

Two Stages of Curve Detection Suggest Two Styles of Visual Computation

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The problem of detecting curves in visual images arises in both computer vision and biological visual systems. Our approach integrates constraints from these two sources and suggests that there are two different stages to curve detection, the first resulting in a local description, and the second in a global one. Each stage involves a different style of computation: in the first stage, hypotheses are represented explicitly and coarsely in a fixed, preconfigured architecture; in the second stage, hypotheses are represented implicitly and more finely in a dynamically-constructed architecture. We also show how these stages could be related to physiology, specifying the earlier parts in a relatively fine-grained fashion and the later ones more coarsely.

1 Introduction

An extensive mythology has developed around curve detection. In extrapolating from orientation-selective neurons in the visual cortex (Hubel and Wiesel 1962), it is now widely held that curve detection is simply a matter of "integrating" the responses of these cells. More specifically, the mythology holds that this integration process is global, that the initial estimates are local, and that the relationship between them will become clear as a more detailed understanding of cortical circuitry is uncovered. However, this mythical process of "integration" has turned out to be elusive, the search for it has led, instead, to a series of dilemmas, and the quantity of physiological data is exploding. It is rarely clear how new details of cortical circuitry relate to different components of the curve detection problem.

We believe that this situation is typical of vision in general, and amounts to ascribing too little function to the earlier stages, and too

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much to the later ones. For curve detection, virtually all of the complexity is delegated to the process of "integration," so it is not surprising that successful approaches have remained elusive. Part of the problem is that models of integrative processes have been rich in selected detail, but poor in abstract function. In the sense that it is often useful to *see the forest before the trees*, we submit that solutions will likely be found by considering both coarse-grained and fine-grained models, and that such models will suggest a partitioning of function whose abstraction varies with granularity. To make this point concretely, we here outline a coarse-grained solution to the curve detection problem from a computational perspective, and sketch how it could map onto physiology. The sketch is coarse enough to serve as an organizational framework, but fine enough to suggest particular physiological constraints. One of these comprises our first, coarse-grain prediction: curve detection naturally decomposes into two stages, the first in which a local description is computed, and the second in which a global description is computed. These computations are sufficiently different that we are led to hypothesize two different styles of visual computation.

2 The Dilemma of Curve Detection _____

The initial measurement of orientation information is broadly tuned, which suggests the averaging necessary to counteract retinal (sensor) sampling, quantization, and noise. However, the end result of curve detection is unexpectedly precise: corners can be distinguished from arcs of high curvature, and nearby curves can be distinguished from one another to a hyperaccurate level, even though they might pass through the same receptive field.

An analogous dilemma exists for computer vision systems, even with the spectacular numerical precision of which computers are capable: quantization and noise imply smoothing, but smoothing blurs corners, endpoints, and nearby curves into confusion (Zucker 1986). At the foundation is a chicken-and-egg problem: if the points through which the curve passed, together with the locations of discontinuities, were known, then the actual properties of the curve could be inferred. But initially they are not known, so any smoothing inherent in the inference process is potentially dangerous.

3 Two Stages of Curve Detection _____

We have discovered a computational solution to this dilemma, which involves decomposing the full problem into two stages, each of which has a rather different character. In the first stage, the local properties of the curve are computed: its trace (the set of retinotopic points through which the curve passes), its tangent (or orientation at those points), and

its curvature. In the second stage, these properties are refined to create a global model of the curve. This much — proceeding from local to global — is standard; the style of the computations is not. The key to the first stage is to infer the local properties coarsely — not in fine detail — but without sacrificing reliability or robustness. Coarseness is here related to quantization, which must limit error propagation without blurring over corners. Observe that this is precisely what is lacking in the standard myth, where errors (e.g., about placing discontinuities) can have far reaching consequences. The result is a style of computation in which the different (quantized) possibilities are made explicit, and arranged in a fixed, preconfigured computational architecture that imposes no *a priori* ordering over them. Each distinct hypothesis, say rough orientation and curvature at every position, forms a unit in a fixed network that strongly resembles neural-network-style models. Reliability and robustness are then maintained by the network; hence the local description is not computed locally! A mapping onto orientation hypercolumns will be discussed shortly.

