Module 1
Introduction

- Quickstart: Read & Display Images
- Introduction
- Types of Images
- Imaging Geometry
- Image Representation

Read & Display ".bin" Images

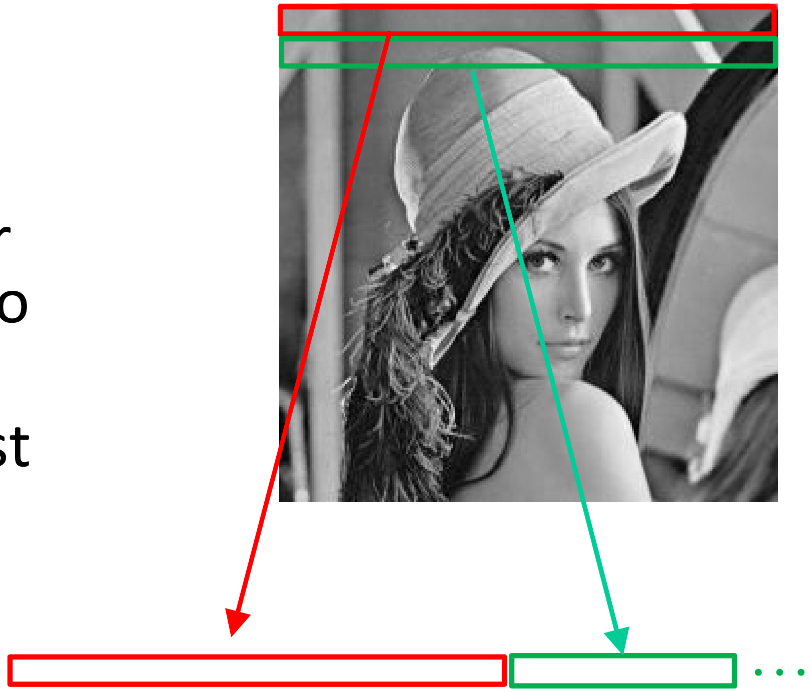
- Many of our images will have file type ".bin"
- This is not a "standard" file type!
  - ► These files contains raw image data without any header information.
- Programs like *Microsoft Office Picture Manager* can't display ".bin" files directly.
- But raw image files are easy to work with because the format is simple and there's no complicated header to parse.

What's Inside a ".bin" Image File

- It is usually a grayscale image.
- Each pixel (picture element) is one byte.
  - ► The data type is uchar (also known as uint8).
  - ► The min value is 00000000b = 00h = 0d, which displays as the darkest black.
  - ► The max value is 11111111b = FFh = 255d, which displays as the brightest white.

Inside a ".bin" Image File

- The file contains a linear array of bytes: one for each pixel.
- The pixels are stored in "raster scan" order: left to right, top to bottom.
- For a 256 × 256 image, the first 256 bytes are the pixels of the top row from left to right.
- The next 256 bytes are the pixels of the second row, from left to right, and so on.



Read & Display ".bin" Using Matlab

```
fidLena = fopen('lena.bin','r');
[Lena,junk] = fread(fidLena,[256,256],'uchar');
junk % echo the number of bytes that were read
Lena = Lena'; % you must transpose the image

figure(1);colormap(gray(256));
image(Lena);
axis('image');
title('Original Lena Image');
print -dtiff M_Lena.tif; % write figure as tif

fidOut = fopen('Outfile.bin','w+');
LenaOut = Lena'; % transpose before writing
fwrite(fidOut,LenaOut,'uchar'); % write raw image data
fclose(fidLena);fclose(fidOut);
```

Some Notes About Matlab

- When you use fread to read a ".bin" image, you must transpose the array after reading.
  - ► This is a legacy issue related to the fact that Matlab was originally written in FORTRAN, but was later re-implemented in C.
  - ► In FORTRAN, 2D arrays are stored in memory in column-major order, but in C they are stored in row-major order (see next page).
- If you read the image into a 2D Matlab array X (and transpose), then X(m,n) is the pixel at row=m and col=n. X(1,1) is the upper left pixel of the image. X(5,7) is the pixel on row 5 and column 7.
- Reasons TO use Matlab: it's easy and has lots of built in function support (to display images, for example).
- Reasons NOT to use Matlab: it can be slow for big images!
- Use matrix operations and avoid loops wherever possible!
  - ► Ex: to copy a block of pixels, use K(1:256,1:128) = J(1:256,129:256) instead of a loop.

More on 2D Array Indexing

- A 2D C array is stored in memory in row-major order. If you traverse the elements in order, the **last** index varies fastest. To avoid cache faults when accessing x[m][n] with nested loops, the outer loop should be m and the inner loop should be n.
- A FORTRAN 2D array is stored in column-major order. If you traverse the elements in order, the **first** index varies fastest. To avoid cache faults when accessing x(m,n) with nested loops, the outer loop should be n and the inner loop should be m.
- When using large 2D arrays in Matlab, it is important to remember that Matlab was originally written in FORTRAN.

```
%
% LoopTime.m
%
xsize = 20000;
x = rand(xsize,xsize);
y = zeros(xsize,xsize);
tic
for row=1:xsize
  for col=1:xsize
    y(row,col) = x(row,col);
  end
end
toc
tic
for col=1:xsize
  for row=1:xsize
    y(row,col) = x(row,col);
  end
end
toc
```

Matlab Console Output:

```
>> LoopTime
Elapsed time is 28.483111 seconds.
Elapsed time is 2.889330 seconds.
```

►The loops run 10x faster the 2^{nd} way!

Read & Display “.bin” Using C

```
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <string.h>

#define BYTE unsigned char

/*
 * Function Prototypes (forward declarations)
 */
void disk2byte();
void byte2disk();


/*----------------------------------------------------------------------*/
/*   MAIN                                                               */
/*----------------------------------------------------------------------*/

main(argc,argv)

  int     argc;
  char   *argv[];
{

  int      size;                /* num rows/cols in images */
  int      so2;                 /* size / 2 */
  int      i;                   /* counter */
  int      row;                 /* image row counter */
  int      col;                 /* image col counter */
  BYTE    *I1;                  /* input image I1 */
```

```
  BYTE    *I2;                    /* input image I2 */
  BYTE    *J;                     /* output image J */
  BYTE    *K;                     /* output image K */
  char    *InFn1;                 /* input filename for image I1 */
  char    *InFn2;                 /* input filename for image I2 */
  char    *OutFnJ;                /* output filename for image J */
  char    *OutFnK;                /* output filename for image K */

 /*
  * Check for proper invocation, parse args
  */
  if (argc != 6) {
    printf("\n%s: Swap image halves for hw01.",argv[0]);
    printf("\nUsage: %s size InFn1 InFn2 OutFnJ OutFnK\n",
           argv[0]);
    exit(0);
  }
  size = atoi(argv[1]);
  if (size % 2) {
    printf("\n%s: size must be divisible by 2.\n",argv[0]);
    exit(0);
  }
  InFn1 = argv[2];
  InFn2 = argv[3];
  OutFnJ = argv[4];
  OutFnK = argv[5];

  so2 = size >> 1;

/*
  * Allocate image arrays
  */
  if ((I1 = (BYTE *)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted.\n",argv[0]);
    exit(-1);
  }
```

```
 if ((I2 = (BYTE *)malloc(size*size*sizeof(BYTE))) == NULL) {
   printf("\n%s: free store exhausted.\n",argv[0]);
   exit(-1);
 }
 if ((J = (BYTE *)malloc(size*size*sizeof(BYTE))) == NULL) {
   printf("\n%s: free store exhausted.\n",argv[0]);
   exit(-1);
 }
 if ((K = (BYTE *)malloc(size*size*sizeof(BYTE))) == NULL) {
   printf("\n%s: free store exhausted.\n",argv[0]);
   exit(-1);
 }

/*
 * Read input images
 */
 disk2byte(I1,size,size,InFn1);
 disk2byte(I2,size,size,InFn2);

/*
 * Make output image J: left half is I1, right half is I2
 */
 for (i=row=0; row < size; row++) {
   for (col=0; col < so2; col++,i++) {
     J[i] = I1[i];
   }
   for ( ; col < size; col++,i++) {
     J[i] = I2[i];
   }
 }
```

```
 /*
  * Make output image K: swap left and right halves of J
  */
  for (row=0; row < size; row++) {
    for (col=0; col < so2; col++) {
      K[row*size + col] = J[row*size + col+so2];
    }
    for ( ; col < size; col++) {
      K[row*size + col] = J[row*size + col-so2];
    }
  }

 /*
  * Write the output images
  */
  byte2disk(J,size,size,OutFnJ);
  byte2disk(K,size,size,OutFnK);

  return;
} /*----------------  Main  ----------------------------------------------*/

/*----------------------------------------------------------------------
 * disk2byte.c
 *
 *   function reads an unsigned char (byte) image from disk
 *
 *
 *  jph 15 June 1992
 *
 ----------------------------------------------------------------------*/

void disk2byte(x,row_dim,col_dim,fn)

  BYTE    *x;             /* image to be read */
  int     row_dim;        /* row dimension of x */
  int     col_dim;        /* col dimension of x */
  char   *fn;             /* filename */
{
```

```
int fd;               /* file descriptor */
int n_bytes;          /* number of bytes to read */

 /*
  * detect zero dimension input
  */
  if ((row_dim==0) || (col_dim==0)) return;

 /*
  * open the file
  */
  if ((fd = open(fn, O_RDONLY))==-1) {
    printf("\ndisk2byte.c : could not open %s !",fn);
    return;
  }

 /*
  * read image data from the file
  */
  n_bytes = row_dim * col_dim * sizeof(unsigned char);
  if (read(fd,x,n_bytes) != n_bytes) {
    printf("\ndisk2byte.c : complete read of %s did not succeed.",fn);
  }

 /*
  * close file and return
  */
  if (close(fd) == -1) printf("\ndisk2byte.c : error closing %s.",fn);
  return;
}
```

```
/*---------------------------------------------------------------------
 * byte2disk.c
 *
 *   function writes an unsigned char (byte) image to disk
 *
 *
 *  jph 15 June 1992
 *
 ---------------------------------------------------------------------*/

void byte2disk(x,row_dim,col_dim,fn)

  BYTE  *x;              /* image to be written */
  int   row_dim;         /* row dimension of x */
  int   col_dim;         /* col dimension of x */
  char *fn;              /* filename */
{

  int fd;               /* file descriptor */
  int n_bytes;          /* number of bytes to read */

 /*
  * detect zero dimension input
  */
  if ((row_dim==0) || (col_dim==0)) return;

 /*
  * create and open the file
  */
  if ((fd = open(fn, O_WRONLY | O_CREAT | O_TRUNC, 0644))==-1) {
    printf("\nbyte2disk.c : could not open %s !",fn);
    return;
  }
```

```
 /*
  * write image data to the file
  */
  n_bytes = row_dim * col_dim * sizeof(unsigned char);
  if (write(fd,x,n_bytes) != n_bytes) {
    printf("\nbyte2disk.c : complete write of %s did not succeed.",fn);
  }

 /*
  * close file and return
  */
  if (close(fd) == -1) printf("\nbyte2disk.c : error closing %s.",fn);
  return;
}
```

Some Notes About C

- C is good because it is FAST and has powerful syntax for performing low level (bit & byte) operations on image data.
- You need a good compiler. See “links” on the course web site to obtain the excellent GNU gcc compiler. It will compile the code in the previous example.
- You need a good debugger. See “links” on the course web site to get DDD.
- You need good library routines to display images and to read images with headers. See “links” on the course web site to get ImageMagick.
  - Also see the “Image Magick HOWTO” under “Handouts” on the course web site.
- Array indexing in C starts at ZERO. This is an important difference from Matlab.
  - The top row of the image is row 0. The first column is col 0.
  - For a 256 × 256 image, X[m*256 + n] is the pixel at row=m and col=n.
  - For a 2D C array, X[m][n] is the pixel at row=m and col=n.
- If you read the image into a 1D C array, it’s easy to handle the case where the image SIZE is unknown at compile time.
- The main reasons to use C are that it is FAST and PORTABLE… faster debugging and doesn’t depend on having a Matlab installation.

