Computer Graphics
using openGL

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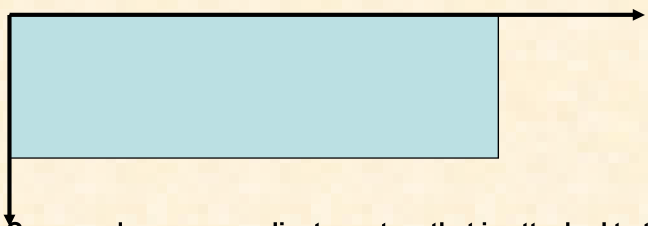
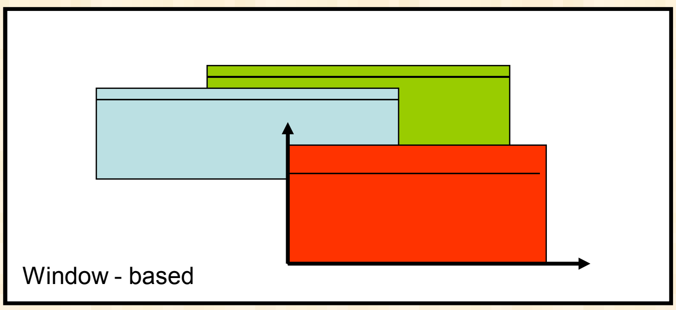
## Getting Started



**Graphics Commands use a coordinate system that is attached to the window**

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## What Is OpenGL?

- OpenGL is a software interface to graphics hardware. You can use to specify the objects and operations needed to produce interactive three-dimensional applications
- OpenGL is designed as a hardware-independent interface to be implemented on many different hardware platforms.



## OpenGL (1/3)

- The most popular raster graphics library, providing a powerful but primitive set of rendering commands
- Already supported by every window systems
- OpenGL Utility Library (GLU) : higher-level routines, part of OpenGL implementation
  - Setting up matrices for specific viewing orientations and projections
  - Performing polygon tessellation and rendering surfaces
- OpenGL Utility Toolkit (GLUT): window-system-independent high-level library. Need to install this library separately.

## OpenGL (2/3)

- Install OpenGL Utility Toolkit (GLUT) for MS Windows
  - Download GLUT from http://reality.sgi.com/opengl/glut3/glut3.html
  - Unzip the package
  - Set "include directory" and "lib directory" in the C Compiler to include the directory containing glut.h, glut.lib
  - Copy glut32.dll into directory DRIVE:\WINNT\SYSTEM
- Add #include <glut.h> to the beginning of the program

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## OpenGL (3/3)

- OpenGL Programming Guide:
  - http://www.cs.ucf.edu/dsg/dtran/teaching/cps560/openGL/install/theredbook.zip
- Nate Robins' OpenGL Tutors
  - http://www.cs.utah.edu/~narobins/opengl.html

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## GLUT

**GLUT stands for OpenGL Utility Toolkit.**

**In order to write a C++ application using GLUT you'll need three files:**

**1- glut.h - You'll have to include This is the file in your source code. The common place to put this file is in C:\Program Files\Microsoft Visual Studio\VC98\Include\GL folder.**

**2- glut.lib and glut32.lib**

**This file must be linked to your application so make sure to put it your *lib* folder.**

**3- glut32.dll and glut.dll - choose one according to the OpenGL you're using. If using Microsoft's version then you must choose glut32.dll. You should place the dll file in your system folder.**

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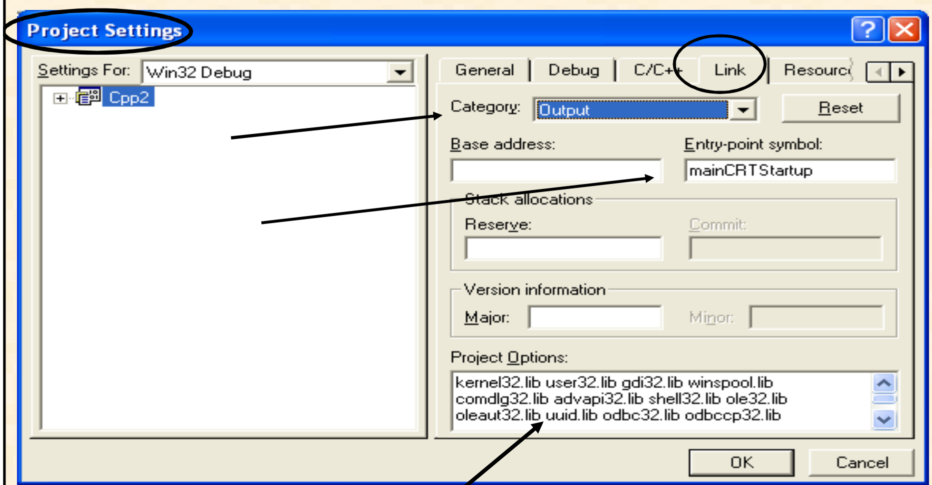
# SETUP




In the "Project options" textbox replace

**"subsystem:console"**

with

**"subsystem:windows"**

The following files to the *Object/library* modules: opengl32.lib glut32.lib glu32.lib

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## Programming with OpenGL
## Part 1: Background





## Objectives

- Development of the OpenGL API
- OpenGL Architecture
  - OpenGL as a state machine
- Functions
  - Types
  - Formats
- Simple program

## OpenGL

The success of OpenGL (1992), a platform-independent API that was

- Easy to use
- Close enough to the hardware to get excellent performance
- Focus on rendering
- Omitted windowing and input to avoid window system dependencies




## GLUT

- OpenGL Utility Toolkit (GLUT)
  - Provides functionality common to all window systems
    - Open a window
    - Get input from mouse and keyboard
    - Menus
    - Event-driven
  - Code is portable but GLUT lacks the functionality of a good toolkit for a specific platform
    - No slide bars

## OpenGL Functions

- Primitives
  - Points
  - Line Segments
  - Polygons
- Attributes
- Transformations
  - Viewing
  - Modeling
- Control (GLUT)
- Input (GLUT)
- Query




## OpenGL State

- OpenGL is a state machine
- OpenGL functions are of two types
  - Primitive generating
    - Can cause output if primitive is visible
    - How vertices are processed and appearance of primitive are controlled by the state
  - State changing
    - Transformation functions
    - Attribute functions

## Lack of Object Orientation

- OpenGL is not object oriented so that there are multiple functions for a given logical function
  - **`glVertex3f`**
  - **`glVertex2i`**
  - **`glVertex3dv`**
- Underlying storage mode is the same
- Easy to create overloaded functions in C++ but issue is efficiency




## OpenGL function format

function name

dimensions

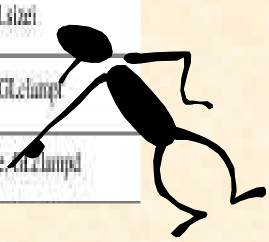
**glVertex3f(x,y,z)**

**x,y,z** are floats

belongs to GL library

## OpenGL Function Format

| | | | |
|---|---|---|---|
| s | 16-bit integer | short | GLshort |
| i | 32-bit integer | int or long | GLint, GLsizei |
| f | 32-bit floating point | float | GLfloat, GLclampf |
| d | 64-bit floating point | double | GLdouble, GLclampd |



Why does this matter?

