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Compression-Designs in Artificial and Living Systems

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***Abstract* --- A novel practical and theoretical foundation for signal processing, named *processor coding*, is advanced as the *computational time compression dual* of source coding. Source coding is concerned with signal source memory space compression while processor coding is with signal processing computational time compression. Since source coding and processor coding solutions are characterized by compression designs, their combined use is given the name *co*mpressio*n-de*signs (referred as *Conde* in short). A compelling and pedagogically appealing descriptive diagram of Conde is also given which highlights its remarkable successful application to knowledge-aided (KA) airborne moving target indicator (AMTI) radar subjected to severely taxing environmental disturbances.**

I. INTRODUCTION

In the systems arena two design problems prominently reign. One has as its fundamental goal the efficient storage of signals that are produced by a signal source of either artificial or biological origin, e.g., voice, music, video and computer data sources. The other relates to the efficient processing of these signals that may for instance result in their Fourier transform, covariance, etc. The design of efficient signal storage algorithms relies heavily on Shannon's mathematical theory of communication [1] which is also known as source coding. The area of source coding has a conspicuous recent history and has been one of the enabling technologies for what is known today as the information revolution. The reason why this is the case is because source coding provides a sound practical and theoretical measure for the information associated with any possible signal source outcome (or output) and its average value or entropy. This knowledge can then be used to provide an efficient replacement or source coder for the signal source that can be either lossless or lossy depending if its output matches that of the signal source. Examples of lossless source coders are Huffman, Entropy, and Arithmetic coders [2] while for the lossy case the standards of JPEG, MPEG and wavelets based JPEG2000 [3], minimum mean squared error (MMSE) predictive-transform (PT) source coding [4], etc., have been advanced. On the other hand, the design of fast signal processing strategies is approached with a myriad of techniques that, unfortunately, are not similarly guided by a theoretical framework that encompasses both lossless and lossy solutions. This is the problem that is addressed here.

The rest of this paper is organized as follows. In Section II background material is presented on the most basic theoretical underpinnings of source coding. In Section III the fundamentals of the computational time dual of source coding are stated that give rise to a brand new practical and theoretical foundation for the design of fast signal processors. This foundation is named 'processor coding' and can also, possibly, be named 'the mathematical theory of signal processing' in the same way that Shannon's 'mathematical theory of communication' is named 'source coding' [1]. Finally in Section IV a summary of source coding and processor coding, named, when combined, ***co***mpressio***n-de***signs (or Conde in short), is given in the form of a pedagogically appealing descriptive diagram. This diagram summarizes Conde in the context of its remarkable successful application to knowledge aided (KA) airborne moving target indicator (AMTI) radar subjected to severely taxing environmental disturbances [5]-[6].

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II. BACKGROUND

In Fig. 1 the source coding system is shown where the output of the signal source is a discrete random variable X whose possible realizations belong to a finite alphabet of L elements, i.e., $X \in \{a_1,...,a_L\}$. Furthermore, the amount of "information" associated with the appearance of the element a_i on the output of the signal source is denoted as $I(a_i)$ and is defined in terms of the probability of a_i, $P[a_i]$, as follows [1]

$$I(a_i) = \log_2(1/P[a_i]) \qquad (2.1)$$

in units of bits (***b****inary dig****its***). Clearly from this expression it is noted that a high probability outcome conveys a small amount of information while one that rarely occurs conveys a lot of information. The source entropy is then defined as the average amount of information in bits/outcome $H(X)$ that is associated with the random variable X. Thus

$$H(X) = \sum_{i=1}^{L} P[a_i]\log_2(1/P[a_i]) \qquad (2.2)$$

The signal source rate (in bits/outcome) is defined by R_{SS} and is usually significantly greater than the source entropy $H(X)$ as indicated in the figure. In the same figure a source

