Computer Graphics (CS 543)
Lecture 11.a: Image Manipulation

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Announcement

- Project 5 mailed out tomorrow
- On image manipulation
- Due in 2 weeks time

Reference Book for Image Manipulation

- Graphics Shaders, Cunningham and Bailey, 2nd edition

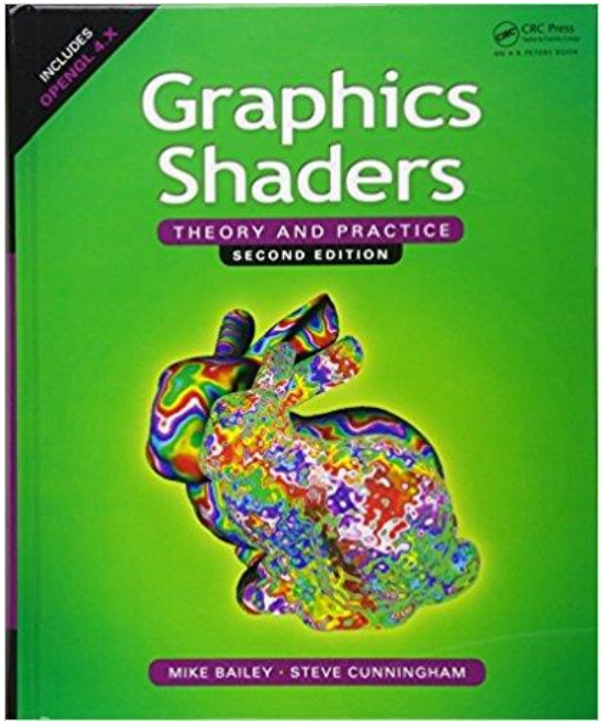


Image Processing

- Graphics concerned with creating artificial scenes from geometry and shading descriptions
- Image processing
  - Input is an image
  - Output is a modified version of input image
- Image processing operations include altering images, remove noise, super-impose images

Image Processing

- Example: Sobel Filter

Original Image

Sobel Filter

Image Processing

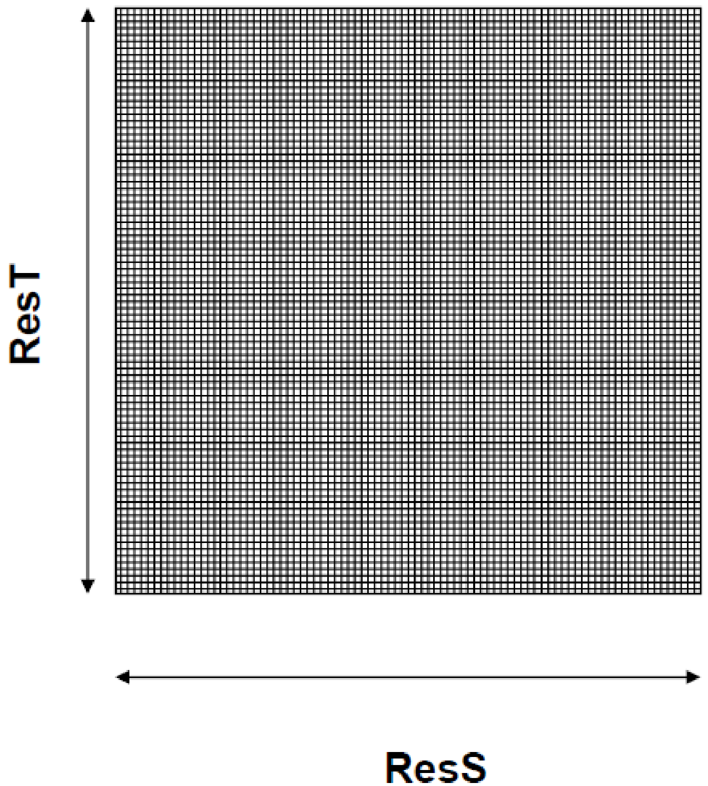
- Image processing the output of graphics rendering is called **post-processing**
- To post-process using GPU, rendered output usually written to offscreen buffer (e.g. color image, z-depth buffer, etc)
- Image in offscreen buffer treated as texture, mapped to screen-filling quadrilateral
- Fragment shader invoked on each element of texture
  - Performs calculation, outputs color to pixel in color buffer
- Output image may be
  - Displayed, saved as a texture, output to a file

Image Manipulation Basics

Treat the image as a texture.
The resolution of this texture
can be found by saying:

```
ivec2 ires = textureSize( ImageUnit, 0 );
float ResS = float( ires.s );
float ResT = float( ires.t );
```

To get from the current texel to a neighboring texel, add ± (1./ResS , 1./ResT) to the current (S,T)



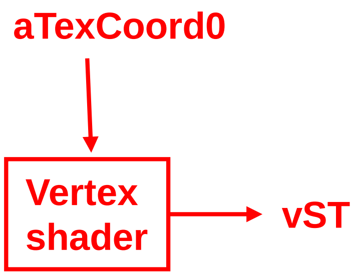
Note: Since S and T range from 0 to 1

- Image center is at vec2(0.5, 0.5)

Vertex Shader

- Most image processing in fragment shader
- Vertex shader just sets texture coordinates

```
out vec2 vST;

Void main( )
{
    vST = aTexCoord0.st;
    gl_Position = uModelViewProjectionMatrix * aVertex;
}
```



Luminance

- Luminance of a color is its **overall brightness**
- Given a color in R G B,
- Compute it luminance by multiplying by a set of weights (0.2125, 0.7154, 0.0721). i.e.

Luminance = **R** * 0.2125 + **G** * 0.7154 + **B** * 0.0721

- Note that sum of weights **0.2125 + 0.7154 + 0.0721 = 1**

Code (Fragment Shader) for Luminance

```
const vec3 W = vec3(0.2125, 0.7154, 0.0721);
vec3 irgb = texture( uImageUnit, vST).rgb;
float luminance = dot(irgb, W);

fFragColor = vec4( luminance, luminance,luminance, 1.);
```

// look up RGB of texel at vST

Color with R = G = B is Shade of gray

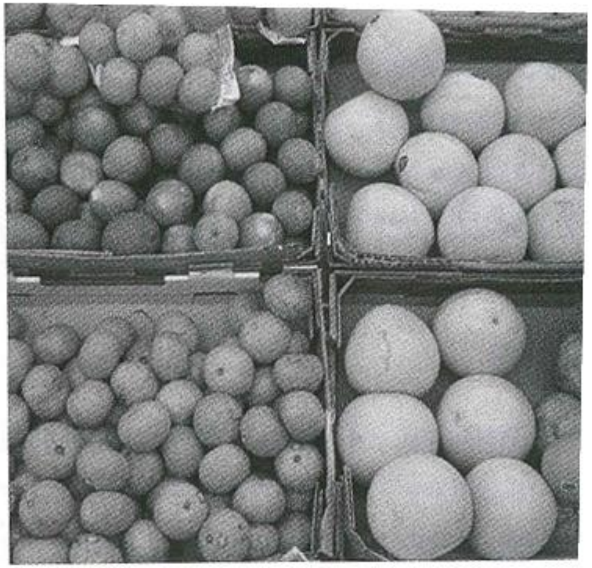


Image Negative

- Another example

(R, G, B)