1. On some operating systems the C/C++ same C/C++ datatypes have different sizes -> the OpenGL types are consistent.
2. 0 is not always 0 e.g. could be 0.0000000011111. Therefore to insure accuracy we should say:

GLfloat myFloat = 0.0f



## Graphics Library

- Primitives: lines, circles, ellipses, polygons, filling, clipping
- Attributes
  - – Color
  - – Line style
  - – Material properties for 3D
- Lights
- Transformations

## OpenGL

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- Already supported by every window systems
- OpenGL Utility Library (GLU) : higher-level routines, part of OpenGL implementation
  - Setting up matrices for specific viewing orientations and projections
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## OpenGL

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OpenGL

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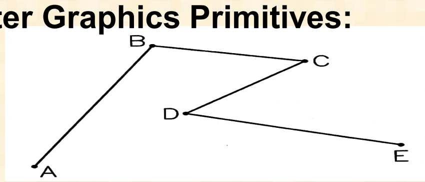
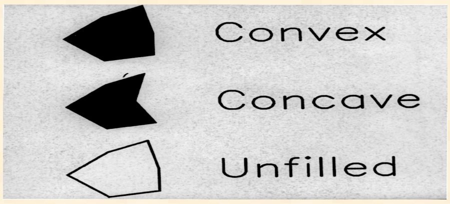
  - http://www.cs.utah.edu/~narobins/opengl.html

## Elements of Pictures in Computer Graphics

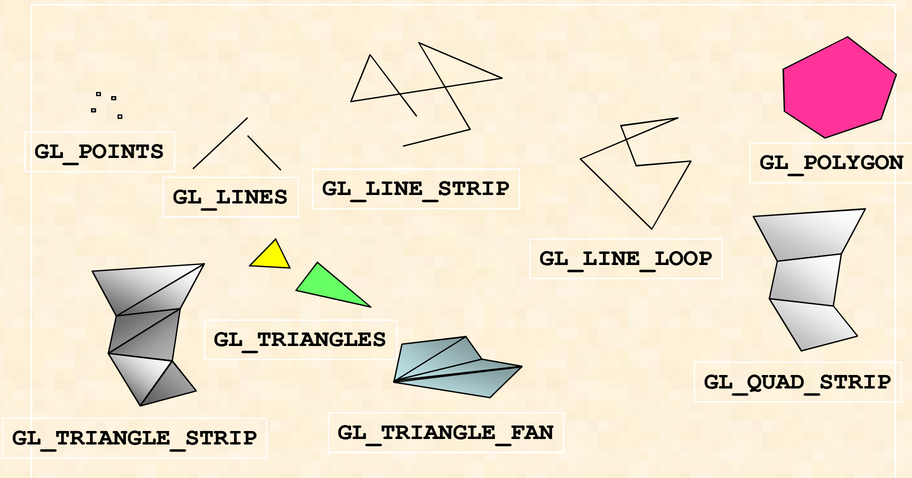
**It could be named Computer Graphics Primitives:**

- Dot
- Lines
- Polylines
- Polygons
- Text
- Filled regions
- Raster Images



## OpenGL Primitives

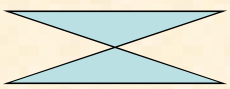




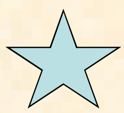


## Polygon Issues

- OpenGL will only display polygons correctly that are
  - Simple: edges cannot cross
  - Convex: All points on line segment between two points in a polygon are also in the polygon
  - Flat: all vertices are in the same plane
- User program can check if above true
  - OpenGL will produce output if these conditions are violated but it may not be what is desired
- Triangles satisfy all conditions



nonsimple polygon



nonconvex polygon

## Attributes

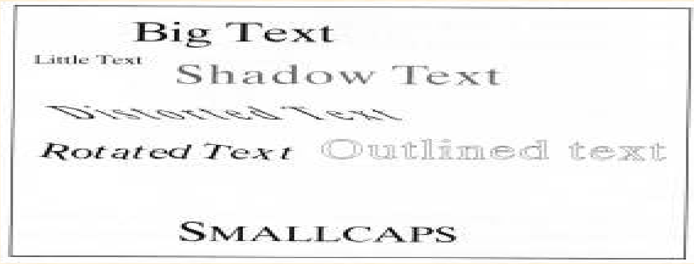
- Attributes are part of the OpenGL state and determine the appearance of objects
  - Color (points, lines, polygons)
  - Size and width (points, lines)
  - Stipple pattern (lines, polygons)
  - Polygon mode
    - Display as filled: solid color or stipple pattern
    - Display edges
    - Display vertices




**Polylines with different attributes**

The first two polylines in Figure 1.12 are distinguished by the line-thickness attribute. The third polyline is drawn using dashed segments. The attributes of a polyline are sometimes set by calling routines.
**setDash(dash7) or setLineThickness(thickness).**

- Some graphics devices have two distinct display modes: a **text mode** and a **graphics mode.**
- **The text mode** is used for the simple input and output of characters. Usually, these characters cannot be placed arbitrarily on the display, but rather, can be put only in some row and column of a built-in grid.
- **The graphics mode** offers a richer set of character shapes than the text mode does, and characters can be placed arbitrarily. Figure 1.14 shows some examples of text drawn graphically.




A routine to draw a character string might look like

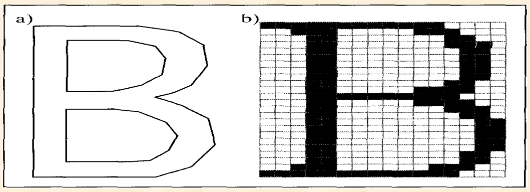
**drawString(x, y, string);**

This routine places the starting point of the string at position (x, y) and draws the sequence of characters stored in the variable string.

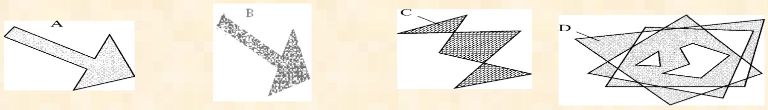
- **Text Attributes:**

**text's font - color – size - spacing - orientation.**

- **The shape of each character can be defined by a polyline (or more complicated curves as shown in Figure 1.16a, or by an arrangement of dots, as shown in Figure 1.16(b).**
- **Graphics packages come with a set of predefined fonts**



- **Filled-Regions**
- The **filled-region** (sometimes called "fill area") primitive is a shape filled with some color or pattern.
- The boundary of a filled region is often a polygon.
- Figure 1.17 shows several filled polygons.



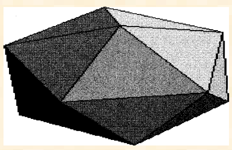

Polygon A is filled with its edges visible, whereas *B* is filled with its border left undrawn. Polygons C and *D* are non-simple. Polygon *D* even contains polygonal holes. Such shapes can still be filled.

To draw a filled polygon, one would use a routine like

**fillPolygon ( poly, pattern);**

where the variable **poly** holds the data for the polygon the same kind of list as for a polyline and the variable **pattern** contains some description of the pattern to be used for filling.

- **Figure 1.18 shows the use of filled regions to shade the different faces of a three dimensional object. Each polygonal face of the object is filled with a cer-tain shade of gray that corresponds to the amount of light that would reflect off that face. This combination of shading makes the object exposure to light from a certain direction.**



**The attributes of a filled region include the *attributes of the enclosing border* that encloses the region, as well as the *pattern* and *color* of the filling.**

## Colours

- Before you start drawing you will want to set the colour of the window (background) and the colour of the drawing (foreground).
- The background and foreground can be changed at anytime during the program.



## Colours

- Colours are specified using a mixture of Red, Green and Blue (RGB).
- Each amount of colour is specified by a float value between 0 and 1.
  - 0 = none of this colour
  - 1 = all of this colour
- A colour is specified as (R,G,B) e.g (1, 0.5, 0.2)
- Can you guess what R, G and B are set to for black and white?

## Colours

- White is:
  – (1,1,1)
- Black is:
  – (0,0,0);

- Did you think Black would be the addition of all the colours and hence, (1,1,1) ????



## Black is not Black

- Even in art (with paints and stuff) if you mix the primary colours together you will NOT get black!!!
- Mixing pixels of different colours of light is different from mixing paint pigments.
- Adding lights of colour together means adding the light EM waves together.

## Additive Colour Mixing

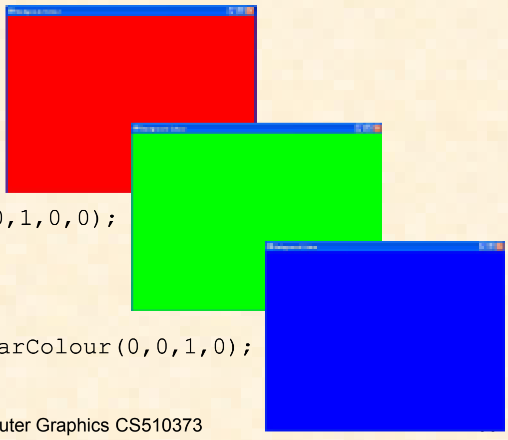
- Each primary colour provides about 1/3 of the wavelengths in the total spectrum.



