Embodied Models
of Language Learning and Use

(A Neural Theory of Language primer)

Srini Narayanan and Nancy Chang
{snarayan,nchang}@icsi.berkeley.edu
UC Berkeley / International Computer Science Institute

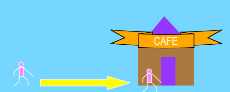
Course Overview

- **Session 1: Foundations of embodied language**
  - Introduction to NTL: language, neural computation
- **Session 2: Embodied representations**
  - Modeling actions and perception
  - Simulative inference
- **Session 3: Language understanding**
  - Construction Grammar
  - Metaphor, aspect, perspective
- **Session 4: Grammar learning**
  - Modeling child language acquisition

What does language do?

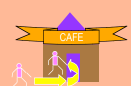
A sentence can evoke an imagined **scene** and resulting **inferences**:

"Harry walked to the cafe."



- Goal of action = **at** cafe
- Source = **away** from cafe
- cafe = **point-like** location

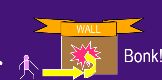
"Harry walked into the cafe."



- Goal of action = **inside** cafe
- Source = **outside** cafe
- cafe = **containing** location

Embodied inferences

The scientist walked into the wall.



The hobo drifted into the house.

The smoke drifted into the house.

Disembodied models

Computation is assumed to be largely independent of the structure and the mode of development of the nervous system, just as a piece of computer software can run on different machines with different architectures.

What's missing?

Embodied knowledge needed

- What things can serve as containers?
  - rooms but not walls (usually)
- How do different entities interact?
  - how people and gases interact with houses.
- How are different actions/states related?
  - stumbling / walking, falling / containment
- How can actions vary?
  - rate, direction, degree of force, etc.

… that is, more than predicate-argument structure!
WALK(*x*), FALL(*y*), HIT(*x,y*), etc.

Theories of Language: goals

1. **Theory of Language Structure**
   defining structural properties of natural languages
2. **Theory of Language Acquisition**
   how children acquire their native language
3. **Theory of Language Use**
   how linguistic and nonlinguistic knowledge interact in comprehension and production

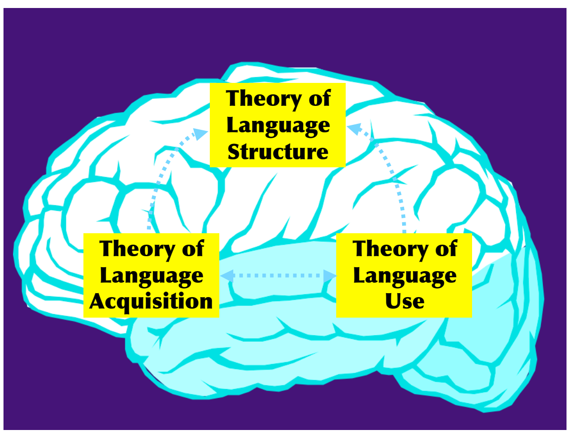
(Chomsky 1972)

