10 Sensors and Sensing

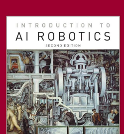
How do you make a robot “see”?

What sensors are essential for a robot?

What’s sensor fusion?

A subtle distinction between sensors and sensing

- **Sensors** provide the raw data, while
- **Sensing** is the combination of algorithm(s) and sensor(s) that produces a percept or world model



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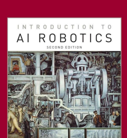
Objectives

Motivation
Dimensions
Non-imaging
Vision
-depth
-cues
AI
Summary

- Describe the difference between active and passive sensors, and give examples of each.
- List at least one advantage and disadvantage of common robotic sensors: GPS, INS, IR, cameras.
- Define image, pixel, and image function.
- If given a small interleaved RGB image and a range of color values for a region, be able to write code to extract color affordances using 1) threshold on color and 2) a color histogram.
- Write computer vision code to enable a robot to imprint on, and track, a color.



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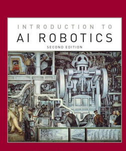
Objectives (Cont.)

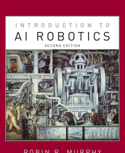
- Define each of the following terms in one or two sentences: proximity sensor, logical sensor, false positive, false negative, hue, saturation, and computer vision.
- Describe the three types of behavioral sensor fusion: fission, fusion, fashion.
- List the attributes for designing a sensor suite, and apply these attributes to a particular application.
- Define locomotion load and hotel load and explain why sufficient hotel load is critical for design of intelligent robots.



10 Return to Layers

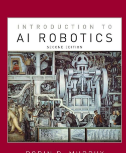
Motivation
Dimensions
Non-imaging
Vision
-depth
-cues
AI
Summary

- **In *behavioral layer*, sensing…**
  - **Supports a behavior**
  - **Releases a behavior**
- In *deliberative layer*, sensing…
  - Recognizes objects
  - **Builds world model** — When it acts as a *virtual sensor*
- In *interactive layer*, social sensing…
  - Personal spaces, facial features, and gestures



Ways of Organizing Sensors

- Types of Perception
  - Proprioceptive, exteroceptive, exproprioceptive
- Input
  - Active vs. passive
- Output
  - Image vs. non-image



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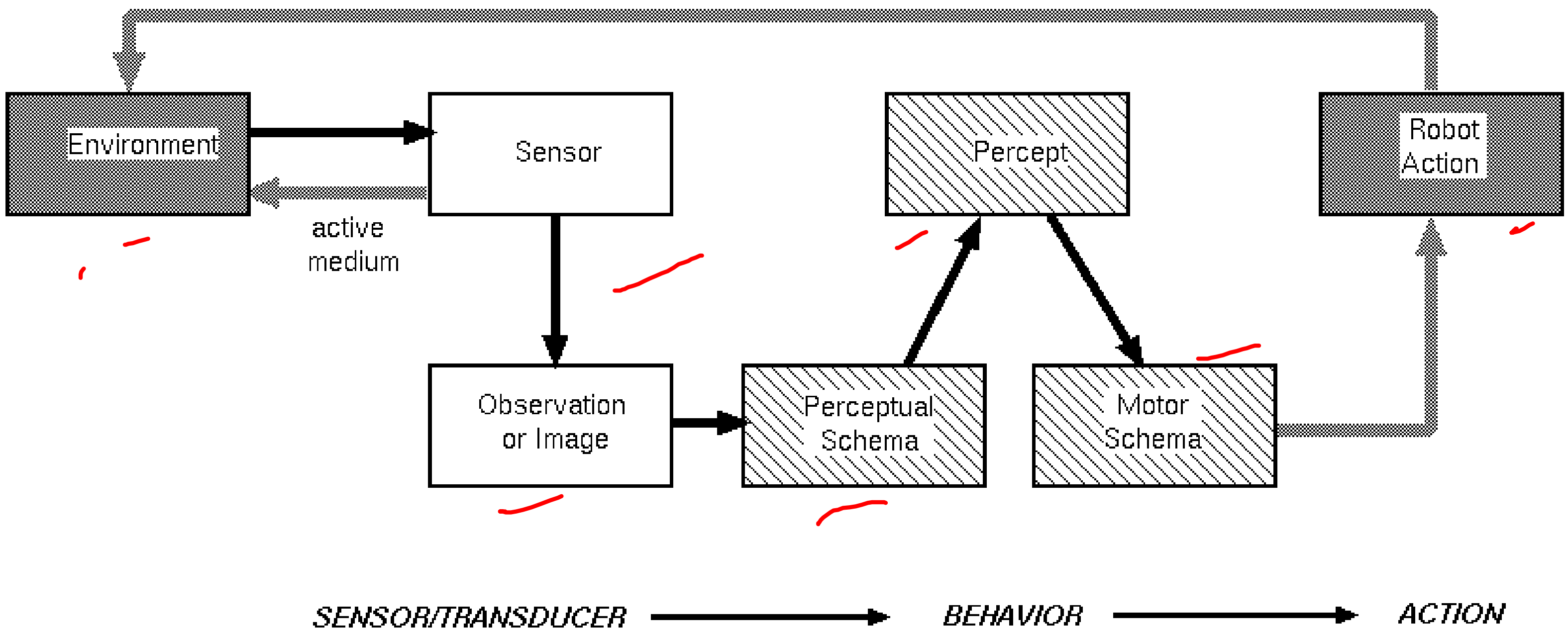
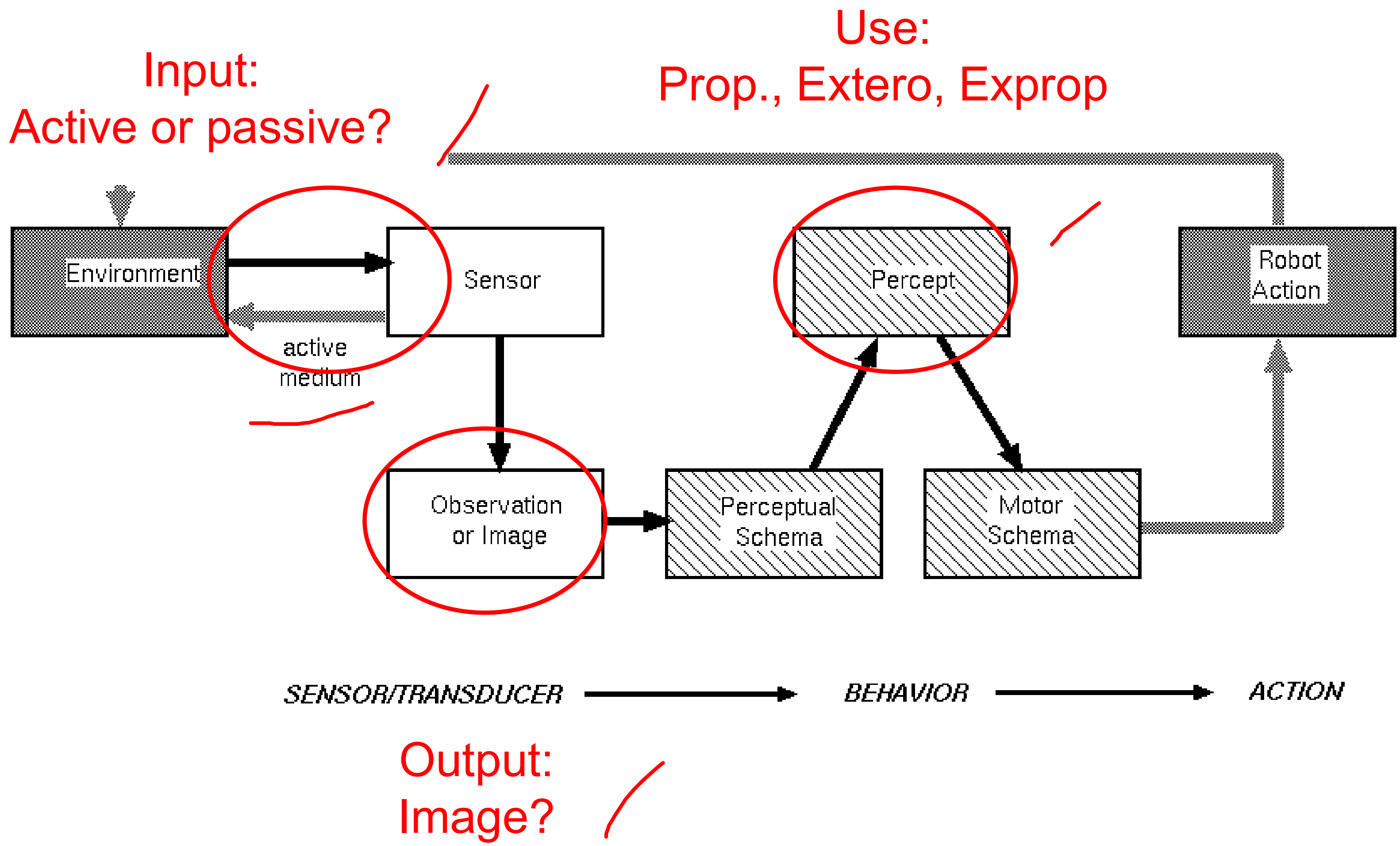
Sensor Model



