The Vision Pipeline and Color Image Segmentation

15-494 Cognitive Robotics
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Carnegie Mellon
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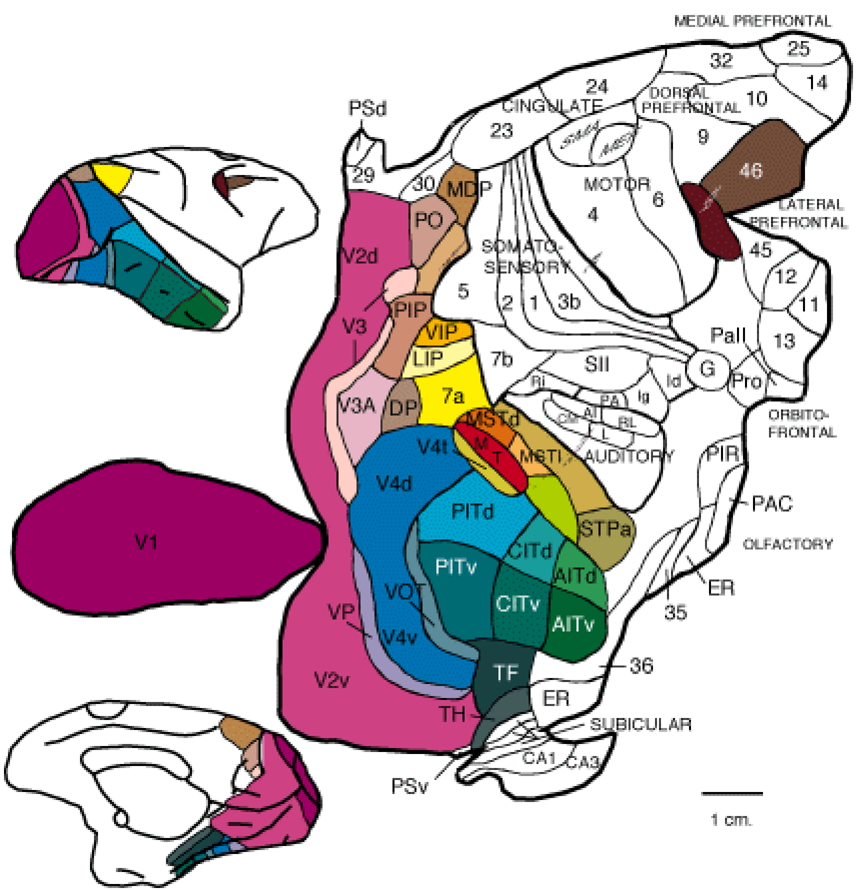
Why Don't Computers See Very Well?

Approx. 1/3 of the human brain is devoted to vision!

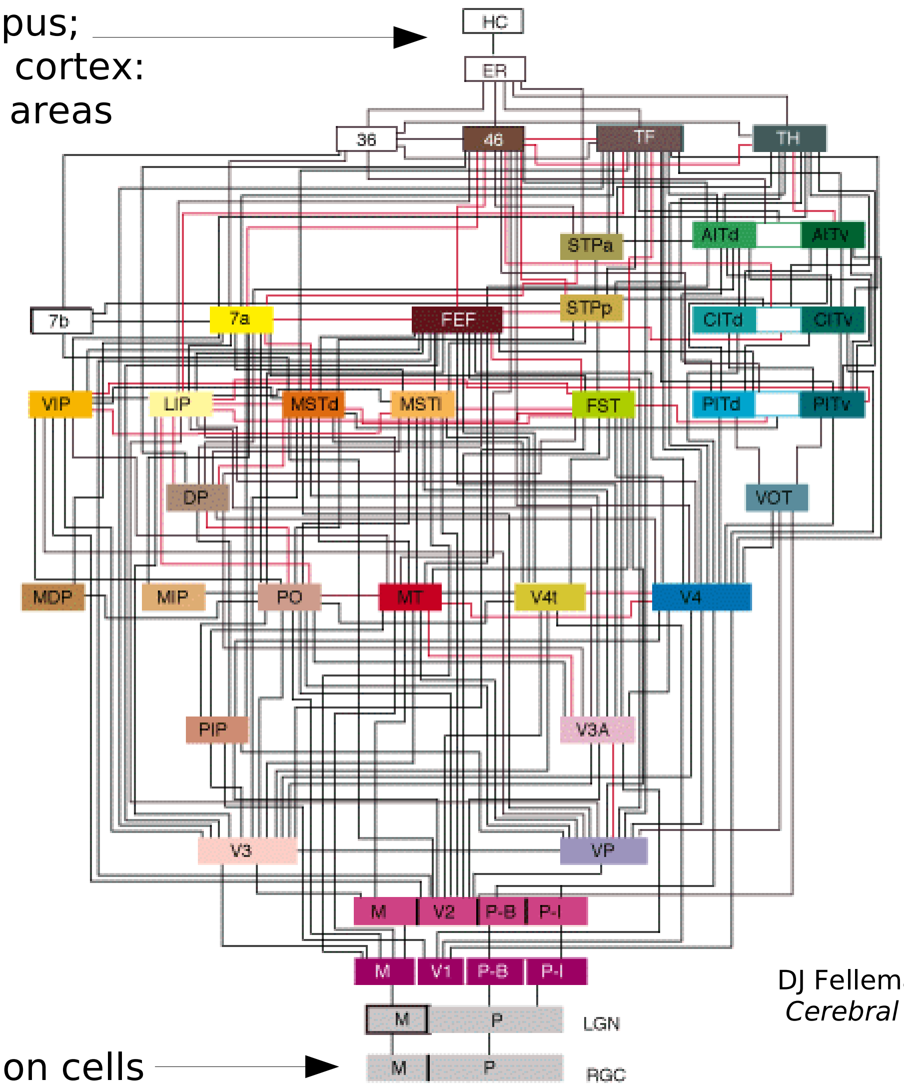


Felleman and Van Essen's Flat Map of the Macaque Brain

DJ Felleman and DC Van Essen (1991), *Cerebral Cortex* **1:**1-47.

The Macaque "Vision Pipeline" as of December 1990

HC = hippocampus;
ER = entorhinal cortex:
high level brain areas



RGC = retinal ganglion cells

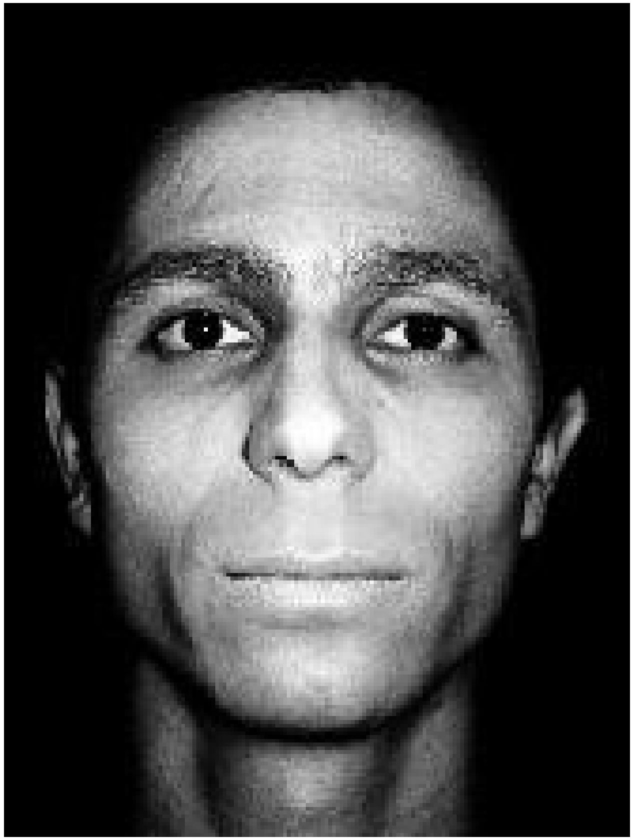
DJ Felleman and DC Van Essen (1991), *Cerebral Cortex* **1:**1-47.

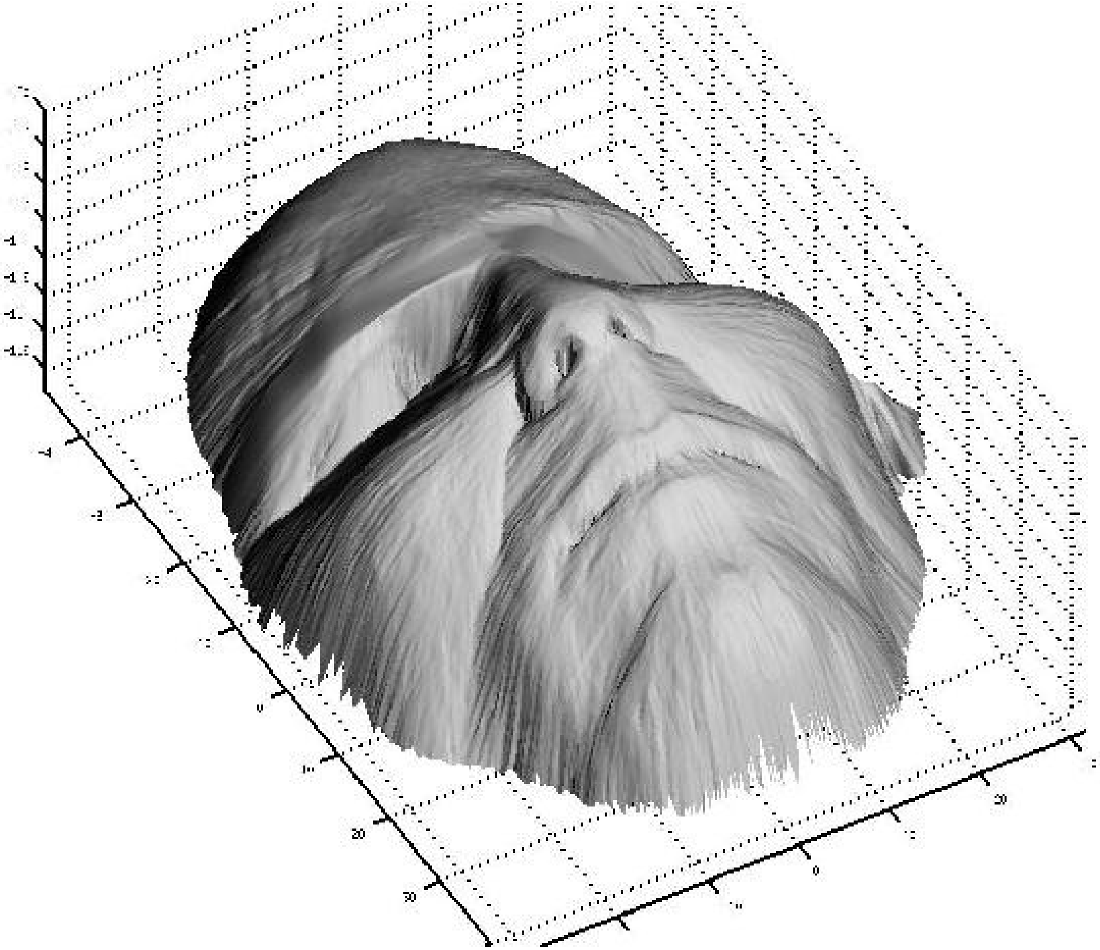
Why Is Vision Hard?