(1.-R, 1.-G, 1.-B)

Image Filtering

- A filter convolves (weighted addition?) a pixel with its neighbors
- Different algorithms have different filter sizes (how many neighbors) and weight values

Original Image

$$\begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

Sobel Filter applied

Sobel Filter

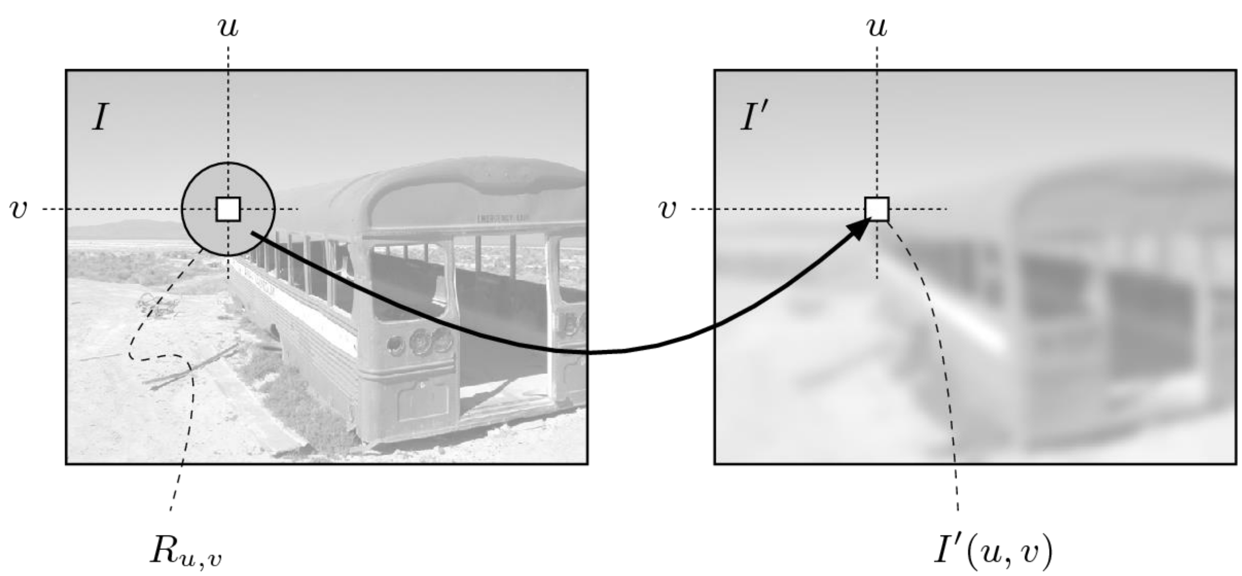
What is a Filter?

- **Filters:** combine a pixel's value with its neighbors
- **E.g:** Compute average intensity of block of pixels (Blurring)

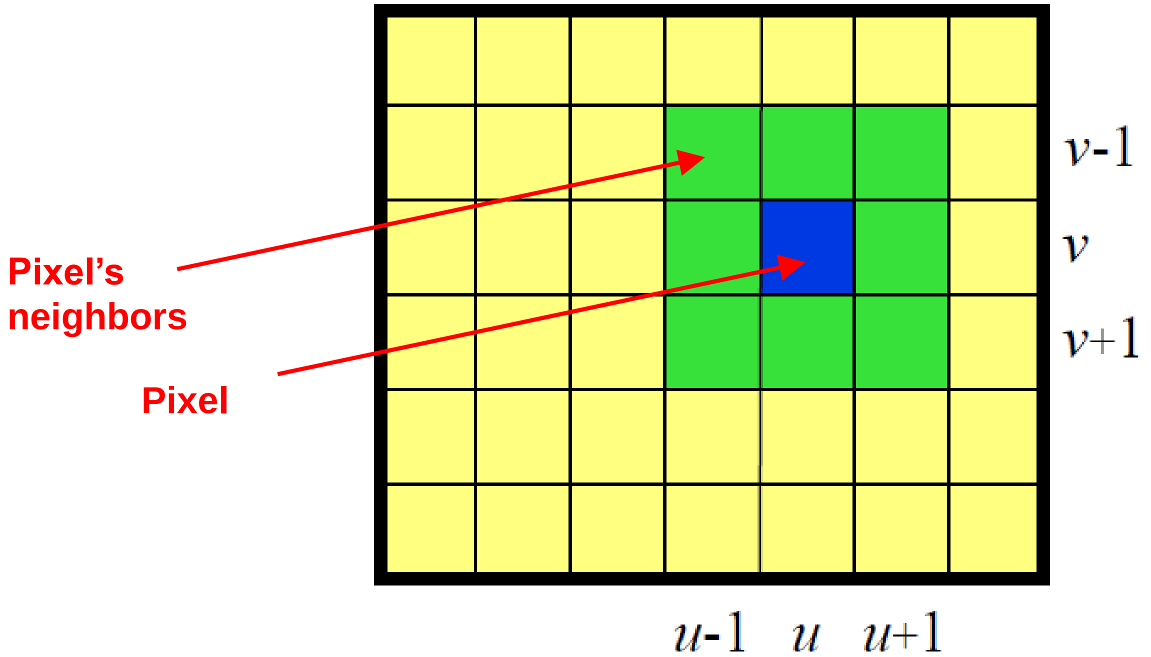
- Combining multiple pixels necessary for certain operations:
  - Blurring, Smoothing
  - Sharpening

Definition: Spatial Filter

- An image operation that combines each pixel's intensity $I(u, v)$ with that of neighboring pixels
- **E.g:** average/weighted average of group of pixels



