

Computer Graphics 2019

3. Introduction to OpenGL

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2. 2D Graphics Algorithms (cont.)

Today's Outline

OpenGL introduction

OpenGL primitives

Demos / code

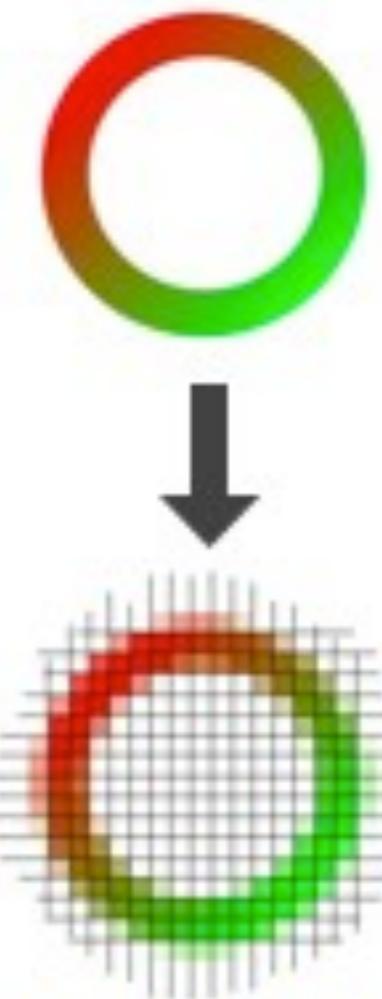
Rasterization rules

The OpenGL graphics pipeline

Graphics hardware

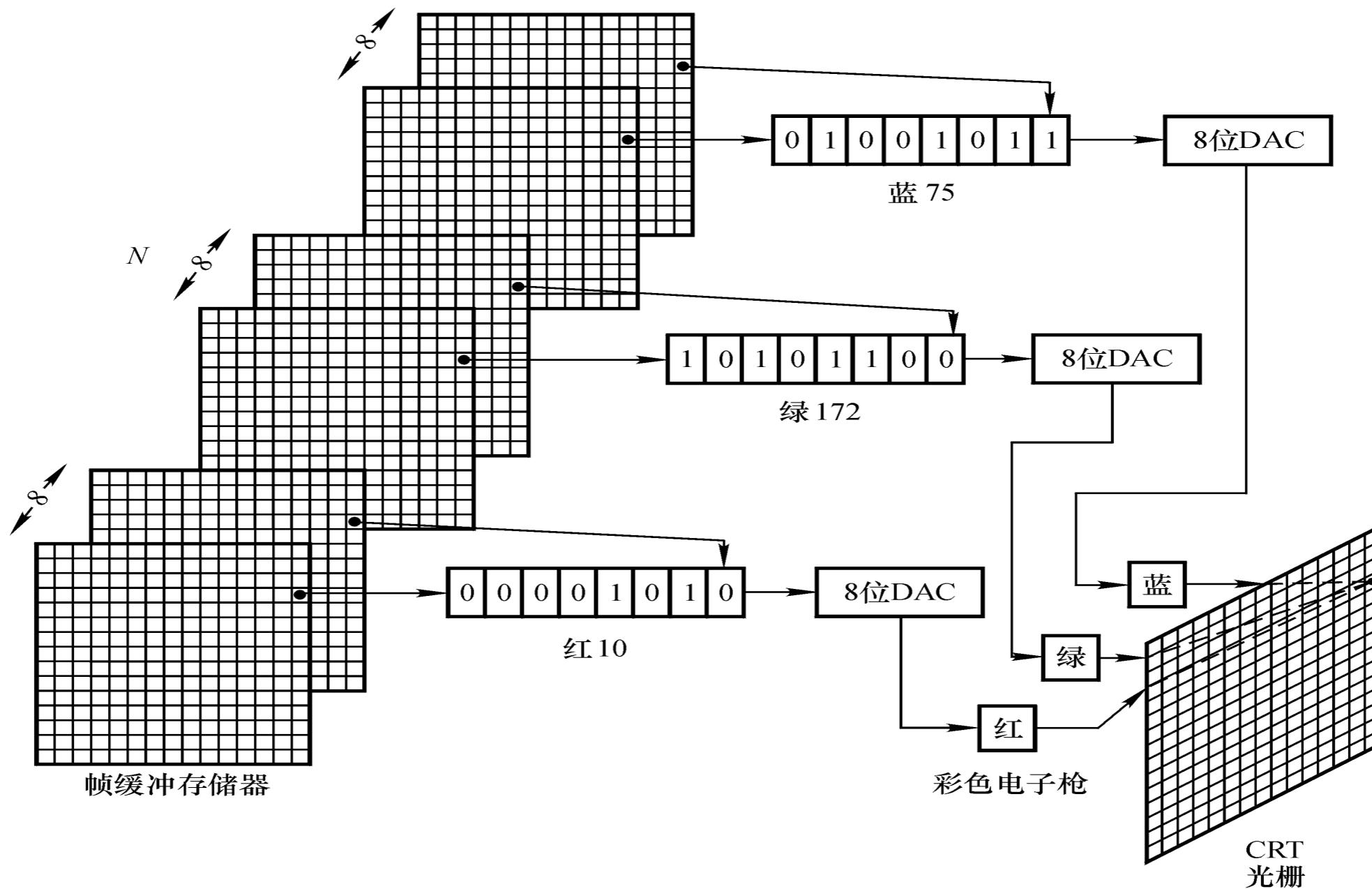
**Goal: Understand the graphics pipeline
and learn how to create pictures
using OpenGL**

**shapes, lines, points
images, text**

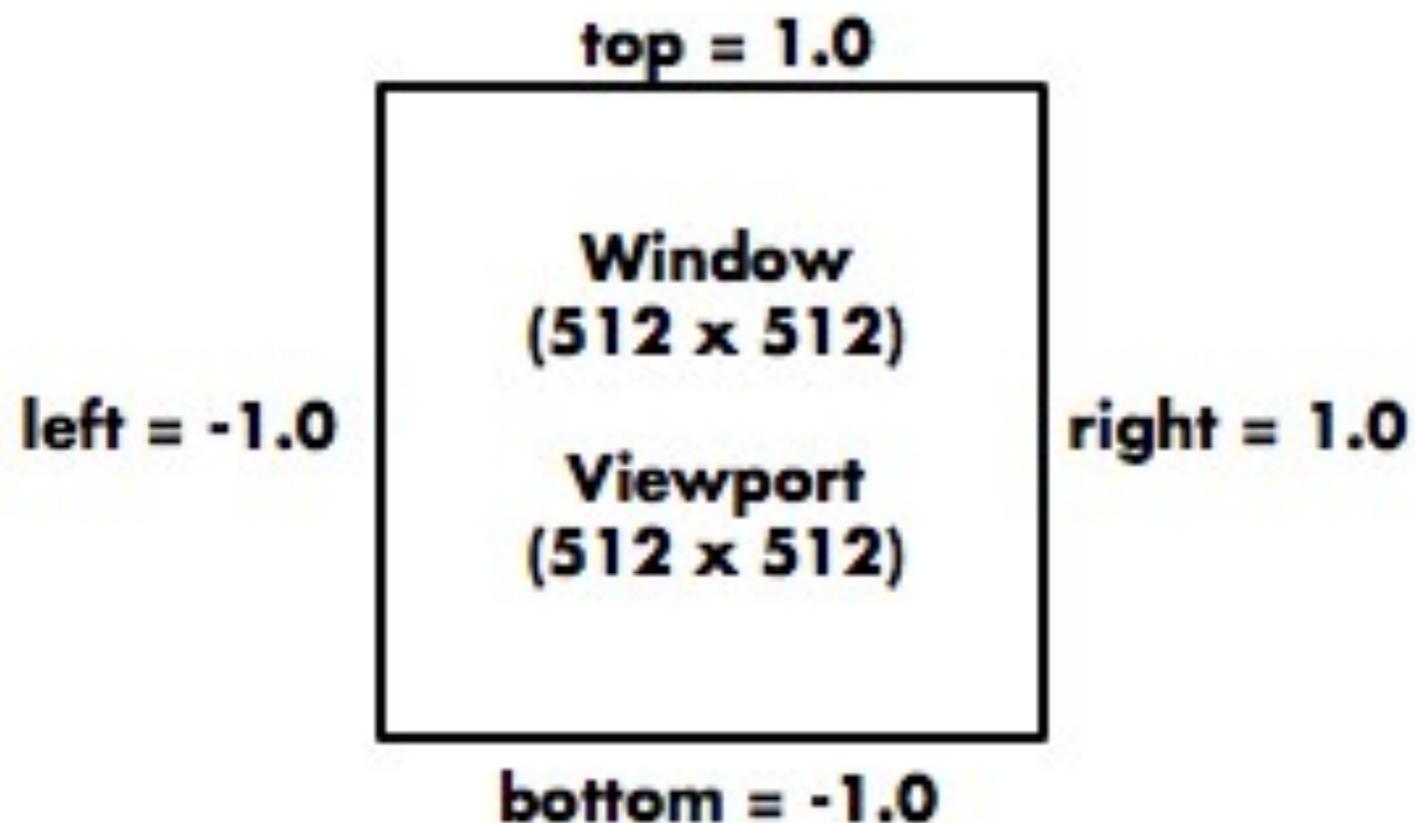


**Colored pixels
on screen**

Rasterization



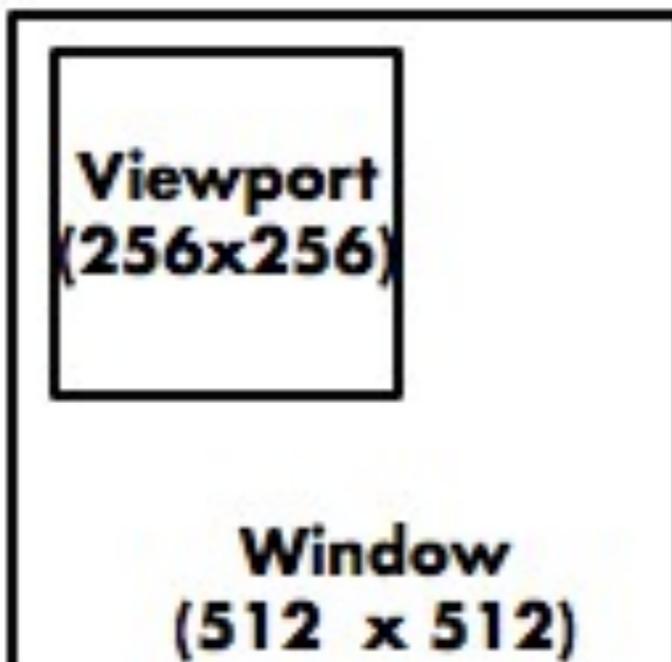
Viewports and Coordinate Systems



Each window has a user coordinate system
A 2D coordinate system is specified by assigning
coordinates to the edges of the window
left need not be less than right ...

Framebuffer and Viewport

My Macbook Pro Framebuffer: 1440 x 900



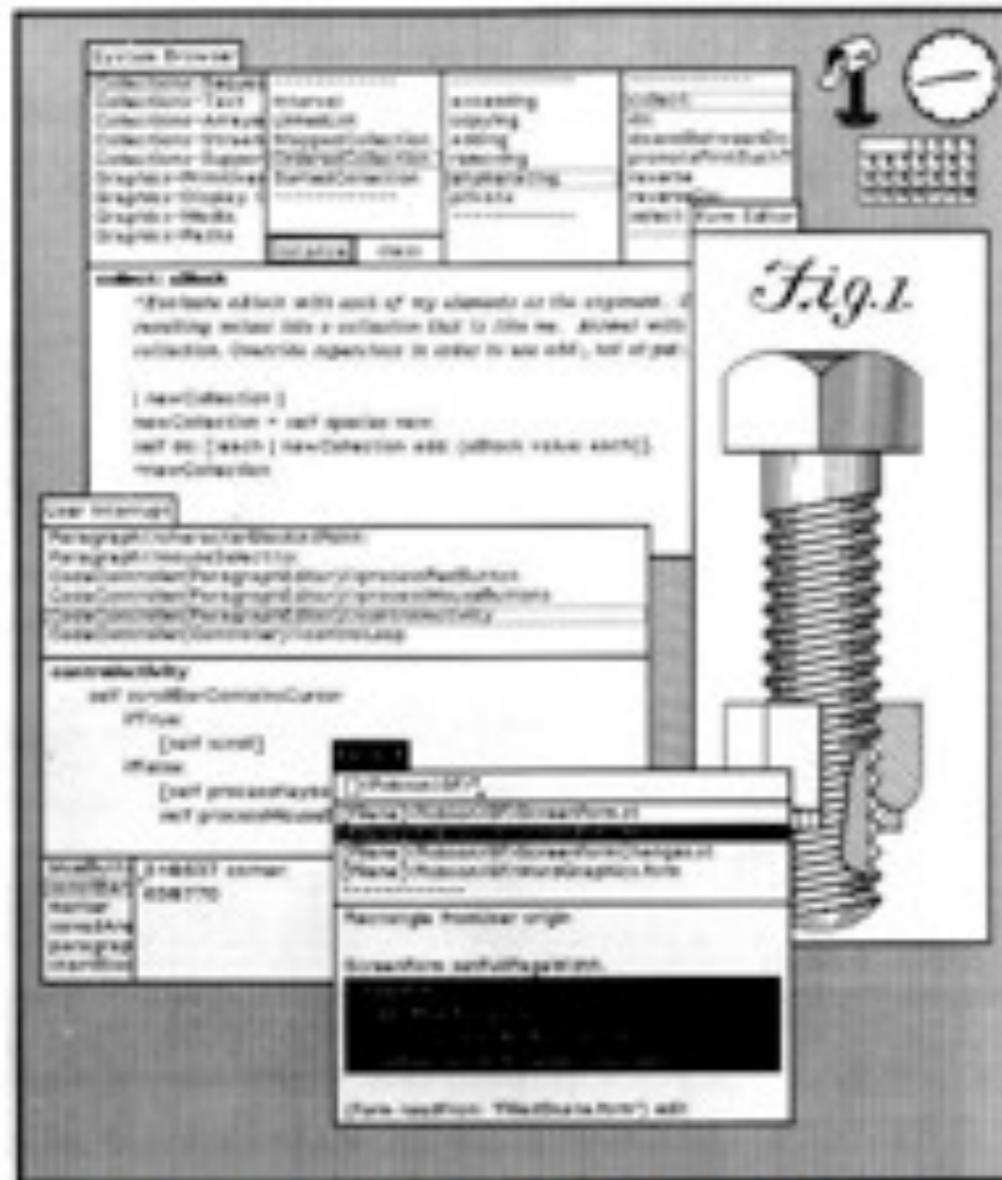
The **window** is
the portion of the display
usable by the application
(under control of the
“window system”)