10 Sensor Model



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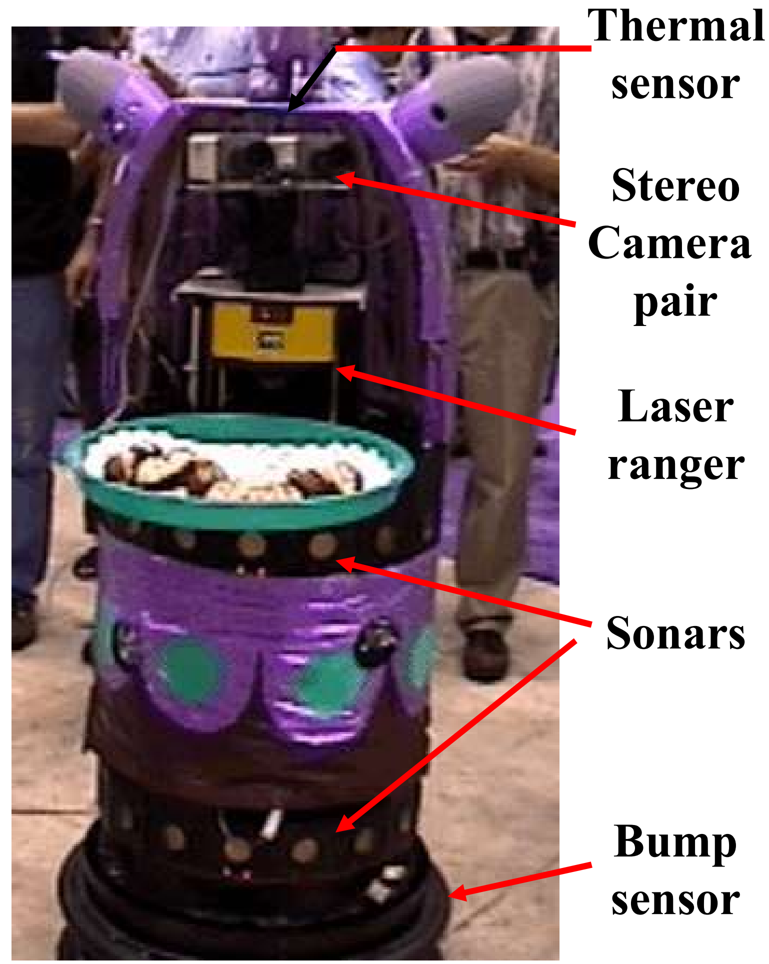
Sensor Input: Active vs. Passive

- Active sensors
  - Sensor emits some form of energy and then measures the impact as a way of understanding the environment
  - Ex. Ultrasonics, laser
- Passive sensors
  - Sensor receives energy already in the environment
  - Ex. Camera
- Passive consume less energy, but often signal:noise problems
- Active often have restricted environments



Sensor Output: Imagery vs. Observation

Motivation
Dimensions
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-cues
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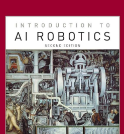
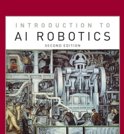
Summary

- Observation
  - Single value or vector
- Image
  - A picture-like format where there is a direct physical correspondence to the scene being imaged
  - Has an image function which maps a signal onto a pixel value



Types of Sensors

Motivation
Dimensions
Non-imaging
Vision
-depth
-cues
AI
Summary



- **Proprioception**
  - To locate the position of limbs and joints of the robot or to determine how much they have moved
  - Self-control
- **Exteroception**
  - To detect objects in the external world and often the distance to those objects
  - Navigation
  - Object recognition
- **Exproprioception**
  - To detect the position of the robot relative to objects in the world
  - Manipulation