Convert ".bin" Image to ".pgm"

- If you want to directly display a ".bin" image using standard programs like *Microsoft Office Picture Manager*, you need to add a header.
- The easiest way is to make a ".pgm" file.
- For a 256 × 256 ".bin" image, add the following 15-byte header:

HEX	50	35	0A	32	35	36	20	32
ASCII	P	5	.	2	5	6	_	2

HEX	35	36	0A	32	35	35	0A
ASCII	5	6	.	2	5	5	.

- You can do this manually with a hex-capable editor like vi (unix) or Vim (windows or unix).
- Or you can use a program like the function "pgm_convert.m" available on the course web site under "Code."

Course Objectives

- Learn **Digital Image & Video Processing**
  - ► Theory
  - ► Algorithms and Programming
  - ► Applications and Projects
- Have fun doing it

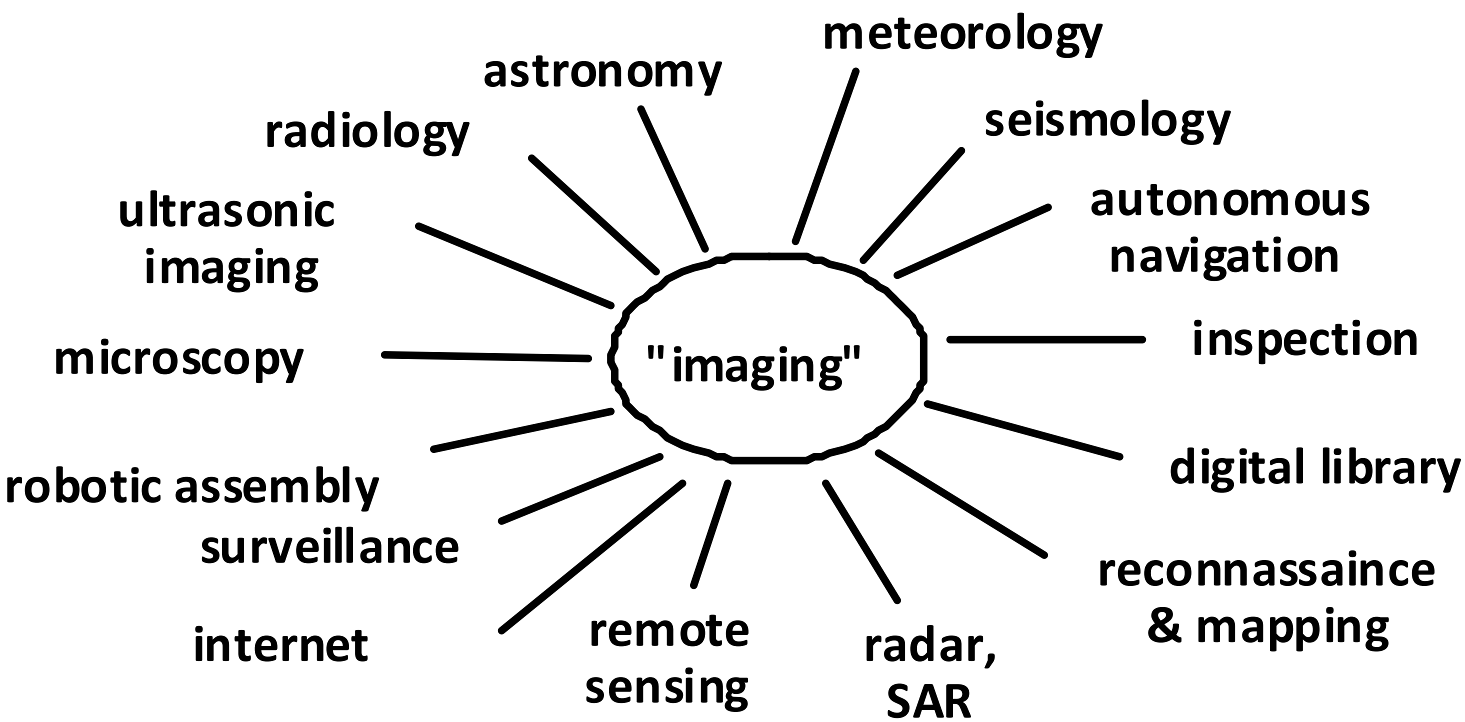
Some Good Books

- ***Digital Image Processing***, R.C. Gonzalez and R. Woods, 3rd Edition, 2012.
  User-friendly textbook, nicely illustrated. Used previously in this course
- ***Digital Image Processing***, W.K. Pratt, Wiley, 4th Edition, 2007.
  Encyclopedic, rather dated.
- ***Digital Picture Processing,*** Rosenfeld & Kak, 2nd Edition, 1982.
  Encyclopedic but readable.
- ***Fundamentals of Digital Image Processing***, Jain, 1988.
  Handbook-style, terse. Meant for advanced level.
- ***Digital Video Processing***, M. Tekalp, Prentice-Hall, 1995.
  Only book devoted to digital video; high-level; excellent
- ***Machine Vision***, Jain, Kasturi, and Schunk, McGraw-Hill, 1995
  Beginner's book on computer vision.
- ***Robot Vision***, B.K.P. Horn, MIT Press, 1986
  Advanced-level book on computer vision.

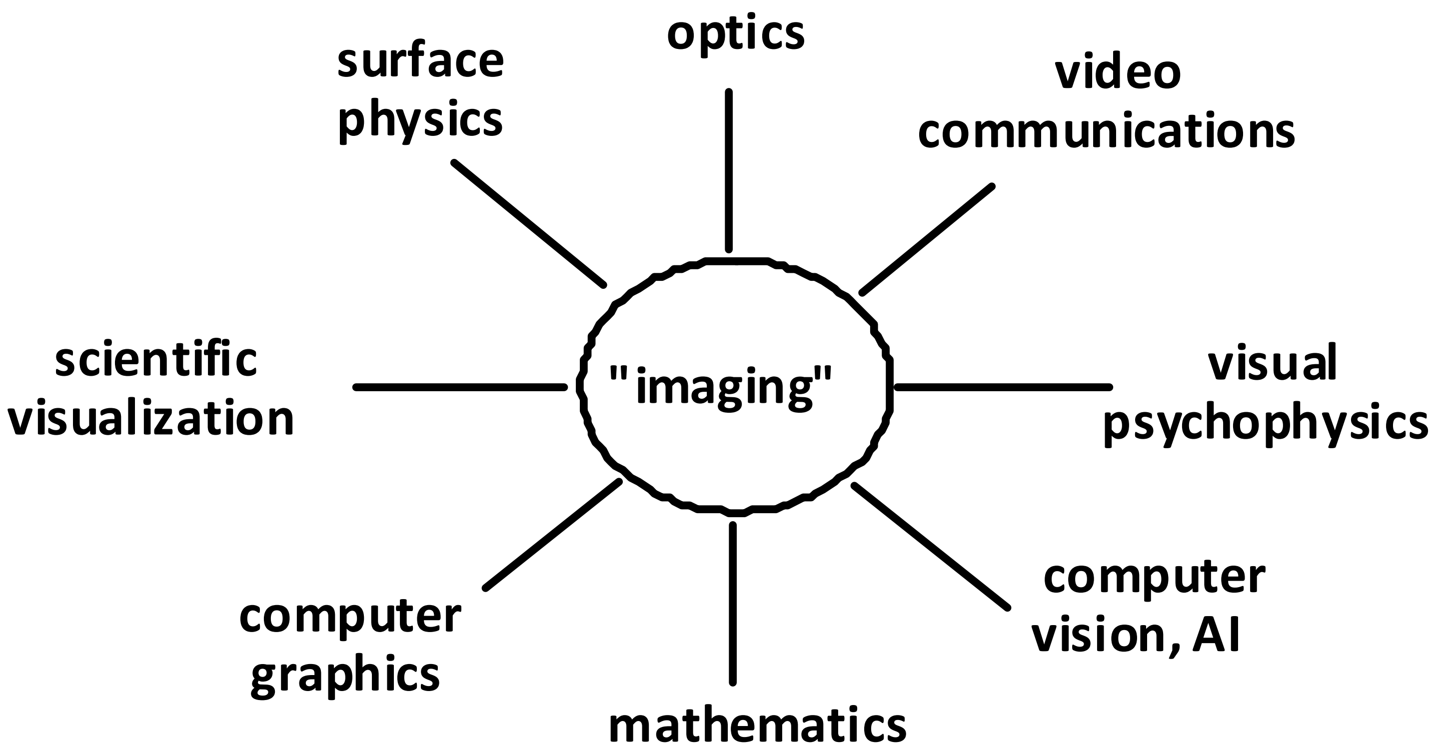
Journals

- ***IEEE Transactions** on:*
  - *Image Processing*
  - *Pattern Analysis & Machine Intelligence*
  - *Multimedia*
  - *Geoscience and Remote Sensing*
  - *Medical Imaging*
- *Computer Vision, Graphics, and Image Processing*
  - *Image Understanding*
  - *Graphics and Image Processing*
- *Pattern Recognition*
- *Image and Vision Computing*
- *Journal of Visual Communication and Image Representation*

