6. Perception

Outline

A. Biology of Perception
B. Primary Visual Cortex
C. Object Recognition and "What" Pathway
D. Attention and "How" Pathway

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A. Biology of Perception

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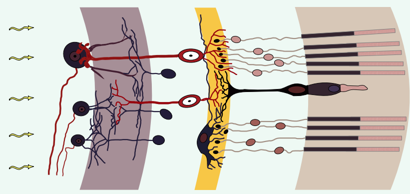
Retinal Layers



From right:
(1) rods and cones (tan),
(2) bipolar and horizontal cells (yellow),
(3) amacrine and retinal ganglion cells (purple)

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Retinal Cells

- Retina is CNS tissue
- Nonuniform distribution of cells
  - rods in periphery specialized for sensitivity and motion
  - cones in macula/fovea specialized for color & form (acuity)
  - humans are *foveating* animals
- Information compression:
  - 120 million rods (low light)
    - huge convergence of rods on bipolars ⇒ sensitivity
  - 6 million cones (color and high acuity)
  - 1 million RGC (retinal ganglion cells)
    - estimated to transmit 10^9 bits/sec
    - spontaneously active; information conveyed by change in rate

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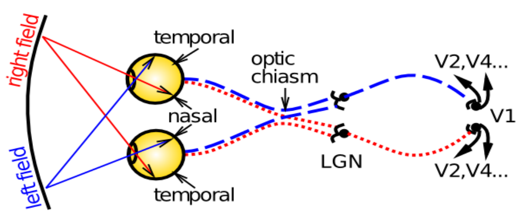
Optic Pathway



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Key Organizing Principles

- Transduction of different information
  - — wavelength (rods; blue, green, red cones)
  - — spatial frequency (resolution)
  - — motion
- Topographic organization
  - — contrasting similar information
- Filtering to extract relevant information

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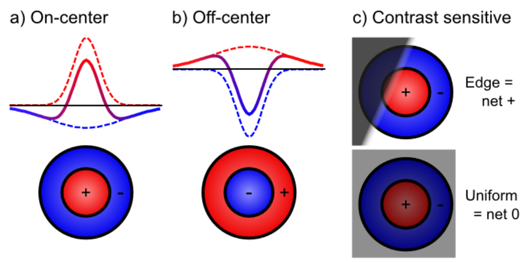
Retinal Contrast Filtering



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LGN of the Thalamus

- A "relay station," but also much more
- Organizes different types of information into different layers with aligned retinotopic maps
- Performs dynamic processing: magnocellular motion processing cells, attentional processing
- On- and off-center information from retina is preserved in LGN

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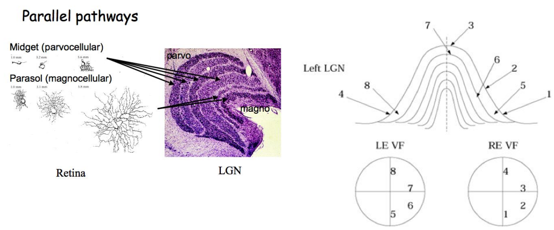
(slide based on Frank)

Structure of LGN



- Cells have monocular input
- Six layers alternate input from two eyes (RGC)

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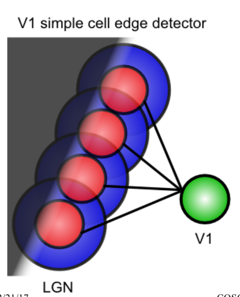
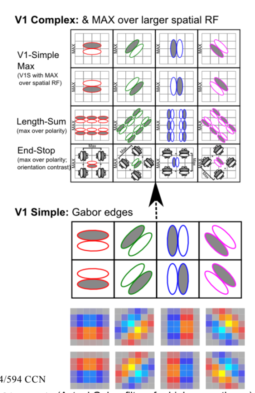
(figs < Heeger)

V1





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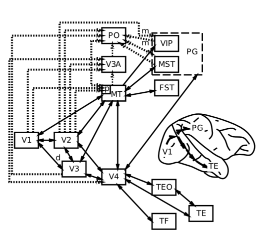
(slide < O'Reilly) (Actual Gabor filters for high-res pathway)

"What" vs. "Where" Pathways



- "What" ignores differences in location, illumination, size, rotation
- "Where" emphasizes location, size, and ignores object identity