The second stage embodies a rather different style of computation. Now the possibilities no longer need be general, but are constrained to be in the range dictated by the first stage. Thus the architecture can be tailored to each problem—that is, constructed adaptively rather than preconfigured—and variables can be represented implicitly. With these highly focused resources, the key limitation on precision is implementation, and it need not be hampered by uncontrolled error propagation. From the outside, this constructive style of computation holds certain key properties in common with later visual areas, such as V4 and IT, where receptive field structure has been shown to vary with problem constraints (e.g., Maunsell and Newsome 1987; Moran and Desimone 1985).

4 The Model of Curve Detection

In physiological terms, neurons are said to be orientation selective if they respond differentially to stimulus (edge or line) orientation. We take this operational statement one step further by defining orientation selection to be the inference of a local description of the curve everywhere along it, and postulate orientation selection as the goal of our first stage. In the second stage, global curves are inferred through this local description. The various stages of our process are shown in figure 1, and expanded below.

4.1 Stage 1: Inferring the Tangent Field. Formally orientation selection amounts to inferring the trace of the curve, or the set of points (in the image) through which the curve passes, its (approximate) tangent and curvature at those points, and their discontinuities (Zucker 1986). We refer to such information as the *tangent field*, and note that, since the initial

measurements are discrete, this will impose constraints on the (inferred) tangents, curvatures, and discontinuities (Parent and Zucker 1985).

This first stage of orientation selection is in turn modeled as a two step process:

Step 1.1. *Initial Measurement* of the local fit at each point to estimate orientation and curvature. These estimates derive from a model of simple cell receptive fields instantiated at multiple scales and orientations at each image position. However, these local measurements are inherently inaccurate (e.g., broadly tuned), so we require:

Step 1.2. *Interpretation* into an explicit distributed representation of tangent and curvature by establishing consistency between the local measurements. This is accomplished by modifying them according to their geometric relationships with nearby estimates.

4.2 Stage 2: Inferring a Covering of the Curve. Since the tangent is the first derivative of a curve (with respect to arc length), the global curve can be recovered as an integral through the tangent field. Such a view typically leads to sequential recovery algorithms (e.g., Kass and Witkin 1987). But these algorithms require global parameters, starting points, and some amount of topological structure (i.e., which tangent point follows which); in short, they are biologically implausible. In contrast, we propose a novel approach in which a collection of short, dynamically modifiable curves ("snakes" in computer vision; see Montanari 1971; Kass et al. 1988) move in parallel.

The key idea behind our approach is to recover the global curve by computing a *covering* of it; i.e., a set of objects whose union is equivalent to the original curve. The elements of the covering are unit-length dynamic splines, initially equivalent to the elements of the tangent field, but which then evolve according to a potential distribution constructed from the tangent field. The evolution takes two forms: (i) a migration in position to achieve smooth coverings; and (ii) a "growth" to triple their initial length. Furthermore, since the splines are initially independent, it is not known which should be grouped into the covering of each distinct global curve. For graphical purposes we represent this by creating each one with a different "color," and include a second process which converts overlapping splines to the same color. In the end, then, the cover is given by a collection of overlapping splines, or short "snakes," each of which is the same color.

Again, there are two conceptually distinct steps to Stage 2 of the algorithm (David and Zucker 1989):

Step 2.1. *Constructing the Potential Distribution* from the discrete tangent field. Each entry in the tangent field actually represents a discretization of the many possible curves in the world that could project onto that particular (tangent, curvature) hypothesis. Now these pieces

must be put together, so consider a measure (or envelope) over all of these possible curves. Assuming the curves are continuous but not necessarily differentiable everywhere, each contribution to the potential can be modeled as a Gaussian (the Wiener measure) oriented in the direction of the tangent field entry. The full potential distribution is their pointwise sum; see figure 3.

Step 2.2. *Spline Dynamics* The discrete entities in the tangent field are converted into unit splines initialized in the valleys of the potential distribution. They evolve according to a variational scheme that depends on spline properties (tension and rigidity) as well as the global potential.