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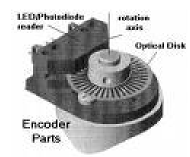
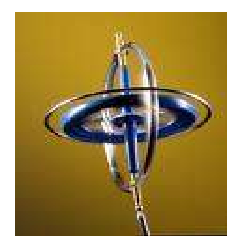
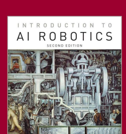
Proprioceptive Sensors

- Sensors that give information on the internal state of the robot, such as:
  - Motion
  - Position (x, y, z)
  - Orientation (about x, y, z axes)
  - Velocity, acceleration
  - Temperature
  - Battery level
- Example proprioceptive sensors:
  - Encoders (dead reckoning)
  - Inertial navigation system (INS)
  - Global positioning system (GPS)
  - Compass
  - Gyroscopes

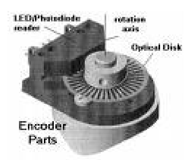


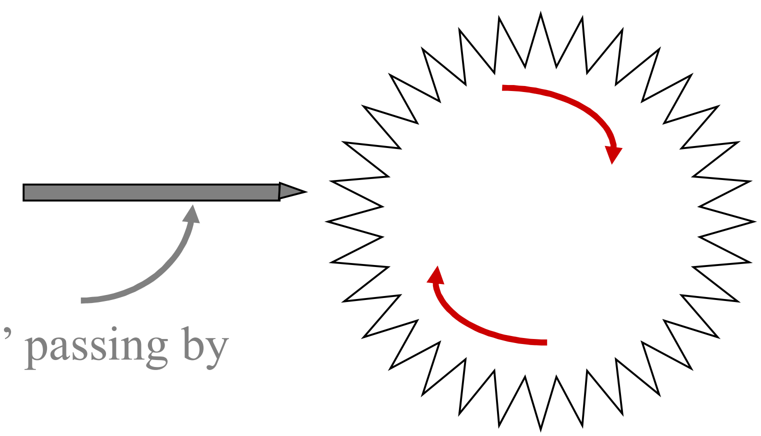




10 Dead Reckoning/Odometry/Encoders

- Purpose:
  - To measure turning distance of motors (in terms of numbers of rotations), which can be converted to robot translation/rotation distance
- If gearing and wheel size known, number of motor turns ➔ number of wheel turns ➔ estimation of distance robot has traveled
- Basic idea in hardware implementation:





Device to count number of "spokes" passing by

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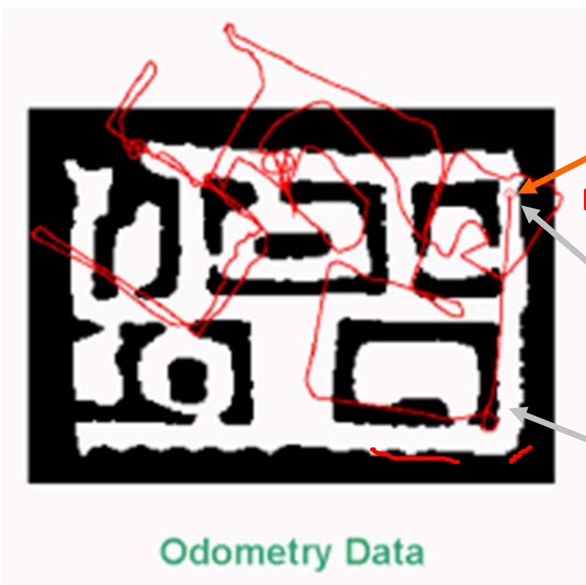
Encoders (cont.)

- Challenges/issues:
  - Motion of wheels not corresponding to robot motion, e.g., due to wheel spinning
  - Wheels don't move but robot does, e.g., due to robot sliding
- Error accumulates quickly, especially due to turning:



Robot start position

Red line indicates estimated robot position due to encoders/odometry/dead reckoning.

Begins accurately, but errors accumulate quickly

10 Inertial Navigation Sensors (INS)

- Inertial navigation sensors: measure movements electronically through miniature accelerometers

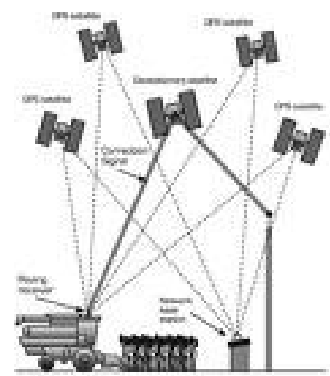
- Accuracy: quite good (e.g., 0.1% of distance traveled) if movements are smooth and sampling rate is high

- Problem for mobile robots:
  - Expensive: \$50,000 - \$100,000 USD
  - Robots often violate smooth motion constraint
  - INS units typically large

10

Differential Global Positioning System (DGPS)

- Satellite-based sensing system
- Robot GPS receiver:
  - Triangulates relative to signals from 4 satellites
  - Outputs position in terms of latitude, longitude, altitude, and change in time
- Differential GPS:
  - Improves localization by using two GPS receivers
  - One receiver remains stationary, other is on robot
- Sensor Resolution:
  - GPS alone: 10-15 meters
  - DGPS: up to a few centimeters



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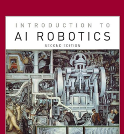
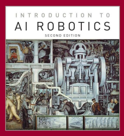
DGPS Challenges

- Does not work indoors in most buildings
- Does not work outdoors in “urban canyons” (amidst tall buildings)
- Forested areas (i.e., trees) can block satellite signals
- Cost is high (about $30,000)

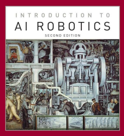


Proximity Sensors

- Proximity sensors directly measure the relative distance (range) between sensor and objects in the environment
  - Usually short distance (within one meter).
    - Ranger sensors will sense over much larger distance
  - Active sensors can detect objects before contact.
    - Infrared sensor (IR)
  - Passive sensors require contact with an object or surface
    - Contact (Tactile) Sensors: bumper, feeler (whisker)
- Note: Will talk about ranger sensors next chapter
  - Ultrasonics
  - Lasers



Contact Sensors

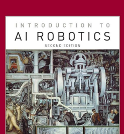


- About them:
  - Passive
- Advantages:
  - Cheap
- Disadvantages:
  - Poor sensitivity
  - Poor coverage
  - Poor localization
- *In development*
  - *Capacitance based "skins"*
  - *Mouse whiskers for robots*