Example: Mean of 3x3 Neighborhood

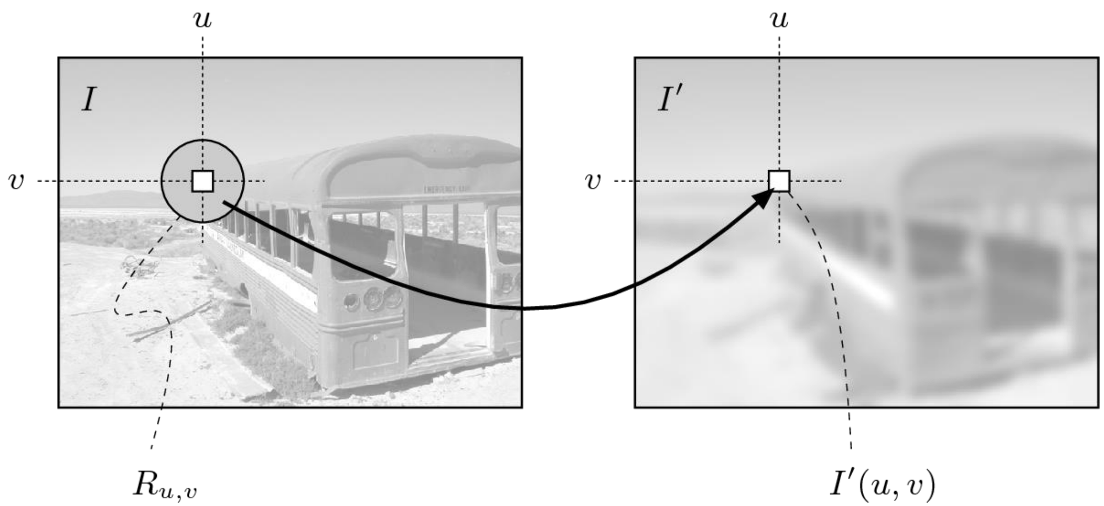


$$I'(u,v) = \frac{1}{9} \sum_{i=-1}^{1} \sum_{j=-1}^{1} I(u+i, v+j)$$

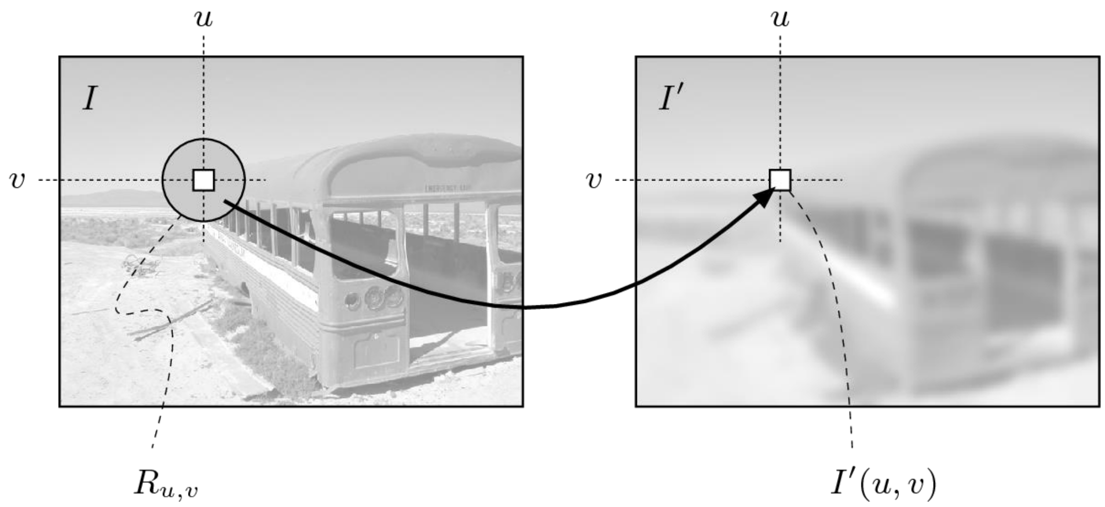
Smoothing an Image by Averaging

- Replace each pixel by average of neighboring pixels
- For 3x3 neighborhood:

$$I'(u,v) \leftarrow \frac{p_0 + p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8}{9}$$



Smoothing an Image by Averaging

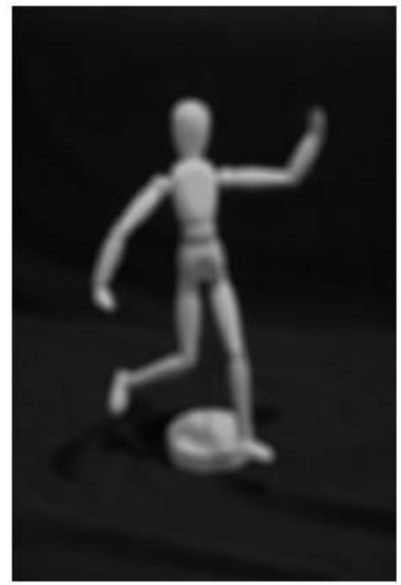


- Filter applies a function over small pixel neighborhood
- **Filter size (size of neighborhood):** 3x3, 5x5, 7x7, …,21x21,..
- **Filter shape:** not necessarily square, can be rectangle, circle…
- **Filters function:** can be linear of nonlinear

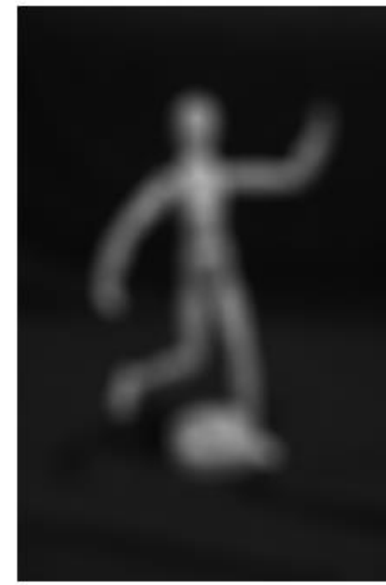
Mean Filters: Effect of Filter Size

Original

7×7



15×15



41×41

Usually make the Weights Integers

$$H(i,j) = \begin{bmatrix} 0.075 & 0.125 & 0.075 \\ 0.125 & \underline{0.200} & 0.125 \\ 0.075 & 0.125 & 0.075 \end{bmatrix} = \frac{1}{40} \begin{bmatrix} 3 & 5 & 3 \\ 5 & \underline{8} & 5 \\ 3 & 5 & 3 \end{bmatrix}$$

Filters

- Filters are usually square matrix and odd. E.g. 3x3 or 5x5
- Example of a 5x5 image blur filter

$$\frac{1}{273} * \begin{bmatrix} 1 & 4 & 7 & 4 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 26 & 41 & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{bmatrix}$$