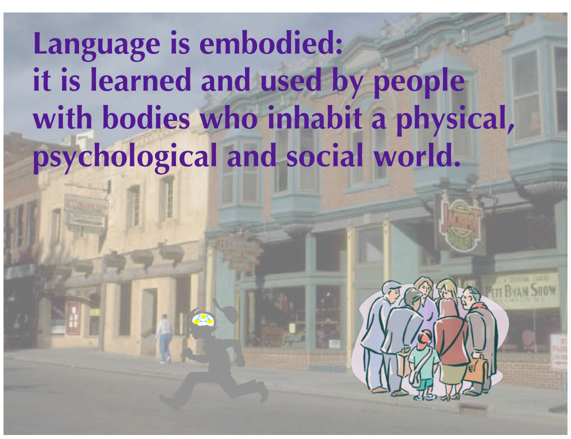
Theory of Language Structure

Theory of Language Acquisition

Theory of Language Use

Goal: computationally precise theories of language





The ICSI/Berkeley Neural Theory of Language Project

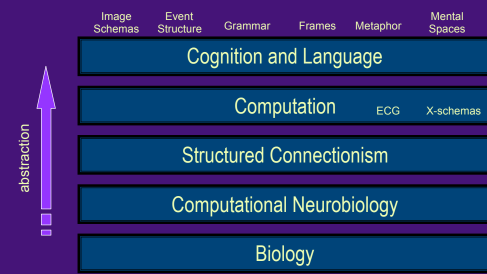
- **Principal investigators**
  - Jerome Feldman (UCB CS)
  - George Lakoff (UCB Ling)
  - Srini Narayanan (ICSI)
  - Lokendra Shastri (ICSI)
- **Affiliated faculty**
  - Chuck Fillmore (UCB Ling)
  - Eve Sweetser (UCB Ling)
  - Dan Slobin (UCB Psych)
- **Post-doctoral researcher**
  - Lisa Aziz-Zadeh (ICSI)
- **Graduate Students**
  - Johno Bryant (CS)
  - Nancy Chang (CS)
  - Ellen Dodge (Ling)
  - Joseph Makin (CS)
  - Eva Mok (CS)
  - Shweta Narayan (Ling)
  - Steve Sinha (CS)
- **Alumni**
  - Terry Regier (U. Chicago Psych)
  - David Bailey (Google)
  - Andreas Stolcke (ICSI, SRI)
  - Dan Jurafsky (Stanford Ling)
  - Benjamin Bergen (U. Hawaii Ling)
  - Carter Wendelken (UCB)
  - Olya Gurevich (Ling)

Language, Learning and Neural Modeling

http://www.icsi.berkeley.edu/NTL

- Scientific Goal
  Understand how people learn and use language
- Practical Goal
  Build systems that analyze and produce language
- Approach
  Embodied linguistic theories +
  biologically motivated computational methods

5 levels of the Neural Theory of Language



Lecture outline

1. Introduction to NTL
2. Cognition and language
   - Language: the basics
   - Psycholinguistic evidence
3. Neural computation
4. Computational modeling

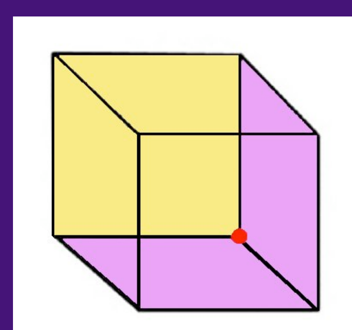
What is knowledge of language?

- Basic sound patterns (Phonology)
- How to make words (Morphology)
- How to put words together (Syntax)
- What words (etc.) mean (Semantics)
- How to do things with words (Pragmatics)
- Rules of conversation (Pragmatics)

English around the world

- Ladies may have a fit upstairs.
  - Outside a Hong Kong tailor shop
- Our wines leave you nothing to hope for.
  - On the menu of a Swiss restaurant
- Dresses for street walking.
  - Outside a Paris dress shop
- The lift is being fixed for the next day. During that time we regret that you will be unbearable.
  - In a Bucharest hotel lobby
- Visitors are expected to complain at the office between the hours of 9 and 11 A.M. daily.
  - In a hotel in Athens

The Necker Cube



What's so hard about language?

- **Ambiguity**
  - A man walks into a bar. (lexical)
  - The man saw the girl with the telescope. (syntactic)
  - Every boy kissed a girl. / Do not spit everywhere. (quantifier scope)
  - apple seat, topless legislators (modifier)
- **Context-dependence**
  - We cannot. (anaphor, ellipsis)
  - Lisa bought a car. The engine was broken. (reference)
  - John sneezed for five minutes. (aspect)
- **Creativity**
  - workaholic, chocoholic, sleepaholic (blending)
  - Pat sneezed the napkin off the table. (sense extension)
  - Mark googled his new friend. (coinage)

A: Time flies.

B: We cannot.

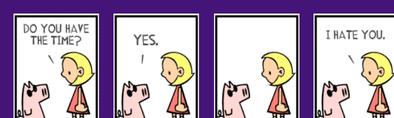
Their flight is too erratic.

More fun with language

- **Figurative language**
  - Our relationship is at a dead end. (metaphor)
  - No man is an island.
  - The ham sandwich wants his check. (metonymy)
  - Get your butt over here.
- **Conceptual blending**
  - workaholic, information highway, birth mother, fake gun
- **"Mental space" phenomena** (Fauconnier)
  - The girl with blue eyes in the painting really has green eyes.
  - If I were him I'd hate me/myself too.
- **Conversational implicature**

Gricean cooperation: Maxims of communication

(H.P. Grice)



- **Quality** — Be truthful.
- **Quantity** — Give an appropriate amount of information.
- **Relevance** — Be relevant.
- **Clarity** — Be clear.

