Digital Image Fundamentals

1

Imaging process

- Light reaches surfaces in 3D.
- Surfaces reflect.
- Sensor element receives light energy.
- Intensity is important.
- Angles are important.
- Material is important.

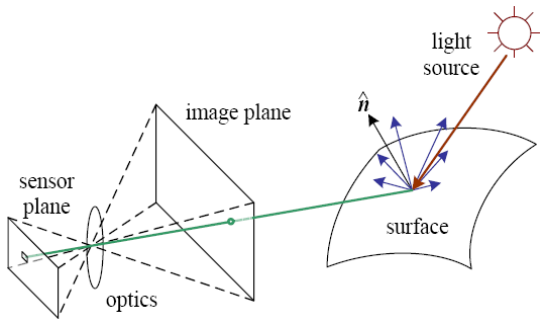


Figure 2.14: *A simplified model of photometric image formation. Light is emitted by one or more light sources, and is then reflected from an object's surface. A portion of this light is directed towards the camera. This simplified model ignores multiple reflections, which often occur in real-world scenes.*

Adapted from Rick Szeliski

2

2

Physical parameters

- Geometric
  - Type of projection
  - Camera pose
- Optical
  - Sensor's lens type
  - Focal length, field of view, aperture
- Photometric
  - Type, direction, intensity of light reaching sensor
  - Surfaces' reflectance properties
- Sensor
  - Sampling, etc.

Adapted from Trevor Darrell, UC Berkeley

3

3

Image acquisition

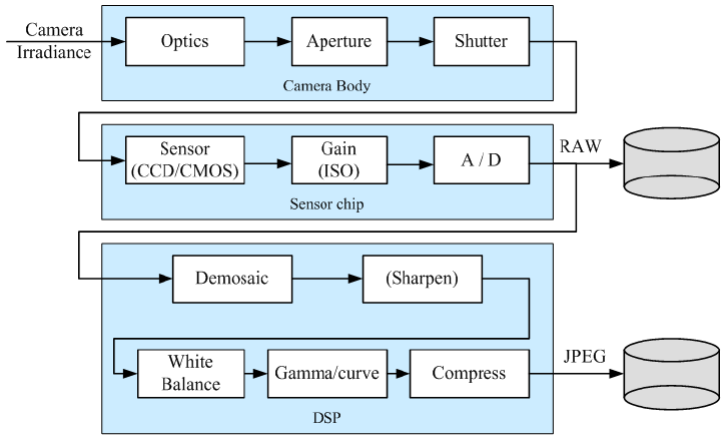


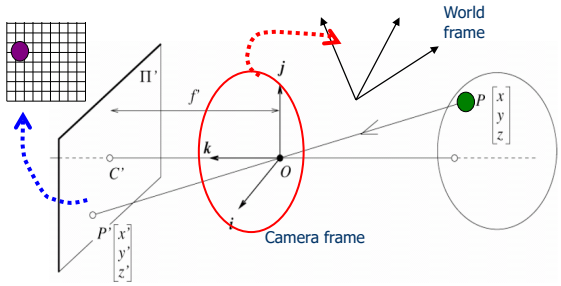
Figure 2.26: *Image sensing pipeline, showing the various sources of noise as well as the typical digital post-processing steps.*

Adapted from Rick Szeliski

4

4

Camera calibration



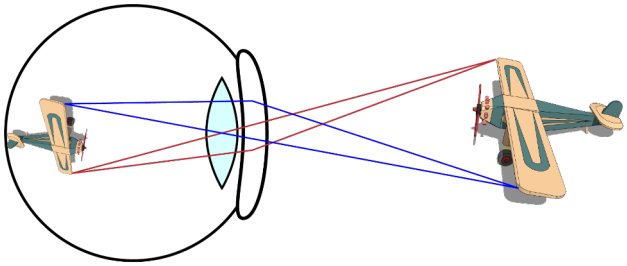
- Camera's extrinsic and intrinsic parameters are needed to calibrate the geometry.
- Extrinsic: camera frame ↔ world frame
- Intrinsic: image coordinates relative to camera ↔ pixel coordinates

