preparedness of his mind that enables him to so encode them.

The problem of how to encode experiential encounters for saliency in anticipated uses by the same user has its counterpart in indexing. Both involve embedding the input in several associational nets so that it will be associated in any of several future situations in which this input is useful. In indexing, a person must encode experiential encounters in anticipation of their use by others, and that is quite different. It must rely on those aspects of his associational net which are shared by the indexer and the intended user. At any time, the mind is prepared to screen inputs for possible use in numerous potential future situations, and it must screen a vast number of such inputs. Therein lies the difficulty.

A formal framework that uses some of the thinking of information theory and that may also be a starting point for inquiry into representations and coding for saliency and future use is the data model of Elias[2] and Elias & Flower [3]. We sketch it as follows:

Definition 1

A data problem, $\langle D, F\rangle$, is specified by a finite ensemble of possible databases $D = \{d_1, \ldots, d_A\}$ and a finite set of retrieval questions, $F = \{f_1, \ldots, f_B\}$ with $f_j(d_i)$ being the answer to question f_j about database d_i.

Example 1. Consider a set of 1000 people a database user knows, each specified by name coupled with what each of these persons is known to him for. If he is a businessman, a typical entry might be "Mary Redgreen, who is looking for a computerized vacuum cleaner," and if he is a systems engineer, it might be "Lotfi Zadeh, known for fuzzy set theory." The retrieval system must provide for all possible combinations of 1000 names combined with associated terms; if each name were a string of 20 English lower-case characters, including blanks, and each term 30 characters from a set of 29 possible characters, then as many as $\binom{27^{20}}{1000} \cdot 29^{30 \cdot 1000}$ such combinations are theoretically possible and d_1 is one such combination, the single one that may be recorded at a given time. Of course, in reality, most of these theoretically enumerable combinations are not possible either, due to constraints. A retrieval question may be to request the associated term given the name, e.g. Mary Redgreen, and there are 27^{20} such questions which are theoretically possible; denote them by $f_1, \ldots, f_{27}^{20}$. Another is a request for all people with a given associated term; this adds another 29^{30} theoretically possible questions:

$$f_{27}^{20} + 1, \ldots, f_{27}^{20} + 27^{30}.$$

Definition 2

A retrieval system, $\langle R, Q, U \rangle$, is specified by: a representation scheme R that maps D into $\{0, 1\}^L$; a set of retrieval algorithms Q that generate address in $\{1, \ldots, L\}$, read the contents of cell i, which is 0 or 1, and generate a new address, output an answer or halt; a set of updating algorithms U such that if it is started with the memory in an initial state in $U_i R(d_i)$, the algorithm in U for d_i reads and/or writes some memory cells and halts with memory in a state in $R(d_i)$.

Example 2. Consider example 1, except that $A = 3$ instead of $\binom{27^{20}}{1000} \cdot (27)^{30000}$ and $B = 2$ instead of $27^{20} + 29^{30}$. Thus,

$D = \{d_1, d_2, d_3\}$ = databases $F = \{f_1, f_2\}$ = questions

$d_1 = \langle$Einstein, relativity theory; Maxwell, electromagnetic theory; . . .$\rangle$

$d_2 = \langle$Einstein, photoelectric effect; Maxwell, electromagnetic theory; . . .$\rangle$

$d_3 = \langle$Einstein, relativity theory; Hertz, electromagnetic theory;
Dyson, electromagnetic theory; . . .$\rangle$

f_1: What about Einstein?
f_2: Who on electromagnetic theory?
$f_1(d_1)$ = relativity theory $f_2(d_1)$ = Maxwell
$f_1(d_2\}$ = photoelectric effect $f_2(d_2)$ = Maxwell
$f_1(d_3)$ = relativity theory $f_2(d_3)$ = Hertz, Dyson

R: $d_1 \to 001$, $d_2 \to 101$, $d_3 \to 110$

Q_1, the algorithm to answer f_1 (in any database) is:

```
read the contents of address 1
if it is 0
then output "Relativity theorem" and halt
else read contents of address 3
  if it is 1
  then output "Photoelectric effect" and halt
  else output "Relativity theorem" and halt
```

Q_2, the algorithm to answer f_2, is:

```
read the contents of address 2
if it is 1
then output "Hertz, Dyson" and halt
else output "Maxwell" and halt
```

U_1, the algorithm to update what is recorded to database d_1 is:

```
write 0 in address 1
read address 3
if it is 1
then halt
  else write 0 in address 2
    write 1 in address 3
    halt
```

There is another algorithm U_2 and U_3, such as:

```
write 1 in address 1
write 1 in address 2
write 0 in address 3
halt
```

Theorem (Flower). Let $a_i(s)$ be the number of read or write accesses to some memory address made by update algorithm U_i when it is started in initial memory state s (e.g. $a_1(001) = a_1(101) = 2$, $a_1(110) = 4$ in example 2). For any system $\langle R, Q, U \rangle$ that solves the data problem $\langle D, F \rangle$, the following inequalities hold:

(1) $\sum_{s \in R(D)} 2_{-} a_i(s) \leq |R(d_i)|$, the no. of L-bit strings assigned to d_i.