From single words to complex utterances

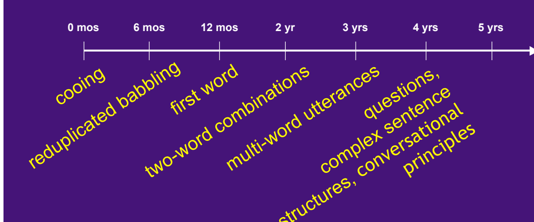
FATHER: Nomi are you climbing up the books?
NAOMI: **up.**
NAOMI: **climbing.**
NAOMI: **books.**
1;11.3

MOTHER: what are you doing?
NAOMI: **I climbing up.**
MOTHER: you're climbing up?
2;0.18

FATHER: what's the boy doing to the dog?
NAOMI: **squeezing his neck.**
NAOMI: **and the dog climbed up the tree.**
NAOMI: **now they're both safe.**
NAOMI: **but he can climb trees.**
4;9.3

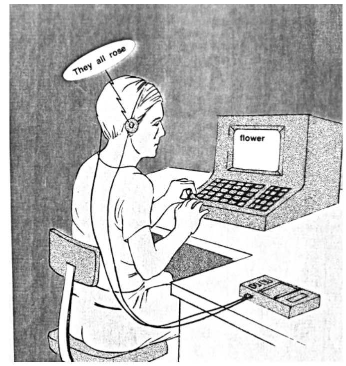
Sachs corpus (CHILDES)

The course of acquisition



Psycholinguistic evidence

- **Experimental paradigms**
  - Priming: lexical identification (homophone contextual bias)
  - Syntactic priming
  - Eye-tracking: expectations
- **Integration, competition and interference**
  - Parallel processing, rapid multimodal integration:
    - Linguistiic and nonlinguistic; across linguistic levels
  - Interference between form and meaning (Stroop effect)
- **Top-down and bottom-up information**
  - Bottom-up stimulus drives processing…
  - …but also initiates top-down effects of knowledge and context
  - Word superiority effect (faster letter recognition in word context)



Tanenhaus et al. (1979) [also Swinney, 1979

Reaction times after hearing: "They all rose"

	0 delay	200 ms delay
flower	685 priming	659 no priming
stood	677 priming	623 priming
desk	711	652