- Segmentation: where are the boundaries of objects?
- Need to recover 3-D shapes from 2-D images:
  - Shape from shading
  - Shape from texture
- Need to fill in occluded elements – what aren't we seeing?
- Importance of domain knowledge:
  - Experience shapes our perceptual abilities
  - Faces are *very* special; there are “face cells” in IT (inferotemporal cortex)
  - Reading is also special; learning to read fluently alters the brain

The Segmentation Problem

Shape From Shading

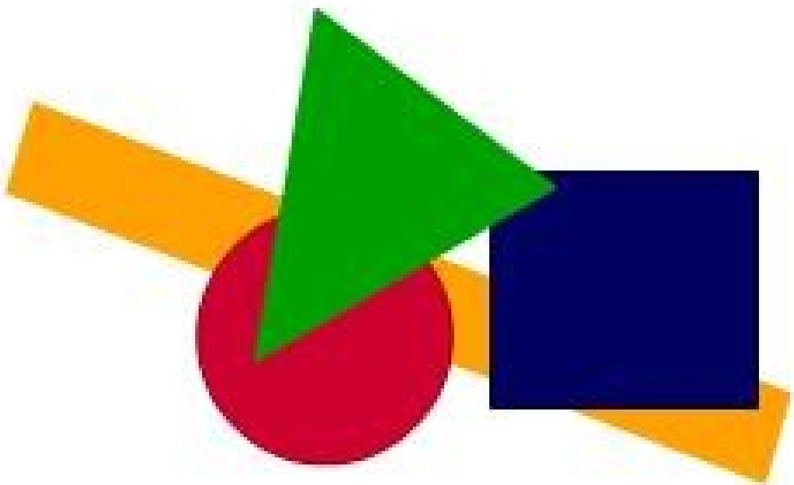




Images from: www.cs.ucla.edu/~eprados/

Occlusion

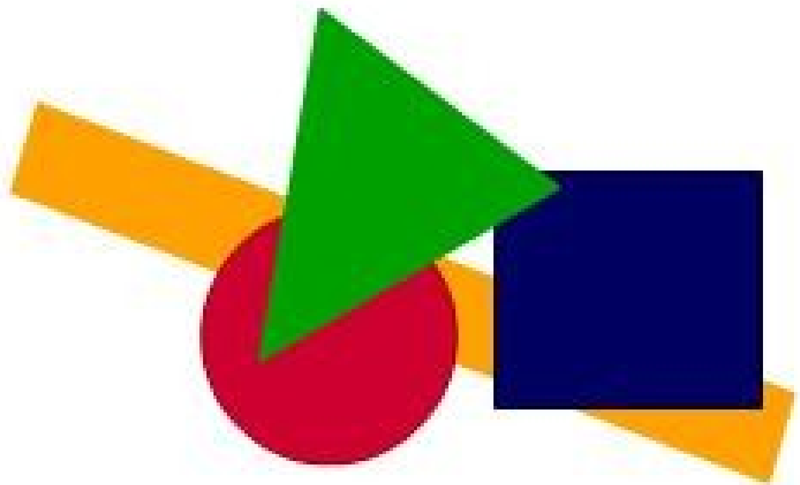
- How many *rectangles* can you find?



- What shapes are present in the image?

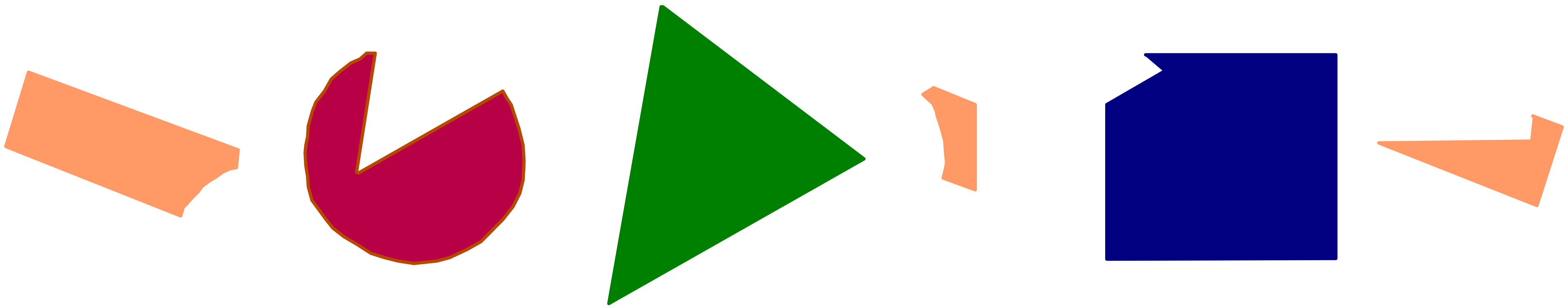
Occlusion

- How many *rectangles* can you find?



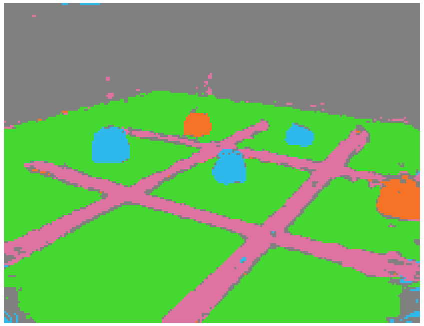
None! (Or two.)

- What shapes are present in the image?



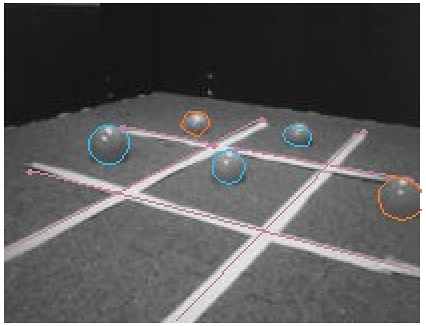
Vision is Hard!
How Can a Poor Robot Cope?

- Use color to segment images.
- Discard shading and texture cues.



From colors to objects:
green = floor
pink = board
blue, orange = game pieces

- Planar world assumption (can be relaxed later).
- Domain knowledge for occlusion (blue/orange occludes pink.)



What is “Color” ?

- Humans have 3 types of color receptors (cones).
- Dogs have 2: they're red/green colorblind.
- Cats have 3, but sparse: weak trichromants.
- Birds have 4 or 5 types.
- Birds and honeybees can see ultraviolet; honeybees can't see red.
- Rats lack color vision.

