Image Representation and Production

What's An Image?

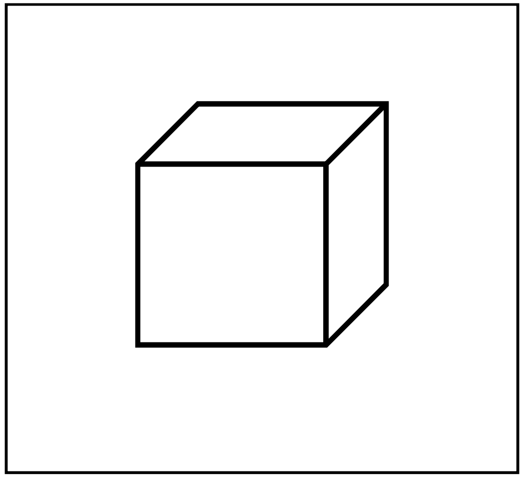


Image: distribution of light energy on 2D "film" : $E(x, y, \lambda, t)$

(x, y) - position

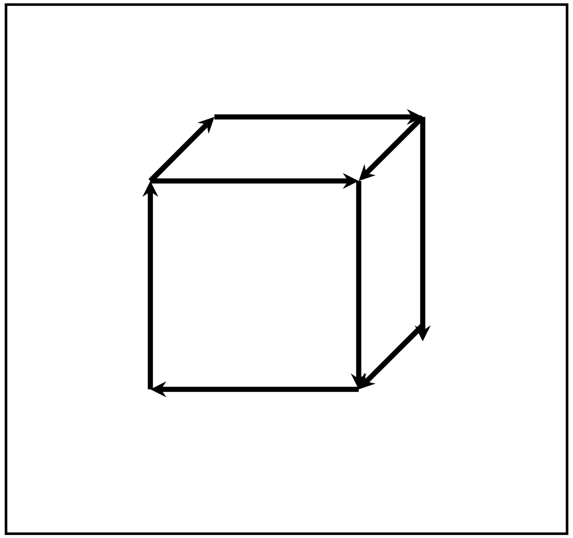
λ - wavelength (blue, green, yellow, red, violet)

t - time

This is a *continuous* representation

- Not easily represented on a computer

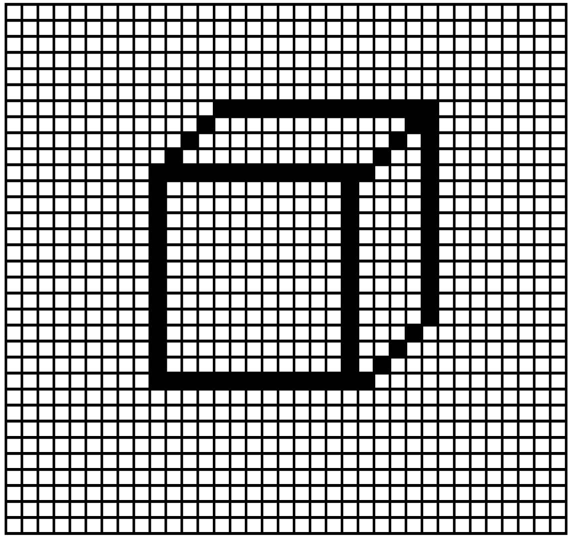
How Do We Represent Images?



Vector Representation

+ arbitrary resolution
+ good for line drawings (text)