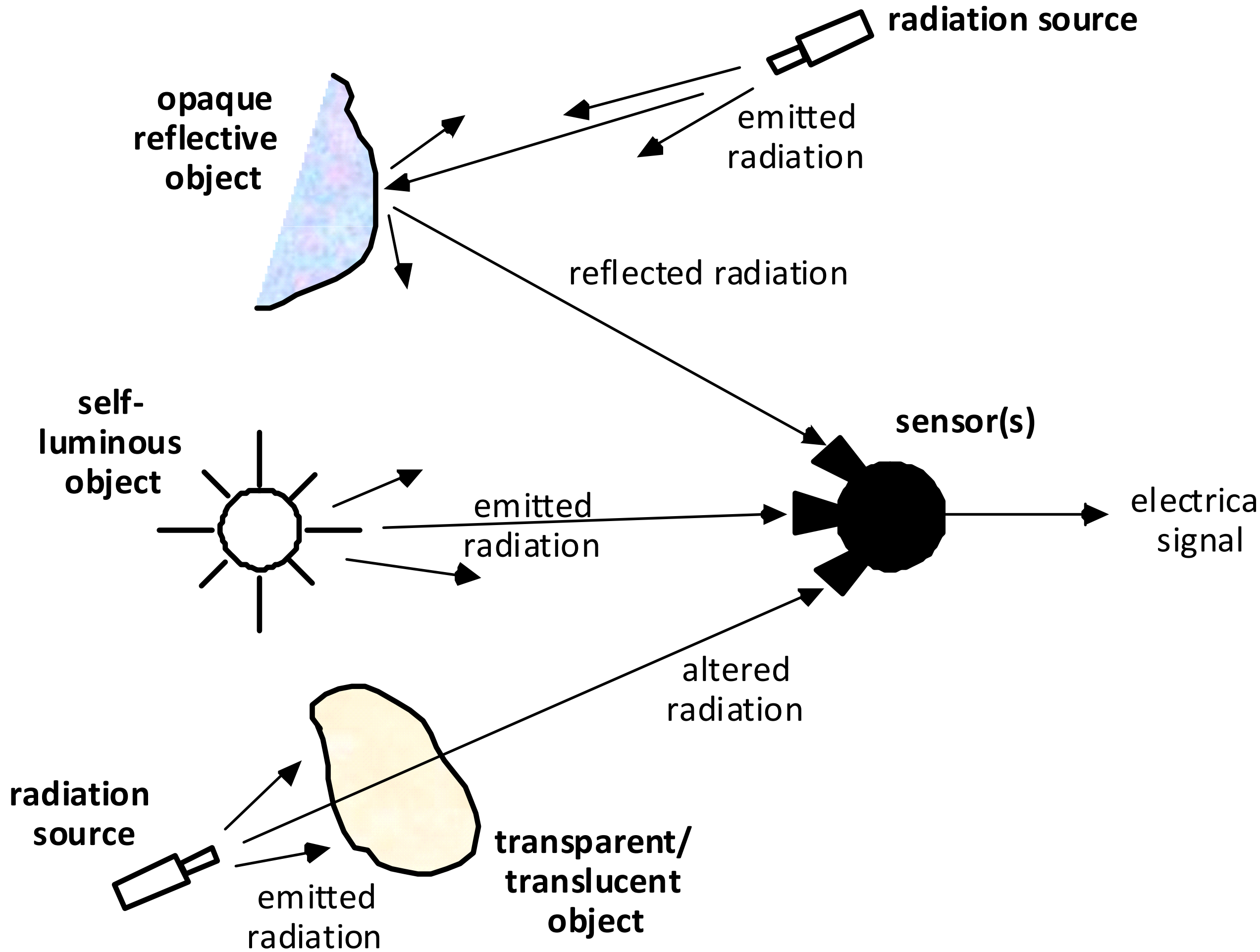
Applications of DIP/DVP



A Multidisciplinary Science



Three Types of Images



Type #1: Reflection Images

- Image information is **surface** information: how an object **reflects/absorbs** radiation

  - **Optical** (visual, photographic)

  \- **Radar**

  \- **Ultrasound, sonar** (non-EM)

  - Electron Microscopy

Type #2: Emission Images

- Image information is **internal** information: how an object **creates** radiation

  - Thermal, infrared (FLIR)

  - Astronomy (stars, nebulae, etc.)

  - Nuclear (particle emission, e.g., MRI)

Type #3: Absorption Images

- Image information is **internal** information: how an object **modifies/absorbs** radiation

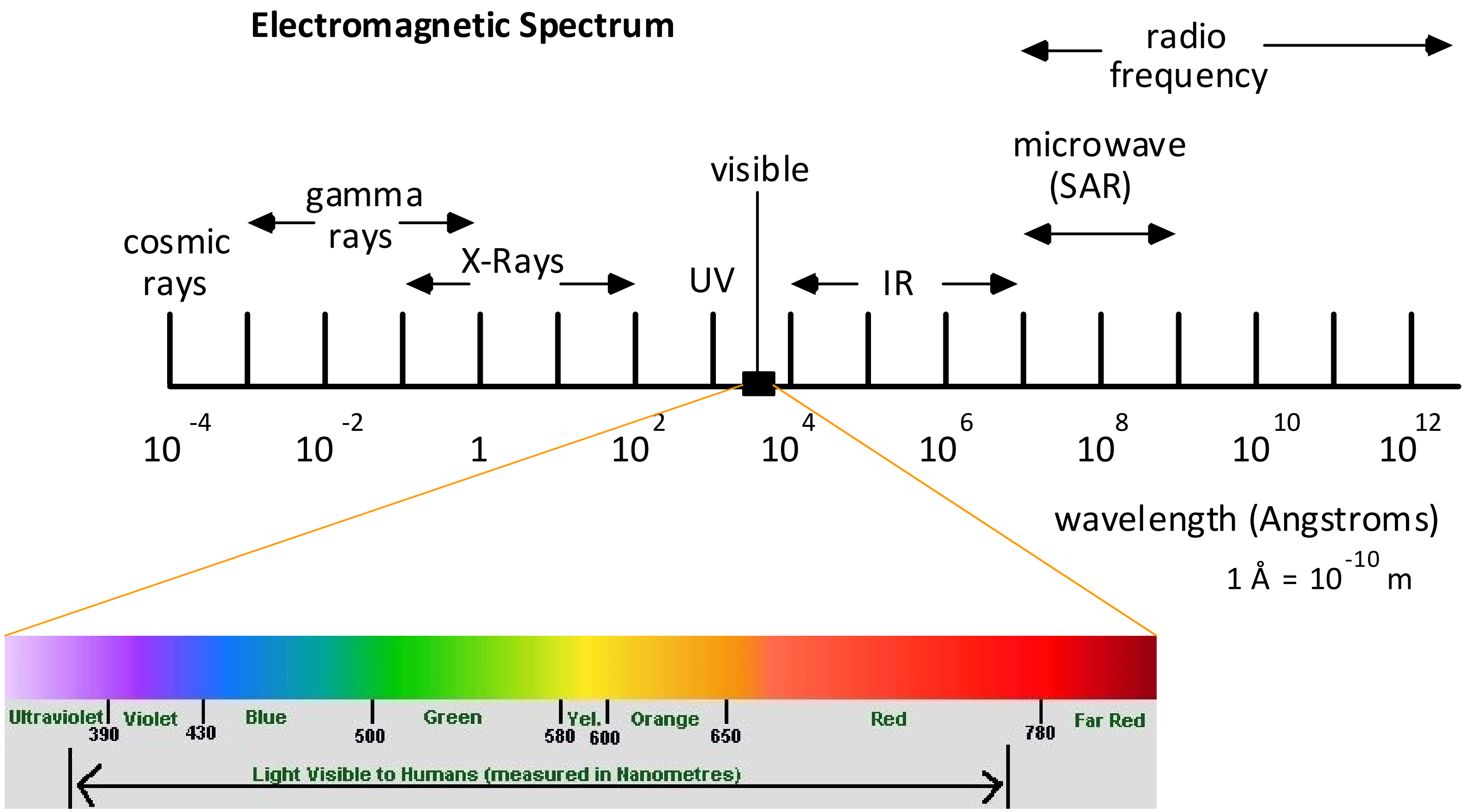
  - X-Rays in many applications

  - Brightfield optical microscopy

  - Tomography (CAT, PET) in medicine

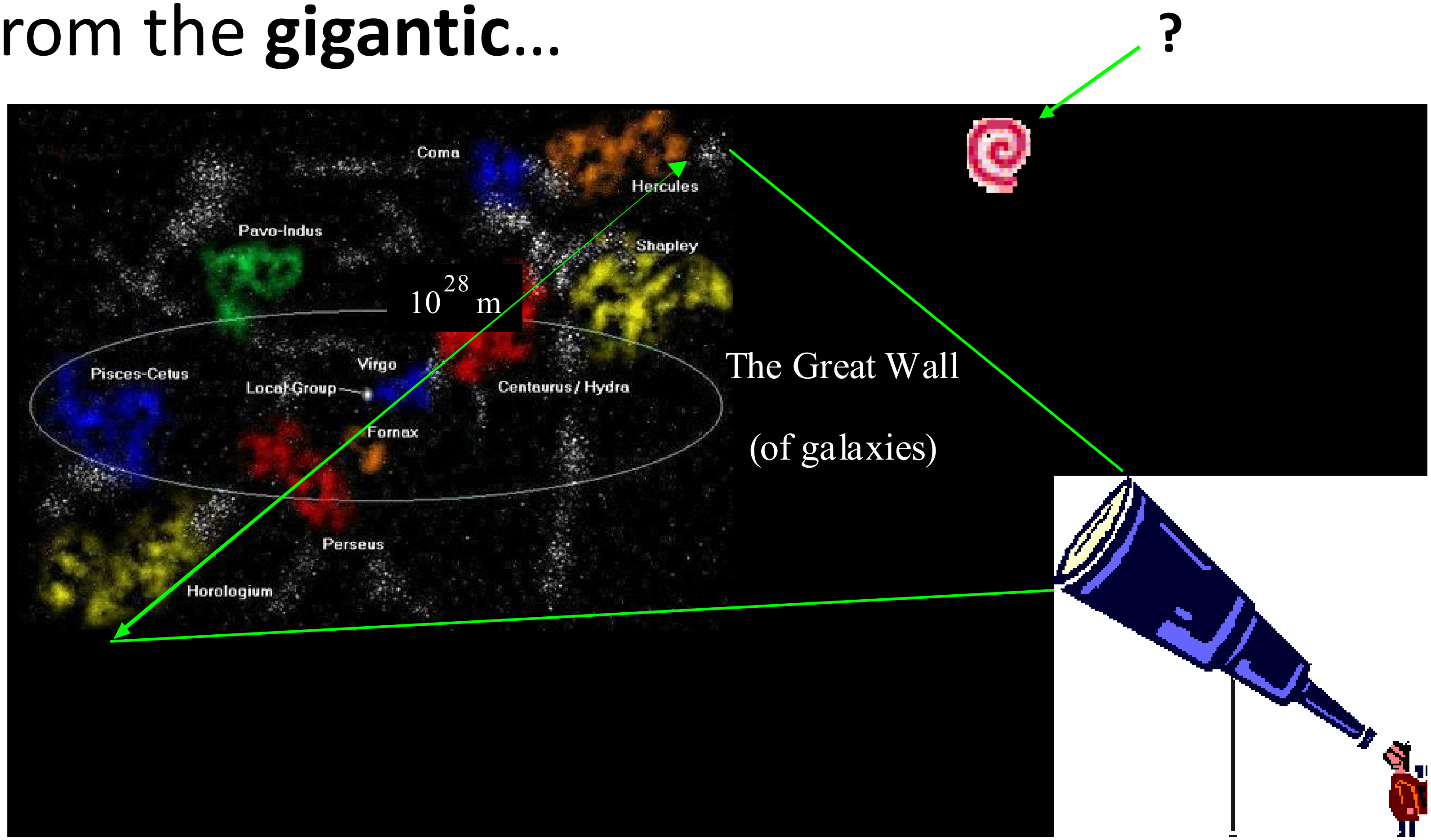
  - “Vibro-Seis**”** in geophysical prospecting