5 Implementing the Model

Each stage of the model has different implementation requirements. To differentiate between smooth curves, curves with corners, crossing curves and branching curves, it is necessary to represent each possible tangent (orientation) and curvature value at every possible position. Smooth curves are then represented as a single (tangent, curvature) hypothesis at each (retinotopic) trace point, corners as multiple tangents at a single point, and bifurcations as a single tangent but multiple curvatures at a single point. Orientation hypercolumns in the visual cortex are thus a natural representational substrate, with explicit representation of each possible orientation and curvature at each position. This leads to a new observation regarding discontinuities: explicit neurons to represent them are unnecessary, and leads to our first physiological prediction:

Prediction 1. Crossings, corners, and bifurcations are represented at the early processing stages by multiple neurons firing within a “hypercolumn.”

5.1 Stage 1, Step 1: Intra-Columnar Initial Measurements. We first seek a physiologically plausible mechanism for measuring orientation and curvature. Observe that an orientation-selective cortical neuron carries information about the tangent to curves as they pass through its receptive field, and an ensemble of such cells of different size carries information about how orientation is changing over it. Such differences are related to curvature (or deviation from straightness), and adding appropriate rectification leads to a model of endstopped neurons (Dobbins et al. 1987; cf. Hubel and Wiesel 1965). This model exhibits curvature-selective response at the preferred orientation, as do endstopped neurons. Thus

Prediction 2. Endstopped neurons carry the quantized representation of orientation and (non-zero) curvature at each position.

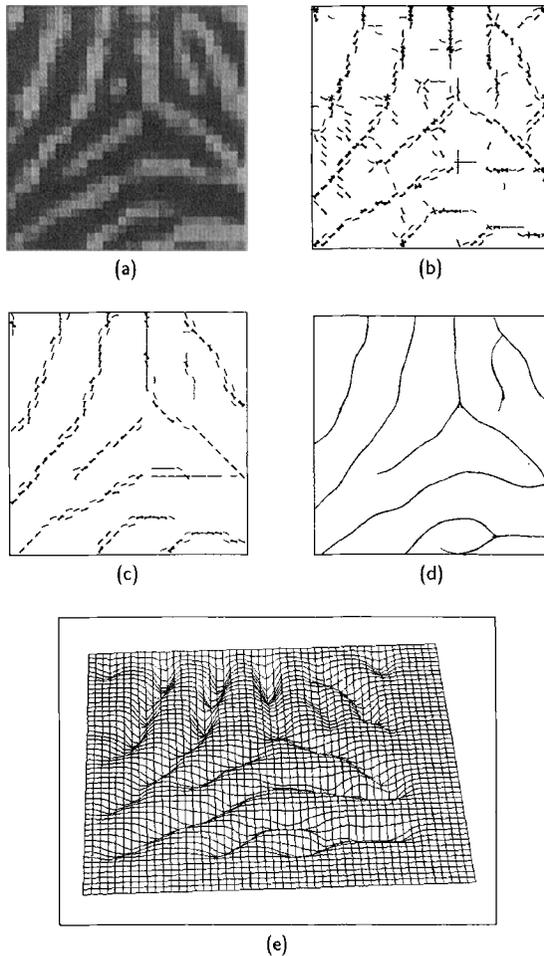


Figure 1: An illustration of the different stages of curve detection. In (a) we show a section of a fingerprint image; note the smooth curves and discontinuities around the "Y" in the center. (b) Graphical illustration of the initial information, or those orientation/curvature hypotheses resulting from convolutions above the noise level. (c) The discrete tangent field resulting from the relaxation process after 2 iterations; note that most of the spurious initial responses have been eliminated. (d) Final snake positions, or coverings of the global curves. (e) The potential distribution constructed from the entries in the tangent field.

By varying the components one obtains cells selective for different ranges and signs of curvature.