- may draw same point twice
- hard to do color changes

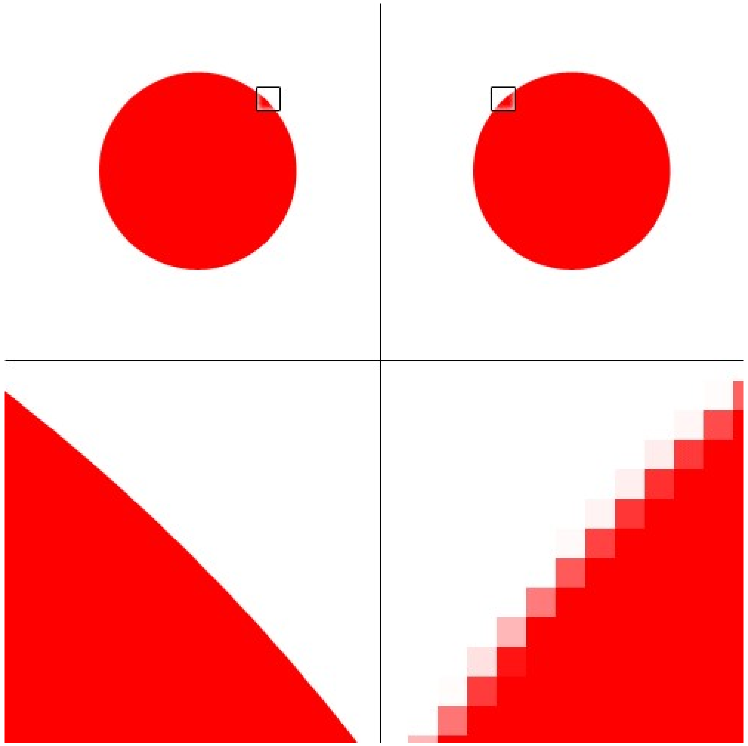


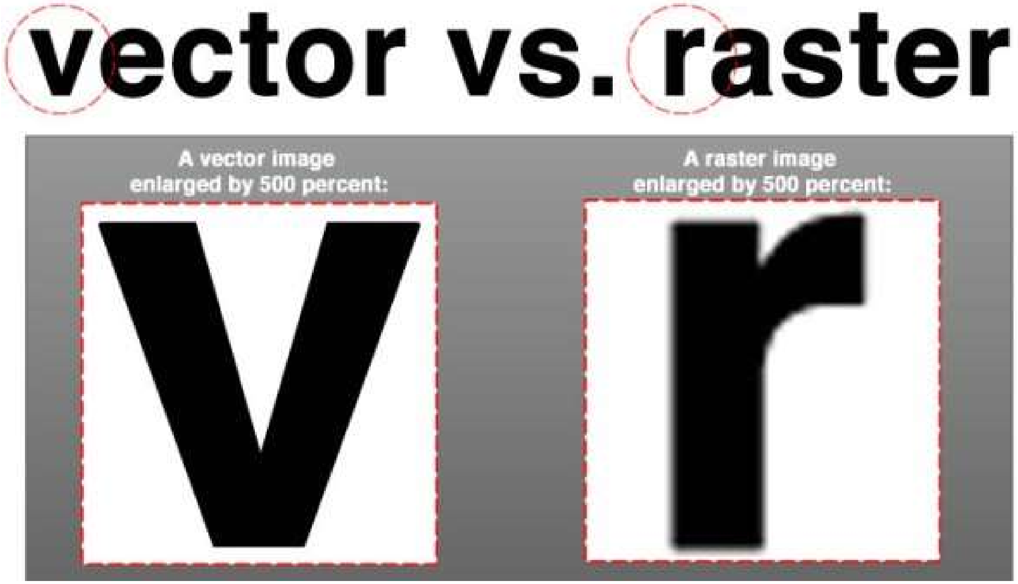
Raster Representation

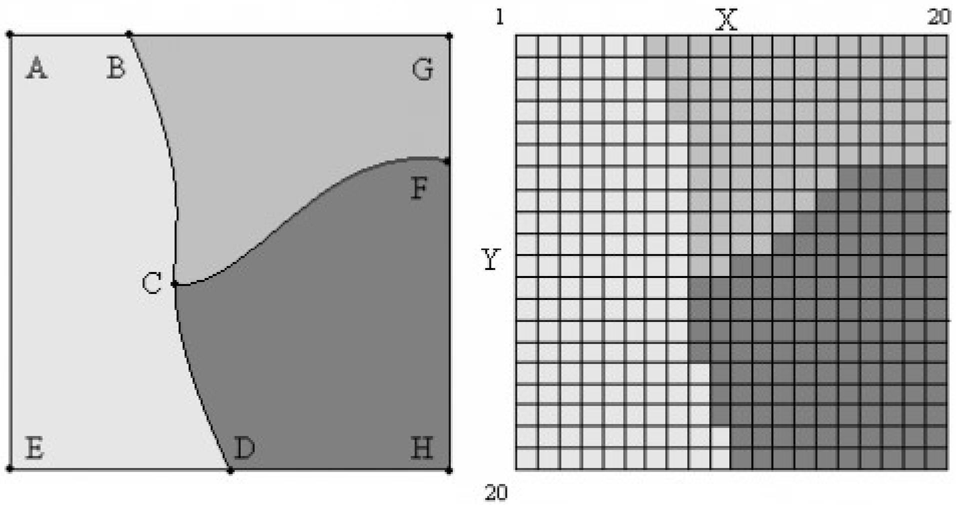
+ good for color images
+ general purpose

- bounded resolution (aliasing)
- store EVERY pixel

Vector and Raster



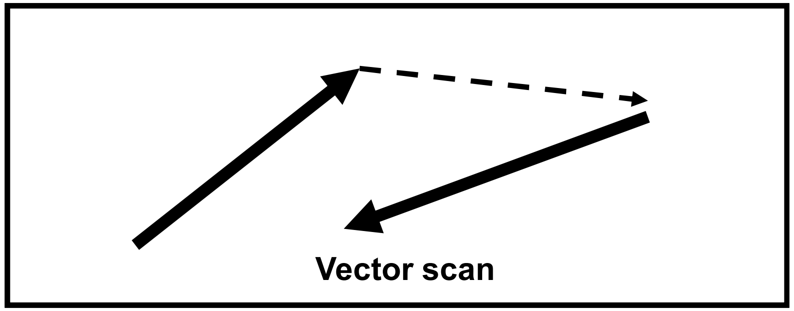


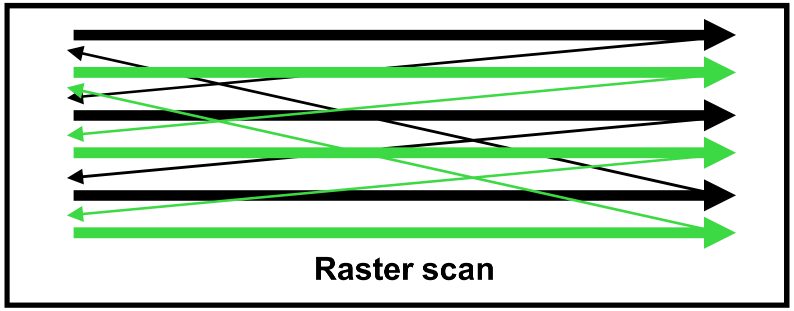


Vector and Raster

- Early displays were *vector* displays
  - electron beam traces out line segments
  - image is a sequence of endpoints

- Raster displays (TV’ s, LCD’ s)
  - electron beam traces out a regular pattern: *raster scan*
  - other raster technologies: LCD, plasma, micro-mirror
  - image is a raster: a 2D array of pixels