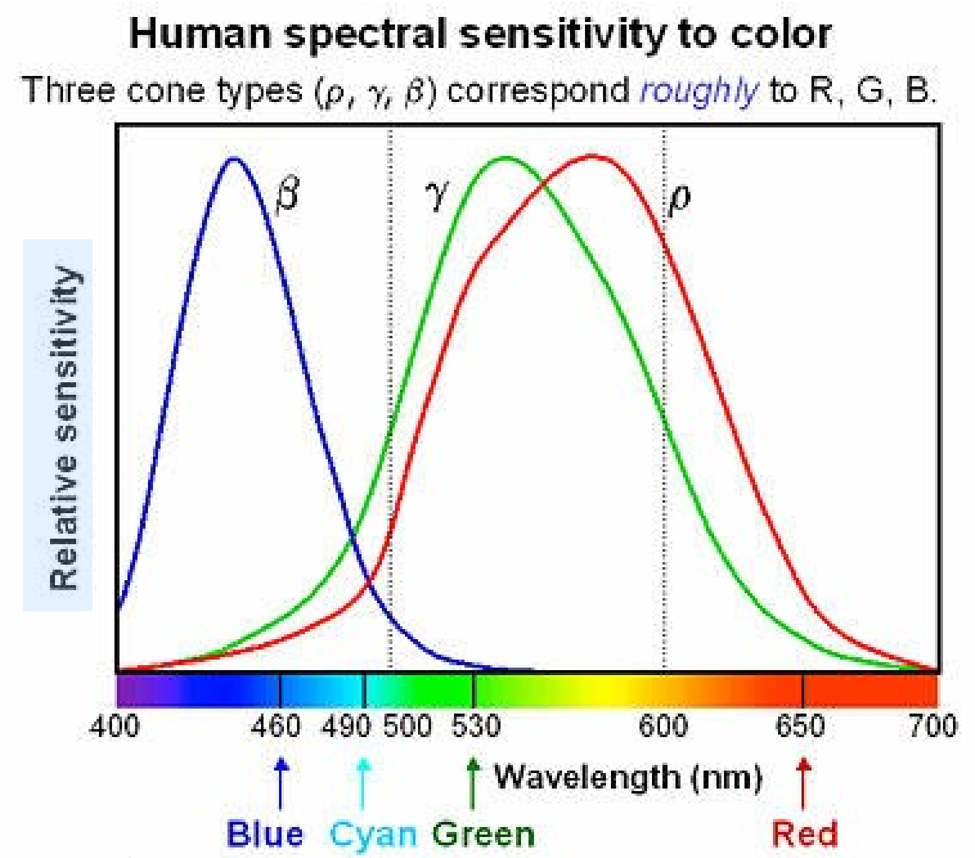
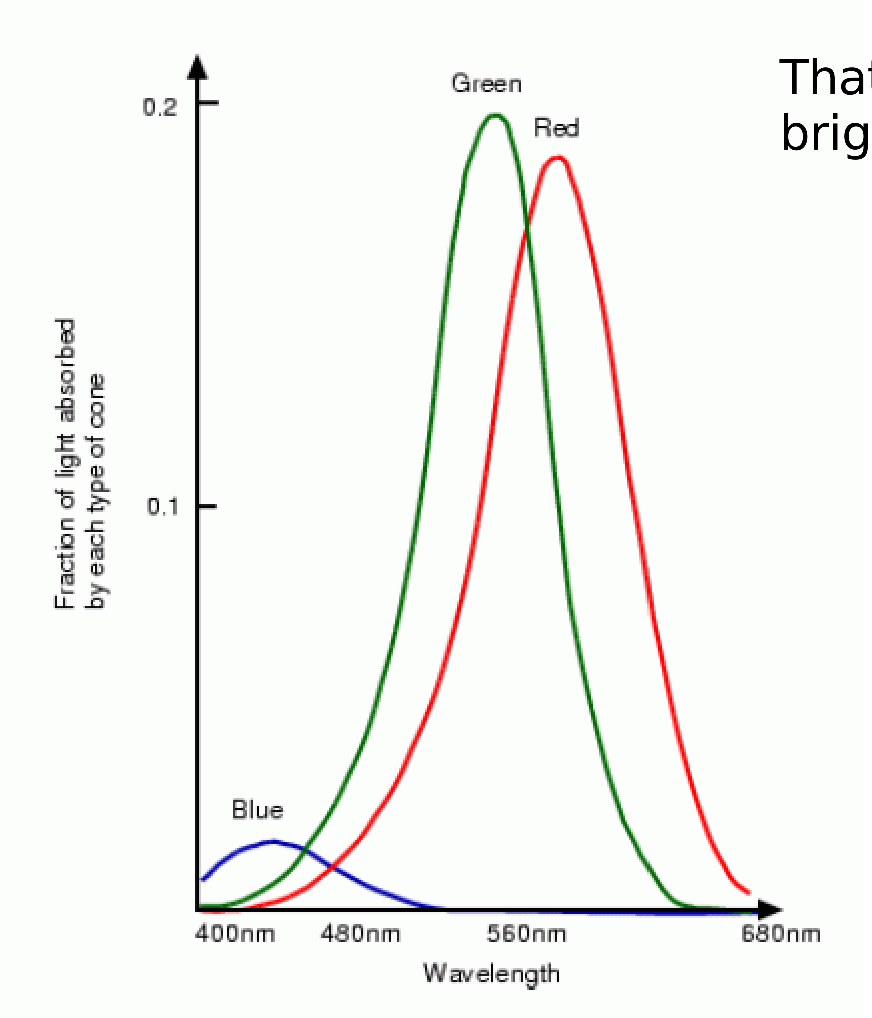
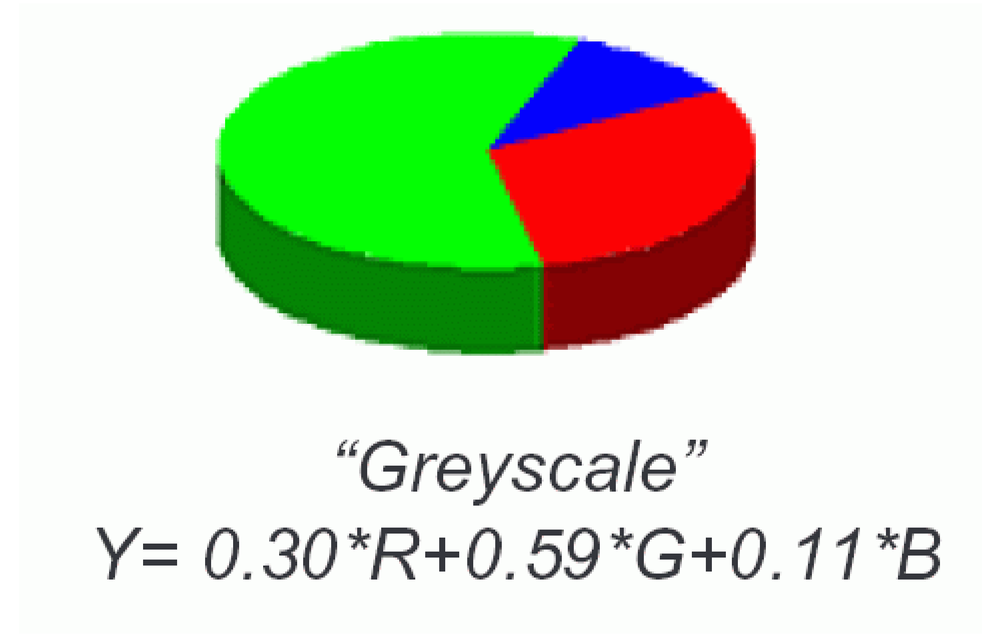


Image from:
http://www.normankoren.com/Human_spectral_sensitivity_small.jpg

The Human Retina is Most Responsive to Green Light



That's why green laser pointers look brighter than red ones of the same power.



Images from http://www.cse.lehigh.edu/%7Espletzer/cse398_Spring05/lec002_CMVision.pdf

Color and Computers

- Video cameras don't see color the same way the human eye does:
  - Different spectral sensitivity curves.
- Colors that look different to you may look the same to a computer that sees through a camera, and vice versa.
- Computer monitors try to synthesize colors by blending just three frequencies: red(ρ), green(γ), and blue(β).
- No computer monitor can produce the full range of color sensations of which humans are capable.

RGB Color Space

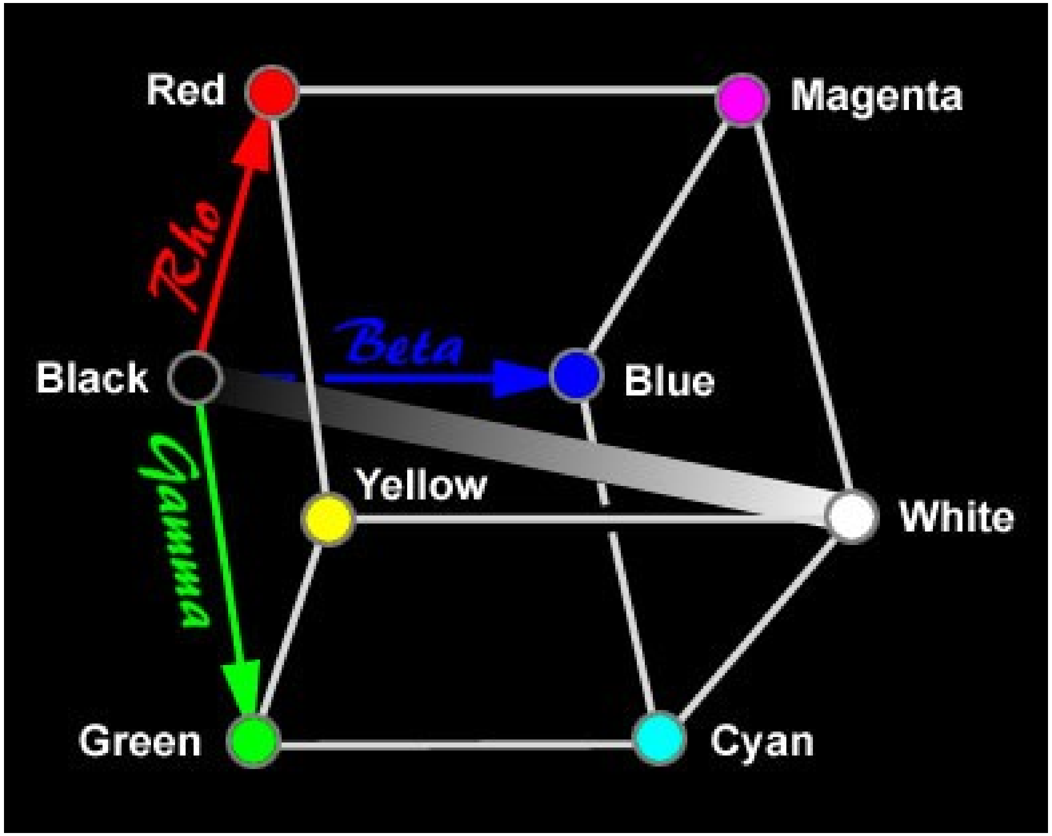


Image from http://www.photo.net/learn/optics/edscott/vis00020.htm

Edge of Fully Saturated Hues

Move from one corner to the next by increasing or decreasing one of the three RGB components.