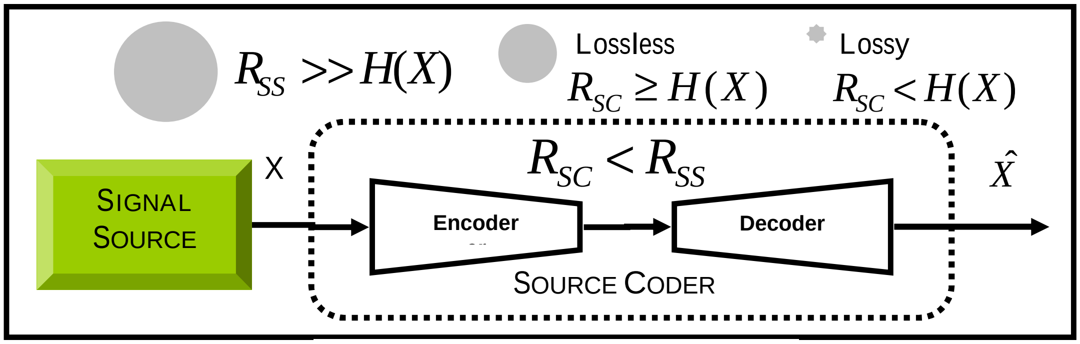

Fig. 1 The Source Coding System

coder is presented which is made up of an encoder followed by a decoder section. The input of the source coder is the output of the signal source while its output is an estimate $\hat{X}$ of its input X. The source coder rate is defined as R_{SC} and is generally smaller than the signal source rate R_{SS}. The source coder will be lossless ($\hat{X} = X$) when R_{SC} is greater than or equal to the source entropy $H(X)$ and lossy when R_{SC} is smaller that the source entropy as shown in the figure.

Next the problem addressed in this paper is stated and a solution is provided.

III. THE PROBLEM STATEMENT AND SOLUTION

In this section a novel practical and theoretical framework, namely, ***processor coding***, which arises as the computational time dual of source coding is presented. Processor coding directly addresses the problem of designing fast signal processors. The aforementioned duality readily surfaces when it is noted that the key concern of source coding is 'memory space compression' while that of the novel processor coding methodology is 'computational time compression'. Since both source coding and processor coding solutions are characterized by compression designs their combined use is given the name ***co***mpressio***n***-***de***signs and referred as Conde in short in this paper.

The development of processor coding as the computational time dual of source coding is rather straightforward. It begins by noticing that the computational time duals of bits, information, entropy, and a source coder in source coding are ***bors, latency, ectropy*** and a ***processor coder*** in processor coding, respectively. The definition of these brand new concepts is as follows: 1) 'Bor' is short for a specified ***b***inary operat***or*** time delay [7]; 2) 'Latency' is the minimum time delay from the input to a specified scalar output of the signal processor that can be derived from redesigning the internal structure of the signal processor subjected to implementation components and architectural constraints as is done in digital design [7]; 3) 'Ectropy' is the maximum latency associated with all the scalar outputs of the signal processor. It is of interest to note that the word ectropy is a newly coined word which has Greek roots 'ec' meaning outside and 'tropy' to look. Thus this new word reflects the fact that it denotes an 'external measure' of the signal processor since it is the time delay of the redesigned signal processor; and 4) 'Processor coder' is the fast signal processor that is derived using the processor coding methodology. A processor coder like a source coder can be either lossless or lossy depending whether its output matches the original signal processor output.

In Fig. 2 the processor coding system is given where the output of the signal processor is an M dimensional vector $\mathbf{y}=[y_1,\ldots,y_M]$ and its input is the N dimensional vector $\mathbf{x}=[x_1,\ldots,x_N]$. Furthermore, the amount of 'latency' associated with the appearance of the element y_i on the output of the signal processor is denoted as $L(y_i)$ and as