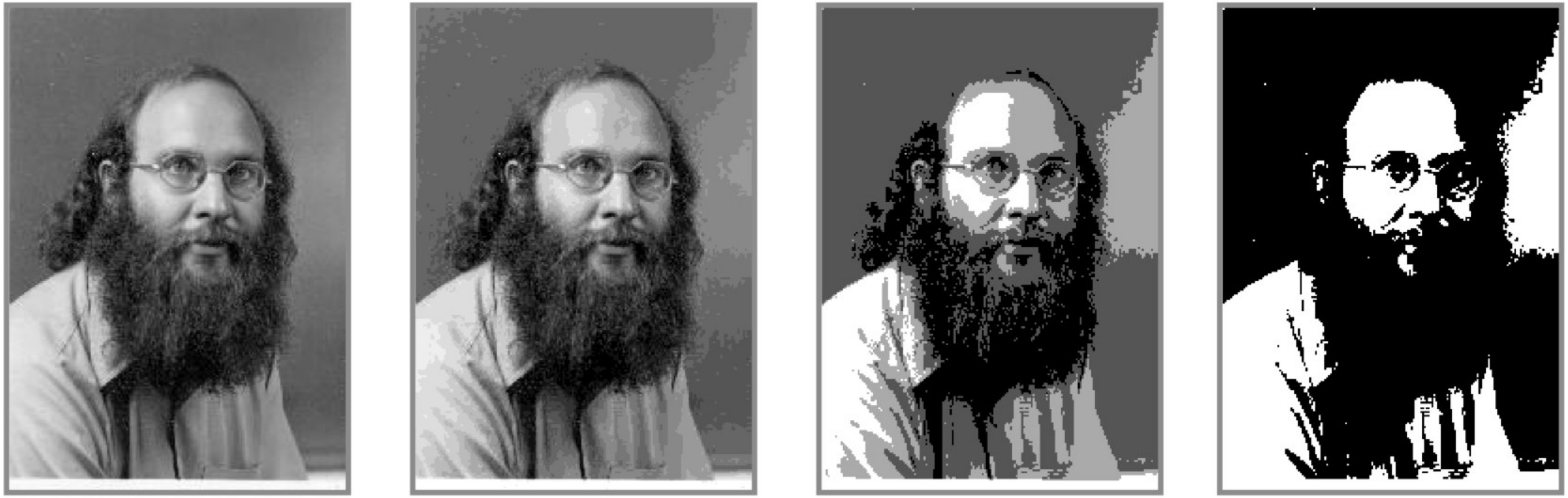




Displays and Framebuffers

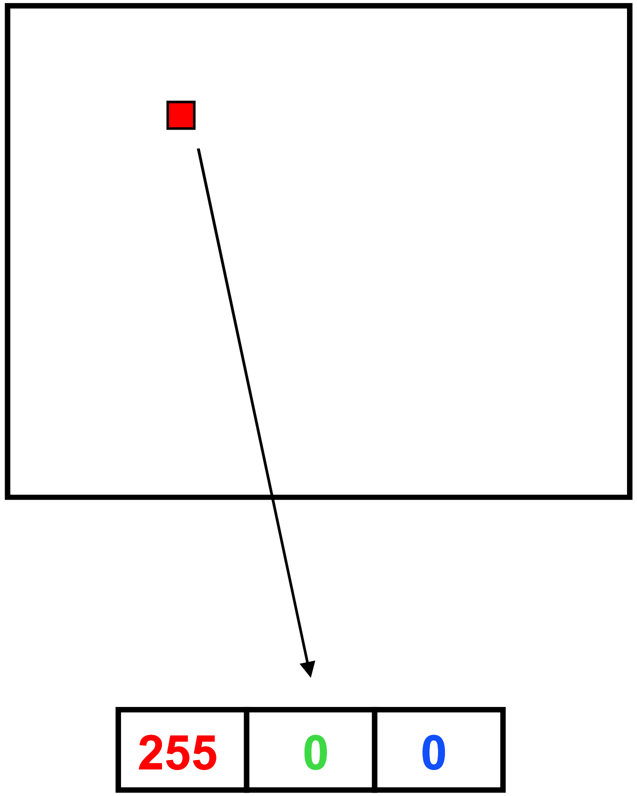
- The picture drawn by a raster display is stored in memory as a 2-D array of *pixels*.
- The value stored in each pixel controls the brightness of the beam (or beams, for color displays) as it sweeps past the corresponding screen location.
- The memory that stores the 2-D array of pixel values is called a *framebuffer*.
- The video hardware scans the framebuffer at ~60Hz
  - changes appear immediately
- Displays support different types of pixels
  - B&W displays: 1 bit/pixel *(bitmap)*.
  - Basic color displays: 8, 16, or 24 bits.
  - High-end displays: 96 or more bits.

Images with decreasing bits per pixel



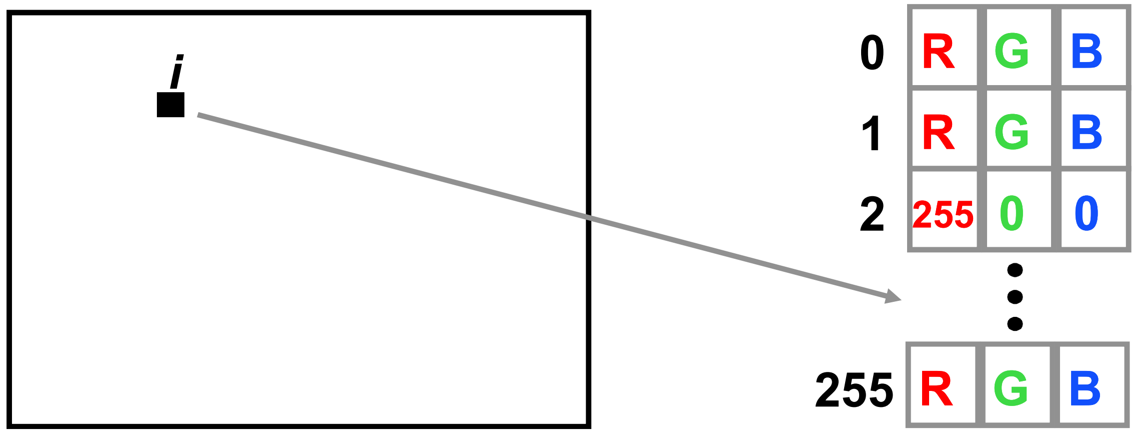
8 bits　　4 bits　　2 bits　　1 bit

Full-color (RGB) displays



- **For 24 bit color:**
  - **store 8 bits each of red, green, and blue per pixel.**
  - **E.g. (255,0,0) is pure red, and (255, 255, 255) is white.**
  - **Yields 2^24 = 16 million colors.**
- **For 15 bit color:**
  - **5 bits red + 5 green + 5 blue**
- **The video hardware uses the values to drive the R, G, and B guns.**
- **You can mix different levels of R, G, and B to get (almost) any color you want**

Colormaps (LUT's)



- A single number (e.g. 8 bits) stored at each pixel.
- Used as an *index* into an array of RGB triples.
- With 8 bits per pixel, you get 256 colors of your choice
- Simple things to fill up color-maps with:
  - A gray ramp (for grayscale pictures)
  - A bunch of pre-chosen colors
  - A set of colors adaptively chosen for a given picture

Some Picture File Formats

JPEG: Joint Photographic Experts Group Format
TIFF: Tagged-Image File Format
GIF: CompuServe Graphics Interchange Format
PPM: Portable PixMap Format (ASCII or binary)
EPS: Encapsulated PostScript Format (ASCII)

	BITS PER PIXEL	FILE SIZE	COMMENTS
JPEG	24	small	lossy compression
TIFF	8, 24	medium	good general purpose
GIF	1, 4, 8	medium	popular, but 8-bit
PPM	24	big	easy to read/write
EPS	1, 2, 4, 8, 24	huge	good for printing

Others: BMP, XPM, RAS, PICT, PNG, etc...

