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Symbolic Space Determinations on Physical Limitations

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In the quest for the determination of the physical limitations imposed on computing (Bledsoe, 1961; Bremermann, 1962; Ligomenides, 1967, 1968; Keyes and Landauer, 1970; Keyes, 1975), unless we introduce basic considerations relating to such things as the computing philosophy and methodology employed, the encoding and translation languages, and techniques, and the question of computability and intractability, our investigation limits itself to pursuit of outer bounds on energy, time, and spacing requirements for the transfer storage and processing of two-state signal quanta, rather than dealing with bounds on processing information which is specially encoded for computation. It seems that limitations imposed in the symbolic space precede by several orders of magnitude those in the energy space.

1. INTRODUCTION

Computation in machines is the manifestation of the execution of some causal or heuristic algorithm, resident in the "symbolic space," by physical processes which occur in the "energy space." To put it in better perspective, as illustrated in Fig. 1a, tools, i.e., "energy machines," operate exclusively in the energy-action space. Programmable digital computers operate in two spaces, while general information-processing machines ("intelligent machines") and cybernetic systems operate in three spaces: the "planning or Ψ space," where a conceptual strategy is formulated for the solution of some computational task and is possibly altered throughout its implementation; the "symbolic or Σ space," where the conceived plan is manifested in symbolic form, and is decomposed and translated down to the lowest level of symbolic expression in terms of "control symbols"; and the "energy or ε space," where data and control symbols are represented by corresponding

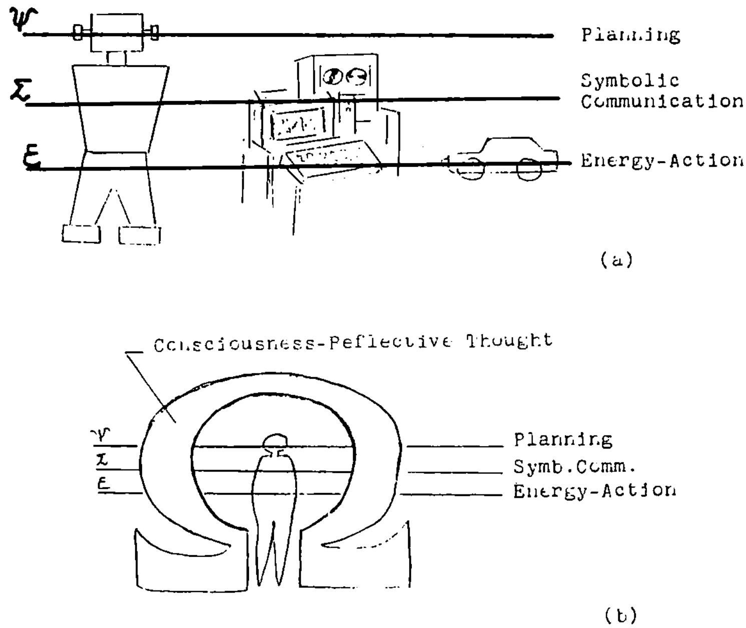

Fig. 1. (a) Single-dimension machines ("energy machines," e.g., automobiles); two-dimension machines ("information-processing machines," e.g., computers; three-dimension machines ("intelligent machines and cybernetic systems"). (b) Man in four dimensions. The Ω dimension of consciousness separates man from the rest of the universe.

data and control signal-quanta (e.g., binary signals) by means of measurable physical attributes, and are transferred, stored, and processed in physical devices for the actual implementation of the computation algorithm. One may note here that, in addition to these three spaces, man operates also in a fourth space, that of "consciousness," (Fig. 1b), a space which is unattainable by machines.

Limitations on feasibility and efficiency of symbolic representation and algorithmic execution, as well as limitations on energy, time, and spacing requirements, must be traced in all three spaces and must be cross-correlated for their coupling effects. The feasibility and tractability of an algorithmic solution to a computation problem, the nature and effectiveness of encoding philosophy, as well as the specific computational objectives sought, often determine whether a causal or a heuristic computational approach is employed. In turn, the heuristic search for solution may employ such things as fuzzy algorithms (Zadeh, 1968), fuzzy instructions, fuzzy encoding schemes and fuzzy bits, or some global but selective recognition and processing scheme on input data (more common in intelligent machines).