The **viewport** is
the portion of the window
that can be drawn in,
no pixels will appear
outside the viewport

All coordinates are integers;
they refer to pixels in the framebuffer

Two Interpretations of Window

<http://www.imaginativeinteriors.co.uk/trompe.shtml>



**Window on the Display
(Virtual Framebuffer)**

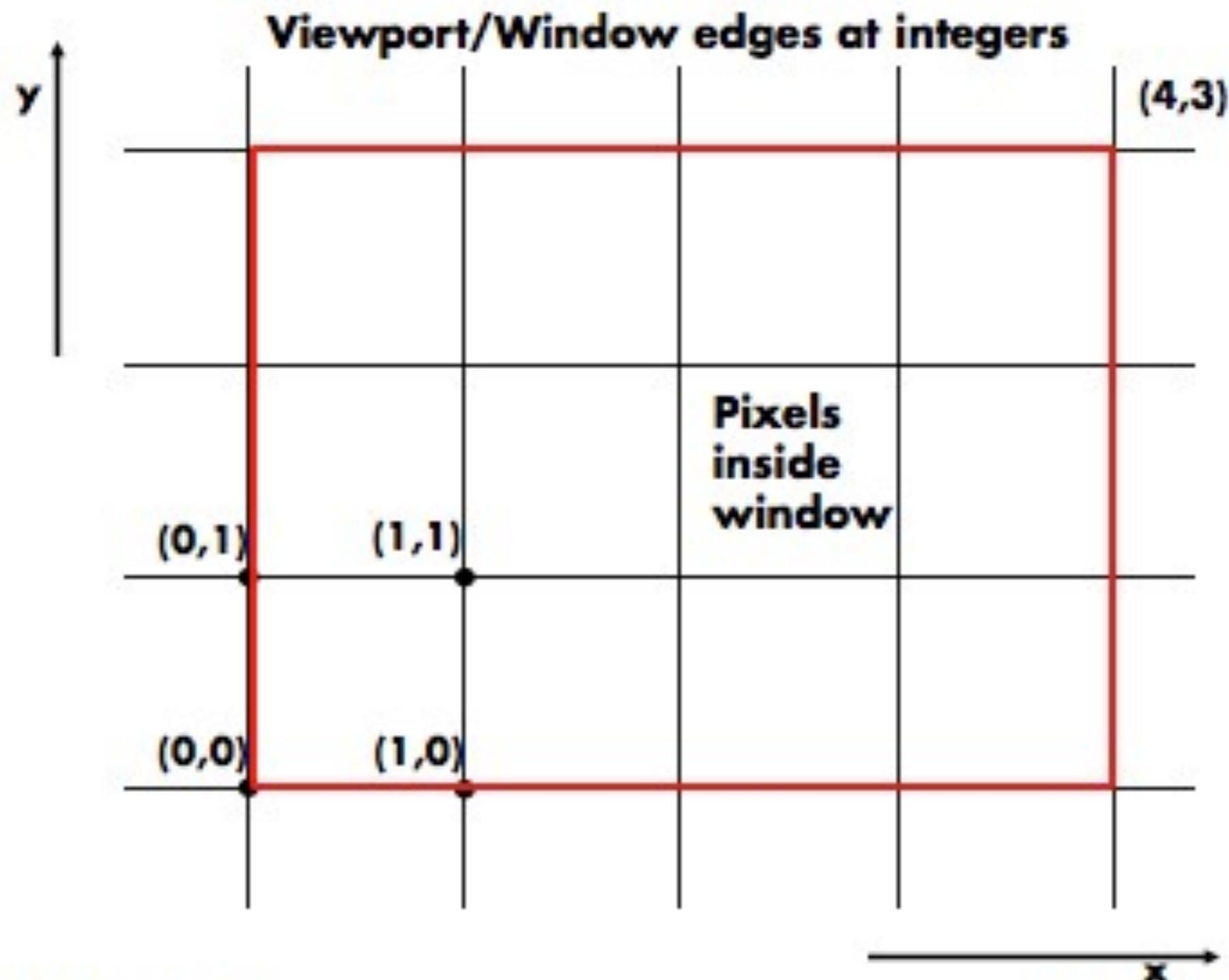
CS148 Lecture 2



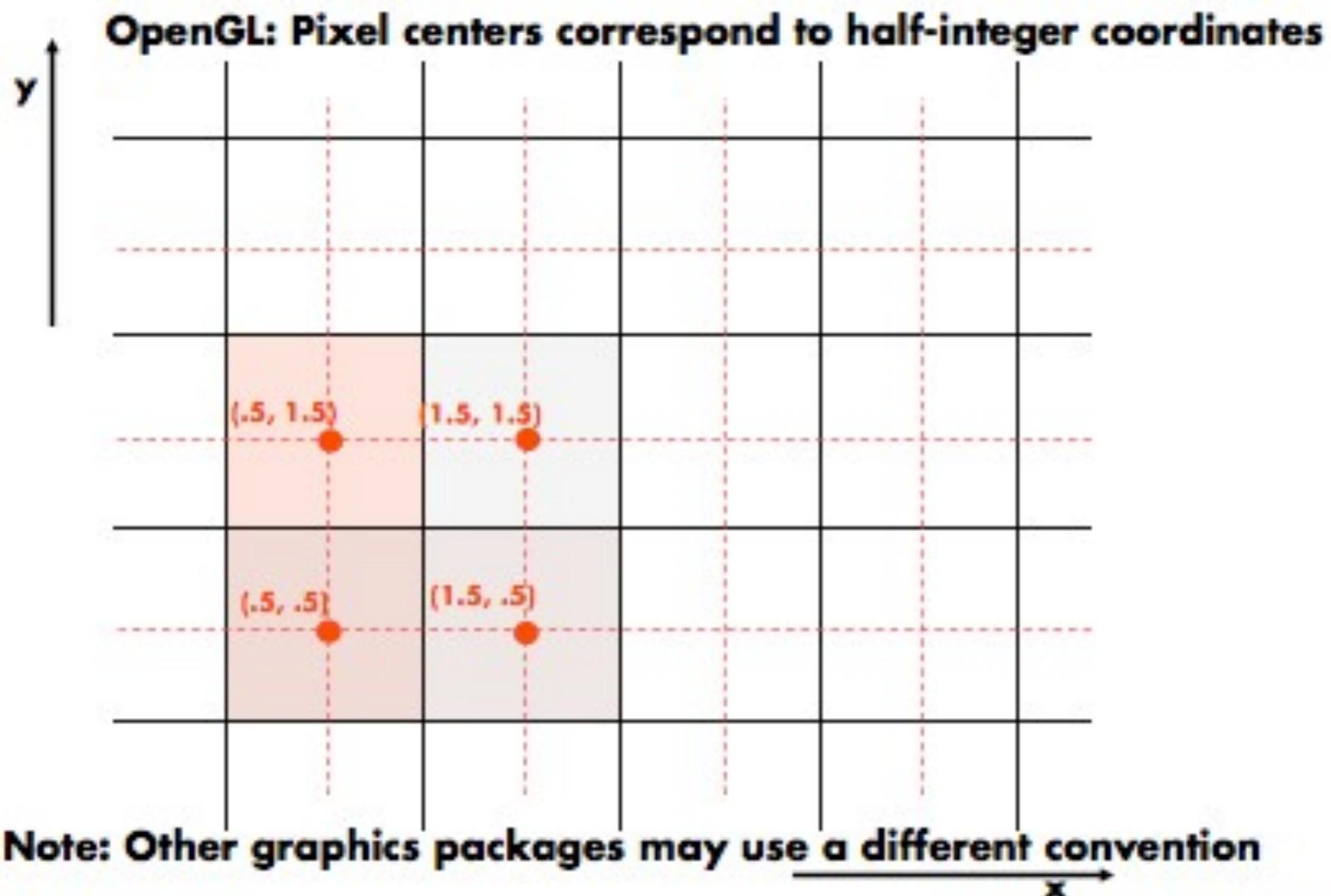
Window into a Virtual World

Pat Hanrahan, Fall 2010

Pixel Coordinates

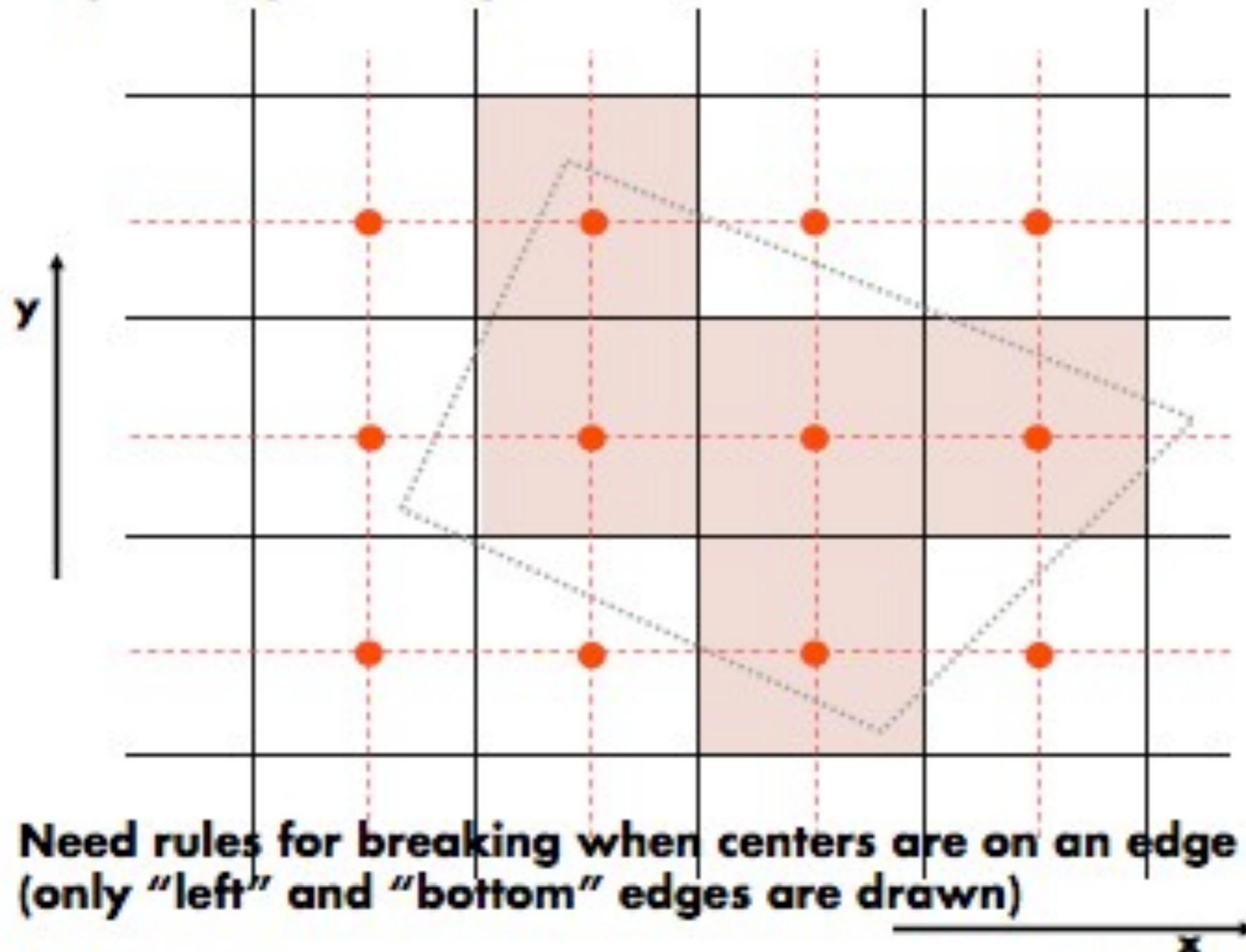


Pixel Coordinates



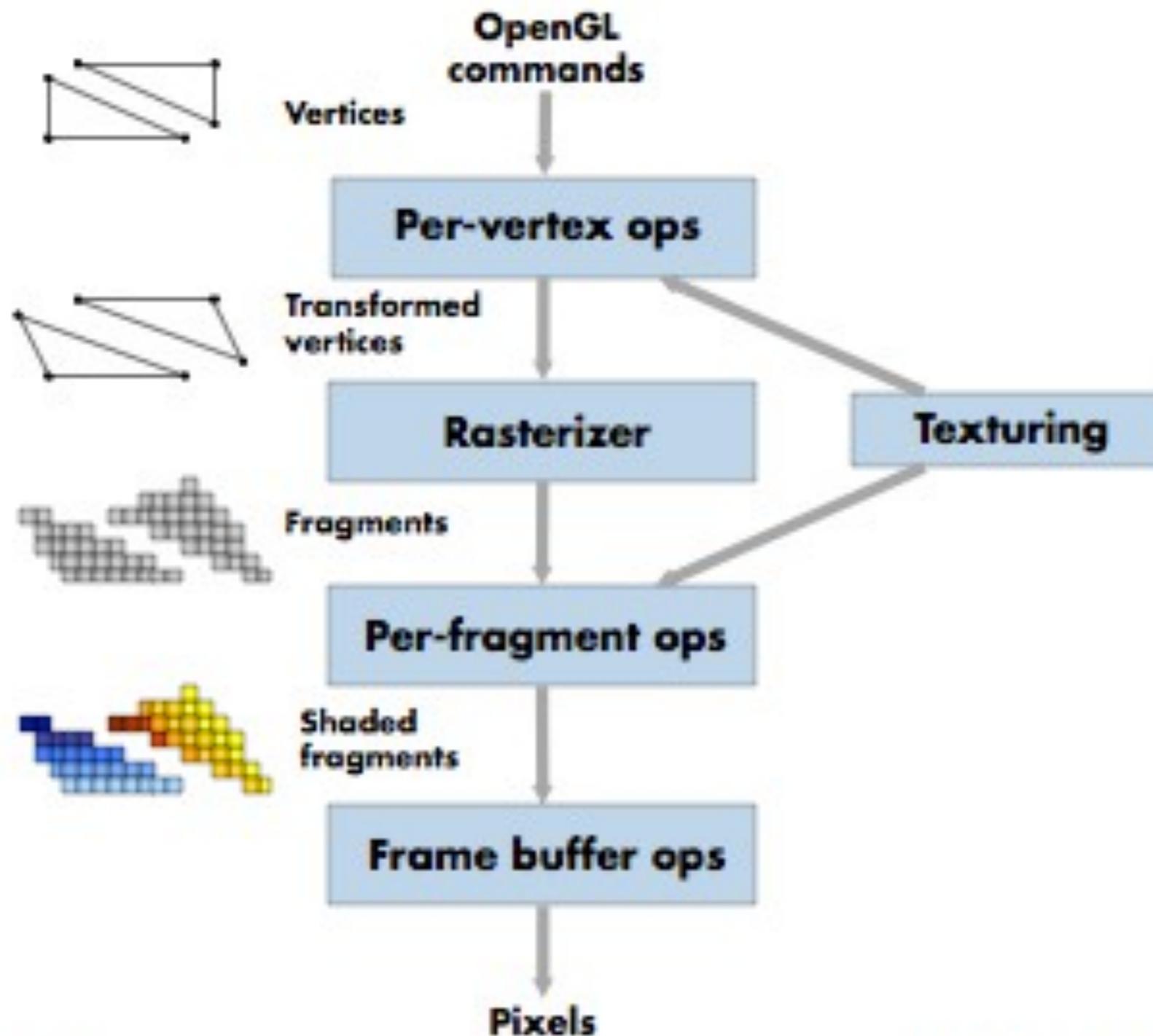
Rasterization Rules: Area Primitives

Output fragment if pixel center is inside area



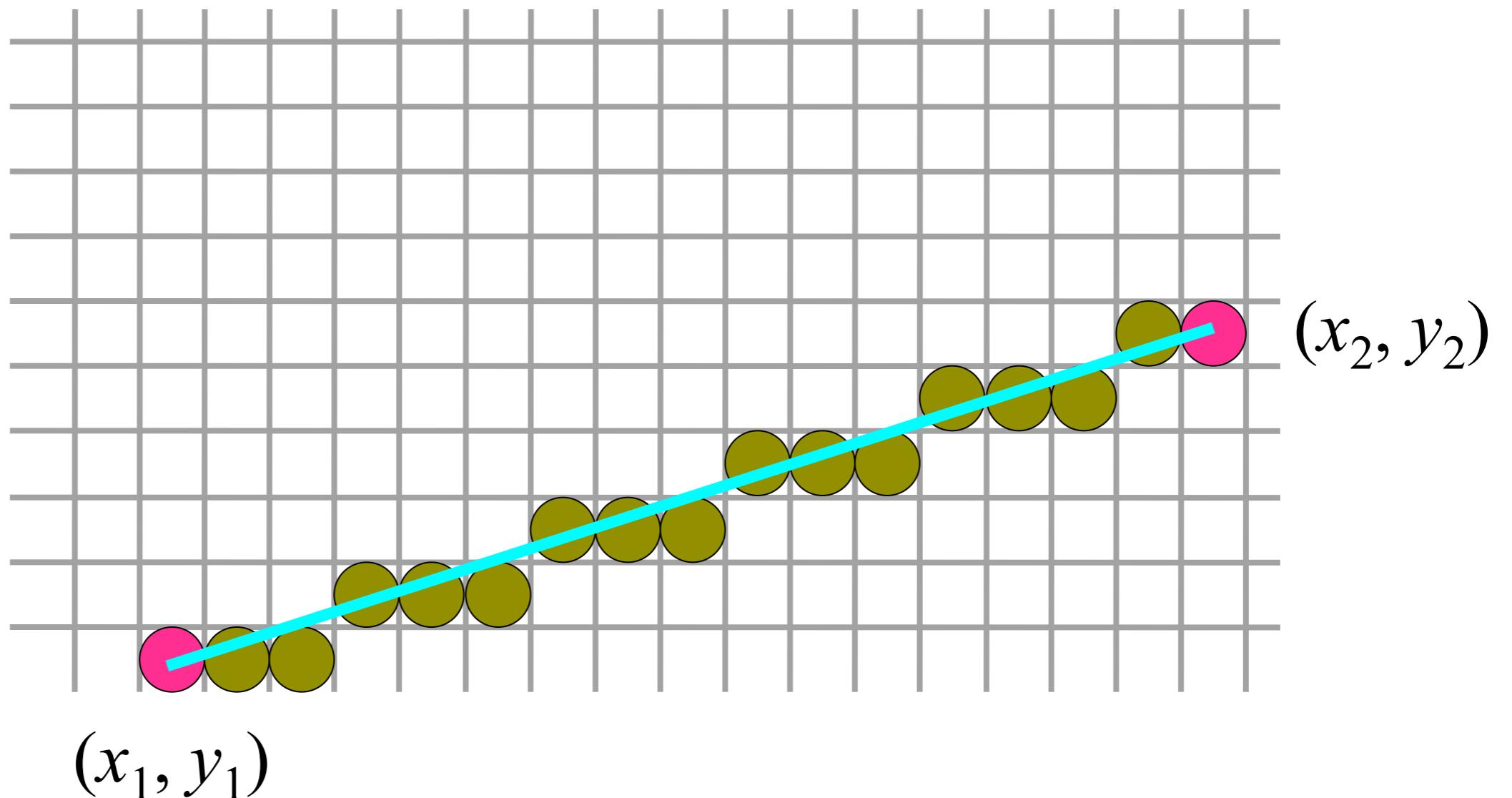