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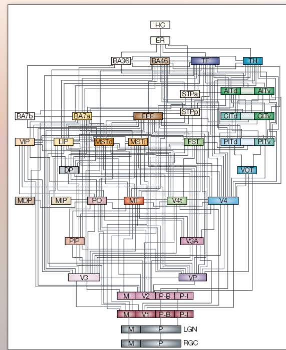
Hierarchy of Macaque Visual Areas



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(fig. from Van Essen & al. 1992)

Principal Regions in "What" Pathway

- V1: Primary Visual Cortex
  - — encodes image in terms of oriented edges
- V2: Secondary Visual Cortex
  - — encodes in terms of intersections & junctions
- V4
  - — more complex features over wider range of locations
- PIT: Posterior Inferotemporal (IT) Cortex
  - — location & size invariant object recognition
  - — includes FFA (fusiform face area)
- AIT: Anterior IT Cortex
  - — abstract/semantic visual information

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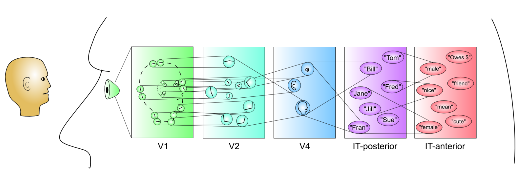
Hierarchy of Visual Detectors



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B. Primary Visual Cortex

What is the origin of detectors for oriented bars of light?

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Self-Organization of V1 Orientation Selective Neurons

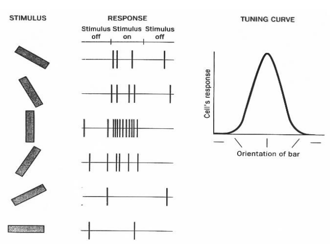

FIGURE 4.8 Response of a single cortical cell to bars presented at various orientations.

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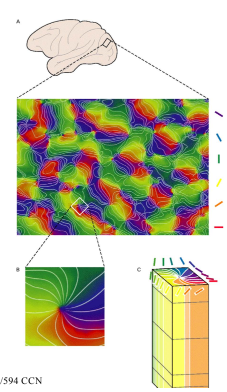
Topographic Maps

- Map of orientations
- Hypercolumn: Full set of coding for each position
- Pinwheel can arise from learning and lateral connectivity: not hard-wired!



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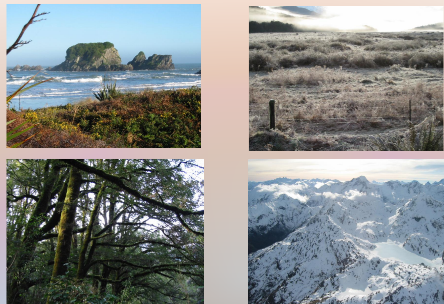
What is Common?



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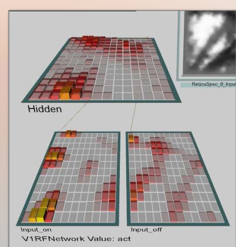
V1Rf: Simulating One Hypercolumn

- Natural visual scenes are preprocessed by passing them (separately) through layers of on-center and off-center inputs
- Hidden layer: edge detectors seen in layers 2/3 of V1; Layer 4 (input) just represents unoriented on/off inputs like LGN (but can be modulated by attention)
- Circular neighborhood of lateral excitatory connectivity in Hidden layer



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emergent demonstration: V1Rf

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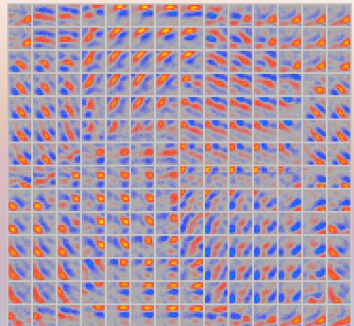
Self-Organized Topography



Model shows how documented V1 properties can result from interactions between learning, architecture (connectivity), and structure of environment

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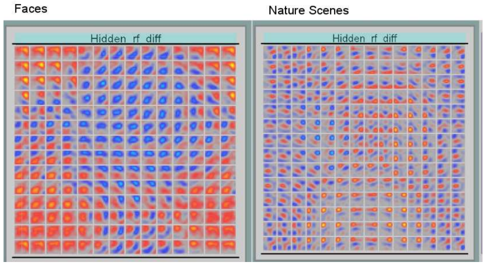
(slide < O'Reilly)