Adapted from Trevor Darrell, UC Berkeley

5

5

Eyes: projection onto retina

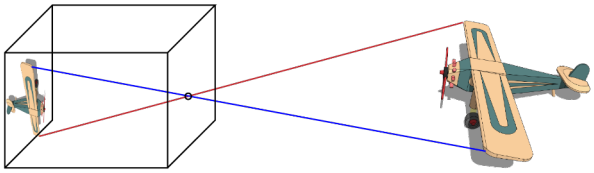


Adapted from Joseph Redmon, U of Washington

6

6

Model: pinhole camera

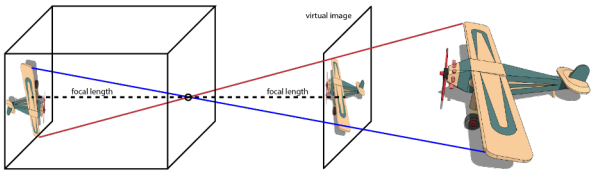


Adapted from Joseph Redmon, U of Washington

7

7

Model: pinhole camera

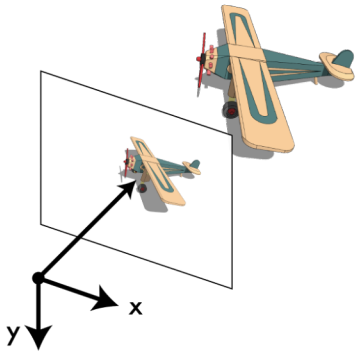


Adapted from Joseph Redmon, U of Washington

8

8

Image: 3d->2d projection of the world

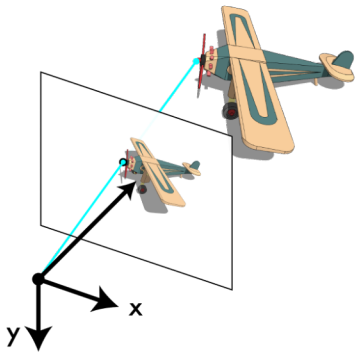


Adapted from Joseph Redmon, U of Washington

9

9

Image: 3d->2d projection of the world

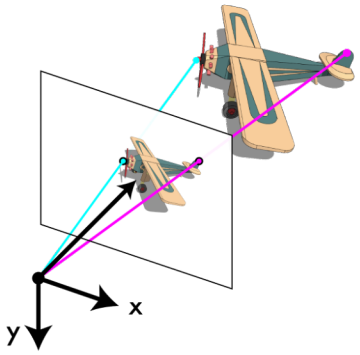


Adapted from Joseph Redmon, U of Washington

10

10

Image: 3d->2d projection of the world

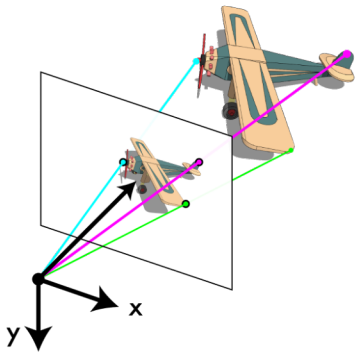


Adapted from Joseph Redmon, U of Washington

11

11

Image: 3d->2d projection of the world

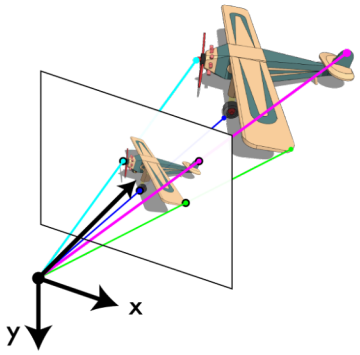


Adapted from Joseph Redmon, U of Washington

12

12

Image: 3d->2d projection of the world



Adapted from Joseph Redmon, U of Washington

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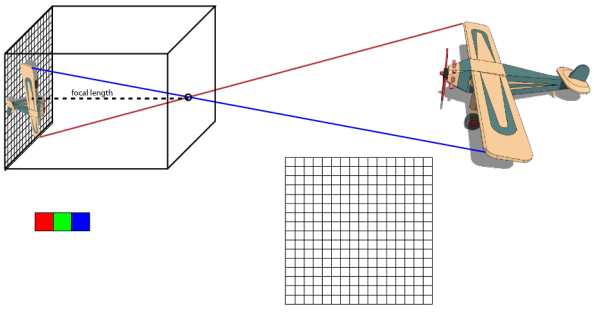
How do we record color?



At each point we record incident light

Adapted from Joseph Redmon, U of Washington

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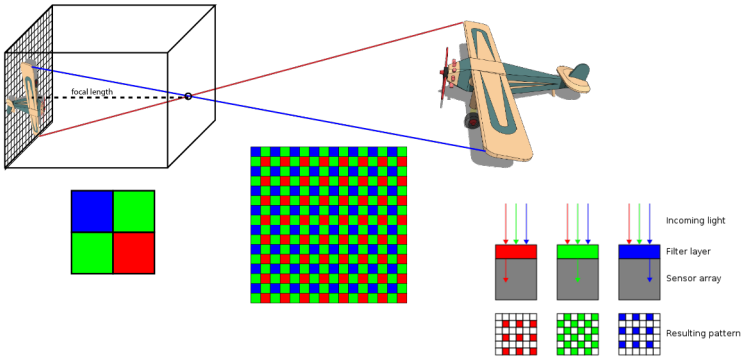
14

How do we record color?



Bayer pattern for CMOS sensors

Adapted from Joseph Redmon, U of Washington

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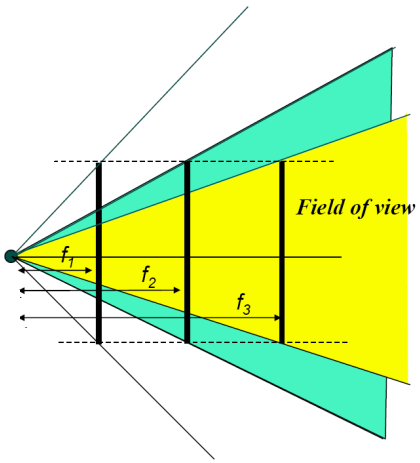
Focal length

- Field of view depends on focal length.
- As **f** gets smaller, image becomes more *wide* angle
  - more world points project onto the finite image plane
- As **f** gets larger, image becomes more *telescopic*
  - smaller part of the world projects onto the finite image plane



Adapted from Trevor Darrell, UC Berkeley

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Focal length

28 mm

35 mm

50 mm

70 mm

Adapted from Matthew Brown, U of Washington

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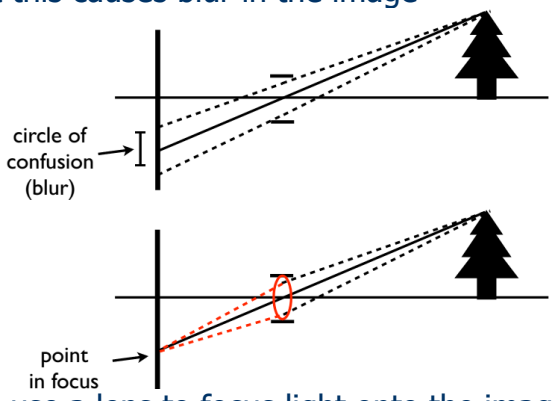
Aperture

- A real camera must have a finite aperture to get enough light, but this causes blur in the image



- Solution: use a lens to focus light onto the image plane

Adapted from Matthew Brown, U of Washington

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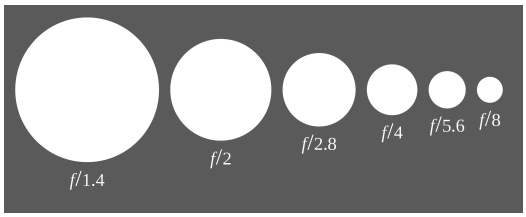


Diagram of decreasing aperture sizes (increasing f-numbers) for "full stop" increments. Each white circle has double the surface of the white circle to its right.

The size of the aperture is described as an "f-stop". This is a number that describes the size of the hole in relation to the focal length of the lens. A low number (such as f1.4 or f2.8) means the aperture is wide open, and lets in a lot of light. A high number (such as f8 or f11) means that the aperture is small, and does not let in as much light.

f/2.8

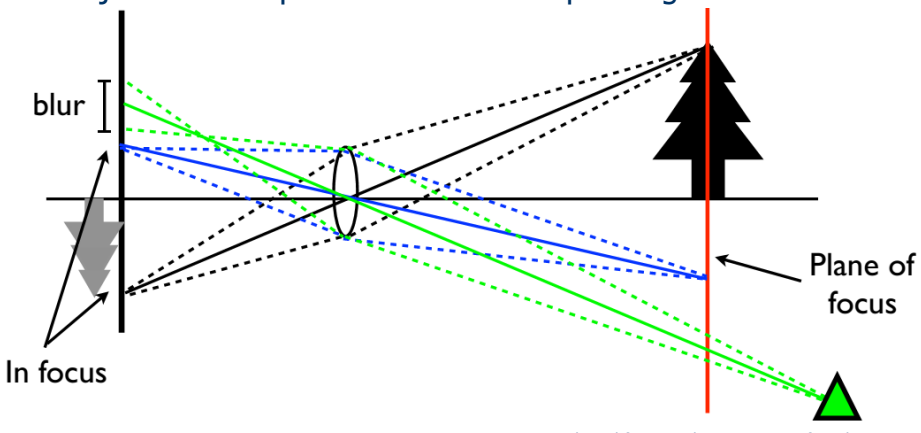
f/16

19

19

Aperture

- Note that lenses focus all rays from a plane in the world
- Objects off the plane are blurred depending on distance

