University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2008

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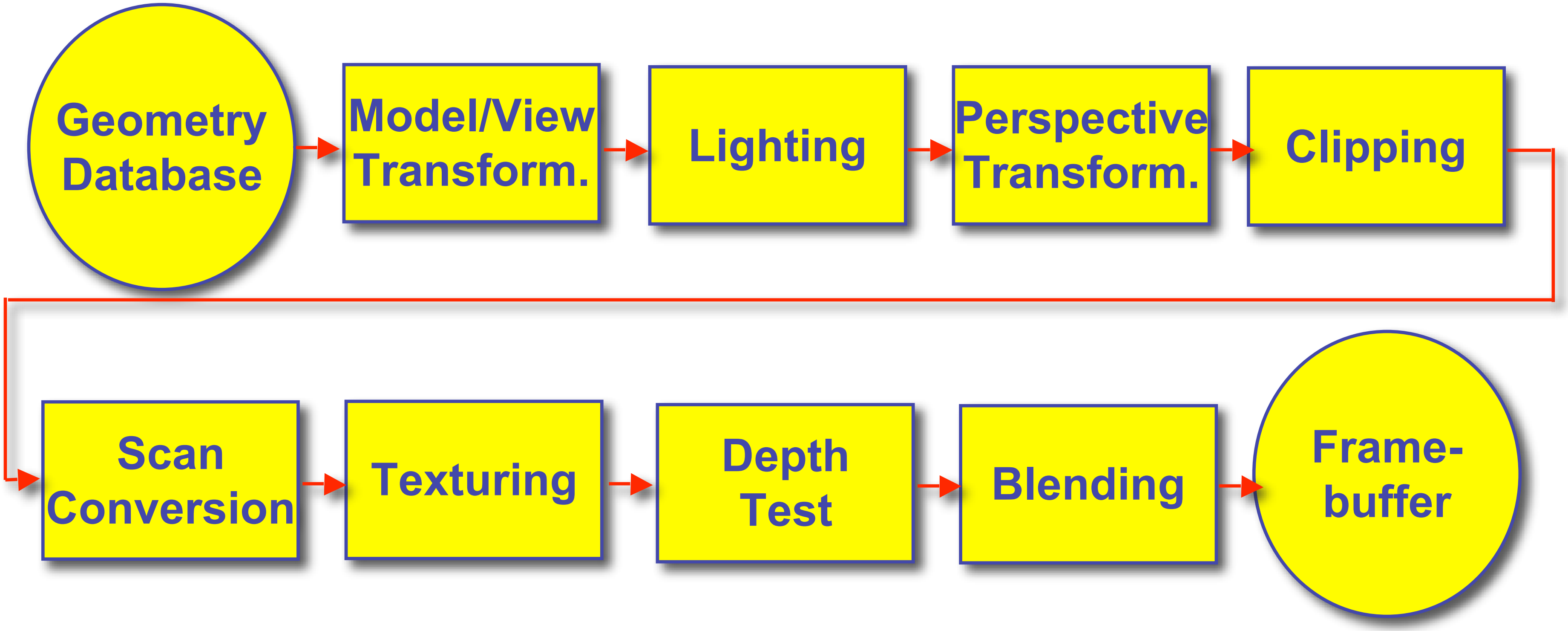
OpenGL, GLUT, Transformations I

Week 2, Wed Jan 16

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2008

Review: Rendering Pipeline


Geometry Database
Model/View Transform.
Lighting
Perspective Transform.
Clipping
Scan Conversion
Texturing
Depth Test
Blending
Frame-buffer

OpenGL (briefly)

OpenGL

- API to graphics hardware
  - based on IRIS_GL by SGI
- designed to exploit hardware optimized for display and manipulation of 3D graphics
- implemented on many different platforms
- low level, powerful flexible
- pipeline processing
  - set state as needed

Graphics State

- set the state once, remains until overwritten
  - glColor3f(1.0, 1.0, 0.0) → set color to yellow
  - glSetClearColor(0.0, 0.0, 0.2) → dark blue bg
  - glEnable(LIGHT0) → turn on light
  - glEnable(GL_DEPTH_TEST) → hidden surf.

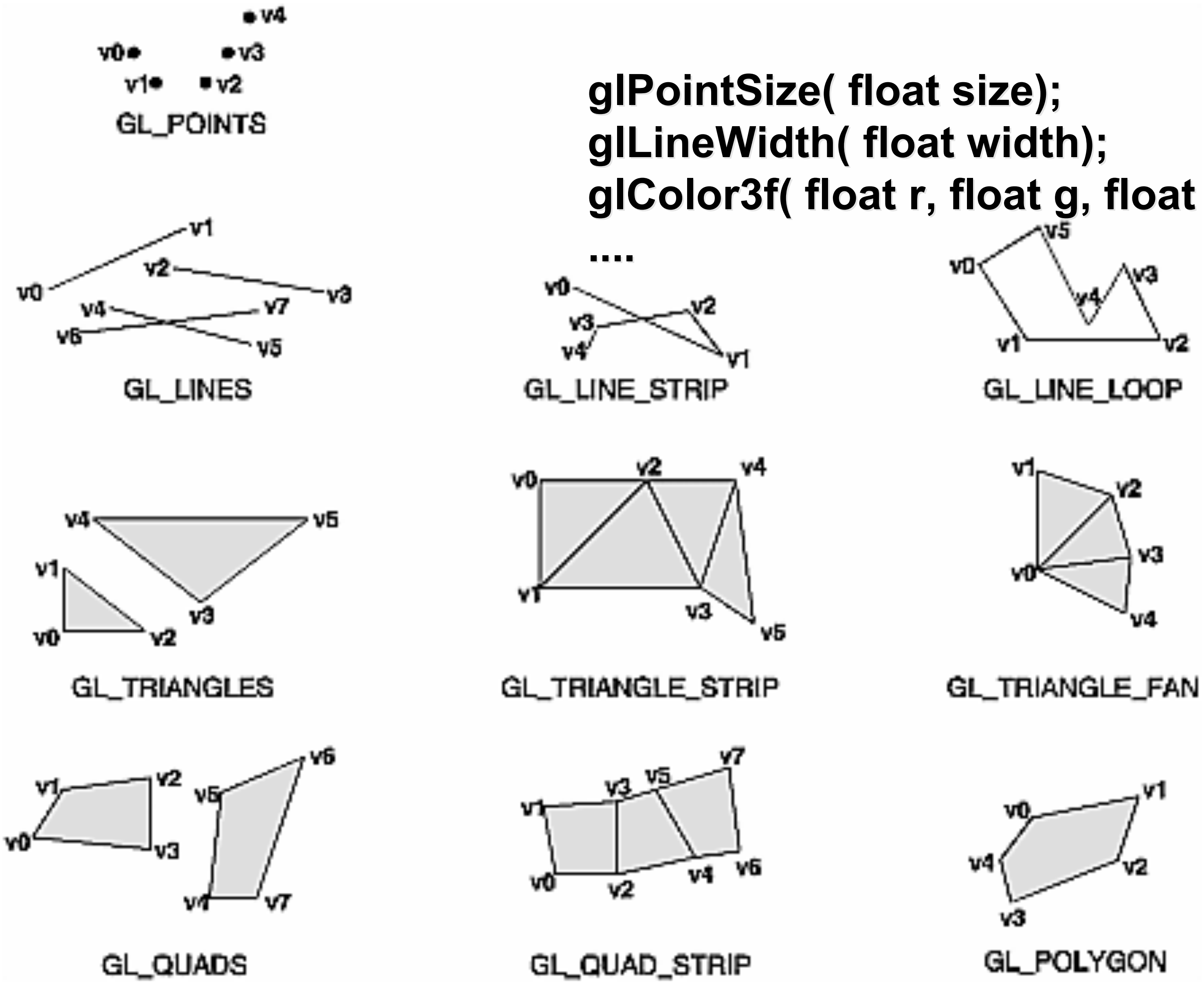
Geometry Pipeline

- tell it how to interpret geometry
  - glBegin(<*mode of geometric primitives*>)
  - *mode* = GL_TRIANGLE, GL_POLYGON, etc.