Thus the initial measurements can be built up by intra-columnar local circuits, with the match to each (quantized) orientation and curvature represented explicitly as, say, firing rate in endstopped neurons. However, these measurements of orientation and curvature are broadly tuned; nearby curves are blurred together and multiple possibilities arise at many positions. Introducing further non-linearities into the initial measurements eliminates some spurious responses (Zucker et al. 1988), but the broadly-tuned smearing remains. We thus seek an abstract principle by which these broadly tuned responses can be refined into crisper distributions.

5.2 Stage 1, Step 2: Inter-Columnar Iterative Refinement. Again curvature enters the model, but now as a way of expressing the relationship between nearby tangent (orientation) hypotheses. Consider an arc of a curve, and observe that tangents to this arc must conform to certain position and orientation constraints for a given amount of curvature; we refer to such constraints geometrically as co-circularity (Fig. 2a). Discretizing all continuous curves in the world that project into the columnar space of coarse (orientation, curvature) hypotheses partitions these curves into equivalence classes, examples of which are shown in figure 2b (Parent and Zucker 1985; Zucker et al. 1988). Interpreting the (orientation, curvature) hypotheses as endstopped neurons, such co-circularly-consistent relationships are what is to be expected of the firing pattern between endstopped neurons in nearby orientation hypercolumns given such a curve as stimulus. Turning this around, when such intercolumnar patterns arise from the initial measurements, a curve from one of the equivalence classes is to be expected.

Such inter-columnar interactions can be viewed physiologically as excitatory and inhibitory projections between endstopped cells at nearby positions (adjacent hypercolumns), and can be used as follows. Since curvature is a relationship between tangents at nearby positions, two tangents should support one another if and only if they agree under a curvature hypothesis, and co-circularity provides the measure of such support. In addition, two tangents that disagree with the curvature estimate should detract support from one another. Relaxation labeling provides a formal mechanism for defining such support, and for specifying how to use it (Hummel and Zucker 1983). Mathematically it amounts to gradient descent; physiologically it can be viewed as a mechanism for specifying how the response of neighboring neurons will interact. In summary:

Prediction 3. Inter-columnar interactions exist between curvature consistent (co-circular) tangent hypotheses.

