Week 4: EARLY VISUAL PATHWAYS

1) Anatomical and physiological techniques
2) Retinal structure and function
3) ON and OFF channels
4) Anatomy and physiology of the early visual pathways

1) Brightness perception: Quantifying percepts
2) Isomorphistic and nonisomorphistic theories
3) Craik-O’Brien-Cornsweet (COCE) effect
4) Retinex algorithm

Visual Neurophysiology, II

1. Anatomy of early visual pathways
2. Physiology of early visual pathways
3. Processing strategies
4. Parting thoughts
5. Your responsibilities

with thanks to Piers Howe for development of some of what follows

EARLY PATHWAYS

The LGN is often said to be a “relay station”.

Arguments for:
1) Position: it connects to the retina and to area V1 (primary visual cortex).
2) It performs relatively simple processing.

Argument against::
Receives feedback from V1; in some species 80-90% of inputs to LGN are extraretinal in origin. Why? Attention??
**INPUT INTO V1**

Projections of *magno* and *parvo* cells of LGN arrive at specific **sublaminas** of V1.

- **Magno:** 4Cα
- **Parvo:** 4Cβ and 4A

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**ORIENTATION COLUMNS**

Cells in a vertical penetration tend to respond to similar orientations.

**OCULAR DOMINANCE COLUMNS**

Input from each eye often remains segregated (at least in input layers).

**HYPERCOLUMN**

A hypercolumn contains all the apparatus needed to process input from a specific retinal location: ocular dominance columns, each with a **complete set of orientation columns** as well as several “**puffs**” (Wong-Wiley) or “**blobs**” (Livingstone & Hubel) (regions of high cytochrome oxidase staining).

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**PINWHEELS**

Pinwheel representation of orientation columns: Note “smooth” variation and vortex singularity. (Scale: 1 X 1 X 2 mm)

... averaging over many cells!
**Figure 34.** Our current model of the modular organization of macaque striate cortex (modified from Hubel and Wiesel, 1977). from Livingstone and Hubel (1984)

**Figure 5.** Orientation preferences of units in a single 5-mm-long penetration in layers 2 and 3 of macaque parafoveal striate cortex. The orientation preference changes in a remarkably regular way, with only two reversals in the entire 5 mm. The rectangles indicate blobs [cytochrome oxidase “puffs”], where there is no orientation preference, and the sequence continues linearly as if the blob were not there.

**Hornton, 1984**

An alternative hypothesis about the relation of orientation tuning “layout” with respect to the location of the blobs.

Note that “pinwheel” centers coincide with blob locations.

**Grinvald et al. 1992/1999**

Using optical recording technique, one sees pinwheel centers displaced from cytochrome oxidase blobs.
BLURRING OF ORIENTATION DATA

Finding the “average” of orientation tuning is tricky.

Note that in the previous panel:

1) Corresponding edges at two adjacent scales may be *shifted* in location.

2) Edges that exist in one scale *may not exist at all* at the next larger scale.

This image stolen from scale space tutorial available at:
http://www.nada.kth.se/~tony/cern-review/cern-html/
Research in Eric Schwartz’s lab indicates that the effective blurring region for averaging orientation tuning in optical recording is on the order of 300 microns.

Reasons include:
1) Photon scatter in cortical tissue.
2) Optics of macroscope lens.
3) Signal-to-noise issues in processing data.

These facts have important implications re: the “reall” location of pinwheel centers w/r/t blobs.

For details: Contact Eric and/or see CN 780 course materials.

2. PHYSIOLOGY OF EARLY VISUAL PATHWAYS

Midget (M) and parasol (P) cells of retina input to parvocellular (P) and magnocellular (M) pathways, respectively!

The pathways are often said* to have qualitatively different functional roles:

P pathway: form, fine stereopsis and color

M pathway: motion and coarse stereopsis

*a hypothesis, not yet proven

Determination of the roles of magno and parvo streams is one of the core issues in visual neuroscience today.

One simple hypothesis is that magno and parvo are really not that different (apart from sensitivity to wavelength), with magno favoring higher temporal frequencies and lower spatial frequencies while parvo can resolve higher spatial frequencies but lower temporal frequencies.

There are conflicting views of both:
1) the degree of differentiation vs. overlap of function, and
2) the degree of anatomical interaction and physiological cross-talk between the pathways.

There is much psychophysics on e.g., “form-motion interactions” that rules out a clean separation of function.