Stroop Effect

Book Car Table Box Trash Man Bed

Corn Sit Paper Coin Glass House Jar

Key Rug Cat Doll Letter Baby Tomato

Check Phone Soda Dish Lamp Woman

Stroop effect: Name the print color

Blue Green Red Yellow Orange Black Red

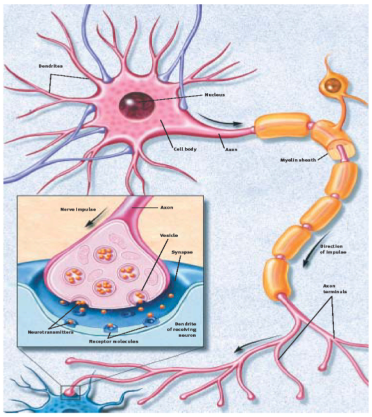
Purple Green Red Blue Yellow Black Red

Green White Blue Yellow Red Black Blue

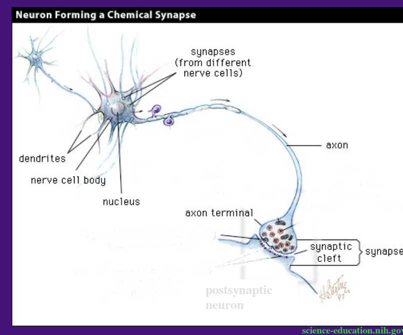
White Red Yellow Green Black Purple

Lecture outline

1. Introduction to NTL
2. Cognition and language
3. Neural computation
4. Computational modeling

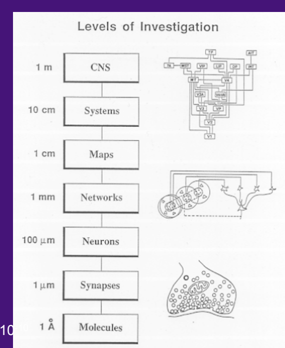


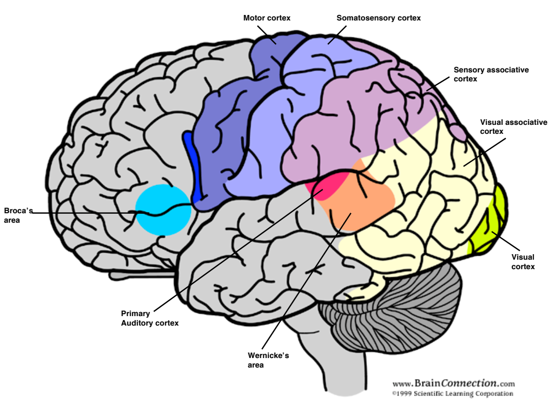
NEURON. A neuron fires by transmitting electrical signals along its axon. When signals reach the end of the axon, they trigger the release of neurotransmitters that are stored in pouches called vesicles. Neurotransmitters bind to receptor molecules that are present on the surfaces of adjacent neurons. The point of virtual contact is known as the synapse.

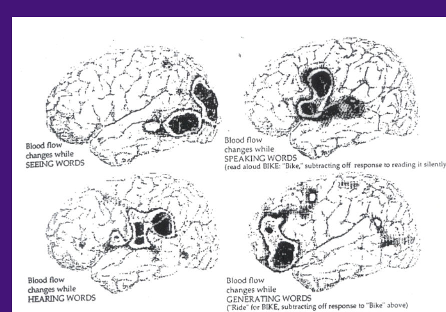


Neurons

- cell body
- dendrites (input structure)
  - receive inputs from other neurons
  - perform spatio-temporal integration of inputs
  - relay them to the cell body
- axon (output structure)
  - a fiber that carries messages (spikes) from the cell to dendrites of other neurons

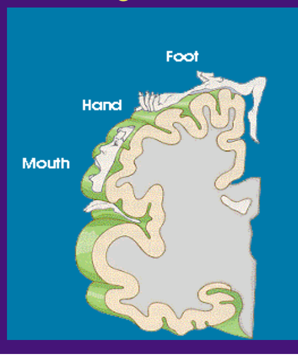




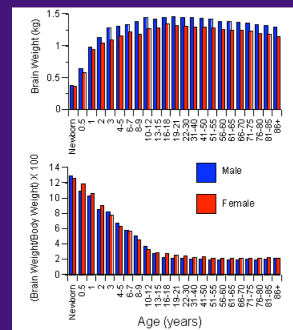


PET scan of blood flow for 4 word tasks

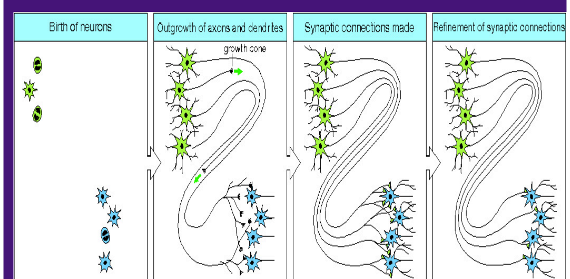
The Motor System is somatotopically organized



Neural development: brain weight



Overall Process



Nature requires Nurture

- **Initial wiring is genetically controlled**
  - E.g. regrowth of frog optic nerve (Sperry 1956) connecting retina to tectum
- **But environmental input is critical in early development**
  - Occular dominance columns
    - Hubel and Wiesel experiment

Turning a (frog's) blind eye

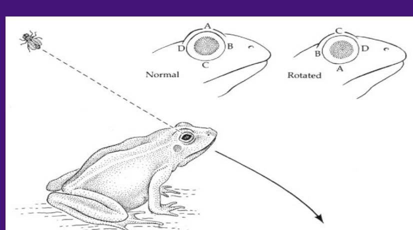


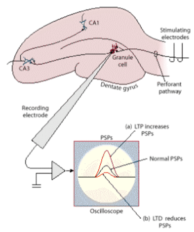
FIGURE 2. *The effects of eye rotation on the visual behavior of a frog following optic nerve regeneration. This picture shows the response of a frog, the right optic nerve of which had been cut some weeks earlier; at the time of surgery the eye was rotated through 180° and sutured in position (inset). Following recovery, the animal was able to see again through the affected eye. However, when a target of interest (a fly) appeared in the visual field, the frog's attack was misdirected by approximately 180° (arrow). This result suggests that retinal axons reinnervate their original target cells in the tectum (or cells near them) and that the central nervous system has little or no ability to compensate for the maladaptive behavior that results. (After Sperry, 1956.)*