## Setting the Background Colour

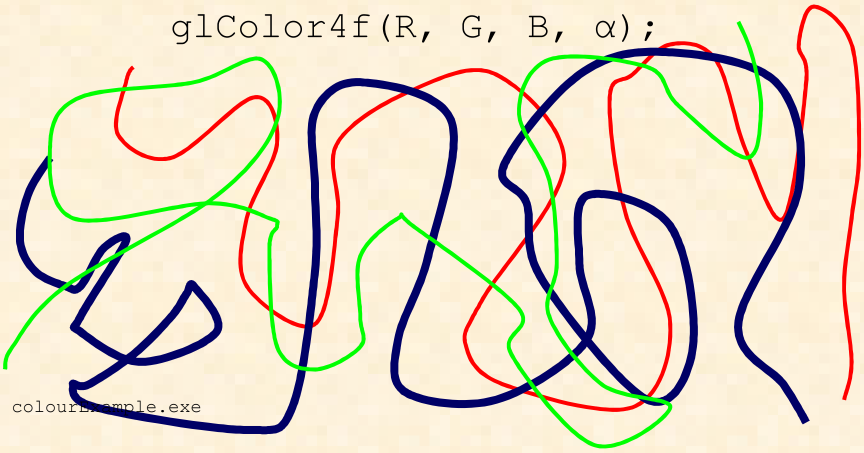
```
glClearColour(R, G, B, α);
```

```
glClearColour(1,0,0,0);
glClearColour(0,1,0,0);
glClearColour(0,0,1,0);
```



## Setting the Foreground Colour

```
glColor3f(R, G, B);
glColor4f(R, G, B, α);
```



- colourExample.exe



## OpenGL #defines

- Most constants are defined in the include files **`gl.h`**, **`glu.h`** and **`glut.h`**
  - **Note**
  - **`#include <GL/glut.h>`** should automatically include the others
  - Examples
  - **`glBegin(GL_POLYGON)`**
  - **`glClear(GL_COLOR_BUFFER_BIT)`**
- include files also define OpenGL data types: **`GLfloat`**, **`GLdouble`**,….

## Compilation on Windows

- Visual C++
  - Get glut.h, glut32.lib and glut32.dll from web
  - Create a console application
  - Add opengl32.lib, glut32.lib, glut32.lib to project settings (under link tab)
- Borland C similar
- Cygwin (linux under Windows)
  - Can use gcc and similar makefile to linux
  - Use –lopengl32 –lglu32 –lglut32 flags




# 1- Initialization

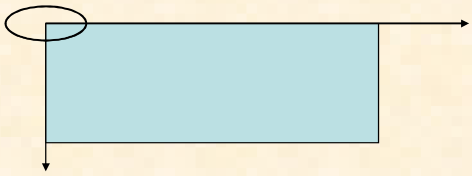
- All the functions in GLUT have the prefix *glut*, and those which perform some kind of initialization have the prefix *glutInit*.
- The first thing you must do is call the function *glutInit*.

```
void glutInit(int *argc, char **argv);
```

Parameters: argc argv are the standard ones for passing information about the command line ( not used here)

## Define our window

- After initializing GLUT itself, we're going to define our window.



- First we establish the window's position, i.e. its top left corner.

In order to do this we use the function *glutInitWindowPosition*.

void glutInitWindowPosition(int x, int y);

glutInitWindowPosition( 100, 150);

Parameters:
- *x* - the number of pixels from the left of the screen.
- *y* - the number of pixels from the top of the screen.



## Window size

- Next we'll choose the window size. In order to do this we use the function *glutInitWindowSize*.

void glutInitWindowSize(int width, int height);
glutInitWindowSize(640, 480);

Parameters:
- *width* - The width of the window
- *height* - the height of the window
- The values for *width* and *height* are only a suggestion, so avoid choosing negative values.
- When the program is running the user can resize the window

# Display mode

- **Then you should define the display mode using the function**

  ***glutInitDisplayMode***

**void glutInitDisplayMode(unsigned int mode)**

**Parameters:**

- ***mode*** **- specifies the display mode**

**You use *mode* to specify the color mode, and the number and type of buffers.**

**Examples:**

- **GLUT_RGBA or GLUT_RGB - selects a RGBA window. This is the default color mode.**
- **GLUT_INDEX - selects a color index mode.**



# glutInitDisplayMode

- glutInitDisplayMode(unsigned int mode) specifies whether to use an RGBA or color-index color model. You can also specify whether you want a single- or double-buffered window. (If you're working in color-index mode, you'll want to load certain colors into the color map; use glutSetColor() to do this.) Finally, you can use this routine to indicate that you want the window to have an associated depth, stencil, and/or accumulation buffer.
- For example, if you want a window with double buffering, the RGBA color model, and a depth buffer, you might call glutInitDisplayMode(GLUT_DOUBLE |GLUT_RGB | GLUT_DEPTH).

- After all the above steps, the window can be created with *glutCreateWindow*
- *int glutCreateWindow(char *title);*

  *Parameters:*
- *title - sets the window title*

  glutCreateWindow(“my first attempt");

```
#include <windows.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>
void main (int argc, char ** argv)
{
glutInit(&argc, argv);  // initialize the toolkit

                              // set the display mode
glutInitDisplayMode(GLUT_SINGLE| GLUT_RGB);

                              // set window size
glutInitWindowSize(640,480);

                              // open the screen window
glutInitWindowPosition(100,150);

glutCreateWindow("my firstattempt");
}
```

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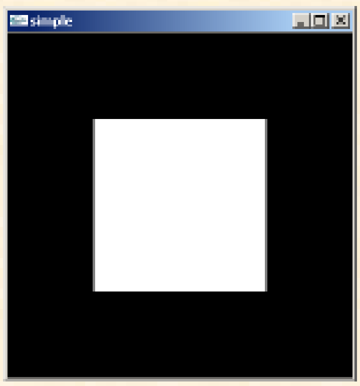
## A Simple Program

Generate a square on a solid background

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## simple.c

```
#include <GL/glut.h>
void mydisplay(){
    glClear(GL_COLOR_BUFFER_BIT);
        glBegin(GL_POLYGON);
                glVertex2f(-0.5, -0.5);
                glVertex2f(-0.5, 0.5);
                glVertex2f(0.5, 0.5);
                glVertex2f(0.5, -0.5);
        glEnd();
        glFlush();
}
int main(int argc, char** argv){
        glutCreateWindow("simple");
        glutDisplayFunc(mydisplay);
        glutMainLoop();
}
```

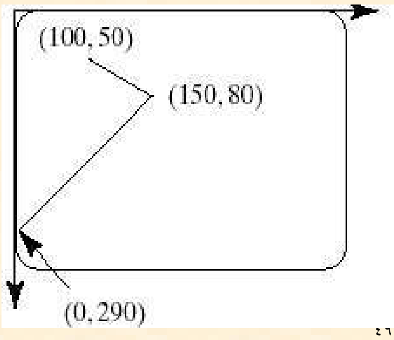



## Event Loop

- Note that the program defines a *display callback* function named **`mydisplay`**
  – Every glut program must have a display callback
  – <u>The display callback is executed whenever OpenGL decides the display must be refreshed</u>, for example when the window is opened
  – The **`main`** function ends with the program entering an event loop

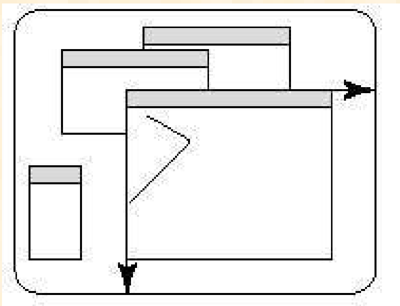
## Making Pictures

- Step One: Initialisation
  - Setting up the graphics display.
    1. Entire Screen is used (computer games, slide shows)



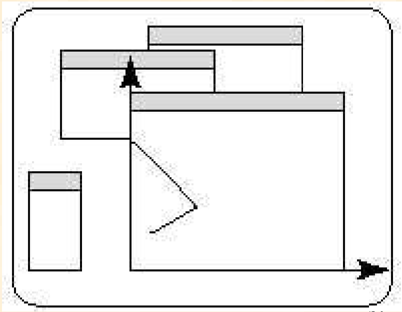

## Making Pictures

- Step One: Initialisation
  - Setting up the graphics display.
    2. Window-based (upside down coordinates) (when multiple windows are useful, paint packages, word processing, graphing)



## Making Pictures

- Step One: Initialisation
  - Setting up the graphics display.
    3. Window-based (right side up coordinates) (an alternative more natural representation)





## Making Pictures

void **gluOrtho2D**( GLdouble *left*,
GLdouble *right*,
GLdouble *bottom*,
GLdouble *top*)