**Need rules for breaking when centers are on an edge
(only “left” and “bottom” edges are drawn)**

Simplified Pipeline



Scan converting lines

start from (x_1, y_1) end at (x_2, y_2)



ALG I. Straightforward

$(x_1, y_1), (x_2, y_2)$



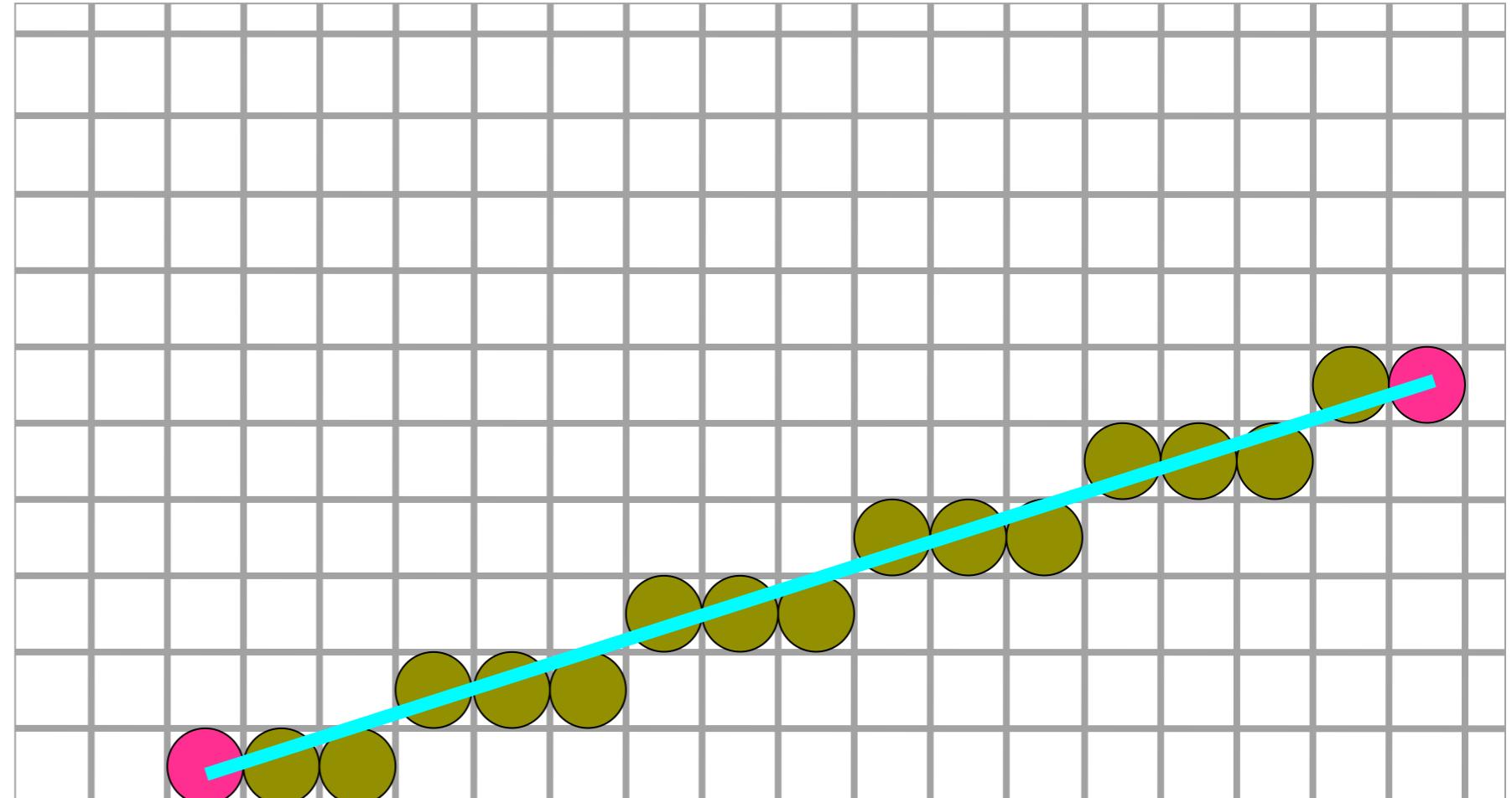
$y = mx + b$



$x_1 + 1 \Rightarrow y = ?, \text{ rounding}$



$x_1 + 2 \Rightarrow y = ?, \text{ rounding} \longrightarrow x_1 + i \Rightarrow y = ?, \text{ rounding}$



ALG II. Digital Differential Analyzer

- We consider the line in the first octant.
Other cases can be easily derived.
- Uses differential equation of the line

$$y_i = mx_i + c$$

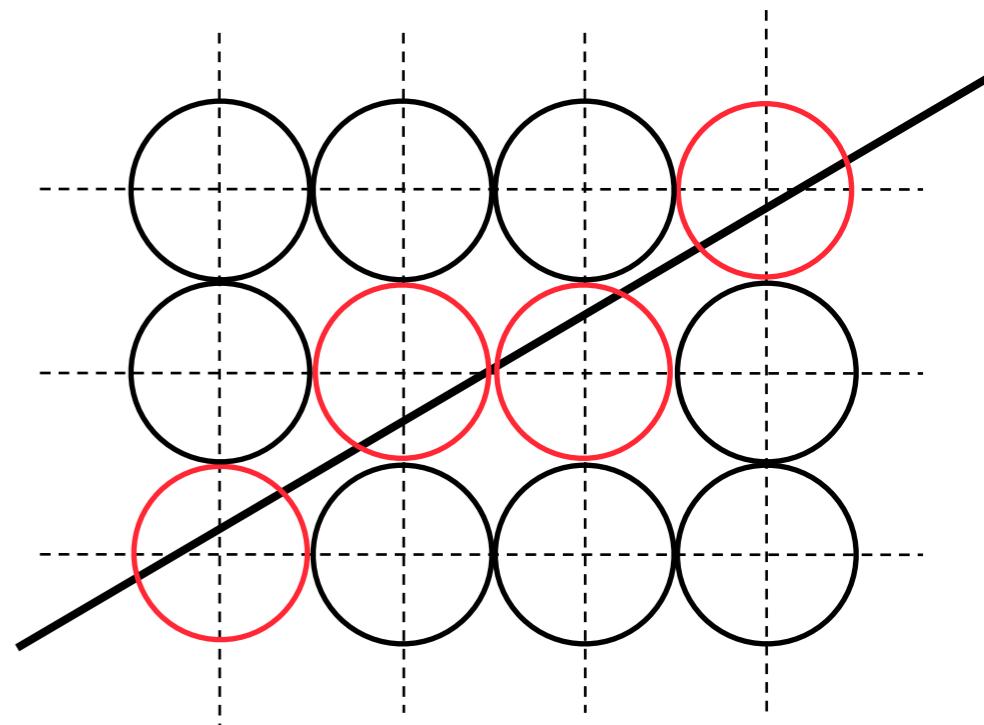
where, $m = \frac{y_2 - y_1}{x_2 - x_1}$

