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~~Completed~~ three technical papers: "Fuzzy Associative Memories" (to appear in 1987 in Fuzzy Expert Systems, Addison-Wesley), "Hidden Patterns in Combined Knowledge Networks" (in review at IJAR), and "Optical Bidirectional Associative Memories" (to appear in 1987 in SPIE Proc., vol. 758). ~~Performed~~ extensive fuzzy cognitive map (FCM) limit cycle stability experiments were performed. was performed

~~Began~~ simulation of an all-optical continuous Cohen-Grossberg symmetric undirectional autoassociator model, as an optical continuous BAM precursor, began. ~~Performed~~ supervised learning (backpropagation) experiment with scale and rotation invariance models of image recognition was performed. ~~Began~~ work on holographic association of phase-encoded images in photo-refractive materials (lithium niobate) began. ~~Demonstration of~~ correlation of (two-wave mixed) pattern images using barium titinate in a reflective pumping arrangement was demonstrated.

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OCCAM 3rd Quarterly R&D Status Report: Dec 1986 - Feb 1987

I. OCCAM at VERAC

1. Three Technical Papers. Bart wrote three full-length technical papers during Qtr 3: "Fuzzy Associative Memories," "Hidden Patterns in Combined Knowledge Networks," and, with Clark Guest, "Optical Bidirectional Associative Memories." Preprints of these papers were sent to AFOSR and DARPA.

"Fuzzy Associative Memories" has been accepted as a chapter in Fuzzy Expert Systems, edited by Abraham Kandel, to appear as an Addison-Wesley book in 1987. This paper contains the results on FAMs reported in the first quarterly R&D status report. It also contains new theorems on fuzzy foundations. Perhaps the most important result is that several popular continuous associative memories--Cohen-Grossberg, Hopfield, BAM, Anderson brain-state-in-a-box, Grossberg competitive learning--all behave in their distributed computations so as to minimize fuzzy entropy. Information is stored as fixed points at the vertices of the unit hypercube $[0, 1]^n$. An ambiguous input enters the cube as a point (fuzzy set) in its interior or on its surface. As the distributed computation proceeds, the input is disambiguated as the point moves toward the nearest (Boolean) vertex.

"Hidden Patterns in Combined Knowledge Networks" is in review at the International Journal of Approximate Reasoning. It discusses the fuzzy cognitive map (FCM) knowledge combination technique developed during the first quarter of OCCAM. The paper also contains results on FCM limit-cycle behavior.

"Optical Bidirectional Associative Memories" will appear in the SPIE Proceedings: Image Understanding, vol. 758, in 1987. A more general version of the paper is in preparation; it will be submitted to Optical Engineering. This papers summarizes the theorems on discrete and continuous BAMs developed during the first two quarters of OCCAM. Four new BAM optical implementations are described that emphasize a spatial light modulator, laser diodes and high-speed detectors, a reflection hologram, and a transmission hologram.

2. Fuzzy Cognitive Map Limit Cycle Experiments. Limit cycles were studied in simple binary FCMs to see whether approximate symmetry of matrix shortened limit cycles or decreased their frequency of occurrence. We were particulary interested in characteristics of FCMs that posssess short limit cycles. Limit cycles (points) of length 1 in FCMs are interpreted as unequivocal predictions.

We hypothesized that high degrees of sparseness or symmetry of FCM connection matrices should often be associated with short limit cycles. For example, if an entire column of an FCM matrix is zero, then the activation of the corresponding concept node cannot change. If M of the N concept nodes cannot change activation, then the maximum possible limit cycle length (for synchronous operation) drops by a factor of 2^{M-N}, and actual lengths should be expected to drop accordingly.

We computed all limit cycles for tractable-sized FCM matrices with randomly chosen connection strengths, and tried to relate short limit cycles to sparseness, symmetry, or other matrix properties.

We also investigated other limit cycle properties besides length, such as the number of different limit cycles and the number of (the 2^N possible) initial states that resulted in a given limit cycle.

Sparseness was measured in two ways: by the ratio fo nonzero columns to total columns, and by the ratio of nonzero elements to total elements.

Symmetry was measured by the ratio S/(S+D) of the sum norm S of the matrix to the sum of the sum norm and difference norm D of the matrix. Here the sum norm of a matrix is defined as the norm of the sum of the matrix and its transpose. The difference norm is defined as the norm of the difference of the matrix and its transpose. The matrix norm we used was the l^1 norm, the sum of the absolute values of the matrix entries. A little thought shows that this symmetry is unity for a symmetric matrix and zero for an anti-symmetric (real Hermitian) matrix. Such a symmetry measure therefore is not totally satisfactor for anti-symmetry is in some sense highly symmetric.

Consequently, no strong tendency was shown between matrices with large symmetry ratios and short limit cycles, though many suggestive cases did arise. Sparseness also proved largely uncorrelated with our sparseness measure.