There is some degree of cross-talk at a physiological level, though the “amount” of cross-talk is hard to quantify. Why?!
M AND P PATHWAYS

**Magnocellular pathway**
- Larger receptive fields
- Less responsive to high spatial frequencies
- Wavelength insensitive
- Transient responses to stimuli
- Higher sensitivity to luminance contrast
- Faster response to change

**Parvocellular pathway**
- Smaller receptive fields
- More responsive to high spatial frequencies
- Wavelength sensitive
- Sustained responses to stimuli
- Lower sensitivity to luminance contrast
- Slower response to change

HISTORICAL NOTE

Certain older sources refer to “X” and “Y” cells, rather than to magno and parvo.

X and Y refer to CAT only.
Magno and parvo refer to primate brains.

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>“linear”</td>
<td>“nonlinear”</td>
</tr>
<tr>
<td>medium velocity axons</td>
<td>rapid velocity axons</td>
</tr>
<tr>
<td>sustained response</td>
<td>transient response</td>
</tr>
<tr>
<td>small receptive fields</td>
<td>large receptive fields</td>
</tr>
</tbody>
</table>

Note: While X and Y are superficially similar to magno and parvo characteristics, respectively, there are important differences.

More generally: Any anatomical or physiological feature may be more or less specific to an individual species (e.g., macaque, owl monkey, . . .)

*Moral: Note which species is being referred to!*

COLOR OPPONENCY IN RETINAL GANGLION CELLS

1. Small white spot
2. Small red spot
3. Small green spot
4. Large white spot
5. Large red spot
6. Large green spot

Cf. Hering theory of color perception

**COLOR OPPONENCY IN LGN AND CORTEX**

Single-opponent, double opponent, and broad-band cells:

<table>
<thead>
<tr>
<th>Lateral geniculate neurons</th>
<th>Cortical neurons</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>V2</td>
</tr>
</tbody>
</table>

KSJ3, Fig 31-5

concentric single-opponent
centric broad-band
co-extensive single-opponent

concentric double-opponent
complex double-opponent
RELATIONSHIP BETWEEN OPPONENCY AND ANATOMY IN LGN

Complicated, and varies by species, but in monkey:

- **Parvocellular** (layers 3-6) — mostly color opponent
- **Magnocellular** (layers 1,2) — broad band

Properties were subsequently traced back to retinal cells.

INTERDISCIPLINARY NOMENCLATURE

Bonus question: What is the difference between a cortical **pathway** and a **channel**?

Answer: “pathway” is an **anatomical** term, whereas “channel” is purely a **functional** term.

A psychophysicist might speak of “spatial frequency **channels**,” without making any claims at all about anatomically distinct pathways for processing different spatial frequencies.

The issue of “how many (spatial frequency) channels?” then becomes a question of how many basis functions are needed to span the space of psychophysically measured performance . . . under blah-blah-blah assumptions . . .

However, in practice the terms “pathways” and “channels” (and “streams”) are often used loosely.

BASIC CORTICAL CELL RECEPTIVE FIELDS (V1)

- **Unoriented** — layer 4 or “blob”
- **Simple cell -- oriented**
  - *odd* symmetric*
  - distinct excitatory and inhibitory subregions
- **Simple cell -- oriented**
  - *even* symmetric*
  - distinct excitatory and inhibitory subregions
- **Complex cell -- oriented**
  - no distinct excitatory and inhibitory subregions

* Many, and possibly most, simple cells are neither odd nor even.

ENDSTOPPED CELLS

**Complex** and (even) **“simple”** cells may be **endstopped**. How can you tell?

- **response:**
  - weak
  - moderate
  - strong
  - zero*  

* Perhaps the response is only severely reduced from maximum.
Hubel and Wiesel's original nomenclature referred to a presumed hierarchy of simple, complex, and hypercomplex cells.

The latter are now generally referred to as “end-stopped complex cells.”

Meanwhile, endstopping has been observed in some simple cells.

The interconnected circuitry of the various cell types makes the idea of going “from” simple to complex to hypercomplex suspect.

More Physiology: Receptive Fields

What does the phrase “receptive field” mean? . . . to a neurophysiologist? . . . to neural network modelers?

“Receptive field” is a functional, not an anatomical concept.

“The receptive field of a ganglion cell (or any other cell in the visual pathways) is that area of the retina where stimulation of photoreceptors with light causes either an increase or decrease of the ganglion cell's firing rate.”