OpenGL – Inverted Windows

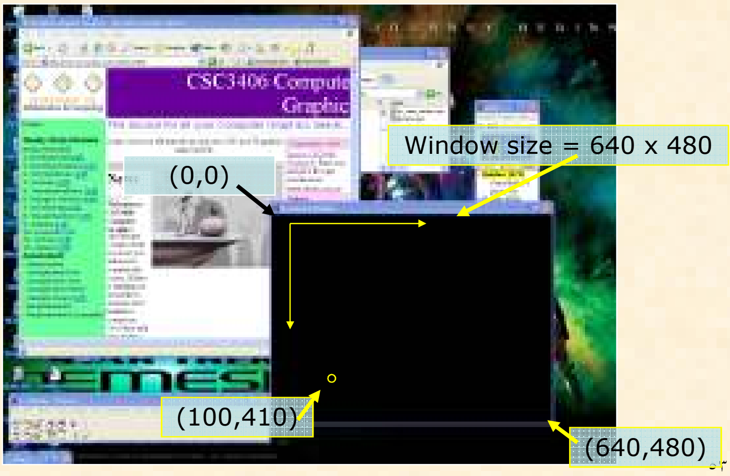
```
glutInitWindowSize(640,480);
glutInitWindowPosition(100, 150);
glutCreateWindow("An OpenGL Window");


gluOrtho2D(0.0, 640.0, 480.0, 0.0);
```

*void **gluOrtho2D**(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top);*
*Creates a matrix for projecting two-dimensional coordinates onto the screen and multiplies the current projection matrix by it. The clipping region is a rectangle with the lower-left corner at **(left, bottom)** and the upper-right corner at **(right, top).***

## Making Pictures

### OpenGL – Inverted Windows

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## Making Pictures

### OpenGL – “Right-side Up” Windows

```
glutInitWindowSize(640,480);
glutInitWindowPosition(100, 150);
glutCreateWindow(“An OpenGL Window");


gluOrtho2D(0.0, 640.0, 0.0, 480.0);
```

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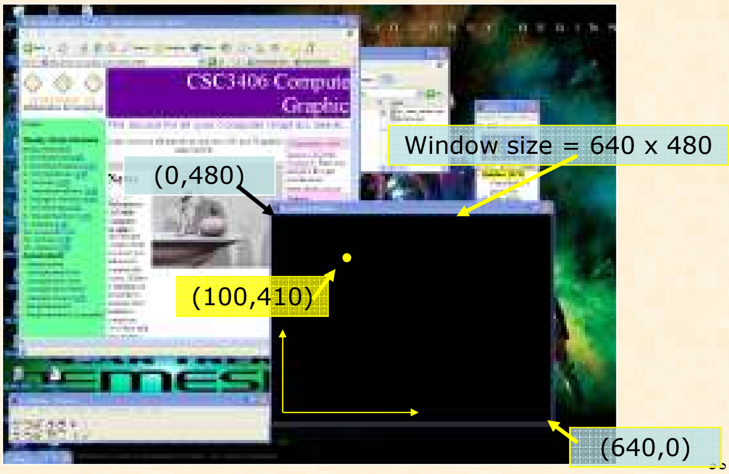
Making Pictures

OpenGL – “Right-side Up” Windows

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## Skeleton program

```
#include <windows.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>
void myInit(void)
{
    glClearColor(1.0,1.0,1.0,0.0);  // set white background color
    glColor3f(0.0f, 0.0f, 0.0f);  // set  drawing color
    glPointSize(8.0);// the dot is 8 by 8 pixels

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluOrtho2D(0,640,480,0);
}
void myDisplay(void)  // The name is option
{
    /* code written here*I
}
```

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```
void main (int argc, char ** argv)
{
glutInit(&argc, argv);  // initialize the toolkit
                        // set the display mode
glutInitDisplayMode(GLUT_SINGLE| GLUT_RGB);
                        // set window size
glutInitWindowSize(640,480);
                        // open the screen window
glutInitWindowPosition(100,150);

glutCreateWindow("my firstattempt");
myInit();          // additional initializations as necessary
                   // register callback functions
glutDisplayFunc(myDisplay);
glutMainLoop();
}
```

GLUT provides a function that gets the application in a never ending loop, always waiting for the next event to process. The GLUT function is *glutMainLoop*,



If you run this code, you'll obtain an empty black console window. Furthermore after a few seconds the window disappears.

**Example 1:**

The function presented bellow will clear the color buffer and draw 3 points.

```
void myDisplay(void)  // The name of this       //function is up to you
{
    glClear(GL_COLOR_BUFFER_BIT);

    glBegin(GL_POINTS);
            glVertex2i(100,50);
            glVertex2i(100,130);
            glVertex2i(150,130);
    glEnd();

    glFlush();         // send all output to display
}
```

The openGL function that will call our implemented myDisplay function is

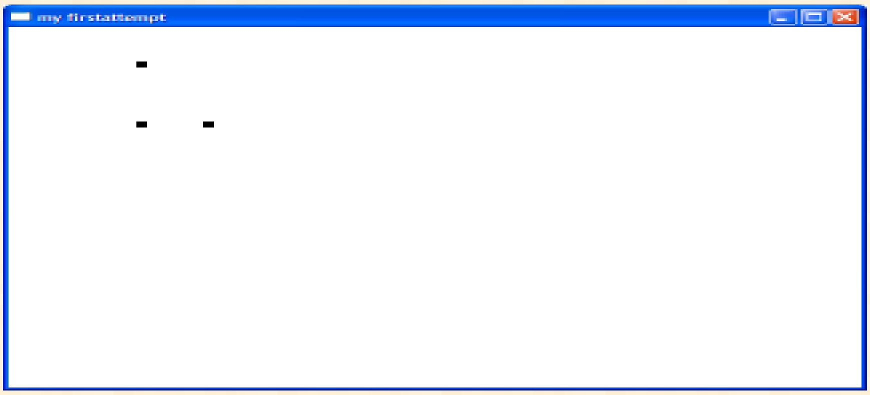
void glutDisplayFunc(void (*func)(void));

Parameters:

*func* - the name of the function to be called when the window needs to be redrawn.

In our example myDisplay

glutDisplayFunc(myDisplay);






## simple.c revisited

- In this version, we shall see the same output but we have defined all the relevant state values through function calls using the default values
- In particular, we set
  - Colors
  - Viewing conditions
  - Window properties

## main.c

```c
#include <GL/glut.h>

int main(int argc, char** argv)
{
   glutInit(&argc,argv);
   glutInitDisplayMode(GLUT_SINGLE|GLUT_RGB);
   glutInitWindowSize(500,500);
   glutInitWindowPosition(0,0);
   glutCreateWindow("simple");
   glutDisplayFunc(mydisplay);

   init();

   glutMainLoop();
}
```

includes gl.h

define window properties

display callback

set OpenGL state

enter event loop



## GLUT functions

- **`glutInit`** allows application to get command line arguments and initializes system
- **`gluInitDisplayMode`** requests properties for the window (the *rendering context*)
  - RGB color
  - Single buffering
  - Properties logically ORed together
- **`glutWindowSize`** in pixels
- **`glutWindowPosition`** from top-left corner of display
- **`glutCreateWindow`** create window with title “simple”
- **`glutDisplayFunc`** display callback
- **`glutMainLoop`** enter infinite event loop

# init.c

```
void init()
{
   glClearColor (0.0, 0.0, 0.0, 1.0);

   glColor3f(1.0, 1.0, 1.0);

   glMatrixMode (GL_PROJECTION);
   glLoadIdentity ();
   glOrtho(-1.0, 1.0, -1.0, 1.0, -1.0, 1.0);
}
```

**black clear color**

**opaque window**

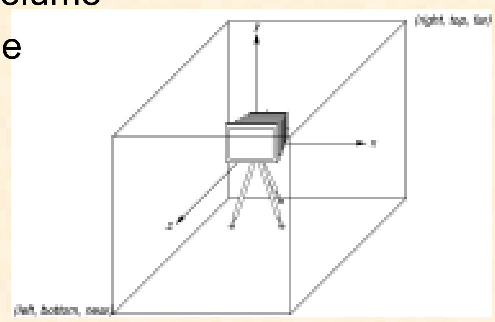
**fill/draw with white**

**viewing volume**



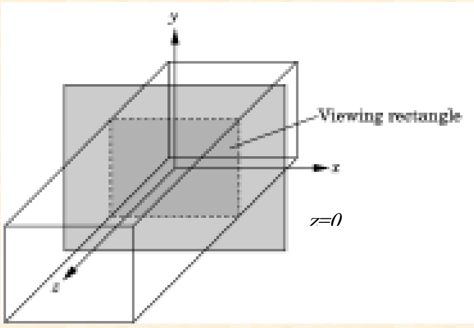
# OpenGL Camera

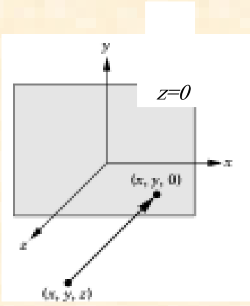
- OpenGL places a camera at the origin in object space pointing in the negative $z$ direction
- The default viewing volume is a box centered at the origin with a side of length 2



## Orthographic Viewing

In the default orthographic view, points are projected forward along the *z* axis onto the plane *z=0*








## Transformations and Viewing

- In OpenGL, projection is carried out by a projection matrix (transformation)
- There is only one set of transformation functions so we must set the matrix mode first