Bump sensor

Infrared (IR) Sensor

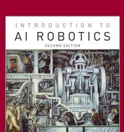
- About them:
  - Usually a *point sensor*, active
  - Emits a particular wavelength (near-infrared energy), then detects time to bounce back
  - Popular for indoor detection of collisions
- Advantages
  - Cheap
- Disadvantages
  - Sensitive to lighting conditions
    - the light emitted is often “washed out” by bright ambient lighting or is absorbed by dark materials
  - Short range so can’t go fast



10 Computer Vision Overview

Motivation
Dimensions
Non-imaging
Vision
-depth
-cues
AI
Summary

- Computer vision is the primary source of general purpose exteroceptive sensing for
  - Direct perception
  - Object recognition
- Will study a few of the basic algorithms used in direct perception (affordance)
  - Typically recognize specific things by pattern of color, heat signature, or fusion of these algorithms
- Computer vision can also be used for measuring distances (Next chapter)



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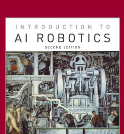
Computer Vision Introduction

- Computer vision: processing data from any modality that uses the electromagnetic spectrum which produces an image
- Image:
  - A way of representing data in a picture-like format where there is a direct physical correspondence to the scene being imaged
  - Results in a 2D array or grid of readings
  - Every element in array maps onto a small region of space
  - Elements in image array are called pixels
- Modality determines what image measures:
  - Visible light ➔ measures value of light (e.g. color or gray level)
  - Thermal ➔ measures heat in the given region
- Image function: converts a signal into a pixel value

Pan-Tilt-Zoom camera

CMU Cam (for color blob tracking)

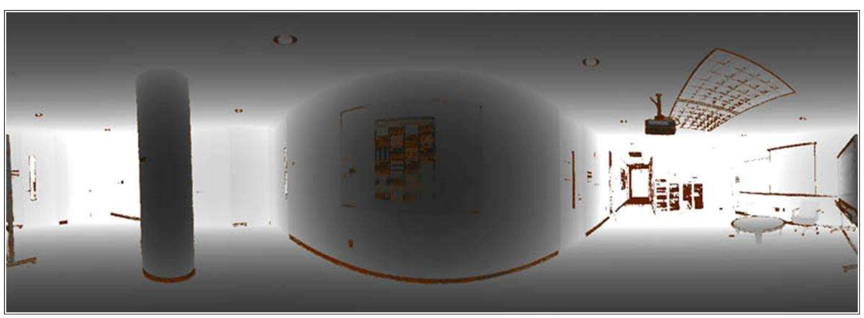
Stereo vision



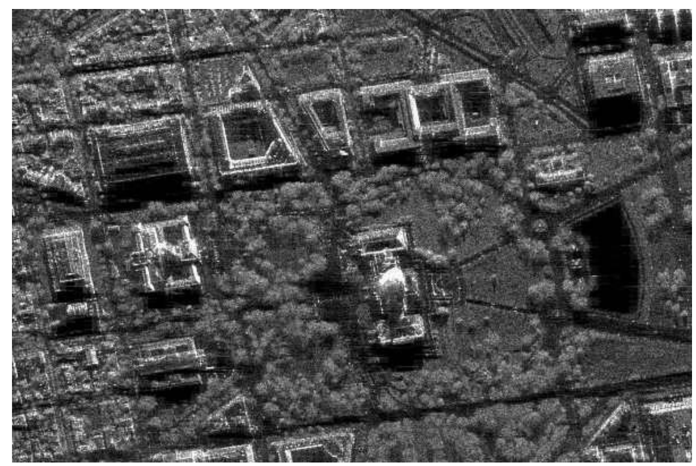
10 Types of Computer Vision

- Computer vision includes:
  - Cameras (produce images over same electromagnetic spectrum that humans see)
  - Thermal sensors
  - X-rays
  - Laser range finders
  - Synthetic aperture radar (SAR)

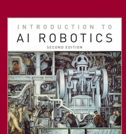
Thermal image



3D Laser scanner image



SAR image (of U.S. capitol building)



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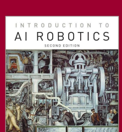
Computer Vision is a Field of Study on its Own

- Computer vision field has developed algorithms for:
  - Noise filtering
  - Compensating for illumination problems
  - Enhancing images
  - Finding lines
  - Matching lines to models
  - Extracting shapes and building 3D representations
- *However, behavior-based/reactive robots tend not to use these algorithms, due to high computational complexity*



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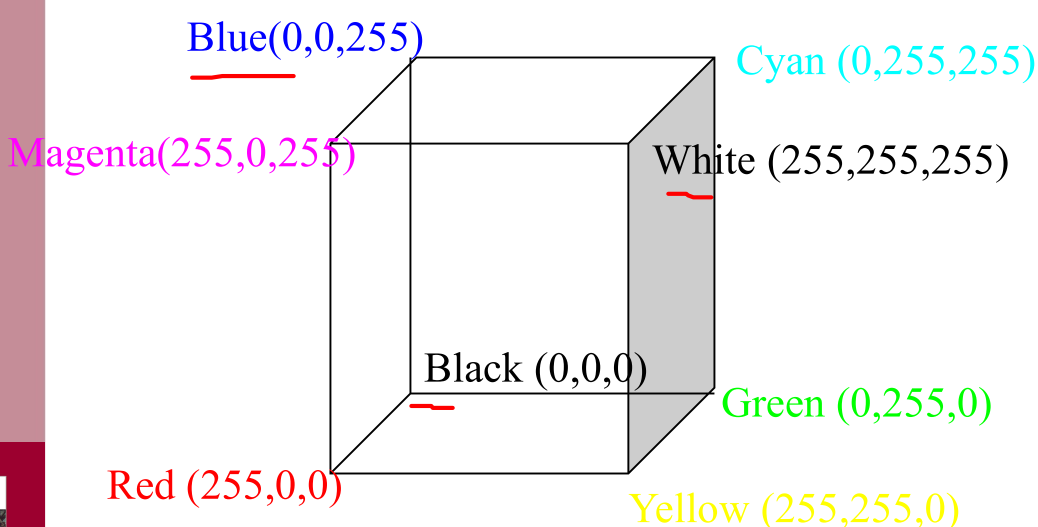
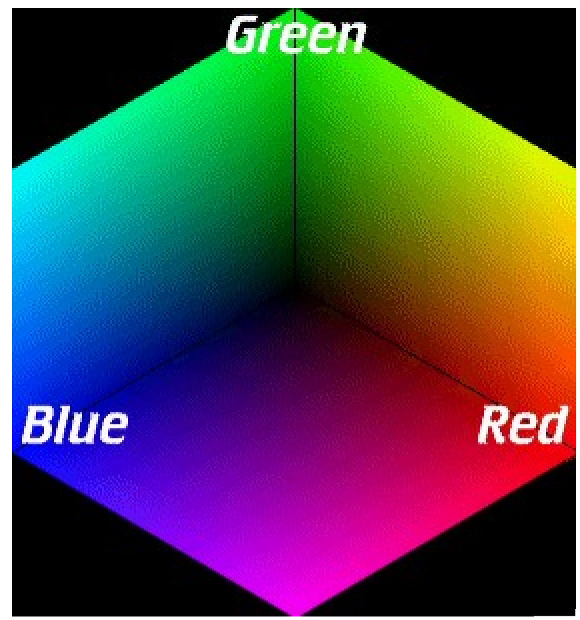
Representation of Color