Faces vs. Natural Scenes



Some differences, but pinwheels still emerge

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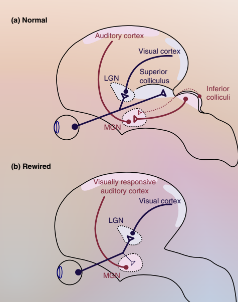
(slide < Frank)

Rewiring Cortex

- Experiments by Mriganka Sur & colleagues (MIT)
- What happens if retinal axons are redirected into auditory thalamus (MGN) instead of its usual inputs?
- Answer: Auditory cortex (A1) develops orientation columns and retinotopic maps similar to V1
- Animals experience activity in A1 as visual perception



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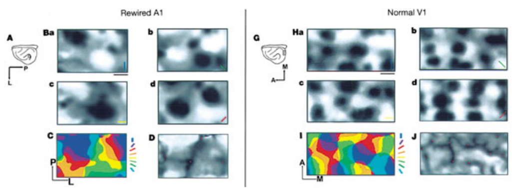
Orientation Columns in A1



Orientation columns develop in A1 similar to those in V1

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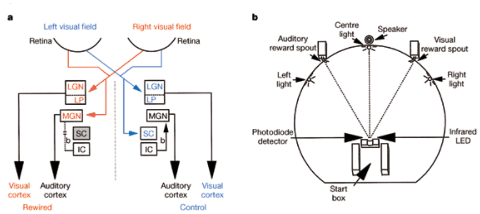
Are They Having Visual Experiences?



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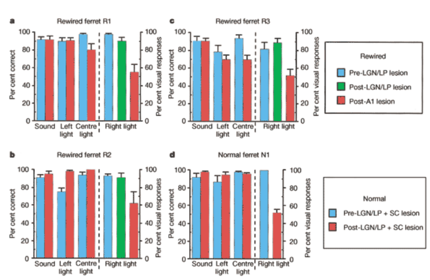
They Are Having Visual Experiences



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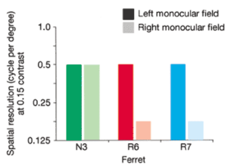
Visual Acuity



- There is less visual acuity in the rewired pathway
- Suggests there may be intrinsic factors in organization of auditory cortex as well as extrinsic factors

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C. Object Recognition and "What" Pathway

How do we recognize objects (across locations, sizes, rotations with wildly different retinal images)?

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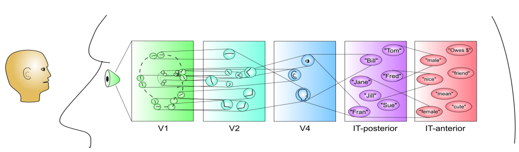
Invariant Object Recognition



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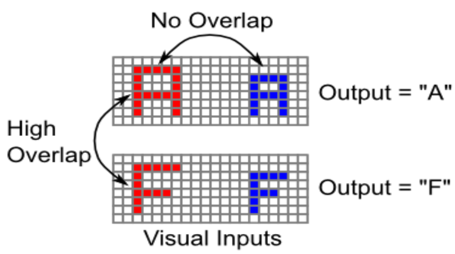
It's Hard



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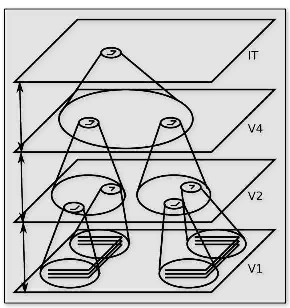
Invariant Object Recognition



- Hierarchy of increasing:
  - Feature complexity
  - Spatial invariance
- Increasing RF size:
  - Conjunction of features (to form more complex objects)
  - Collapsing over location information ("spatial invariance")
- Strong match to RF's in corresponding brain areas

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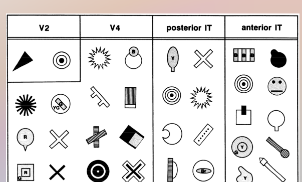
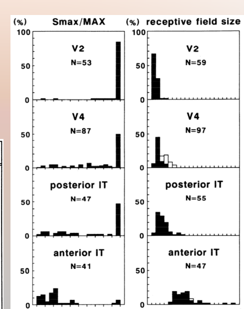
(slide based on O'Reilly & Frank)

Biological Data: Increasing Complexity and Invariance





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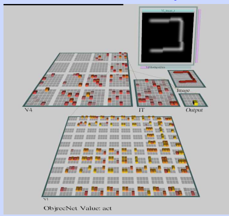
The Model: combining Fukushima with convolutional neural nets, bidirectional connectivity and learning!