```
glMatrixMode (GL_PROJECTION)
```

- Transformation functions are incremental so we start with an identity matrix and alter it with a projection matrix that gives the view volume

```
glLoadIdentity();
 glOrtho(-1.0, 1.0, -1.0, 1.0, -1.0, 1.0);
```

## Two- and three-dimensional viewing

- In `glOrtho(left, right, bottom, top, near, far)` the near and far distances are measured from the camera
- Two-dimensional vertex commands place all vertices in the plane z=0
- If the application is in two dimensions, we can use the function

  `gluOrtho2D(left, right,bottom,top)`
- In two dimensions, the view or clipping volume becomes a *clipping window*




## mydisplay.c

```
void mydisplay()
{
  glClear(GL_COLOR_BUFFER_BIT);
  glBegin(GL_POLYGON);
     glVertex2f(-0.5, -0.5);
     glVertex2f(-0.5, 0.5);
     glVertex2f(0.5, 0.5);
     glVertex2f(0.5, -0.5);
  glEnd();
  glFlush();
}
```

**Example 2:**

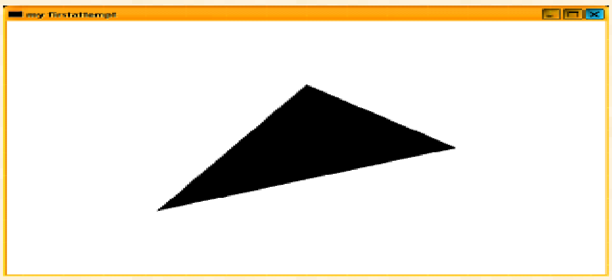
The function presented bellow will clear the color buffer and draw a triangle.

```
void renderScene(void) {
   glClear(GL_COLOR_BUFFER_BIT);
   glBegin(GL_TRIANGLES);
        glVertex3f(-0.5,-0.5,0.0);
        glVertex3f(0.5,0.0,0.0);
        glVertex3f(0.0,0.5,0.0);
   glEnd();
   glFlush();
}
```

Do not forget to add the following line to your code

`glutDisplayFunc(renderScene);`





The constant GL_POINTS is built-into OpenGL. to draw other primitives, you replace GL_POINTS with GL_LINES, GL_POLYGON, etc.

glColor3f()

glVertex2i(…)

**Table 1-1 :** Command Suffixes and Argument Data Types

| Suffix | Data Type | Typical Corresponding C-Language Type | OpenGL Type Definition |
|---|---|---|---|
| b | 8-bit integer | signed char | GLbyte |
| s | 16-bit integer | short | GLshort |
| i | 32-bit integer | long | GLint, GLsizei |
| f | 32-bit floating-point | float | GLfloat, GLclampf |
| d | 64-bit floating-point | double | GLdouble, GLclampd |
| ub | 8-bit unsigned integer | unsigned char | GLubyte, GLboolean |
| us | 16-bit unsigned integer | unsigned short | GLushort |
| ui | 32-bit unsigned integer | unsigned long | GLuint, GLenum, GLbitfield |

```
Void drawDot(GLint x , GLint y)
{// draw dot at integer point (x, y)
    glBegin(GL_POINTS);
        glVertex2i(x, y);
    glEnd();
}
```

**is better than the function written as**

```
Void drawDot(int x , int y) //Danger writting
{// draw dot at integer point (x, y)
    glBegin(GL_POINTS);
        glVertex2i(x, y);
    glEnd();
}
```

```
glPointSize(3.0) ;  // the size of drawing point is 3 x 3 pixels

glColor3f(1.0, 0.0, 0.0);   // drawing is red
glColor3f(0.0, 1.0, 0.0);   // drawing is green
glColor3f(0.0, 0.0, 1.0);   // drawing is blue
glColor3f(0.0, 0.0, 0.0);   // drawing is black
glColor3f(1.0, 1.0, 1.0);   // drawing is white
```

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Example 3

```
#include <windows.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>

class GLintPoint{
public:
    GLint x, y;
};

int random (int m)
{
    return rand()%m;
}
void myInit(void)
{
    glClearColor(1.0,1.0,1.0,0.0);  // set white background color
    glColor3f(0.0f, 0.0f, 0.0f);  // set  drawing color
    glPointSize(8.0);             // the dot is 8 by 8 pixels

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluOrtho2D(0,640,0,480);
```

X

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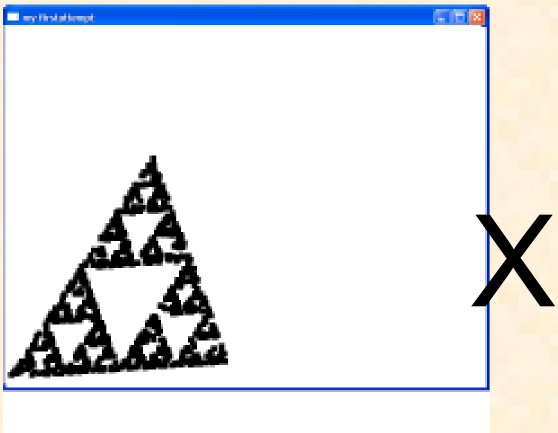
```
void drawDot(GLint x , GLint y)
{// draw dot at integer point (x, y)
     glBegin(GL_POINTS);
             glVertex2i(x, y);
     glEnd();
}

void Sierpinski(void)  // The name of this function is upto you
{
     GLintPoint T[3] = {{10,10} , {300,30} , {200, 300}}; //  array of points
     int index = random(3);  // 0, 1, 2 equally likely
     glClear(GL_COLOR_BUFFER_BIT);

     GLintPoint  point = T[index] ; // initial point (10,10) or (300,30) or (200, 300)
     drawDot(point.x, point.y);  // draw initial point

     for(int i=0; i< 1000; i++) // raw 1000 dots
     {
             index = random(3);
             point.x=(point.x +T[index].x) / 2;
             point.y=(point.y +T[index].y) / 2;
              drawDot(point.x, point.y);
                          }

     glFlush();        // send all output to display
}
```



```
void main (int argc, char ** argv)
{
     glutInit(&argc, argv);  // initialize the toolkit
                                 // set the display mode
     glutInitDisplayMode(GLUT_SINGLE| GLUT_RGB);
     glutInitWindowSize(640,480);  // set window size
     glutInitWindowPosition(100,150);  // open the screen window
     glutCreateWindow("Drawings Sierpinski");
          // register callback functions
     glutDisplayFunc(Sierpinski);
     myInit();       // additional initializtons as necessary
     glutMainLoop();
}
```

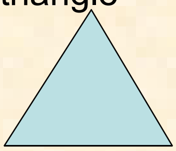




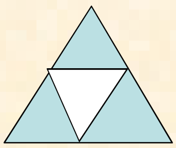

**Example 3**

## Sierpinski Gasket (2D)

- Start with a triangle



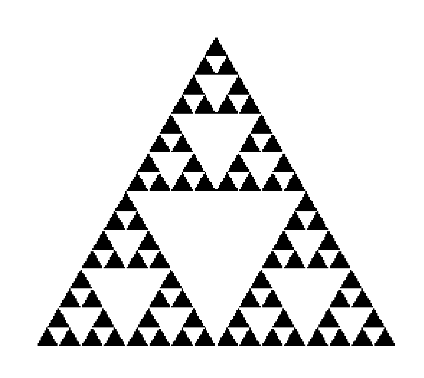
- Connect bisectors of sides and remove central triangle



- Repeat

# Example

- Five subdivisions





## The gasket as a fractal

- Consider the filled area (black) and the perimeter (the length of all the lines around the filled triangles)
- As we continue subdividing
  – the area goes to zero
  – but the perimeter goes to infinity
- This is not an ordinary geometric object
  – It is neither two- nor three-dimensional
- It is a *fractal* (fractional dimension) object

## Gasket Program

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

/* initial triangle */

GLfloat v[3][2]={{-1.0, -0.58},
           {1.0, -0.58}, {0.0, 1.15}};

int n; /* number of recursive steps */
```