Example: moving...
From green to yellow:
[0,255,0] → [255,255,0]
From yellow to red:
[255,255,0] → [255,0,0]
From red to magenta:
[255,0,0] → [255,0,255]

Saturation in RGB space = max(r,g,b) - min(r,g,b)

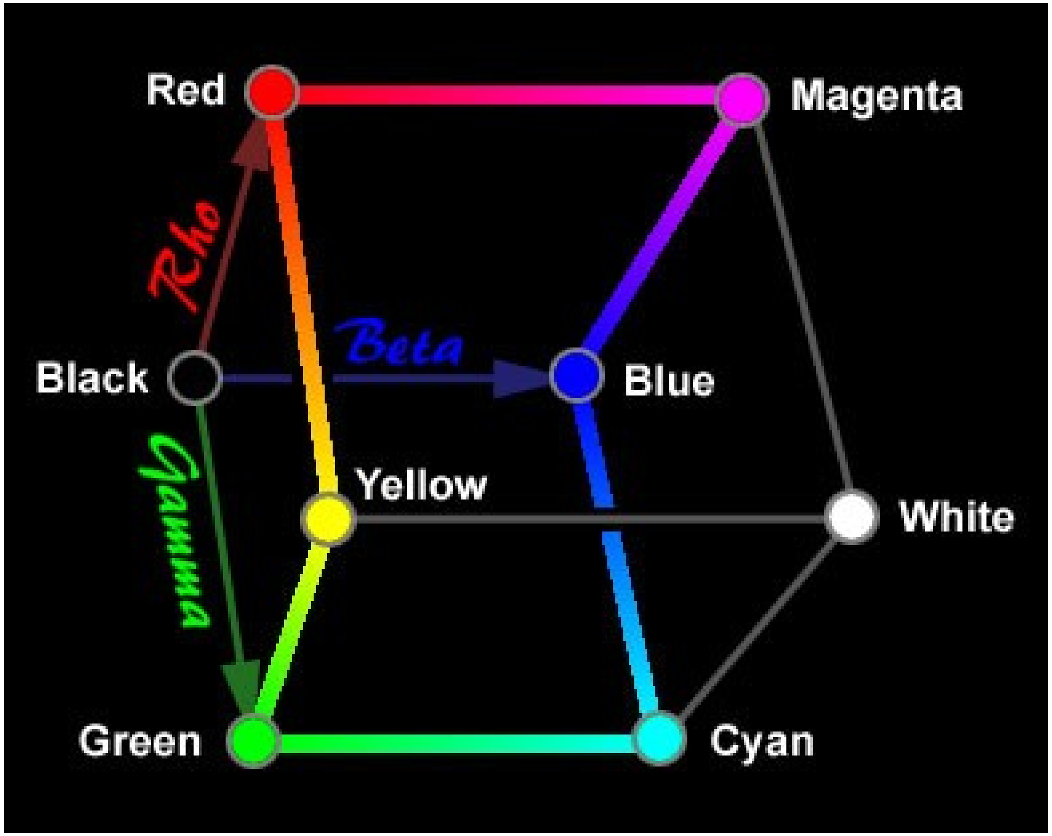


Image from http://www.photo.net/learn/optics/edscott/vis00020.htm

Saturation in Images

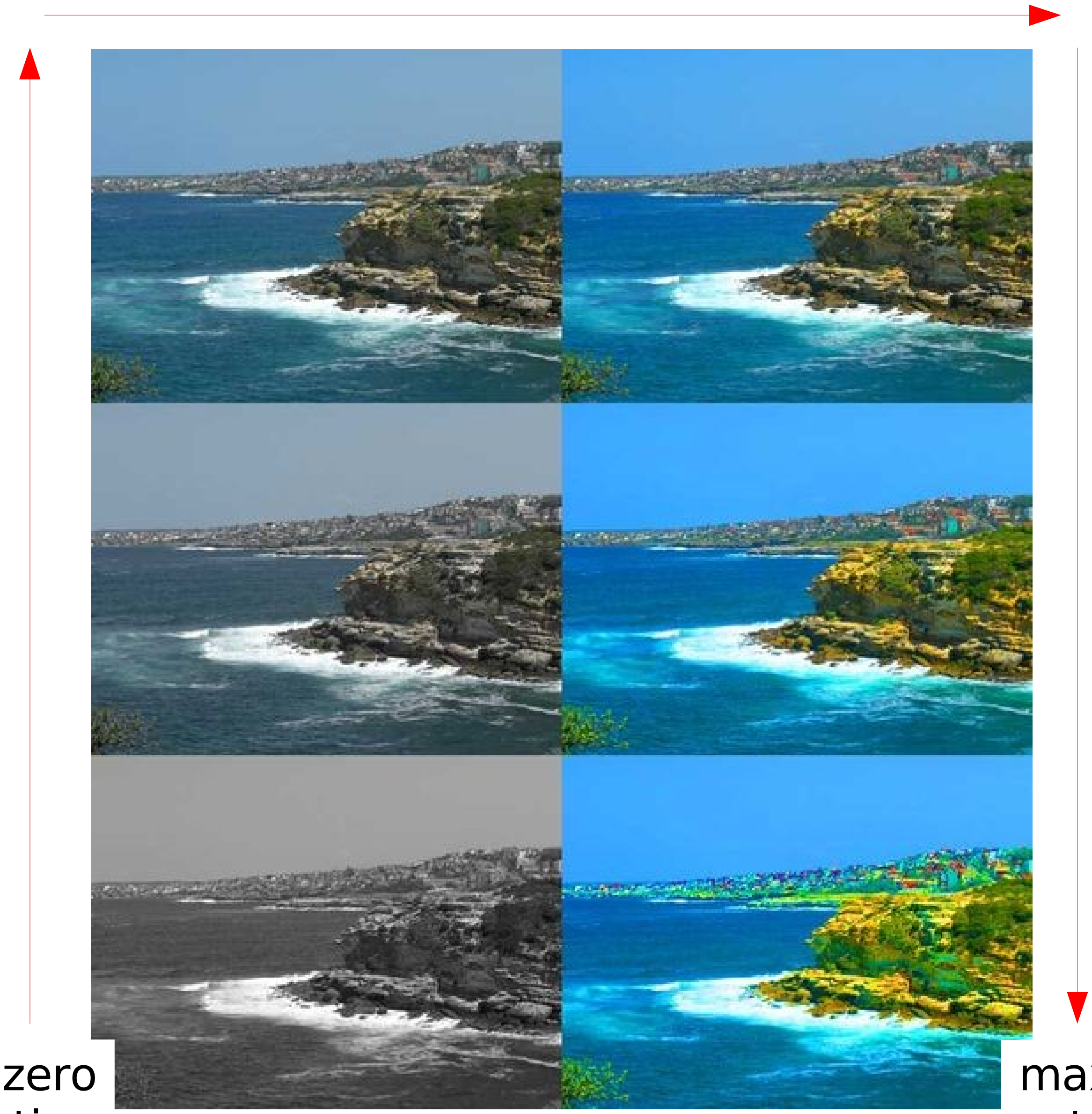


Image source: Wikipedia "Color Saturation"

zero saturation

maximum saturation

YUV / YCbCr Color Space

- Y = intensity
- U/Cb = “blueness”
  (green vs. blue)
- V/Cr = “redness”
  (green vs. red)

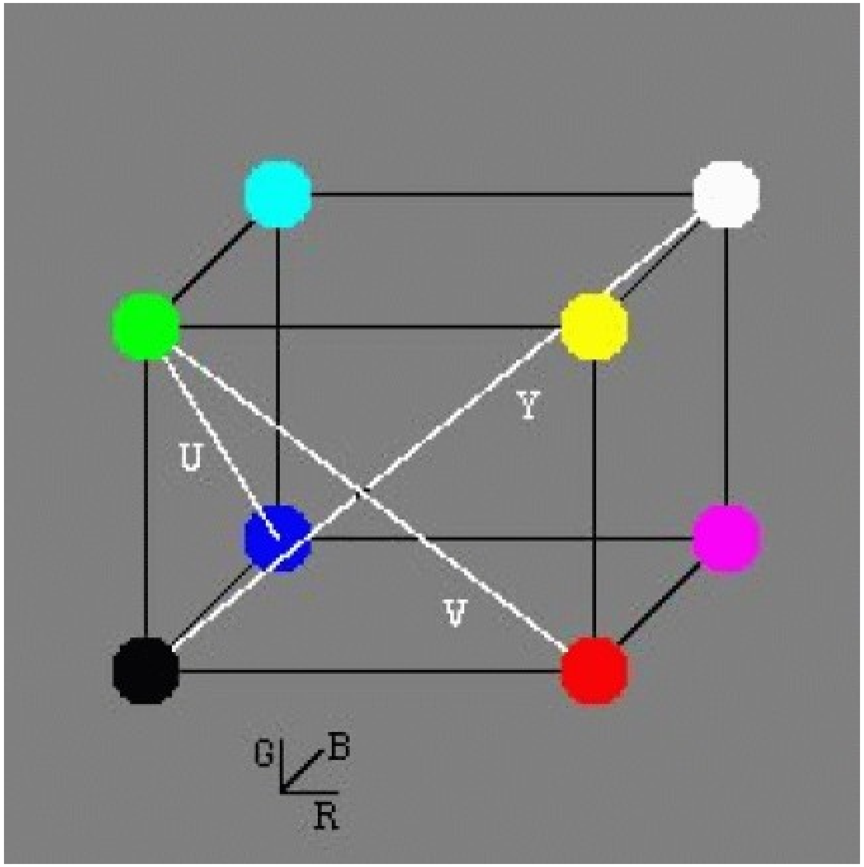
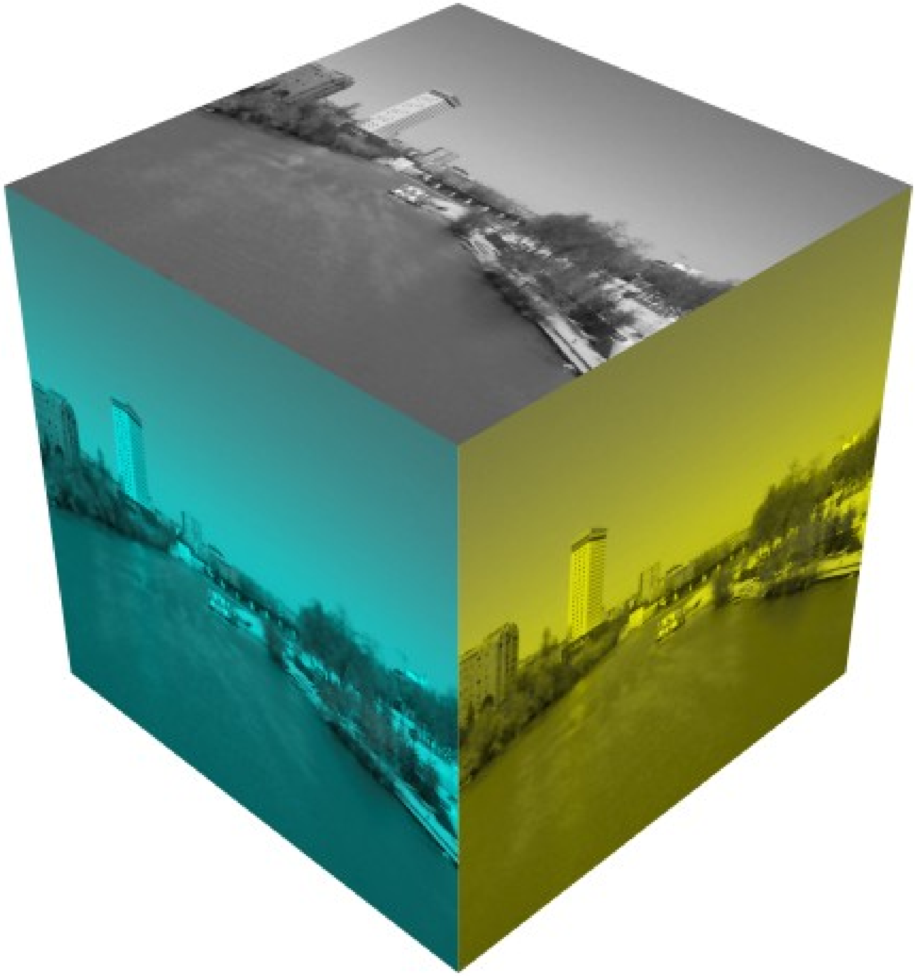