- Incrementing X-coordinate by 1

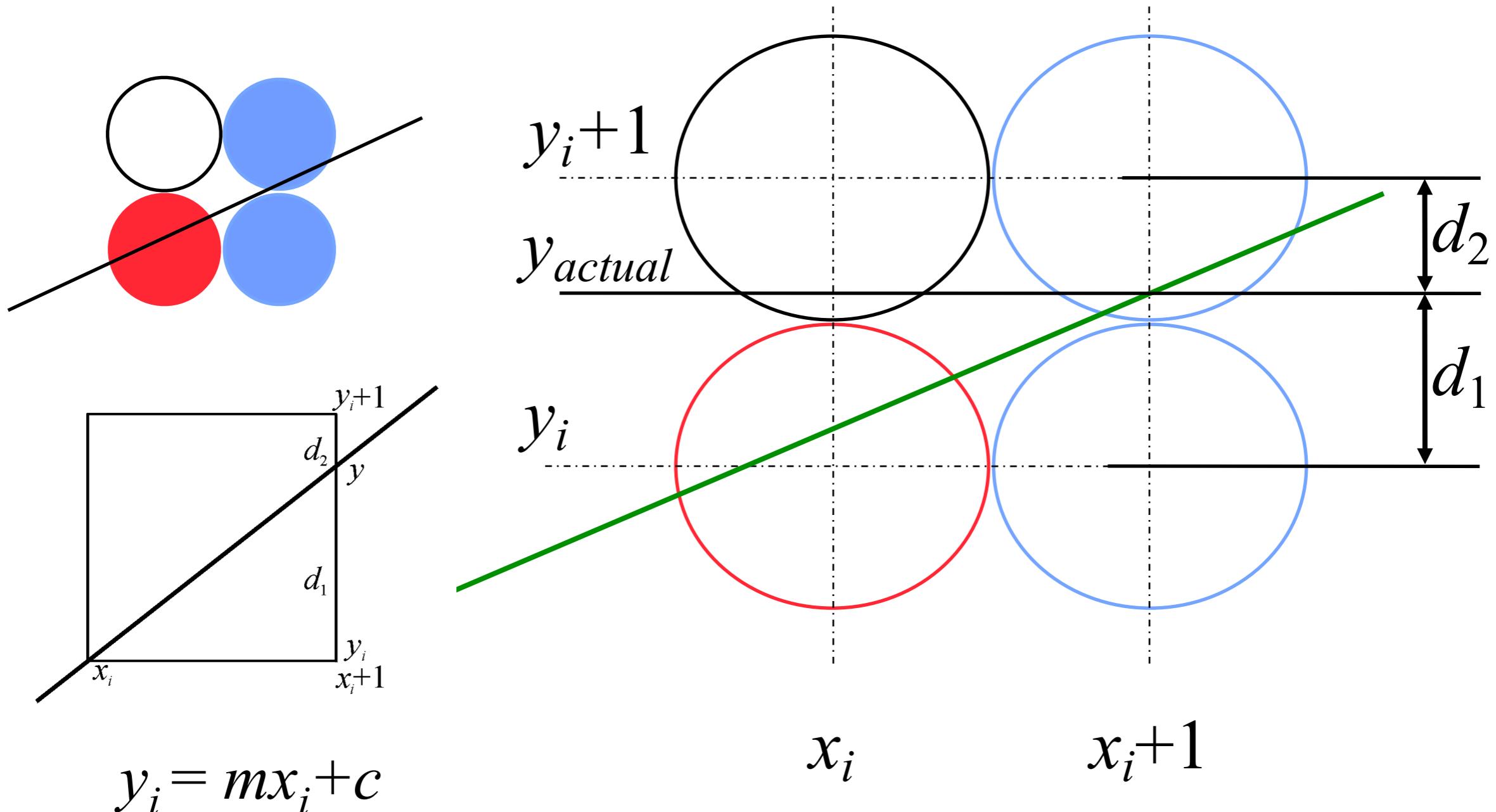
$$x_i = x_{i_prev} + 1$$

$$y_i = y_{i_prev} + m$$

- Illuminate the pixel $[x_i, round(y_i)]$



ALG III. Bresenham Line Drawing

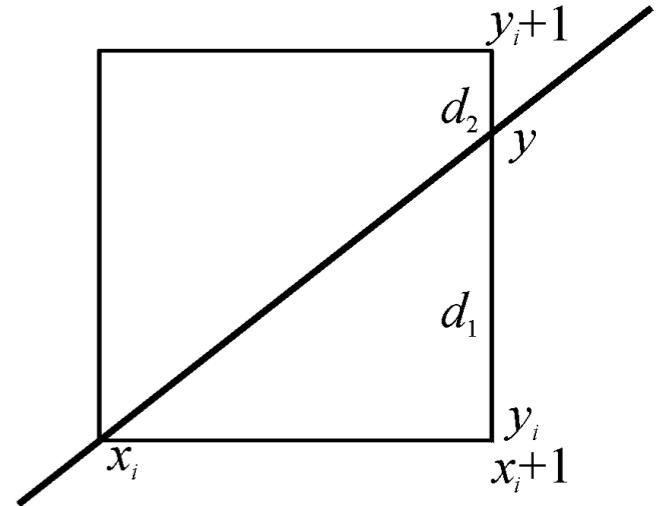


$d_1 > d_2 \Rightarrow y_{i+1} = y_i \text{ or } y_{i+1} = y_i + 1$

$$y = m(x_i + 1) + b \quad (2.1)$$

$$d_1 = y - y_i \quad (2.2)$$

$$d_2 = y_i + 1 - y \quad (2.3)$$



If $d_1 - d_2 > 0$, then $y_{i+1} = y_i + 1$, else $y_{i+1} = y_i$

substitute (2.1)、(2.2)、(2.3) into $d_1 - d_2$,

$$d_1 - d_2 = 2y - 2y_i - 1 = 2dy/dx * x_i + 2dy/dx + 2b - 2y_i - 1$$

on each side of the equation, * dx, denote $(d_1 - d_2) dx$ as P_i , we have

$$P_i = 2x_i dy - 2y_i dx + 2dy + (2b - 1)dx \quad (2.4)$$

Because in first octant $dx > 0$, we have $\text{sign}(d_1 - d_2) = \text{sign}(P_i)$

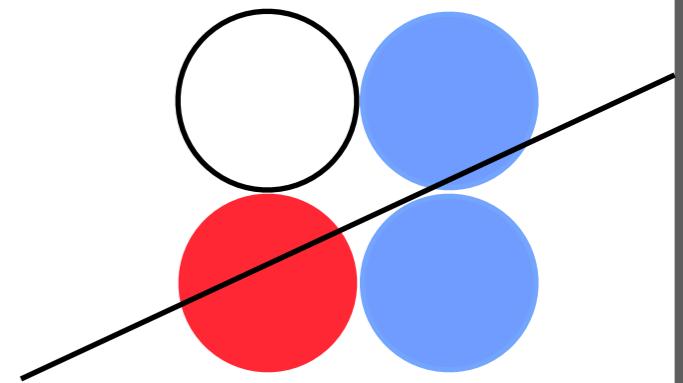
If $P_i > 0$, then $y_{i+1} = y_i + 1$, else $y_{i+1} = y_i$

$$P_{i+1} = 2x_{i+1} dy - 2y_{i+1} dx + 2dy + (2b - 1)dx, \quad \text{note that } x_{i+1} = x_i + 1$$

$$P_{i+1} = P_i + 2dy - 2(y_{i+1} - y_i) dx \quad (2.5)$$

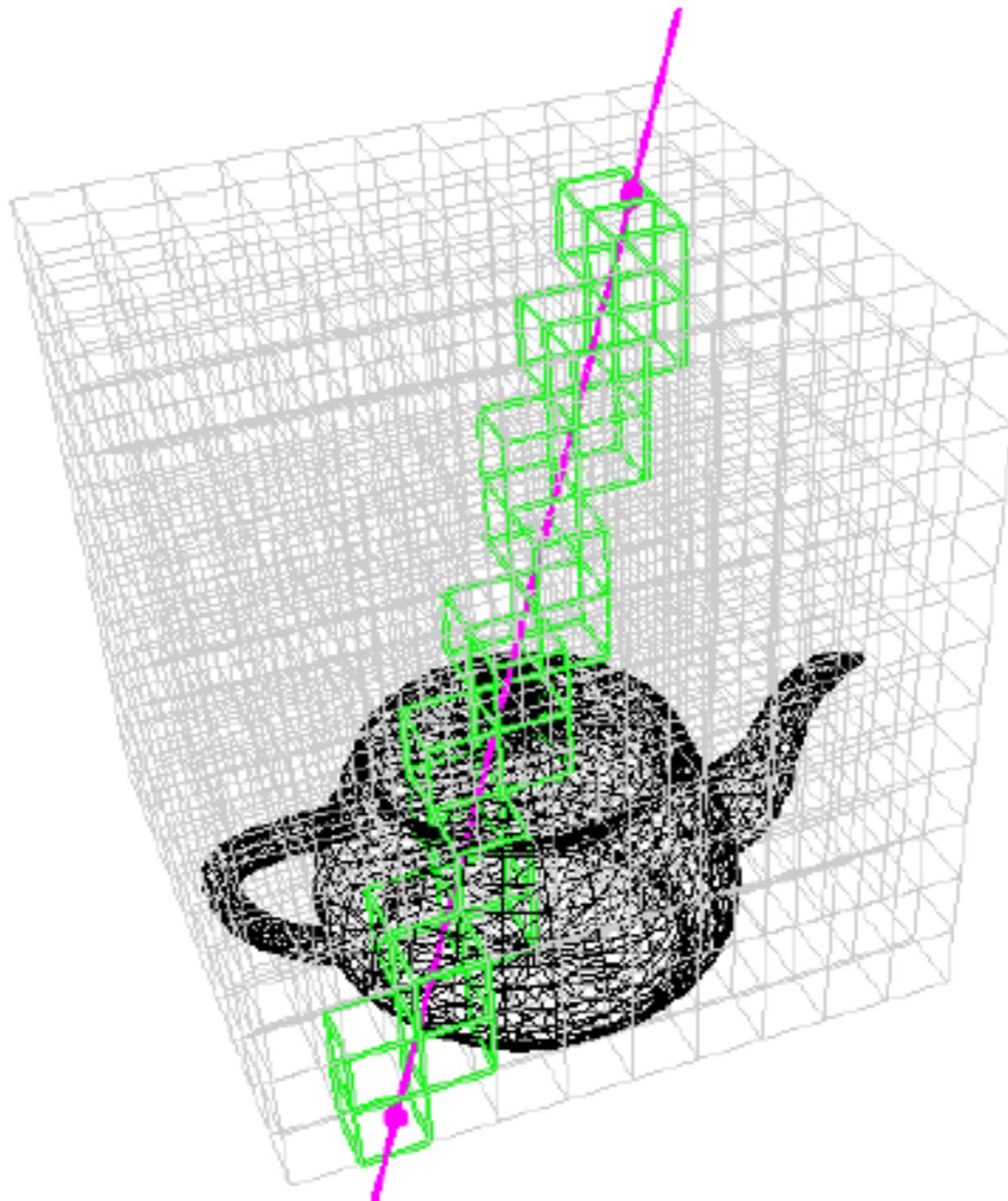
Bresenham algorithm in first octant

1. Initialization $P_0 = 2 dy - dx$
2. draw (x_1, y_1) , $dx=x_2-x_1$, $dy=y_2-y_1$,
Calculate $P_1=2dy-dx$, $i=1$;
3. $x_{i+1} = x_i + 1$
if $P_i > 0$, then $y_{i+1}=y_i+1$, else $y_{i+1}=y_i$;
4. draw (x_{i+1}, y_{i+1}) ;
5. calculate P_{i+1} :
if $P_i > 0$ then $P_{i+1}=P_i+2dy-2dx$,
else $P_{i+1}=P_i+2dy$;
6. $i=i+1$; if $i < dx+1$ then goto 3; else end