- feed it vertices
  - glVertex3f(-1.0, 0.0, -1.0)
  - glVertex3f(1.0, 0.0, -1.0)
  - glVertex3f(0.0, 1.0, -1.0)

- tell it you’re done
  - glEnd()

Open GL: Geometric Primitives



glPointSize(float size);
glLineWidth(float width);
glColor3f(float r, float g, float b);
....

Code Sample

```
void display()
{
  glClearColor(0.0, 0.0, 0.0, 0.0);
  glClear(GL_COLOR_BUFFER_BIT);
  glColor3f(0.0, 1.0, 0.0);
  glBegin(GL_POLYGON);
    glVertex3f(0.25, 0.25, -0.5);
    glVertex3f(0.75, 0.25, -0.5);
    glVertex3f(0.75, 0.75, -0.5);
    glVertex3f(0.25, 0.75, -0.5);
  glEnd();
  glFlush();
}
```

- more OpenGL as course continues

GLUT

GLUT: OpenGL Utility Toolkit

- developed by Mark Kilgard (also from SGI)
- simple, portable window manager
  - opening windows
    - handling graphics contexts
  - handling input with callbacks
    - keyboard, mouse, window reshape events
  - timing
    - idle processing, idle events
- designed for small/medium size applications
- distributed as binaries
  - free, but not open source

Event-Driven Programming

- main loop not under your control
  - vs. batch mode where you control the flow
- control flow through event callbacks
  - redraw the window now
  - key was pressed
  - mouse moved
- callback functions called from main loop when events occur
  - mouse/keyboard state setting vs. redrawing

GLUT Callback Functions

```
  // you supply these kind of functions

void reshape(int w, int h);
void keyboard(unsigned char key, int x, int y);
void mouse(int but, int state, int x, int y);
void idle();
void display();


  // register them with glut

glutReshapeFunc(reshape);
glutKeyboardFunc(keyboard);
glutMouseFunc(mouse);
glutIdleFunc(idle);
glutDisplayFunc(display);
```

```
void glutDisplayFunc (void (*func)(void));
void glutKeyboardFunc (void (*func)(unsigned char key, int x, int y));
void glutIdleFunc (void (*func)());
void glutReshapeFunc (void (*func)(int width, int height));
```

GLUT Example 1

```
#include <GLUT/glut.h>
void display()
{
  glClearColor(0,0,0,1);
  glClear(GL_COLOR_BUFFER_BIT);
  glColor4f(0,1,0,1);
  glBegin(GL_POLYGON);
  glVertex3f(0.25, 0.25, -0.5);
  glVertex3f(0.75, 0.25, -0.5);
  glVertex3f(0.75, 0.75, -0.5);
  glVertex3f(0.25, 0.75, -0.5);
  glEnd();
  glutSwapBuffers();
}
```

```
int main(int argc,char**argv)
{
  glutInit( &argc, argv );
  glutInitDisplayMode(
  GLUT_RGB|GLUT_DOUBLE);
  glutInitWindowSize(640,480);
  glutCreateWindow("glut1");
  glutDisplayFunc( display );
  glutMainLoop();
  return 0; // never reached
}
```

GLUT Example 2

```
#include <GLUT/glut.h>
void display()
{
  glRotatef(0.1, 0,0,1);

  glClearColor(0,0,0,1);
  glClear(GL_COLOR_BUFFER_BIT);
  glColor4f(0,1,0,1);
  glBegin(GL_POLYGON);
  glVertex3f(0.25, 0.25, -0.5);
  glVertex3f(0.75, 0.25, -0.5);
  glVertex3f(0.75, 0.75, -0.5);
  glVertex3f(0.25, 0.75, -0.5);
  glEnd();
  glutSwapBuffers();
}
```

```
int main(int argc,char**argv)
{
  glutInit( &argc, argv );
  glutInitDisplayMode(
   GLUT_RGB|GLUT_DOUBLE);
  glutInitWindowSize(640,480);
  glutCreateWindow("glut2");
  glutDisplayFunc( display );
  glutMainLoop();
  return 0; // never reached
}
```

Redrawing Display

- display only redrawn by explicit request
  - glutPostRedisplay() function
  - default window resize callback does this
- idle called from main loop when no user input
  - good place to request redraw
  - will call display next time through event loop
- should return control to main loop quickly
- continues to rotate even when no user action

GLUT Example 3

```
#include <GLUT/glut.h>
void display()
{
  glRotatef(0.1, 0,0,1);

  glClearColor(0,0,0,1);
  glClear(GL_COLOR_BUFFER_BIT);
  glColor4f(0,1,0,1);
  glBegin(GL_POLYGON);
  glVertex3f(0.25, 0.25, -0.5);
  glVertex3f(0.75, 0.25, -0.5);
  glVertex3f(0.75, 0.75, -0.5);
  glVertex3f(0.25, 0.75, -0.5);
  glEnd();
  glutSwapBuffers();
}
```

```
void idle() {
    glutPostRedisplay();
}

int main(int argc,char**argv)
{
  glutInit( &argc, argv );
  glutInitDisplayMode(
  GLUT_RGB|GLUT_DOUBLE);
  glutInitWindowSize(640,480);
  glutCreateWindow("glut1");
  glutDisplayFunc( display );
  glutIdleFunc( idle );
  glutMainLoop();
  return 0; // never reached
}
```

Keyboard/Mouse Callbacks

- again, do minimal work
- consider keypress that triggers animation
  - do not have loop calling display in callback!
    - what if user hits another key during animation?
  - instead, use shared/global variables to keep track of state
    - yes, OK to use globals for this!
  - then display function just uses current variable value

GLUT Example 4

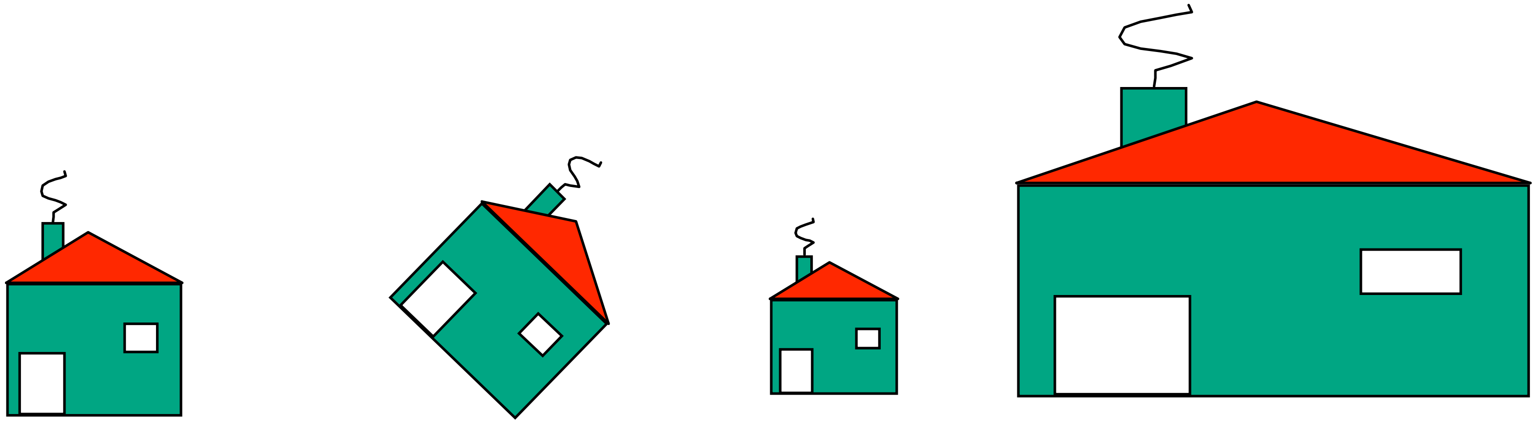
```
#include <GLUT/glut.h>

bool animToggle = true;
float angle = 0.1;

void display() {
  glRotatef(angle, 0,0,1);
   ...
}
void idle() {
  glutPostRedisplay();
}
int main(int argc,char**argv)
{   ...
  glutKeyboardFunc( doKey );
   ...
}
```

```
void doKey(unsigned char key,
                int x, int y) {
  if ('t' == key) {
    animToggle = !animToggle;
    if (!animToggle)
      glutIdleFunc(NULL);
    else
      glutIdleFunc(idle);
  } else if ('r' == key) {
    angle = -angle;
  }
  glutPostRedisplay();
}
```