## Draw one triangle

```
void triangle( GLfloat *a, GLfloat *b,
  GLfloat *c)

/* display one triangle  */
{
      glVertex2fv(a);
      glVertex2fv(b);
      glVertex2fv(c);
}
```

## Triangle Subdivision

```
void divide_triangle(GLfloat *a, GLfloat *b, GLfloat *c,
   int m)
{
/* triangle subdivision using vertex numbers */
    point2 v0, v1, v2;
    int j;
    if(m>0)
     {
        for(j=0; j<2; j++) v0[j]=(a[j]+b[j])/2;
        for(j=0; j<2; j++) v1[j]=(a[j]+c[j])/2;
        for(j=0; j<2; j++) v2[j]=(b[j]+c[j])/2;
        divide_triangle(a, v0, v1, m-1);
        divide_triangle(c, v1, v2, m-1);
        divide_triangle(b, v2, v0, m-1);
    }
    else(triangle(a,b,c));
 /* draw triangle at end of recursion */
}
```



## display and init Functions

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

    glBegin(GL_TRIANGLES);
       divide_triangle(v[0], v[1], v[2], n);
    glEnd();

    glFlush();
}

void myinit()
{
    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluOrtho2D(-2.0, 2.0, -2.0, 2.0);
    glMatrixMode(GL_MODELVIEW);
    glClearColor (1.0, 1.0, 1.0,1.0)
    glColor3f(0.0,0.0,0.0);
}
```

## main Function

```
int main(int argc, char **argv)
{
   n=4;
   glutInit(&argc, argv);
   glutInitDisplayMode(GLUT_SINGLE|GLUT_RGB);
   glutInitWindowSize(500, 500);
   glutCreateWindow("2D Gasket");
   glutDisplayFunc(display);
    myinit();
   glutMainLoop();
}
```

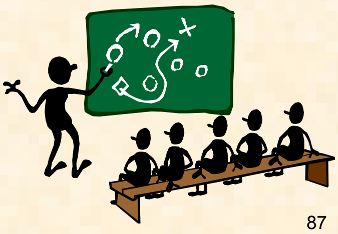


## Efficiency Note

By having the **glBegin** and **glEnd** in the display callback rather than in the function **triangle** and using **GL_TRIANGLES** rather than **GL_POLYGON** in **glBegin**, we call **glBegin** and **glEnd** only once for the entire gasket rather than once for each triangle

# Fitting it in

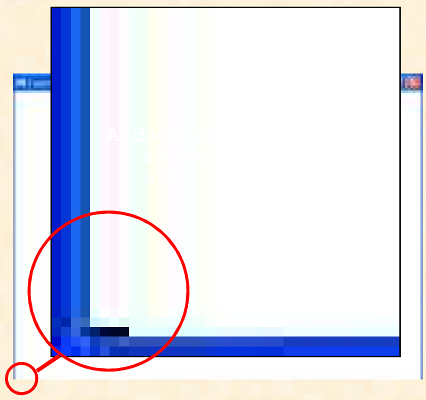
- Sometimes you may want to print out a plot of some data when the data ranges are unknown.
- However, you want them to appear in the window presented in a visually pleasing manner.





Fitting it in

- E.g. Let's plot $e^{-x}\cos(2\pi x)$
- Plotted with screen coordinates of 640 x 480 we will get:



## Fitting it in

How do we MAGNIFY the data?

**Stretch out X**

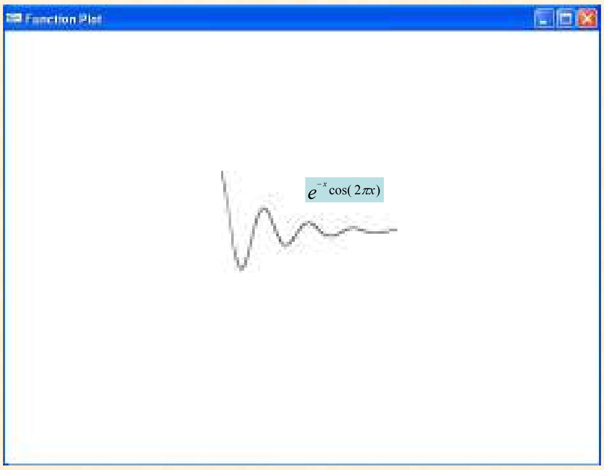
**Stretch out Y**



## Fitting it in

- The X coordinates of the window range over 640 values (from 0 to 639).
- The X values for the data range from 0 to 4.
- We need to modify the data values so that data point 0 maps to window coordinate 0 and data point 4 maps to window coordinate 640.

## Fitting it in






## Fitting it in

- In essence we want 4 to be plotted at 640.
- 4 * A = 640;
- A = 160; ….. or for all cases
  - A = SCREENWIDTH/$x_{max}$
- Therefore, x’ = x * A
  - …. if x ranges from 0 .. $x_{max}$

## Fitting it in

- If x ranges from say 1 to 4 then we will want to stretch a range of 3 out instead of 4, therefore:
  - ➢A = SCREENWIDTH/($x_{max} - x_{min}$)
- The same applies for the y coordinates:
  - ➢B = **`SCREENHEIGHT`** /($y_{max}$-$y_{min}$)

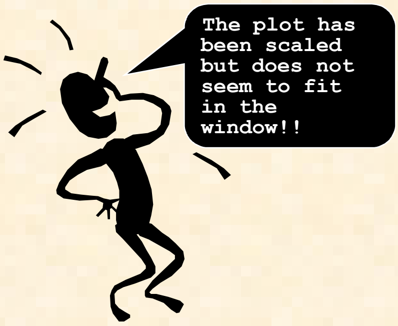


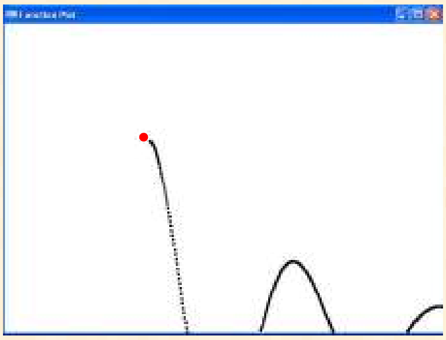
## Fitting it in

- But what is $y_{min}$ and $y_{max}$ ??
- We know x because it is the range we set… but <u>y is not known unless you calculate y for each x and record the minimum and maximum values</u>.

## Moving it around

- After scaling the plot would now look like this:





## Moving it around

- Or…

```
glVertex2d(
(x - xmin) * SCREENWIDTH/(xmax-xmin),
(pow(2.7183, -x)*cos(2*3.14*x))* SCREENHEIGHT/(ymax-
ymin) + fabs(ymin));
```

- Or in the format (as per the textbook on page 51)

$$x' = Ax + C \text{ and } y' = By + D$$

fabs(x) : Calculates the absolute value of the floating-point argument.

## Moving it around

$$x' = Ax + B \text{ and } y' = Cy + D$$

```
A = SCREENWIDTH/(xmax-xmin)
B = -xmin*A
C = SCREENHEIGHT/(ymax-ymin)
D = |ymin|*C
```

**A and C are *scalars***

**B and D are *translators***

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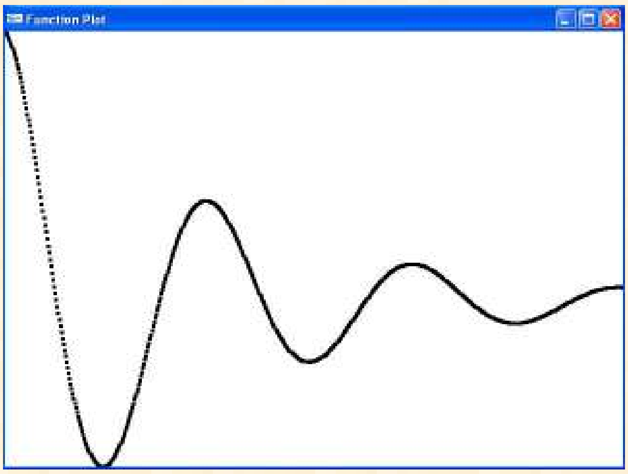
## Moving it around

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## A dot plot of function

### Example 4

```
#include <windows.h>
#include <math.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>
const int screenWidth = 640;
const int screenHeight = 480;
GLdouble A,B,C,D;

void myInit(void)
{
    glClearColor(1.0,1.0,1.0,0.0);  // set white background color
    glColor3f(0.0f, 0.0f, 0.0f);  // set  drawing color
    glPointSize(4.0);                          // the dot is 4 by 4 pixels