Derek Tonn

Deeper Framebuffers

- Some frame buffers have 96 or more bits per pixel. What are they all for? We start with 24 bits for RGB.
- *Alpha channel*: an extra 8 bits per pixel, to represent "transparency." Used for digital compositing. That's 32 bits.
- A Z-buffer, used to hold a "depth" value for each pixel. Used for hidden surface 3-D drawing. 16 bits/pixel of "z" brings the total to 48 bits.
- Double buffering:
  - For clean-looking flicker-free real time animation.
  - Two full frame buffers (including alpha and z).
  - Only one at a time is visible—you can toggle instantly.
  - Draw into the "back buffer" (invisible), then swap.
  - Can be faked with off-screen bitmaps (slower.)
  - 2 x 48 = 96.

Image Compositing

- Represent an image as layers that are composited (matted) together
- To support this, use pixel's extra *alpha* channel in addition to R, G, B
- Alpha is opacity: 0 if totally transparent, 1 if totally opaque
- Alpha is often stored as an 8 bit quantity; usually not displayed.
- Mathematically, to composite a_2 over a_1 according to matte α

  $b = (1-\alpha)\bullet a_1 + \alpha\bullet a_2$

  α = 0 or 1 -- a hard matte, α = between 0 and 1 -- a soft matte
- Compositing is useful for photo retouching and special effects.
- Compositing is useful for translucent polygon rendering and volume rendering!

Image Processing

- *Point Processing*: modify each pixel as a function of its pixel value
- *Filtering*: output is a function of the (usually) local neighborhood around the pixel
- Image processing is a discrete version of signal processing (some lingo: image is a two-dimensional "signal")
- Other topics :
  - Image transformation (resize, warp)
  - Image compression
  - Texture maping
  - …

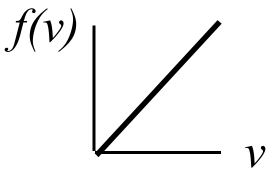
Point Processing

- Input: a[x,y], Output b[x,y] = f(a[x,y])
- f transforms each pixel value separately
- Useful for contrast adjustment

Suppose our picture is grayscale (a.k.a. monochrome).

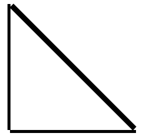
Let v denote pixel value, suppose it's in the range [0,1].

$f(v) = v$ **identity**; no change

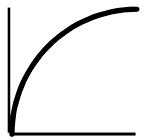


$f(v) = 1-v$ **negate** an image

(black to white, white to black)



$f(v) = v^p, p<1$ **brighten**



$f(v) = v^p, p>1$ **darken**

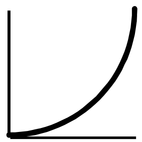


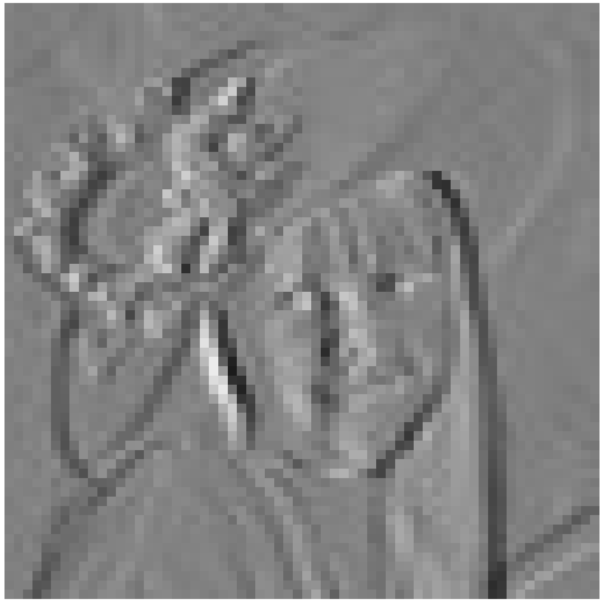
Image Filtering: Blurring

original, 64x64 pixels

3x3 blur

5x5 blur

Image Filtering: Edge Detection



horizontal derivative

vertical derivative

Image Filters

- In 1-D such a simple filter can be written:

$$b[x] = \sum_{t=-\infty}^{+\infty} a[t]h[x-t]$$

where $a[x]$ = input signal
$b[x]$ = output signal
$h[x]$ = filter
x takes on only integer values

- This is convolution, written b = a⊗h for short. Convolution is commutative, i.e. a⊗h=h⊗a
- 2-D is similar, but with a double-summation:

$$b[x,y] = \sum_{u=-\infty}^{+\infty} \sum_{v=-\infty}^{+\infty} a[u,v]h[x-u,y-v]$$

- This class of filters is called "linear, shift-invariant"

Image Filter Example

$$b[x,y] = \sum_{u=-\infty}^{+\infty} \sum_{v=-\infty}^{+\infty} a[u,v]h[x-u, y-v]$$

a[x,y] = input signal

b[x,y] = output signal

h[x,y] = 3x3 filter

x,y take on only integer vals

$\frac{1}{4}$

-1	0	1
-2	0	2
-1	0	1

h

(0,0) at center

0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25

a

0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0

b

Blurring Filters

A simple blurring effect can be achieved with a 3x3 filter centered around a pixel,

written explicitly:

```
b[x,y] = (a[x-1,y-1] + a[x,y-1] + a[x+1,y-1]
          +a[x-1,y] + a[x,y] + a[x+1,y]
          +a[x-1,y+1] + a[x,y+1] + a[x+1,y+1])  / 9
```

or as coefficient matrix:

$$\frac{1}{9}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

More blurring is achieved with a wider $n \times n$ filter:

$$\frac{1}{n*n} \begin{matrix} 1 & \ldots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \ldots & 1 \end{matrix}$$

Edge Filter

To find edges, use approximation to the magnitude of the gradient of the image.