Image from http://www.andrew.cmu.edu/course/15-491/lectures/Vision_I.pdf

YUV Color Cube



Images from http://commons.wikimedia.org/wiki/Image:Cubo_YUV_con_las_capas_de_color.png

Converting RGB to YUV (assuming 8 bits per channel)

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \frac{1}{256} \cdot \begin{bmatrix} 65.738 & 129.057 & 25.064 \\ -37.945 & -74.494 & 112.439 \\ 112.439 & -94.154 & -18.285 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}$$

HSV Color Space

- H = hue
- S = saturation
- V = value (intensity)

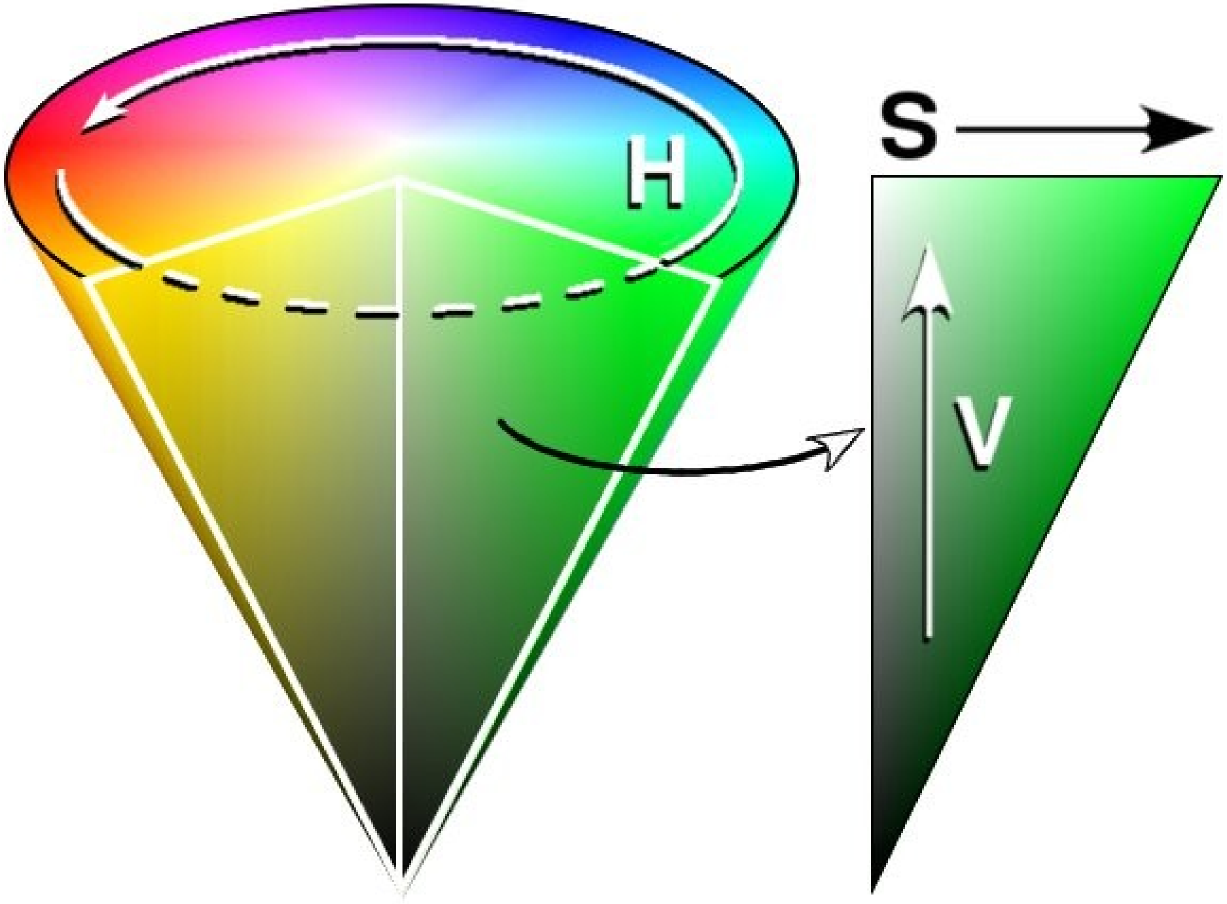


Image from http://www.wordiq.com/definition/Image:HSV_cone.jpg

Many Cameras Use YUV

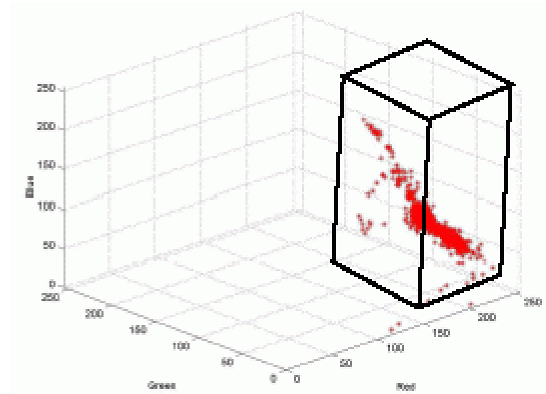
What the robot sees

What is displayed
for humans

Segmented image

Color Classification 1

- Define a set of color classes: “pink”, “orange”, etc.
- Each class is assigned some region of color space.
- Simplest case: use rectangles.




```
isOrange[i] =
     imR[i] >= orangeMinR && imR[i] <= orangeMaxR &&
     imG[i] >= orangeMinG && imR[i] <= orangeMaxG &&
     imB[i] >= orangeMinB && imR[i] <= orangeMaxB;
```

- Drawbacks: (1) the “real” regions aren't rectangular, so errors result; (2) lots of colors = slow processing.

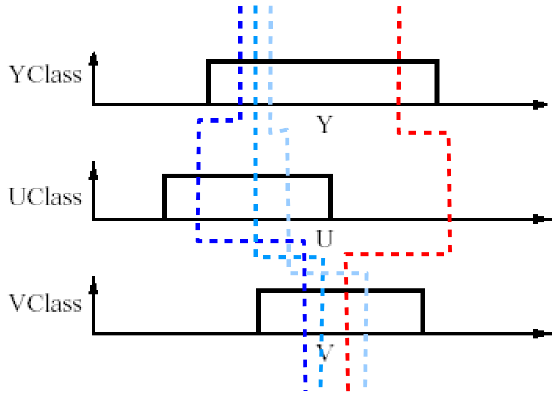
Color Classification 2

- We can have arbitrary-shaped color regions by creating a lookup table.
- For each (R,G,B) value, store the color class (integer).
- Problem: 24 bit color = 16 million entries = 16 MB.
- Could use fewer bits, but that would reduce accuracy.