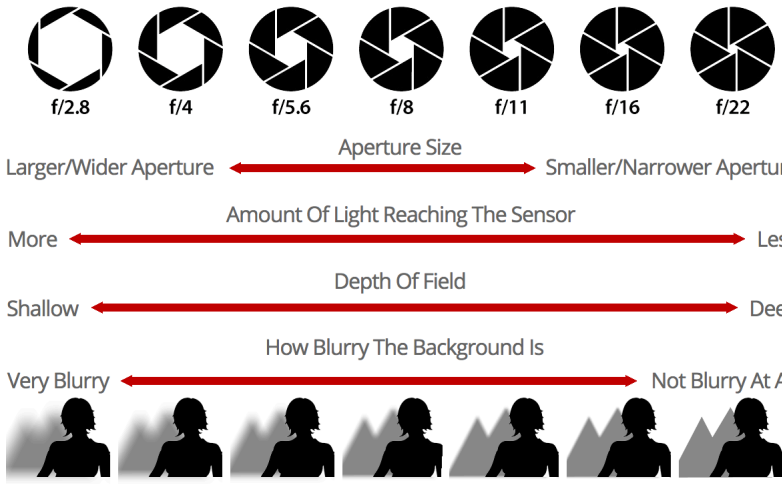


Adapted from Matthew Brown, U of Washington

20

20

Aperture



https://photographypro.com/aperture/

21

21

Aperture

- Smaller aperture -> smaller blur, larger depth of field

Adapted from Matthew Brown, U of Washington

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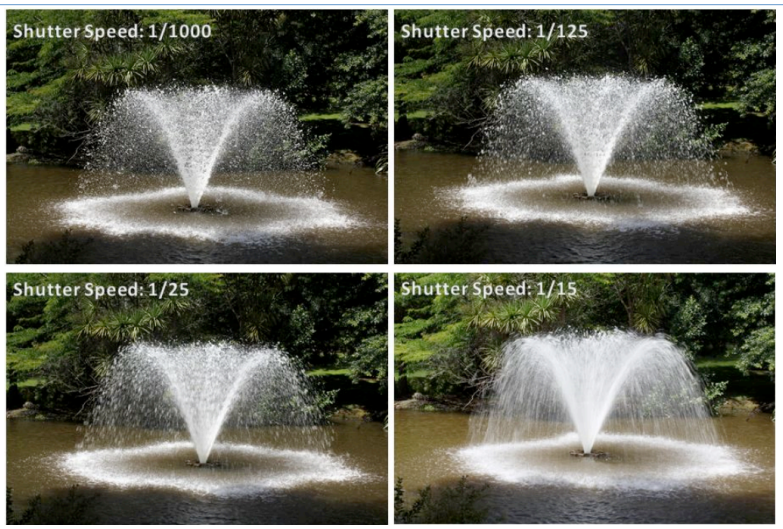
Shutter speed



Adapted from Matthew Brown, U of Washington

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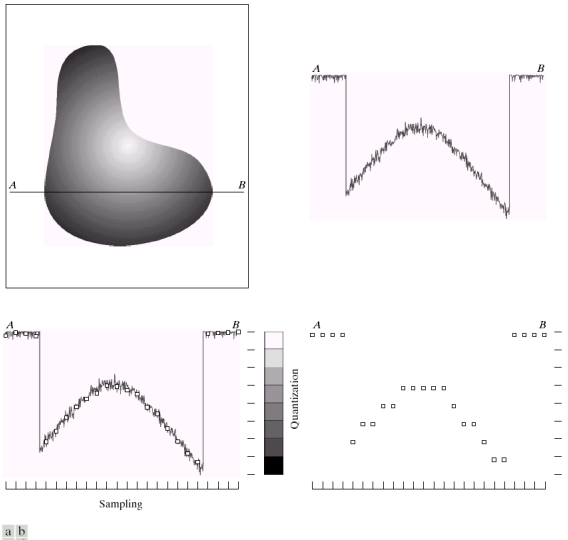
Sampling and quantization



a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

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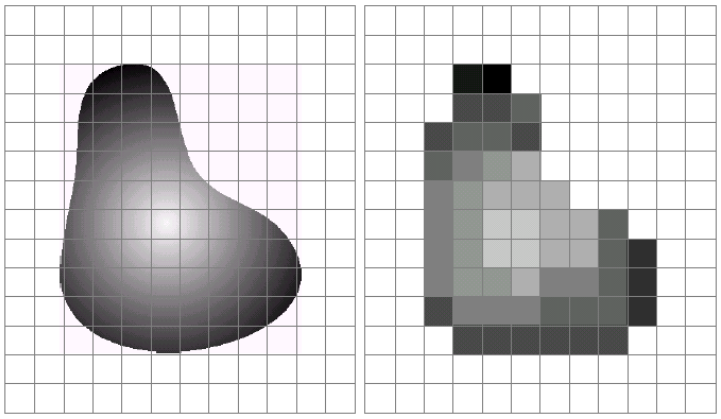
Sampling and quantization



a b

FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

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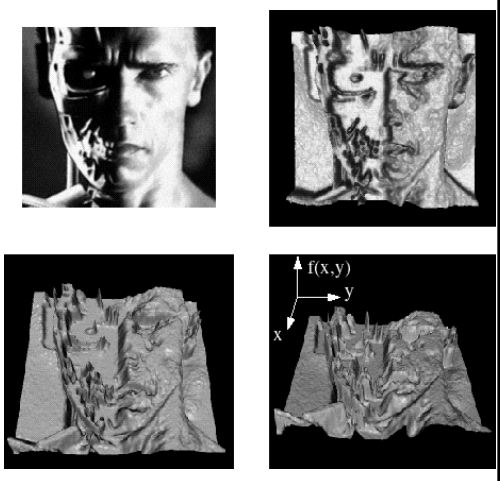
Image representation

- Images can be represented by 2D functions of the form f(x,y).
- The physical meaning of the value of f at spatial coordinates (x,y) is determined by the source of the image.



Adapted from Shapiro and Stockman

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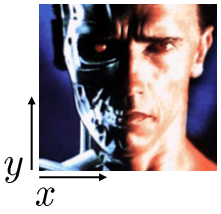
Image representation

- In a digital image, both the coordinates and the image value become discrete quantities.
- Images can now be represented as 2D arrays (matrices) of integer values: I[i,j] (or I[r,c]).
- The term gray level is used to describe monochromatic intensity.



j →, i ↓

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

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Spatial resolution

- Spatial resolution is the smallest discernible detail in an image.
- Sampling is the principal factor determining spatial resolution.