- Example of 3x3 image blur filter

$$\frac{1}{16} * \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

Image Blurring

- Sample images from 3x3 and 5x5 blur filters

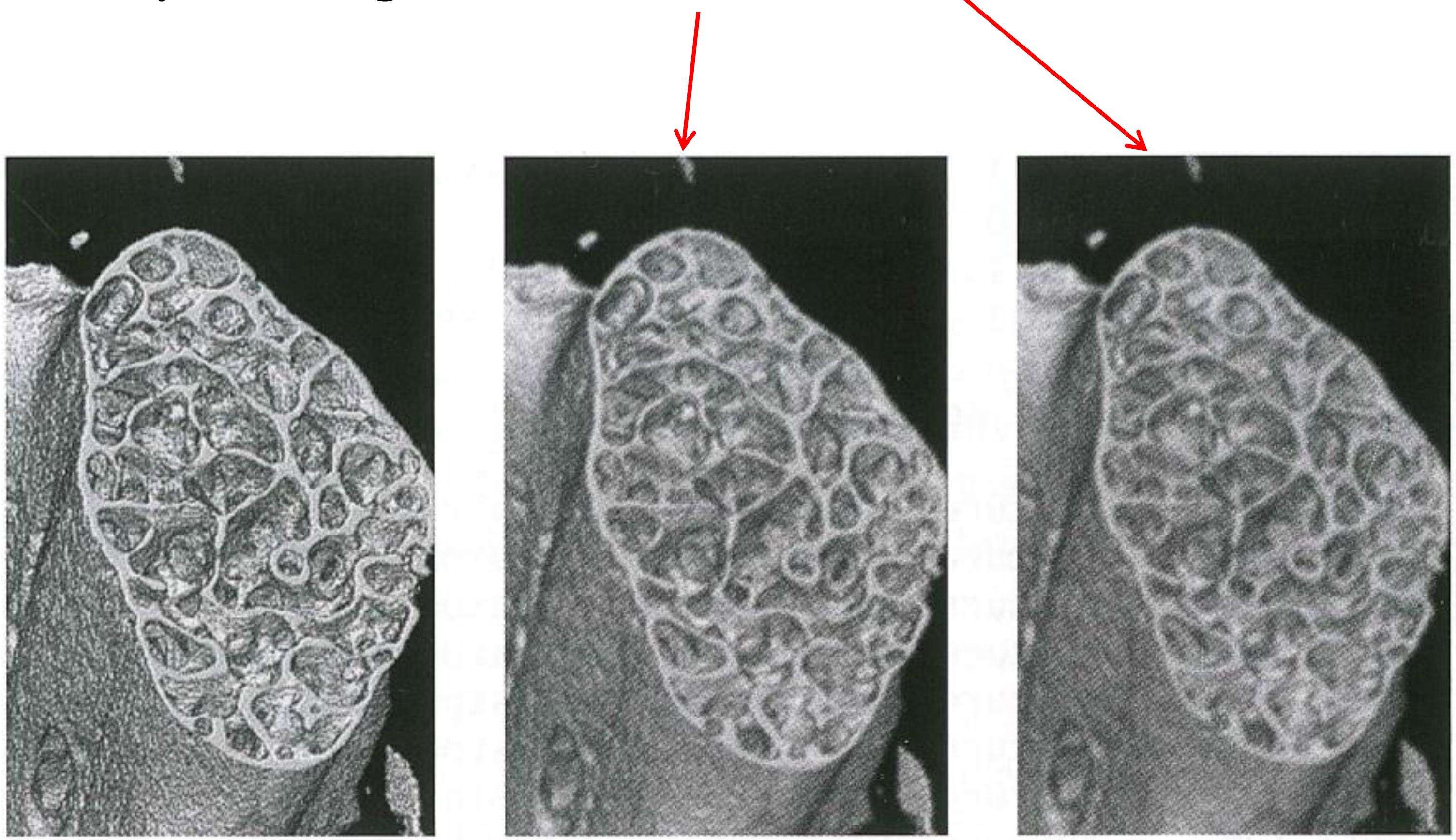
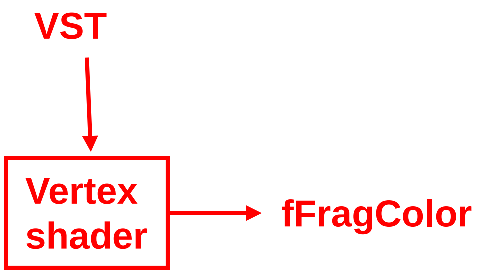


Image Blurring Fragment Shader

- Applying filter

$$\frac{1}{16} * \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$




```
Uniform sampler2D uImageUnit;
in vec2 VST;
out vec4 fFragColor;

void main( )
{
    ivec2 ires = textureSize( uImageUnit, 0);
    float ResS = float( ires.s );
```

Texture

Mipmap level

Image Blurring Fragment Shader (contd)

```
float ResT = float( ires.t );
vec3 irgb = texture(uImageUnit, VST ).rgb;

                             s    t
vec2 stp0 = vec2(1.ResS, 0. ); //texel offsets
vec2 st0p = vec2(0.   , 1./ResT);
vec2 stpp = vec2(1./ResS, 1./ResT);
vec2 stpm = vec2(1./ResS, -1./ResT);
```

$$\frac{1}{16} * \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

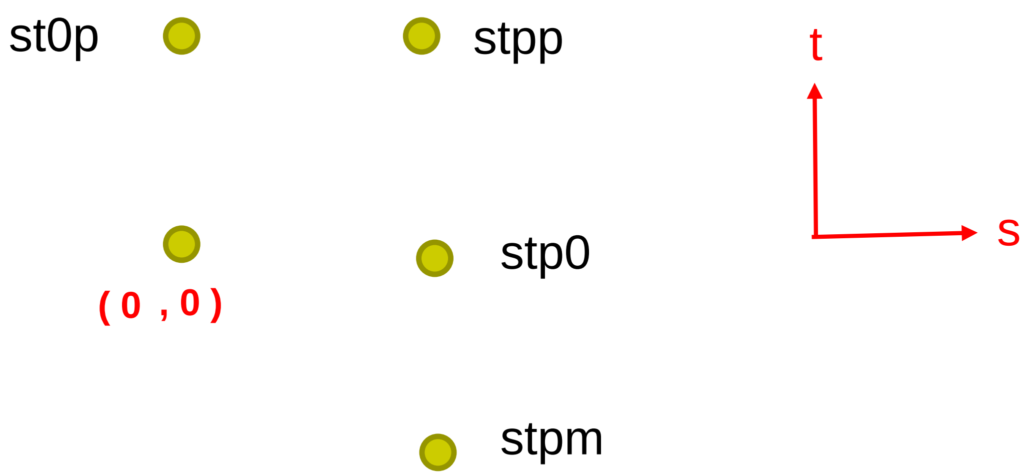


Image Blurring Fragment Shader (contd)

```
// 3x3 pixel colors next
vec3 i00 = texture( uImageUnit, vST ).rgb;
vec3 im1m1 = texture( uImageUnit, vST-stpp ).rgb;
vec3 ip1p1 = texture( uImageUnit, vST+stpp ).rgb;

vec3 im1p1 = texture( uImageUnit, vST-stpm ).rgb;
vec3 ip1m1 = texture( uImageUnit, vST+stpm ).rgb;

vec3 im10 = texture( uImageUnit, vST-stp0 ).rgb;
vec3 ip10 = texture( uImageUnit, vST+stp0 ).rgb;

vec3 i0m1 = texture( uImageUnit, vST-st0p ).rgb;
vec3 i0p1 = texture( uImageUnit, vST+st0p ).rgb;
```