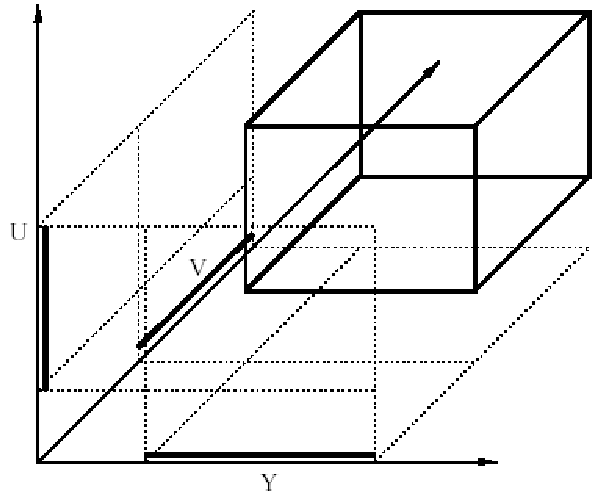
Color Classification 3

- J. Bruce, T. Balch, and M. Veloso, IROS 2000:
- Table lookup with bit-wise AND function can handle 32 color classes at once.

```
int Ytable[256], Utable[256], Vtable[256];
ColorClasses[i] =
   Ytable[imY[i]] & Utable[imU[i]] & Vtable[imV[i]];
```



Binary Signal Decomposition of Threshold



Visualization as Threshold in Full Color Space

Bruce et al. (continued)

- We assigned a bit to each color:

  1000 = “pink”

  0100 = “orange”

  0010 = “blue”

  0001 = “green”

- Suppose the “pink” and “orange” classes both include some colors with a Y value of 214:

  Ytable[214] = 0x1100

- Suppose all four classes include a U value of 56:

  Utable[56] = 0x1111

- If “orange” and “green” both include V values of 118:

  Vtable[118] = 0x0101

- Color classes of (214,56,118) are: 0x0100 = orange

Color Classification 4: CMVision

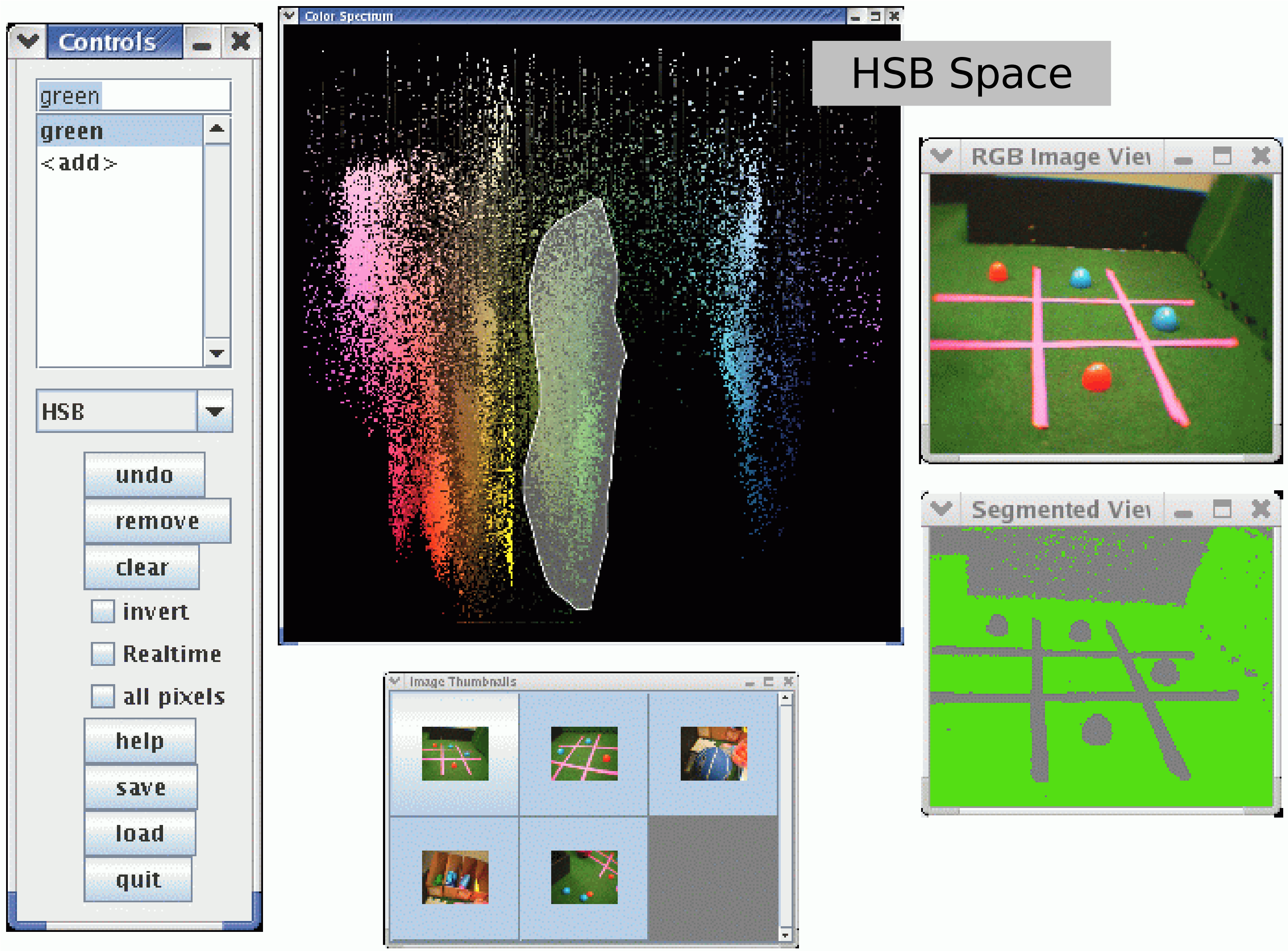
- CMVision is a vision package developed by Jim Bruce, Tucker Balch, and Manuela Veloso at Carnegie Mellon. Used for many robotics projects.

- Current implementation operates in YUV space. Uses a reduced-resolution lookup table so it's not limited to rectangular decision boundaries.
  - 4 bits for Y, 6 bits each for U and V: 65,536 entries.

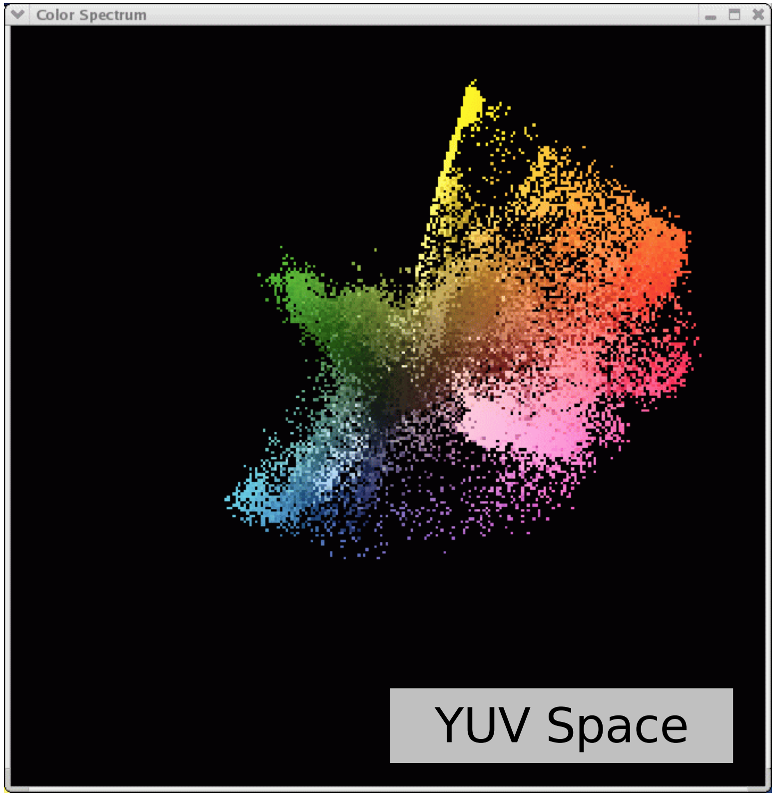
- The format of a CMVision threshold map (.tm) file is:

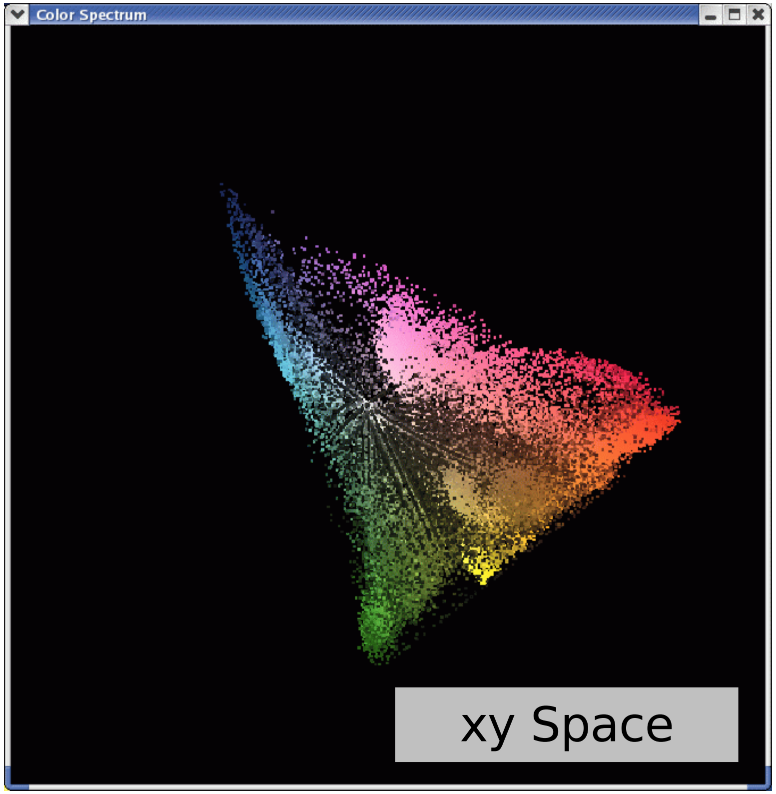
```
TMAP
YUV8
16 64 64
<65,536 1-byte table entries>
```