- Color measurements expressed as three color planes – red, green, blue (abbreviated RGB)
- RGB usually represented as axes of 3D cube, with values ranging from 0 to 255 for each axis





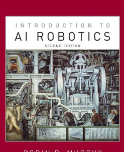
Software Representation

1. Interleaved: colors are stored together (most common representation)
   - Order: usually red, then green, then blue

Example code:

```
#define RED 0
#define GREEN 1
#define BLUE 2

int  image[ROW][COLUMN][COLOR_PLANE];
…
red = image[row][col][RED];
green = image[row][col][GREEN];
blue = image[row][col][BLUE];
display_color(red, green, blue);
```



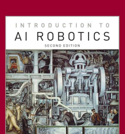
10 Software Representation (cont.)

2. Separate: colors are stored as 3 separate 2D arrays

Example code:

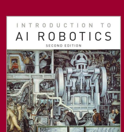
```
int   image_red[ROW][COLUMN];
int   image_green[ROW][COLUMN];
int   image_blue[ROW][COLUMN];

…
red = image_red[row][col];
green = image_green[row][col];
blue = image_blue[row][col];
display_color(red, green, blue);
```



10 Challenges Using RGB for Robotics

- Color is function of:
  - Wavelength of light source
  - Surface reflectance
  - Sensitivity of sensor
- → Color is not absolute;
  - Object may appear to be at different color values at different distances due to intensity of reflected light
- Digital camera devices are notoriously insensitive to red

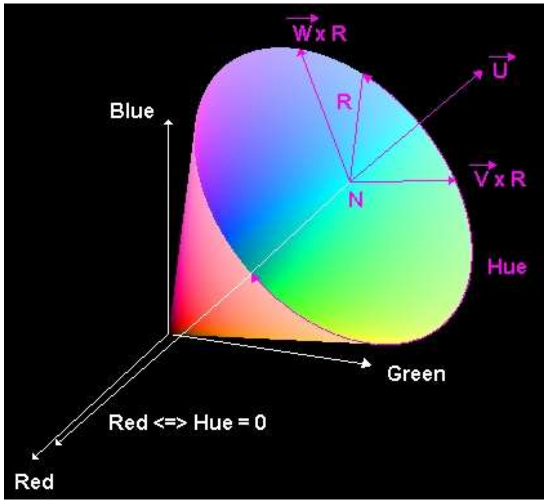


10 Better: Device which is sensitive to absolute wavelength

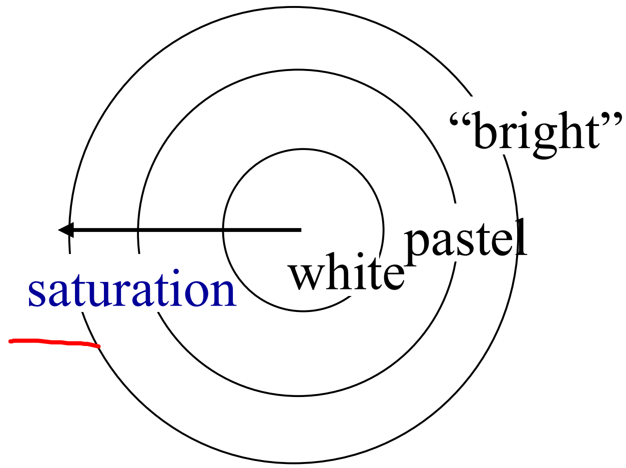
Better: Hue, saturation, intensity (or value) (HSV) representation of color – HSV has theoretical color constancy

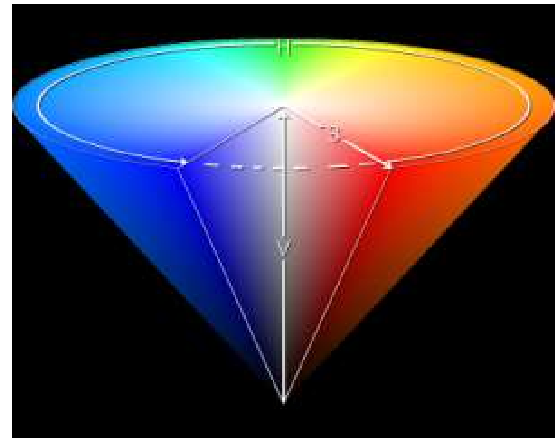
- Hue: dominant wavelength, does not change with robot's relative position or object's shape
- Saturation: lack of whiteness in the color (e.g., red is saturated, pink is less saturated)
- Intensity/Value: quantity of light received by the sensor

