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EXAMPLES OF CODING SCHEMES BASED ON STRATEGIC VALUE

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SUMMARY

Procedures are developed to construct variable-length codes for alphabets containing messages with assigned weighted-information content. The resulting coding procedures are similar in form to the Shannon-Fano-Huffman redundancy reduction schemes, but differ in scope; the former maximize the strategic value, while the latter maximize the number of letters for a specified finite channel capacity. Criteria specifying the strategic value of a code are defined, and codes are examined on the basis of alphabets containing messages with weighted-information content. Figures-of-merit are established and utilized to compare different types and possible trade-offs for simple codes. Algorithms governing these codes are established and examined on the basis of representative examples.

INTRODUCTION

The figure-of-merit of a coding scheme measures its effectiveness to meet specific criteria in transmitting information. Table I lists figures-of-merit and objectives of typical binary alphabets. An extensive review and evaluation of the pertinent literature are given in the bibliography.

A strategy can be defined as a management plan to execute effectively probable operations. This plan consists of a set of guidelines for formulating specific objectives which must be met or approached by a particular operation. The operation to be examined is the coding procedure. A strategy can be specified by a single figure-of-merit, such as accuracy, error rate, and compaction ratio. In general, strategy is based on:

(1) Two or more figures-of-merit describing the effectiveness of the operation;

(2) Calculated or estimated trade-offs between figures-of-merit in terms of the parameters of the system; for example, an algorithm relating the average length of a letter to statistical properties of the assumed distribution;

(3) Guidelines to control parameters, with an aim to optimize partially conflicting trade-offs by assigning weights to each set of trade-off parameters.

TABLE I

REPRESENTATIVE CODING SCHEMES

Coding Scheme	Figure-of-Merit	Objectives
Uniform k-digit length	Binary 2^k letter alphabet	Accuracy of 1 in 2^k
Variable length (Huffman)	Average digits per letter	Bandwidth
Orthogonal (Hamming) code	Index of comma freedom	Error elimination

Coding schemes, such as the Shannon-Fano-Huffman code, strive towards economy; other codes minimize error rate.

From an "operations research" point-of-view, it is not purposeful to ask "Is Huffman coding better than binary coding?", but the question is rather "What strategy is required?". Once the strategy is specified, objectives and figures-of-merit can be specified. Only then is it possible to determine if existing coding schemes, such as Huffman coding, serve a specified purpose.

To illustrate a strategy with competing figures-of-merit, two examples are used. First, a set of coded messages from an observer to a command post is assumed and analyzed. Secondly, run-length distributions of clustered events are examined. Following these elementary examples, algorithms governing strategic coding are established. The application of game theory, dynamic programming, and other "or" optimization techniques to coding strategy is to be explored at a later date.

EXAMPLE 1: TWO-PARAMETER STRATEGY

Table II lists the input data for optimization of message transmission from an observer to a command post. The probability of occurrence of a message P(R) is given as a percentage of 100% of transmitted data. On the other hand, not all letters carry the same information content. Respective weights P(A) can be assigned to each letter, such that P(A) measures the information content or strategic value associated with each letter.

The term "information content" is intended to define the relative importance placed on transmitting this letter as compared to others. The term "strategic value" describes the same concept and is therefore used interchangeably by "information content"; both terms are denoted by P(A). Similarly the term "letter" is used interchangeably with "strategic event".

Two codes are developed in Table II on the basis of different criteria of effectiveness. The Redundancy Code employs the Shannon-Fano-Huffman technique to maximize the average information transfer. Assuming inadequate channel capacity, the Minimum Redundancy Code generates unmanageably large backlogs at the very time when data of high strategic value place a premium on available channel capacity.