The most striking result of the experiment was that "zero-symmetric" matrices only have fixed points. Here we define zero-symmetry as follows: if f_{ij} is nonzero, then $f_{ji} = 0$, We studies zero-symmetric 10-by-10 matrices with uniformly random integer entries in $\{-100, \ldots, 100\}$ or real entries in [-1, 1] (with uniformly varying sparseness). Only 1 out of 15 matrices had a limit cycle not of length 1; this could have been due to the synchronous operation (e.g., even Hopfield/Cohen-Grossberg symmetric autoassociators exhibit small limit-cycles in synchronous operation). Decreased sparseness made some longer limit cycles somewhat more likely. In a FCM context, zero-symmetry means unidirectional causal flow, which does not seem a significant restriction considering the resulting gain of usually unanimous expert opinion.

Finally, sparseness turned out not correlated with limit cycle length but with limit cycle number. Indeed, very sparse matrices seemed to have many short limit cycles and very dense matrices seemed to have fewer limit cycles.

3. DARPA Program Review. Bart presented an OCCAM briefing on 11 February 1987 to DARPA's (AFOSR's) Optical Computing Program.

II. OCCAM at UCSD

During Qtr 3 of the OCCAM Program at UCSD the systems work begun in the second quarter provided its initial research results. This report reviews results obtained in the areas of an all-optical implementation of the continuous symmetric unidirectional Cohen-Grossberg autoassociator model (which subsumes the Hopfield model), neural net implementations of sclase and rotation invariance, and pattern correlation in photorefractive crystals.

Before proceeding iwth review of specific results, it is important to review guiding concepts that have emerged to date through OCCAM. The primary charter of OCCAM is to implement cognitive processing or conceptual computing on optical systems. The Bidirectional Associative Memory (BAM) has been identified as a promising network paradigm to carry out much of this charter. Not only has the BAM been shown to have important architectural properties such as heteroassociativity, guaranteed convergence for pattern recognition and completion, and stable limit cycles for temporal coding, it also naturally lends itself quite naturally to optical implementations (see "Optical BAMs," discussed above). The bidirectional optical connectivity provided by matrix masks or holograms can be directly used.

An additional attractive feature of the BAM is the way its basic architecture can be extended in steps toward the features of a full adaptive resonance theory (ART) model, as discussed in the OCCAM Phase II Proposal. A powerful synergism has been identified between optical implementations of fuzzy logic operations, which have been studied in OCCAM, and the competitive self-normalizing fields of ART. Both systems require essentially a maximum (minimum) operation over a field fo elements. It appears likely that a single optical implementation will serve these purposes.

A second charter for OCCAM has been the specification of an operating system for optical associative memories. Operating systems perform two functions: interface of a processor to the outside world, and task sequencing or goal orientation. the problem of interface has been studied in OCCAM Phase I (goal orientation has been scheduled for study during OCCAM Phase II). the specific problem of where traditional preprocessing should leave off and neural processing should commence has been of particular interest. It now appears that the dividing line is not as sharp as first believed. Though traditional implementations predominate in processing raw real-world data, benefit can be drived by incorporating some neural processing functions. Likewise, neural processing predominates at the abstract level, but some traditional methods may still be of use.

An all optical system for implementing the continuous Cohen-Grossberg meodel was compleded during Qtr 3. This system may be viewed as a subset, or simplification, of a full continuous BAM that will eventually be implemented. Initial findings from the system are that characteristics of the threshold function curve are rather critical to acceptable system operation. The displacement of high gain to moderately high input values and the magnitude of the saturation gain appear to be particularly important. A theoretical and computer simulation study has been commenced to quantify the effects of threshold parameters on system operation.

For the purpose of comparing traditional methods of scale and rotation invariant image recognition to neural implementations of the same, work began on computer modelling of a "backpropagation" network trained for invariant recognition. The model is trained on the letters "A" and "T" in a number of different rotations. It then is able to classify input "A" and "T" patterns presented at those and similar angles. Work is proceeding to determine if it is possible to train the network for geneneral rotation invariant recognition. That is, if it is trained to be rotation invariant for "A" and "T" patterns, will it exhibit invariance for other untrained patterns?

In the area of application of photorefractive materials to neural nets, one project was completed and another begun. Work begun during the second quarter on two-wave mixing in a reflection configuration culminated during the third quarter with a demonstration of correlation of pattern images using barium titinate in a reflective pumping arrangement. Images were brought in from opposite sides of the crystal, one image weak, and one strong. Power in the weak image was amplified in proportion to its correlation (overlap) with the strong image. Maximum amplification factors of 60 or greater were achieved. This correlation operation can be expected to prove useful in pattern identification for optical neural networks.

Work started in Qtr 3 on holographic association of phase encoded images in photorefractive materials. Previous methods of association have used angular multiplexing of images and fractal decimation of associated pixels to prevent Bragg-cone degeneracy crosstalk. Only phase encoding of images provides full image heteroassociation and low crosstalk. Pseudorandom computer generated phase masks will be used, and lithium niobate is the photorefractive that will intially be studied.