Electromagnetic Radiation



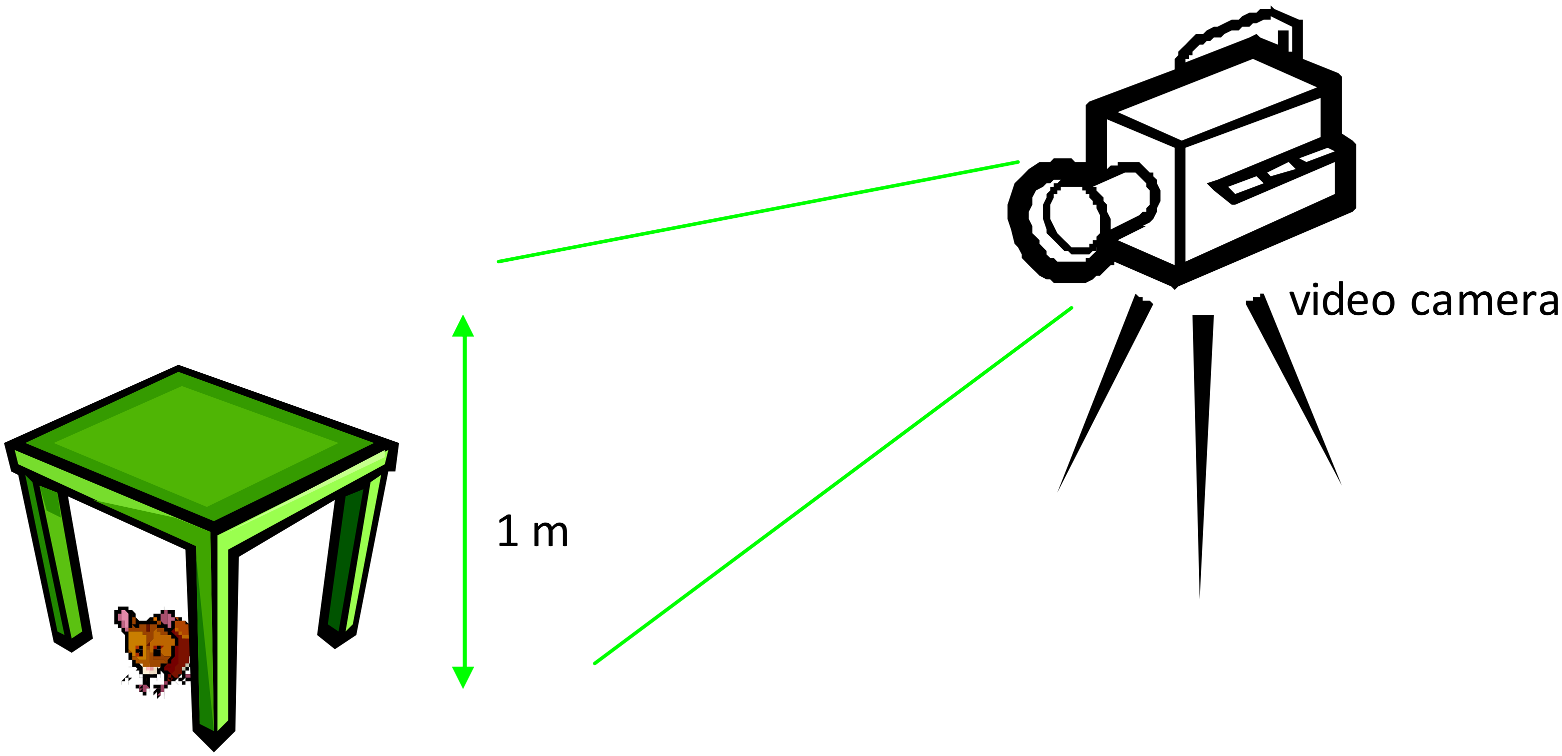
Scales of Imaging

From the **gigantic**…



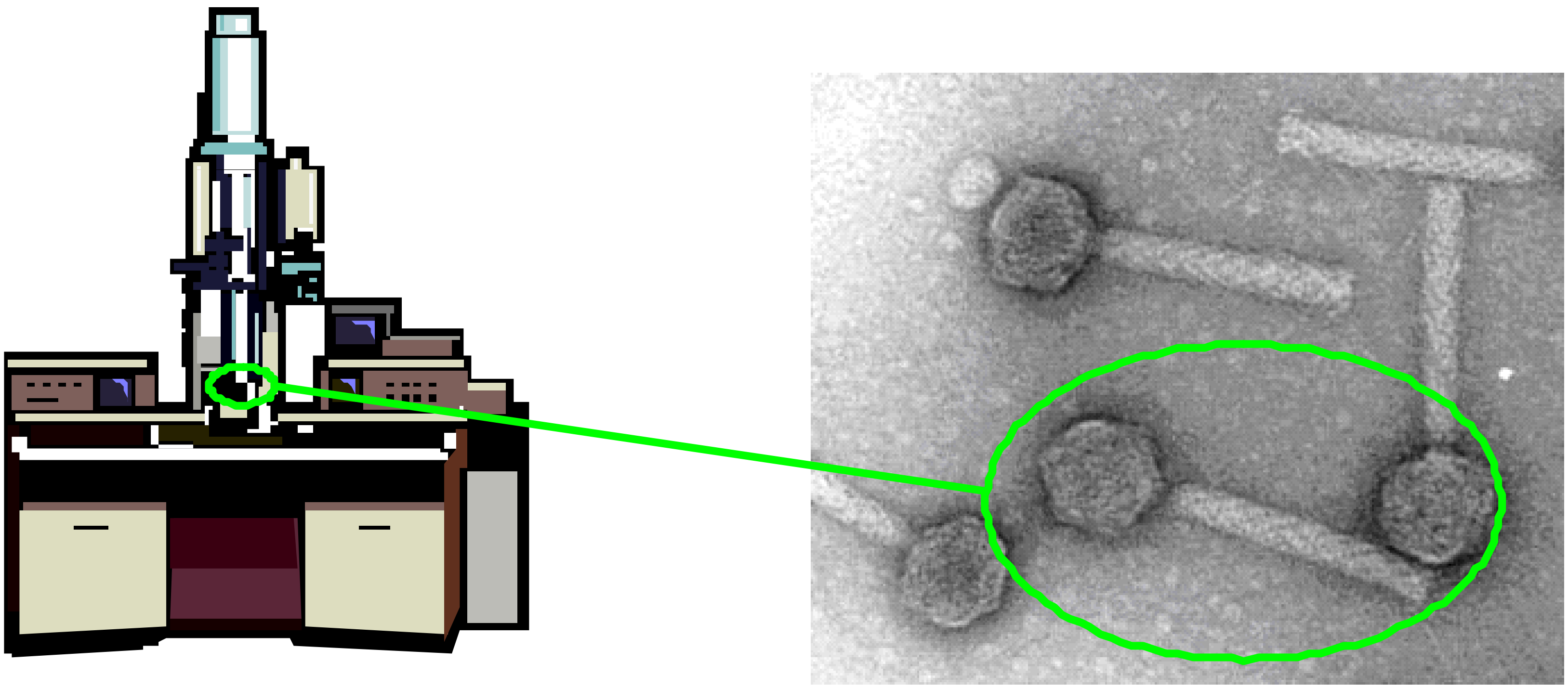
Scales of Imaging

…to the **everyday** …



Scales of Imaging

…to the **tiny**.

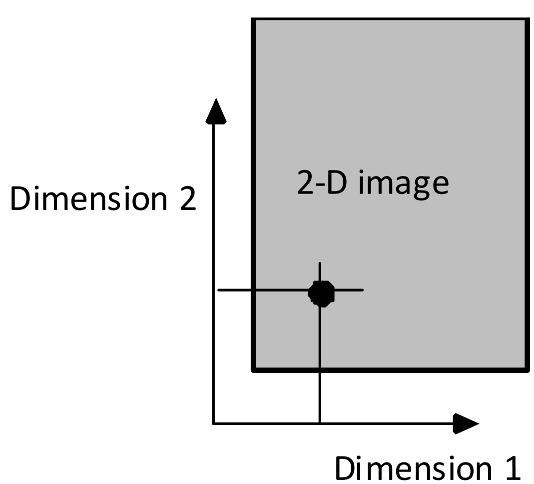


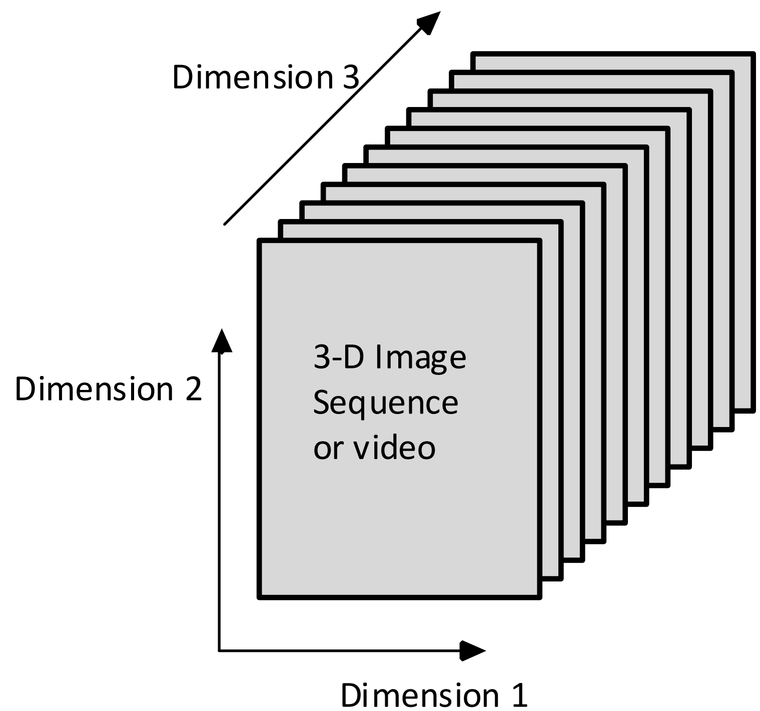
electron microscope

10^{-6} m

Dimensionality of Images

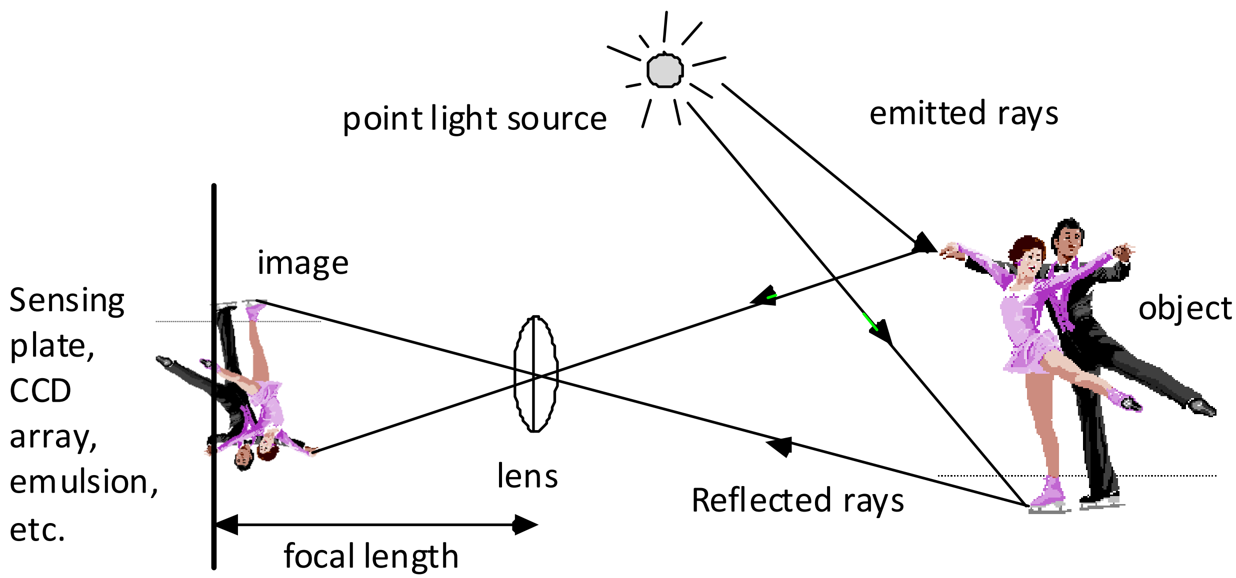
- Images and videos are **multi-dimensional** (≥ 2 dimensions) signals.