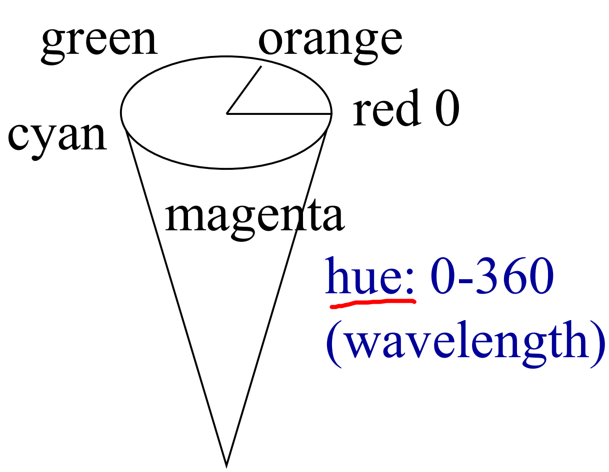
Transforming RGB to HSV

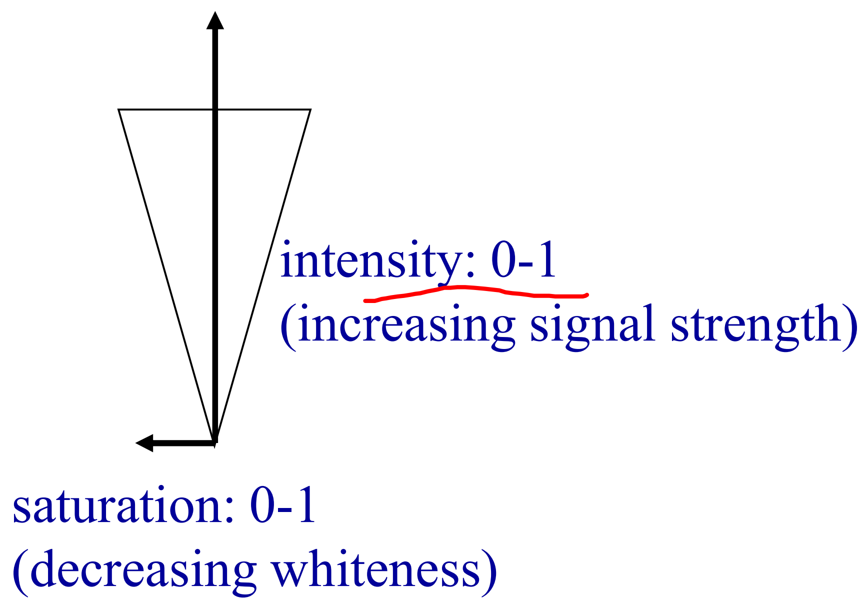


Representation of HSV





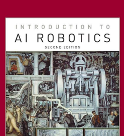




HSV Challenges for Robotics

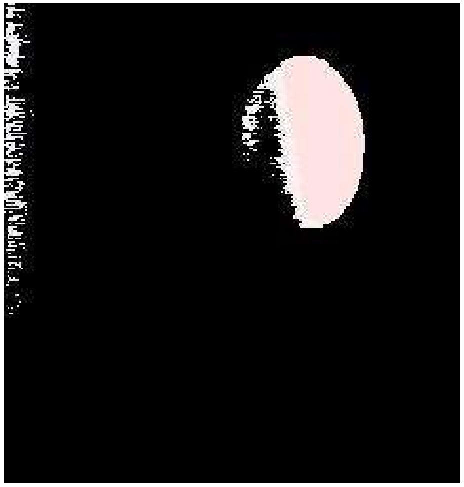
- Requires special cameras and framegrabbers
- Very expensive equipment

- Alternative: Use algorithm to convert -- Spherical Coordinate Transform (SCT)
  - Transforms RGB data to a color space that more closely duplicates response of human eye
  - Used in biomedical imaging, but not widely used for robotics
  - Much more insensitive to lighting changes

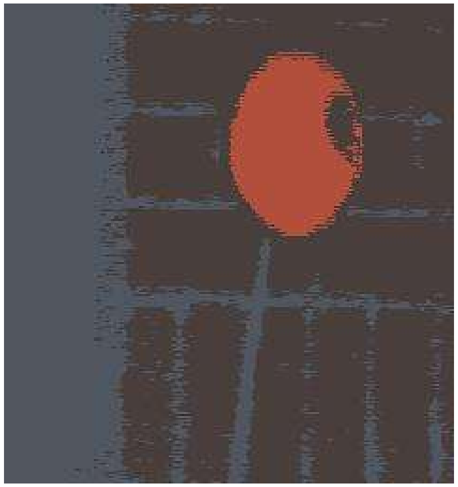


A comparison of color spaces

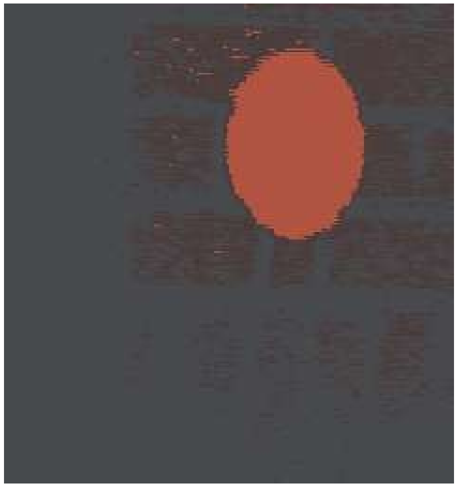
Original image



RGB Segmentation



HSV Segmentation



SCT Segmentation

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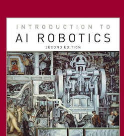
Region Segmentation

- Region Segmentation: most common use of computer vision in robotics, with goal to identify region in image with a particular color

- Basic idea: identify all pixels in image which are part of the region, then navigate to the region's centroid

- Steps:
  - Threshold all pixels which share same color (thresholding)
  - Group those together, throwing out any that don't seem to be in same area as majority of the pixels (region growing)



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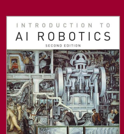
Example Code for Region Segmentation

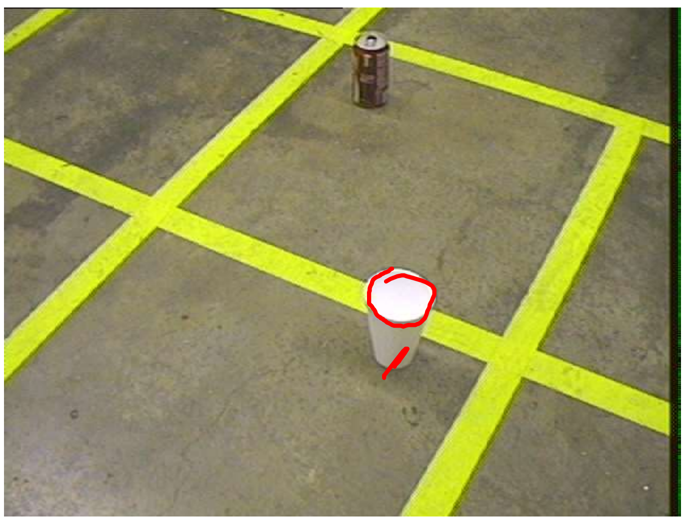
```
for (i=0; i<numberRows; i++)
  for (j=0; j<numberColumns; j++)
    { if (((ImageIn[i][j][RED] >= redValueLow)
          && (ImageIn[i][j][RED] <= redValueHigh))
          && ((ImageIn[i][j][GREEN] >= greenValueLow)
          && (ImageIn[i][j][GREEN] <= greenValueHigh))
          && ((ImageIn[i][j][BLUE] >= blueValueLow)
          && (ImageIn[i][j][BLUE] <= blueValueHigh)))
          ImageOUT[i][j] = 255;
      else
          ImageOut[i][j] = 0;
    }
```