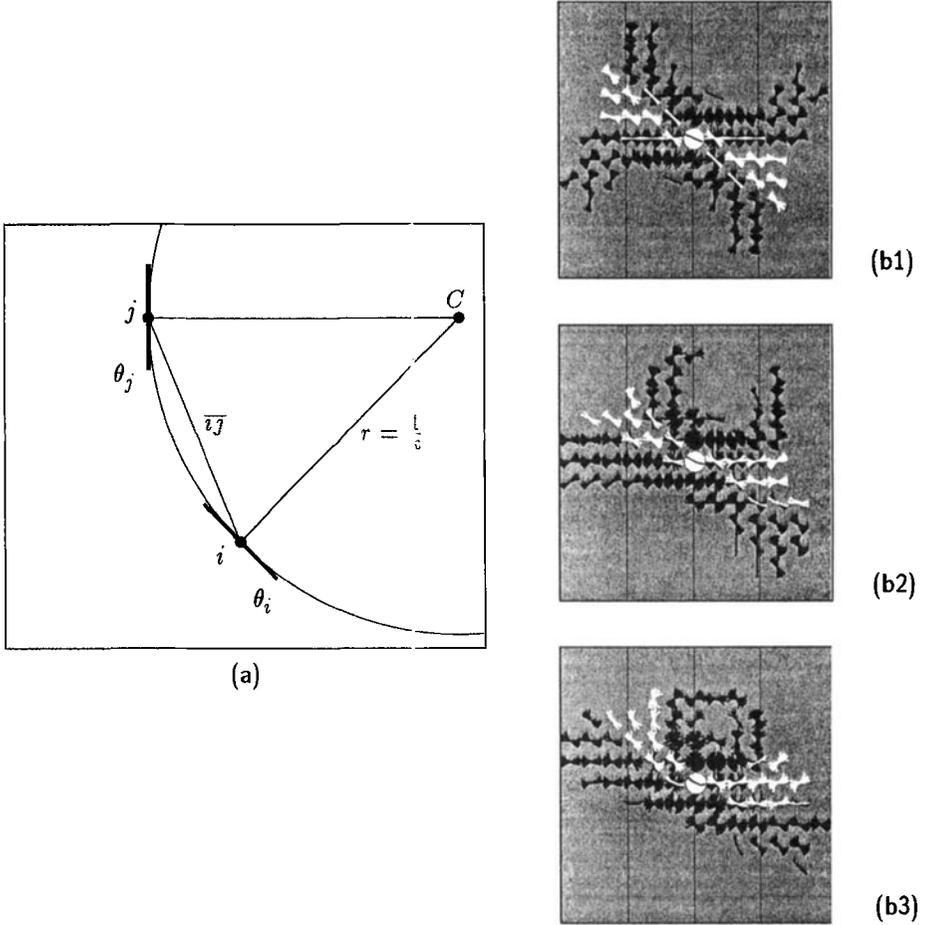


Figure 2: (a) The geometric relationships necessary for defining the compatibilities between two label pairs at points i and j . (b) Compatibilities between coarse (orientation, curvature) hypotheses at nearby positions. 8 distinct orientations and 7 curvatures were represented, and 3 examples are shown. (top) The labels which give positive (left) and negative (right) support for a diagonal orientation that curves slightly left; (middle) positive and negative support for a straight curvature class; (bottom) positive and negative support for the maximum curvature class. The magnitude of the interactions varies as well, roughly as a Gaussian superimposed on these diagrams. The values were obtained by numerically solving a 6-dimensional closest point problem (Zucker et al. 1988). Physiologically these projective fields represent inter-columnar interactions. Multiplied by the original tangent receptive fields, they represent the units for building the potential distribution that guides Stage 2.

Given interaction, the next question relates to precision. Earlier we hypothesized that this first stage was coarse. Both computational experiments (Zucker et al. 1988), psychophysics (Link and Zucker 1988), and the range of receptive field sizes in striate cortex (Dobbins et al. 1988) provide independent evidence about the quantization of curvature:

Prediction 4. The initial representation of curvature in the visual cortex is quantized into 5 ± 2 distinct classes; namely, straight, curved to the left a small amount, curved to the left a large amount, and similarly to the right.

Relaxation processes can be realized iteratively, and computational experiments suggest that about 3 iterations suffice (Zucker et al. 1988). At this time we can only speculate how these iterations relate to physiology, but perhaps the first iteration is carried out by a recurrent network within V1, and the subsequent iterations through the feed-forward and -back projections to extrastriate cortex (e.g., V2 or V4 in monkey). There is no doubt, however, that interactions beyond the classical receptive field abound (Allman et al. 1985).

The advantage of this style of “coarse modeling” is that a number of testable physiological hypotheses do emerge, and we are now beginning to explore them. The requirement of initial curvature estimates led to the connection with endstopping, and the current model suggests roles for inter-columnar interactions. In particular, we predict that they should be a function of position and orientation, a prediction for which some support exists (e.g. Nelson and Frost 1985) in the zero-curvature case; experiments with curved stimuli remain to be done.

5.3 Stage 2: Potential Distributions and Evolving Spline Covers.

The tangent field serves as a coarse model for the curve, represented locally. The next task is to infer a smooth, global curve running through it. We perform this inference in a rather different kind of architecture, one that involves potential distributions constructed specifically for each instance. It proceeds as follows.

The potential distribution is created by adding together contributions from each element in the tangent field; see figure 3. Changing the representation from the tangent field to the potential distribution changes what is explicit and what is implicit in the representation. In Stage 1 there were discrete coarse entities; now there are smooth valleys that surround each of the global curves, with a separation between them. The “jaggies” imposed by the initial image sampling have been eliminated, and interpolation to sub-pixel resolution is viable.