[emphasis added] (K, S, & J., 3rd Ed., p. 409*)

Note: Receptive field regions (or “sub-regions”) may be excitatory or inhibitory.

Q: How can an inhibitory receptive field region be measured?

A1: With difficulty, if a cell’s spontaneous firing rate is low.

A2: With more difficulty, if the inhibition is “silent” i.e., purely shunting, whereby no hyperpolarization occurs, and there must be excitatory input provided in order for the inhibition to be “noticed” by the experimenter.

*Note: This definition is absent in the 4th edition! Why??!
**RECEPTIVE FIELD ATTRIBUTES**

In practice, we speak of attributes of a receptive field, not just its location in retinal coordinates. E.g., What about a RF’s center-surround organization? contrast sensitivity? orientational tuning? directional selectivity? etc.

**Contextual modulation** of RF attributes: E.g. “disappearance” of OFF-surround of ganglion cells at low light levels.

**Temporal characteristics:**
- a) sensitivity to flicker rate, speed, etc.
- b) rate of adaptation (to contrast, motion, etc.)
- c) dynamics of tuning to dimensions of sensitivity (e.g. orientation, motion direction, etc.)

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**SPACE-TIME RECEPTIVE FIELDS, I**

“Traditionally, the receptive field of a neuron is defined as the area of visual field within which visual stimulation influences neural responses. This classical notion no longer provides an adequate framework for understanding visual receptive fields. We must consider an additional dimension of time, and define receptive fields in the joint domain of space and time. For many cells in the visual cortex, there is no such thing as a unique spatial receptive field.” [emphasis added] [Izumi Ohzawa]

Go to Ohzawa’s excellent site:

Space-Time Receptive Fields of Visual Neurons

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**SPACE-TIME RECEPTIVE FIELDS, II**

**LGN cell:** “ON-center, OFF-surround” (?)

Demos on this page downloaded from: [http://www.bpe.es.osaka-u.ac.jp/ohzawa-lab/teaching/AA_RFtutorial.html](http://www.bpe.es.osaka-u.ac.jp/ohzawa-lab/teaching/AA_RFtutorial.html)

Go there to learn about the reverse correlation technique.
NONCLASSICAL RECEPTIVE FIELDS

More on contextual modulation --
Identified RF attributes grow in complexity each year.
E.g., Cells of MST have been called
"differential geometers:" “Center-surround” for
radial expansion and contraction.

Also, cells exist that fire vigorously
whenever a contrastive pattern moves
horizontally to the right within a relatively
clearly defined circular region, and that will
not respond to movement in any direction
anywhere else within the visual field.

But motion of the entire visual field horizontally
to the right can null the response of the cell,
even though the preferred
pattern motion occurs within its
“classical receptive field.”

FOOD FOR MENTAL INDIGESTION

The idea of “nonclassical receptive fields” is a bit tricky.

Do some cells have classical receptive fields, while others
have nonclassical receptive fields?

Or . . .

Are all cells that used to be thought of as having classical
receptive fields now thought of as also having nonclassical
receptive fields?

Or

Is there just one unified way that we should think about
receptive fields, which is a “nonclassical” way, compared
to how we used to think?

RECEPTIVE FIELD SELECTIVITY

Barlow (1953) (rabbit) found cells that respond to small but not
large stimuli; he devised the concept of “trigger feature.”

Lettvin, Maturana, McCulloch & Pitts (1959) “What the frog’s
eye tells the frog’s brain.” discovered four classes of cells in
frog’s retina (classified by function and morphology.)

Boundary detectors
Movement-gated-dark-convex-boundary (i.e., ____ detectors.)
Moving or changing contrast detectors
Dimming detectors

Lettvin was “laughed off the stage” (Schiller, 1986).

3. PROCESSING STRATEGIES

Processing strategies for which physiological evidence exists:

- **Topography** (retinotopic maps)
- **Space-variant processing** (cortical magnification factor)
- **Hierarchy** -- and “heterarchy”
- **Laminae** (layers) (functional significance?)
- **Feedback** -- within and between laminae and across
cortical areas (time scales?)
- **Parallelism** (“branching” and “massive”)
- **Columns** and hypercolumns
- **Opponency** (and opponent channels)
- **Multiple scales** (channels) for spatial frequency tuning

Open question: How does the brain utilize these different strategies? Why are these different strategies needed?
4. PARTING THOUGHTS

1) Utility of data:
Q: Given the complexity of the visual system only through LGN (tip of iceberg), how can psychophysical data be related to cell physiology?

