vivability and therefore reliability. Survivability is also a central issue in a variety of systems with complex behavior encountered in biology, economics, societal models, and military science. One can therefore expect neuromorphic processing to play an increasing role in the modeling and study of such complex systems especially if optical techniques can be made to furnish speed and flexibility.

Finally, one should expect that software development for emulating neural functions on serial and parallel digital machines will not continue to be confined to the realm of straight-forward simulation, but, spurred by the mounting interest in neural processing, will move into the algorithmic domain where fast efficient algorithms are likely to be developed, becoming to neural processing what the FFT was to the discrete Fourier transform. Thus we expect that advances in optical and digital neuromorphic signal processing will proceed in parallel.

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Optical resonators, mode competition, and associative memory

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The mathematical description of the laser is of a rather universal character that emerges in many fields of science.[1,2] The same mathematics has been applied to the interaction among neurons forming a network to model brain behavior and cognitive function.[3–5] That these two systems share a common mathematical heritage leads one to wonder whether one can extract useful brain-like behavior from a laser or a similar nonlinear optical system. Some recent work with holographic optical resonators has been motivated by precisely this notion.[6–10]

A conventional resonator composed of mirrors and lenses supports a set of eigenmodes—optical fields that propagate in a self-consistent manner in the optical circuit. A nonlinear gain medium internal to the resonator can supply energy to these modes. This is the principle of a laser or, more generally, of an optical oscillator. These modes of the oscillator will compete for the finite energy available from the medium. If the medium and optical configuration are appropriately chosen, the competition can be sufficiently intense that only one mode can survive; its presence suppresses the generation of all other models. Competition for the energy in the optical resonator can be prejudiced by the presence of a signal injected into the resonator. Now the competition will be biased in favor of the mode that *most* resembles the injected signal.

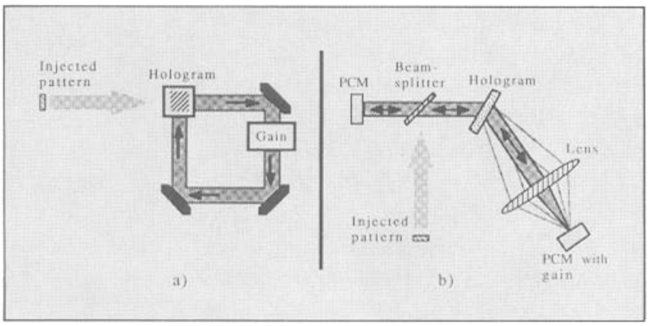
Mode competition in the face of external constraints (an injected signal) is a fundamental principle underlying many neural network models of human associative memory and other cognitive functions as well. When we hear a part of a familiar melody, we can easily complete the tune even if the original information comes to us somewhat distorted or confused by background noise. Hence, we can recollect the entire tune, perhaps the composer, and maybe the place we often listened to the tune in the past, with that small piece of information. In these models of memory, the associative recall can be likened to the optical oscillator's behavior in the presence of an injected signal.

The eigenmodes of a conventional resonator are governed by the shape and placement of the mirrors and lenses comprising the resonator. With a hologram in place of a conventional element, however, one can program the set of eigenmodes to carry information in the form of patterns or images. Using photorefractive media as a holographic element, patterns can be stored and recalled in real-time. The story concerning the gain medium and competition remains the same, but now stored patterns become the competitors. One can address the resonator with a distorted or partial picture and have it recall the entire scene of the pattern that provides the closest match to the input.

Holographic resonator associative memories have so far been demonstrated using both unidirectional ring resonators[6] and phase-conjugating resonators[7,8] (see figure). The manner in which the hologram is created differs in the two cases, but the principles of operation are very similar.

The behavior of the optical oscillator in the absence of an injected signal is rather interesting. With nothing to otherwise bias the competition, any mode can win. What has actually been observed in the optical ring oscillator are mode fluctuations whereby the output wanders, apparently randomly, from pattern to pattern. Sometimes the system will settle onto one pattern for a length of time, sometimes it will undergo continual change. Although mode fluctuations are a common phenomena among some types of lasers, no current neural network model anticipates this behavior.

Resonator memories demonstrate the principle of associative recall in an optical system where the physics directly implements the mathematics of a neural network model. However, associative memories based on these simple schemes are rather restricted in power. In particular, their ability to store certain groups of patterns and classify them is very limited. Neural network models exist that have more interesting and more sophisticated processing capabilities. Among these models are systems that learn behavior or gather information about their input environment through a teaching process or through some self-organizing mechanism. Resonator memories represent a simple example of nonlinear optical implementations of neural network models. These models serve as a guide towards more complex optical systems that can implement more sophisticated brainlike behavior.



Optical resonator memories. Patterns are stored as eigenmodes of the resonator. Recall is through a competitive process in the gain medium. a) Ring resonator: during hologram formation the desired pattern provides both the object and the reference waves. The optical fields representing the stored patterns compete among themselves for the energy supplied by the gain medium. b) Phase-conjugating resonator: for each pattern to be stored the hologram is recorded with a different reference plane-wave traveling a predetermined direction, that is, each pattern is encoded by the direction of propagation of an associated plane-wave. During recall, the plane-waves associated with the stored patterns, rather than the patterns themselves, compete for the energy supplied by the phase-conjugating mirror (PCM) having gain.

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Optical associative memory incorporating holography and phase conjugation

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The goal of our recent work has been to use optics to mimic some aspects of the way in which the human brain handles information. The human brain processes data in an associative, parallel, nonalgorithmic manner that is significantly different and sometimes more desirable than the symbolic, rule-based approach of most electronic and optical approaches to computing. This sort of approach may be particularly effective when the input data is incomplete or fuzzy. The brain is able to recall complete and undistorted stored data when prompted only by a partial or distorted version of the data. It can generally do this independent of the orientation or scale size.

In addition to this robustness, the brain uses heteroassociation to associate various elements of the stored data in an intricate manner. This type of memory is entirely different from conventional location-addressed memory. Because of the benefits of this type of memory, the study of neural network modeling has given an impetus to workers in both the fields of electronic and optical data processing.

At the Hughes Research Laboratories we have developed an all-optical associative memory[1–3] that utilizes ideas from holography, phase conjugation, and neural net-