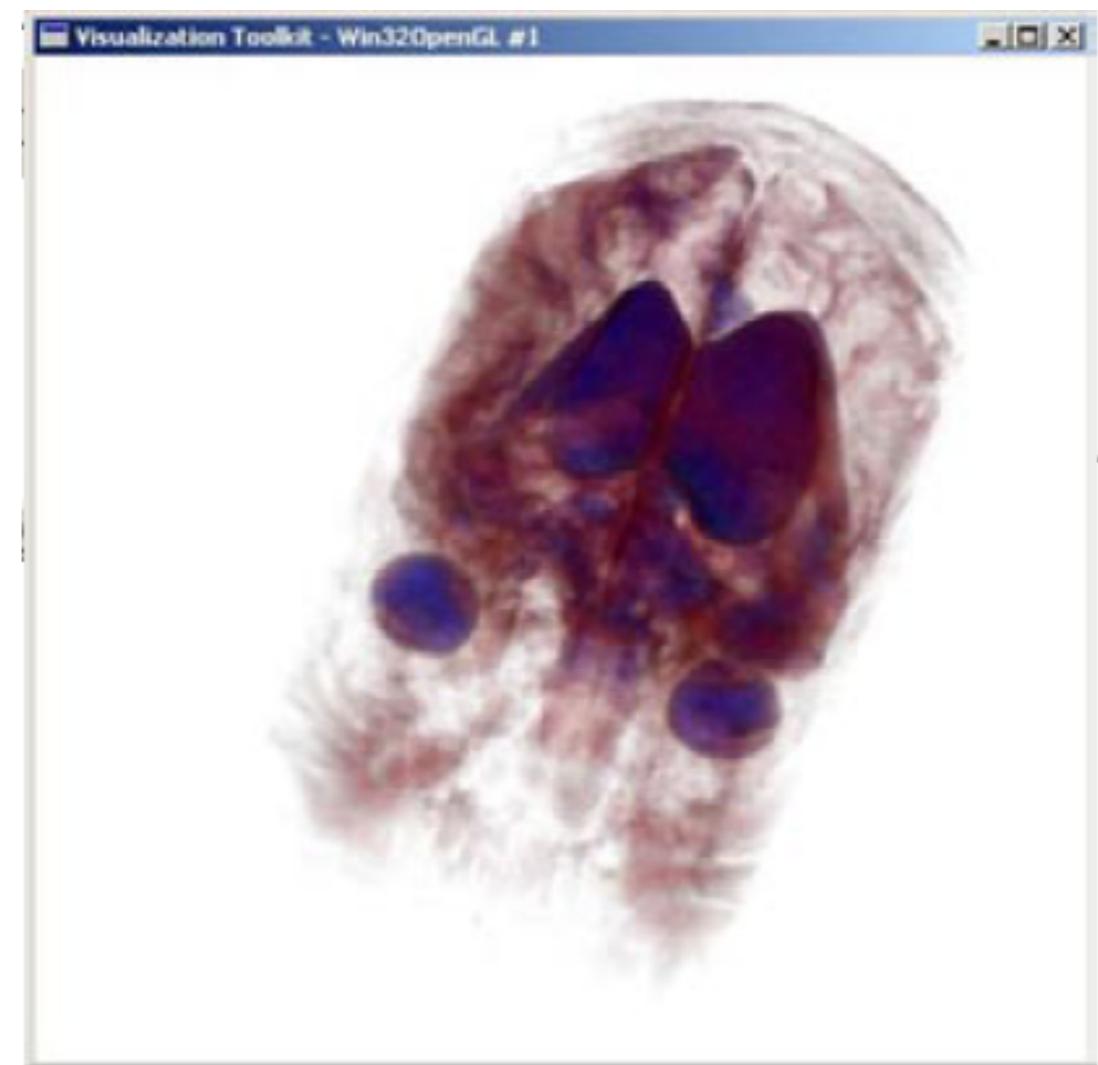
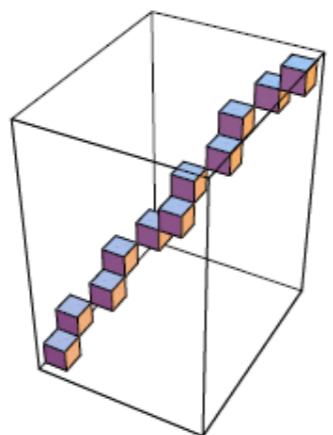
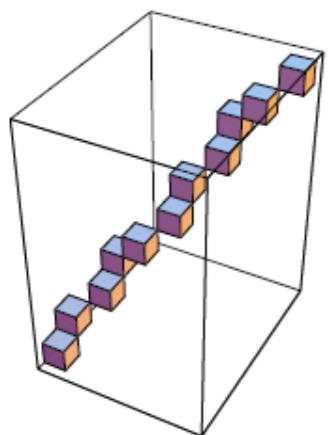
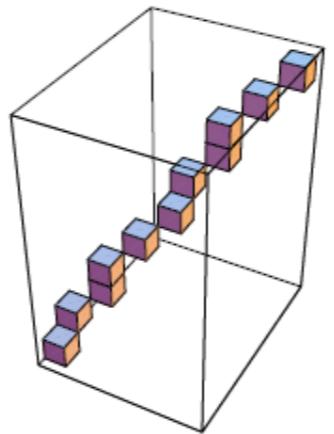
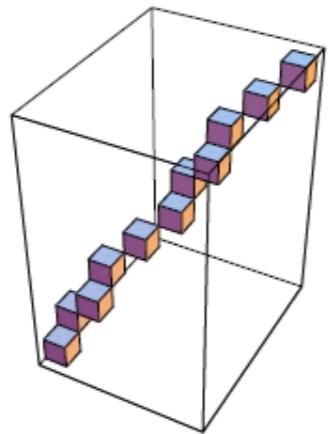
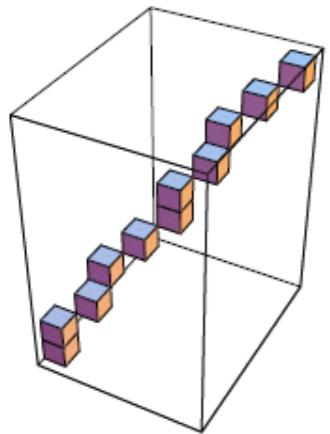


3D DDA and 3D Bresenham

Volume
Rendering



3D DDA and 3D Bresenham algorithm



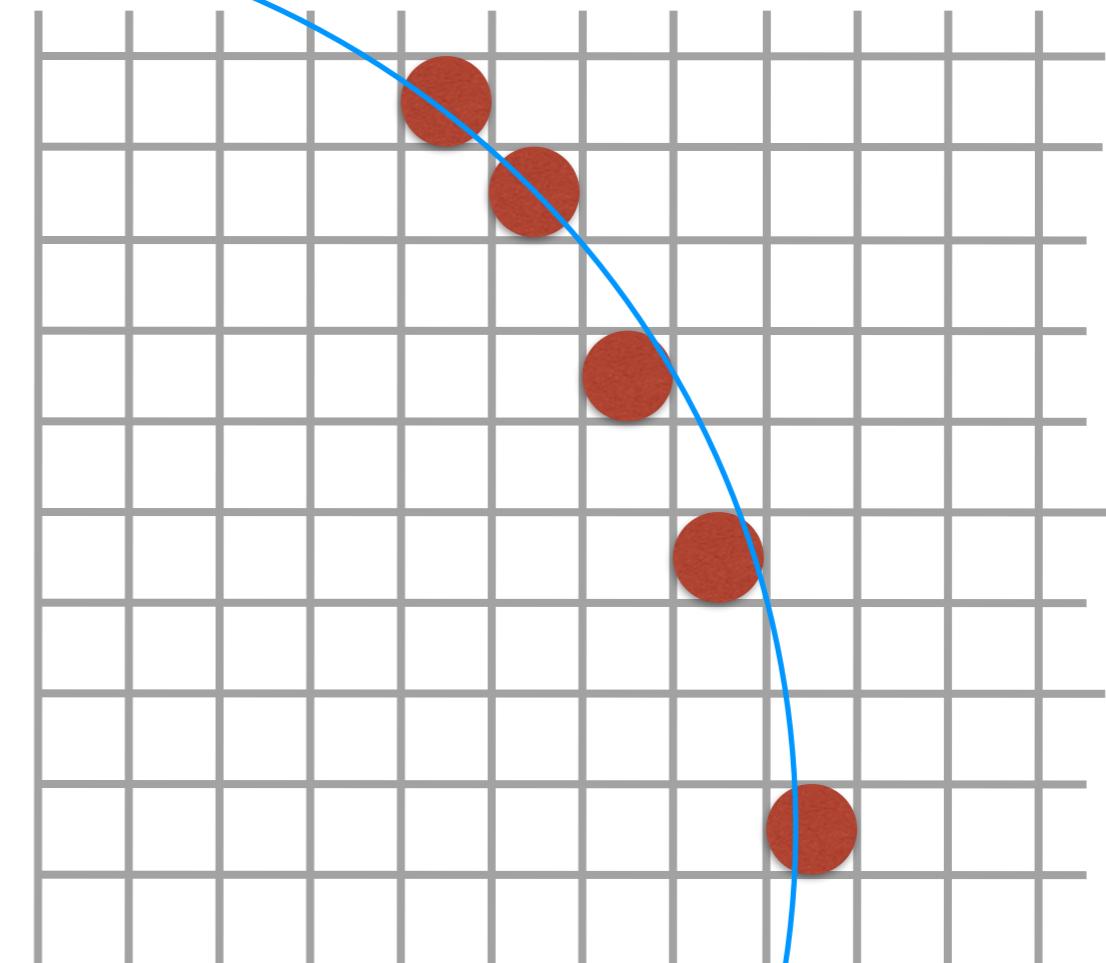
Scan converting circles

A circle with center (x_c, y_c) and radius r :

$$(x - x_c)^2 + (y - y_c)^2 = r^2$$

orthogonal coordinate

$$y = y_c \pm \sqrt{r^2 - (x - x_c)^2}$$



polar coordinates

$$x = x_c + r \cdot \cos\theta$$

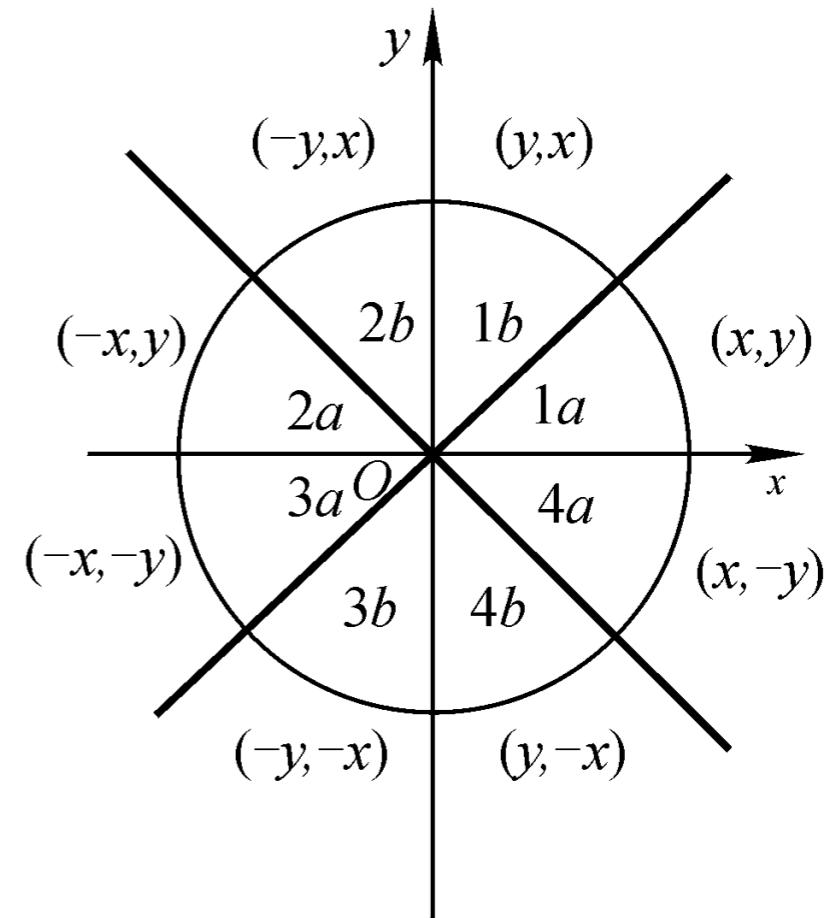
$$y = y_c + r \cdot \sin\theta$$

$$x_i = x_c + r \cdot \cos(i * \Delta\theta)$$

$$y_i = y_c + r \cdot \sin(i * \Delta\theta)$$

Can be accelerated by
symmetrical characteristic

$$\theta = i * \Delta\theta, \quad i=0,1,2,3,\dots$$



Discussion: How to speed up?

$$x_i = r \cos\theta_i$$

$$y_i = r \sin\theta_i$$

$$x_{i+1} = r \cos(\theta_i + \Delta\theta)$$

$$= r \cos\theta_i \cos\Delta\theta - r \sin\theta_i \sin\Delta\theta$$

$$= x_i \cos\Delta\theta - y_i \sin\Delta\theta$$

Bresenham Algorithm

Different representations

$$y = y_c \pm \sqrt{r^2 - (x - x_c)^2} \longrightarrow y = f(x) \quad x \in (x_0, x_1)$$

(explicit curve)

$$\begin{aligned} x &= x_c + r \cdot \cos\theta \\ y &= y_c + r \cdot \sin\theta \end{aligned} \longrightarrow \begin{cases} x = x(t) \\ y = y(t) \end{cases} \quad t \in (t_0, t_1)$$

(parametric curve)

$$(x - x_c)^2 + (y - y_c)^2 = r^2 \longrightarrow g(x, y) = 0$$

(implicit curve)

Discussion: How to display an explicit curve,
How to display a parametric
curve

3. OpenGL: A first look



What is OpenGL?

- “A software interface to graphics hardware”
 - A graphics library (modeling and rendering)
 - Very fast (a standard to be accelerated)
 - Open standard
 - Was SGI’s IRIS GL
 - Regularly released by the Khronos Group
 - OpenGL 1.0 (January, 1992)
 - OpenGL 4.5 (August, 2014)
 - OpenGL 4.6 (July, 2017)

Before and with OpenGL

- Before:
 - IRIS GL
 - GKS
 - PHIGS / PHIGS+ (<http://en.wikipedia.org/wiki/PHIGS>)
- Other
 - VRML/X3D
 - Direct3D

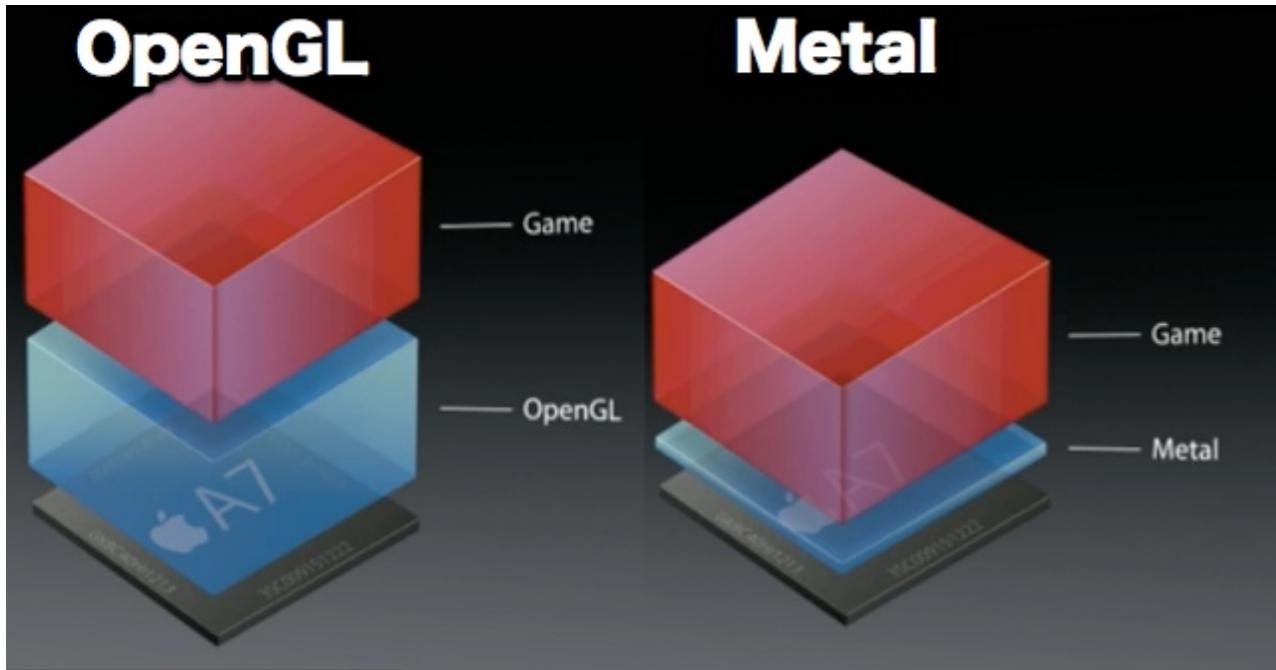
Modern OpenGL

- OpenGL 4.5 (August 11, 2014)
 - Direct State Access (DSA)
 - Flush Control
 - Robustness - providing a secure platform for applications such as WebGL browsers
 - OpenGL ES 3.1 API and shader compatibility
 - DX11 emulation features
- OpenGL NG, fusion with OpenGL ES