TABLE II

TWO-PARAMETER STRATEGY: INPUT DATA AND CODES

Letter	Interpretation	P(R) %	P(A) %	Minimum Redundancy	Maximum Access
A	Alert A	1	25	111111	11
B	Alert B	2	15	111110	10
C	Target C	3	11	11110	0111
D	Target D	3	11	11101	0110
E	Target E	3	11	11100	0101
F	Damage F	5	3	1101	01001
G	Damage G	5	3	1100	01000
H	Damage H	5	3	1011	00111
K	Damage K	5	3	1010	00110
L	Damage L	5	3	1001	00101
M	Damage M	5	3	1000	00100
N	Damage N	5	3	0111	00011
P	Damage P	5	3	0110	00010
Q	Weather Q	16	1	010	000011
R	Weather R	16	1	001	000010
S	Weather S	16	1	000	000001

Several alternatives exist:

(1) Transfer data from "peak load" periods to quieter times.

(2) Assign a priority to processing of data by allocating a weight P(A), referred to as strategic value, to each letter of the alphabet.

(3) Develop a code which permits access of a larger number of letters when information of high information content is transmitted, and which permits lower access rates when letters of low information content are transmitted.

Alternatives (1) and (2) above require additional knowledge of the performance characteristics of the memory devices. Alternative (3) proposes a solution in terms of coding schemes which can be specified in terms of suitable figures-of-merit.

COMPARISON OF ALTERNATIVE STRATEGIES

It will be assumed that the code to be developed is to be effective under the following conditions:

(1) The system is fed data at a rate that exceeds maximum channel capacity, and data compression or elimination is required. This is a reasonable assumption, since with sufficient channel capacity no codes are needed.

(2) One letter only (not two or zero) can be transmitted at one time. The system is in one of several possible states.

(3) The system remains in one state for a period commensurate with the average length of two letters, in accordance with the minimum requirements of the Nyquist sampling theorem.

(4) More letters with high information content can be processed than letters with low information content. Access to information transmission is facilitated for high information content.

Codes, so defined, provide maximum access to available information and may be referred to as Access Generating Codes, as opposed to the Redundancy Eliminating Codes developed by Shannon, Fano, and Huffman. Under the above assumptions, for instance, "Alert" messages would be provided three times the bandwidth allocated "Weather" data. On the other hand, in Redundancy Eliminating Codes, strategic data are discriminated against because they occur only rarely.

Input data in Table II are condensed in Table III, with L(R) and L(A) being the number of digits for each group of letters.

In Table IV, figures-of-merit are then composed for redundancy coding and access coding. A trade-off must be effected between maximizing transmission rates of letters and of information transfer.

TABLE III

COMPARISON OF ALTERNATIVE STRATEGIES

	N	P(R)	P(A)	L(R)	L(A)
Alert	1	.01	.25	6	2
Alert	1	.02	.15	6	2
Targets	3	.03	.11	5	4
Damage	8	.05	.03	4	5
Weather	3	.16	.01	3	6

TABLE IV

TWO-PARAMETER STRATEGY

	Minimum Redundancy Code	Maximum Access Code	Uniform Binary
Average number of letters per 100 bits	27	19	25
Information content per 100 bits	20	33	25

EXAMPLE 2: RUN-LENGTHS WITH CLUSTERS

In many applications requiring readout of coding data, the octal notation has distinct advantages over the decimal notation. Transformation rules between the various notations commonly used are summarized below:

(1) Binary-to-octal rules are listed in Tables V and VI. For example, 5 = 101*B (5 is equivalent to 101 in binary notation), and 7325 becomes 111 011 010 101 in binary.

TABLE V

OCTAL NOTATION

N	Binary	N^2	Log N
0	000	0	-
1	001	1	.00
2	010	4	.25
3	011	11	.43
4	100	20	.53
5	101	31	.63
6	110	44	.70
7	111	61	.74

TABLE VI

OCTAL MULTIPLICATION AND DIVISION

N	1	2	3	4	5	6	7	8
1		02	03	04	05	06	07	10
2	.40		06	10	12	14	16	20
3	.25	.53		14	17	22	25	30
4	.20	.40	.60		24	30	34	40
5	.15	.32	.46	.63		36	43	50
6	.13	.25	.40	.53	.65		52	60
7	.11	.22	.33	.45	.56	.67		70
8	.10	.20	.30	.40	.50	.60	.70	

(2) In decimal-to-octal, 10 = 8*D and 11 = 9*D. For example, 147 = 103*D or 31% = 39*D. Values of N^2 are listed in Table V.