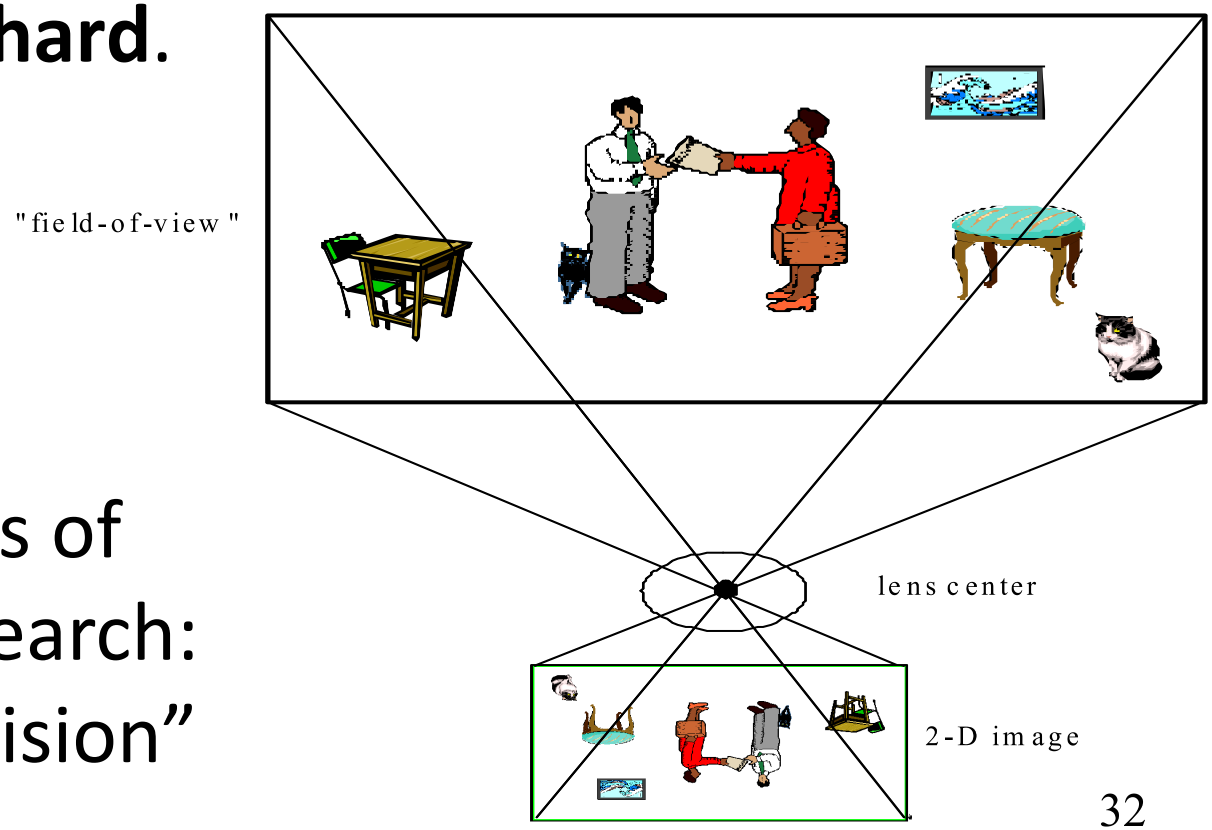
Optical Imaging Geometry

- Assume **reflection imaging** with visible light.
- Let's quantify the **geometric relationship** between 3-D world coordinates and projected 2-D image coordinates.



3D-to-2D Projection

- Image projection is a **reduction of dimension** (3D-to-2D): 3-D info is **lost**. Getting this info back is **very hard**.



- It is a topic of many years of intensive research: “Computer Vision”

Perspective Projection

- There is a geometric relationship between **3-D space coordinates** and **2-D image coordinates** under perspective projection.

- We will require some **coordinate systems**:

Projective Coordinate Systems

Real-World Coordinates

- (X, Y, Z) denote points in 3-D space
- The **origin** (X, Y, Z) = (0, 0, 0) is the **lens center**

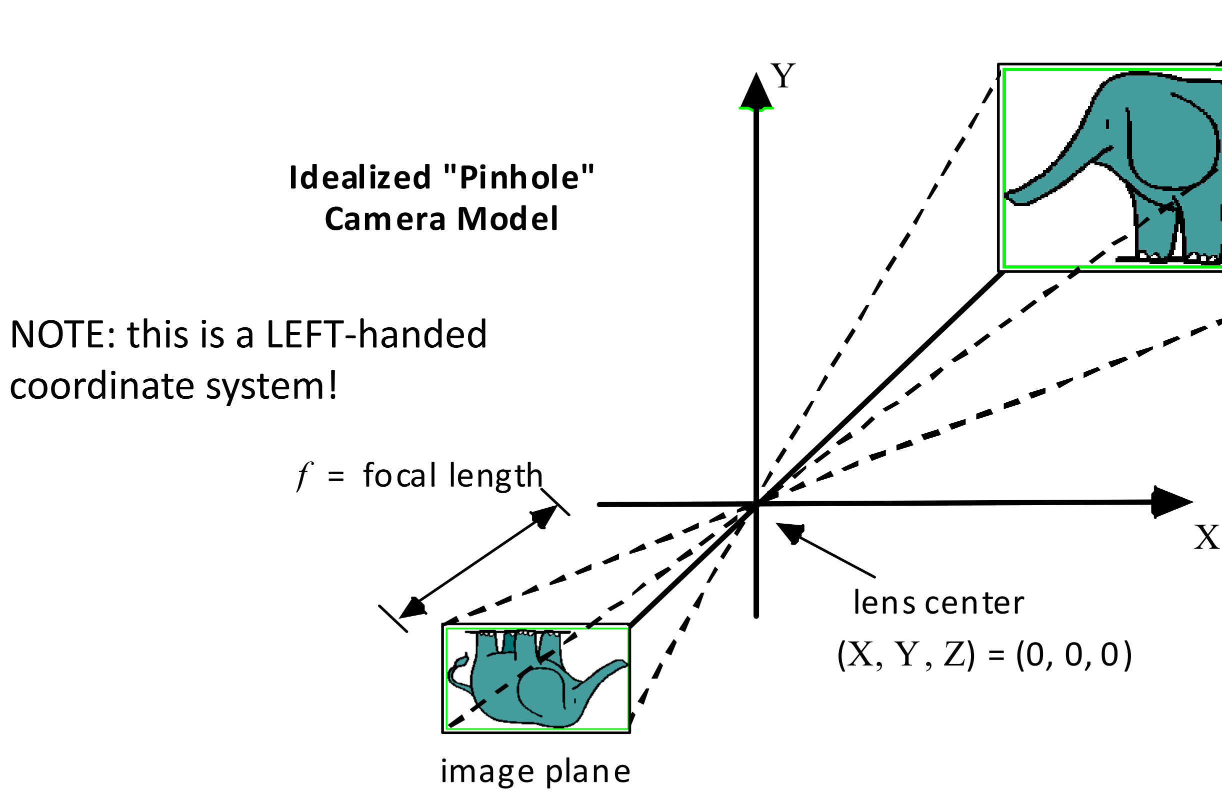
Image Coordinates

- (x, y) denote points in the 2-D image
- The x - y plane is chosen parallel to the X - Y plane
- The **optical axis** passes through both origins

Pinhole Projection Geometry

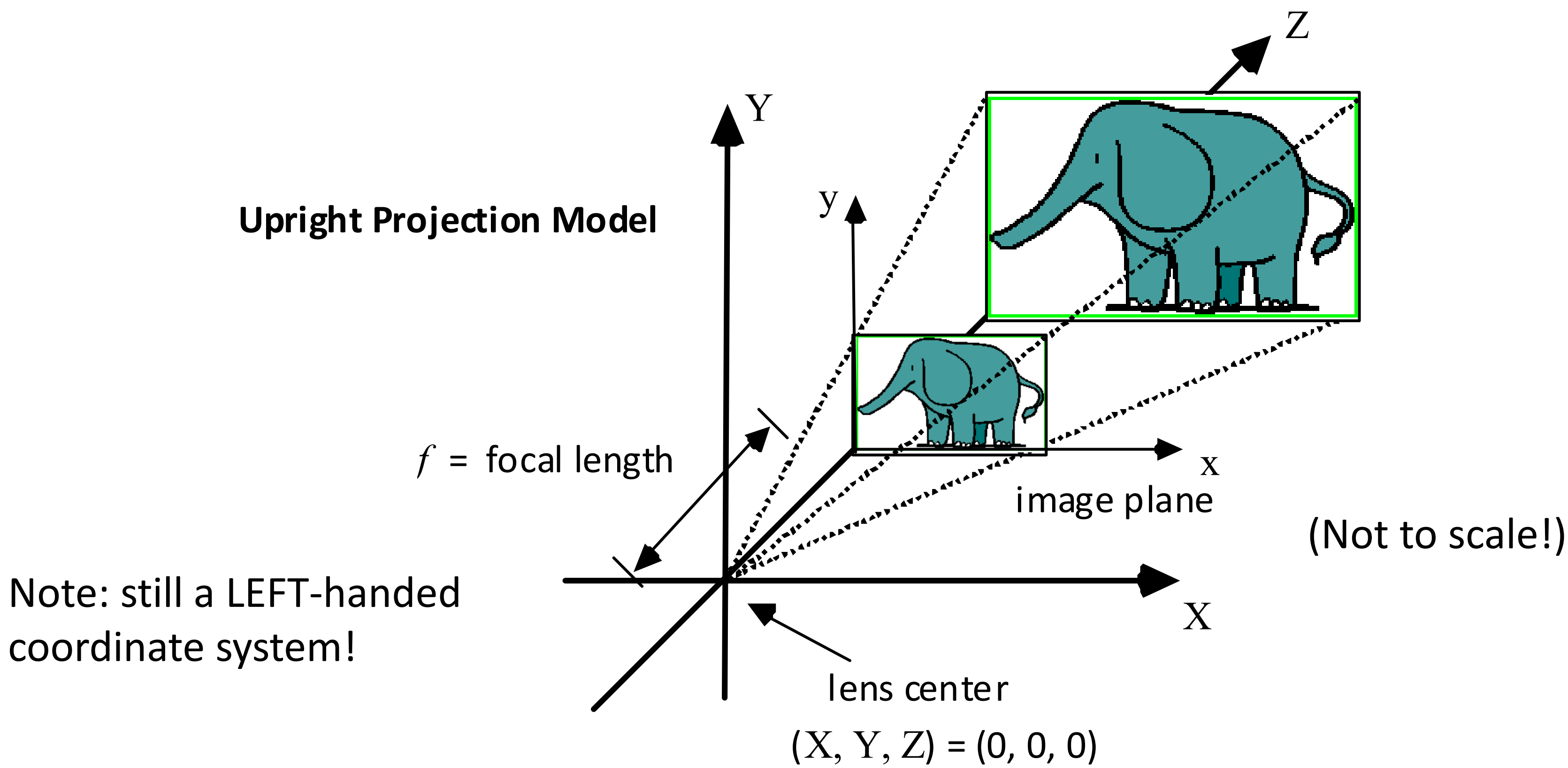
- The lens is modeled as a **pinhole** through which all light rays hitting the image plane pass.
- The image plane is one **focal length** f from the lens. This is where the camera is in focus.
- The image is **recorded** at the image plane, using a photographic emulsion, CCD sensor, etc.