V1 = oriented line (edge) detectors, hard-coded
V4 units encode conjunctions of V1 edges across a subset of space
Each IT unit pays attention to all of V4

(V2 omitted here, important for figure-ground etc)

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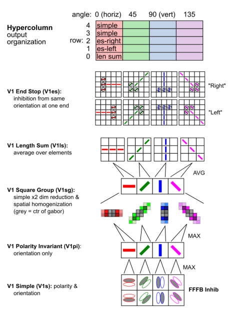
(slide < Frank)

V1 Receptive Fields

- 4×5 hypercolumns
- Two rows of simple cells at 4 orientations and two polarities
- Two rows of end-stop complex cells
- One row of length-sum complex cells
- 50% overlap with adjacent hypercolumns



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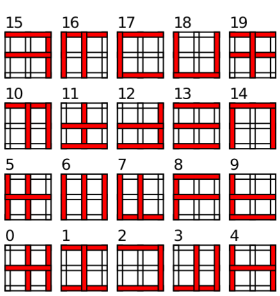
Simple Textbook Test



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Activation-Based Receptive Fields

- How do we plot receptive fields for V4?
- Receiving weights show which V1 units a V4 unit responds to, but they don't show what thing in the world the unit responds to
- <u>Solution</u>: Show the network lots of input patterns.
- Then, display a composite of all the input patterns that activate the unit (weighted by activity).

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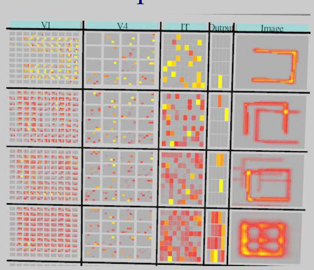
(slide < Frank)

V4 Receptive Fields



- Some V4 units code for location-specific conjunctions of V1 features
- This will show up as a sharp receptive field for Image input

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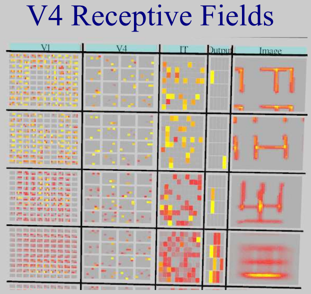
(slide < Frank)

V4 Receptive Fields



- Some V4 units code for simple features in a location invariant way
- This will show up as smeary parallel lines in Image input

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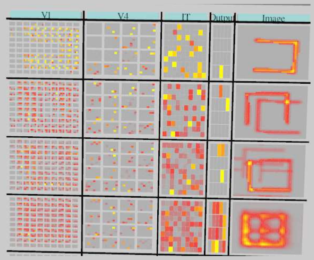
(slide < Frank)

V4 Receptive Fields



- Can also look at which Output units tend to get active for any given V4 unit
- Generally a given V4 unit is associated with multiple objects

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(slide < Frank)

3D Object Recognition Test

3D models from Google SketchUp

100 categories

9–10 objects per category

2 objects left out for testing

+/– 20° horiz depth rotation + 180° flip

0–30° vertical depth rotation

14° 2D planar rotations

25% scaling

30% planar translations

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http://grey.colorado.edu/CompCogNeuro/index.php/CU3D (slide < O'Reilly)

Depth & Lighting Variations for One Object

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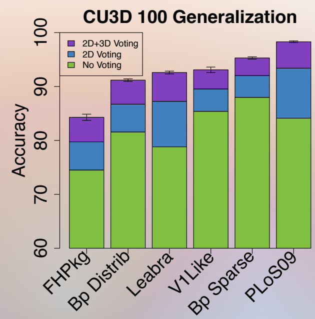
Generalization to Novel Category Exemplars – Better than 90%



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emergent demonstration: Objrec

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D. Attention and "How" Pathway

Why is visual system split into what/where pathways?

Why does parietal damage cause attention problems (neglect)?