Transformations

Transformations

- transforming an object = transforming all its points
- transforming a polygon = transforming its vertices



Matrix Representation

- represent 2D transformation with matrix
  - multiply matrix by column vector $\Longleftrightarrow$ apply transformation to point

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$$x' = ax + by$$

$$y' = cx + dy$$

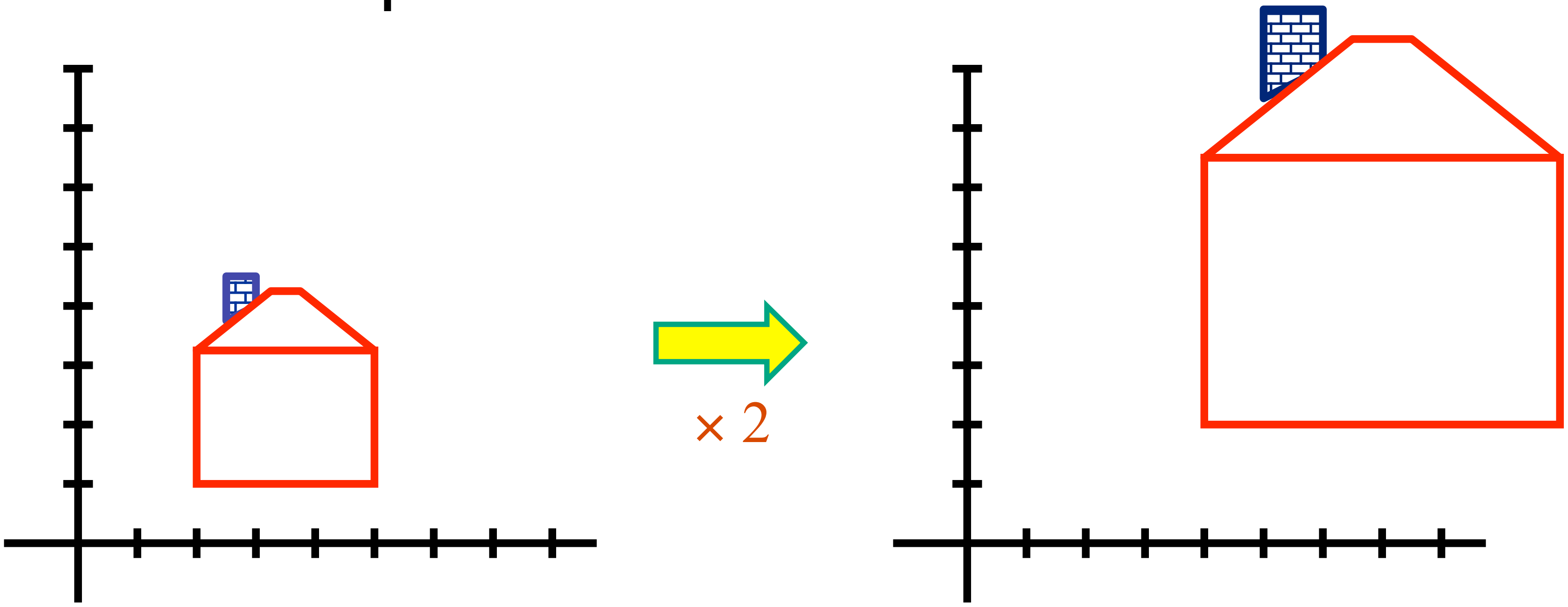
- transformations combined by multiplication

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} d & e \\ f & g \end{bmatrix} \begin{bmatrix} h & i \\ j & k \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

  - matrices are efficient, convenient way to represent sequence of transformations!

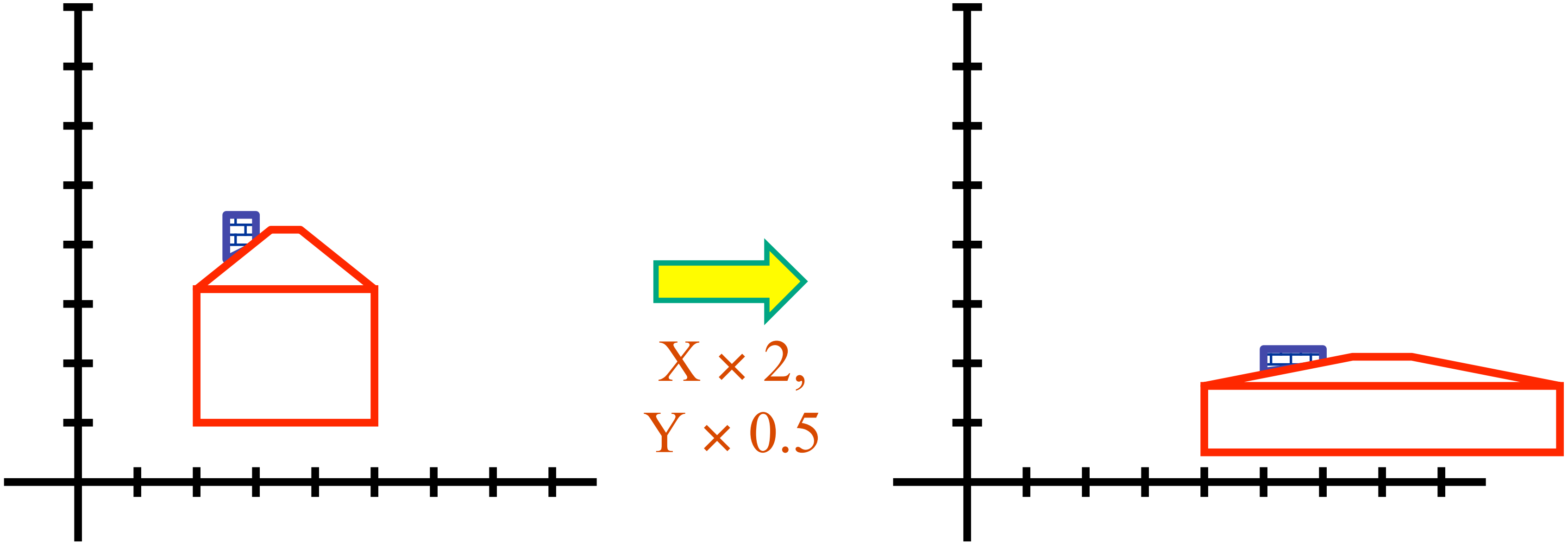
Scaling

- scaling a coordinate means multiplying each of its components by a scalar
- uniform scaling means this scalar is the same for all components:



Scaling

- non-uniform scaling: different scalars per component:

