| Topic | ¶¶ |
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| • ☐ (title) | 1 |
|   • ☐ **length**<br>IEEE standard double-column format (6 pages normally and 10 pages maximum)<br>6pp = 5000ww (Word): 25–50¶¶ (40–83 for 10pp)<br>100-200 w/¶ (figure 200) | |
|   • ☐ ***Abstract*** | ***1*** |
| • ☐ (text) | 46 |
|   • ☐ **I. Introduction** | **5** |
|     • ☐ *A. Expanding the Concept of Computation* | *3* |
|       • ☐ 1. We are approaching the limits of digital electronics and the von Neumann architecture, so we need to develop new computing technologies and methods of using them. | 1 |
|       • ☐ 2. Neural networks and similar applications show the need for analog computation. | 1 |
|       • ☐ 3. Nature gives many examples of unconventional computation. | 1 |
|     • ☐ *B. Exploiting Novel Materials & Processes* | *2* |
|       • ☐ 1. New materials may be used, but they present challenges, such as difficulty in structuring them for computing and high error/defect rates. | 1 |
|       • ☐ 2. Our goal should be to match computational processes to the physical processes most suited to implement them. | 1 |
|   • ☐ **II. Generalized Computation** | **4** |
|     • ☐ *A. Why a general definition is needed* | *1* |
|       • ☐ 1. We do not want to limit our options by beginning with too narrow a definition of computation. | 1 |
|     • ☐ *B. The definition* | *2* |
|       • ☐ 1. The purpose of a *computational system* is the mathematical manipulation of mathematical objects. | 1 |
|       • ☐ 2. A computational process can be *realized* by any physical system that can be described by the same mathematics. | 1 |
|     • ☐ *C. Goal* | *1* |
|       • ☐ 1. My goal is a model of generalized computation that can be implemented in a wide variety of physical processes. | 1 |
|   • ☐ **III. Representation of Data** | **18** |
|     • ☐ *A. Urysohn Embedding* | *8* |

| **<u>Topic</u>** | **¶¶** |
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| • ☐ 1. Problem: How do we represent quite general mathematical objects on a physical system? | 1 |
| • ☐ 2. Continua can be embedded in Hilbert spaces (Urysohn) | 1 |
| • ☐ 3. An epsilon-mesh defines a convenient base. | 1 |
| • ☐ 4. As usual, finite-precision approximations can be used. | 1 |
| • ☐ 5. Discrete spaces (for generalized digital computation) can be embedded in continua. | 1 |
| • ☐ 6. The representation can make use of the discrete set of Fourier coefficients, which is like a layer in a neural net. | 1 |
| • ☐ 7. Some generalized computers may operate directly on the function space (of fields) as a representation. | 1 |
| • ☐ 8. A finite set of coefficients corresponds to band-limited fields. | 1 |
| • ☐ *B. An Abstract Cortex* | *5* |
| • ☐ 1. The memory of general-purpose computer should be an unstructured medium that can be programmatically structured into multiple variables. | 1 |
| • ☐ 2. A field can be subdivided into subfields, representing different field variables. | 1 |
| • ☐ 3. Similarly, a discrete set of coefficients can be partitioned. | 1 |
| • ☐ 4. This is analogous to the definition of areas in the cortex, which can serve as a model for memory structuring in the U-machine. | 1 |
| • ☐ 5. Direct products of continua can be handled simply. | 1 |
| • ☐ *C. Transduction* | *5* |
| • ☐ 1. Physical spaces are almost always vector spaces (other continua are mostly useful for internal variables). | 1 |
| • ☐ 2. Input | 2 |
| • ☐ (a) Input transductions are analogous to receptive fields of sensory neurons. | 1 |
| • ☐ (b) Often they will be simple RBFs or linear transformations. | 1 |
| • ☐ 3. Output | 2 |
| • ☐ (a) Physical output spaces are virtually always vector spaces, and so outputs usually can be generated by linear superposition. | 1 |
| • ☐ (b) More generally, we invert the embedding of the output variable. | 1 |
| • ☐ **IV. Representation of Process** | **17** |
| • ☐ *A. Multivariate Interpolation* | *5* |
| • ☐ 1. Transformations on continua are replaced by functions on Hilbert spaces. | 1 |
| • ☐ 2. Multivariate interpolation based on linear combinations of nonlinear basis functions can be used for general computation. | 1 |

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| • ☐ 3. For example, an RBF network (or other universal approximator) can be used for general-purpose computation. | 1 |
| • ☐ 4. For unknown functions, RBF training can be used. | 1 |
| • ☐ 5. For known functions, weights can be computed and set directly (if physically feasible), or RBF training can be used. | 1 |
| • ☐ *B. Decomposing Processes* | *4* |
| • ☐ 1. Description of feed-forward and feedback processes. | 1 |
| • ☐ 2. As in conventional computing (in which we don't reduce everything to table lookup), it will be convenient to reduce complex computations to compositions of simpler ones. | 1 |
| • ☐ 3. Optimal computations of standard functions can be provided in libraries. | 1 |
| • ☐ 4. Standard processes might include those found in general-purpose analog computers (e.g., sum, product, integration, differentiation). | 1 |
| • ☐ *C. Programming Methods* | *4* |
| • ☐ 1. The U-machine is divided into a variable (data) space and a function (program) space. | 1 |
| • ☐ 2. If the function space is 3D, then arbitrary interconnections can be accomplished. | 1 |
| • ☐ 3. In many cases training can be accomplished by accessing only the input and output variables (not the weights). | 1 |
| • ☐ 4. The exact methods of programming the weights will depend on the physical medium, but might be analogous to FPGA programming. | 1 |
| • ☐ *D. Analogies to Neural Morphogenesis* | *4* |
| • ☐ 1. The variable space corresponds to neural grey matter (cortex) and the function space to (axonal) white matter. | 1 |
| • ☐ 2. Signals applied to variable areas can be used to guide projections from one to the other. | 1 |
| • ☐ 3. Weights are programmed by training with complete patterns, or by pairs of individual Fourier coefficients or basis functions. | 1 |
| • ☐ 4. Connections do not have to be perfect. | 1 |
| • ☐ **V. Conclusions** | **2** |
| • ☐ *A. In summary, the U-machine provides a model of generalized computation, which can be applied to massively-parallel nanocomputation in bulk materials.* | *1* |
| • ☐ *B. Future work will explore alternative embeddings and interpolation methods, as well as widely applicable techniques for creating interconnections.* | *1* |
| • ☐ References | |
| • ☐ 1. (citation) | |