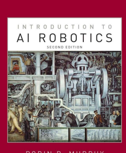
Note range of readings required due to non-absolute color values



Example of Color Segmentation

- Looked for red and white regions
- Note: yellow is ignored, shadows on cup cause problem





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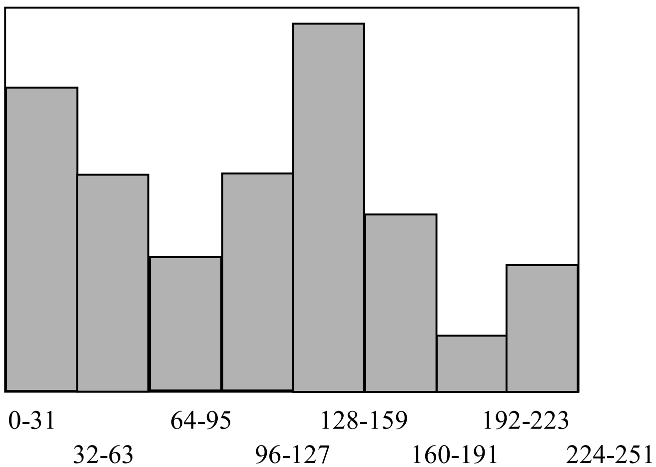
Color Histogramming

- Color histogramming:
  - Used to identify a region with several colors
  - Way of matching proportion of colors in a region
- Histogram:
  - Bar chart of data
  - User specifies range of values for each bar (called buckets)
  - Size of bar is number of data points whose value falls into the range for that bucket
- Example:

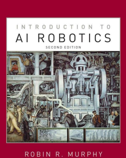


Color Cueing Algorithms Summary

- **Thresholding/color segmentation, blob analysis**
  - Make a binary image with all pixels in color range
  - Each group of connected pixels== region (or blob)
  - Extract region statistics
    - Size (change in size can be tied to looming, relative position)
    - Centroid (where to aim)
  - Lots of neat program tricks exploiting arrays
    - Scan *columns* until find first region pixel to see where to avoid

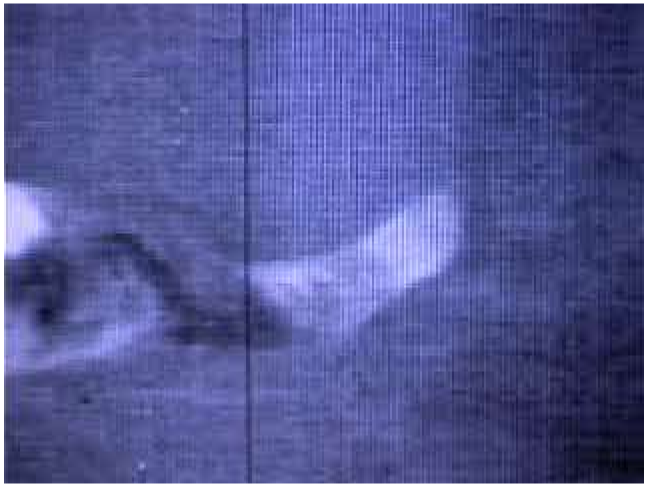
- **Color histogramming**
  - Distinguish an object by the proportions of each color in its signature

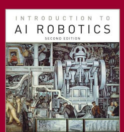
- Problems with these algorithms
  - Color constancy is hard
    - Some colors/ color spaces are better than others
  - Often have to do some pre-processing to clean up the image(s)
    - Mean/median Filtering



People Detection

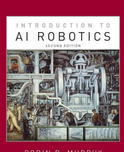
- Movement
  - Substract images/image differencing
  - Lots of work in this area, don't write your own!
- Heat
  - Digital thermometer v. FLIR
- Expectations
  - Color at certain height, heat from that area





10 Choosing Sensors and Sensing

- Three concepts for choosing sensors and sensing
  - **Logical or equivalent sensors**, that it may be possible to generate the same percept from different sensors or algorithms.
  - **Behavioral sensor fusion**, which describes the general methods of combining sensors to get a single percept or to support a complex behavior
  - **Attributes of a sensor suite** that can be used to help design a system



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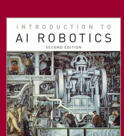
Sensor Modalities

- Sensor modality:
  - Sensors which measure same form of energy and process it in similar ways
  - “Modality” refers to the raw input used by the sensors
- Different modalities:
  - Sound
  - Pressure
  - Temperature
  - Light
    - Visible light
    - Infrared light
    - X-rays
    - Etc.



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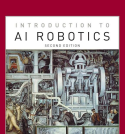
Logical Sensors

- Logical sensor:
  - Unit of sensing or module that supplies a particular percept
  - Consists of: signal processing from physical sensor, plus software processing needed to extract the percept
  - Can be easily implemented as a perceptual schema
- Logical sensor contains all available alternative methods of obtaining a particular percept
  - Example: to obtain a 360^{o} polar plot of range data, can use:
    - Sonar
    - Laser
    - Stereo vision
    - Texture
    - Etc.