(2) $\text{MAX}_{s \in R(D)} a_i(s) \geq \left\lceil \log_2 \frac{\Sigma |R(d_i)|}{|R(d_i)|} \right\rceil$ (smallest integer $\geq$)

(3) $\text{MAX}_{i \in \{1, \ldots, |D|\}} \max_{s \in R(D)} a_i(s) \geq [\text{Log}_2 |D|]$

This formulation stresses the efficient use of computer resources. By searching for bounds on the number of read or write accesses, or the number of memory cells, it assumes that computer memory or time is a limiting or even a scarce resource. This is no longer realistic; it is the time of persons using the computer system that is most valuable, and it is important to design information systems so as to be used by and helpful to persons, even if the system is used inefficiently.

A more important problem is that of recognizing what information is needed, either at the time it is needed or in anticipation of such a time. Such recognition is helped by the availability and use of a map by which its user can orient and steer himself. A map is a representation of its user's environment, internal and external, that indicates the relation between states and actions, which to avoid, which to select.

In what follows, we will describe a sample of examples in which this problem arises and abstract from these two prototype problems, one to serve as a paradigm for experiments, the other for analysis and computer simulation. We use these to analyze ways of extending the communication models now in use. We then examine coding algorithms. This leads to new views of the nature of information.

2. A SAMPLE OF EXAMPLES

2.1 *The Professor*

Preparing a lecture or a research paper (or even income tax returns) involves the active search for facts and ideas relevant to the topic. This can be done systematically by subject searching if there is time and the necessary facilities. Otherwise, the professor must rely on what comes to mind when he prepares the lecture or paper. If he does not think of a certain item that he has encountered before the time the occasion to use it arises—i.e. at the appropriate point in the logical flow of ideas in the structure of the lecture or paper—then it is less likely to be thought of and used later. (It might be thought of before, but is not likely to be used unless it is especially recorded for such use). Once an item is thought of, it must be retrieved from long-term or external memories. But we will focus this paper only on the first process of attending to items encountered previously, of "thinking of them," of initiating the search for them.

Suppose, for example, that the professor is working on a problem of antenna design, and thinks of bringing in electromagnetic theory. He will search his database with the second kind of question, f_2 in example 2. He must first call algorithm Q_2. That is part of a frame or schema[4] that will be in force when he is concentrating on antenna design theory. He may also have recorded different databases, one for each frame, with a higher-level database directing him to the lower-level ones.

Suppose, however, that he encounters relevant inputs for the first time while he is preparing and while his mind is also prepared to recognize such inputs. If he cannot use the input right away, he must update the appropriate database so that he will think of the new item when the time comes. What he is to think of is more likely to be something highly specific than something as general as electromagnetic theory. He must somehow incorporate a saliency feature into the code, that results from the updating algorithm so that it automatically comes to his attention at the right time.

2.2 *The Physician*

In making judgments about diagnosis and treatment, most doctors in a sample of 17 who were asked say that they always or usually rely primarily on their own experience; eleven of the 17 usually rely on what they read; five rely heavily on what they learned at meetings and only two said they relied primarily on what they learned in medical school. Most of them organize their files by patient's last names, but only one of the 17 always recalled the names of past patients representing relevant prior experiences, while eight said usually, two said half the time, and six said occasionally. Two said they provide cues or associations to the office staff, two recalled the problem or clinical situation and two recalled the face.

If experience is so important, it may pay to investigate how well physicians record experiences with a view toward being sure to think of them in a future case in which that experience can be fruitfully brought to bear. If they don't do it as well as they would like (or as well as the patient has a right to expect), then it may pay to find means of helping them to improve this recording process.

2.3 *The Lawyer*

He must often think on his feet, recording all statements made by witnesses, adversaries and the judges during a trial as well as out of court so that he can think of these items during cross-examination and summation. Like other professionals, he must also record, for future attention when an occasion calls for it, all new laws, important opinions and cases that he encounters.