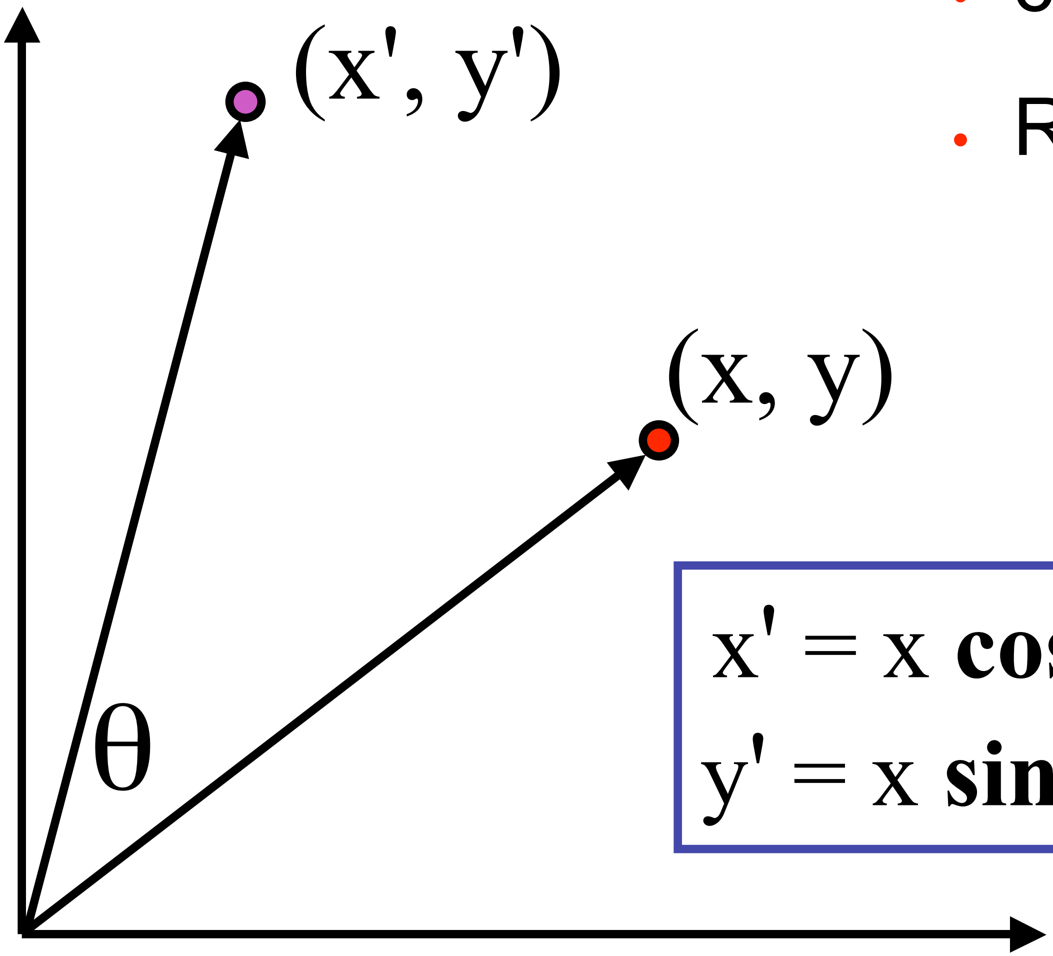


- how can we represent this in matrix form?

Scaling

- scaling operation: $\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} ax \\ by \end{bmatrix}$
- or, in matrix form: $\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}}_{\textit{scaling matrix}} \begin{bmatrix} x \\ y \end{bmatrix}$

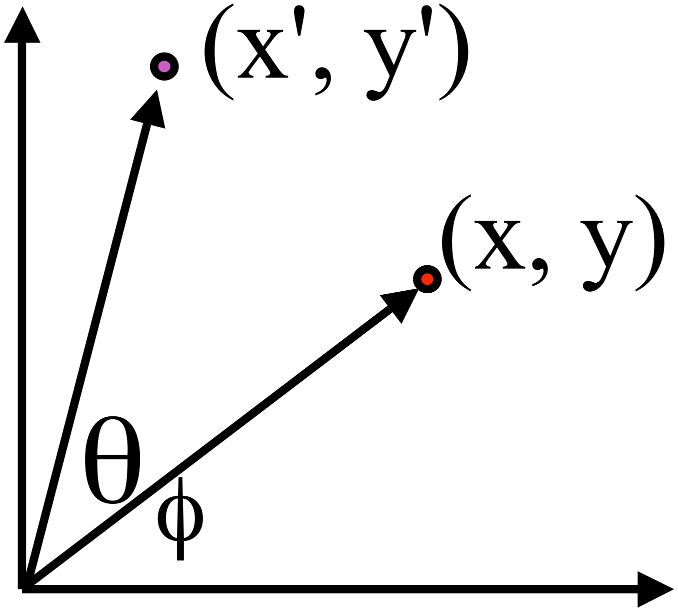
2D Rotation



- counterclockwise
- RHS

$$x' = x\,\mathbf{cos}(\theta) - y\,\mathbf{sin}(\theta)$$
$$y' = x\,\mathbf{sin}(\theta) + y\,\mathbf{cos}(\theta)$$

2D Rotation From Trig Identities



$x = r \cos(\phi)$

$y = r \sin(\phi)$

$x' = r \cos(\phi + \theta)$

$y' = r \sin(\phi + \theta)$

Trig Identity…

$x' = r \cos(\phi) \cos(\theta) - r \sin(\phi) \sin(\theta)$

$y' = r \sin(\phi) \cos(\theta) + r \cos(\phi) \sin(\theta)$

Substitute…

$x' = x \,\mathbf{cos}(\theta) - y \,\mathbf{sin}(\theta)$

$y' = x \,\mathbf{sin}(\theta) + y \,\mathbf{cos}(\theta)$

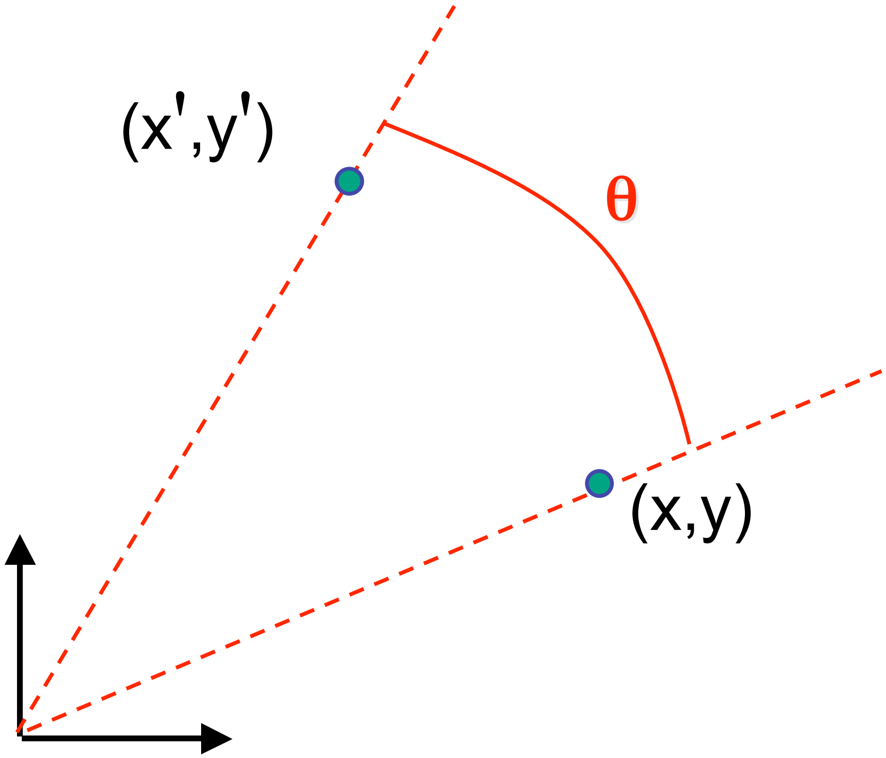
2D Rotation Matrix

- easy to capture in matrix form:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

- even though sin(q) and cos(q) are nonlinear functions of q,
  - x' is a linear combination of x and y
  - y' is a linear combination of x and y