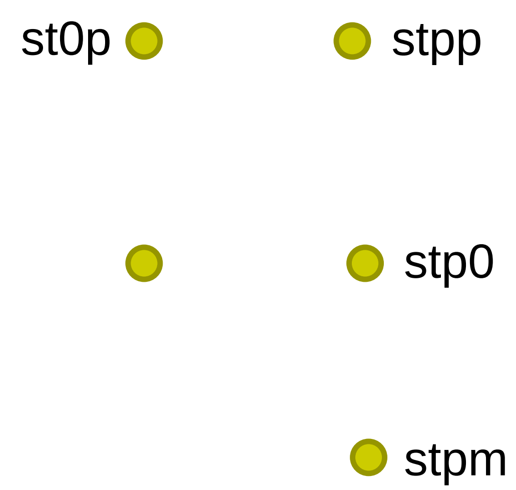


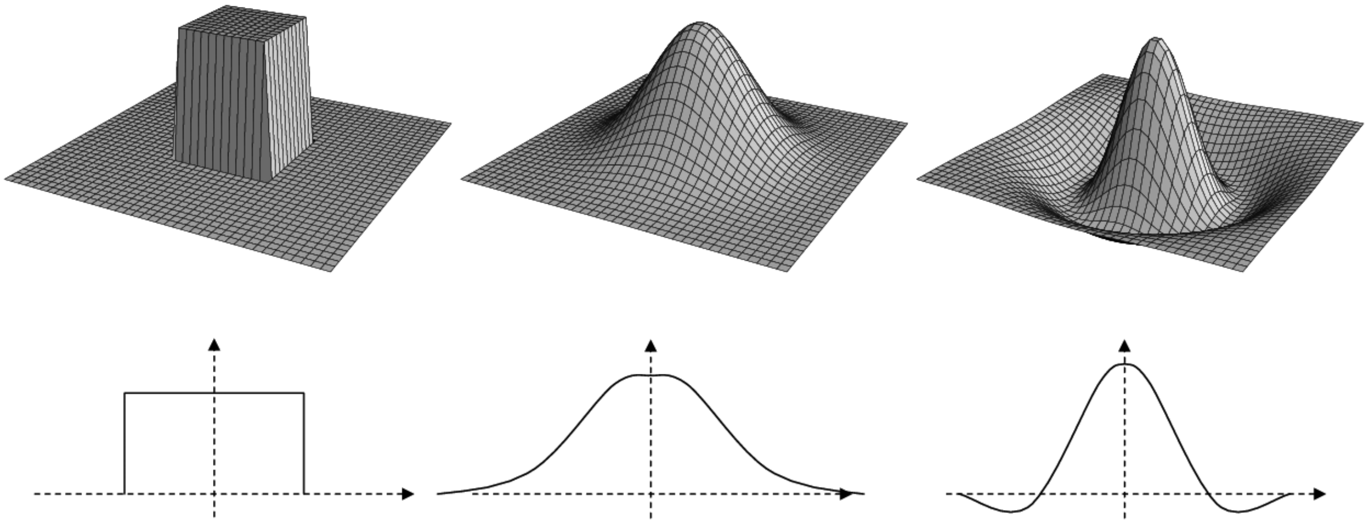
Image Blurring Fragment Shader (contd)

```
vec3 target = vec3(0., 0., 0.);
target += 1.*(im1m1+ip1m1+ip1p1+im1p1);// apply blur
target += 2.*(im10+ip10+i0m1+i0p1);
target += 4.*(i00);

target /= 16.;

fFragColor = vec4( target, 1. );
```

$$\frac{1}{16} * \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

Apply weights

Types of Linear Filters



0	0	0	0	0
0	1	1	1	0
0	1	1	1	0
0	1	1	1	0
0	0	0	0	0

(a)

Box

0	1	2	1	0
1	3	5	3	1
2	5	9	5	2
1	3	5	3	1
0	1	2	1	0

(b)

Gaussian

0	0	-1	0	0
0	-1	-2	-1	0
-1	-2	16	-2	-1
0	-1	-2	-1	0
0	0	-1	0	0

(c)

Laplace

Edge Detection

- Uses 2 filters: 1 vertical and 1 horizontal
- Vertical is actually horizontal rotated 90 degrees

Horizontal Filter

$$H = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

$$V = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

Vertical Filter

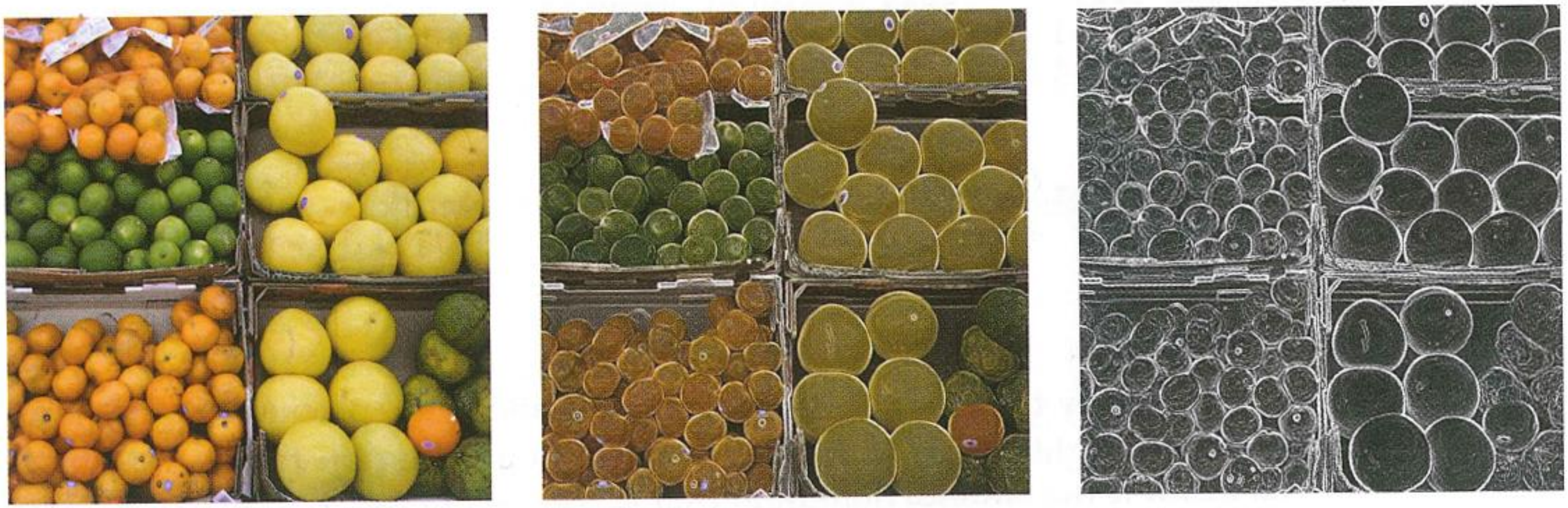
$$S = \sqrt{H^2 + V^2}$$

$$\Theta = \text{atan2}(\text{V}, \text{H})$$

For an edge S will be large

Edge Detection

- Algorithm:
  - Compare 2 columns (or rows)
    - If difference is “large”, this is an edge
    - If difference is “small”, not an edge
- Comparison can be done in color or luminance



Edge Detection Fragment Shader

```
const vec3 LUMCOEFFS = vec3( 0.2125,0.7154,0.0721 );
. . .
vec2 stp0 = vec2(1./ResS,  0. );
vec2 st0p = vec2(0.      ,  1./ResT);
vec2 stpp = vec2(1./ResS,  1./ResT);
vec2 stpm = vec2(1./ResS, -1./ResT);
float i00 =   dot( texture2D( uImageUnit, vST ).rgb      , LUMCOEFFS );
float im1m1 = dot( texture2D( uImageUnit, vST-stpp ).rgb, LUMCOEFFS );
float ip1p1 = dot( texture2D( uImageUnit, vST+stpp ).rgb, LUMCOEFFS );
float im1p1 = dot( texture2D( uImageUnit, vST-stpm ).rgb, LUMCOEFFS );
float ip1m1 = dot( texture2D( uImageUnit, vST+stpm ).rgb, LUMCOEFFS );
float im10 =  dot( texture2D( uImageUnit, vST-stp0 ).rgb, LUMCOEFFS );
float ip10 =  dot( texture2D( uImageUnit, vST+stp0 ).rgb, LUMCOEFFS );
float i0m1 =  dot( texture2D( uImageUnit, vST-st0p ).rgb, LUMCOEFFS );
float i0p1 =  dot( texture2D( uImageUnit, vST+st0p ).rgb, LUMCOEFFS) );
float h = -1.*im1p1 - 2.*i0p1 - 1.*ip1p1  +  1.*im1m1 + 2.*i0m1 + 1.*ip1m1;
float v = -1.*im1m1 - 2.*im10 - 1.*im1p1  +  1.*ip1m1 + 2.*ip10 + 1.*ip1p1;

float mag = sqrt( h*h + v*v );
vec3 target = vec3( mag,mag,mag );
color = vec4( mix( irgb, target, T ), 1. );
```