2) What are valid degrees of abstraction for neural modeling?
McCulloch-Pitts neuron? Integrate and fire neurons? Dendritic level (e.g. Genesis)? Field theory for maps? Waves of activation (e.g. fMRI)?
A combination of the above?

3) Uncertainty: Same response:
E.g. low amplitude, centered vs. high amplitude, displaced stimulus
Note: Uncertainty is an issue cells’ selectivities for orientation, scale, direction of motion, etc., as we shall see.

STILL MORE PARTING THOUGHTS

4) Sensitivity: What does it mean for a cell to be sensitive to some input dimension (e.g. contrast, wavelength, orientation, direction, speed)?
a) Weaker form: (Too weak?) Change along that dimension of stimulation sometimes changes response.
b) Stronger form: Under appropriate controls, monotonic (stronger still: linear) relation of response magnitude with stimulus variation can be shown for some range.

Functional significance? Even though a cell’s response varies systematically with, e.g., stimulus speed, that does not necessarily mean that the cell’s function is to signal speed. There may be factors of spatial or temporal frequency that affect the cells response to, e.g., stimulus onset, and that happen to covary with stimulus speed.

5. YOUR RESPONSIBILITIES

There will not be another anatomical/physiological lecture in CN530, though physiological data will be addressed in many places in upcoming lectures.

You are responsible for covering physiological material from required readings at a level of detail exemplified in this lecture.

Pay particular attention to material on:
general function of major processing areas (e.g. LGN, V1, V2, V4.)
motion-sensitive cells
binocularly tuned cells
anatomical and physiological evidence for functional pathways (e.g. form, motion, color pathways etc).
The festival was over, the boys were all plannin' for a fall,
The cabaret was quiet except for the drillin' in the wall.
The curfew had been lifted and the gamblin' wheel shut down,
*Anyone with any sense had already left town*.
He was standin' in the doorway lookin' like the Jack of Hearts.

*Lily, Rosemary, and the Jack of Hearts*


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BRIGHTNESS* PERCEPTION

1) Brightness perception: Quantifying percepts
2) Isomorphistic and nonisomorphistic theories
3) Craik-O'Brien-Cornsweet (COCE) effect
4) Retinex algorithm

Next week:

5) Brightness assimilation

6) Grossberg and Todorović *(T)* implementation of BCS/FCS

**NOTE:** It would be a good idea to “skim” *G & T* ‘88 before next week’s lecture!

*We will also be talking about LIGHTNESS PERCEPTION.

First, spend some time at interactive lightness demos at:
[http://www-bcs.mit.edu/people/adelson/illusions_demos.html](http://www-bcs.mit.edu/people/adelson/illusions_demos.html)

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THE PLAN

1) *T* (1987) meta-analysis of models of brightness perception, especially with regard to *motivation* for “filling-in”

2) Cornsweet's analysis of the Craik-O'Brien-Cornsweet Effect

3) Land's *Retinex* theory
   - early form: more “computationally intuitive”
   - later form: more “biologically plausible”

**Note:** We will be considering the “achromatic” analog of Land’s (chromatic) *Retinex* theory.

4) Background for *G & T* (1988) simulations

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Even a few moments at [www.tedadelson.org](http://www.tedadelson.org) should convince you that there is a tremendous amount of complexity in the domain of brightness and lightness perception.

To date, no model has given a comprehensive account of all known perceptual effects.

We will focus initially on models that do a reasonable job on a subset of known effects, conceding limits on scope from the outset.

Later, we will briefly describe some promising paths for extension of models.
MODELS OF BRIGHTNESS PERCEPTION
(After T, 1987)

Styles of theories:
- Nonisomorphistic
- Cognitive
- Mechanistic (Filling-in and “Integration” theories)

Goal: To describe magnitude, \( M \), of brightness sensation as a function of luminance, \( L \): \( M = f(L) \)

What about \( f(\ ) \)? Is it . . . linear, . . . a power function, . . . logarithmic? . . . (at least!) monotone?

The previous panel sidesteps a major issue:

What is the spatial layout of the region whose brightness magnitude we are to judge with respect to its surrounding regions?

As we will later see, everything affects this judgment:

Whether there is one surrounding region or many . . .

Whether the region to be judged has the highest or lowest luminance, or some intermediate luminance . . .

The “figure-ground” relationships in the scene . . .

Slant in depth, corners in depth, curvature in depth . . .