(3) Multiplication and division is simple and is listed in Table VI, together with conversion of rational-to-octal fractions.

(4) Rapid mental calculations are possible from a knowledge of the logarithms listed in Table V.
For example, log 4 = (1/3) $\log_2 4$ = (2/3) = .53.

For clarity and conciseness, all following calculations are given in octal notation unless otherwise specified. For instance, 2/3 = .67*D = .53. Consider a series of runs with a maximum length 10^4 or 3 x 4 = 14 bits. These events are observed to cluster with signature data as specified in Table VII. Events D are of greatest interest, with moderate emphasis on events A, E, C, B, and F, in that sequence.

TABLE VII

HYPOTHETICAL SIGNATURES FOR STRATEGIC EVENTS

Group	Run Length	Strategic Value	
		Event	Group
A	01 - 10	.004	.040
B	11 - 20	.001	.010
C	21 - 40	.002	.040
D	41 - 50	.020	.200
E	51 - 100	.004	.140
F	101 - 200	.001	.100
G	201 - 400	.0003	.060
H	401 - 1000	.00004	.020
K	1001 - 2000	.00003	.030
L	2001 - 4000	.00002	.040
M	4001 - 10000	.00001	.040

EXAMPLE 3: MAXIMUM ACCESS CODE

The procedure to develop a Maximum Access Code, as defined in the preceding example (Run-Lengths with Clusters) presented in Table VIII, is as follows.

(1) List all letters of the alphabet (N_1) in descending order of strategic value (N_3) assigned to each group.

(2) In most cases, the number of events per group (N_2) is a multiple of 2^N. In the above example, this is true for all letters except E. The group E is divided into three subgroups of $2^3 = 10$ events each. The number of events per group is listed also in column B_1 where $B_1 = \log_2 N_2$.

(3) Using the same procedure which led to the Access Code in Table II, a code of length B_2 is derived from N_3. It is not necessary to write out the code explicitly; the set of values B_2 is sufficient to proceed.

(4) The length of the code in bits is given, therefore, by $B_3 = B_1 + B_2$. In Table IX, the letter of each group of letters is listed in descending order of strategic value.

To write down the code explicitly for each letter in descending order of strategic value, the following approach is useful.

(1) A word with 6 bits will start from 00 = 000 000*B and proceed to 17 = 001 111*B, if there are 20 letters in this group.

(2) If binary digits are denoted by 8 = 0*B and 9 = 1*B, then the 10 letters in group A will begin at 208 = 010 000 0*B and end at 239 = 010 011 1*B.

(3) For a 10-bit word, two binary digits are needed; for example, letter C starts at 4388 = 100 011 00*B and runs for 20 numbers to 4799 = 100 111 11*B.

Before embarking on a systematic analysis of figures-of-merit for variable length codes, it is instructive to evaluate relative advantages intuitively.

Binary coding requires 14 bits for an alphabet of 10,000 letters. Thus, while the average length-per-letter is increased by only 20 to 30 percent in this example, the bandwidth for strategically important data is increased by a ratio of 14/6. Improvement of transmission of strategic content by a factor of 100 is well within the capability of suitably designed coding schemes.

TABLE VIII

COMPUTATION OF STRATEGIC CODE

N_1	N_2	N_3	B_1	B_2	B_3
D	20	20	4	2	6
F	100	10	6	3	11
G	200	6	7	4	13
EX	10	4	3	4	7
EY	10	4	3	4	7
EZ	10	4	3	4	7
A	10	4	3	4	7
C	20	4	4	4	10
L	2000	4	12	4	16
M	4000	4	13	4	17
K	1000	3	11	4	15
H	400	2	10	5	15
B	10	1	3	5	10

TABLE IX

CODING SCHEME IN OCTAL NOTATION FOLLOWED BY BINARY 8 = 0*B or 9 = 1*B

N_1	N_2	B_3	Begin	End
D	20	6	00	17
A	10	7	208	239
E	30	7	248	379
B	10	10	4088	4299
C	20	10	4388	4799
F	10	11	500	577
G	200	13	6008	7439
H	400	15	74408	74779
K	1000	15	75008	75779
L	2000	16	760088	767799
M	4000	17	77000	77777

SEARCH FOR FIGURES-OF-MERIT

As an initial step towards developing criteria specifying the usefulness of a code, a mathematically simple distribution of data is assumed. Criteria measuring significant properties of the code are then defined, with the aim of developing an underlying theory and of searching for a unified and general treatment of strategic codes.