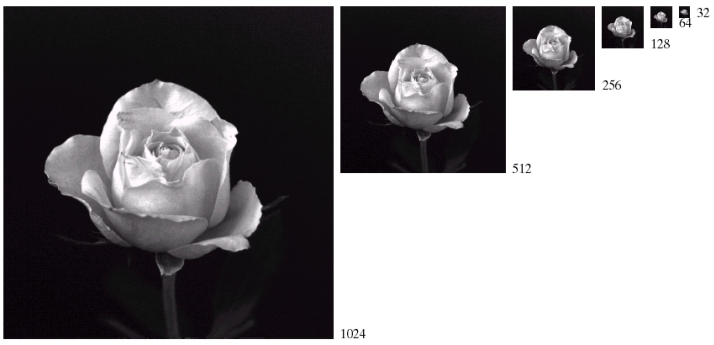

FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

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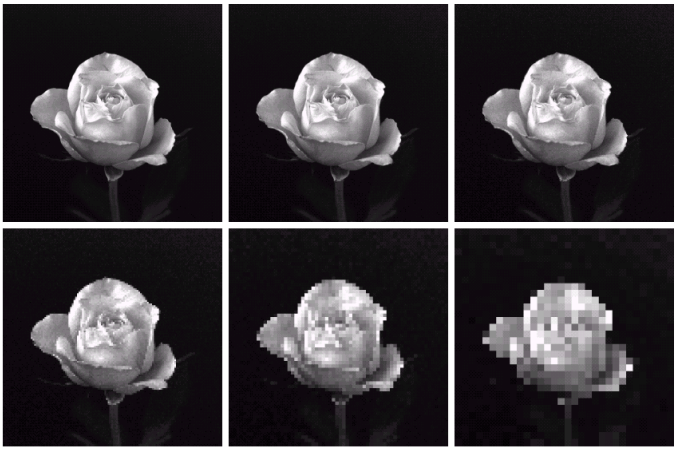
Spatial resolution



a b c
d e f

FIGURE 2.20 (a) 1024 × 1024, 8-bit image. (b) 512 × 512 image resampled into 1024 × 1024 pixels by row and column duplication. (c) through (f) 256 × 256, 128 × 128, 64 × 64, and 32 × 32 images resampled into 1024 × 1024 pixels.

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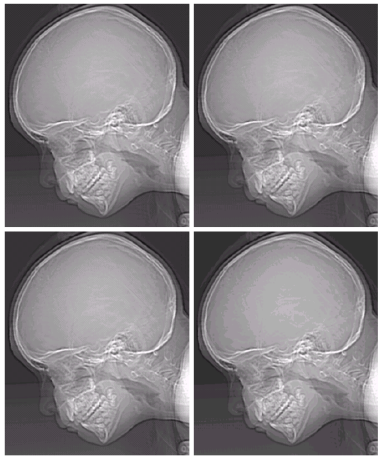
Gray level resolution

- Gray level resolution refers to the smallest discernible change in gray level (often power of 2).

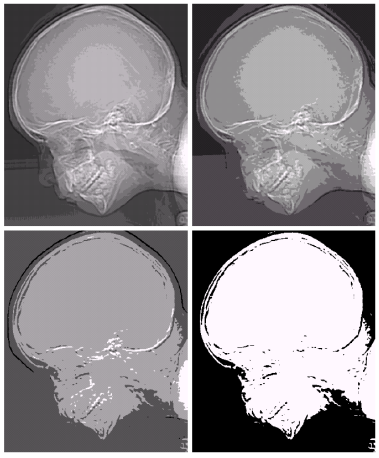


a b
c d

FIGURE 2.21 (a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

e f
g h

FIGURE 2.21 *(Continued)* (e)–(h) Image displayed in 16, 8, 4, and 2 gray levels. (Original courtesy of Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)



30

30

Bit planes

a b c
d e f
g h i

FIGURE 3.14 (a) An 8-bit gray-scale image of size 500 × 1192 pixels. (b) through (i) Bit planes 1 through 8, with bit plane 1 corresponding to the least significant bit. Each bit plane is a binary image.

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Electromagnetic (EM) spectrum

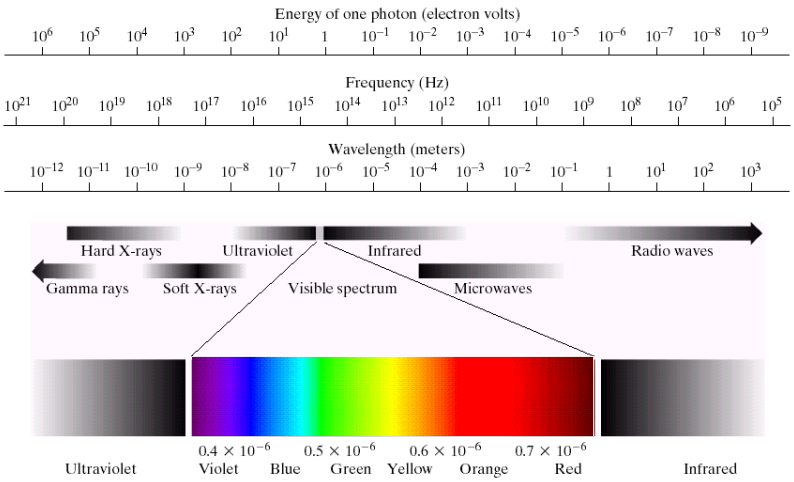

FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

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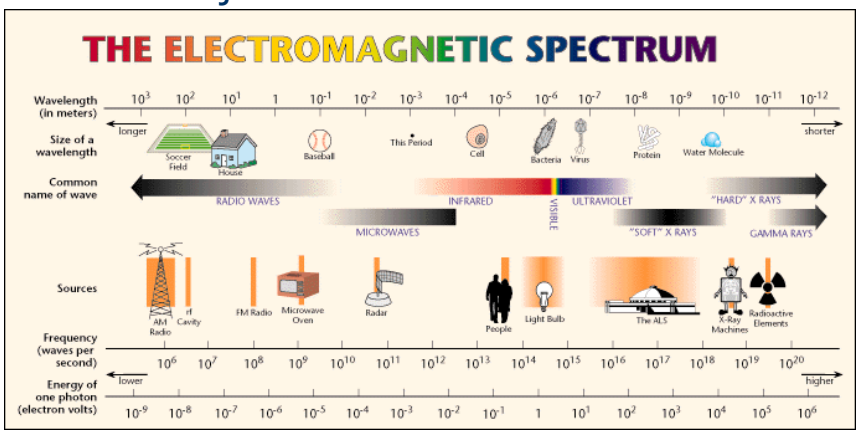
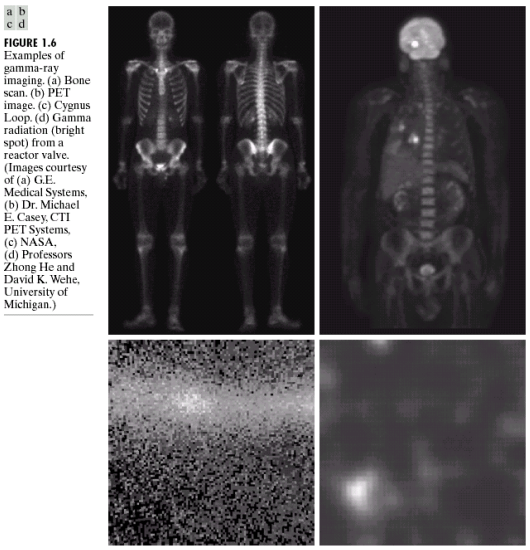
Electromagnetic (EM) spectrum

- The wavelength of an EM wave required to "see" an object must be of the same size as or smaller than the object.