Structural change via activity-dependent tuning

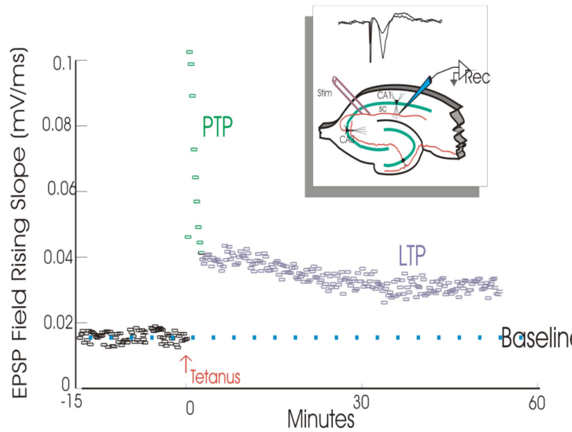
- **Activity-dependent tuning and plasticity**
  - In pre-natal, post-natal, and adult brain
- **Long-term potentiation (LTP)**
  - Rapid, long-term increase in synaptic strength resulting from the pairing of presynaptic activity with postsynaptic depolarization
  - Synapse-specific
  - ubiquitous in the hippocampal system and cortico-hippocampal pathways
- **Basis for biological accounts of perceptual, motor, cognitive and language learning**

LTP in the hippocampus

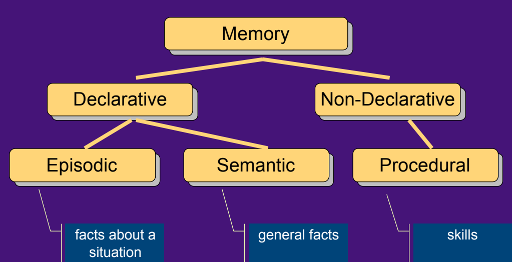
Schafer collateral pathway
Pyramidal cells



1 sec. stimuli
At 100 hz



Learning and Memory: Introduction



Gradual vs. one-shot learning

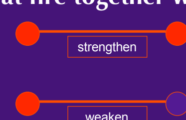
- Gradual learning
  based on multiple exemplars/experiences
  - perceptual-motor skills
  - natural categories
- Rapid one-shot learning
  - episodic memories
  - Faces
  - "fast mapping"

Hebb's Rule

- The key idea underlying theories of neural learning go back to the Canadian psychologist Donald Hebb and is called Hebb's rule.
- From an information processing perspective, the goal of the system is to increase the strength of the neural connections that are effective.

LTP and Hebb's Rule

- Hebb's Rule:
  Neurons that fire together wire together



- Long Term Potentiation (LTP) is the biological basis of Hebb's Rule
- Calcium channels are the key mechanism

Brains vs. Computers

Brains	Computers
100,000,000,000 units	1-100 processors
1000 ops/sec	1,000,000,000 ops/sec
10,000 connections	~ 4 connections
graded, stochastic	binary, deterministic
fault-tolerant	crash-prone
development, adaptation, learning	designed, programmed

Constraints on Connectionist Models

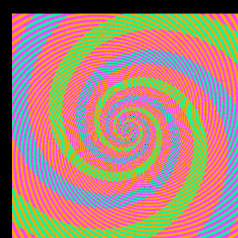
100-step rule
  Human reaction times ~ 100 milliseconds
  Neural signalling time ~ 1 millisecond
Simple messages between neurons
Long connections are rare
No new connections during learning
Developmentally plausible

Lecture outline

1. Introduction to NTL
2. Cognition and language
3. Neural computation
4. *Computational modeling (Session 2)*

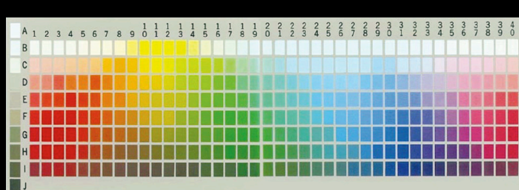
Case study in embodiment:
crosslinguistic color terms