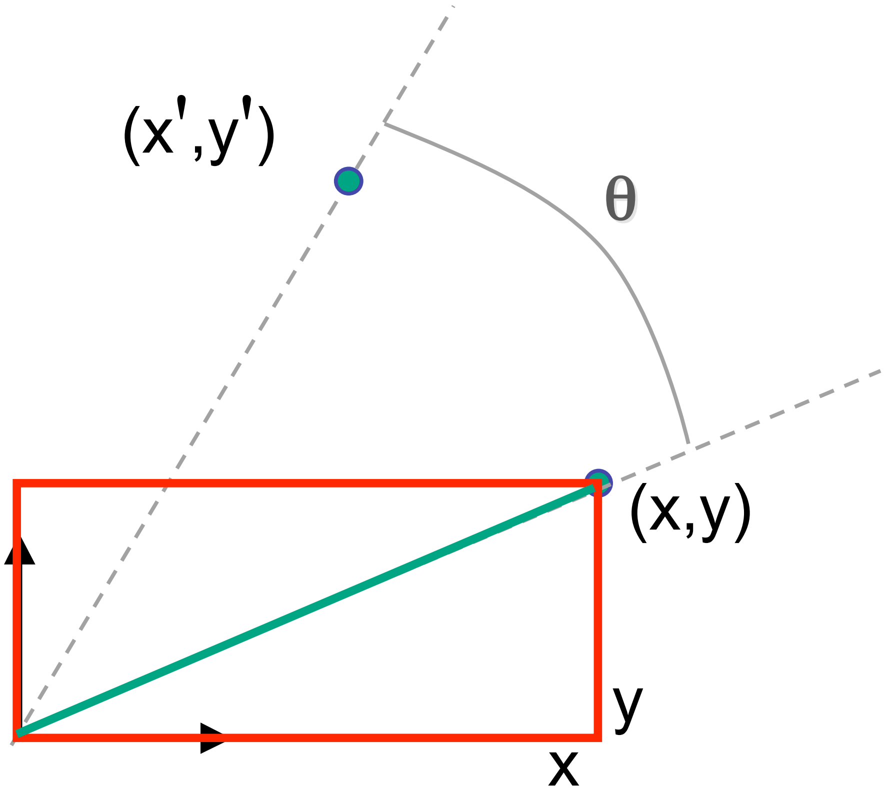
2D Rotation: Another Derivation



$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

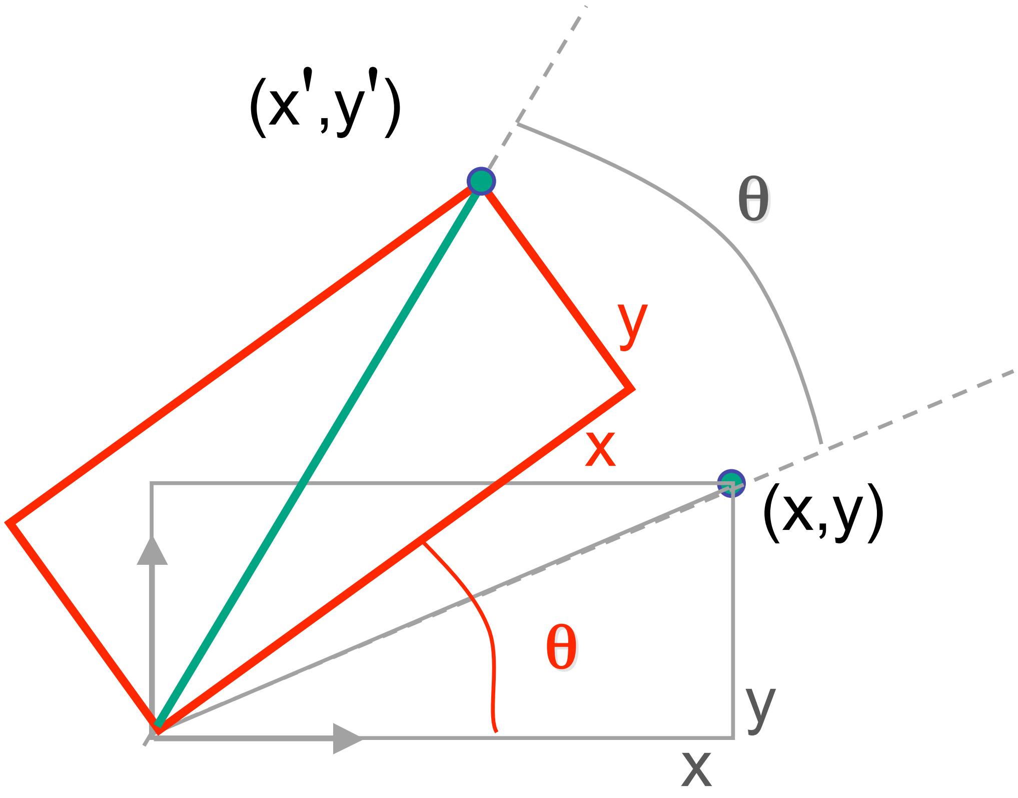
2D Rotation: Another Derivation



$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

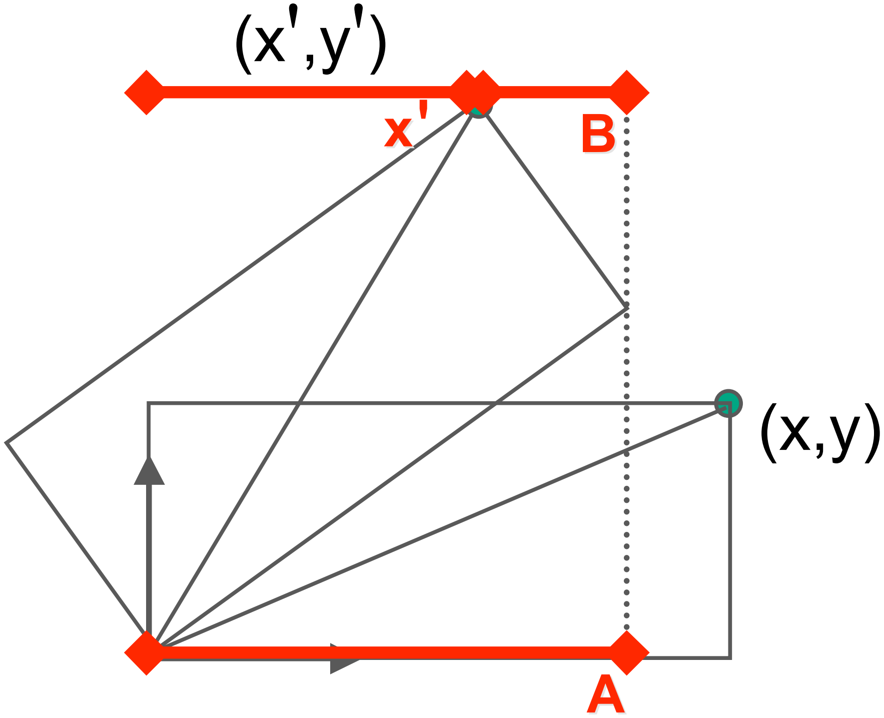
2D Rotation: Another Derivation



$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

2D Rotation: Another Derivation

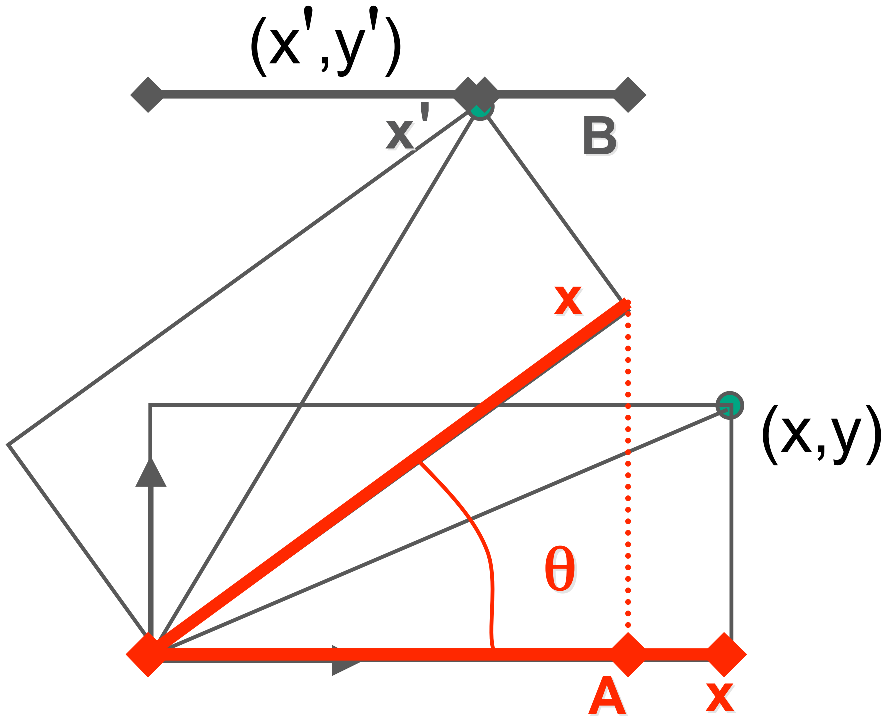


$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

$$x' = A - B$$

2D Rotation: Another Derivation