Multiply by luminance coeffs to convert colors to gray

Compute horizontal and vertical filters

(1 – T).irgb + T.target

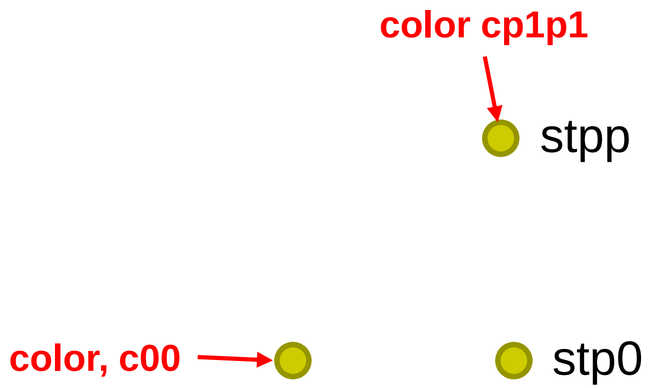
For an edge, target will be large, color will be washed out (> 1 or white)

$$H = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \qquad V = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

Embossing

- Embossing is similar to edge detection
- Depending on edge angle (how sharp)
  - Replace color by luminance
  - Highlight images differently
    depending on edge angles (magnitude of difference)

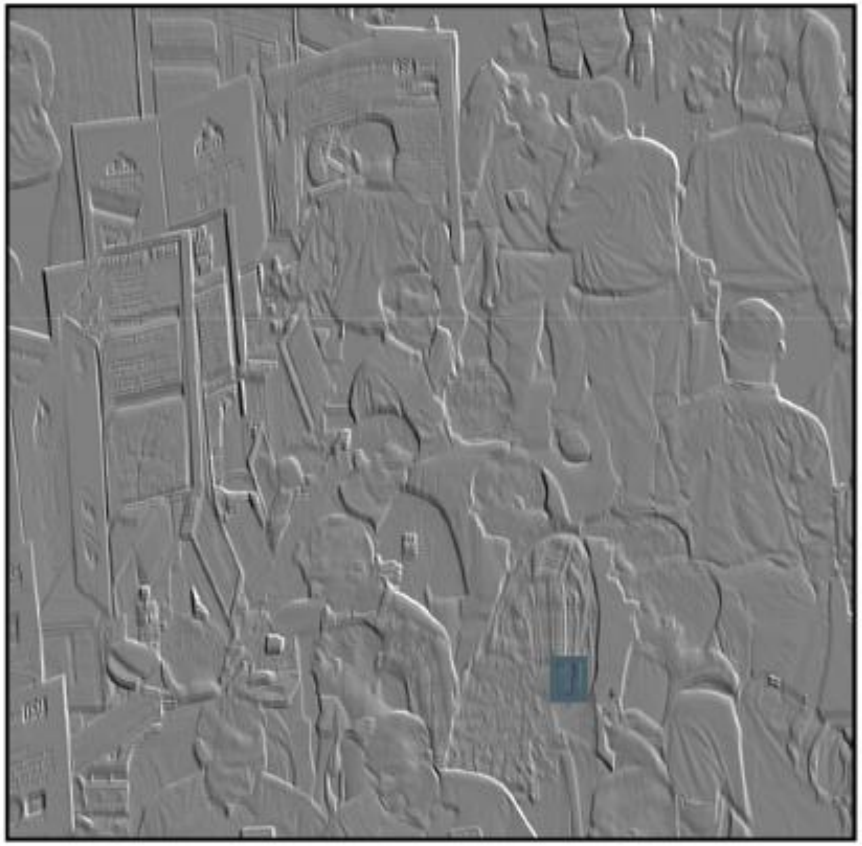
Embossing




```
vec2 stp0 = vec2( 1./ResS,  0. );
vec2 stpp = vec2( 1./ResS,  1./ResT);
vec3 c00    = texture2D(    uImageUnit, vST ).rgb;
vec3 cp1p1  = texture2D( uImageUnit, vST + stpp ).rgb;

vec3 diffs = c00 - cp1p1;
float max = diffs.r;
if( abs(diffs.g) > abs(max) )
                max = diffs.g;
if( abs(diffs.b) > abs(max) )
                max = diffs.b;

float gray = clamp( max + .5, 0., 1. );
vec4 grayVersion  = vec4( gray, gray, gray, 1. );
vec4 colorVersion = vec4( gray*c00, 1. );
fFragColor = mix( grayVersion, colorVersion, T );
```

Find largest difference, r, g or b

Convert largest difference to gray



Toon Rendering for Non-Photorealistic Effects

Toon Shader

- Implement Toon shader based using Sobel filter
- Algorithm
  - Calculate luminance of each pixel (brightness)
  - Apply Sobel edge detection filter and get a magnitude
  - If magnitude > threshold, color pixel black
  - Else, quantize pixel’s color
  - Output the colored pixel

Toon Fragment Shader (Some Code)

```
… insert code for Sobel Filter

// Calculate magnitude, then draw edges or quantize
float mag = length( vec2(h, v) );// how much change?

if( mag > uMagTo )  // if too much, use black
    fFragColor = vec4( 0., 0., 0., 1.);
else{                    // else quantize the color
    rgb.rgb *= uQuantize;       // multiply by number of quanta
    rgb.rgb += vec3( .5, .5, .5);   // round
    ivec3 intrgb = ivec3( rgb.rgb ); // truncate
    rgb.rgb = vec3( intrgb )/ Quantize; // calc. quantized color
    fFragColor = vec4( rgb, 1.);
}
```

Toon Rendering

Image Flipping, Rotation and Warping

- We can transform image (flip, rotate, warp)
- Basic idea: Look up a **transformed pixel address** instead of the current one
- To flip an image upside down:
  - At pixel location *st*, look up the color at location *s (1 – t)*
  - Fragment shader code:

```
vec2 st = vST;
st.t = 1 - st.t;
vec3 irgb = texture( uImageUnit, st ).rgb;
fFragColor = vec4( irgb, 1);
```

Note: For horizontal flip, look up *(1 – s) t* instead of *s t* !!