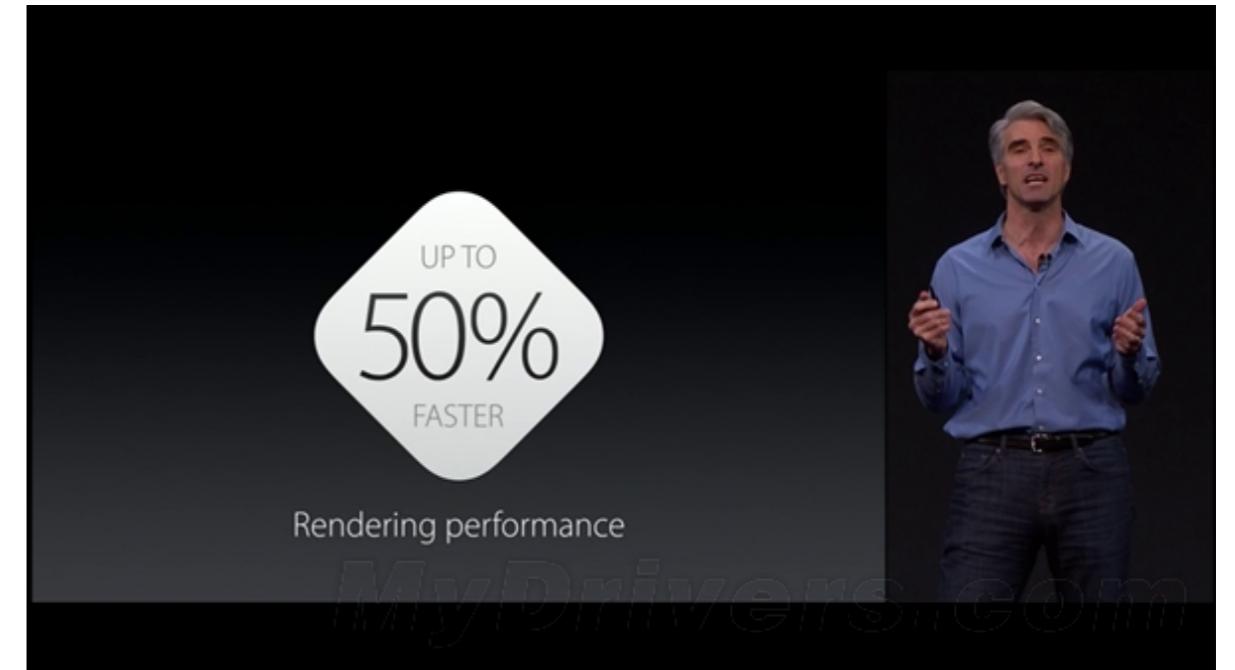
Modern OpenGL

- OpenGL 4.6 (July 31, 2017)
 - SPIR-V Support: standard intermediate language for parallel compute and graphics
 - ARB extensions

New 3D API in Mobile Platforms

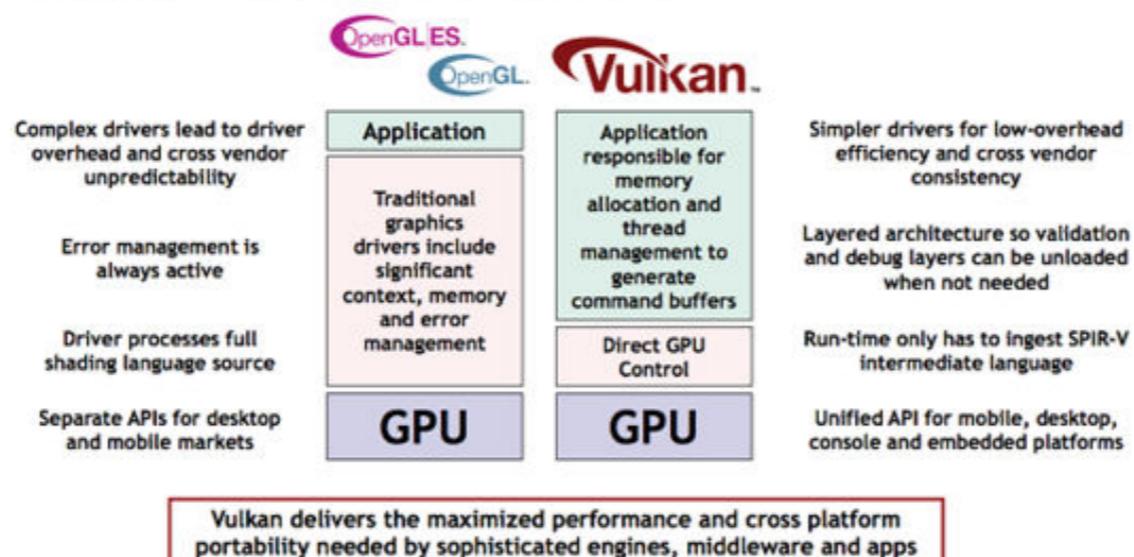


introduced in iOS 8



introduced in OSX El Capt.

Vulkan Explicit GPU Control



Vulkan has been introduced in Android

OpenGL Next Step

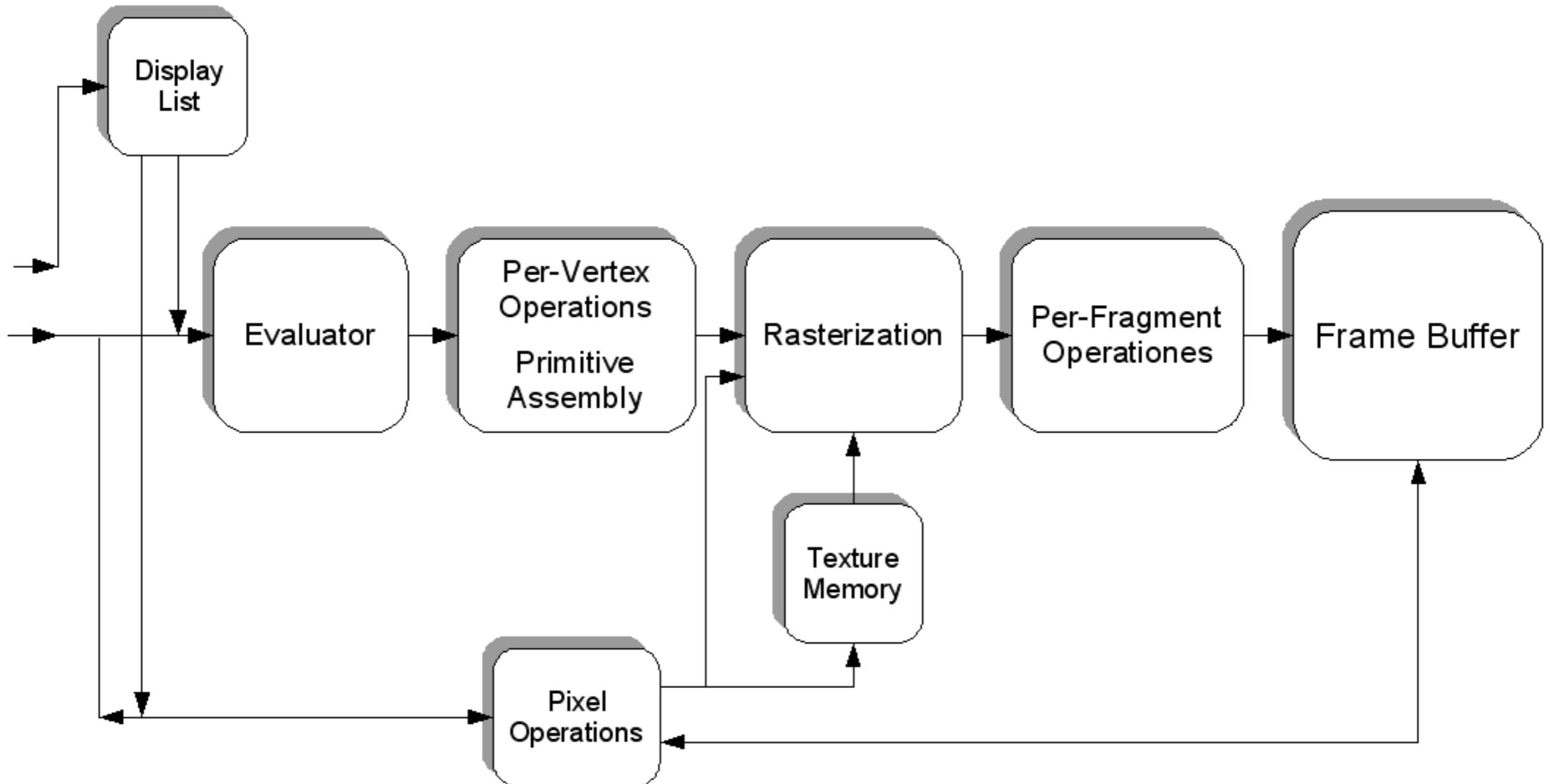
- Vulkan
- [http://v.youku.com/v_show/
id_XMTY0NjgzODA1Mg==.html](http://v.youku.com/v_show/id_XMTY0NjgzODA1Mg==.html)

Create new world in OpenGL

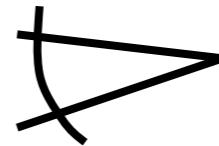
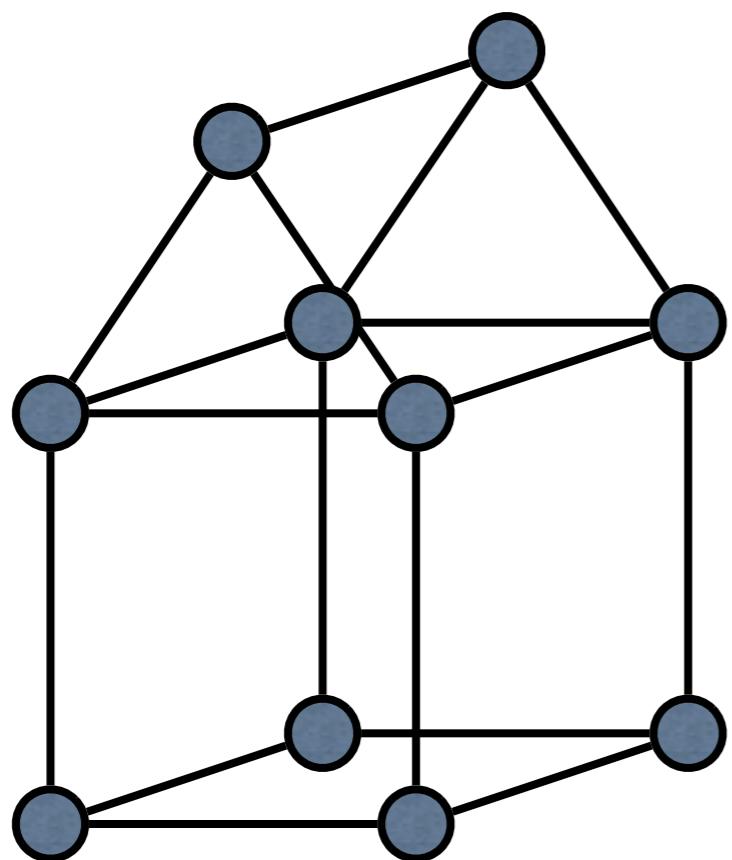
- <https://minecraft.net/>



A Graphics Pipeline Process



Given 3D data, generate 2D view



OpenGL

- OpenGL is a multi-platform graphics API
- Applications make calls to OpenGL, which then renders an image (by handling the graphics hardware) and displays it
- The API contains about 150 commands
- Provides NO platform-dependent functionality (input, windowing, etc.)
- toolkit: GLUT

What OpenGL Does

- Allows definition of object shapes, material properties and lighting
- Arranges objects and interprets synthetic camera in 3D space
- Converts mathematical representations of objects into pixels (rasterization)
- Calculates the color of every object