2.4 *The Businessman*

Remembering the names and associated key impressions about the persons he meets, as in example 1, helps him to build up an image of potential customers or other business relations for use in judging whether to diversify a product line, for example. It is more important to recall, at the right future time, that there is a significant number of reliable potential customers than exactly who they are, because the second retrieval question does not arise unless the first one is settled.

2.5 *The Board Member*

During a council session or board meeting, each member should be able to screen all that is said and encode what is filtered through for attention when the question is called or when it is his or her turn to speak.

2.6 *Simplest problem*

If a person is asked to draw a stick figure, it is possible that he invokes a structured program somewhat similar to the following LOGO program[5]: TO MAN, VEE,

FORWARD 50, VEE, FORWARD 25, HEAD, END, where VEE = RIGHT 120, LINE: 50, RIGHT 20, LINE: 50, RIGHT 120, END and LINE:DIST = FORWARD:DIST, BACK:DIST, END, and HEAD = RIGHT 45, SQUARE:20, END and SQUARE:D = FD D, RT D, FD D, RT 90, FD D, RT 90, END. FORWARD 25–FD 25 instructs a "turtle" or pointed cursor on a TV screen to move 25 mm in the direction it is pointing and to leave a line marking its trail. RIGHT 120 = RT 120 causes this cursor to change its direction by 120 degrees counterclockwise. If the same person is asked to draw the same stick figure a week later, the results are remarkably similar. There are minor variations is precision and detail, but the figure is almost as consistently recognizable as a signature.

Information theory can be used to analyze the trade-off between details and precision[6], but the analysis rapidly becomes complex because increased precision in a few details cannot compensate for more but imprecise details, and because the essential details cannot be regarded as if they were independent variables. Nontheless, it is a structured procedure that appears to be stored in a database, and these may be selected from a pre-existing repertoire. Thus, if a stimulus in the form of a circle on a card were presented to a subject, first a procedure corresponding to "compass use", or an appropriate LOGO subroutine, may be selected. The radius is selected next, with less weight. The location of the center may be given third priority and recorded with least precision. A subject would never store the circle as a set of x and y coordinates, though that contains the same information to some approximation.

The priority given to a procedure need not reflect how often it is used. It reflects centrality and presumably also saliency. Saliency, however, must be specific and context-dependent. The information in stored procedures corresponds to optimal representations, allowing for a degree of variety required for discrimination without overloading or confusion, by means of cooperative rather than destructive interference.

It may be the storage of such procedures as the LOGO program with fuzzy parameters, organized into frames, that comprises our long-term memory of stick figures. These can be thought of as representations of a database, encoded as L-bit words over L memory cells. If a new stick figure is encountered, the database is appropriately updated by an algorithm. But such an algorithm must recognize that the database consists of programs, and must preserve essential relations among elements of the database as well as across databases. We encode a new form—e.g. a stick figure unlike any other we have seen before, or a Chinese character for a previously unencountered concept—both because we recognize it as a stick figure of Chinese character *and* because it differs from all previously encountered instances or classes of instance in striking ways.

2.7 *A prototype program*

Consider a computer program for solving a class of problems, such as determining the convergence of series and finding the sum if it exists. Input at occasion-time (when someone wants to use the program) consists of the description of a series in a variety of ways, involving man-machine conversation. Output consists of "It diverges", "It converges to ____", with the blank filled in with a variety of descriptions also allowing for man-machine interaction, or "I cannot analyze this series". For our purposes, we consider a related program that accepts inputs at encounter-time (whenever such an input is entered) in the form of a result (new method, theorem, etc.), possibly from an author directly or form the primary literature or the secondary literature, such as Mathematical Reviews. This program screens such inputs and encodes those it considers relevant to one of its problem-solving programs.

There are several kinds of relevance. The procedure for problem-solving may be a general algorithm, and its effectiveness and efficiency may be subject to improvement on particular problems; inputs that improve this efficiency are relevant, and are targeted for use by an algorithm improvement program. That may occur at encounter-time or during free time in between. The problem-solving procedure may be based on heuristics (if-then-else rules, the effectiveness of thich is not fully or algorithmically determined, as opposed to algorithms, the effectiveness of which is proved). The input may be a new heuristic or it may stimulate the formation of one, in which case it is to be used by a program that integrates new heuristics into existing procedures or one that forms new ones and integrates the results. An input may be the very answer that is requested at occasion-time, or it may be a more general or more special case of what is requested.