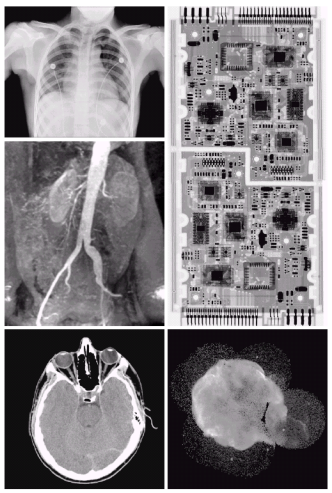


Other types of sensors



a b c d

FIGURE 1.6 Examples of gamma-ray imaging. (a) Bone scan. (b) PET image. (c) Cygnus Loop. (d) Gamma radiation (bright spot) from a reactor valve. (Images courtesy of (a) G.E. Medical Systems, (b) Dr. Michael E. Casey, CTI PET Systems, (c) NASA, (d) Professors Zhong He and David K. Wehe, University of Michigan.)



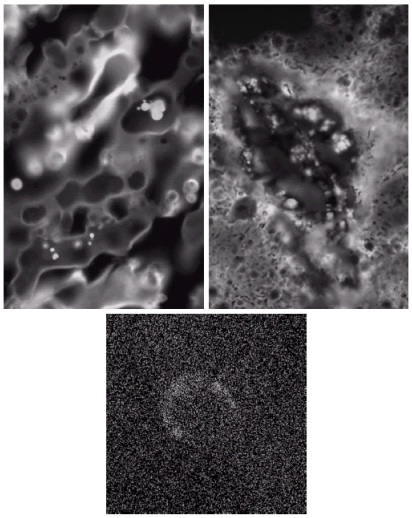
a d b c e

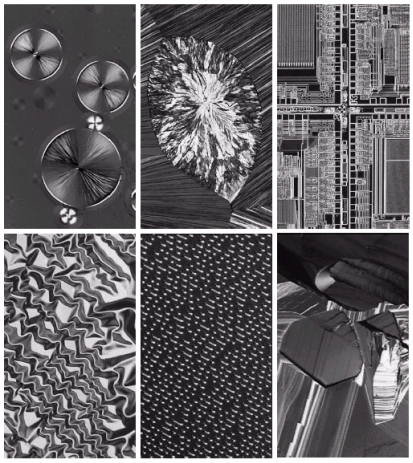
FIGURE 1.7 Examples of X-ray imaging. (a) Chest X-ray. (b) Aortic angiogram. (c) Head CT. (d) Circuit boards. (e) Cygnus Loop. (Images courtesy of (a) and (c) Dr. David R. Pickens, Dept. of Radiology & Radiological Sciences, Vanderbilt University Medical Center, (b) Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School, (d) Mr. Joseph E. Pascente, Lixi, Inc., and (e) NASA.)

Other types of sensors

a b c

FIGURE 1.8 Examples of ultraviolet imaging. (a) Normal corn. (b) Smut corn. (c) Cygnus Loop. (Images courtesy of (a) and (b) Dr. Michael W. Davidson, Florida State University, (c) NASA.)





a b c d e f

FIGURE 1.9 Examples of light microscopy images. (a) Taxol (anticancer agent), magnified 250×. (b) Cholesterol—40×. (c) Microprocessor—60×. (d) Nickel oxide thin film—600×. (e) Surface of audio CD—1750×. (f) Organic superconductor—450×. (Images courtesy of Dr. Michael W. Davidson, Florida State University.)

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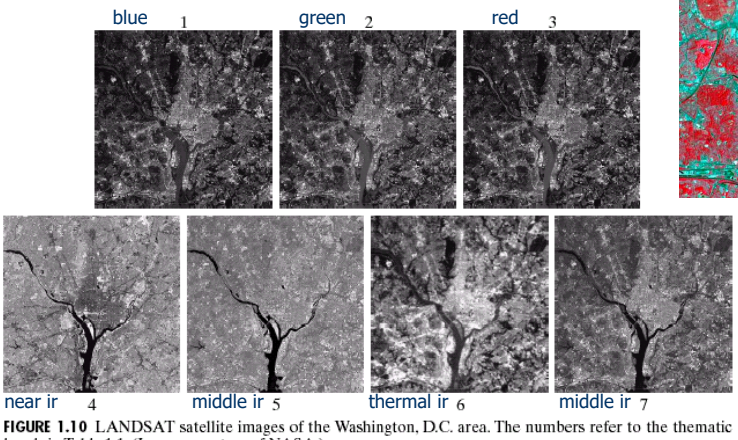
Other types of sensors



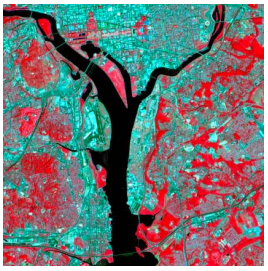


FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

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Other types of sensors

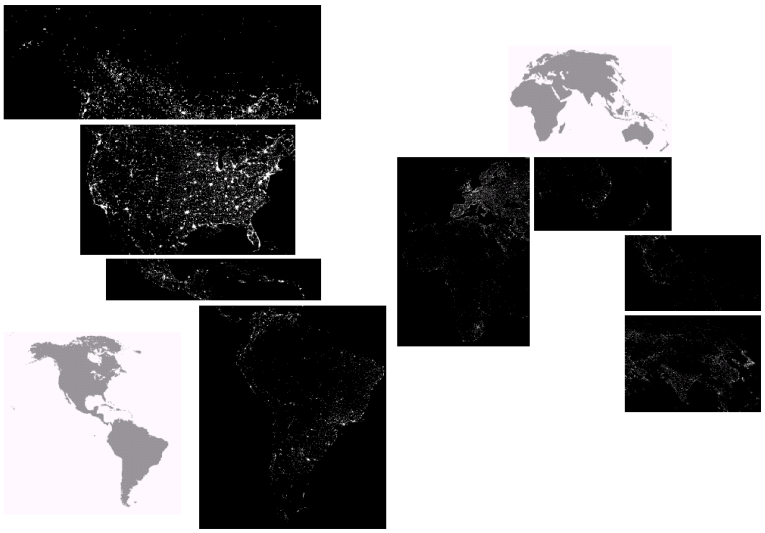

FIGURE 1.12 Infrared satellite images of the Americas. The small gray map is provided for reference. (Courtesy of NOAA.)

FIGURE 1.13 Infrared satellite images of the remaining populated part of the world. The small gray map is provided for reference. (Courtesy of NOAA.)

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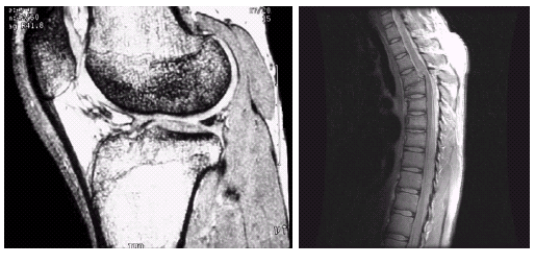
Other types of sensors



a b

FIGURE 1.17 MRI images of a human (a) knee, and (b) spine. (Image (a) courtesy of Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School, and (b) Dr. David R. Pickens, Department of Radiology and Radiological Sciences, Vanderbilt University Medical Center.)