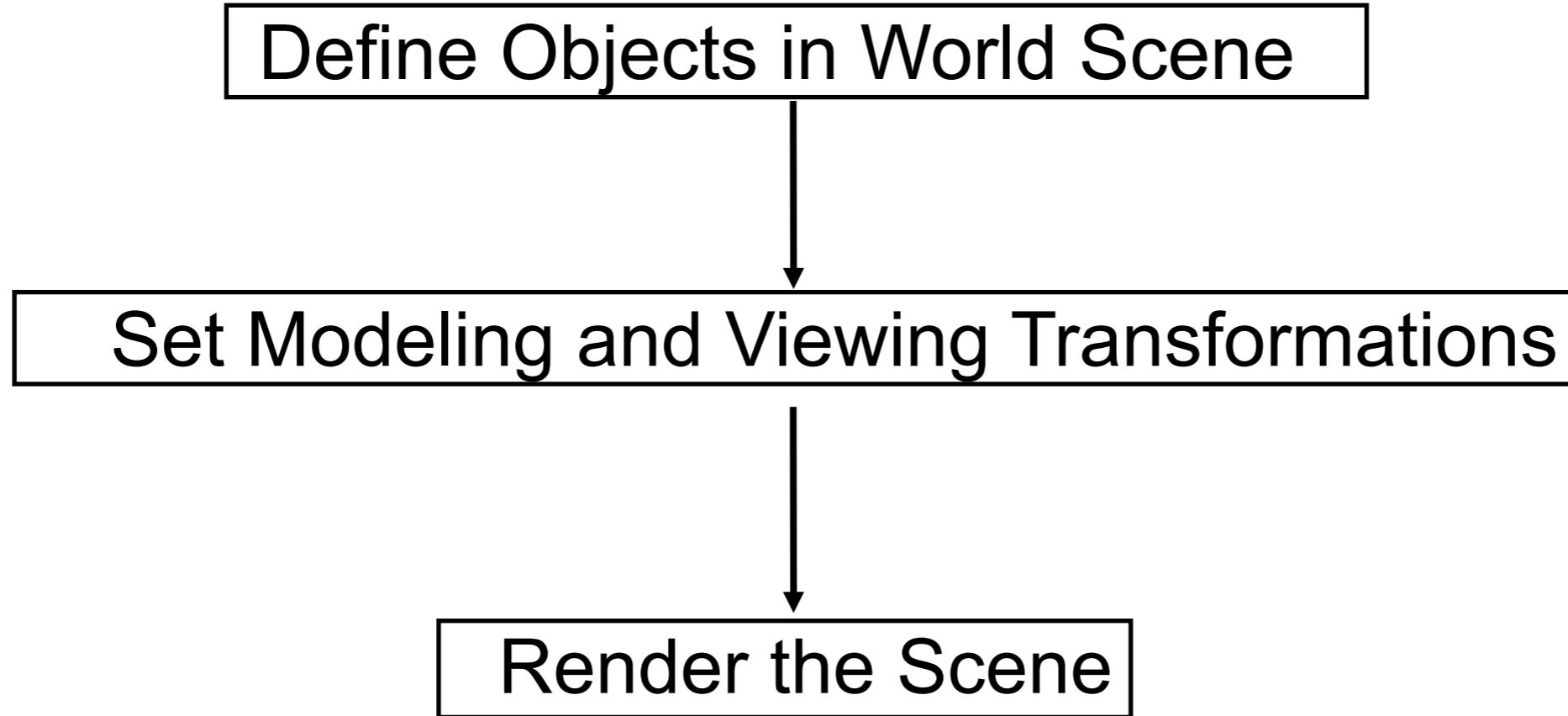
OpenGL

- NO high-level rendering functions for complex objects
 - build your shapes from primitives, points, lines, polygons, etc.
- The utility library GLU provides additional support

OpenGL tool chain

- OpenGL `#include <GL/gl.h>`
 - the “core” library that is platform independent
- GLU `#include <GL/glu.h>`
 - an auxiliary library that handles a variety of graphics accessory functions
- GLUT `#include <GL/glut.h>`
 - an auxiliary library that handles window creation, OS system calls (mouse buttons, movement, keyboard, etc), callbacks
- GLUI is a GUI manager written by Paul Rademacher (rademach@cs.unc.edu).

3 Stages in OpenGL



How OpenGL Works

- OpenGL is a state machine
 - You give it orders to set the current state of any one of its internal variables, or to query for its current status
 - The current state won't change until you specify otherwise
 - Ex.: if you set the current color to Red, everything you draw will be painted Red until you change the color explicitly
 - Each of the system's state variables has a default value

Example Code

```
int main(int argc, char **argv)
{
    glutInit(&argc, argv);
    glutInitDisplayMode (
        GLUT_SINGLE | GLUT_RGB | GLUT_DEPTH);

    glutInitWindowPosition(100,100);
    glutInitWindowSize(300,300);
    glutCreateWindow ("square");

    glClearColor(0.0, 0.0, 0.0, 0.0);
    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    glOrtho(0.0, 10.0, 0.0, 10.0, -1.0, 1.0);

    glutDisplayFunc(display);
    glutMainLoop();
    return 0;
}
```

```
void display(void)
{
    glClear( GL_COLOR_BUFFER_BIT);

    glColor3f(0.0, 1.0, 0.0);

    glBegin(GL_POLYGON);

        glVertex3f(2.0, 4.0, 0.0);
        glVertex3f(8.0, 4.0, 0.0);
        glVertex3f(8.0, 6.0, 0.0);
        glVertex3f(2.0, 6.0, 0.0);

    glEnd();

    glFlush();
}
```

OpenGL Primitives

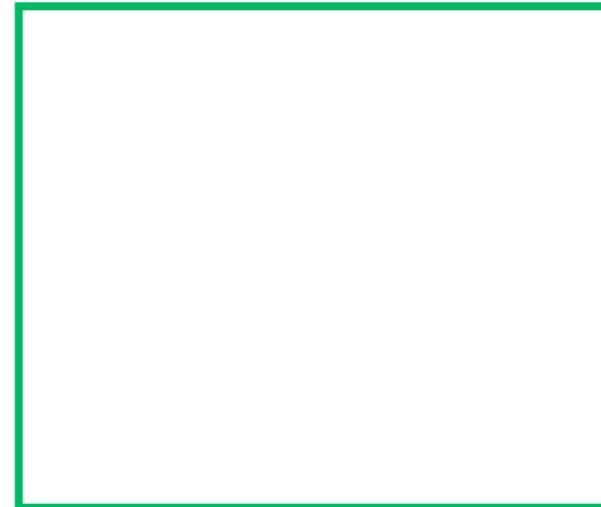
- `GL_POINTS`
- `GL_LINES`
- `GL_LINE_STRIP`
- `GL_LINE_LOOP`
- `GL_TRIANGLES`
- `GL_QUADS`
- `GL_POLYGON`
- `GL_TRIANGLE_STRIP`
- `GL_TRIANGLE_FAN`
- `GL_QUAD_STRIP`

1. `GL_POLYGON` and `GL_TRIANGLE` are the only ones in common usage

2. valid OpenGL polygons are closed, convex, co-planar and non-intersecting, which is always true for triangles!

Examples

```
glBegin(GL_POLYGON);
    glVertex2i(0,0);
    glVertex2i(0,1);
    glVertex2i(1,1);
    glVertex2i(1,0);
    glEnd();
```



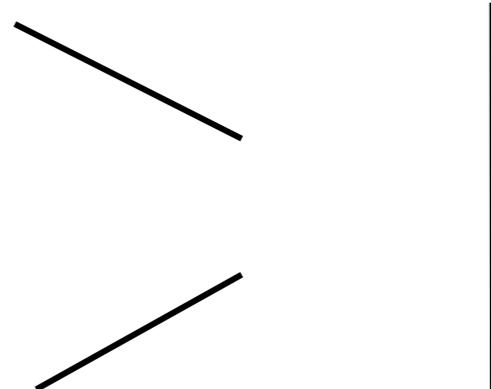
```
glBegin(GL_POINTS);
    glVertex2i(0,0);
    glVertex2i(0,1);
    glVertex2i(1,1);
    glVertex2i(1,0);
    glEnd();
```



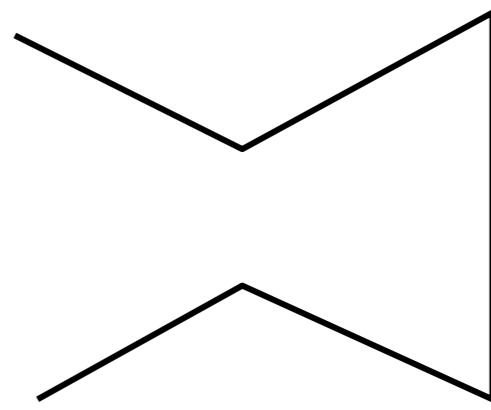
Examples

```
GLfloat list[6][2] ;
```

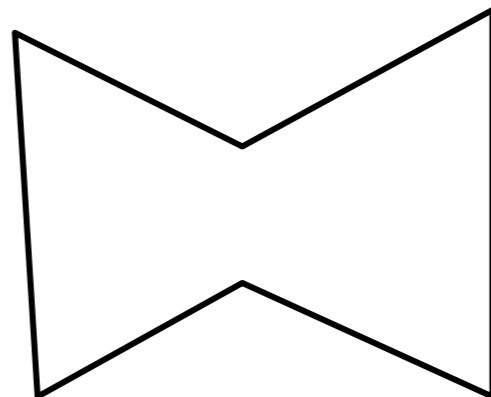
```
    glBegin(GL_LINES)
    for (int i = 0 ;i < 6 ;i++)
        glVertex2v(list[i]);
    glEnd() ;
```



```
glBegin(GL_LINE_STRIP)
for (int i = 0 ;i < 6 ;i++)
    glVertex2v(list[i]);
glEnd() ;
```



```
glBegin(GL_LINE_LOOP)
for (int i = 0 ;i < 6 ;i++)
    glVertex2v(list[i]);
glEnd() ;
```

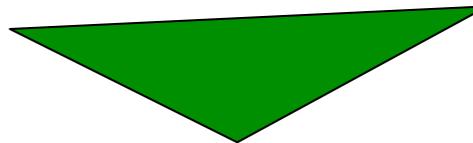


Examples

```
GLfloat list[6][2] ;
```

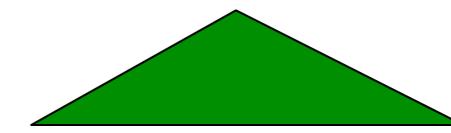
```
glColor3f(0.0, 1.0, 0.0);  
glBegin(GL_TRIANGLES)  
    for (int i = 0 ;i < 6 ;i++)  
        glVertex2v(list[i]);
```

```
glEnd() ;
```



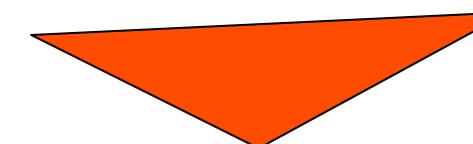
```
glBegin(GL_TRIANGLES)
```

```
    glColor3f(1.0, 0.0, 0.0);  
    for ( i = 0 ;i < 3 ;i++)  
        glVertex2v(list[i]);
```



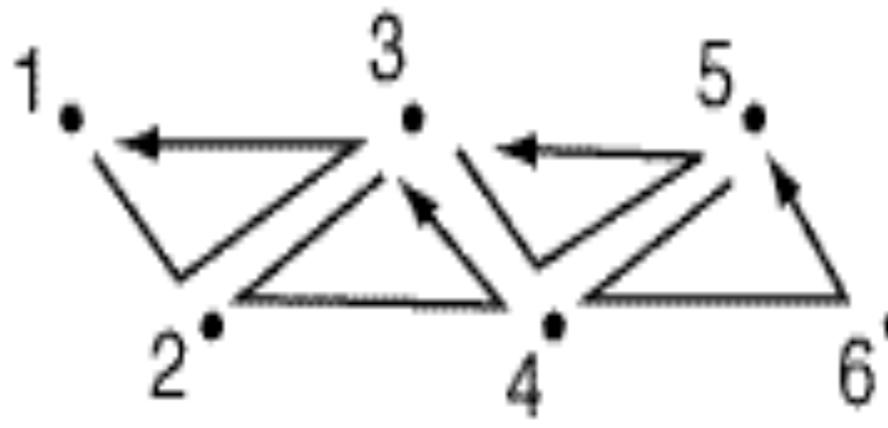
```
    glColor3f(1.0, 1.0, 1.0);  
    for ( i = 3 ;i < 6 ;i++)
```

```
        glVertex2v(list[i]);  
  
glEnd() ;
```



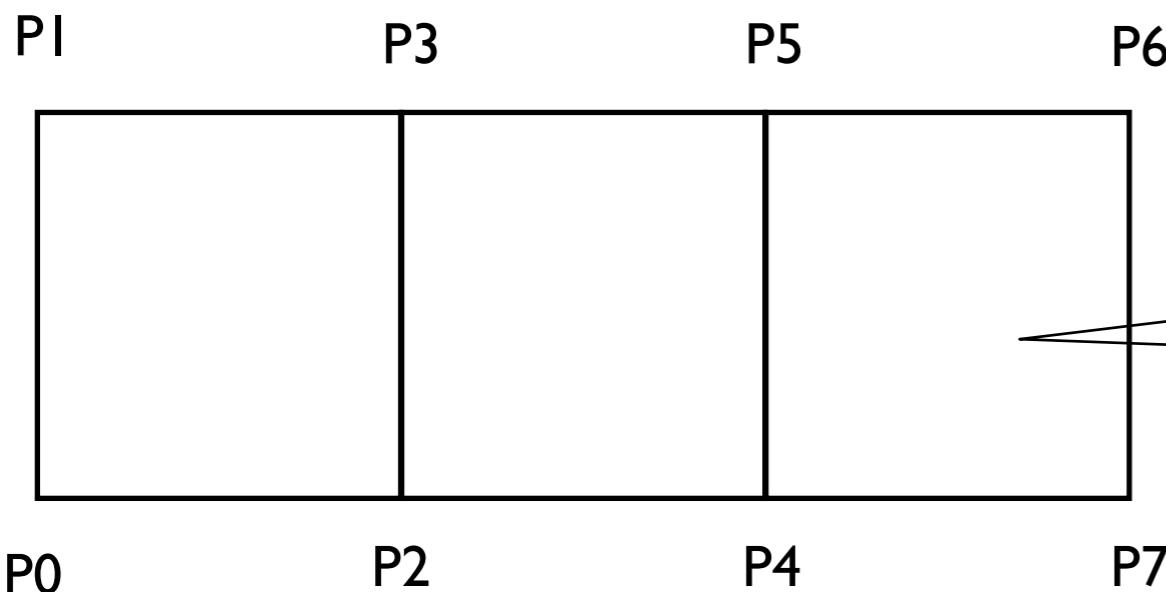
Examples

GL_TRIANGLE_STRIP



GL_TRIANGLE_FAN

GL_QUAD_STRIP



Must be
planar convex

OpenGL Command Syntax

- All command names begin with `gl`
 - Ex.: `glVertex3f(0.0, 1.0, 1.0);`
- Constant names are in all uppercase
 - Ex.: `GL_COLOR_BUFFER_BIT`
- Data types begin with `GL`
 - Ex.: `GLfloat onevertex[3];`
- Most commands end in two characters that determine the data type of expected arguments
 - Ex.: `glVertex3f(...)` => 3 `GLfloat` arguments

glVertex

- All primitives are defined in terms of vertices
 - `glVertex2f(x, y);`
 - `glVertex3f(x, y, z);`
 - `glVertex4f(x, y, z, w);`
 - `glVertex3fv(a); // with a[0], a[1], a[2]`