Variable length codes are derived, therefore, by minimizing the average number of digits per letter for an alphabet governed by the geometrical distribution. By applying the Shannon-Fano-Huffman redundancy reduction procedure to an alphabet in which successive letters have a geometrically tapered probability of occurrence, figures-of-merit of the code can be evaluated. An algorithm relating the tapering ratio of the number of letters of equal length is then derived and compaction ratios for values of practical interest are computed.

PROPERTIES OF ASSUMED DATA DISTRIBUTION

The geometric probability distribution (ref. 1) is a single-parameter distribution with a mean m of the distribution. It is sometimes convenient to define $q = 1/m$, $p = 1 - q$, and $r = 1/p$. The probability of obtaining n successive digits of one type is then $f(n) = qp^n$ and $g(n,s) = q(1 - pe^{ns})^{-1}$ is the corresponding generating function. For example, the probability of obtaining the letter 11110 is the conditional probability of obtaining four favorable trials p^4 followed by one unfavorable trial. Experimentally the single parameter m is obtained from either

$E(n) = m$	the expected value
$S(n) = m$	the standard deviation
$D(n) = 2\ m\ f(m)$	the mean deviation.

In a previous report (ref. 1, p. 10), an algorithm of Huffman coding for the geometric distribution was developed, namely; the condition

$$r^k = 2 \qquad \text{or} \qquad k = \frac{\ln(1/2)}{\ln(p)}$$

gives the minimum value of p; such that each k letters of the alphabet have exactly the same length.

Typical maximum values for m which correspond to a preassigned k are given in Table X. If $m \gg 1$, then $\ln p \sim -1/m$ and $k = m \ln 2$.

CRITERIA FOR ASSUMED DATA DISTRIBUTION

The geometric probability distribution is a useful mathematical artifice because of its simplicity; however, its justification is difficult on the basis of a valid statistical model of incoming data samples. The geometrical distribution of a dependent variable x as a function of an independent variable t is based on an occurence of phenomena of the type

$$f(t) = -dx/dt = x/m \quad \text{or} \quad x/m = \exp\,(1 - t/m)\ .$$

The constant m will then be the ratio of the mean time of occurrence of an event to the sampling time. It is also useful to define the so-called "half-time" of the distribution $k = m \ln 2$, that is, the time interval during which x falls to one half its initial value. If the resulting distribution $x_2/x_1 = (1/2)^{t/k}$ is sampled at regular intervals T, the ratio of any two successive samples, such as x_1 and x_2, is:

$$r = x_2/x_1 = (1/2)^{t/k} \quad \text{or} \quad r^k = 1/2 \text{ if } t = 1.$$

Thus, k is the number of samples during the time required for the signal probability to change to one half its value. To appraise the nature of k, the similarity to concepts leading to the definition of the Nyquist sampling rate is noteworthy. If k = 1, a large number of short samples remain unresolved, similar in fact to the Nyquist frequency, which states that if the sampling frequency is less than one half the period, the higher frequencies have an increasingly significant probability of remaining unresolved.

INTERPRETATION OF CRITERIA

The number of samples per half-time k is then a measure of the probable change in letter length and, hence, is related to m, the number sampled during the mean time between changes. The value of m specifies

(1) The mean time between occurrences in units of sampling time;

(2) The time for changes of 1/e in the probability spectrum;

(3) The rate of change dx/dt.

For a discrete distribution $t = n$ and $\Delta t = 1$ with $f(t) \rightarrow f(n)$. Thus, there are n digits in a letter and $f(n) = m^{-n}(1 - m)$ is the corresponding probability density. The resultant geometric distribution of mean length m is defined by m samples taken during the mean time between changes.

