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To summarize, progress has been made on a family of related problems, including: A model of endstopped visual cortical neurons was extended to include complex components; An extensive simulation of the model was completed with regard to orientation, positional, spatial frequency, curvature, chevron, and end-line sensitivity; Orientation discontinuities were extended into the motion domain, and psychophysical and computational experiments were performed to confirm the hypothesis of multiple directions being represented at a point of discontinuity; A theory was developed to capture the non-linearities necessary for early measurement of orientation and curvature; A totally different theory has begun to take shape for functionally characterizing cytochrome oxidase blobs; and The mathematical foundations were laid for a theory of shape.

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# Final Technical Report
# AFOSR Grant 89-0260
# 31 Jan 91

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of vision sufficent to support both early and high level function; i.e., to start with images, infer local descriptions of their geometric structure (both in space and in motion), to group these into global constructs and, ultimately, to recognize the objects depicted in the images. Progress was made at all of these levels, and a listing of AFOSR-supported publications attests to this activity. The logical/linear machinery has also been applied to the co-circularity computation within our relaxation network, and has greatly enhanced its selectivity just as it improved the operator responses above.

The development of logical/linear operators and the advancements to our co-circularity relaxation networks also enabled us to achieve another of our design goals: the representation of discontinuities (e.g., corners in the case of orientation) in early vision. The representation of discontinuities has eluded physiologists, and research in computer vision has been inconclusive. That is, "optimal corner detectors" have been proposed, but no one has been able to discriminate corners from smooth points of high curvature. Such differences are key to vision, because they facilitate object segmentation (recall that whenever one object occludes another, a discontinuity is created at the points where their bounding contours intersect). We have proposed that such corners (and discontinuities in general) are represented via multiple tangents at the same position. In physiological terms this amounts to several cells firing simultaneously in the same hypercolumn signaling different orientations. Standard (linear) orientation operators typically select for only one orientation at each position. The non-linearities in our logical/linear operators, however, enable the signaling of such situations, and thus we are able to detect them. Such singularities were also found to be important for motion and optical flow as well.

Finally, we have made progress on the global aspects of vision as well. Cortical hypercolumn-like representations are local, in the sense that they represent an estimate of the orientation at a point; how can global curves be inferred from these local representations? We have discovered a class of algorithms for computing coverings of them, in parallal, which have important implications for parallel computation. Also, the global curves that we find are sufficent, in many cases, to support a theory of shape that we are also developing.

To summarize, progress has been made on a family of related problems, including

- A model of endstopped visual cortical neurons was extended to include complex components;
- An extensive simulation of the model was completed with regard to orientation, positional, spatial frequency, curvature, chevron, and end-line sensitivity;
- Orientation discontinuities were extended into the motion domain, and psychophysical and computational experiments were performed to confirm the hypothesis of multiple directions being represented at a point of discontinuity;
- A theory was developed to capture the non-linearities necessary for early measurement of orientation and curvature;
- A totally different theory has begun to take shape for functionally characterizing cytochrome oxidase blobs; and
- The mathematical foundations were laid for a theory of shape.

During the past 3 years, and aided by the support of AFOSR Grant 89-0260, we have begun to evolve a rather novel perspective on how early visual computations should be constructed. Theoretically our position is a mixture of insights from mathematics and computation, on one hand, and physiology and psychophysics, on the other. In practice, our laboratory has taken these ideas into the domains of robotics, biomedicine, and space exploration.

To elaborate our theoretical position, we began with a rather standard view of the [illegible]tational machinery for early vision, derived from a Hubel/Wiesel-like system of cor[illegible] columns, in which direct measurements of image features were available. We now are beg[illegible] to elaborate the functional circuitry that must underlie these computations for pragmatically successful systems. There is far more to vision than designing local operators; rather one must couple the design of operators to the inference of image features by computational networks to achieve pragmatically successful systems.

In particular, we began with the specific goal of designing operators for measuring the curvature of visual features (namely, lines and edges) from the information initially available in cortical orientation hypercolumns. This was necessary to support the neural networks that we were building for curve and edge detection. The columns were populated with linear models of simple cells, such as Gabor functions or differences of Gaussians, and these fed into standard Hochstein models of complex cells. Our insight was that a non-linear (rectified) combination of the responses of cells with similar orientation preferences, but with differently sized receptive fields, could provide the orientation signal. This was substianted by both simulation and electrophysiology. An important consequence of these studies was the discovery of a relationship between endstopping and curvature estimation, an observation that has now changed the way many physiologists functionally interpret the visual cortex.

In addition to these theoretical concerns, our laboratory is also very concerned with pragmatic computer vision, so we naturally tried to apply these ideas to realistic images as well. However, we found the model did not work for complex, applied tasks (e.g., those that arise in biomedicine). The problem was not with the conceptual ideas, but rather with the shortcomings of the initial, linear operators. When multiple curves appeared nearby, or when one object obscured another, estimates of orientation were wrong and the entire system failed. And no subsequent network structuring was able to repair it.

We thus turned our attention to getting better initial estimates, and to uncovering the structural conditions necessary to define them. We are now developing this into an entire theory of "logical/linear operators", In particular, we have developed a calculus for the logical combination of local evidence from subunits in which support is accumulated linearly, but incompatible evidence enters nonlinearly. This led to a class of operators that appears linear for one class of stimuli but markedly nonlinear for others; hence the reason for calling them logical/linear operators. They exhibit dual advantages: they are considerably more stimulus-specific than purely linear operators, while more robust to incidental stimulus variation than logical operators. Curiously, the viability of such operators as models of visual cortical neurons (e.g. simple cells) is also being examined, although it requires stimuli rather different from the bars, gratings, and edges typically employed. In short, the non-linearities inherent in logical/linear operators would *not* appear in standard physiological tests. We believe, however, that they will appear if more complex stimuli were used.

The larger context of our work, into which this project fits, is the construction of theories

Together these results are crystalizing a new perspective on early visual processing, as indicated by the following publications that acknowledge AFOSR support. Three graduate students have also been supported by this grant: Allan Dobbins (McGill), Lee Iverson (McGill), and Erica Strumpf (U.B.C.). While we are proud of our accomplishments during this period, we also believe that much remains to be done. And we feel that we are in an excellent position to continue [illegible]

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