Gradient and its magnitude:

$$\nabla a = \left(\frac{\partial a}{\partial x} \quad \frac{\partial a}{\partial y} \right), \qquad |\nabla a| = \sqrt{\left(\frac{\partial a}{\partial x} \right)^2 + \left(\frac{\partial a}{\partial y} \right)^2}$$

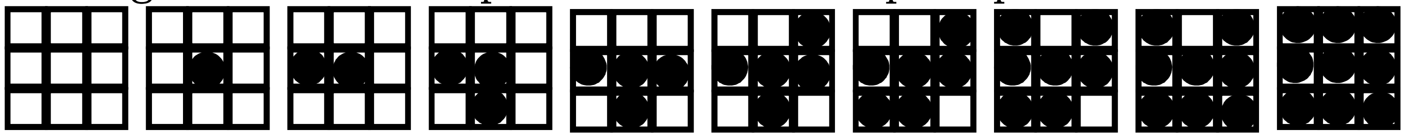
Sobel edge filter uses these weights:

$$\frac{\partial}{\partial x} \Rightarrow \begin{matrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{matrix}, \qquad \frac{\partial}{\partial y} \Rightarrow \begin{matrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{matrix}$$

This is a *nonlinear filter* because of the sqrt and square operations.

Image Display and Print

- How to draw grayscale on a 1-bit screen, or full color on an 8-bit screen
- Basic idea: give up *spatial* resolution in return for greater *brightness* or *color* resolution
- The eye does *spatial averaging*, so present a pattern whose *average* color matches the color you want
- In the patterns below, each square is either black or white.
  - From far away, the eye sees the average brightness of each grid, not the individual squares.
  - The average brightness of each 3x3 grid depends on the number of black and white squares—you can get ten distinct brightness levels ranging from black to white.
  - To draw a grayscale picture, each input pixel is represented by an ouput pattern. The pattern of dots that gets drawn depends on the input pixel value.



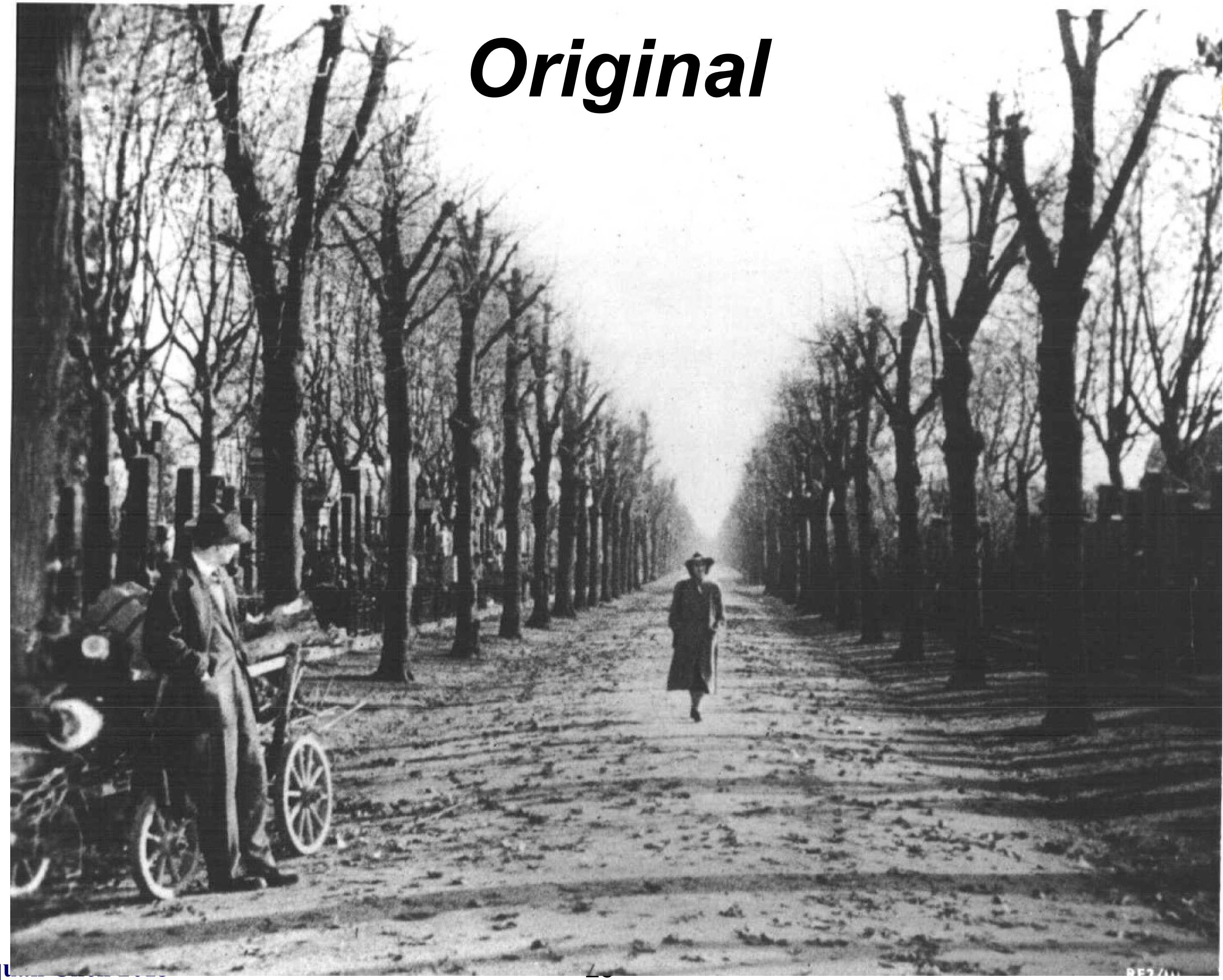
0 1 2 3 4 5 6 7 8 9

Halftone Screens

- How do we select a good set of patterns
- Pick patterns that avoid annoying artifacts:
  - Constant-brightness regions should not have obvious stripes.
  - On many devices (e.g. laser printers) isolated pixels should be avoided.
  - Growth-sequence: pixels that are "on" at one brightness levels should remain on for all higher levels. This avoids contouring artifacts.
- The full set of dot patterns can be encoded in a single n x n *dither matrix*. Each element in the matrix is a threshold: the dot is turned on for input values greater than the threshold. A sample 3x3 dither matrix is