Such philosophies of computation, different from the exact, bit-by-bit, computing philosophy, which is common in commercial digital computers, may significantly alter the requirements on accuracy, which in turn may notably modify the outer limitations on energy, time, and spacing costs required for computation. Such determinations in the symbolic space, having to do with the "symbologic" of computation, must have a notable effect on the physical limits in the energy space.

Thus, the study of the physics of computation for the determination of the "ultimate" limits of computation, imposed on the operation of man-made information-processing machines (Keyes, 1975; Landauer, 1981), may now be looked upon as a unified discipline that combines computer science and engineering, information theory, thermodynamics, and quantum mechanics. This new discipline will make it possible to do comparisons of performance in computation over a wide range of algorithmic modes, coding, and computing structures and technologies. In addition, it will lead us to the understanding and the determination of the fundamental constraints imposed on physical spacing, on the speed and on the power requirements of machine computations, in ways which transcend any specific machine-bound schemes and configurations in the ε or in the Σ space.

2. SYMBOLIC SPACE DETERMINANTS

The operation and organization of a generalized information-processing machine may be illustrated by the hierarchical, multifeedback engineering–cybernetic (EC) model (Ligomenides, 1981), shown in Figs. 2 and 3. The machine operates in three spaces. A strategy (plan) conceived in the Ψ space is encoded into communicable symbols (a language), following some encoding methodology, and it is manifested in the Σ space. The resulting algorithm is then decomposed along a command decomposition (symbolic language translation) hierarchy, eventually down to some control language. The elementary control symbols, along with the encoded data symbols, are then represented by corresponding primitive control and data signal quanta in the ε space, where actual physical processes implement the execution of the algorithm. An ascending sensory data integration hierarchy, along with cross-feedback and predictive memory-template action (associative recall), which provides for adaptation and goal-seeking mechanisms, complete the model. $\mathcal{P}$, $\mathcal{Q}$, and $\mathcal{R}$, are operators along the command decomposition, data filtering, and predictive memory hierarchies.

The nature of these operators is dependent on the encoding philosophy and on the computational notions which are employed in the operation of the machine. Their implementation may also take advantage of computa-

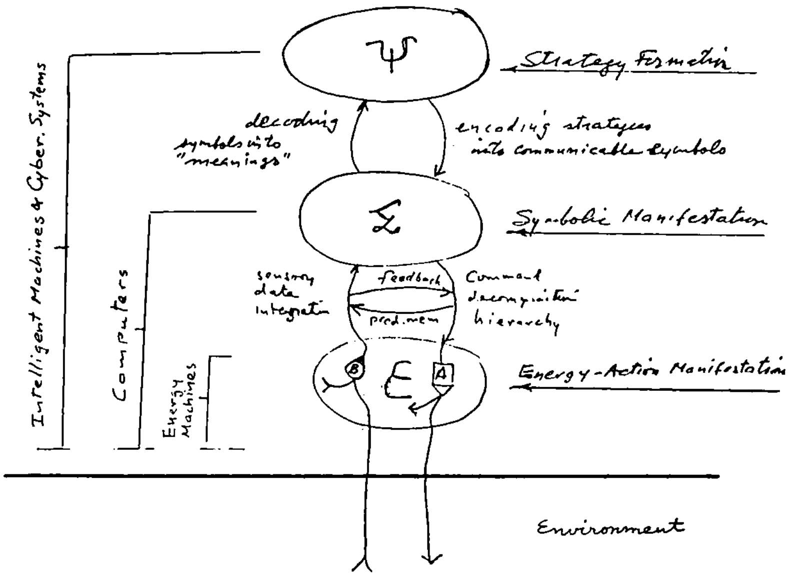

Fig. 2. Three-space operation of a generalized information-processing machine.

tional resources offered by the exploitation of physical phenomena, processes, and laws. Thus, such determinations in the symbolic space, or even questions of compatibility and tractability in the planning space, may lead to definitions of the types and of the measurable properties of the signal quanta which are sensed, tested, and measured in the energy space. It should be noted that these cross-space coupling effects are bilateral, in the sense that physical limitations imposed on the transfer, storage, and processing of signal quanta in the energy space may also determine the most efficient coding and computational methodology.