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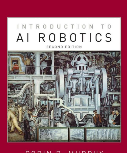
Behavioral Sensor Fusion

- Sensor suite: set of sensors for a particular robot
- Sensor fusion: any process that combines information from multiple sensors into a single percept
- Multiple sensors used when:
  - A particular sensor is too imprecise or noisy to give reliable data
- Sensor reliability problems:
  - False positive:
    - Sensor leads robot to believe a percept is present when it isn't
  - False negative:
    - Sensor causes robot to miss a percept that is actually present



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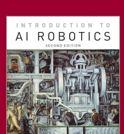
Three Types of Multiple Sensor Combinations

1. Redundant (or, competing)
   - Sensors return the same percept
   - Physical vs. logical redundancy:
     - Physical redundancy:
       - Multiple copies of same type of sensor
       - Example: two rings of sonar placed at different heights
     - Logical redundancy:
       - Return identical percepts, but use different modalities or processing algorithms
       - Example: range from stereo cameras vs. laser range finder



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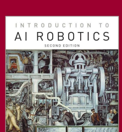
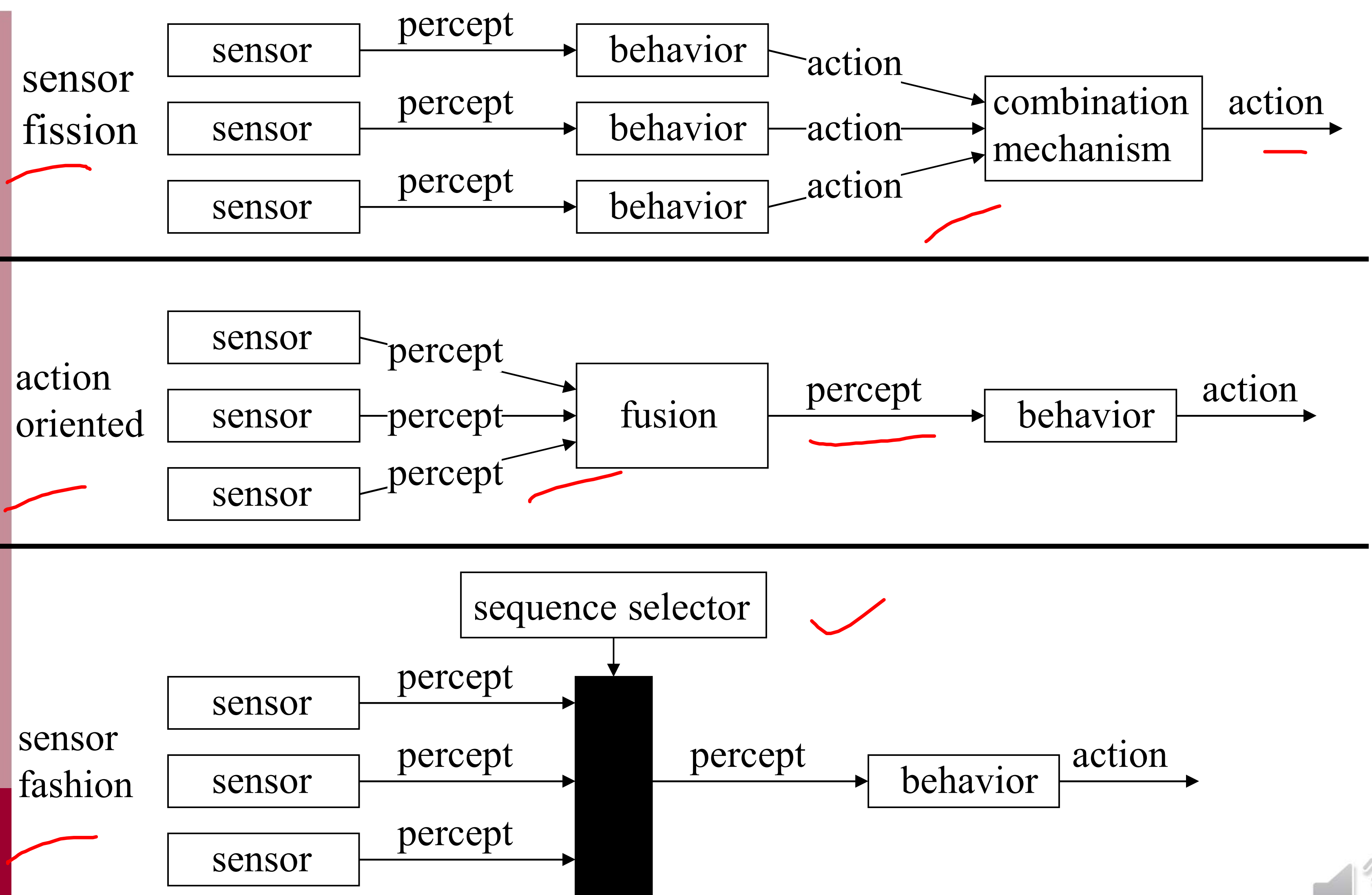
Three Types of Multiple Sensor Combinations (cont.)

2. Complementary
   - Sensors provide disjoint types of information about a percept
   - Example: thermal sensor for detecting heat + camera for detecting motion

3. Coordinated
   - Use a sequence of sensors
   - Example: cueing or focus-of-attention; see motion, then activate more specialized sensor



Three Types of behavior Sensor Fusion



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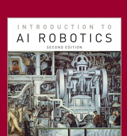
Returning to Questions

- **How do you make a robot "see"?**
  - – Sensor or transducer provides a measurement, which is then transformed into a percept
  - – Non-imaging sensors
    - Pose, location, range
  - – Imaging sensors
  - – Active or passive
  - – Transformations are either
    - Direct perception
      - – Color, motion, heat segmentation and blob analysis
    - Recognition
      - – Object recognition- semantics, models
      - – Construction of 3D representation from 2D sensor data



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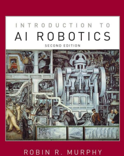
Designing a Sensor Suite

- Please read section 10.6.3 for details
- In order to construct a sensor suite, the following attributes should be considered for each sensor:
  1. Field of View and Range
  2. Accuracy, Repeatability, and Resolution
  3. Responsiveness in the target domain
  4. Power consumption
     - Locomotion load: the power needed to move the robot
     - Hotel load: the power required to support a sensor package and any other electronics, such as a microprocessor and communications links
  5. Size
  6. Computational complexity



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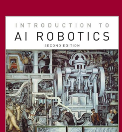
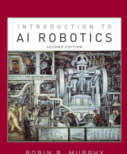


Returning to Questions

- **What sensors are essential for a robot?**
  - Movement and Navigation
    - Proprioception- joint, wheel encoders; accelerometers
    - Exteroception- at least a camera, range is helpful
    - Exproprioception- put the camera or haptics in the right place!
    - GPS
  - Health
    - Power
    - Communications status (heart beat)
    - General diagnostics!
  - Two-way audio
  - MISSION SENSORS



10 Returning to Questions

- **What's sensor fusion?**
  - Getting a single "percept"
  - Behavioral: fusion, fission, fashion
    - Create combinations of redundant, complementary, competing sensors