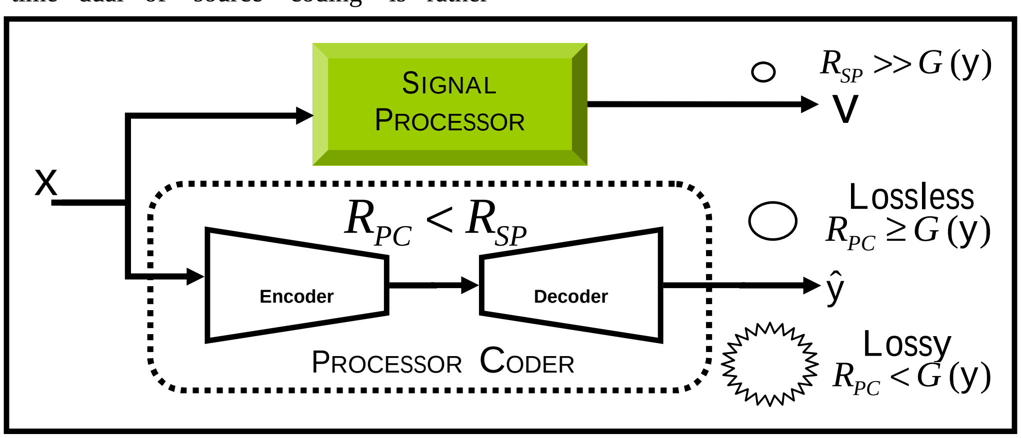

Fig. 2 The Processor Coding System

mentioned earlier is the minimum time delay in time units of bors from the input **x** to scalar output y_i of the signal processor. This latency can then be derived from redesigning the internal structure of the signal processor subjected to implementation components and architectural constraints [7]. Obviously this definition implies that the more severe the implementation components and architectural constraints are the larger will be the latency, e.g., this is the case in digital design when a state machine is sought rather than a combinational one [7]. These constraints are the time dual of probability in source coding when determining the amount of information. The ectropy of the signal processor G(**y**) or processor ectropy is then the maximum latency among all the *M* latency terms associate with the *M* elements of the signal processor output **y**, i.e.,

$$G(\mathbf{y}) = \max_{L(y_i)}[L(y_1),...,L(y_M)]. \qquad (3.1)$$

The signal processor rate (in bors/**y**) is defined by R_{SP} and is normally significantly greater than the processor ectropy G(**y**) as indicated in the figure. In the same figure a processor coder is presented that is made up of an encoder followed by a decoder section [5]. The input of the processor coder **x** is the same as the input of the signal processor while its output is an estimate $\hat{\mathbf{y}}$ of the signal processor output **y**. The processor coder rate is defined as R_{PC} and is smaller than the signal processor rate R_{SP}. The processor coder will be lossless ($\hat{\mathbf{y}} = \mathbf{y}$) when R_{PC} is greater than or equal to the processor ectropy and lossy when its R_{PC} is smaller than the processor ectropy as shown in the figure. This concludes our development of the processor coding practical and theoretical foundation.

Clearly with the previously derived 'dual based mathematical foundation for signal processing' an edifice of new theoretical and practical ideas can be conceived with some inherently appearing from duality studies and some from the integration of memory space and computational time compression strategies. A vivid example of this is briefly discussed next when source and processor coding were merged together as Conde in [5] to address a real-world knowledge-aided detection problem. More specifically, Conde was applied to the design of an efficient intelligent system for KA-AMTI radar that is subjected to severely taxing environmental disturbances. The studied intelligent system consists of clutter in the form of SAR imagery used as the intelligence or prior knowledge and a clutter covariance processor (CCP) used as the intelligence processor. In Fig. 3 the basic structure of the intelligent system is shown consisting of a storage device for the clutter and the intelligence processor containing a clutter covariance processor receiving external inputs from the storage device as well as internal inputs. The internal inputs of the CCP are the antenna pattern and range bin geometry (APRBG) of the radar system and the complex clutter steering vectors. This intelligent system is responsible for the high signal to interference plus noise ratio (SINR) radar performance achieved with KA-AMTI but, unfortunately, is characterized by prohibitively expensive storage and computational requirements [6]. In [5] and [8] this problem was addressed using Conde with the following two results highlighted:

1. For a 'lossless' CCP coder to achieve outstanding SINR radar performance it is essential that the source coder that replaces the clutter source be designed with knowledge of the radar system APRBG: in other words the source coder is radar seeing [8]. This result yields a compression ratio of 8,192 for the tested 4 MB SAR imagery but has the drawback of requiring knowledge about the radar system before the compression of the SAR image is made.