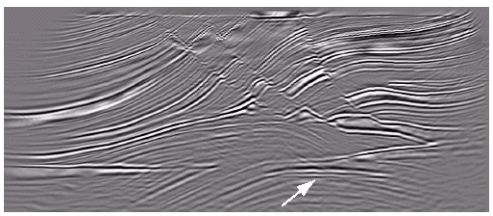


FIGURE 1.19 Cross-sectional image of a seismic model. The arrow points to a hydrocarbon (oil and/or gas) trap. (Courtesy of Dr. Curtis Ober, Sandia National Laboratories.)

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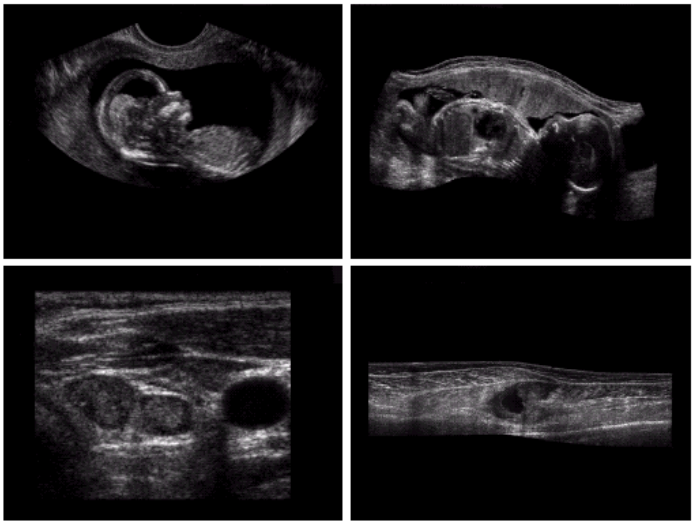
Other types of sensors



a b
c d

FIGURE 1.20 Examples of ultrasound imaging. (a) Baby. (2) Another view of baby. (c) Thyroids. (d) Muscle layers showing lesion. (Courtesy of Siemens Medical Systems, Inc., Ultrasound Group.)

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Image enhancement

- The principal objective of enhancement is to process an image so that the result is more suitable than the original for a *specific* application.
- Enhancement can be done in
  - Spatial domain,
  - Frequency domain.
- Common reasons for enhancement include
  - Improving visual quality,
  - Improving machine recognition accuracy.

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Image enhancement

Transformation function of the form

s = T(r)

where "r" is the original pixel value and "s" is the new value after enhancement.

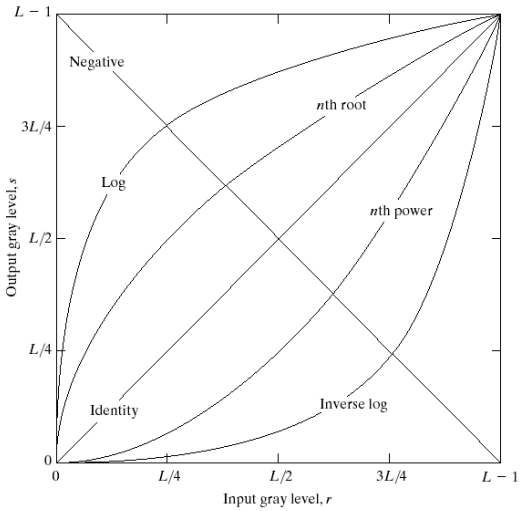

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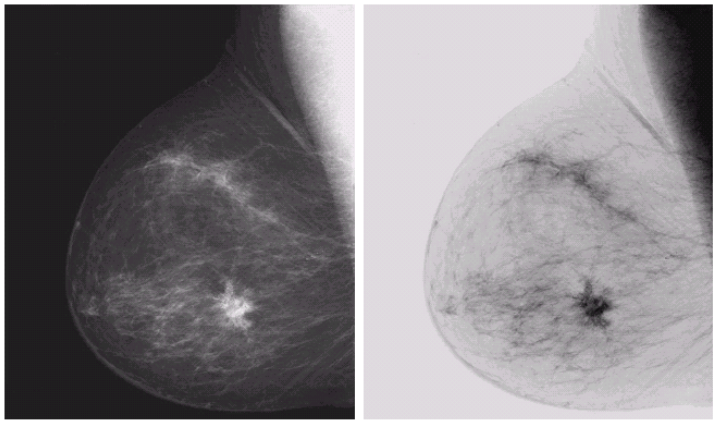
Image enhancement



a b

FIGURE 3.4 (a) Original digital mammogram. (b) Negative image obtained using the negative transformation in Eq. (3.2-1). (Courtesy of G.E. Medical Systems.)

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Image enhancement

- Contrast stretching:

$$I'[r,c] = \frac{I[r,c] - \min}{\max - \min}$$

$$I'[r,c] = \begin{cases} 0 & I[r,c] \leq \text{low} \\ \frac{I[r,c]-\text{low}}{\text{high}-\text{low}} & \text{low} < I[r,c] < \text{high} \\ 1 & I[r,c] \geq \text{high} \end{cases}$$

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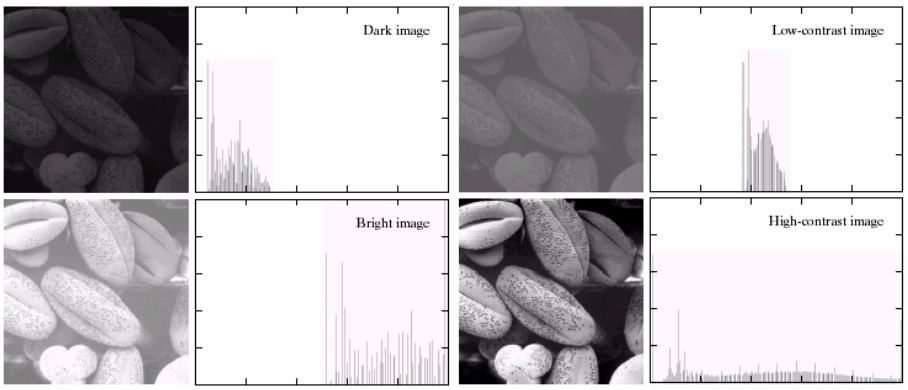
Histogram processing



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Histogram processing

- Intuitively, we expect that an image whose pixels
  - tend to occupy the entire range of possible gray levels,
  - tend to be distributed uniformly

  will have a high contrast and show a great deal of gray level detail.
- It is possible to develop a transformation function that can achieve this effect using histograms.