For now, we will consider only the simplest spatial arrangements.

Note: There is much confusion about the nature and even the number of dimensions of achromatic color experience:

Brightness -- dim to bright vs. Lightness -- black to white

Can one have a “dim” white? . . . a “bright” black?

Katz (1935) also includes “pronouncedness” and “insistence” as dimensions of achromatic color, specifically to get at distinctions such as “white surface in bright light” vs. “white surface in dim light.”

WOULDN’T IT BE NICE?

Desired simplicity:

Perceived magnitude is always some function of luminance.

E.g. power law: \( M = kL^n \) is often found when an observer is asked to report the subjective magnitude (e.g. brightness) associated with a test region, relative to some constant background (“magnitude estimation”).
**BUT, HANG ON . . .**

Compare last panel to Weber/Fechner paradigm for **just noticeable differences** (JNDS), where *luminance* of a “target region” *and the background covary*, yielding a logarithmic law, e.g. \( M = k \log(L) \).

In any case, we still desire, for some \( f \), \( M = f(L) \).

Is inverse of \( f \) well-defined? For that matter, is \( f \) well-defined?

**TROUBLE AHEAD, TROUBLE BEHIND**

1) **Many** values of \( L \) can map to **one** value of \( M \).
   (Consider “brightness constancy!”)

2) **One** value of \( L \) can map to **many** values of \( M \), as in Craik--O'Brien--Cornsweet Effect.

Bottom line: Power and log laws only work for (simple situations, such as s) **target on a homogeneous background**; to explain more requires tasting the fruit of the tree of knowledge.

**UNFULFILLED DESIRE: BACKGROUND EFFECTS**

In other words,

1) you are trying to find a function that relates the **magnitude of a visual stimulus** in some region (luminance, given by the *height of the six central plateaus in the above plots*) to the **magnitude of some internal sensation**.

2) The answer you get depends on the way you set up the backgrounds, as well as on the magnitude of the “stimulus,” in the sense that the shape of the resulting response function differs.

**SAME \( L \), DIFFERENT \( M \)**

All the diamonds in the same row as the one marked “1” have the same luminance as all the ones in the row marked “2”. (!)

Figure source:
Logvinenko A D, 1999 "Lightness induction revisited" *Perception* 28 803–816
long-range interactions in what we see in a region.

After Todorović, 1987

Consider COCE:

Nonisomorphistic account (e.g. Cornsweet):
Illusion is based on attenuation of low spatial frequency information -- cf. MTF.

Square wave is “composed” of sine waves at many spatial frequencies, and we are not very sensitive to the low spatial frequency components.

So: a luminance step and a luminance cusp are (nearly) functionally equivalent. (Cf. Cornsweet, p 346, Arend & Goldstein, p 67.)

Bonus question: What would be a good direct test of this idea?

Nonisomorphistic account:
Through early visual processing:
  square wave: luminance step goes to neural cusp
  COCE: luminance cusp also goes to neural cusp. Q.E.D.

Note: The transformation of C’s account on the previous panel -- attenuation of low spatial frequencies -- can also be phrased in terms of the “natural” result of center-surround processing.

Proponents of isomorphistic account argue that we also need an explanation for why any neural cusp looks like a brightness step.
**A HIGHER STANDARD**

Todorović  
Don’t just ask “why they look alike,” but also “what they look like!”

<table>
<thead>
<tr>
<th>Nonisomorphistic:</th>
<th>Isomorphistic:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus:</td>
<td></td>
</tr>
<tr>
<td>Neural (early):</td>
<td></td>
</tr>
<tr>
<td>“Bridge locus” (neural):</td>
<td></td>
</tr>
<tr>
<td>Percept:</td>
<td></td>
</tr>
</tbody>
</table>

Note: Equal parts of “early” representation yield unequal parts of percept. . . HOW?

**GREAT MINDS THINK ALIKE**

T (1987) shows that the configuration of luminance discontinuities (“edges”) can have profound effects on brightness, even in places distant from the cusp.

CLAIM: Both the step edges (“s”) and the cusp (“c”) are implicated in experiencing the COCE in the above configuration.

NOTE: Cornsweet’s account only deals with the cusp.

Resulting conclusions:
1) A filling-in process is needed (to turn cusp into a step.)
2) Boundaries are needed to contain filling-in. (Sound familiar?)