The EasyTrain Tool Creates Threshold Files for CMVision



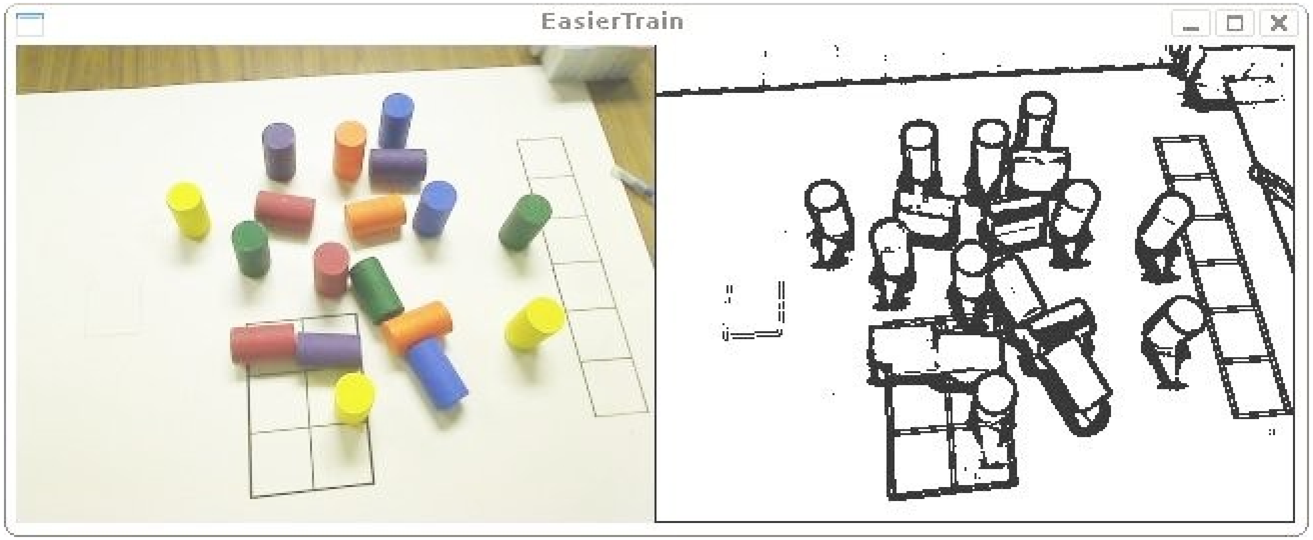
Other Color Spaces Supported



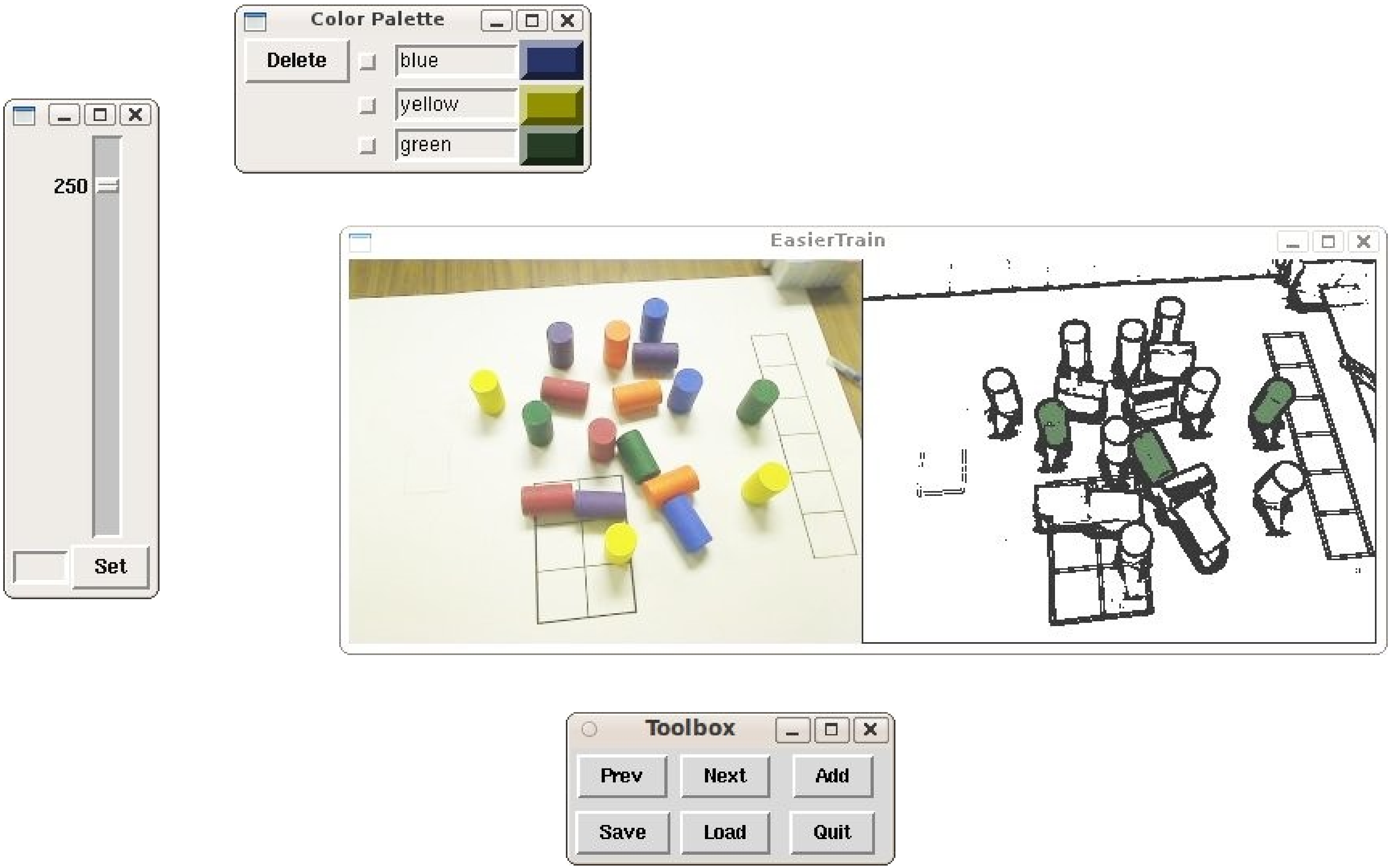


EasierTrain

- Created by Michael Gram and Nathan Hentoff at RPI.
- http://code.google.com/p/tekkotsu-easiertrain
- Automatically segments the image and allows the user to assign color names and adjust segmentation thresholds.

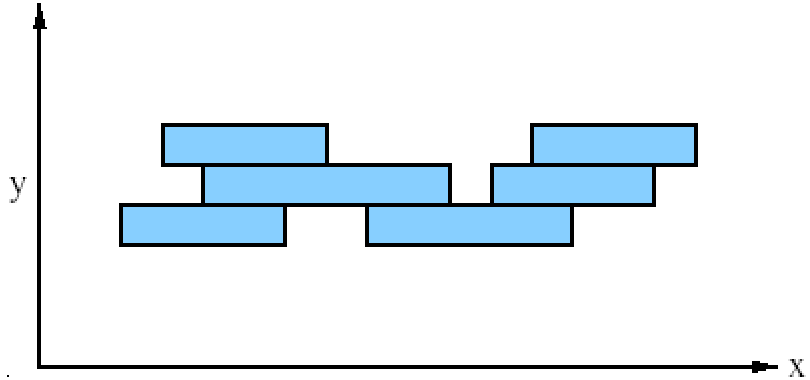


EasierTrain



Run Length Encoding

- Next step after color segmentation.
- Replace identical adjacent pixels by run descriptions:
  - Lossless image compression.
- An image is now a list of *rows*.
  A *row* is a list of *runs*, of form:
  <starting column, length, color class>



- Run length encoding also does noise removal, by skipping over short gaps between runs.

Connected Components Labeling

- Assemble adjacent runs of the same color into regions.
- This gives crude object recognition, assuming *that identically-colored objects don't touch.*