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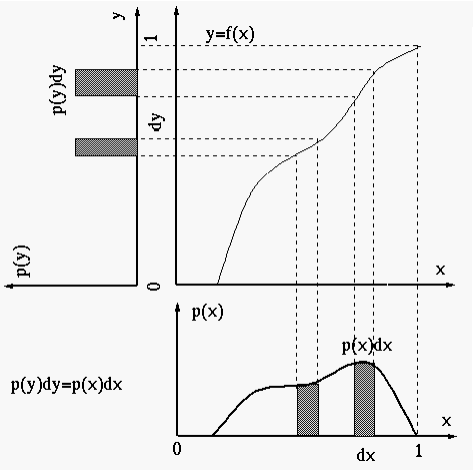
Histogram equalization - theory



$p(x), 0 < x < 1$, is the pdf of the input image.
$p(y), 0 < y < 1$, is the pdf of the output image.
Number of pixels mapped from x to y is unchanged, so

$$p(y)dy = p(x)dx.$$

Let $p(y)$ be constant, i.e., $p(y) = 1, 0 < y < 1$. Then,

$$dy = p(x)dx$$
$$\frac{dy}{dx} = p(x)$$
$$y = \int_0^x p(u)du = F(x) - F(0) = F(x)$$

where $F(x)$ is the cdf of the input image.

http://fourier.eng.hmc.edu/e161/lectures/contrast_transform/node3.html

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Histogram equalization

Let f be a given image represented as a m_r by m_c matrix of integer pixel intensities ranging from 0 to $L-1$. L is the number of possible intensity values, often 256. Let p denote the normalized histogram of f with a bin for each possible intensity. So

$$p_n = \frac{\text{number of pixels with intensity } n}{\text{total number of pixels}} \qquad n = 0, 1, ..., L-1.$$

The histogram equalized image g will be defined by

$$g_{i,j} = \text{floor}((L-1)\sum_{n=0}^{f_{i,j}} p_n), \tag{1}$$

where floor() rounds down to the nearest integer. This is equivalent to transforming the pixel intensities, k, of f by the function

$$T(k) = \text{floor}((L-1)\sum_{n=0}^{k} p_n).$$

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Histogram equalization - algorithm

Method

New Pixel Value = (L – 1) × Cumulative Probability of Original Pixel Value

Steps

1. Traverse the image and calculate the probabilities of the individual gray levels and store it in an **array[256]** on the respective index number.
2. Find the cumulative probabilities of the gray levels and multiply with **(L-1)**. This should result in an **array[256]** containing the mapping of original gray levels (indices) to be replaced by the new gray levels (values at the indices of the array)
3. Traverse the image again and replace the old gray values with the new gray values using the array found in step 2.

Adapted from https://xplaind.com/370945/histogram-equalization

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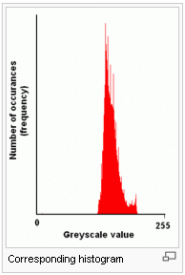
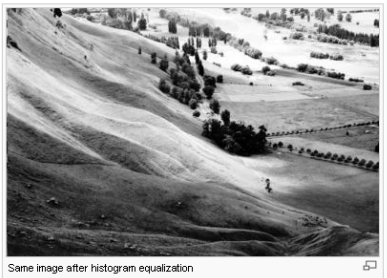
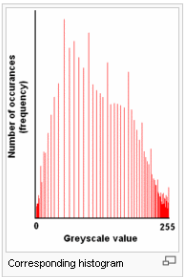
Histogram equalization


An unequalized image



Corresponding histogram

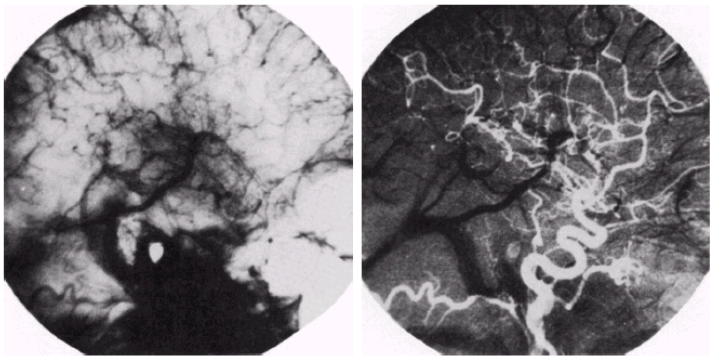

Same image after histogram equalization



Corresponding histogram

Adapted from Wikipedia

Enhancement using arithmetic operations

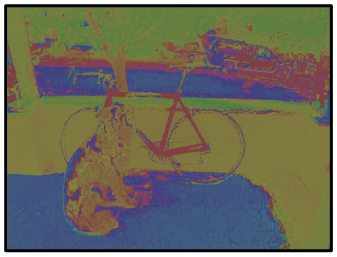


a b

FIGURE 3.29 Enhancement by image subtraction. (a) Mask image. (b) An image (taken after injection of a contrast medium into the bloodstream) with mask subtracted out.

Enhancement using color channels

RGB



Hue

Saturation

Value

Adapted from Joseph Redmon, U of Washington

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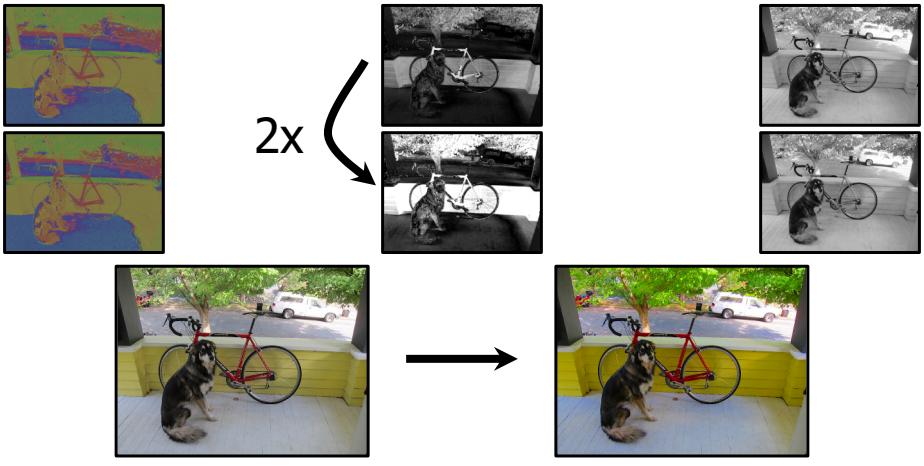
Enhancement using color channels



More saturation -> intense colors

Adapted from Joseph Redmon, U of Washington

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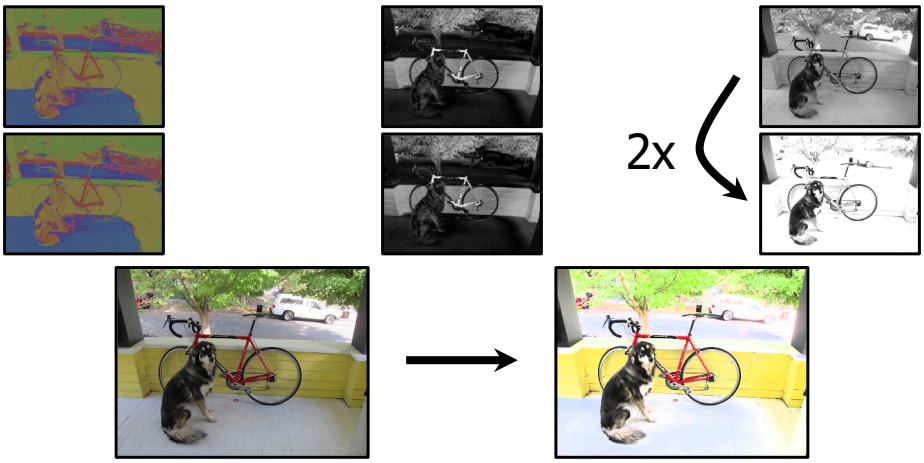
Enhancement using color channels