The Color Story: A Bridge between Levels of NTL



(http://www.ritsumei.ac.jp/~akitaoka/color-e.html)

The WCS Color Chips



- Basic color terms:
  - Single word (not *blue-green*)
  - Frequently used (not *mauve*)
  - Refers primarily to colors (not *lime*)
  - Applies to any object (not *blonde*)

Color Naming

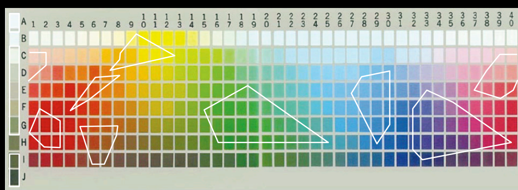
Focal Colors (Berlin & Kay)

Studied color categories in two ways

Boundaries

Best examples

The WCS Color Chips



- Basic color terms:
  - Single word (not *blue-green*)
  - Frequently used (not *mauve*)
  - Refers primarily to colors (not *lime*)
  - Applies to any object (not *blonde*)

FYI:
English has 11 basic color terms

Color Naming

BCTs in English

Red	Gray
Green	Brown
Blue	Purple
Yellow	Orange*
Black	Pink
White	

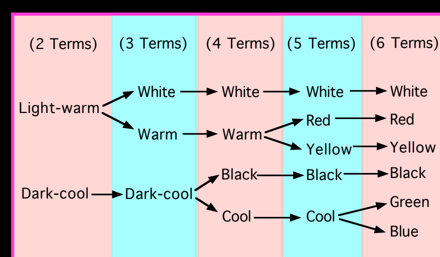
Color Naming

Five more BCTs in a study of 98 languages

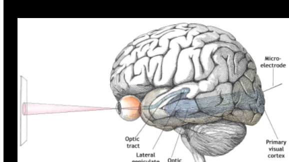
Light-Blue
Warm
Cool
Light-Warm
Dark-Cool

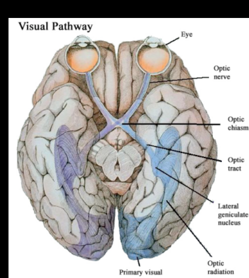
Color Naming

Typical "developmental" sequence of BCTs



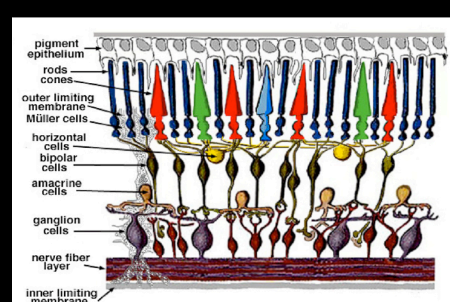
A Tour of the Visual System



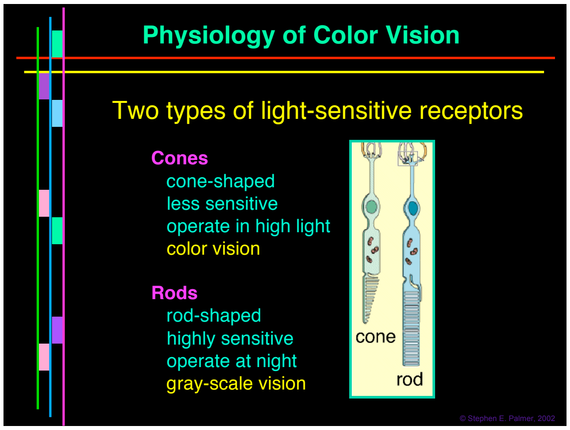


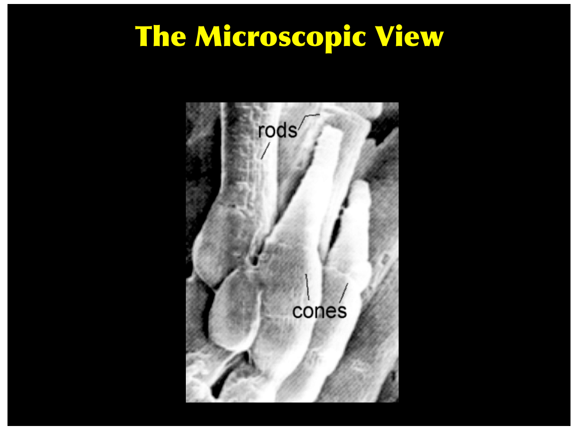
- two regions of interest:
  - retina
  - LGN