6	8	4
1	0	3
5	2	7

Original



Half Toning

Dithering

- Distribute errors among pixels
  - Exploit spatial integration in our eye
  - Display greater range of perceptible intensities

Original
(8 bits)

Uniform
Quantization
(1 bit)

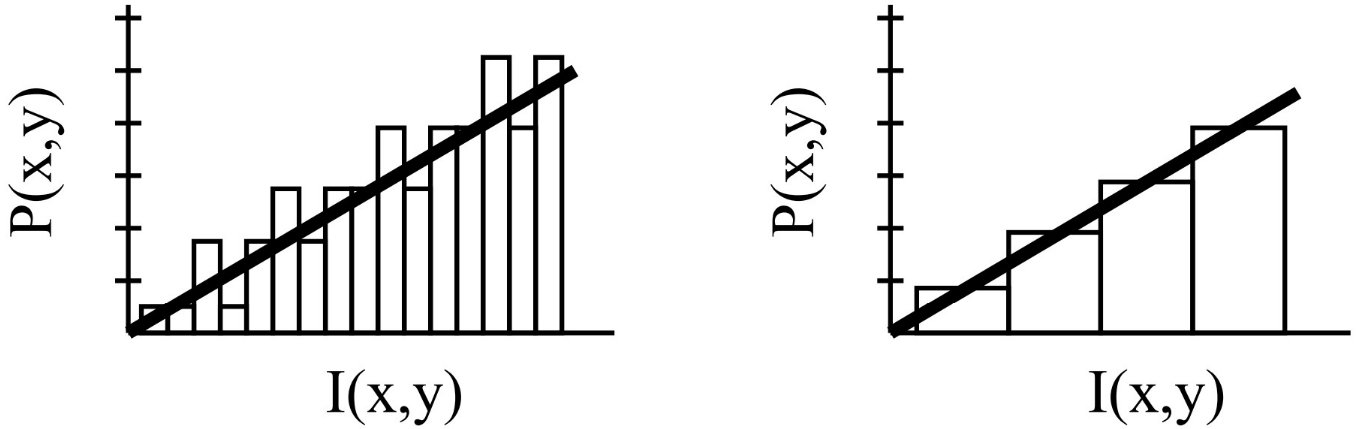
Floyd-Steinberg
Dither
(1 bit)

Dithering

- Three dithering methods
  - Random dither
  - Ordered dither
  - Error diffusion dither

Random Dither

- Randomize quantization errors
  - Errors appear as noise



$$P(x, y) = \mathrm{trunc}(I(x, y) + \mathrm{noise}(x,y) + 0.5)$$

Random Dither

- Randomize quantization errors
  - Errors appear as noise

Original
(8 bits)

Uniform
Quantization
(1 bit)

Random
Dither
(1 bit)

Ordered Dither

- Pseudo-random quantization errors
  - Matrix stores pattern of thresholds

i = x mod n
j = y mod n
e = I(x,y) - trunc(I(x,y))
if (e > D(i,j))
    P(x,y) = ceil(I(x, y))
else
    P(x,y) = floor(I(x,y))

$$D_2 = \begin{bmatrix} 3 & 1 \\ 0 & 2 \end{bmatrix}$$

$$D_n = \begin{bmatrix} 4D_{n/2} + D_2(1,1)U_{n/2} & 4D_{n/2} + D_2(1,2)U_{n/2} \\ 4D_{n/2} + D_2(2,1)U_{n/2} & 4D_{n/2} + D_2(2,2)U_{n/2} \end{bmatrix}$$

$$D_4 = \begin{bmatrix} 15 & 7 & 13 & 5 \\ 3 & 11 & 1 & 9 \\ 12 & 4 & 14 & 6 \\ 0 & 8 & 2 & 10 \end{bmatrix}$$

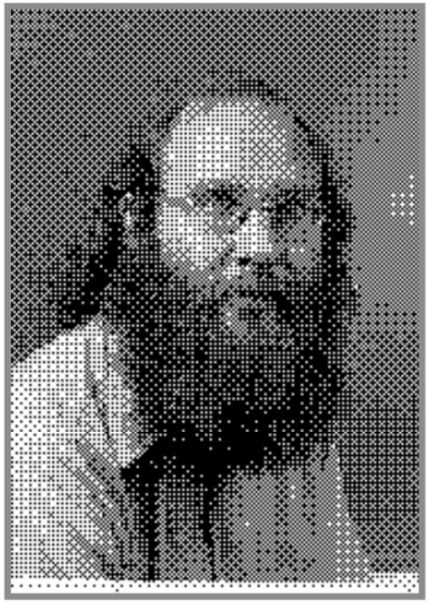
Bayer's ordered dither matrices

Ordered Dither

- Pseudo-random quantization errors
  - Matrix stores pattern of thresholds

Original (8 bits)

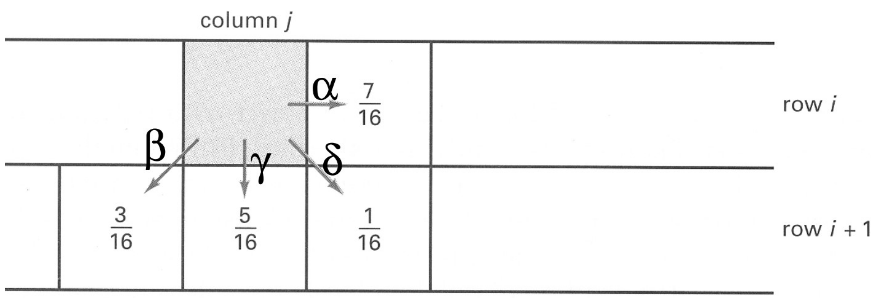
Random Dither (1 bit)