In all these cases, inputs at encounter time are not attended to unless they are judged to be relevant to some problem-solving program, i.e. directly or indirectly useful at occasion-time. This assumes that all problem-occasions can be anticipated, an assumption subject to errors of omission and commission. The first occurs when problems are presented that are important or frequent that have not been anticipated. The second occurs when the problems that have been anticipated occur rarely or are not considered as important by users. It is, however, the existence of procedures that influence to some extent what users will consider important and how frequently they will call for their use. Nonetheless, certain seminal inputs or a critical cluster of these may signal the potential for a new problem-class and procedures in anticipation of requests never made before.

What is critical is that inputs that are attended to be encoded so that, if they are not fully used at encounter time, they will be attended to again, either at occasion-time or before.

This can be done by the creation of a meta-message, specifying when or under what conditions this input message is to be used and how. An attending program, then, has to screen continually these meta messages, or the meta messages must have a built-in alarm, with varying degrees of saliency, that invokes the attending program.

2.8 *A prototype experiment*

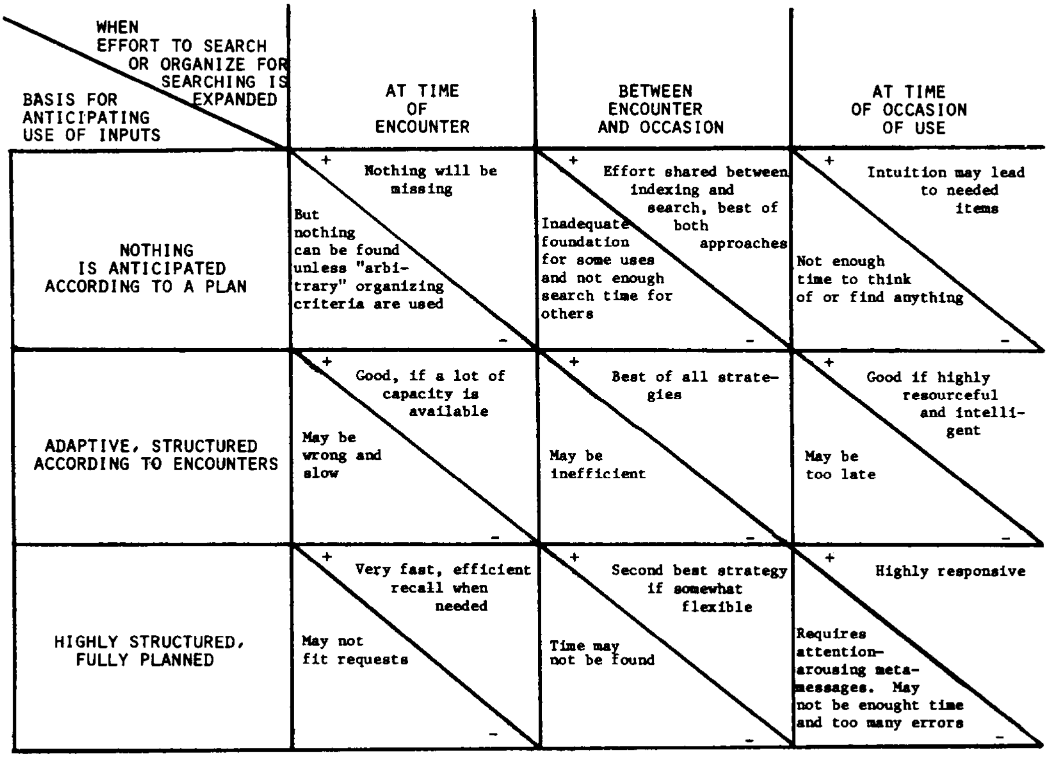
A subject S is presented with a large sample of messages packaged into a few books or journals that we have called inputs at encounter time. He is instructed to commit awareness of their existence to memory during a fixed period of time for use in a subsequent memory test. At test or occasion-time, he is asked a few questions requiring recall of the content of a few of the messages previously encountered. The books and journals are available to the subject and he is most unlikely to recall the specific context of the messages without looking at them again. He must, however, think of the fact that he has encountered them before, that the answers exist and are within easy reach.

A version of this experiment that was performed on ten subjects showed that in most cases in which they did not answer the questions asked at occasion-time or answered them incorrectly, it was failure to think of the existence of the the relevant message, i.e. recall its previous encounter, rather than thinking of it and failing to retrieve or recall it.