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluOrtho2D(0.0,(GLdouble) screenWidth,0.0, (GLdouble) screenHeight);

    A = screenWidth / 4.0 ;
    B = 0.0;
    C = D = screenHeight /2.0;
}
```

```
A = screenWidth / 4.0 ;     // x    0 …4
B = 0.0;  // shift = 0
C = D = screenHeight /2.0;
//  C  →  y   1… -1
//  D  →  shift = screenHeight /2.0
```

```
void dotplotfunction(void)   // The name of this function is upto you
{
    glClear(GL_COLOR_BUFFER_BIT);

    glBegin(GL_POINTS);

    for (GLdouble x = 0; x< 4.0; x+=0.005)
    {
        GLdouble func = exp(-x) * cos(2*3.14159265 * x);

        glVertex2d(A * x + B , C * func + D);
    }
    glEnd();
    glFlush();
}
```

d double

```
A = screenWidth / 4.0 ;     // x    0 …4
B = 0.0;  // shift = 0
C = D = screenHeight /2.0;
//  C  →  y   1… -1
//  D  →  shift = screenHeight /2.0
```

```
void main (int argc, char ** argv)
{
                                    // initialize the toolkit
    glutInit(&argc, argv);

                                   // set the display mode
    glutInitDisplayMode(GLUT_SINGLE| GLUT_RGB);

                                      // set window size
    glutInitWindowSize(640,480);
                                   // set window position
    glutInitWindowPosition(100,150);

                                // open the screen window
    glutCreateWindow("Dot plot of function");

          // register callback functions
          glutDisplayFunc(dotplotfunction);

          myInit();  // additional initializtons as necessary
          glutMainLoop();
}
```

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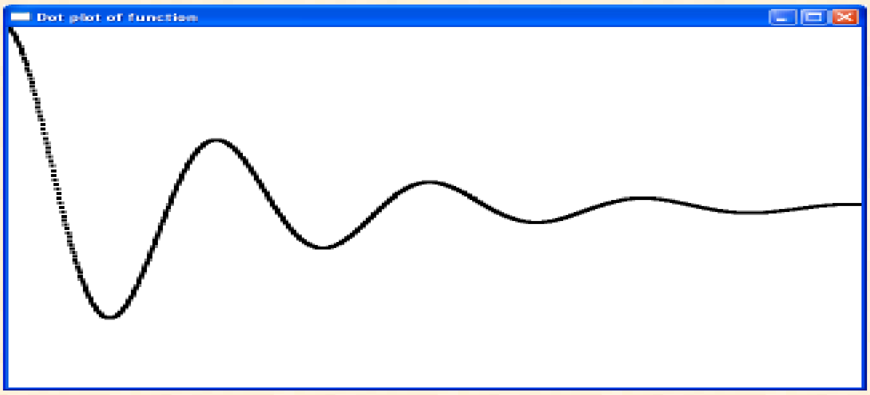


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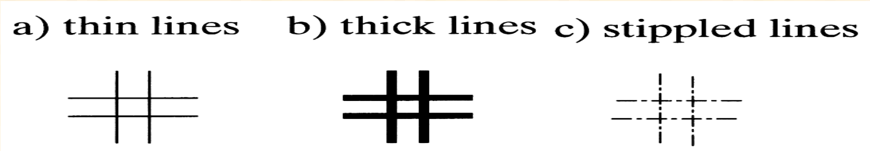
## Making Line Drawings

- **Use GL_LINES as the argument to glBegin(), and pass it the two end points as vertices.**

```
void  drawLineInt ( GLint x1, GLint y1, Glint x2, Glint y2)
{
glBegin(GL_LINES);
    glVertex2i(x1, y1);
    glVertex2i(x2, y2);
glEnd();
```

**Example 5**




**Simple picture  built from four lines.**

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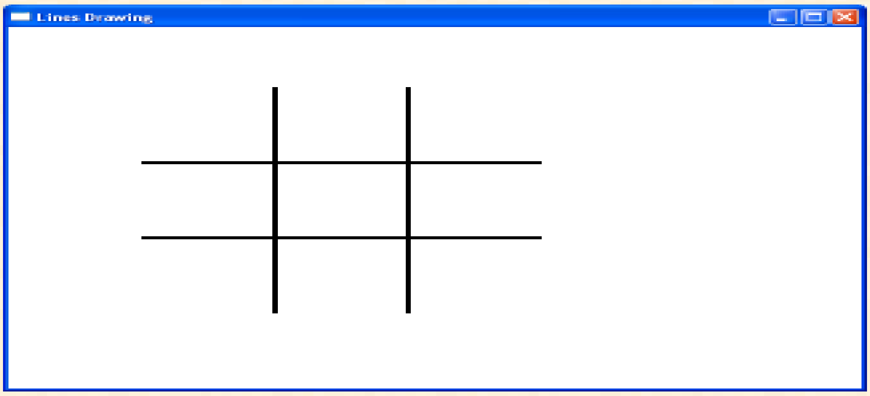
If more than two vertices are specified between glBegin(GL_LINES) and glEnd (), they are taken in pairs, and a separate line is drawn between each pair.

would be drawn using the following commands:

```
glBegin(GL_LINES) ;
    glVertex2i(10, 20) ; // first horizontal line
    glVertex2i(40, 20) ;
    glVertex2i(20, 10) ; // first vertical line
    glVertex2i(20, 40) ;
// calls to to glVertex2i() here for the other two lines
glEnd() ;
glFlush() ;
```

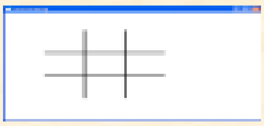
- A line's color is set in the same way as that for points, using **glColor3f().**
- Thick of lines are set by **glLineWidth (4.0)**. The default thickness is 1.0. ١٠٤






```
#include <windows.h>
#include <math.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>
const int screenWidth = 640;
const int screenHeight = 480;
GLdouble A,B,C,D;

void myInit(void)
{
                                        // set white background color
     glClearColor(1.0,1.0,1.0,0.0);
                                              // set  drawing color
     glColor3f(0.0f, 0.0f, 0.0f);
                                          // the line width is  4 pixels
     glLineWidth(4.0);
     glMatrixMode(GL_PROJECTION);
     glLoadIdentity();
     gluOrtho2D(0.0,(GLdouble) screenWidth, 0.0, (GLdouble) screenHeight);
}
```



```
void myDisplay(void)  // The name of this function is up
    to you
{
    glClear(GL_COLOR_BUFFER_BIT);

    glBegin(GL_LINES) ;
    glVertex2i(100, 200) ; // first horizontal line
    glVertex2i(400, 200) ;
    glVertex2i(200, 100) ; // first vertical line
    glVertex2i(200, 400) ;
    glVertex2i(100, 300) ; // Second  horizontal line
    glVertex2i(400, 300) ;
    glVertex2i(300, 100) ; // Second  vertical line
    glVertex2i(300, 400) ;
glEnd() ;
glFlush() ; // send all output to display
}
```

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```
void main (int argc, char ** argv)
{
    glutInit(&argc, argv);  // initialize the toolkit
                            // set the display mode
    glutInitDisplayMode(GLUT_SINGLE| GLUT_RGB);
    glutInitWindowSize(640,480);  // set window size
                            // open the screen window
    glutInitWindowPosition(100,150);
    glutCreateWindow("Lines Plot");
        // register callback functions
    glutDisplayFunc(myDisplay);

    myInit();     // additional initializtons as necessary
    glutMainLoop();
}
```

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## Drawing Polylines and Polygons

Polyline is a collection of line segments joined end to end. It is described by an ordered list of points, as in the equation

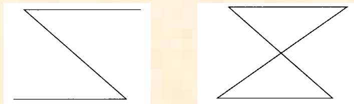
po = (xo,yo), p1 = (x1, y1), ...,pn = (xn, yn).

In OpenGL, a polyline is called a "line strip" and is drawn by specifying the vertices,in turn, between glBegin (GL_LINE_STRIP) and glEnd ().

For example, the code

```
glBegin(GL_LINE_STRIP); // draw an open polyline
    glVertex2i(20,10);
    glVertex2i(50,10) ;
    glVertex2i(20,80);
    glVertex2i(50,80) ;
glEnd();

glFlush() ;
```



produces the polyline shown

If it is desired to draw polygon, simply replace GL_LINE_STRIP with GL_LINE_LOOP

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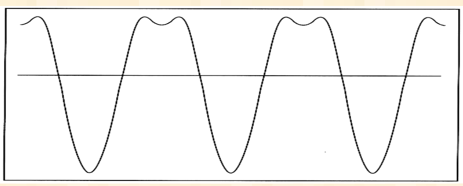
- Polygons drawn using GL_LINE_LOOP <u>cannot be filled with a color</u> or pattern.
- To draw filled polygons, you must use

  glBegin (GL_POLYGON).