Ordered Dither (1 bit)

Error Diffusion Dither

- Spread quantization error over neighbor pixels
  - Error dispersed to pixels right and below



$$\alpha + \beta + \gamma + \delta = 1.0$$

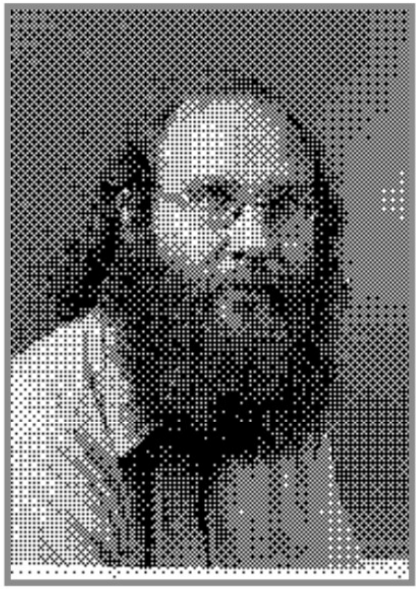
Floyd-Steinberg Error Diffusion

```
for (x = 0; x < width; x++) {
        for (y = 0; y < height; y++) {
                P(x,y) = trunc(I(x,y) + 0.5)
                e = I(x,y) - P(x,y)
                I(x,y+1) += α*e;
                I(x+1,y-1) += β*e;
                I(x+1,y) += γ*e;
                I(x+1,y+1) += δ *e;
        }
}
```

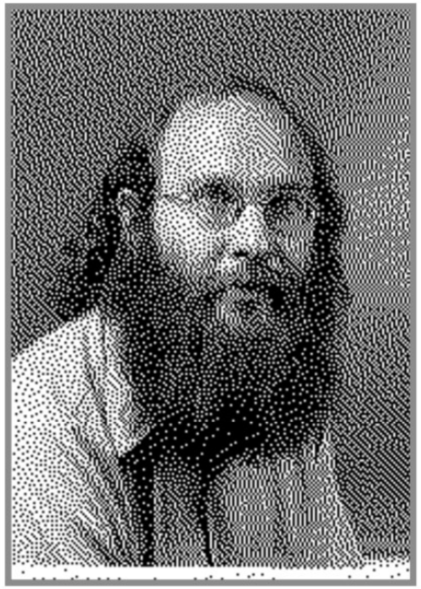
Floyd-Steinberg Error Diffusion

Original
(8 bits)

Random
Dither
(1 bit)



Ordered
Dither
(1 bit)

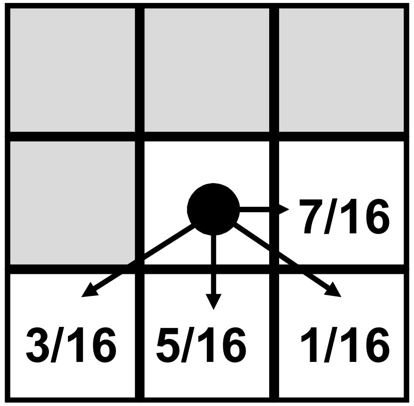


Floyd-Steinberg
Dither
(1 bit)

Floyd-Steinberg Error Diffusion

If image and display have the same resolution:

- Scan in raster order.
- At each pixel, draw the least-error output value (round off.)
- Divide the error into 4 (uneven) chunks.
- Add the error chunks back into the input values, at the 4 neighboring pixels you haven't hit yet:
- Can alternate scan direction



Floyd-Steinberg Error Diffusion

Original image

After Floyd-Steinberg dithering

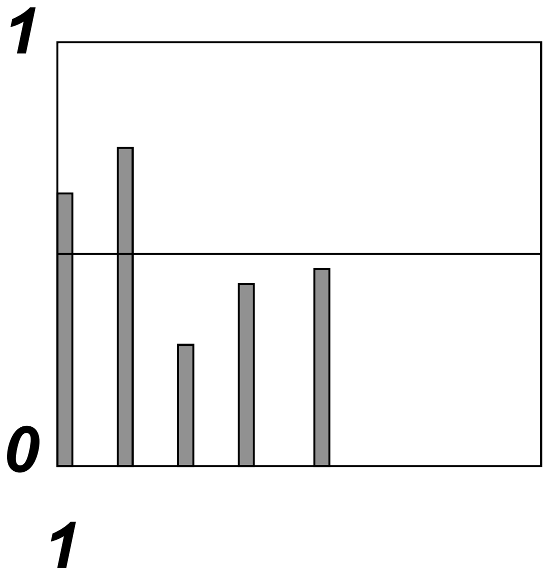
Color Dithering

- You can mix Red, Green, and Blue to get any color you like.
- If you have an RGB image and a 3bit display, 1 per color, you just dither R, G, and B separately.
- On an 8 bit display, you can use the color map to divide the 8 bits into three parts (3, 3, 2) for R, G, and B. (Blue gets shortchanged because we can't see blue very well.) So you get 8 levels each for R and G, and 4 for B.
- Dither R, G, and B separately (Floyd-Steinberg works fine for multi-bit output,) assemble the results into an 8-bit byte, and write to the frame buffer.
- The results generally look excellent, particularly on a high-res monitor.