Image Flipping, Rotation and Warping

- Rotating an image 90 degrees counterclockwise:
  - Look up *(t, 1 – s)* instead of *s t*

- **Image warping:** we can use a function to select which pixel somewhere else in the image to look up
- For example: apply function on both texel coordinates (s, t)

$$x = x + t * \sin(\pi * x)$$

Image Flipping, Rotation and Warping

$$x = x + t * \sin(\pi * x)$$

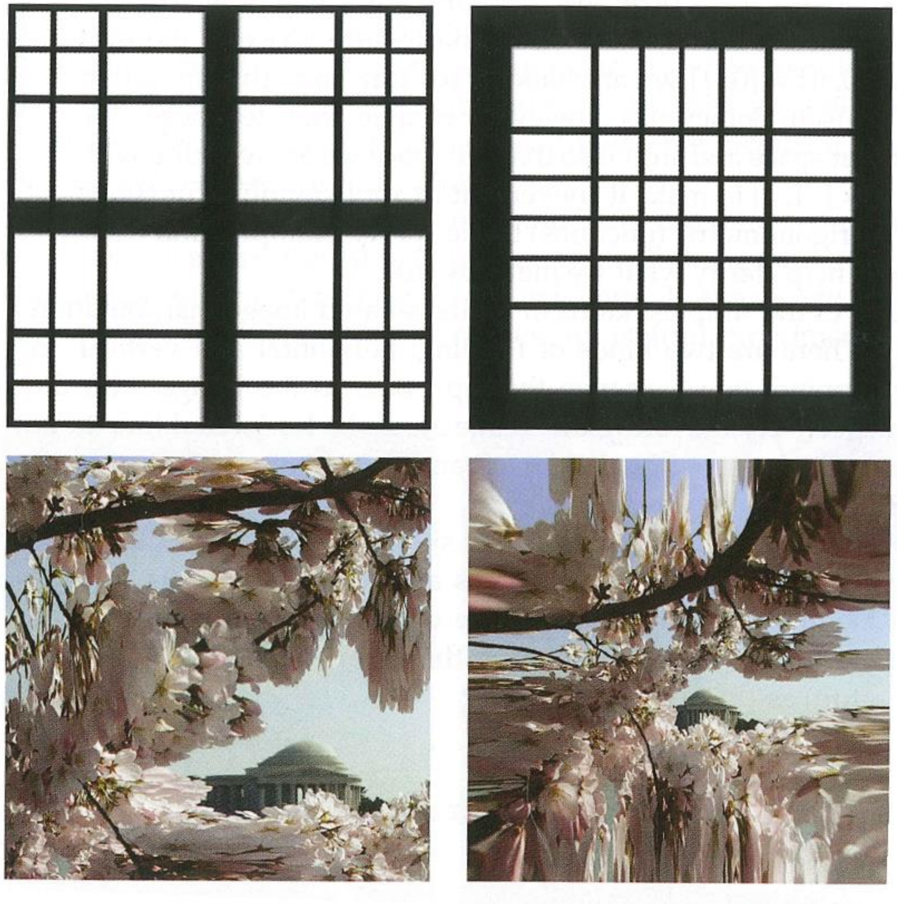


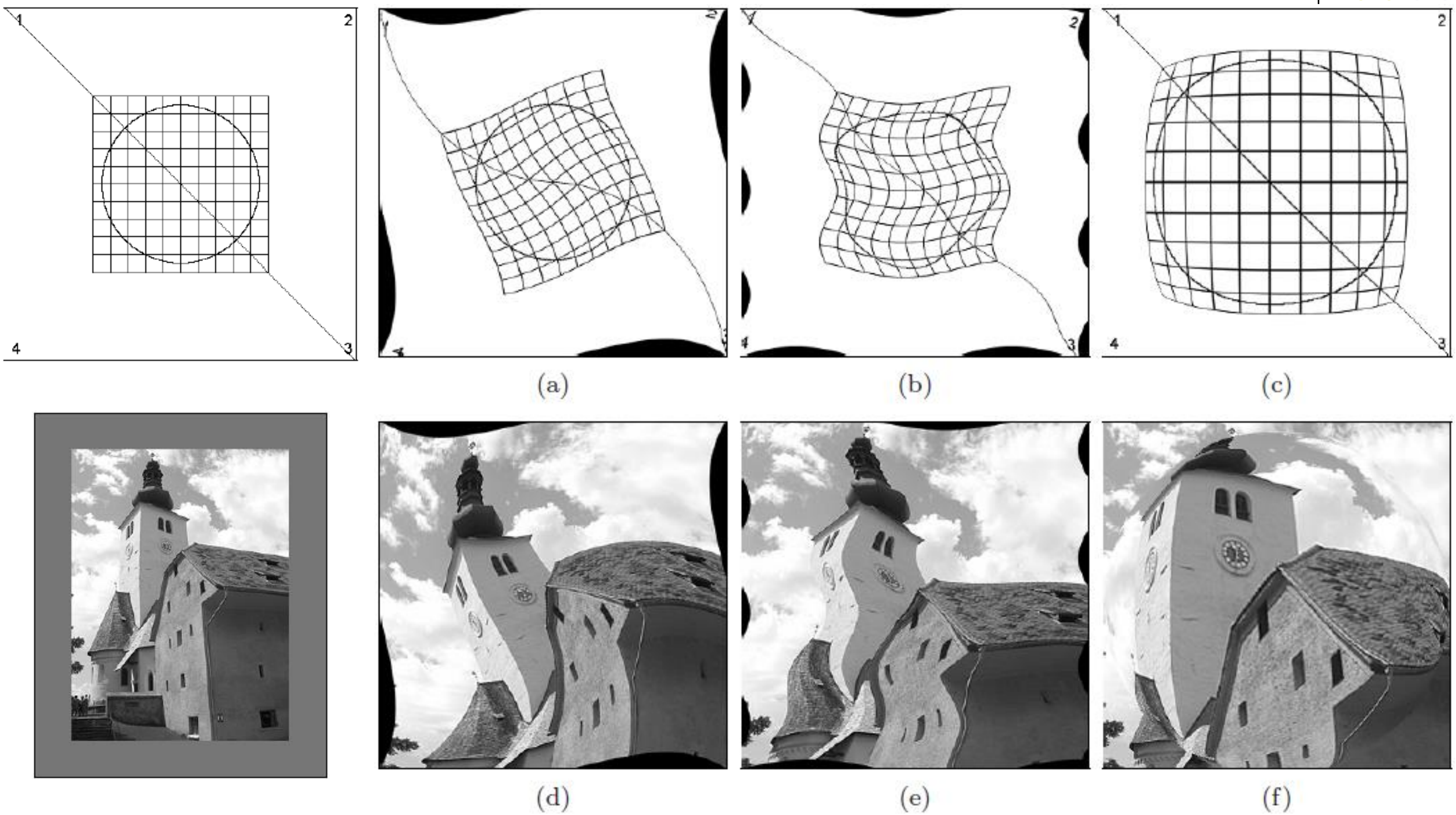
Image Flipping, Rotation and Warping

- Fragment shader code to implement

$$x = x + t * \sin(\pi * x)$$

```
const float PI = 3.14159265
uniform sampler2D uImageUnit;
uniform float uT;
in vec2 vST;     out vec4 fFragColor;

void main( ){
    vec2 st = vST;
    vec2 xy = st;
    xy = 2. * xy - 1;      // map to [-1,1] square
    xy += uT * sin(PI*xy);
    st = (xy + 1.)/2.;     // map back to [0,1] square
    vec3 = irgb = texture(uImageUnit, st ).rgb; // use transformed st

    fFragColor = vec4( irgb, 1.);     }
```