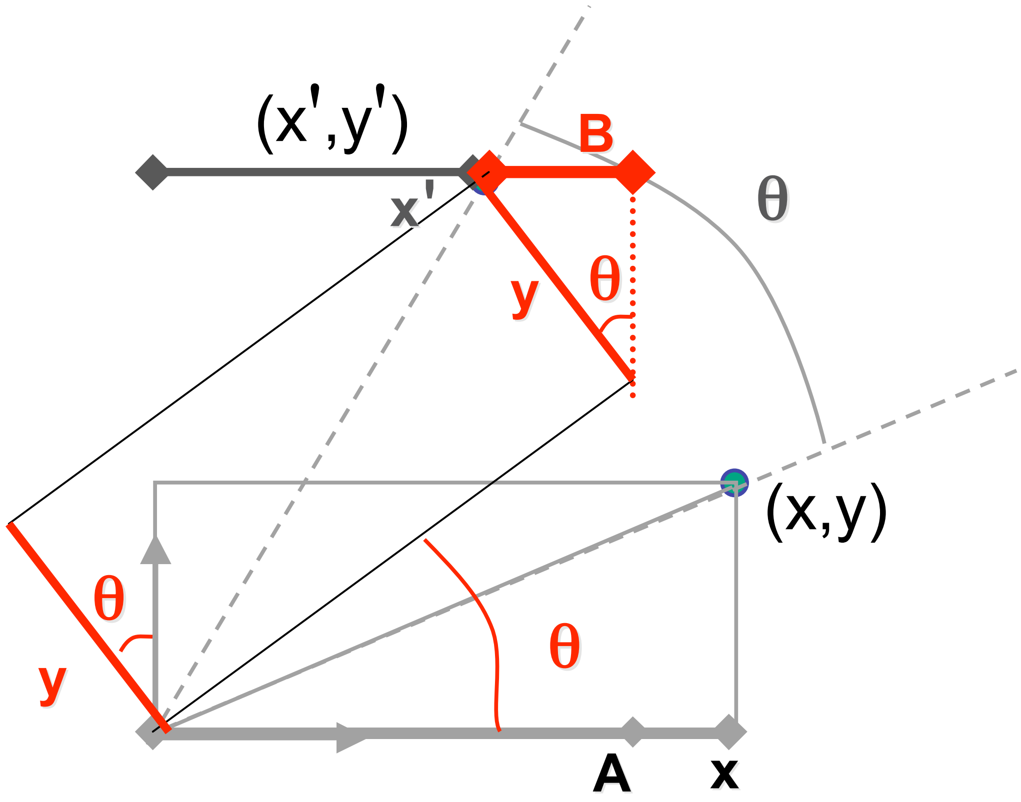
$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

$$x' = A - B$$

$$A = x\cos\theta$$

2D Rotation: Another Derivation



$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

$$x' = A - B$$

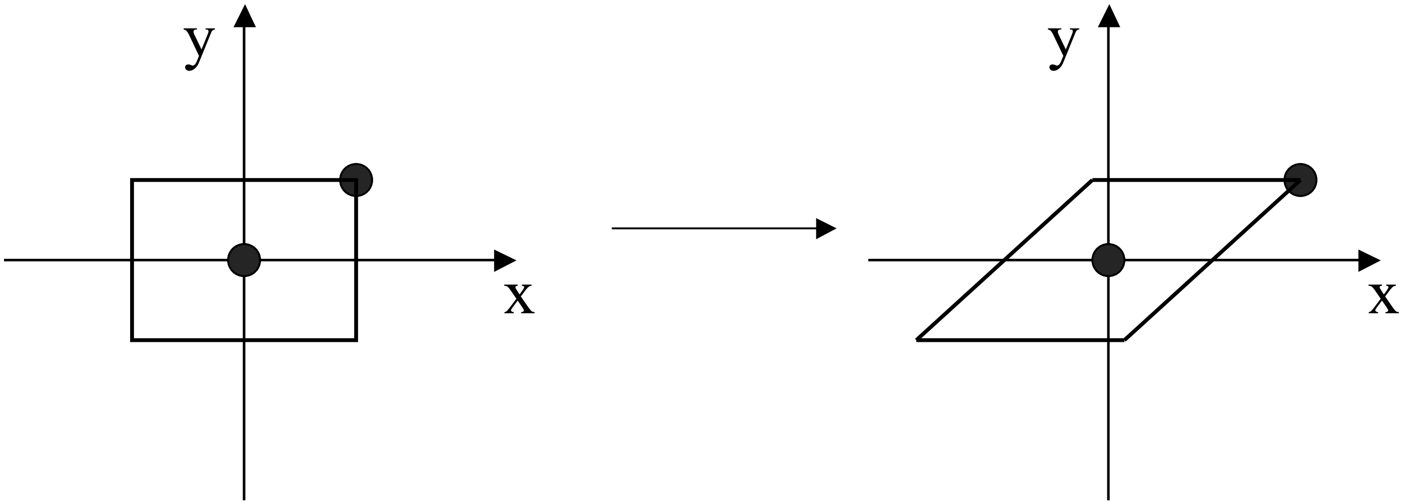
$$A = x\cos\theta$$

$$B = y\sin\theta$$

Shear

- shear along x axis
  - push points to right in proportion to height

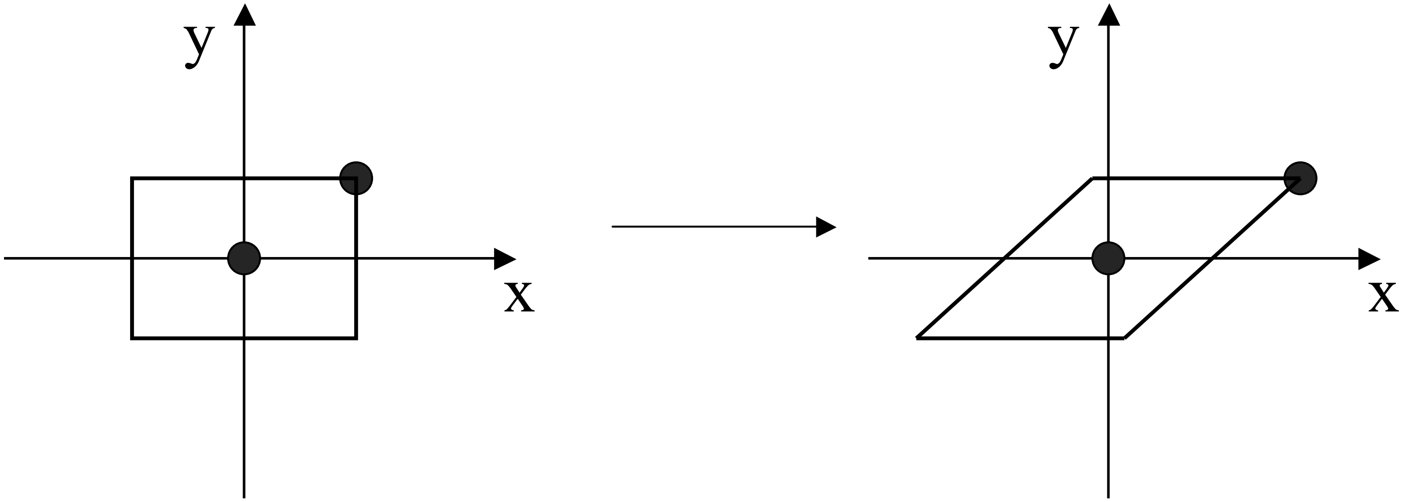
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} ? & ? \\ ? & ? \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} ? \\ ? \end{bmatrix}$$