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Some Functions of Dorsal Pathway

- "Where" pathway (spatial relations)
  - visual attention (this chapter)
- But more broadly "how" pathway
  - maps perception to action (next chapter)
- Numerical and mathematical processing
- Representation of abstract relationships
- Modulation of episodic memory
- Aspects of executive control

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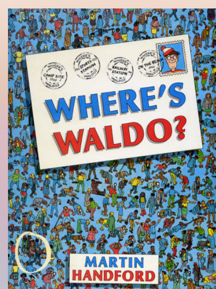
Spatial Attention and Neglect



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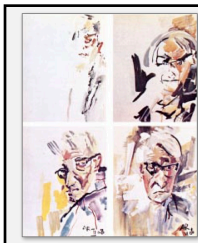
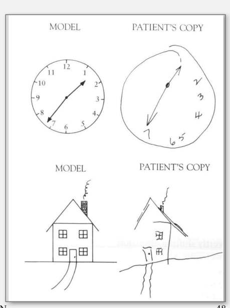
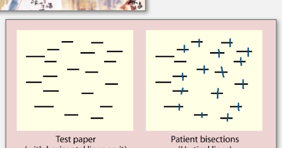
Hemispatial Neglect



Mainly from injuries to right parietal cortex





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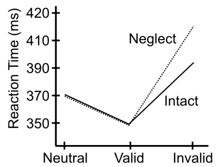
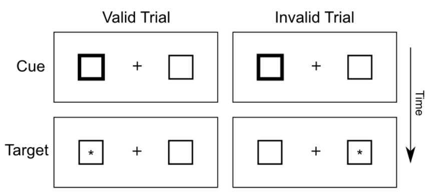
Posner Task

- Valid cues speed performance (relative to “no cue” condition)
- Invalid cues slow performance (relative to “no cue” condition)





- Patients perform normally in the “neutral” (no cue) condition, regardless of where the target is presented
- Patients benefit just as much as controls from valid cues
- Patients are hurt more than controls by invalid cues

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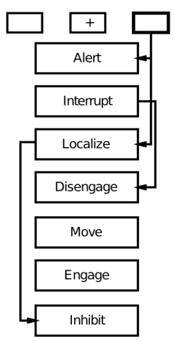
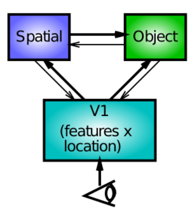
Models: Boxology vs. Biology





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Posner Task Simulation

- Model explains the basic finding that valid cues speed target processing, while invalid cues hurt
- Also explains finding that patients with small unilateral parietal lesions benefit normally from valid cues in ipsilateral field but are disproportionately hurt by invalid cues
- No need to posit “disengage” module
- Also explains finding of **neglect** of contralateral visual field after large, unilateral parietal lesions when some stimulus is present in ipsilateral field (“extinction”)

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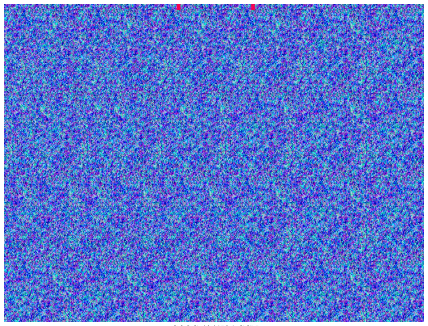
(slide < Frank)

What's Missing? Lacking Depth..



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Supplementary

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Gabor Uncertainty Principle and Gabor Elementary Functions

MacLennan, B. J. *Gabor Representations of Spatiotemporal Visual Images*. University of Tennessee, Knoxville, Computer Science Department technical report CS-91-144, September 1991

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Dennis Gabor

- Dennis Gabor (1900–79) is the father of holography (1947, 1971 Nobel Prize in Physics)
- "the future cannot be predicted, but futures can be invented"
- Developed a theory of information (1946) complementary to Shannon's theory
- Gabor Uncertainty Principle based on same mathematics as derivation of Heisenberg Uncertainty Principle
- Nearly optimal Gabor representations are used in primary visual cortex

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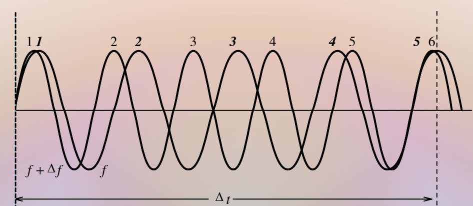
Time to Detect Difference in Frequency



$$\Delta f \, \Delta t \geq 1$$

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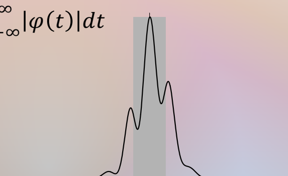
A Little More Formally…

- **Nominal duration** (Δt) = duration of rectangular pulse with same area as signal and height equal to amplitude at origin
- Hence, $\Delta t|\varphi(0)| = \int_{-\infty}^{\infty} |\varphi(t)| dt$
- Some details omitted