2.9 *Classification of the strategies for recording*

One class of strategies applies to a person (or program) who has as yet no basis for anticipating requests and planning or preparing for them. An extreme example is the undiscriminating or compulsive collector of input messages, who behaves so primarily because he feels insecure lest an occasion should arise in which he or one of his customers might need the item. We shall call these strategies input-driven. Another class of strategies applies to persons (or programs) with highly developed goals and well-defined strategies for selection. Here only those input messages are taken account of and possibly recorded which can be judged definitely relevant at encounter time. We call these strategies goal-driven.

This has an analog in intelligence-gathering. The second class of strategies consists of monitoring a small set of indicators. Ideally these are leading indicators. Unfortunately, few such indicators are reliable for something as common as monitoring (forecasting) the major turning points of the business cycle. Where they are known to be reliable (e.g. in monitoring military moves) they account for much less than the entire variability of the situation being monitored and are often ignored. This means gathering a vast mass of data that does not fit into categories such as indicator-variables but scanning the entire data collection for patterns that are unusual or previously unencountered. That comes closer to the first class of strategies. It is very costly and ineffective and its complexity is exponential in the size of the database.



WHEN EFFORT TO SEARCH OR ORGANIZE FOR SEARCHING IS EXPANDED BASIS FOR ANTICIPATING USE OF INPUTS	AT TIME OF ENCOUNTER	BETWEEN ENCOUNTER AND OCCASION	AT TIME OF OCCASION OF USE
NOTHING IS ANTICIPATED ACCORDING TO A PLAN	+ Nothing will be missing But nothing can be found unless "arbitrary" organizing criteria are used -	+ Effort shared between indexing and search, best of both approaches Inadequate foundation for some uses and not enough search time for others -	+ Intuition may lead to needed items Not enough time to think of or find anything -
ADAPTIVE, STRUCTURED ACCORDING TO ENCOUNTERS	+ Good, if a lot of capacity is available May be wrong and slow -	+ Best of all strategies May be inefficient -	+ Good if highly resourceful and intelligent May be too late -
HIGHLY STRUCTURED, FULLY PLANNED	+ Very fast, efficient recall when needed May not fit requests -	+ Second best strategy if somewhat flexible Time may not be found -	+ Highly responsive Requires attention-arousing meta-messages. May not be enought time and too many errors -

Fig. 1. Consequences of some strategies for recording inputs

Most strategies fall between the above two. We call them goal and input-driven. Whether goal-driven or input-driven, a strategy can attend to the inputs to the full extent it will ever attend to them at encounter-time. In this case, there is no need to create meta-messages flagging the inputs for attention at a subsequent time, except when they are recalled at occasion-time in response to a request. This occurs in a library or information center that expends the maximum possible on cataloging or indexing at acquisition time. Card catalog records or abstracts that serve as document surrogates are, of course, meta-messages, but of a passive type.

Alternatively, a mere note of the existence of an input message can be made at encounter-time in the form of a meta-message with a built-in alarm based on its saliency, so that it is attended to more thoroughly after encounter-time but prior to or at occasion-time. This appears to be how most persons record the experiences they encounter.

This leads to a nine-fold classification of recording strategies arranged in the 3 × 3 table shown in Fig. 1.

3. CODING AS EMBEDDING IN ASSOCIATIONAL NETS

3.1 *A multichannel multidirectional model*

The classical model for the mathematical theory of communication dealt with unidirectional flow of messages from a source/sender to an encoder, through a noisy channel, to a decoder to a destination/receiver. The problems of specifying which of several possible destinations to send a given message to or from which of several possible sources to receive messages at a given destination was not stressed. Channels with memory that could store and forward messages have been analyzed, but always in the context of the undirectional flow from a specified sender to a specified receiver.

The development of computer/communication networks, particularly those based on packet switching, led to the incorporation of meta messages, much like the address label for sender and receiver on a mail package. Information flow in such a network is still sender-driven. The telephone network is such a network as it is now used. The caller must have the telephone number of a destination, though one of many alternate routes could be selected.

The possibility of a new kind of network utility (Kochen, 1982) may lead to an extension of the mathematical theory of communication. Here messages from a variety of sources are sent to a large store-and-forward memory, with meta-messages about possible but incompletely specified further destinations. Potential destinations act like sources when they send request messages to the memory, again with incompletely specified destinations (the sources of the primary messages). These request-messages are combined with the meta-messages to select possible circuits or routes between original senders and potential destination, with feedback from the latter so as to converge on a satisfactorily negotiated connection. In addition, there is an intermediate set of sources that continually or periodically scans the memory to generate messages about the memory that are eventually to reach both the request-sources and the sender-sources. This begins to model the kind of communication that takes place in a community of inquiry (Fig. 2).