Shear

- shear along x axis
  - push points to right in proportion to height

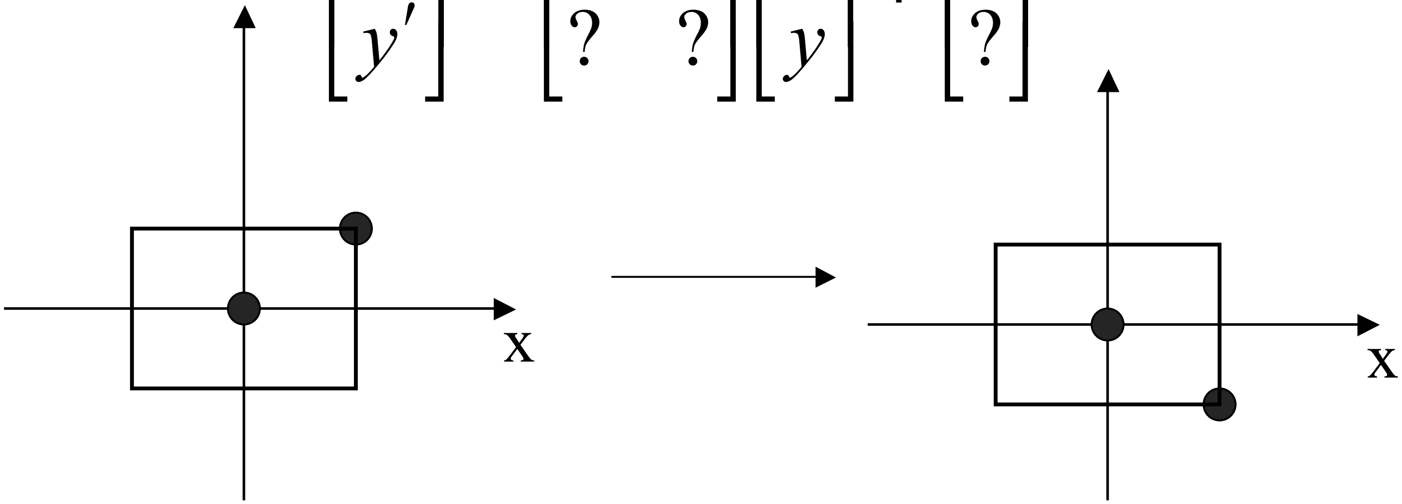
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & sh_x \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$



Reflection

- reflect across x axis
  - mirror

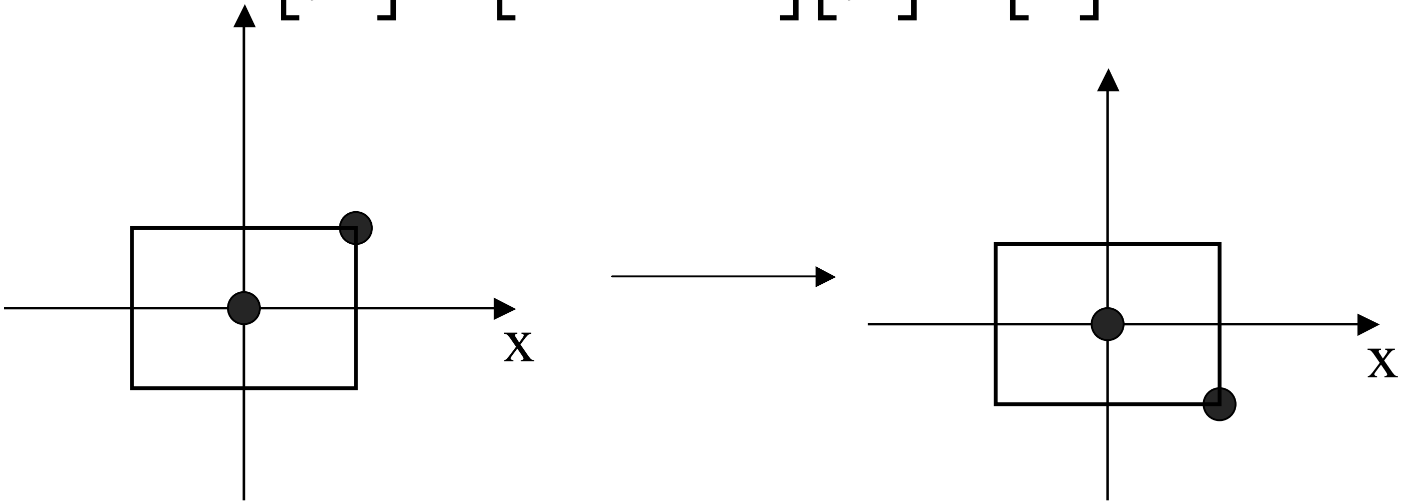
$$\begin{bmatrix}x'\\y'\end{bmatrix}=\begin{bmatrix}? & ?\\? & ?\end{bmatrix}\begin{bmatrix}x\\y\end{bmatrix}+\begin{bmatrix}?\\?\end{bmatrix}$$



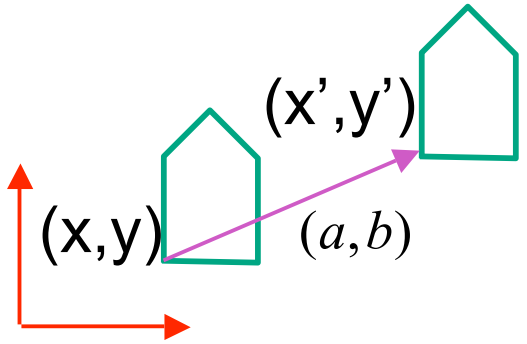
Reflection

- reflect across x axis
  - mirror

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

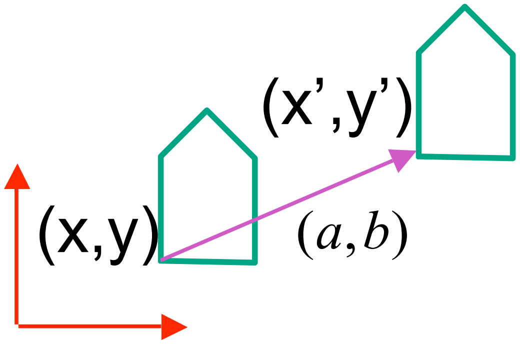


2D Translation



$$\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} x+a \\ y+b \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix}$$

2D Translation

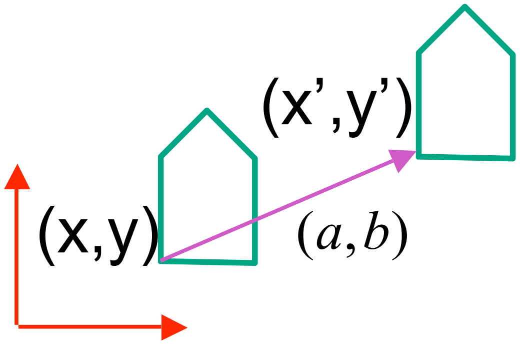


$$\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} x+a \\ y+b \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix}$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}}_{\textit{scaling matrix}} \begin{bmatrix} x \\ y \end{bmatrix}$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}}_{\textit{rotation matrix}} \begin{bmatrix} x \\ y \end{bmatrix}$$

2D Translation



vector addition

$$\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} x+a \\ y+b \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix}$$

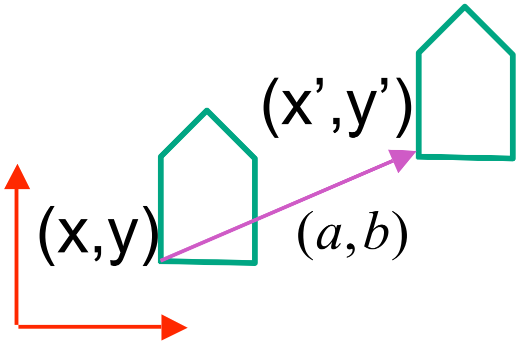
matrix multiplication

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}}_{\textit{scaling matrix}} \begin{bmatrix} x \\ y \end{bmatrix}$$

matrix multiplication

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}}_{\textit{rotation matrix}} \begin{bmatrix} x \\ y \end{bmatrix}$$