<u>Pinhole Projection Geometry</u>

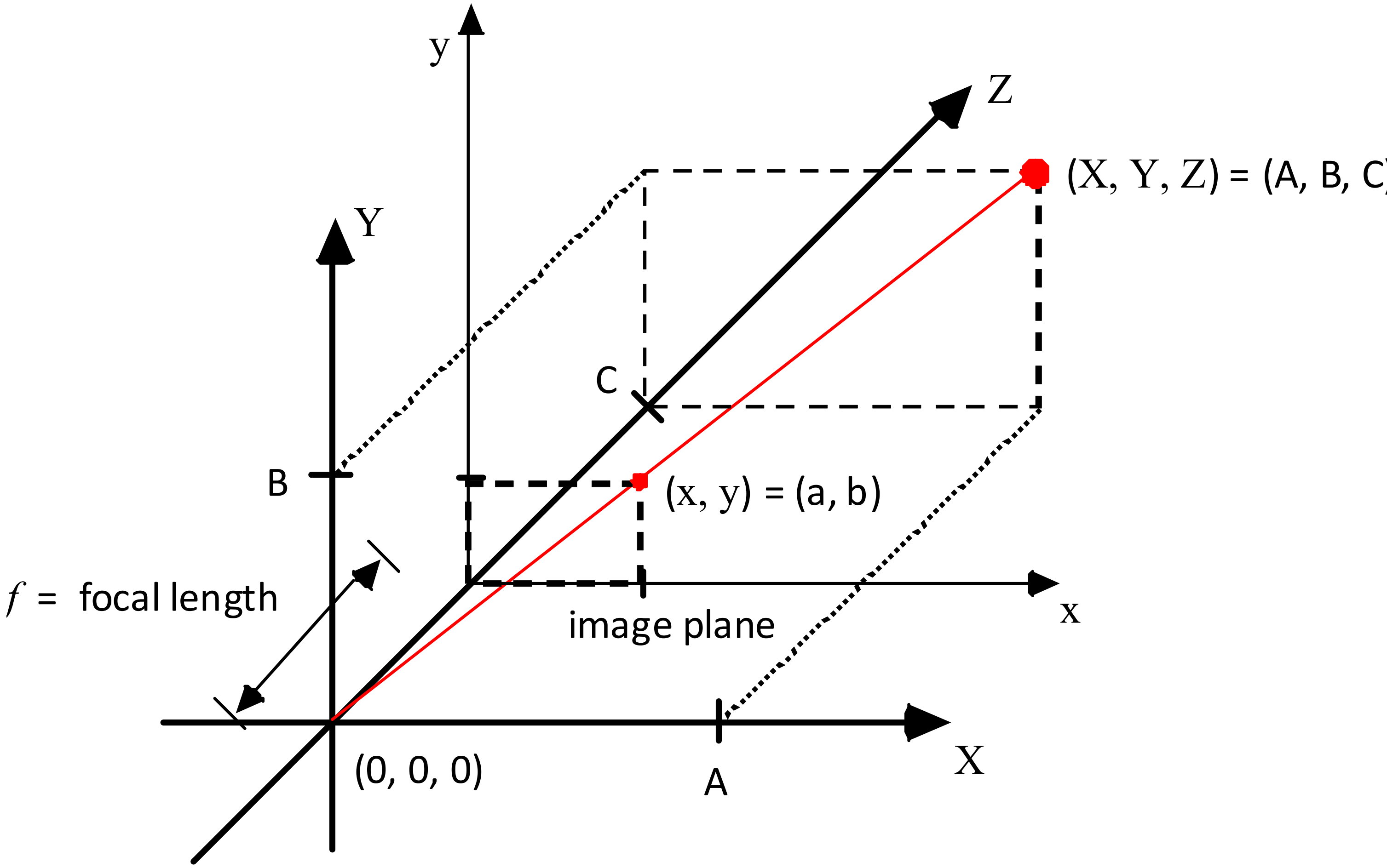


<u>Problem</u>: In this model (and in reality), the image is reversed and upside down. It is convenient to change the model to correct this.

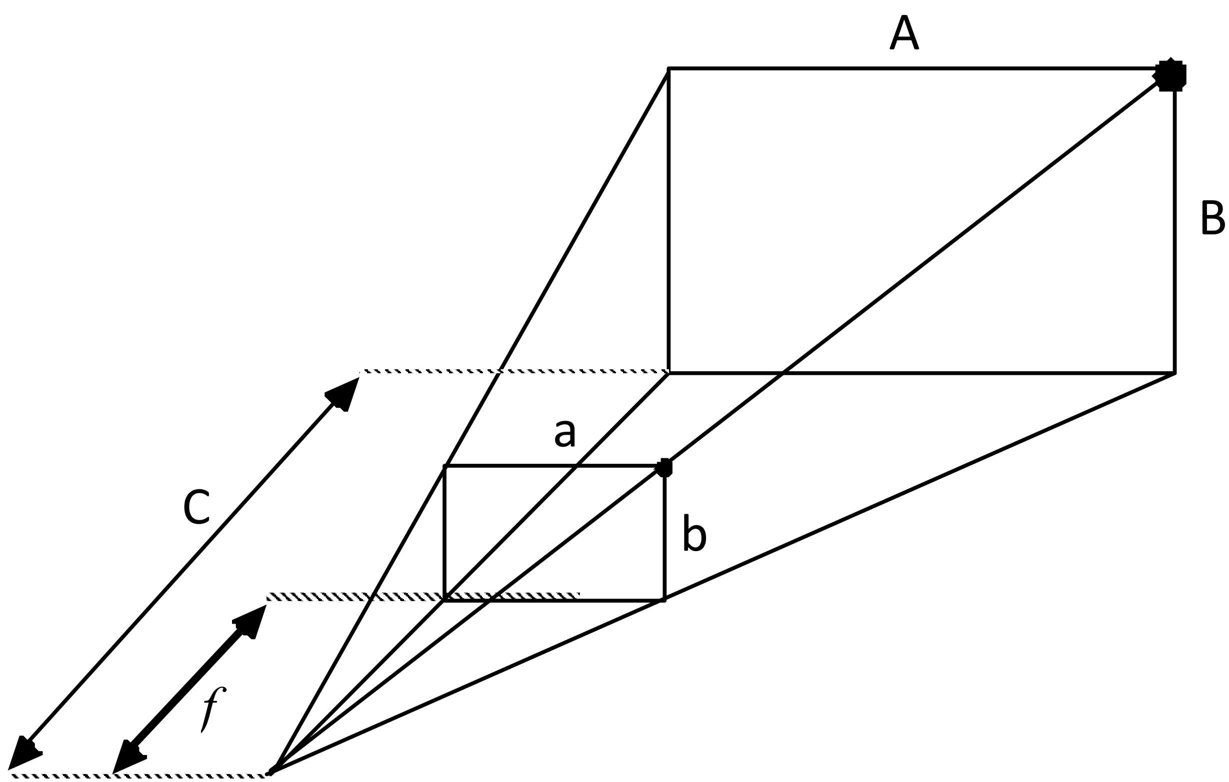
Upright Projection Geometry



- Let us make our model more mathematical…



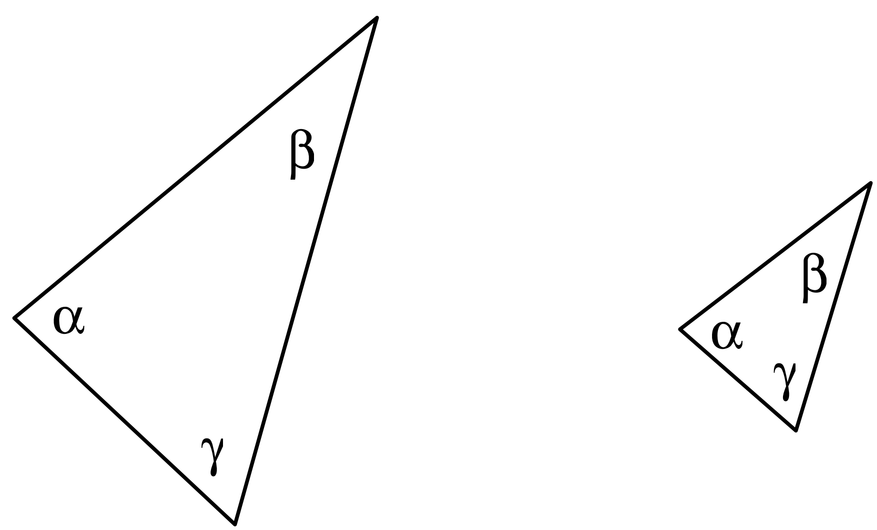
- All of the relevant coordinate axes and labels …



- This equivalent **simplified diagram** shows only the relevant data relating (X, Y, Z) = (A, B, C) to its projection (x, y) = (a, b).

Similar Triangles

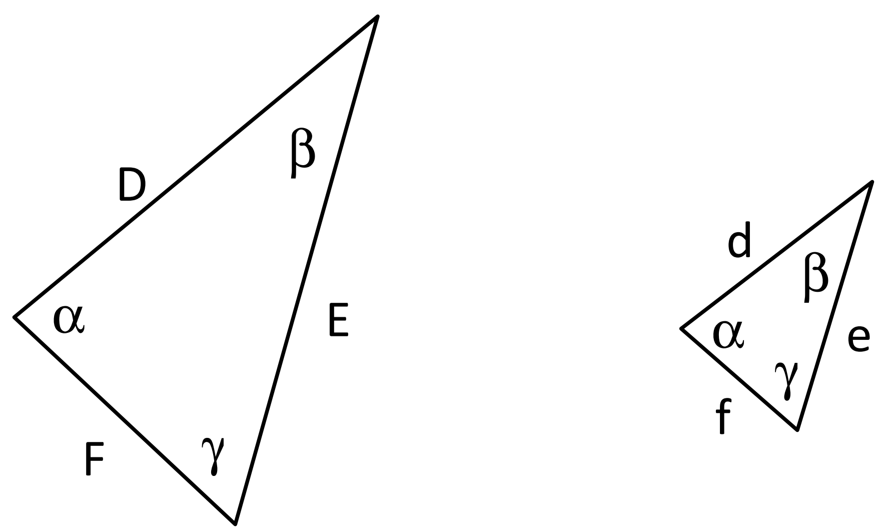
- Triangles are **similar** if their **corresponding angles are equal**:



similar triangles

Similar Triangles Theorem

- Similar triangles have their side lengths in the **same proportions**.



$$\frac{D}{E}=\frac{d}{e}$$

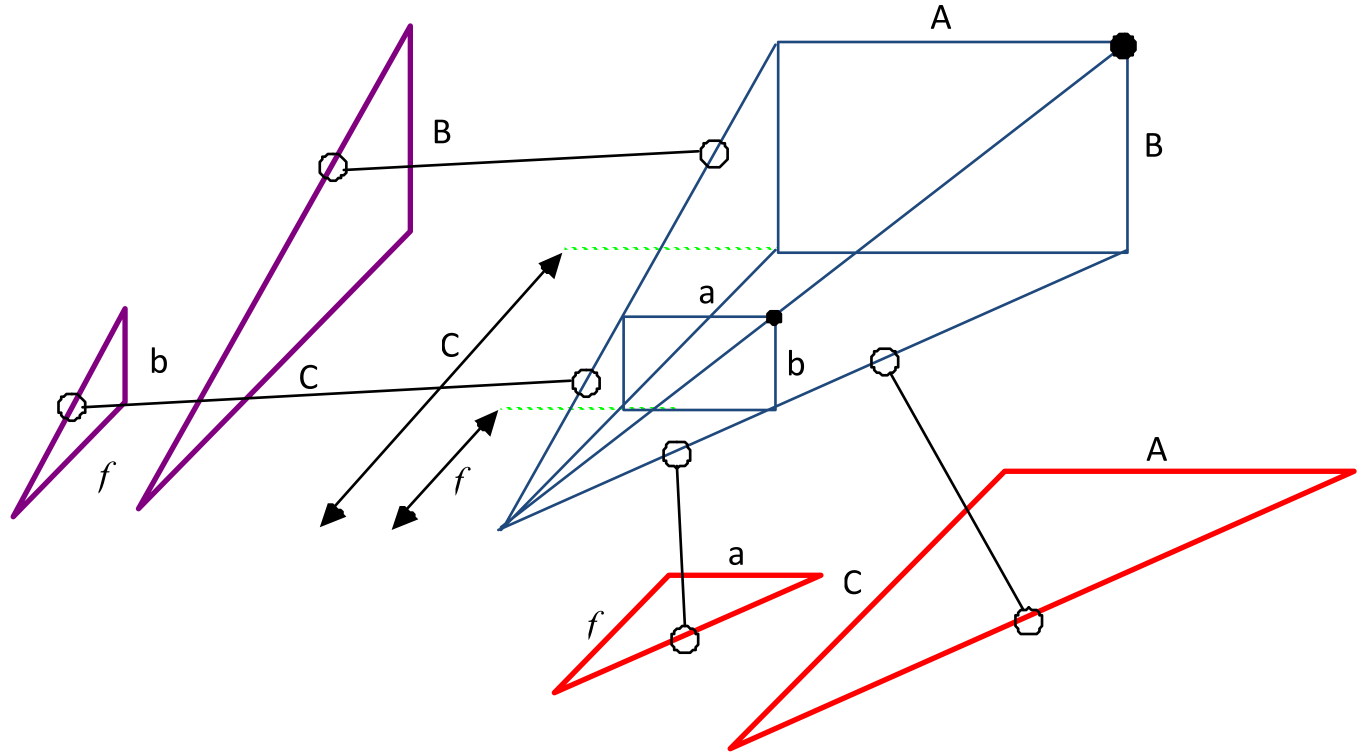
$$\frac{E}{F}=\frac{e}{f} \qquad \text{etc}$$