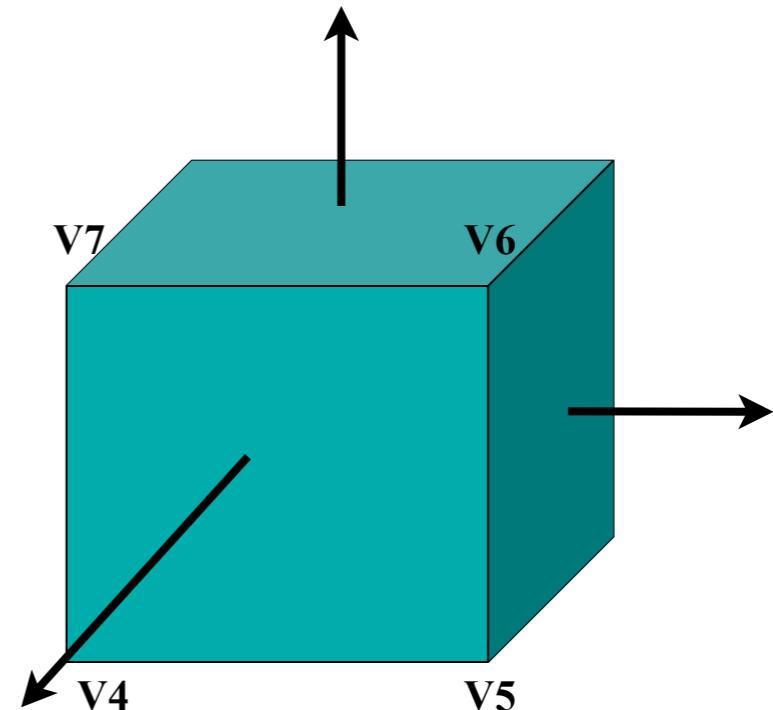
Building Objects From Vertices

- Specify a primitive mode, and enclose a set of vertices in a `glBegin` / `glEnd` block
- `glBegin(GL_POLYGON);`
- `glVertex3f(1.0, 2.0, 0.0);`
- `glVertex3f(0.0, 0.0, 0.0);`
- `glVertex3f(3.0, 0.0, 0.0);`
- `glVertex3f(3.0, 2.0, 0.0);`
- `glEnd();`

OpenGL Example

```
void drawOneCubeface (size)
{
    static GLfloat v[8][3];
    v[0][0] = v[3][0] = v[4][0] = v[7][0] = -size/2.0;
    v[1][0] = v[2][0] = v[5][0] = v[6][0] = size/2.0;
    v[0][1] = v[1][1] = v[4][1] = v[5][1] = -size/2.0;
    v[2][1] = v[3][1] = v[6][1] = v[7][1] = size/2.0;
    v[0][2] = v[1][2] = v[2][2] = v[3][2] = -size/2.0;
    v[4][2] = v[5][2] = v[6][2] = v[7][2] = size/2.0;

    glBegin(GL_POLYGON);
        glVertex3fv(v[0]);
        glVertex3fv(v[1]);
        glVertex3fv(v[2]);
        glVertex3fv(v[3]);
    glEnd();
}
```



Colors

- OpenGL colors are typically defined as RGB components
 - each of which is a float in the range [0.0, 1.0]
- For the screen's background:
 - `glClearColor(0.0, 0.0, 0.0); // black color`
 - `glClear(GL_COLOR_BUFFER_BIT);`
- For objects:
 - `glColor3f(1.0, 1.0, 1.0); // white color`

Other Commands in `glBegin` / `glEnd` blocks

- Not every OpenGL command can be located in such a block. Those that can include, among others:
 - `glColor`
 - `glNormal` (to define a normal vector)
 - `glTexCoord` (to define texture coordinates)
 - `glMaterial` (to set material properties)

Example

```
glBegin( GL_POLYGON );
    glColor3f( 1.0, 1.0, 0.0 ); glVertex3f( 0.0, 0.0, 0.0 );
    glColor3f( 0.0, 1.0, 1.0 ); glVertex3f( 5.0, 0.0, 0.0 );
    glColor3f( 1.0, 0.0, 1.0 ); glVertex3f( 0.0, 5.0, 0.0 );
glEnd();
```

Polygon Display Modes

- `glPolygonMode(GLenum face, GLenum mode);`
 - Faces: `GL_FRONT`, `GL_BACK`, `GL_FRONT_AND_BACK`
 - Modes: `GL_FILL`, `GL_LINE`, `GL_POINT`
 - By default, both the front and back face are drawn filled
- `glFrontFace(GLenum mode);`
 - Mode is either `GL_CCW` (default) or `GL_CW`
- `glCullFace(GLenum mode);`
 - Mode is either `GL_FRONT`, `GL_BACK`, `GL_FRONT_AND_BACK`;
- You must enable and disable culling with
 - `glEnable(GL_CULL_FACE)` or `glDisable(GL_CULL_FACE)`;

Drawing Other Objects

- GLU contains calls to draw cylinders, cones and more complex surfaces called NURBS
- GLUT contains calls to draw spheres and cubes

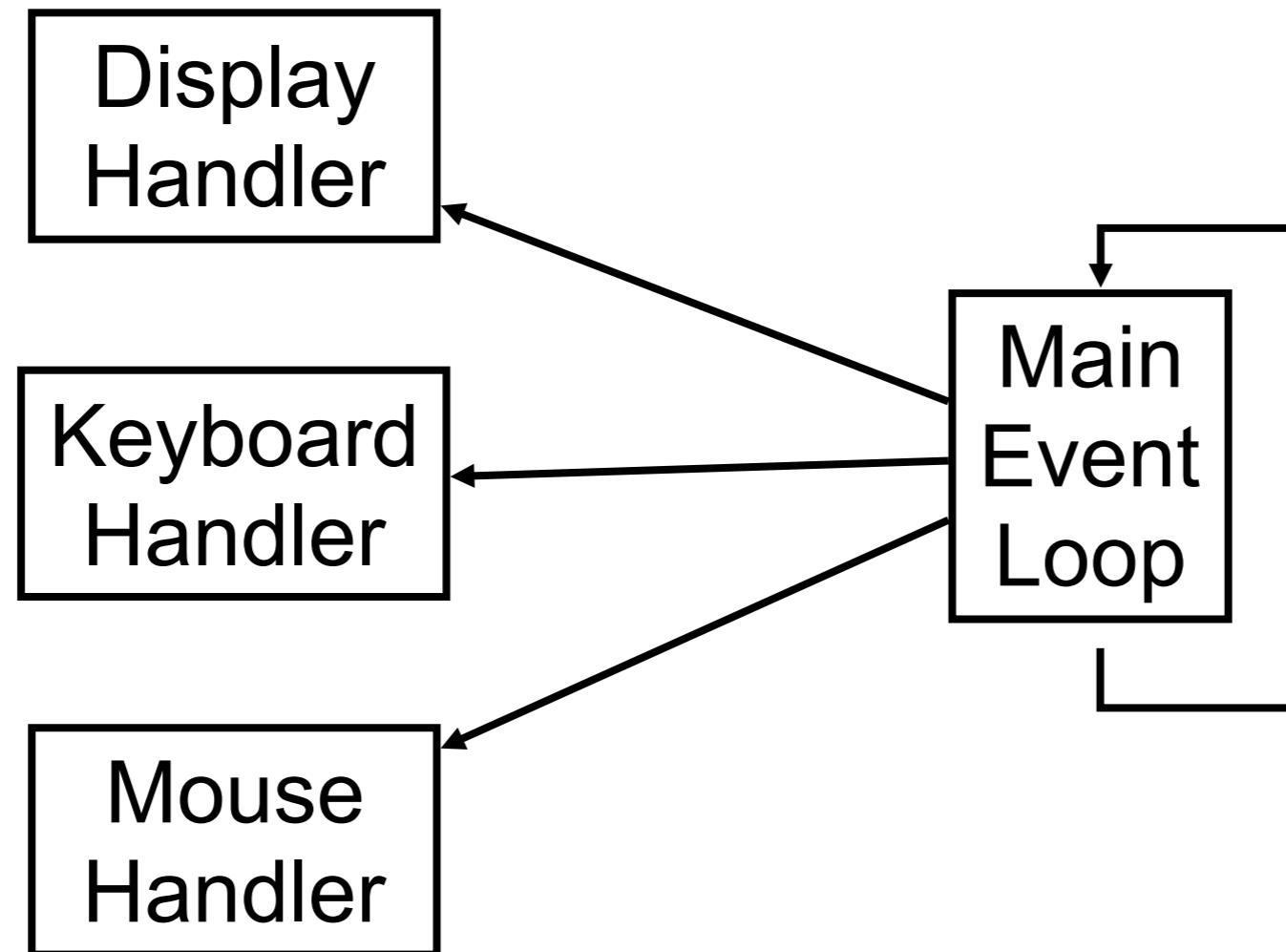
Compiling OpenGL Programs

- To use GLUT :
 - `#include <GL/glut.h>`
 - This takes care of every other include you need
 - Make sure that `glut.lib` (or `glut32.lib`) is in your compiler's library directory, and that the object module or DLL is also available
- See *OpenGL Game Programming* or online tutorials for details

Structure of GLUT-Assisted Programs

- GLUT relies on user-defined callback functions, which it calls whenever some event occurs
 - Function to display the screen
 - Function to resize the viewport
 - Functions to handle keyboard and mouse events

Event Driven Programming



Simple GLUT Example

Displaying a square

```
int main (int argc, char *argv[])
{
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_RGBA | LUT_DOUBLE);

    int windowHandle
        = glutCreateWindow("Simple GLUT App");

    glutDisplayFunc(redraw);
    glutMainLoop();

    return 0;
}
```

Display Callback

Called when window is redrawn

```
void redraw()
{
    glClear(GL_COLOR_BUFFER_BIT);

    glBegin(GL_QUADS);
    glColor3f(1, 0, 0);
        glVertex3f(-0.5, 0.5, 0.5);
        glVertex3f( 0.5, 0.5, 0.5);
        glVertex3f( 0.5, -0.5, 0.5);
        glVertex3f(-0.5, -0.5, 0.5);
    glEnd(); // GL_QUADS

    glutSwapBuffers();
}
```

More GLUT

Additional GLUT functions

glutPositionWindow(int x,int y);
glutReshapeWindow(int w, int h);

Additional callback functions

glutReshapeFunction(reshape);
glutMouseFunction(mousebutton);
glutMotionFunction(motion);
glutKeyboardFunction(keyboardCB);
glutSpecialFunction(special);
glutIdleFunction(animate);

Reshape Callback

Called when the window is resized

```
void reshape(int w, int h)
{
    glViewport(0.0,0.0,w,h);

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    glOrtho(0.0,w,0.0,h, -1.0, 1.0);

    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();
}
```

Mouse Callbacks

Called when the mouse button is pressed

```
void mousebutton(int button, int state, int x, int y)
{
    if (button==GLUT_LEFT_BUTTON && state==GLUT_DOWN)
    {
        rx = x; ry = winHeight - y;
    }
}
```

Called when the mouse is moved with button down

```
void motion(int x, int y)
{
    rx = x; ry = winHeight - y;
}
```

Keyboard Callbacks

Called when a button is pressed

```
void keyboardCB(unsigned char key, int x, int y)
{
    switch(key)
    { case 'a': cout<<"a Pressed"<<endl; break; }
}
```

Called when a special button is pressed

```
void special(int key, int x, int y)
{
    switch(key)
    { case GLUT_F1_KEY:
        cout<<"F1 Pressed"<<endl; break; }
}
```

OpenGL – GLUT Example

```
#include <gl/glut.h>
#include <stdlib.h>
static GLfloat spin = 0.0;
void init( void )
{
    glClearColor( 0.0, 0.0, 0.0, 0.0 );
    glShadeModel( GL_FLAT );
}

void display( void )
{
    glClear( GL_COLOR_BUFFER_BIT );
    glPushMatrix();
    glRotatef( spin, 0.0, 0.0, 1.0 );
    glColor3f( 1.0, 1.0, 1.0 );
    glRectf( -25.0, -25.0, 25.0, 25.0 );
    glPopMatrix();
    glutSwapBuffers();
}
```

OpenGL – GLUT Example

```
void spinDisplay( void )
{
    spin += 2.0;
    if( spin > 360.0 )
        spin -= 360.0;
    glutPostRedisplay();
}
```

```
void reshape( int w, int h )
{
    glViewport( 0, 0, (GLsizei) w, (GLsizei) h );
    glMatrixMode( GL_PROJECTION );
    glLoadIdentity();
    glOrtho( -50.0, 50.0, -50.0, 50.0, -1.0, 1.0 );
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
}
```

OpenGL – GLUT Example

```
void mouse( int button, int state, int x, int y )
```

```
{
```

```
    switch( button )
```

```
{
```

```
    case GLUT_LEFT_BUTTON:
```

```
        if( state == GLUT_DOWN )
```

```
            glutIdleFunc( spinDisplay );
```

```
        break;
```

```
    case GLUT_RIGHT_BUTTON:
```

```
        if( state == GLUT_DOWN )
```

```
            glutIdleFunc( NULL );
```

```
        break;
```

```
    default:    break;
```

```
}
```

```
}
```

OpenGL – GLUT Example

```
int main( int argc, char ** argv )
{
    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_DOUBLE | GLUT_RGB );
    glutInitWindowSize( 250, 250 );
    glutInitWindowPosition( 100, 100 );
    glutCreateWindow( argv[ 0 ] );

    init();
    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutMouseFunc( mouse );
    glutMainLoop();
    return 0;
}
```

Web Resources

Old OpenGL ...

<http://www.opengl.org>

<http://nehe.gamedev.net>

<http://www.xmission.com/~nate/glut.html>

New OpenGL Tutorial

[http://www.opengl-tutorial.org/beginners-tutorials/
tutorial-1-opening-a-window/](http://www.opengl-tutorial.org/beginners-tutorials/tutorial-1-opening-a-window/)