To recover the curves through the valleys, imagine creating, at each tangent field entry, a small spline of unit length oriented according to the tangent and curvature estimates (Fig. 4). By construction, we know that this spline will be born in a valley of the tangent field potential

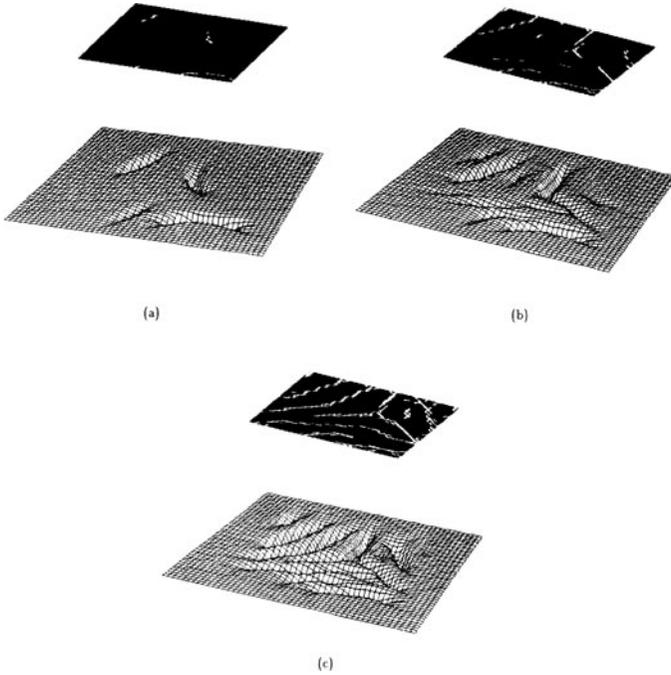


Figure 3: Illustration of how a potential distribution is constructed from tangent field entries. (a) A small number of tangents, showing the individual contributions from each one. (b) As more tangents are included, long "valleys" begin to form when the individual entries are added together. (c) The complete tangent field and potential distribution as shown in figure 1. Physiologically one might think of such potentials as being mapped onto neuronal membranes. Not shown is the possible effect of attention in gating the tangent field contributions, the smallest unit for which could correspond to a tangent field entry.

distribution, so they are then permitted to migrate to both smooth out the curve and to find the true local minima. But the inference of a cover for the global curves requires that the splines overlap, so that each point on every curve is covered by at least one spline. We therefore let the splines extend in length while they migrate in position, until they each reach a prescribed length. The covering is thus composed of these extensible splines which have grown in the valleys of the tangent field potential. Their specific dynamics and properties are described more fully in (David and Zucker 1989).

It is difficult to interpret these ideas physiologically within the classical view of neurons, in which inputs are summed and transformed into

an output train of action potentials. Dendrites simply support passive diffusion of depolarization. Recently, however, a richer view of neuronal processing has emerged, with a variety of evidence pointing to active dendritic computation and dendro-dendritic interaction (Schmitt and Worden 1979). Active conductances in dendrites functionally modify the geometry, and dendro-dendritic interactions suggest that the output transformation is not uniquely mediated by the axon. Taken together, these facts imply that patterns of activity can be sustained in the dendritic arbor, and that this membrane could be the substrate of the above potential distribution computations. For this to be feasible, however, we require

Prediction 5. The mapping of the potential distribution onto the neuronal membrane implies that the retinotopic coordinates are similarly mapped (at least in open neighborhoods) onto the membrane.

The large constructed potential distributions may bear some resemblance to the large receptive fields observed in areas V4 and IT (Maunsell and Newsome 1987). While any such relationship is clearly speculative at this time, it should be noted that they have two key similarities: (i) extremely large receptive fields (potential distributions) have been created, but they maintain about the same orientation selectivity as in V1 (Desimone et al. 1985); (ii) their structure can change. We have stressed how structure is controlled by upward flowing information, but it should be modifiable by "top-down" attentional influences as well (Maunsell and Newsome 1987; Moran and Desimone 1985). Attention could easily "gate" the tangent field entries at the creation of the potential, which leads to:

Prediction 6. There exists a smallest scale of attentional control, and it corresponds (in size) to the scale of the unit potential contributions.