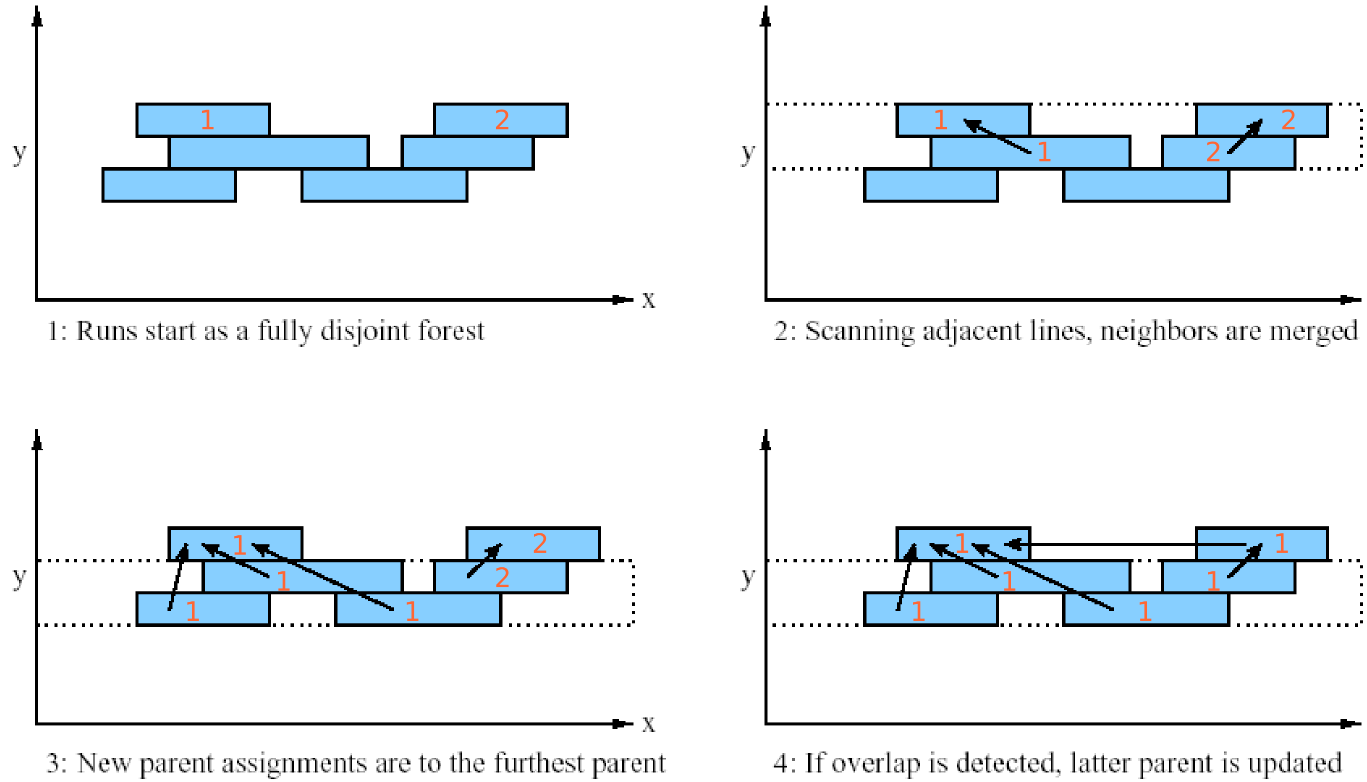
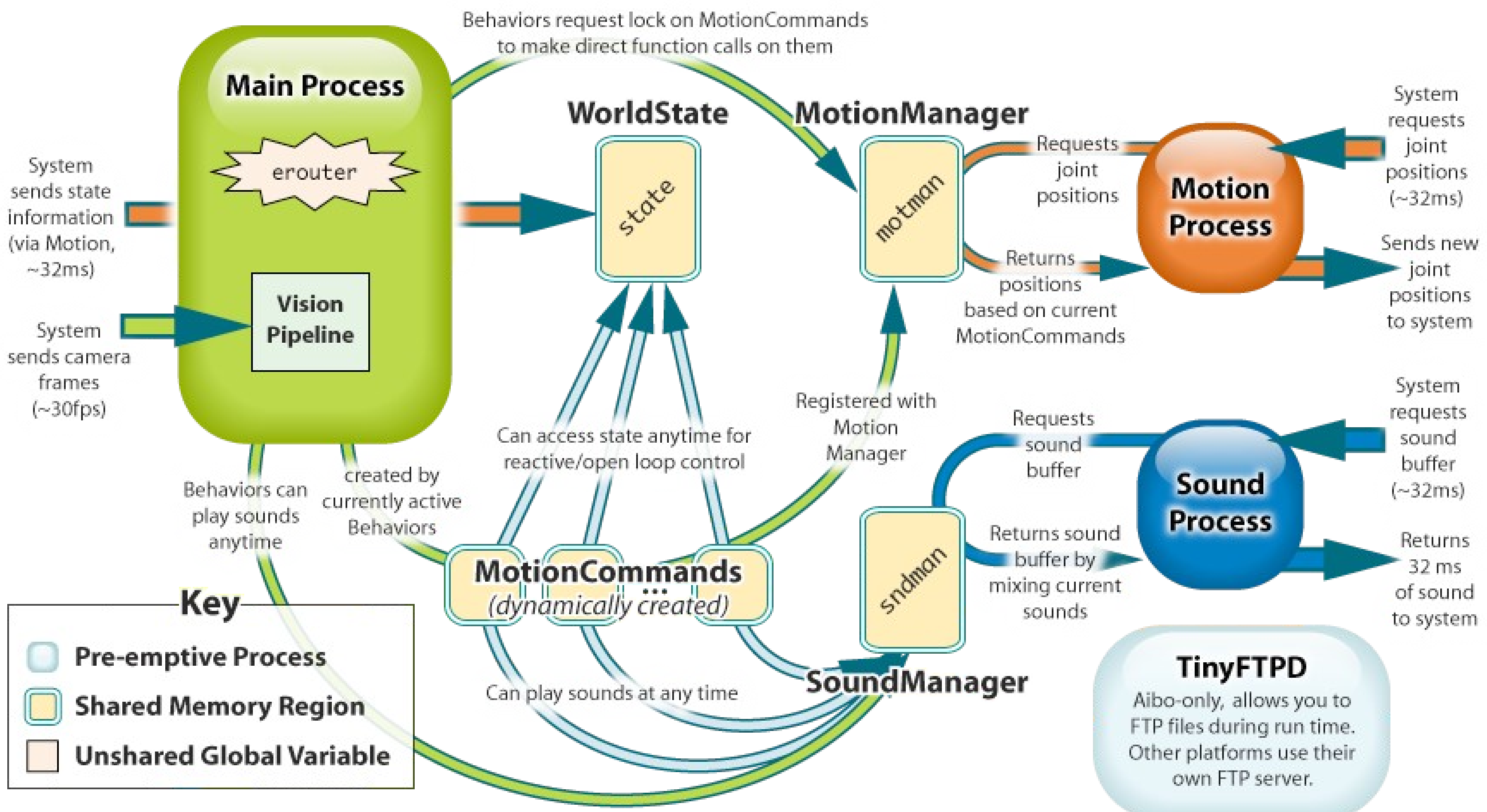


Image from
Bruce et al.,
IROS-2000

Tekkotsu Vision is Done in the Main Process

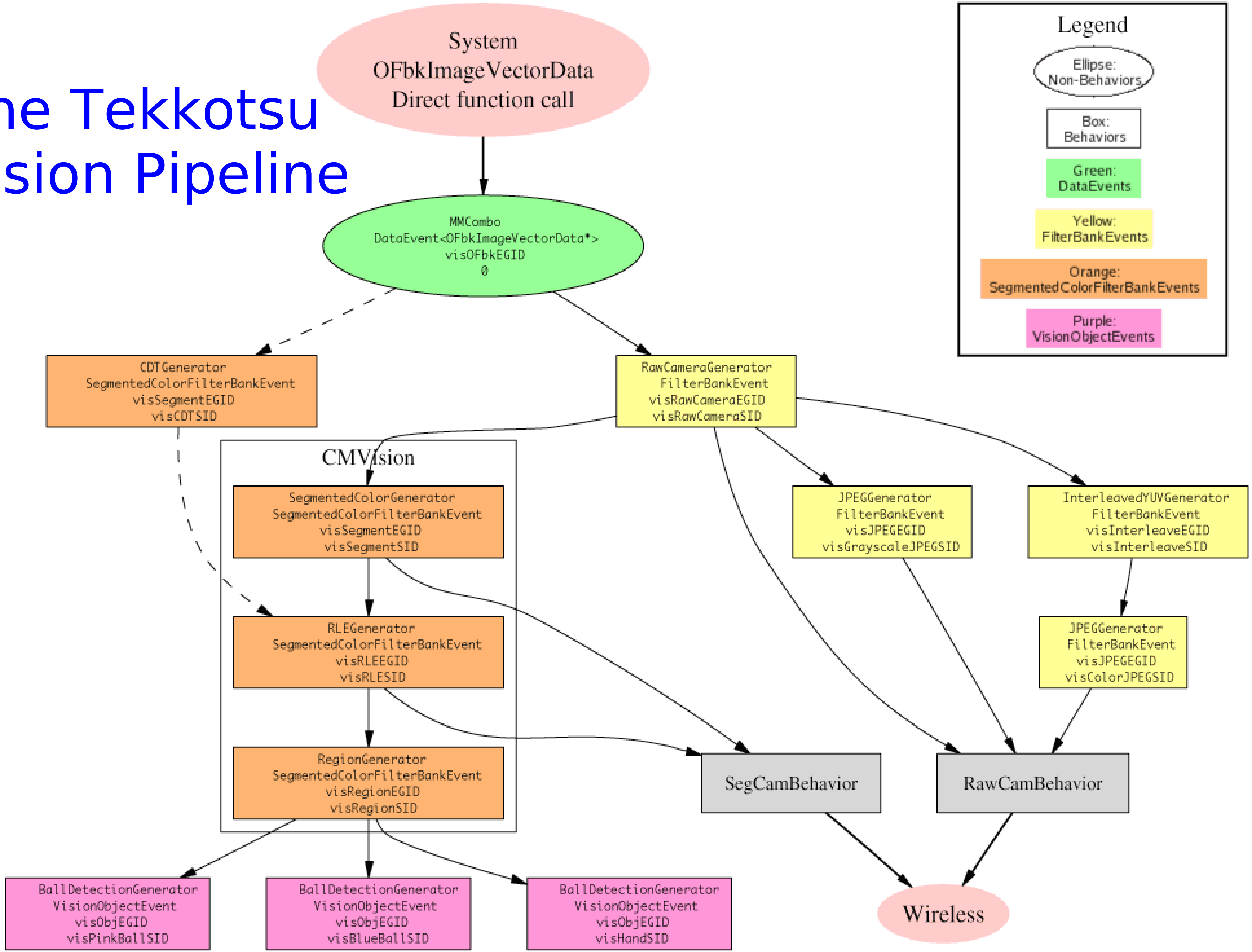


Tekkotsu Vision Pipeline

- CDTGenerator: color detection table (AIBO); unused
- SegmentedColorGenerator
  - Color classified images
- RLEGenerator
  - Run Length Encoding
- RegionGenerator
  - Connected components
- BallDetectionGenerator
  - Posts VisionObjectEvents for largest region if shape is roughly spherical
- DualCoding Representations / MapBuilder

CMVision

The Tekkotsu Vision Pipeline



Tekkotsu Vision Pipeline

- Image pyramid: double, full, half, quarter, eighth, and sixteenth resolution streams are available.
- Six channels available: Y, U, V, Y_dx, Y_dy, Y_dxdy. (The latter three are for edge detection.)
- Lazy evaluation: generators only run if some behavior has subscribed to their events.
- RawCameraGenerator and JPEGGenerator feed RawCamBehavior (for ControllerGUI RawCam viewer)
- SegCamBehavior uses RLE encoded images

Summary of Vision in Tekkotsu

- Simple blob detection using VisionObjectEvent (reports largest roughly spherical blob of a specified color)

- Dualcoding representations:
  - Sketches (pixel representation)
  - Shapes (symbolic representation)
  - Lookout, MapBuilder

- Object recognition using SIFT
  - Preliminary version implemented in 2006 as a student project.
  - New version was developed by Xinghao Pan in 2008 as a CS Senior Honors Thesis; will be released soon.