2. For a significantly faster 'lossy' CCP coder to derive exceptional SINR radar performance the source coder that replaces the clutter source can be designed without knowledge of the APRBG and is therefore said to be radar blind [5]. This result yields the same compression ratio of 8,192 as the radar seeing case but is preferred since it is significantly simpler to implement and can be used with any type of radar system.

The following five observations are directly connected to the above two SINR results of papers [5] and [8]:

- They together imply that only a 'lossy' processor coder can yield superior SINR radar performance when simple and universal radar blind clutter coders are being used. Clearly this result is not obvious or intuitive! Thus it indicates that the 'key' to the derivation of the most efficient intelligent systems for use in real-world radar applications is the combination of source coders that are signal processor independent with 'lossy' processor coders.

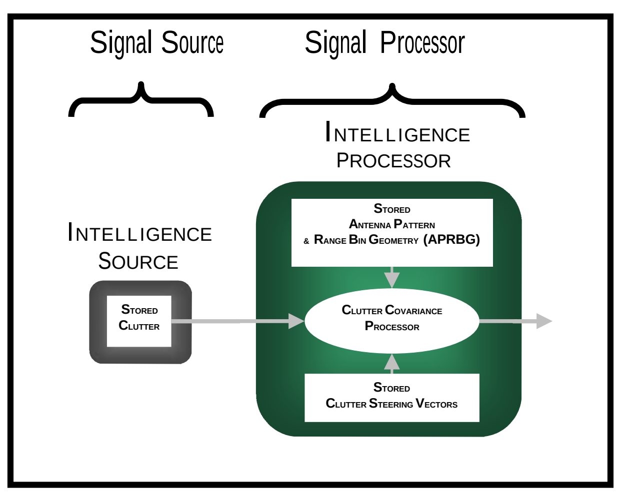

Fig. 3 Intelligent System

- It suggests a paradigm shift in the design of fast signal processors where the emphasis before was placed in the derivation of lossless fast signal processors, such as a lossless Fast Fourier Transform Processor [9], a lossless Fast Covariance Processor, etc., without any regard as to how the processor coder may be used in some particular application such as the target detection problem of radar systems.

- The outstanding SINR detection performance derived with highly compressed prior knowledge, SAR imagery in our application, correlates quite well with how biological systems use highly compressed prior knowledge to make excellent decisions. Consider, for instance, how our brains expertly recognize a human face that had been viewed only once before and could not be redrawn with any accuracy based only on this prior knowledge.

- The duality that exists between space and time compression methodologies is pedagogically, theoretically, and practically appealing and their combined inner workings is extraordinary and worthy of notice.

- It is of interest to note how the system performance remains high as both the space and time compressions are increased suggesting an invariant like property. As a fascinating and interesting practical example it should be noted that in physics there exists an observation frame of reference invariance that clearly constrains the evolution of space and time as it relates to the fact that the speed of light (in space over time units) is measured to be the same in any observation frame.

IV. DESCRIPTIVE SUMMARY OF COMPRESSION-DESIGNS

In Fig. 4 a pictorial descriptive summary is advanced of the previously discussed ideas which will hopefully allow the reader to easily remember the most outstanding properties of compression designs. This illuminating and user friendly figure is in fact given in the spirit of its consistency with compression designs ideas and can be viewed as greatly compressed visual conceptual information in its own right. The detailed explanation of the figure follows. First it is noted that the figure has been decomposed into two columns. In the left column source coding memory space compression (also known as Shannon's mathematical theory of communication) is highlighted while on the right column processor coding computational time compression (or also called 'the mathematical theory of signal processing' continuing with our duality development) is.