$$\frac{F}{D}=\frac{f}{d}$$

Solving Perspective Projection

- Similar triangles solves the relationship between 3-D space and 2-D image coordinates.

- Redraw the geometry once more, this time making apparent two pairs of **similar triangles**:



- By the **Similar Triangles Theorem**, we conclude that: $\frac{a}{f} = \frac{A}{C}$ and $\frac{b}{f} = \frac{B}{C}$

- OR: $(a,b) = \frac{f}{C} \cdot (A, B) = (f\,A/C,\ f\,B/C)$

Perspective Projection Equation

- The relationship between a 3-D point (X, Y, Z) and its 2-D image (x, y) :

$$(x, y) = \frac{f}{Z} \cdot (X, Y)$$

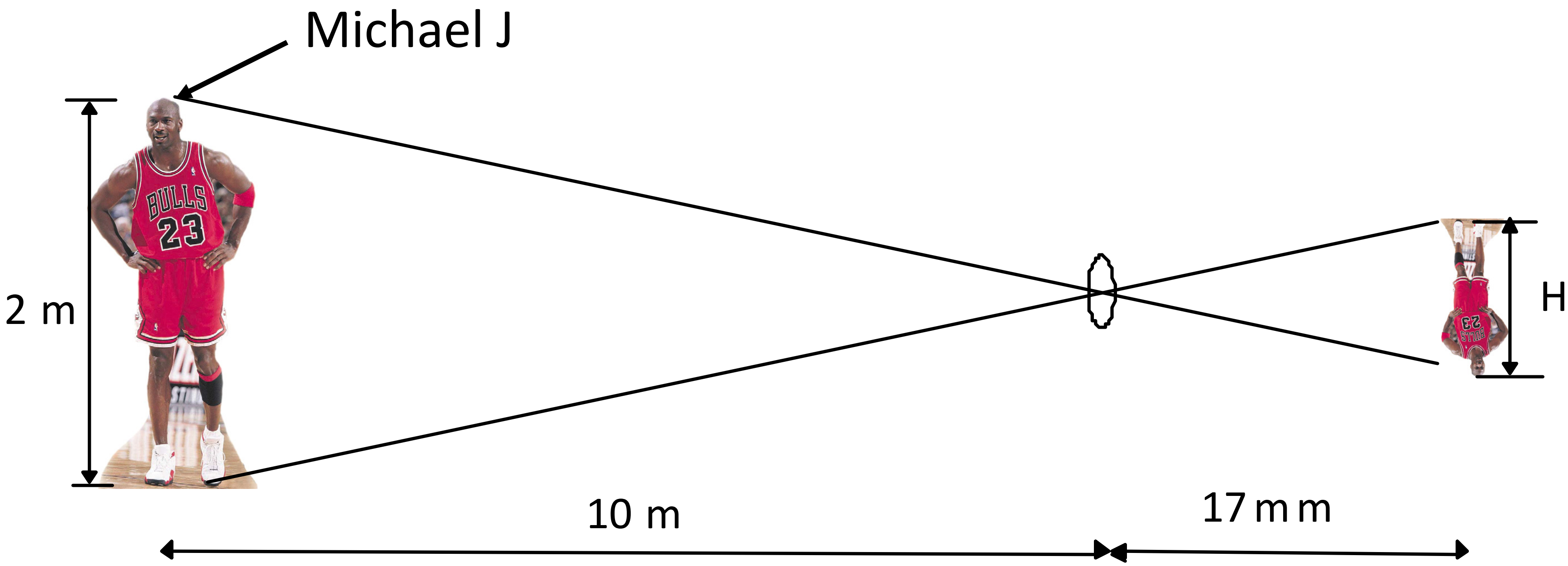
  where f = focal length

- The ratio f/Z is the **magnification factor,** which varies with the **range** Z from the lens center to the **object plane**.

Perspective Projection Equation

- **Example**
  - A man stands 10 m in front of you.
  - He is 2 m tall.
  - Your eye's focal length is about 17 mm

- **Question:** What is the height H of his image on your retina?

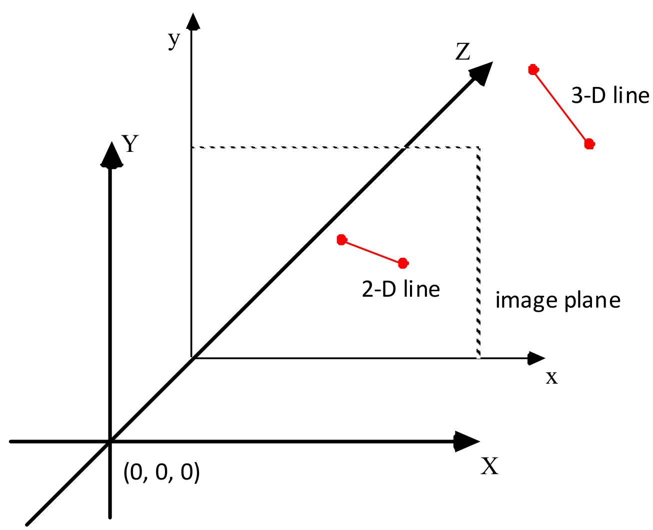


- By similar triangles,

$$\frac{2\ \text{m}}{10\ \text{m}} = \frac{H}{17\ \text{mm}} \Rightarrow \underline{H = 3.4\ \text{mm}}$$

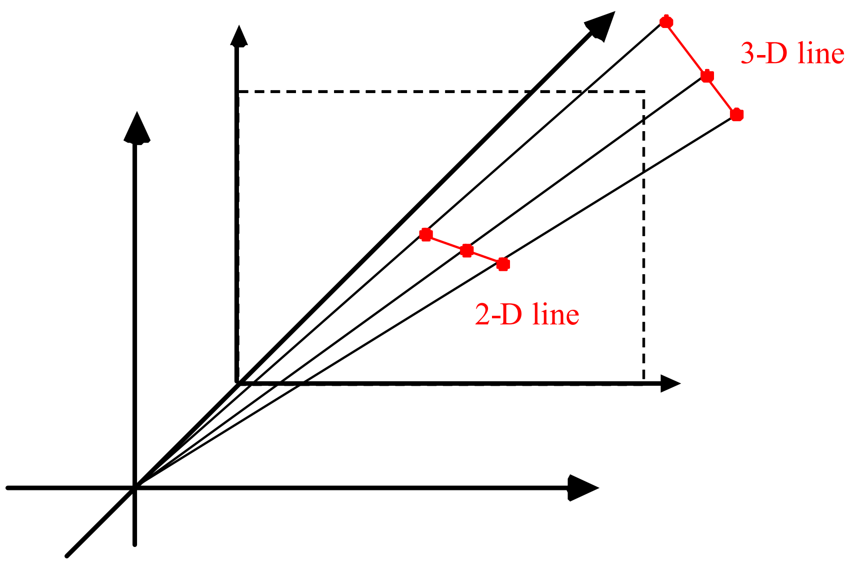
Straight Lines Under Perspective Projection

- Why do straight lines (or line segments) in 3-D project to straight lines in 2-D images?
- Not true of all lenses, e.g. "fish-eye“ lenses do not obey the pinhole approximation.



To show this to be true, one could write the equation for a line in 3-D, and then project it to the equation of a 2-D line…

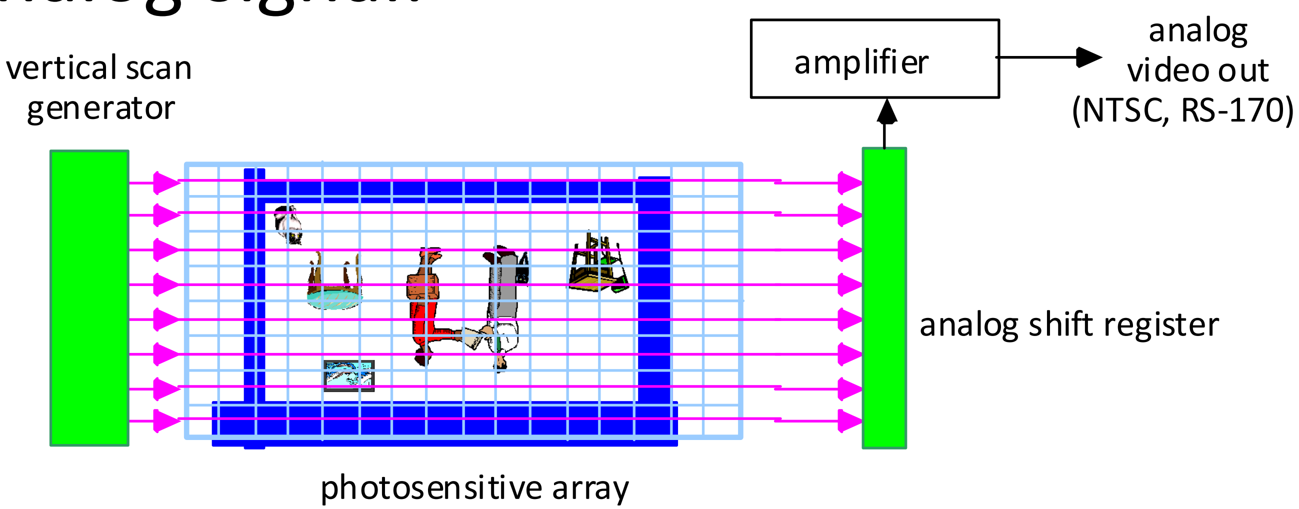
- Easier way:
  - **Any two lines** touching the lens center and the 3-D line must lie in **the same plane** (a point and a line define a plane).
  - The intersection of this plane with the image plane gives the projection of the line.
  - The intersection of two (nonparallel) planes is a line.
  - So, the projection of a 3-D line is a 2-D line.



- In **image analysis**, this property makes finding straight lines much easier.