An alphabet having any k letters of the same length has a mean length of m, but the length of each letter is usually either shorter or longer than m. The value of m can be interpreted in terms of the number of sampling periods necessary to acquire the information content for an average letter. Loosely speaking, the information stored in each letter is m times as long as the sampling period.

To illustrate this, consider two distinct examples. For small m, say $m = 2$, it is reasonable to expect that far greater emphasis is placed on short letters than on long letters of the alphabet; therefore, only one letter is found at each level. For m large, say 20, letters requiring a large number of sampling periods do not differ greatly in probability from shorter letters. It follows that a far larger number of letters can be used effectively; many samples are needed, therefore, for each length of letter.

For large m, the number of letters which will have the same length can be predicted for a binary alphabet from the properties of the tree associated with a variable length code.

FORMULATION OF ALGORITHM

At each branching point associated with the tree, the probability density falls by a factor b. If r is the ratio of probability for successive letters for the simplest case, $b = 2$; hence $k = m \ln 2$. If any k letters have the same length, then $r^k = b$ or $\ln b = k \ln r$. The factor k can, thus, be interpreted from considerations related to information content and may be defined as the number of digits between letters differing in probability by a factor of 2, while m is the difference in digits between letters differing in probability by a factor of "e". In a continuous geometrical distribution, the difference in digits between letters differing in probability by a factor of "e" is clearly equal to the mean length, while in a distribution with discrete values of n this value is approached only if m is large.

COMPACTION RATIOS

Table XI gives a comparison of compaction ratios for codes based upon an assumed geometrical distribution. Given the required accuracy A of coded data, the length L(B) of data coded in binary is an integer equal to or greater than $-\log_2 A$. The mean length of a letter for the geometric distribution is given in Table X for values of k. If k is restricted to integers, then m is a maximum; hence the compaction ratio in Table XI is calculated using the most unfavorable case.

A scale of 2^B binary counter can be used to give logarithmic compaction by measuring on the highest level in operation. This scale is equivalent to a geometric distribution with a ratio of r = 2. If r differs significantly from this ratio, Huffman coding may shorten or lengthen the average length of a letter, depending on the correlation between assumed and actual distribution of data.

TABLE X

ALPHABETS WITH k LETTERS OF EQUAL LENGTH CALCULATED FROM THE EXPECTED VALUE m OF THE ASSUMED GEOMETRICAL DISTRIBUTION*

m	q	p	r	k
2.0	0.40	0.40	2.0	1
3.3	0.24	0.54	1.3	2
5.0	0.1	0.63	1.2	3
24.0	0.04	0.74	1.04	16

*See Bibliography (No. 8)

TABLE XI

COMPACTION RATIO FOR DATA FROM ASSUMED GEOMETRICAL DISTRIBUTION WITH k LETTERS OF EQUAL LENGTH

Binary Code		Geometric Distribution		
A	L(B)	k = 1	k = 3	k = 16
.02	5	2.4	1.4	0.20
.002	11	4.4	2.5	0.35
10^{-7}	25	13.0	6.5	1.1

CONCLUSIONS

An orderly coding scheme is established, yielding at a glance the strategic importance of each message in at least two ways: (1) the shorter the message, the greater its importance; and (2) the higher the initial digit, the shorter its length.

To formulate a more general approach, an analytical model was formulated, which entailed several simplifying assumptions. This simplified model was used to explore the usefulness of performance criteria for alternate codes and coding schemes.

This investigation was directed principally to explore specific examples. Subsequent studies are planned towards the development of a unified and generalized treatment of figures-of-merit for alternative coding schemes.

It appears particularly desirable to define more rigorously the terminology used here; for example, strategic value, strategic events, and strategic coding. Criteria specifying the strategic value of a code deserve rigorous examination. For example, how does the strategic value of a code relate to the strategic value of data? These and related problems deserve scholarly scrutiny and discussion with adequate emphasis on aerospace-oriented applications. Finally, an analysis must be provided to strengthen the validity of the technique and establish further examples of its usefulness. Specifically, it is essential to exhibit those situations in which this technique does or does not apply. Work towards these objectives is now in progress.

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