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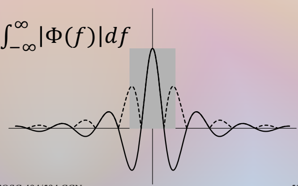
A Little More Formally (2)

- **Nominal bandwidth** (Δf) of spectrum = width of rectangular pulse with height equal to spectrum's amplitude at origin and same area as absolute value of spectrum
- Hence, $\Delta f\,|\Phi(0)| = \int_{-\infty}^{\infty} |\Phi(f)|\,df$



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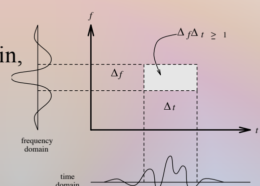
A Little More Formally (3)

- Computing the Fourier transform at origin, $|\Phi(0)| \leq \Delta t\,|\varphi(0)|$
- So $\Delta t \geq |\Phi(0)|/|\varphi(0)|$
- Computing the inverse Fourier transform at origin, $|\varphi(0)| \leq \Delta f\,|\Phi(0)|$
- So $\Delta f \geq |\varphi(0)|/|\Phi(0)|$
- Hence, $\Delta f\,\Delta t \geq 1$



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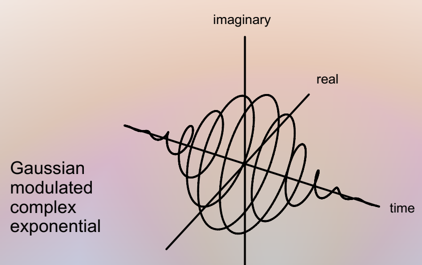
1D Gabor Elementary Function



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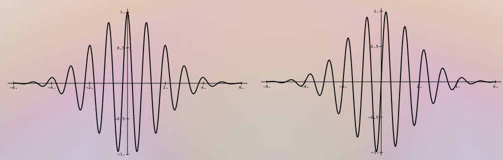
Orthogonal Components of 1D Gabor

Cosine (real) **Sine (imaginary)**



$$e^{ift} = \cos ft + i \sin ft$$

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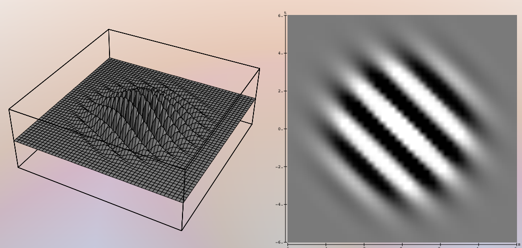
Real Part of 2D Gabor Elem. Function



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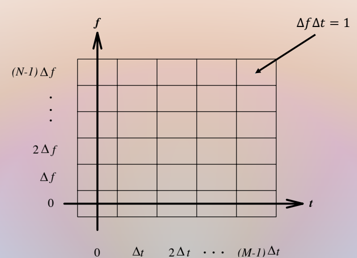
Maximum Logon Content of Signal



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Maximum Logon Content

- If $T = M\Delta t$ is the duration and $F = N\Delta f$ is the bandwidth
- The maximum number of logons *MN* is achieved when $\Delta t \Delta f = 1$ (i.e., Gabor elementary functions)
- In general, the area doesn't have to be divided into rectangles of the same shape, so long as area is 1
- So the maximum logon content is *TF* (duration times bandwidth)
- Any such signal can be represented uniquely as a sum of *TF* Gabor elementary functions

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Gabor Representations

- Any "finite energy" function ψ of finite duration *D* and finite bandwidth *F* is equal to a linear superposition of Gabor elementary functions:

$$\psi(t) = \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} a_{jk} C_{jk}(t) + b_{jk} S_{jk}(t)$$

where $C_{jk}(t) = e^{-\pi(t-j\Delta t)^2/\alpha^2} \cos[2\pi k \Delta f (t - j\Delta t)]$

and $S_{jk}(t) = e^{-\pi(t-j\Delta t)^2/\alpha^2} \sin[2\pi k \Delta f (t - j\Delta t)]$

- The same applies in higher dimensions.

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Gabor Filters in Early Vision

- Measurements of receptive fields of simple cells in cat visual cortex have show them to be like Gaussian-modulated sinusoids (Jones & Palmer, 1987)
- Daugman (1984, 1985, 1993) showed 97% of them are statistically indistinguishable from the odd- or even-symmetric parts of a 2D Gabor elementary function
- Adjacent simple cells have grating patches that are 90° out of phase, but matched in preferred orientation and frequency
- And more… (MacLennan, 1991)

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