More value -> lighter image

Adapted from Joseph Redmon, U of Washington

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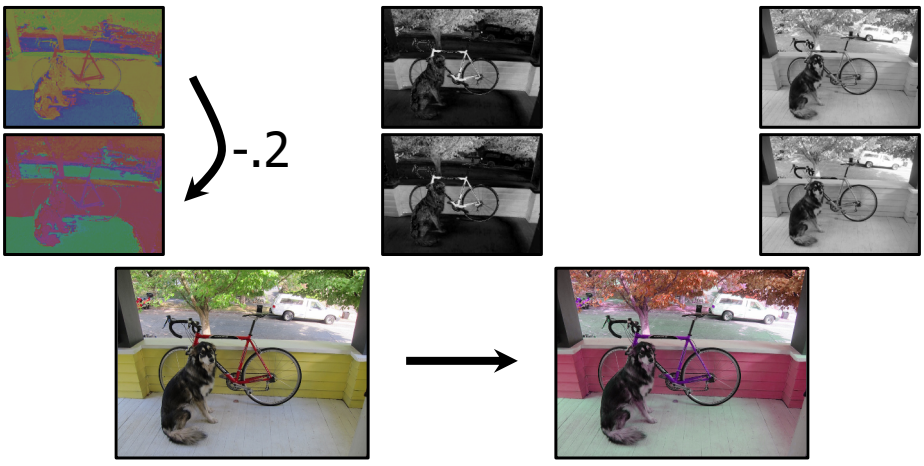
Enhancement using color channels



Shift hue -> shift colors

Adapted from Joseph Redmon, U of Washington

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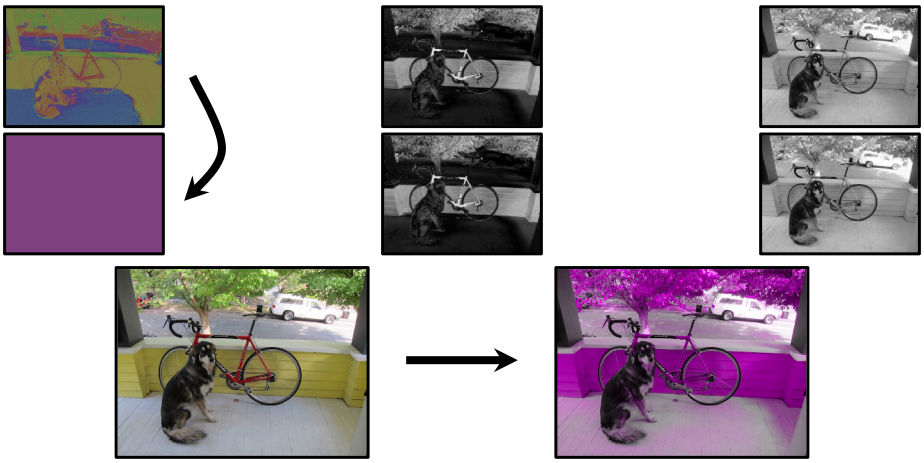
Enhancement using color channels



Set hue to your favourite colour

Adapted from Joseph Redmon, U of Washington

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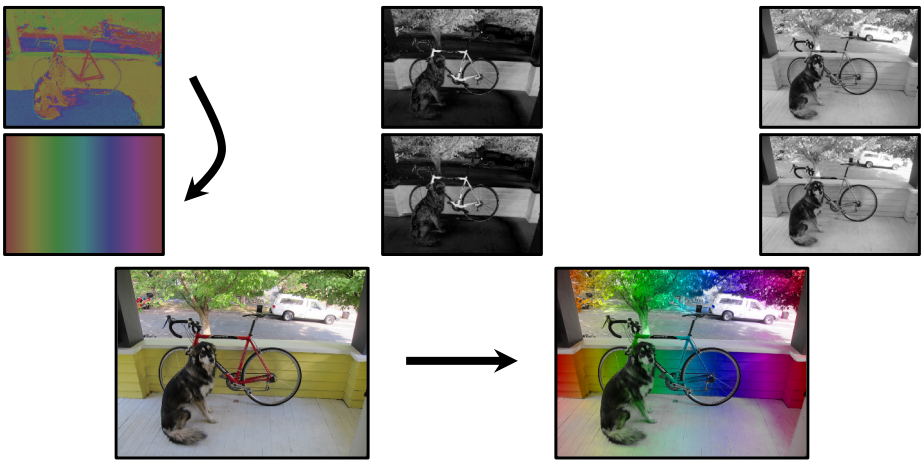
Enhancement using color channels



... or patterns

Adapted from Joseph Redmon, U of Washington

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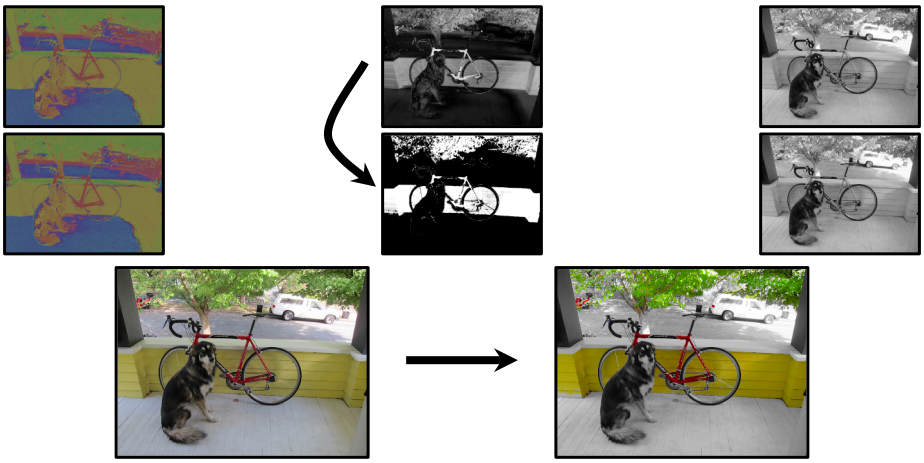
Enhancement using color channels



Increase and threshold saturation

Adapted from Joseph Redmon, U of Washington

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Image formats

- Popular formats:
  - BMP Microsoft Windows bitmap image
  - EPS Adobe Encapsulated PostScript
  - GIF CompuServe graphics interchange format
  - JPEG Joint Photographic Experts Group
  - PBM Portable bitmap format (black and white)
  - PGM Portable graymap format (gray scale)
  - PPM Portable pixmap format (color)
  - PNG Portable Network Graphics
  - PS Adobe PostScript
  - TIFF Tagged Image File Format

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Image formats

- ASCII or binary
- Number of bits per pixel (color depth)
- Number of bands
- Support for compression (lossless, lossy)
- Support for metadata
- Support for transparency
- Format conversion
- …
  http://en.wikipedia.org/wiki/Comparison_of_graphics_file_formats

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