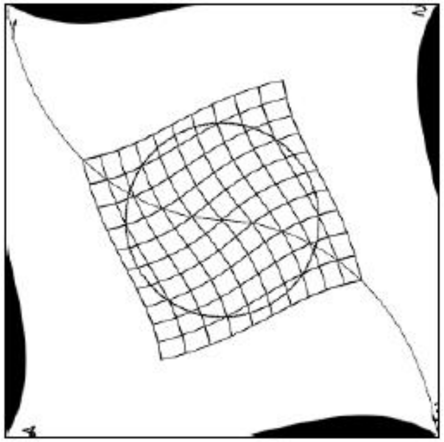
Non-Linear Image Warps



Original **Twirl** **Ripple** **Spherical**

Twirl

- **Notation:** Instead using texture colors at (x',y'), use texture colors at twirled (x,y) location
- Twirl?
  - Rotate image by angle $\boldsymbol{\alpha}$ at center or anchor point (x_c,y_c)
  - Increasingly rotate image as radial distance $\boldsymbol{r}$ from center increases (up to $\boldsymbol{r_{max}}$)
  - Image unchanged outside radial distance $\boldsymbol{r_{max}}$



(a)

(d)

$$T_x^{-1}: \quad x = \begin{cases} x_c + r \cdot \cos(\beta) & \text{for } r \le r_{\max} \\ x' & \text{for } r > r_{\max}, \end{cases}$$

$$T_y^{-1}: \quad y = \begin{cases} y_c + r \cdot \sin(\beta) & \text{for } r \le r_{\max} \\ y' & \text{for } r > r_{\max}, \end{cases}$$

with

$$d_x = x' - x_c, \qquad r = \sqrt{d_x^2 + d_y^2},$$

$$d_y = y' - y_c, \qquad \beta = \operatorname{Arctan}(d_y, d_x) + \alpha \cdot \left(\tfrac{r_{\max} - r}{r_{\max}}\right).$$

Twirl Fragment Shader Code

```
const float PI = 3.14159265
uniform sampler2D uImageUnit;
uniform float uD, uR;

in vec3 vST;
out vec4 fFracColor;

void main( ){
    ivec2 ires = textureSize( uImageUnit, 0);
    float Res = float( ires.s ); // assume it's a square texture image

    vec2 st = vST;
    float Radius = Res * uR;
    vec2 xy = Res * st;   // pixel coordinates from texture coords

    vec2 dxy = xy - Res/2.; // twirl center is (Res/2, Res/2)
    float r = length( dxy );
    float beta = atan( dxy.y, dxy.x) + radians(uD) * (Radius - r)/Radius;
```

Twirl Fragment Shader Code (Contd)

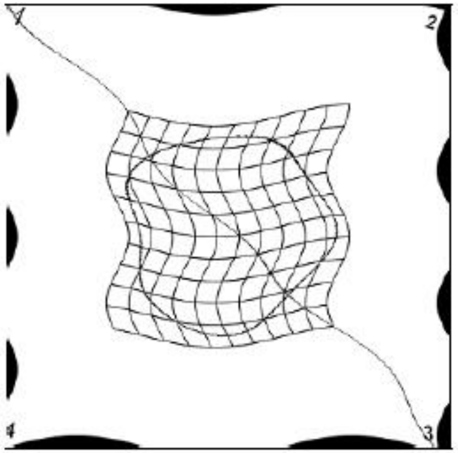
```
    vec2 xy1 = xy;
    if(r <= Radius)
    {
        xy1 = Res/2. + r * vec2( cos(beta), sin(beta) );
    }
    st = xy1/Res;  // restore coordinates

    vec3 irgb = texture( uImageUnit, st ).rgb;
    fFragColor = vec4( irgb, 1. );
}
```

Ripple

- Ripple causes wavelike displacement of image along both the x and y directions

$$T_x^{-1}: \quad x = x' + a_x \cdot \sin\left(\frac{2\pi \cdot y'}{\tau_x}\right),$$
$$T_y^{-1}: \quad y = y' + a_y \cdot \sin\left(\frac{2\pi \cdot x'}{\tau_y}\right).$$

- Sample values for parameters (in pixels) are
  - τ_x= 120
  - τ_y= 250
  - a_x= 10
  - a_y= 15



(b)

(e)

Spherical Transformation

- Imitates viewing image through a lens placed over image
- Lens parameters: center (x_c, y_c), lens radius r_{max} and refraction index ρ
- Sample values ρ = 1.8 and r_{max} = half image width

$$T_x^{-1}: \quad x = x' - \begin{cases} z \cdot \tan(\beta_x) & \text{for } \; r \le r_{\max} \\ 0 & \text{for } \; r > r_{\max}, \end{cases}$$

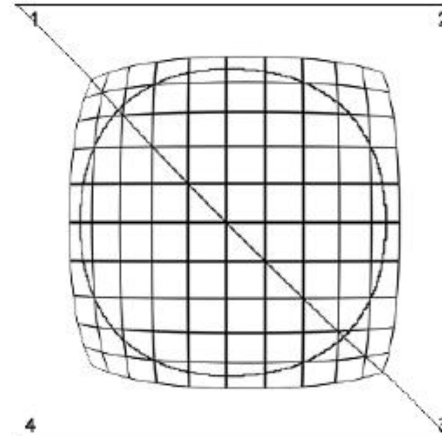
$$T_y^{-1}: \quad y = y' - \begin{cases} z \cdot \tan(\beta_y) & \text{for } \; r \le r_{\max} \\ 0 & \text{for } \; r > r_{\max}, \end{cases}$$

$$d_x = x' - x_c, \qquad r = \sqrt{d_x^2 + d_y^2}\,,$$

$$d_y = y' - y_c, \qquad z = \sqrt{r_{\max}^2 - r^2}\,,$$

$$\beta_x = \left(1 - \tfrac{1}{\rho}\right) \cdot \sin^{-1}\left(\frac{d_x}{\sqrt{(d_x^2 + z^2)}}\right),$$

$$\beta_y = \left(1 - \tfrac{1}{\rho}\right) \cdot \sin^{-1}\left(\frac{d_y}{\sqrt{(d_y^2 + z^2)}}\right).$$



(c)


(f)

Image Warping

```
uniform float         uS0, uT0;
uniform float         uPower;
uniform sampler2D     uTexUnit;
in vec2               vST;
out  vec4             fFragColor;

void
main( )
{
   vec2 delta = vST - vec2(uS0,uT0);
   st = vec2(uS0,uT0) + sign(delta) * pow( abs(delta), uPower );
   vec3 rgb = texture2D( uTexUnit, vST ).rgb;
   fFragColor = vec4( rgb, 1. );
}
```

Image Morphing

- Mark similar points on the images (e.g. nose)
- Distort nose position + fade image 1 into image 2

Motion Blur

- Texture element may be combined with neighboring texture elements to create motion blur

With motion blur

Without motion blur

Color Correction

- Color correction uses a function to convert colors in an image to some other color
- Why color correct?
  - Mimic appearance of a type of film
  - Portray a particular mood
  - Convert from one color space to another (e.g. RGB to CIE)
  - Example of conversion from RGB to CIE's XYZ color space

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Color Correction

Original

After Levels Adjustment

Original

After Levels Adjustment

Color Correction

Original Shot

Day-for-Night Color Corrected shot

References

- Mike Bailey and Steve Cunningham, Graphics Shaders (second edition)
- Wilhelm Burger and Mark Burge, Digital Image Processing: An Algorithmic Introduction using Java, Springer Verlag Publishers
- OpenGL 4.0 Shading Language Cookbook, David Wolff
- Real Time Rendering (3rd edition), Akenine-Moller, Haines and Hoffman
- Suman Nadella, CS 563 slides, Spring 2005