Nine different cases are displayed in this image. CASE 0, appearing in the middle of the figure, displays the signal source and signal processor that one wishes to compress in space and time, respectively. The picture in the middle between the signal source and the signal processor is composed of three major parts. They are: 1) The sun triangles, consisting of eight different ones, and each representing a different application where the signal source and signal processor may be used. The intensity of the red color inside these triangles denotes the application performance achieved in each case. Note that on the lower right hand side of the figure a chart is given where the triangle color is noted to reflect the application performance level. The bright red color is used when an application achieves an optimum performance with the considered signal source and signal processor compressed or not. Clearly the applications performance will be optimum and therefore is bright red for the lossless signal source and signal processor of CASE 0: 2) The large gray colored circle without a highlighted boundary represents the amount of memory space required to store the output of the signal source. On the left and bottom part of the image it is shown how the diameter of the gray colored circle decreases as the required memory space decreases. Furthermore, two cases are displayed. One corresponds to the lossless case and the other to the lossy case. The lossy case in turn can be processor blind or processor seeing which displays an opening in the middle of the gray circle. Also note for the processor blind case the boundary of the gray circle is not smooth: 3) An unfilled black circle where the reciprocal of its diameter reflects the time taken by the signal processor to produce an output. In other words the larger the diameter the faster the processor. On the right and bottom part of the image two cases of time compression are displayed. First the lossless case that has smooth circles and then the lossy case that does not.

CASE 1 displays a 'lossless' source coder using the signal processor of CASE 0 where it is noted that the only difference between the describing picture for CASE 0 and CASE 1 is in the diameter of the space compression gray circle that is now smaller. CASE 2 is the opposite of CASE 1 where the diameter of the time compression unfilled black circle is now larger since the "lossless" processor coder is faster. CASE 3 combines CASES 1 and 2 resulting in an optimum solution in all respects except it may still be taxing in terms of memory space and computational time requirements.

CASES 4 thru 8 are 'lossy' cases. CASES 4 and 5 pertain to either processor blind or processor seeing source coder cases where it is noted that the fundamental difference between the two is that the processor blind case yields a very poor application performance. On the other hand, the performance of the processor seeing case is suboptimum but very close to the optimum one. It should be noted that CASE 5 was the first of two SINR radar results [8] highlighted in Section III.

CASE 6 addresses the 'lossy' processor coder case in the presence of a 'lossless' source coder. For this case everything seems to be satisfactory except that the required