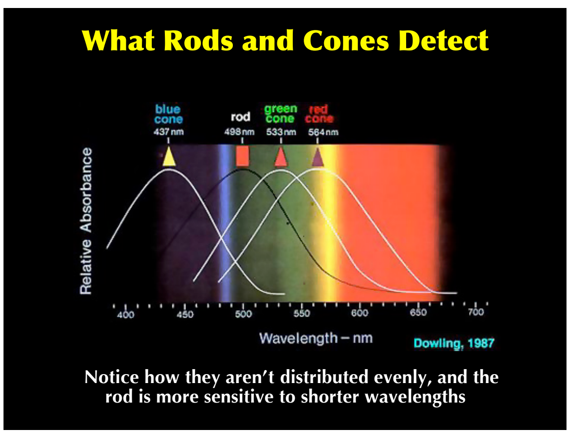
Rods and Cones in the Retina

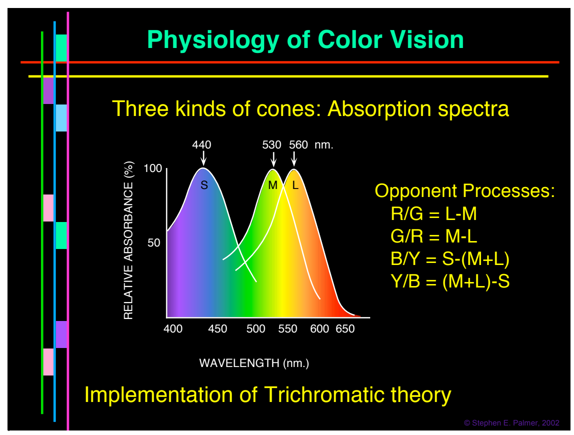


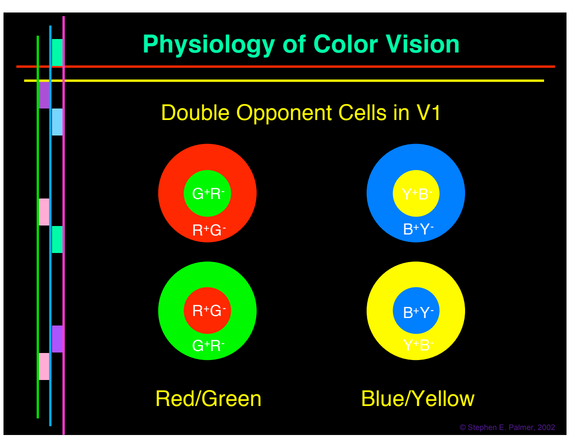
http://www.iit.edu/~npr/DrJennifer/visual/retina.html

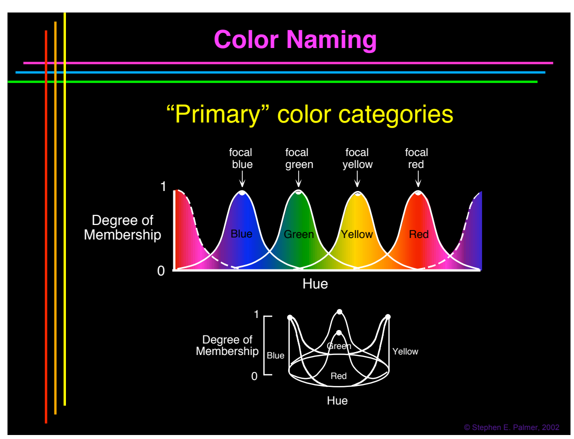

Physiology of Color Vision
Two types of light-sensitive receptors
Cones
cone-shaped
less sensitive
operate in high light
color vision
Rods
rod-shaped
highly sensitive
operate at night
gray-scale vision
cone
rod
© Stephen E. Palmer, 2002


The Microscopic View
rods
cones


What Rods and Cones Detect
blue cone
437 nm
rod
498 nm
green cone
533 nm
red cone
564 nm
Relative Absorbance
400
450
500
550
600
650
700
Wavelength – nm
Dowling, 1987
Notice how they aren't distributed evenly, and the rod is more sensitive to shorter wavelengths