Depending on the desired computation tasks, various coding and computational philosophies, such as, for example, with stochastic, analog, or some other computing methodology, other than the binary, bit-by-bit, computing, may impose different concepts and demands on such things as restandardizing for arbitrary accuracy (Keyes, 1975), and on the extent of nonlinear operations required in the processing of the signal quanta.

Even on binary coded data, different notions of processing, such as "global surveying" and "filtering" of input data by signal sieves operating on approximate time and space "patterns," rather than on detailed bit-by-bit recognition and processing fashion, and on "global processing" performed

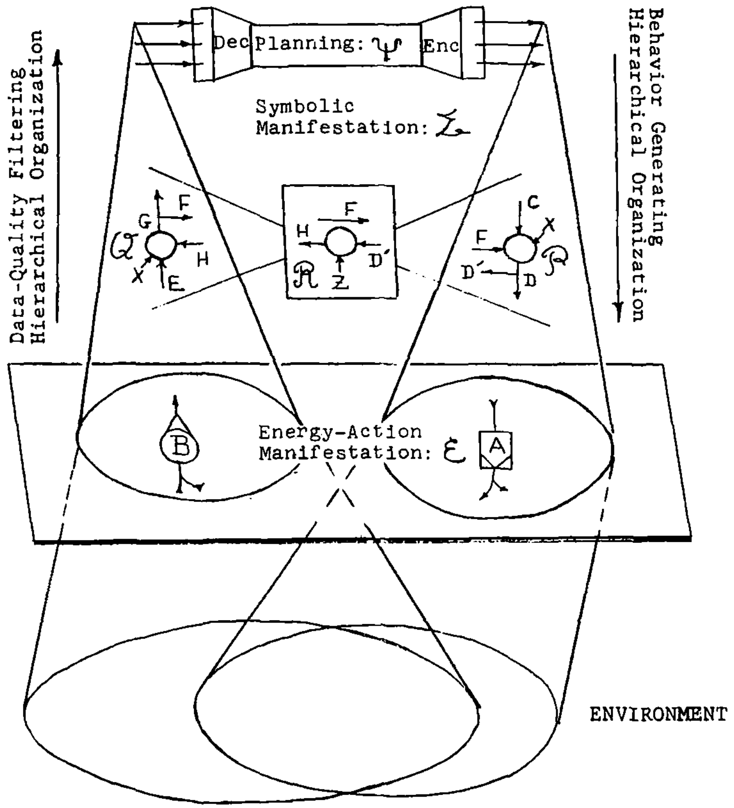

Fig. 3. The engineering–cybernetic model of a generalized "goal-seeking" information-processing system.

by fuzzy algorithms (causal or heuristic), composed by fuzzy instructions, operating on fuzzy-encoded data by processing fuzzy bits (Zadeh, 1968), all these notions and modes of computing may have a decidable effect on energy requirements and on time and spacing limitations in the energy space.

Our preliminary investigations on the various possible encoding notions and computing methodologies, which may be applicable in the implementation of the operators $\mathfrak{P}$, $\mathfrak{Q}$, and $\mathfrak{R}$ of the EC model, indicate that there exists a wide variety of choices in various degrees of variance to the strict two-level coding and computing methodology. The consequences of such alternate choices in the symbolic space upon the outer limitations imposed on the physical processes in the energy space are now open to investigation.

3. SUMMARY

While computation is carried by physical processes having to do with the transfer, storage, and processing of data and control signal quanta in the ε space, it also involves operations in two more spaces, the Σ and the Ψ space. Fundamental questions of "computability" and "tractability" in the Ψ space, as well as methodologies of computing and measures of encoding and translation efficiency in the Σ space, investigated independently of specific forms of implementation, are matters which should have decidable effect on energy, time, and space limitations imposed in the processing of information signal quanta in the energy space. Some such areas of investigation are already underway, beating the bushes for highly promising game.

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