2D Translation



vector addition

$$\begin{bmatrix}x\\y\end{bmatrix}+\begin{bmatrix}a\\b\end{bmatrix}=\begin{bmatrix}x+a\\y+b\end{bmatrix}=\begin{bmatrix}x'\\y'\end{bmatrix}$$

matrix multiplication

$$\begin{bmatrix}x'\\y'\end{bmatrix}=\underbrace{\begin{bmatrix}a&0\\0&b\end{bmatrix}}_{\textit{scaling matrix}}\begin{bmatrix}x\\y\end{bmatrix}$$

matrix multiplication

$$\begin{bmatrix}x'\\y'\end{bmatrix}=\underbrace{\begin{bmatrix}\cos(\theta)&-\sin(\theta)\\\sin(\theta)&\cos(\theta)\end{bmatrix}}_{\textit{rotation matrix}}\begin{bmatrix}x\\y\end{bmatrix}$$

$$\underbrace{\begin{bmatrix}a&b\\c&d\end{bmatrix}}_{\textit{translation multiplication matrix??}}\begin{bmatrix}x\\y\end{bmatrix}=\begin{bmatrix}x'\\y'\end{bmatrix}$$

Linear Transformations

- linear transformations are combinations of
  - shear
  - scale
  - rotate
  - reflect

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$$x' = ax + by$$

$$y' = cx + dy$$

- properties of linear transformations
  - satisifes T(*s***x**+*t***y**) = *s* T(**x**) + *t* T(**y**)
  - origin maps to origin
  - lines map to lines
  - parallel lines remain parallel
  - ratios are preserved
  - closed under composition

Challenge

- matrix multiplication
  - for everything except translation
  - how to do everything with multiplication?
    - then just do composition, no special cases
- homogeneous coordinates trick
  - represent 2D coordinates (x,y) with 3-vector (x,y,1)

Homogeneous Coordinates

- our 2D transformation matrices are now 3x3:

$$\mathbf{R}otation = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \mathbf{S}cale = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

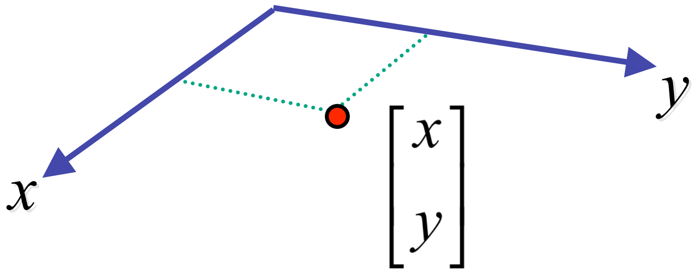
$$\mathbf{T}ranslation = \begin{bmatrix} 1 & 0 & T_x \\ 0 & 1 & T_y \\ 0 & 0 & 1 \end{bmatrix}$$

- use rightmost column

$$\begin{bmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x*1+a*1 \\ y*1+b*1 \\ 1 \end{bmatrix} = \begin{bmatrix} x+a \\ y+b \\ 1 \end{bmatrix}$$

Homogeneous Coordinates Geometrically

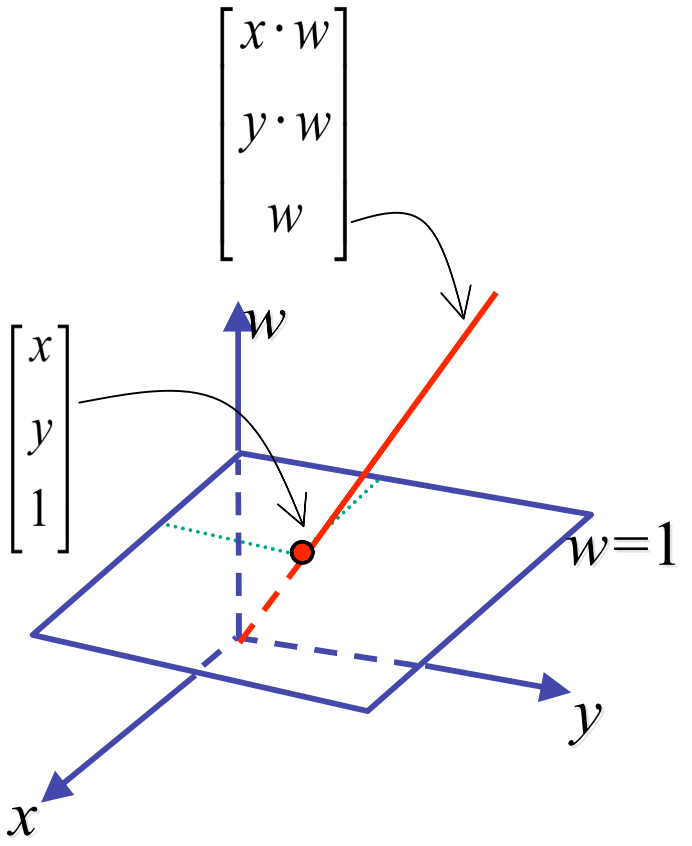
- point in 2D cartesian



Homogeneous Coordinates Geometrically

homogeneous **cartesian**

$$(x, y, w) \xrightarrow{/\, w} \left(\frac{x}{w}, \frac{y}{w}\right)$$

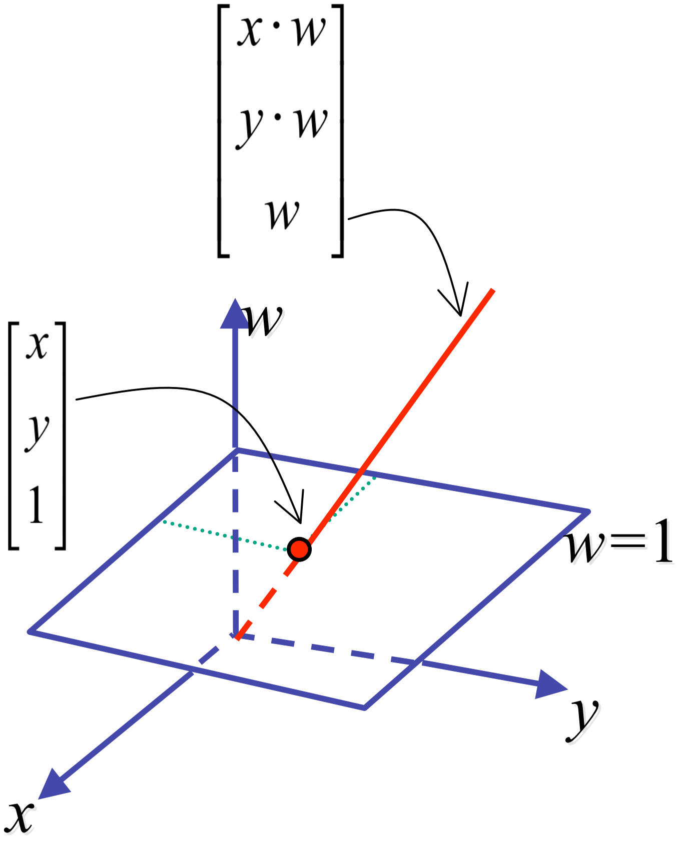


- point in 2D cartesian + weight w = point P in 3D homog. coords
- multiples of (x,y,w)
  - form a line L in 3D
  - all homogeneous points on L represent same 2D cartesian point
  - example: (2,2,1) = (4,4,2) = (1,1,0.5)

Homogeneous Coordinates Geometrically

homogeneous **cartesian**

$$(x, y, w) \xrightarrow{/\ w} \left(\frac{x}{w}, \frac{y}{w}\right)$$



- homogenize to convert homog. 3D point to cartesian 2D point:
  - divide by w to get (x/w, y/w, 1)
  - projects line to point onto w=1 plane
  - like normalizing, one dimension up
- when w=0, consider it as direction
  - points at infinity
  - these points cannot be homogenized
  - lies on x-y plane
- (0,0,0) is undefined

Affine Transformations

- affine transforms are combinations of
  - linear transformations
  - translations

$$\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

- properties of affine transformations
  - origin does not necessarily map to origin
  - lines map to lines
  - parallel lines remain parallel
  - ratios are preserved
  - closed under composition

Homogeneous Coordinates Summary

- may seem unintuitive, but they make graphics operations much easier
- allow all affine transformations to be expressed through matrix multiplication
  - we'll see even more later...
- use 3x3 matrices for 2D transformations
  - use 4x4 matrices for 3D transformations