Three classes of problems arise in the analysis of this model. The first is how to compose a coded meta-message or packet labels that can be used to select channels and help at occasion-time to match request-messages. This is the problem mentioned in Section 2. The second is how to use network sources effectively and efficiently, and the third is how to code for requests that led to the retrieval of primary and secondary messages so as to make the network effective and efficient in the meeting of information needs. This is the representation problem for data bases sketched in Section 1.

3.2 *Associational structures*

The classical mathematical theory of communication took great care to avoid claims related to meaning or semantics. For information science this cannot be avoided. If a person encounters an information-bearing item, we could regard him as receiver of a message from some sender; the sender need not be another person, for the signal could be a traffic light, lightning, a dog's grabbing his leash. We should probably not regard him as a destination in the sense of the unidirectional model unless the sender were a person with the intention of sending him a message. The input item evokes one of several pre-recorded semantic networks, or frames depending on the context. Lightning to a person in a sailboat evokes a different frame than does lightning to one seeking to photograph it. A variety of hypotheses are associated in a sailor's mind upon seeing lightning: "If lightning strikes the mast, I may be electrocuted or burnt", "lightning tends to strike the tallest conductor in a region", etc. Lightning is categorized as a natural event and most "rational" persons would not attribute any intention to nature, while a

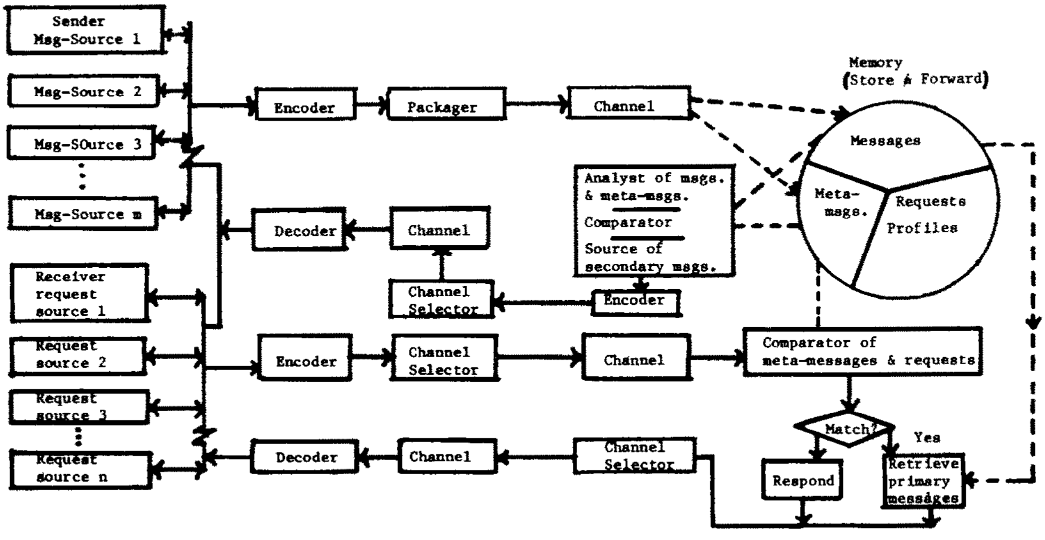


Fig. 2. Model for multi-channel multi-way communication of information to meet needs, using associative store-and-forward memories.

traffic-light is recognized a man-made object and reflects its designer's intention for the recipient of a red signal to stop. The dog, by grabbing his leash, signals his intention directly to persuade the recipient to take him for a walk.

The meaning of an input (item, signal, message) can be regarded as a set of all these associated hypotheses that are formed at encounter-time. During a small enough time period, say 1–20 msec, the number of such associations is a limited subset of all the possibilities, though it may be retained in short-term memory by rehearsal or other mechanisms. Thinking could be imagined to mean the control over the selection of this set of associations, perhaps retaining some and replacing others, playing over the set of possible associations in the frame.

If the person acting as receiver in the above sense acts as a sender at a future time because the message he composes is a synthesis of what he receives, he is unlikely to receive all the needed input simultaneously. He will have to record some of the inputs in his own memory along enough for other inputs to be encountered until synthesis is possible. Synthesis may be input-driven or goal-driven, in which case there is an active search for and discriminating selection of inputs. In most cases, it is probably a mix of opportunistic input-driven and planned goal-driven processes.