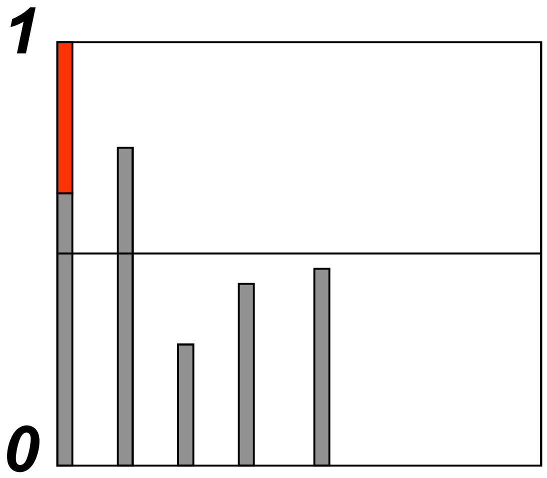
More on dithering:

http://www.iro.umontreal.ca/~ostrom/publications/research.html#halftoning

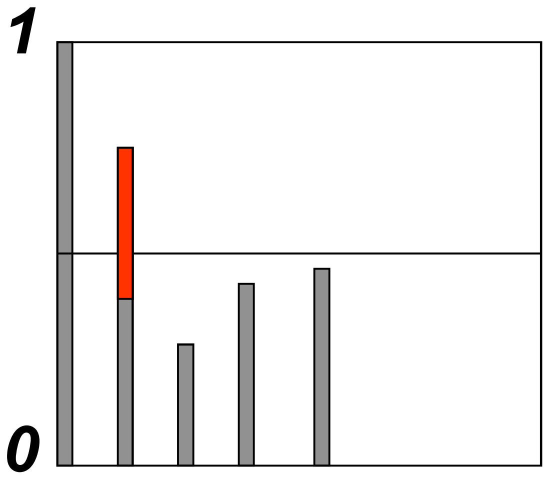
1D Error Diffusion



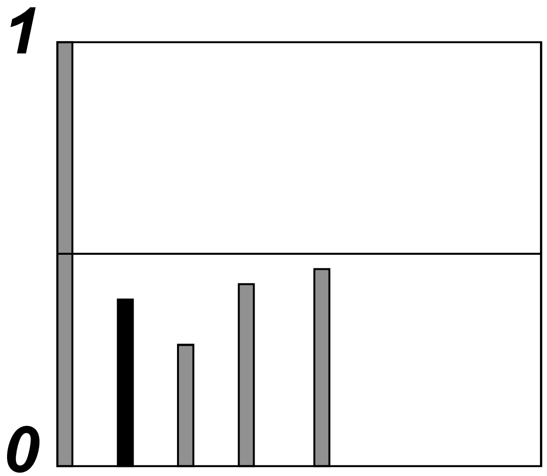
1D Error Diffusion



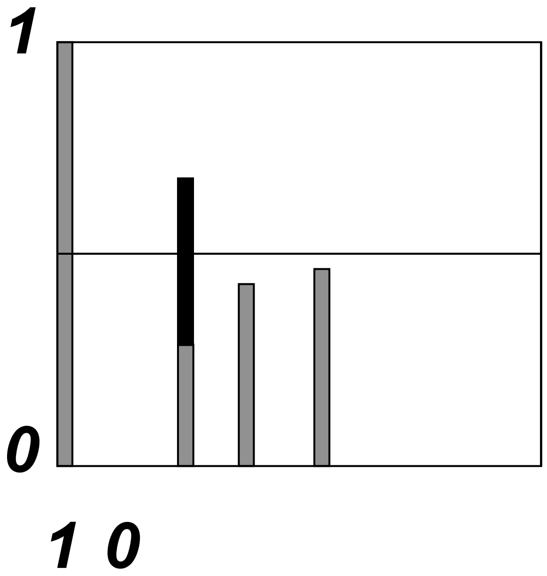
1D Error Diffusion



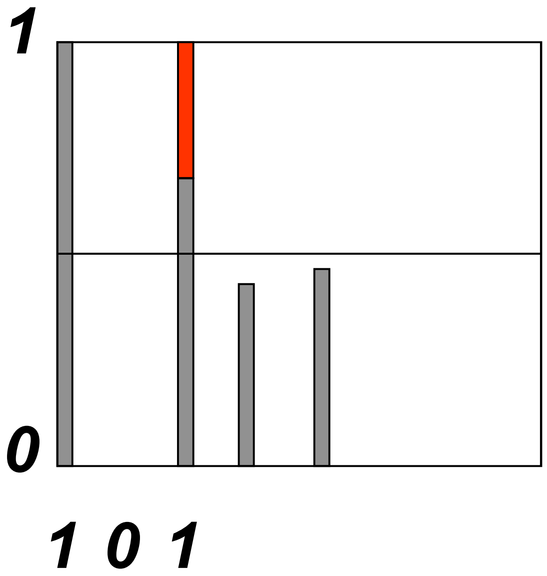
1D Error Diffusion



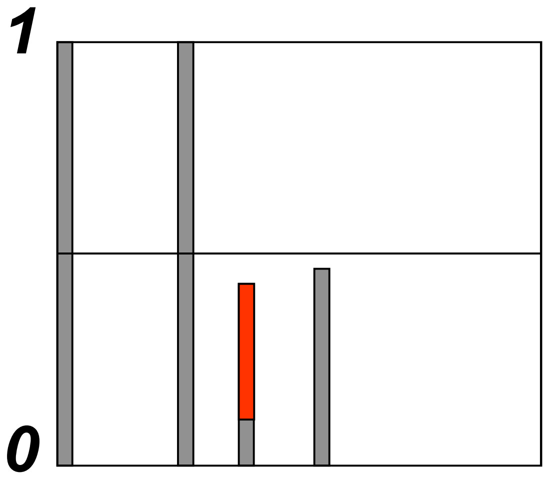
1D Error Diffusion



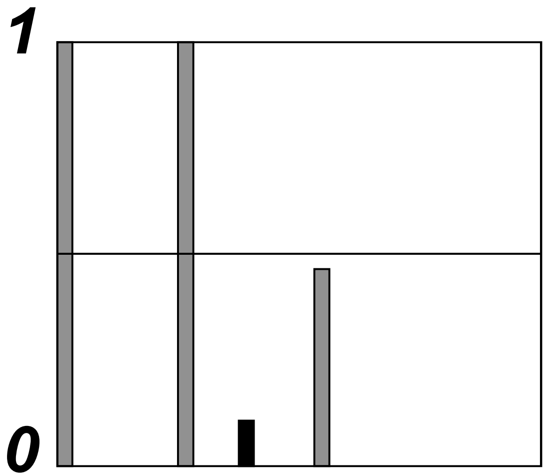
1D Error Diffusion



1D Error Diffusion



1D Error Diffusion



1D Error Diffusion