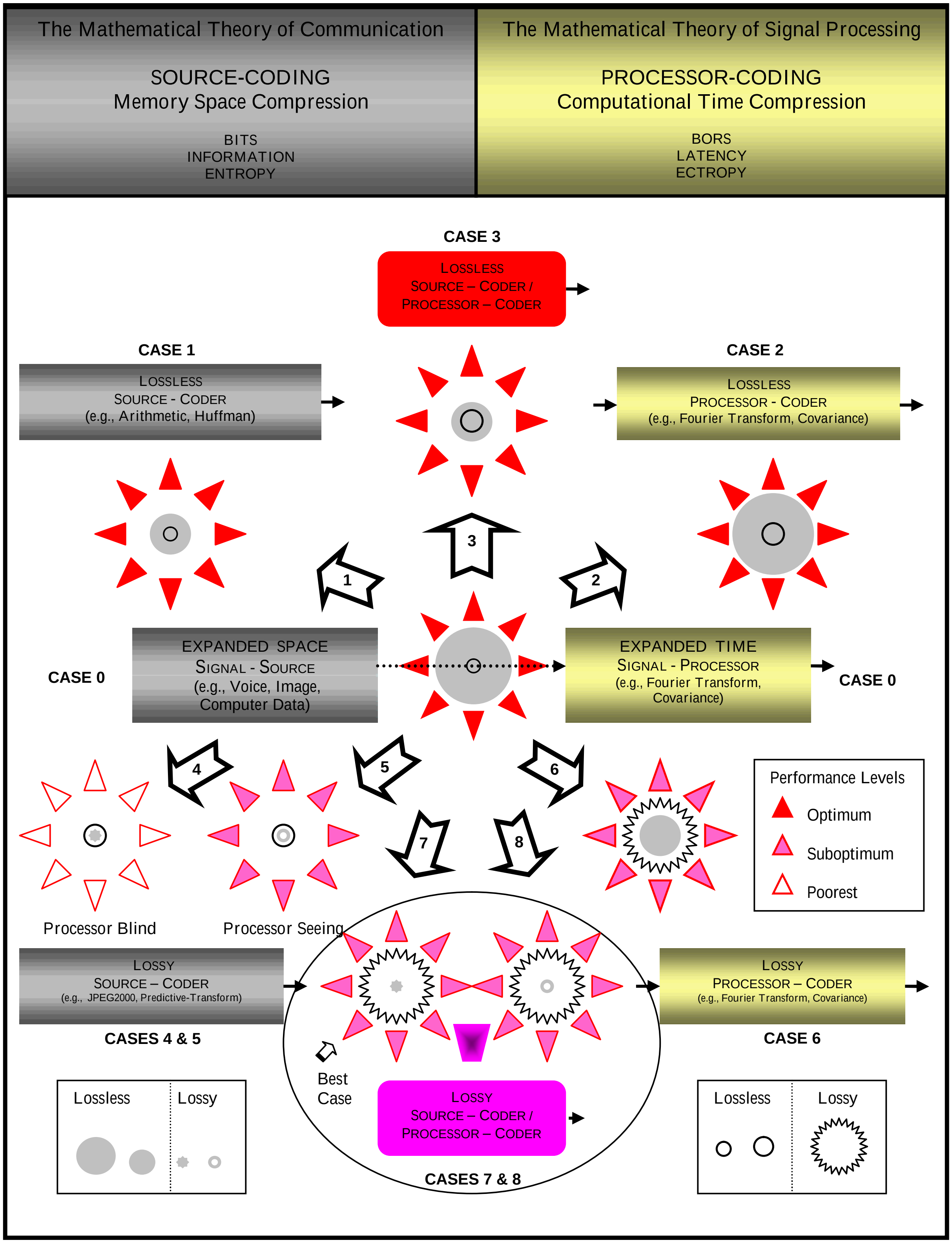

Fig. 4 The Two Complementary Pillars of Compression-Designs

memory of the lossless source coder may still be too large. CASES 7 and 8 present what occurs when the two types of lossy source coders are used together with a 'lossy' processor coder. For these two cases it is found that the application performance is outstanding although suboptimum from a strict mathematical perspective. CASE 7, in particular, is truly remarkable since it was found earlier for CASE 4 that a radar-blind source coder yields a very poor application performance when the processor coder is 'lossless'. Thus it is concluded that CASE 7 is preferred over all other cases since while achieving an outstanding application performance it is characterized by excellent space and time compressions. It should be noted that CASE 7 was the second of the two SINR radar results [5] discussed in Section III.

The paper ends with Table I which summarizes for the reader the terminology terms used in Conde.

Table I Compression-Designs Duality Terminology

The Mathematical Theory of Communication (*) Source Coding Memory Space Compression	The Mathematical Theory of Signal Processing (**) Processor Coding Computational Time Compression
Bit	Bor
Signal Source	Signal Processor
Source Coder	Processor Coder
Information (units of bits)	Latency (units of bors)
Entropy, H (in bits/outcome)	Ectropy, G (in bors/output)
Signal Source Rate, R_{SS} (in bits/outcome)	Signal Processor Rate, R_{SP} (in bors/output)
Source Coder Rate, Rsc Rsc < Rss	Processor Coder Rate, R_{PC} $R_{PC} < R_{SP}$
Lossless Source Coder Rsc ≥ H	Lossless Processor Coder $R_{PC} \geq G$
Lossy Source Coder Rsc < H	Lossy Processor Coder $R_{PC} < G$
(*) Source coding is also known as 'the mathematical theory of communication' that, perhaps, in addition may be called 'the mathematical theory of signal sourcing'.	(**) The emerging processor coding methodology has been given this name due to the duality between memory space and computational time compressions.

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