For the inputs to be synthesized to be thought of together at occasion-(of synthesis) time, some of the hypotheses associated with the inputs should be associated with one another by means of a second-order hypothesis that is to become the essence of the synthesis. This makes for ready recall as well as for attention in context.

3.3 *Coding*

In information science, indexing or the creation of meta-messages that describe what primary messages are about, is a common method of retrieving messages in response to a need. Thus, if a person needs an item he has encountered before, say a medical bill, while preparing his tax returns, having indexed that bill under "1982 taxes" and filed it accordingly would be helpful at the time of need. the same items may, however, also be needed in another context, say for insurance, so that a file labeled "Medical Bills" might have been more appropriate, since it would serve both needs.

Information theory has been applied to find an optimum distribution of a given set of such index terms[7] by grouping the terms according to the number of items posted under them. For example, for an information storage and retrieval system of 1000 documents, each of which is indexed by 22 terms on the average, with a vocabulary of 2000 terms, the frequency distribution that maximizes the average amount of information per term has about 182 terms with just one item posted under each, 165 with two items posted, 146 with three, and so on. This does not, however, take into account that the taxpayer has a choice of posting items (e.g. bills) under "1982 Federal Taxes", "Medical Bills", or "Insurance". The postings in each would be quite different, both in quality and in number.

Coding must take account of the associational structures on which planning and the use of information is based. We can think of coding as the representational mapping sketched in Section 1, combined with the formation of the encoded question-answering and the updating programs. Every time a new item enters the data base, its representation must be changed, as must the associated access algorithms. The procedures for changing them, however, must correspond to the semantic relations in the associational structures common to both the indexer, the request-sender and possibly also the primary-message sender, if these are embodied in different persons.

4. ON THE NATURE OF INFORMATION

The greater the number and variety of hypotheses that can be associated with a given input, the greater the number of steps—accesses to memory, accesses to control of procedural forms, etc.—or the number of memory cells required to choose and change the associations. Thus, the complexity of cases encountered by an experienced and specialized physician is greater than the complexity of the people encountered by a novice businessman because the doctor's frames are much more extensive and more interrelated. There is a richer and larger set of hypotheses that could be associated with the case.

The choice of associated hypotheses, and of second-order hypotheses, is the result of an encoding-selection procedure whose complexity depends on the frames that are used.

The notion of complexity of a procedure may differ from that of complexity of the form that may result. The previously described LOGO program for producing a stick figure is quite complex, but the resulting stick figure is quite simple. If we keep in mind that the given LOGO program is but one of many possible programs intended to produce the same figure, the complexity becomes evident. Prior to structured programming, a programmer would start right into a program or a flow chart, often using unconditional transfers (GOTOs), the destinations of which had to be carefully monitored to avoid making errors. A top-down structured approach analyzed a complex procedure into a simple form built of other forms that were themselves simple, (the result being less prone to errors) and well-organized. This is an example of structured as opposed to unstructured complexity.

Regarding the complexity of output of the program—e.g. the stick figure—we consider it simple (erroneously) mainly because we can usually reconstruct it in a structured way. Patterns made with 10 connected strokes could be regarded of the same formal complexity, though for those in Chinese characters, strokes are structured into left and right, upper and lower parts, built of radicals and a few standard patterns. Unstructured complexity, in a procedure or a form, appears chaotic, random with no discernible pattern. Structured complexity exhibits definite, recognizable patterns both in the components and in their conposition. In non-complex or simple procedures or forms, the distinction between structuredness and its absence is not important. It is easy to confuse structured complexity with simplicity. An ellipse is a simple form, through the procedure for constructing it is fairly complex. But the simple procedure of cutting in straight line (e.g. a Mobius strip lengthwise down the middle) can give rise to forms of great complexity.

Information is the input for procedures; it may also be embodied in forms. To construct an ellipse requires the input message that the sum of the distances form any point on the ellipse to the two foci is a constant. The resulting form embodies such information as the location of its center and the semi-minor and semi-major axis. It requires prior information to realize that these data completely specify the ellipse, as several other sets of parameters that could be deduced from the figure. The information conveyed by the ellipse does not require specifying the number of bits to distinguish it from all possible figures that could be drawn, nor does it consist of specifying the values of the x–y coordinates of all the points on the ellipse. The word "ellipse" and/or all the associated hypotheses already establish the appropriate frame and hence reduce much uncertainty.

Thus, a complex and highly structured procedure or form embodies more information than one that is complex and unstructured or simple, as shown in the following table.