6 Conclusions

This paper is both constructive and speculative. On the constructive side, we have outlined a computational solution to the curve detection problem that fills the wide gulf between initial broad measurements of orientation and precise final descriptions of global curve structure. Much of the mythology that has developed around curve detection is due, we believe, to ascribing too little function to the first (measurement) stage, and too much function to the second (integration) stage. Our solution was to interpose a stable description—the tangent field—between the stages, to represent the local properties of curves (and their discontinuities). Three points emerged: (i) represent the local structure coarsely,

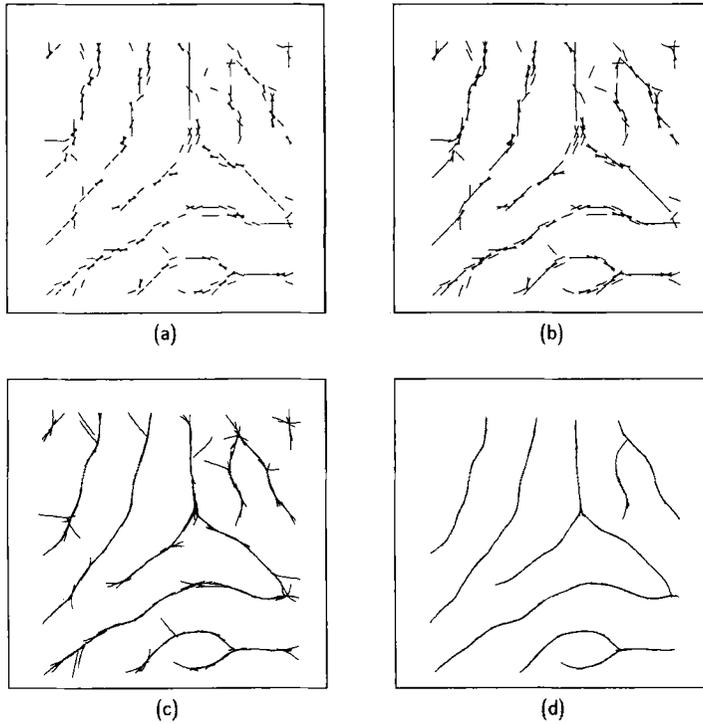


Figure 4: Illustration of the splines in motion. Initially, each spline is born at a tangent field location, with unit length. Then, according to the potential distribution shown in figure 1e, the splines migrate in position (to find minima in the distribution) and in length, so that they overlap and fill in short gaps. At convergence, the length of each spline has tripled. Not shown is the fact that each spline is born with a different "color," and that, as they overlap, the colors equilibrate to a unique value for the entire covering of each global curve. Also, those splines that migrate to positions unsupported by the potential distribution are eliminated at convergence. (a) Initial distribution; (b) and (c) intermediate iterations; (d) final convergence. Physiologically one might think of the spline computations as being supported by localized dendric or dendrodendritic interactions.

not in fine detail; so that (ii) the different possibilities can be represented explicitly and (iii) do not assume that local properties must be computed purely locally. Once the tangent field was in place, the task for the second, global stage could then be posed, and led to the introduction of the mathematical notion of a cover to suggest parallel (and hence at least not biologically implausible) mechanisms for recovering global information.

Finally, we introduced the notion of a potential distribution as the representation for mediating the local to global transition between the two stages.

The paper has also been speculative. Problems in vision are complex, and computational modeling can certainly help in understanding them. But in our view computational modeling cannot proceed without direct constraints from the biology, and modeling — like curve detection — should involve both coarse-grained and finer-grained theories. We attempted to illustrate how such constraints could be abstracted by speculating how our model could map onto physiology. While much clearly remains to be done, the role for curvature at several levels now seems evident. That such roles for curvature would have emerged from more traditional neural network modeling seems doubtful.

Two different styles of computation emerged in the two stages of curve detection. Although we stressed their differences in the paper, in closing we should like to stress their similarities. Both stages enjoy formulations as variational problems, and recognizing the hierarchy of visual processing, we cannot help but postulate that the second, fine stage of curve detection may well be the first, coarse stage of shape description. The fine splines then become the coarse units of shape.

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