**PSYCHOPHYSICS IN THE FIRST CENTURY B.C.**

Note that the spinning disk apparatus -- the standard means of generating smoothly varying luminance profiles before the computer-controlled CRT -- guarantees that a closed region bounded entirely by a luminance cusp is generated!

(from Cornsweet, 1970, p 273)

Compare to the T (1987) configuration of COCE.

**THE THIRD DIMENSION**


See Dan Kersten’s web demos
RETIEX THEORY, I

Recall the proposed strategy for “discounting the illuminant:”

First recover relative reflectances (ratios) near rapid (i.e., discontinuous) changes in image intensity,

then reconstruct perceived color values in region interiors.

LAND! LAND!

Besides the experiments with Mondrians, Land (1977) describes:

1) Take a “black and white” slide of a natural scene.
2) Take another slide of the same scene on (the same type of) monochromatic film, but insert a filter that admits only red (long wave) light in front of the camera lens.
3) Project both slides on a screen, superimposed, and in registration, but use “normal” (white) light to project the first slide and long wave light only to project the second slide.

Paradoxical result: Many (veridical) colors (green, blue, yellow, orange*, etc.) besides red can be perceived.

Such demonstrations formed foundations of Retinex premises.

*The Stroop effect strikes again!

RETIEX PROPOSITIONS

“In summary the three propositions of Retinex Theory [not to be confused with the early Retinex algorithm] are:

I. The composition of the light from an area in an image does not specify the color of that area.

II. The color of a unit area is determined by a trio of numbers each computed on a single waveband to give for that waveband the relationship between the unit area and the rest of the unit areas in the scene.

III. The trio of numbers, the three $R^s$, as computed by the Retinex algorithm, are the designators for the point in Retinex three-space which is the color of the unit area.” (from Land, 1977)

RETIEX ALGORITHM

Summary of Retinex algorithm (older or “early”) version) from Land, 1986a:

The relationship of $i$ to $j$:

$$R^\lambda(i, j) = \sum_k \delta \log \frac{I_{k+1}}{I_k}$$

Note multiple paths
RETINEX EXAMPLE 1
While Retinex was conceived in the chromatic domain, the achromatic Retinex algorithm is an obvious “generalization.”

Here Land describes a "running product" of those ratios sufficiently different from 1 -- product instead of sum, because the log transform was skipped.

DISCOUNTING THE ILLUMINANT A LA RETINEX
Example with shallow gradient of illumination:

NOTE: Retinex -- and many other models -- assume that changes in image intensity owing to illumination effects are more gradual than changes owing to physical reflectances.

SOURCES OF VARIATION IN IMAGE INTENSITY
Simple computer graphics algorithms for rendering typically compute dot products of vectors normal to a surface patches with others pointing to the viewpoint or light source.

Results are weighted by parameters that express the characteristics of reflectance (diffuse, specular, wavelength. . .) of a surface being modeled.

Still difficult to model: effects of rough surface interfections and cast shadows; the latter require qualitatively different algorithms (e.g. ray tracing, radiosity, . . .)

Question: Look around you on a sunny day. Are the outlines of cast shadows qualitatively fuzzier than the outlines of objects?
**HOW PLAUSIBLE?**

Although Land (1977) describes the scanning algorithm as “physiologically plausible” (!), he later described a “more biologically plausible,” version of the Retinex algorithm, in which the “designators” are computed by simple filtering with kernels having

- very narrow ON centers, and
- very very broad OFF surrounds. (Land, 1986b)

**Integration Theories**

Retinex is one example, indeed the archetypal example, of an **Integration Theory**.

Integration theories are one class of “filling-in” theories.

Another “filling-in” theory is BCS-FCS, with boundary-gated diffusion.

Objections have been raised to the diffusion mechanism, and alternatives proposed, as we shall see . . .

**HOMOPHOBIA**

While the computational “core” of the (early, especially) Retinex algorithm is somewhat obscure, it can be viewed as a special case of **homomorphic filtering**.* (Oppenheim, 1967; see Ch. 12 of A.V. Oppenheim and R. W. Schafer, Discrete-time signal processing. Englewood Cliffs, NJ: Prentice Hall, 1989.)

The Retinex “recipe” can be viewed as:

1) **Filter** the image at many scales (e.g. Fourier analysis)
2) “**Throw out**” the outputs of all the large filters (“slow-varying” spatial components)
3) **Deconvolve** the remaining components (e.g. Fourier synthesis)

* With thanks to Mike Cohen.

*Note similarity to Cornsweet’s argument re: COCE!