Physiology of Color Vision
Three kinds of cones: Absorption spectra
440
530 560 nm.
100
50
S
M
L
RELATIVE ABSORBANCE (%)
400
450
500
550
600
650
WAVELENGTH (nm.)
Opponent Processes:
R/G = L-M
G/R = M-L
B/Y = S-(M+L)
Y/B = (M+L)-S
Implementation of Trichromatic theory
© Stephen E. Palmer, 2002

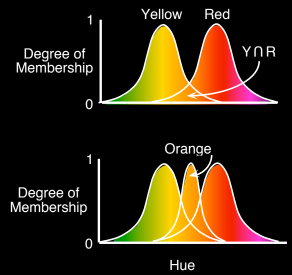

Physiology of Color Vision
Double Opponent Cells in V1
G+R-
R+G-
Y+B-
B+Y-
R+G-
G+R-
B+Y-
Y+B-
Red/Green
Blue/Yellow
© Stephen E. Palmer, 2002


Color Naming
"Primary" color categories
focal blue
focal green
focal yellow
focal red
1
Degree of Membership
0
Blue
Green
Yellow
Red
Hue
1
Degree of Membership
0
Blue
Green
Red
Yellow
Hue
© Stephen E. Palmer, 2002

Color Naming

"Derived" color categories

Fuzzy logical "AND$_f$"



Color Naming

"Derived" color categories

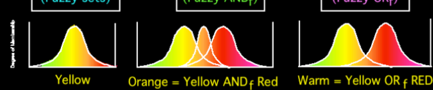
Orange = Red AND$_f$ Yellow
Purple = Red AND$_f$ Blue
Gray = Black AND$_f$ White
Pink = Red AND$_f$ White
Brown = Yellow AND$_f$ Black
(Goluboi = Blue AND$_f$ White)

Color Naming

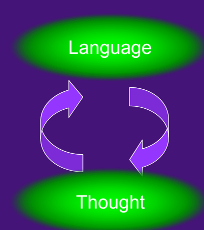
FUZZY LOGICAL MODEL OF COLOR NAMING (Kay & McDaniel)

Only 16 Basic Color Terms in Hundreds of Languages:

Red	Orange	[Warm]
Green	Purple	[Cool]
Blue	Brown	[Light-warm]
Yellow	Pink	[Dark-cool]
Black	Gray	
White	[Light-blue]	
PRIMARY (Fuzzy sets)	DERIVED (Fuzzy AND$_f$)	COMPOSITE (Fuzzy OR$_f$)

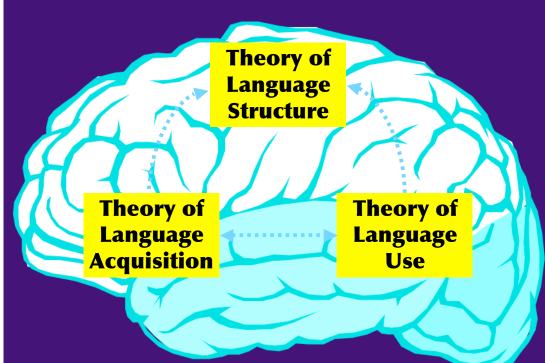


Language and Thought



cognitive processes

- We know thought (our cognitive processes) constrains the way we learn and use language
- Does language also influence thought?
- Benjamin Whorf argues yes
- Psycholinguistics experiments have shown that linguistics categories influence thinking even in non-linguistics task



Embodiment in language

- Perceptual and motor systems play a central role in language production and comprehension
- Theoretical proposals
  - **Linguistics**: Lakoff, Langacker, Talmy
  - **Neuroscience**: Damasio, Edelman
  - **Cognitive psychology**: Barsalou, Gibbs, Glenberg, MacWhinney
  - **Computer science**: Steels, Feldman

A look ahead: Simulation hypothesis

We understand utterances by mentally simulating their content.

- Simulation exploits some of the **same neural structures** activated during performance, perception, imagining, memory…
- Linguistic structure **parametrizes** the simulation.
  - Language gives us enough information to simulate

The ICSI/Berkeley Neural Theory of Language Project