Embodiment of Information in Forms

Structure Complexity	High	Low
High	High	Low
Low	Low	Low

Insofar as information is a meaningful concept, its nature lies in its content-independence. To say that the brain processes information is to say that there are no restrictions on what this information can be about. The same is true for a communication channel, a memory or a general-purpose computer. Consider the proposition: "For any x, a good messenger can transmit messages about x." Compare it with, "For any x, a good counselor can counsel his clients about x." The latter would be true if we replaced counselor by counselor-at-law and x by "a topic in law" or "legal issue". To the extent that such a universally quantified proposition holds without restriction it pertains to information processing and information.

A meta-message that specifies the content of the message to which it refers is still content-independent as a meta-message. The relation between it, the message it refers to and the topic that the primary message is about is the way content-dependence is specified. The more precisely specified the topic, the more specific the meta-message, and the greater the chance of a mismatch between the intent of its sender—e.g. and indexer—and that of the sender of a request for a primary message on that topic or the sender of the primary message.

Information has been fruitfully regarded as the reduction of uncertainty. But we cannot speak of uncertainty in the absence of a cognitive map of some complexity and structure. If there is no map at all—i.e. if a request-sender has no names for the topics to which meta-messages could pertain, then he is unable to formulate a request or to express his need. He is confused rather than uncertain. If the cognitive map is very simple we can begin to explicate the notion of measurable uncertainty, but it does not lead far. For example, a subject may be able to imagine a fair coin-tossing experiment, and we could measure his uncertainty about the outcome as one bit, but conveying the message about the outcome for so simple a situation requires no coding or further analysis. Whether or not the coin is fair (probability of heads = probability of tails) already introduces some complexity. The complexity is considerable if a request-sender is uncertain about which of several previously encountered messages to think of or to retrieve, or whether or not to attend to an incoming message at encounter time. If he has an organized structure into which he can fit the messages, the complexity can be structured into an ensemble of well-defined alternatives and measurable uncertainty can be attributed to that situation.

As a final note on the nature of information, it could possibly be regarded as an invariant of thinking, by analogy to how energy has been fruitfully regarded as an invariant of motion. We may be able to measure information as the total number of bits in the representation (L in section 1) plus those required to store the question algorithms as well as the updating algorithms, plus any auxiliary memory needed for processing.

5. CONCLUSION

The mathematical theory of communication has as one of its central concepts the notion of coding and decoding. This concept is also central for key problems of information science. The two fields of inquiry have in common their stress on the content-independence of messages. As soon as that content is restricted or plays a role, we deal no longer with information science or communication (= information) theory, but with law, medicine, etc. Representation of information or data by means of a code is another common feature. In information retrieval this is required by and makes possible the use of general purpose automata or computers.

Whereas the mathematical theory of communication stresses the one-directional flow of messages from a source or sender to a destination or receiver, information science must deal with multi-channel systems with store-and-forward memories and multi-directional flows of messages and metamessages. Whereas it encodes messages primarily on the basis of their probability, in information science they must be encoded for their saliency or attention-getting potential at time of use as well as for recall and utility. Thus, meaning cannot be avoided in information science. To be sure, meaning depends upon context or frames of reference, but the coding procedures are still content-independent since they specify how to code and decode in each area in a general way that incorporates any required detailed expertise as an encoded database.

The genetic code codes for amino acids. There may be other codes of relevance to development and there may be a neutral code. It is possible that these codes apply to all living forms, suggesting that the coding mechanisms may be general. Indeed, the conceptual foundations of information theory, like those of Norbert Wiener's Cybernetics, have already pervaded much of modern science, providing new ways of patterning and organizing knowledge. If information science is interpreted broadly enough to include theories of search, aspects of physiology and psychology, to name but a few, then the ideas of information theory have spread very widely[8]. Shannon's original paper[9] should be regarded as a classic alongside the works of the top scientists in all the sciences.

The mathematical theory of communication and early attempts to model information retrieval along similar lines stress the optimal use of system resources such as channel capacity, minimizing the number of memory accesses, etc. To do this, it uses methods of probability theory and combinatorial analysis. Information science is far more concerned about optimal use of the time of the people in an information system. The value of an expert's time or that of a user's time is considered to be far more valuable than that of communication channels, computer memory or CPU time. The objectives of coding and representation are therefore to a greater extent to fit the structure of knowledge in these persons' minds so that they could efficiently and effectively record information they encounter and recall it when they need it. Information science, as viewed by M. E. Maron, is the science of knowledge, formulated in terms of "information", "information processing" and "control"; as such, it is a bridge between many disciplines, including that of information theory.

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