CCD Image Sensing

- Modern digital cameras sense **2-D images** using charge-coupled device (CCD) sensor arrays.
- The output is typically a line-by-line (raster) analog signal:

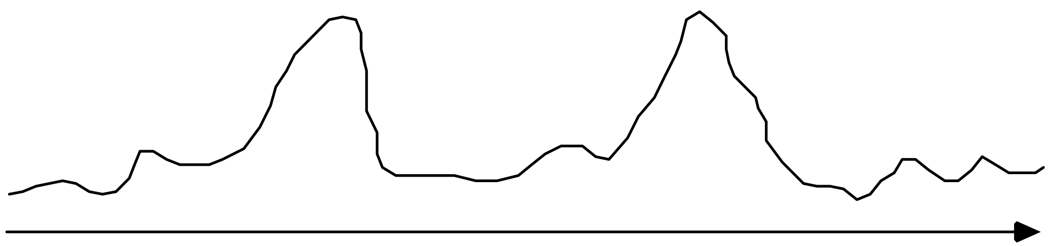


A/D Conversion

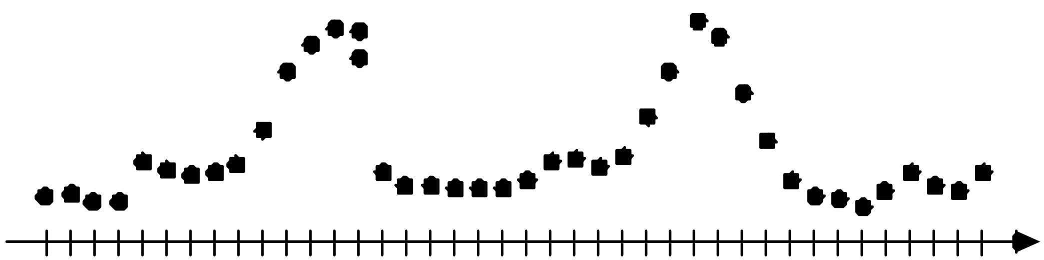
- Consists of **sampling** and **quantization**.
- **Sampling** is the process of creating a signal that is defined only at **discrete points**, from one that is continuously defined.
- **Quantization** is the process of converting each sample into a **finite** digital representation.
- We will explore these in depth **later**.

Sampling

- Each video **raster** is converted from a **continuous voltage waveform** into a sequence of **voltage samples**:



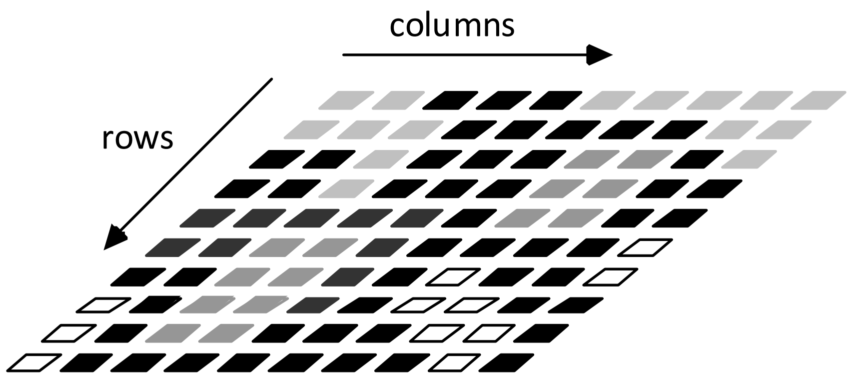
continuous electrical signal from one scanline



sampled electrical signal from one scanline

Digital Image

- A **digital image** is an array of numbers (row, column) representing image intensities



depiction of 10 x 10 image array

- Each of these **picture elements** is called a **pixel.**

Sampled Image

- The image array is rectangular (N x M)
- Examples: square images

128 x 128	($2^{14} \approx$ 16,000 pixels)
256 x 256	($2^{16} \approx$ 65,500 pixels)
512 x 512	($2^{18} \approx$ 262,000 pixels)
1024x1024	($2^{20} \approx$ 1,000,000 pixels)

Sampling Effects

- It is essential that the image be sampled **sufficiently densely**; else the image quality will be severely degraded.
- Can be expressed mathematically via the Sampling Theorem, but the effects are **visually obvious**.
- With sufficient samples, the image **appears continuous**.....

Spatial Downsampling

256×256

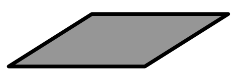
64×64

32×32

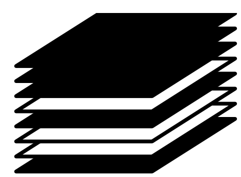
16×16

Quantization

- Each **gray level** is quantized to an integer between 0 and K-1.
- There are $K = 2^B$ possible gray levels.
- Each pixel is represented by B bits; usually $\mathbf{1 \leq \mathit{B} \leq 8}$.



a pixel



8-bit representation

Quantization

- The pixel intensities or gray levels must be quantized **sufficiently densely** so that excessive information is not lost.

- This is **hard** to express mathematically, but again, quantization effects are **visually obvious**.

Quantization

8 bits

4 bits

3 bits

2 bits

The Image/Video Data Explosion

- Total **storage** required for **one digital image** with 2^P x 2^Q pixels spatial resolution and B bits / pixel gray-level resolution is B x 2^{P+Q} bits.
- Usually $\boldsymbol{B}$**=8** and often $\boldsymbol{P}$**=**$\boldsymbol{Q}$**=9**. A common image size is then **¼ megabyte**.
- Five years ago this was **a lot**.

<u>The Image/Video Data Explosion</u>

- Storing **1 second** of a gray-level movie (TV rate = 30 images / sec) requires 7.5 Mbytes.
- A 2-hour gray-level video (8x512x512x30) requires 27,000 megabyte or **27 gigabytes of storage** at nowhere near theatre quality. That's a lot **<u>today</u>**.
- Later, we will discuss ways to **compress** digital images and videos.

Color Images

- A color image has vector-valued pixels. For example, 8 bits of Red, 8 bits of Blue, and 8 bits of Green.
- So you can think of a color image as a collection of three grayscale images.
  - ► E.g., a Red image, a Blue image, and a Green image.
  - ► These images are usually called color "bands" or "channels."
  - ► Note: some color spaces like CMYK have *more* than 3 bands.
- In a grayscale image, the pixel values represent *intensity* or *luminance*, usually denoted I or Y.
- For an RGB color image, the intensity (luminance) is given by

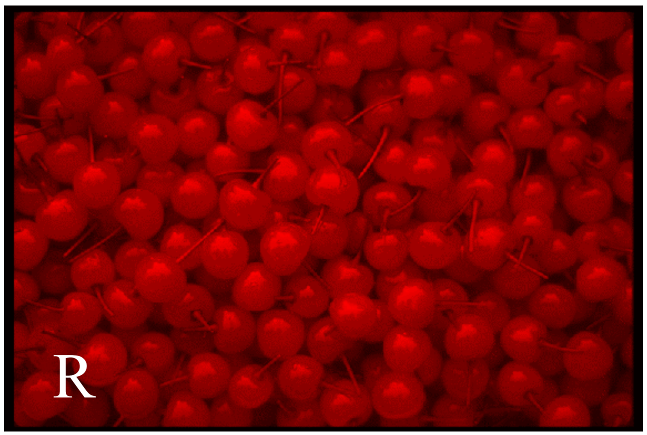
$$I = 0.2989R + 0.5870G + 0.1140B$$

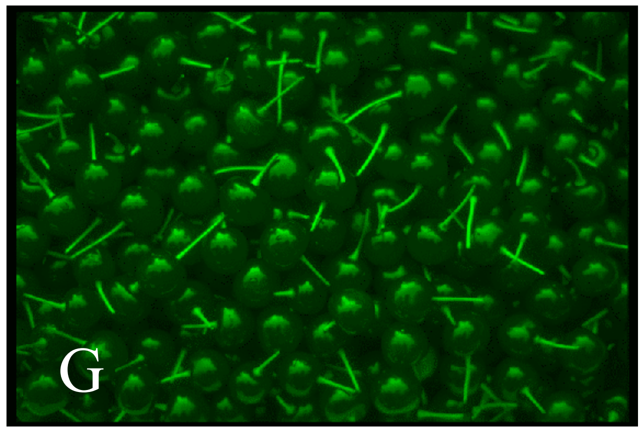
- This formula is not unique (i.e., it is not the only way to convert RGB to luminance), but it is **widely accepted**.
- Matlab provides a function rgb2gray to compute this.

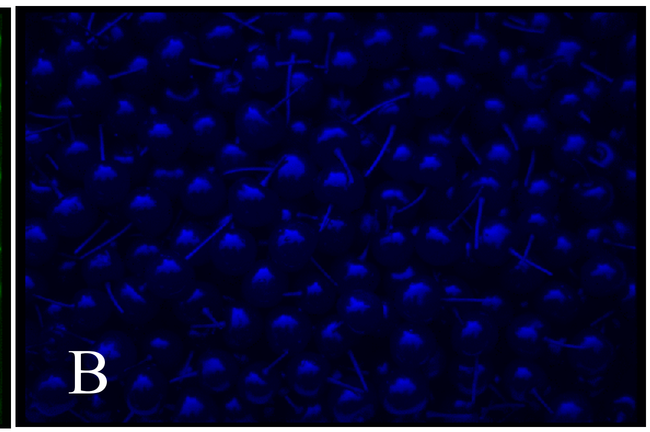
More on Color

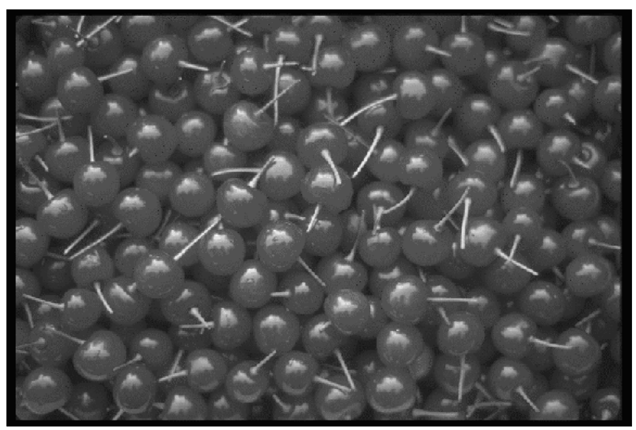
- Some color spaces like YUV and YCbCr represent the grayscale image directly.
  - ► This was originally done so that black-and-white TV's could receive color TV signals… and just display the Y band.
- Many color image processing algorithms process the color bands independently like grayscale images.
  - ► For example, there may be noise that affects the bands independently.
  - ► This approach can produce weird changes in the colors, however.
- Often, it's desirable to modify an image without changing the colors.
  - ► For example, we might want to just make a color image brighter without making any visually obvious changes to the colors of the pixels.
  - ► In such cases, it's usually sufficient to apply the filter to the intensity image (grayscale image) only, then reconstruct the colors.
- We'll spend most of our time on grayscale images in this class.
- Development of true vector color filters is an active research area.

Color









Intensity

Common Image Formats

- **JPEG (Joint Photographic Experts Group)** images are compressed with loss – see Module 7. All digital cameras today have the option to save images in JPEG format. File extension: *image.jpg*

- **TIFF (Tagged Image File Format)** images can be lossless (LZW compressed) or compressed with loss. Widely used in the printing industry and supported by many image processing programs. File extension: *image.tif*

- **GIF (Graphic Interchange Format)** an old but still-common format, limited to 256 colors. Lossless and lossy (LZW) formats. File extension: *image.gif*

- **PNG (Portable Network Graphics)** is the successor to GIF. Supports true color (16 million colors). File extension: *image.png*

- **BMP (bit mapped) format** is used internally by Microsoft Windows. Not compressed. Widely accepted. File extension: *image.bmp*