### EXAMPLE 2.3.1 Drawing line graphs

- A plot of a mathematical formula.

$$f(x) = 300 - 100\cos(2\pi x/100) + 30\cos(4\pi x/100) + 6\cos(6\pi x/100)$$



The process of plotting a function with line segments is almost identical to that for producing a dot plot, so the program of Figure 2.16 can be used with only slight adjustments.

We must scale and shift the lines being drawn here, to properly place them in the window. This requires the computation of the constants A, B, C, and D in the same manner as we did before.

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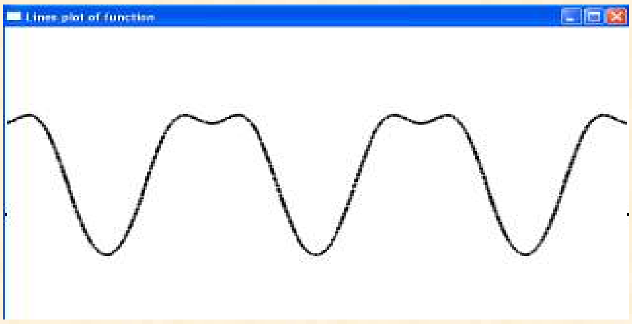




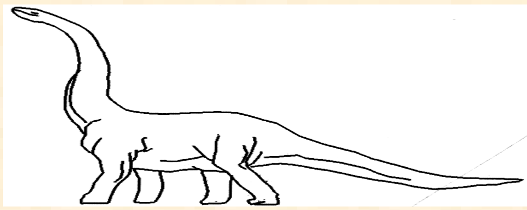

**Most interesting pictures made up of polylines contain a rather large number of lines segments. It is convenient to store a description of polylines in a file, so that the picture can be redrawn at will.**

Parameterizing figures

- Figure 2.23 shows a simple house consisting of a few polylines. It can be drawn using code shown partially in the following

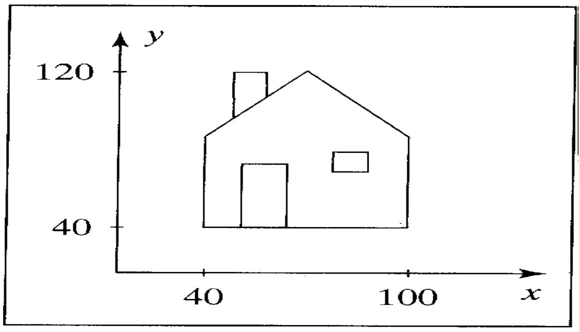


FIGURE 2.23 A House.



```
void hardwiredHouse(void)
{
glClear(GL_COLOR_BUFFER_BIT);
glBegin(GL_LINE_LOOP);
   glVertex2i(40, 40); // draw the shell of house
   glVertex2i(40, 90);
   glVertex2i(70, 120);
   glVertex2i(100, 90);
   glVertex2i(100, 40);
glEnd() ;

glBegin(GL_LINE_STRIP);
   glVertex2i(50, 100); // draw the chimney
   glVertex2i(50, 120);
   glVertex2i(60, 120);
   glVertex2i(60, 110);
glEnd() ;
```

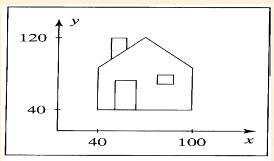


FIGURE 2.23 A House.

```
glBegin(GL_LINE_STRIP);
   glVertex2i(55, 40); // draw the door
   glVertex2i(55, 80);
   glVertex2i(70, 80);
   glVertex2i(70, 40);
glEnd() ;

glBegin(GL_LINE_LOOP);
   glVertex2i(80, 75); // draw the window
   glVertex2i(80, 85);
   glVertex2i(90, 85);
   glVertex2i(90, 75);
glEnd() ;
}
```

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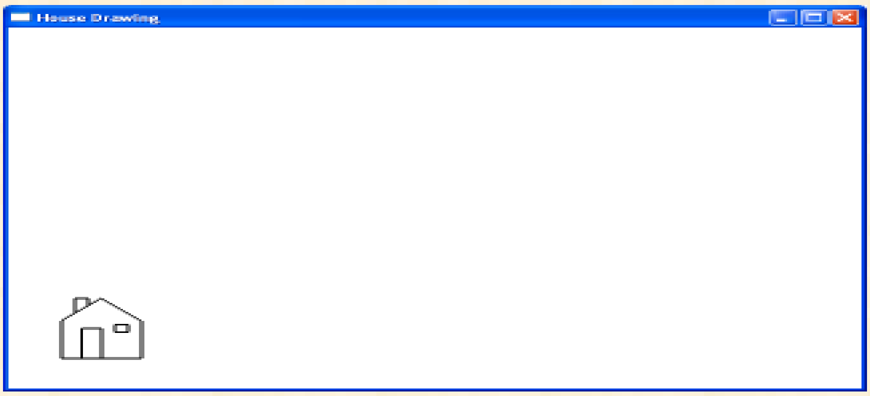


•This is not a very flexible approach. The position of each endpoint is hardwired into the code, so hardwiredHouse () can draw only one house in one size and one location.

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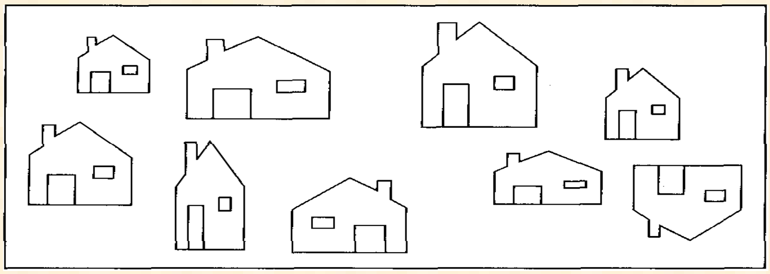

**FIGURE 2.26** A "village" of houses drawn usingparameterizedHouse().

•This routine may be used to draw a "village," as shown in Figure 2.26, by making successive calls to parameterizedHouse () with different parameter values. (How is a house "flipped" upside down? Can *all* of the houses in the figure be drawn using the routine given?)



```
void parameterizedHouse(GLintPoint peak, GLint width, GLint height)

// the top of house is at the peak; the size of house is given
// by the height and width
{
glClear(GL_COLOR_BUFFER_BIT);
glBegin(GL_LINE_LOOP);
    glVertex2i(peak.x,peak.y); // draw shell of house
    glVertex2i(peak.x + width / 2, peak.y - 3 * height /8);
    glVertex2i(peak.x + width / 2, peak.y - height);
    glVertex2i(peak.x - width / 2, peak.y - height);
    glVertex2i(peak.x - width / 2, peak.y - 3 * height /8);
glEnd();

    glBegin(GL_LINE_STRIP);
     // draw the chimney
    glEnd() ;

    glBegin(GL_LINE_STRIP);
     // draw the door
    glEnd() ;

    glBegin(GL_LINE_LOOP);
     // draw the window
    glEnd() ;
glFlush();
}
```

**•The parameters specify the location of the peak of the roof and the width and height of the house.**
**The details of drawing the chimney, door, and window are left as an exercise.**

```
#include <windows.h>
#include <math.h>
#include <GL/GL.h>
#include <GL/GLU.h>
#include <GL/glut.h>

int random (int m)
{
    return rand()%m;
}

class GLintPoint{
public:
    GLint x, y;
};

const int screenWidth = 640;
const int screenHeight = 480;
```

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```
//<<<<<<<<<<<<<<<<<<<<< myInit  >>>>>>>>>>>>>>>>>>
void myInit(void)
{
    glClearColor(1.0,1.0,1.0,0.0);  // set white background color
    glColor3f(0.0f, 0.0f, 0.0f);  // set  drawing color
    glLineWidth(1.0);                       // the line width is  4 pixels
    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluOrtho2D(0.0,(GLdouble) screenWidth,0.0, (GLdouble)
    screenHeight);
}
```

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```
//<<<<< parameterizedHouse  >>>>>>>>>>>>>>>
void parameterizedHouse(GLintPoint peak, GLint width, GLint height)
// the top of house is at the peak; the size of house is given
// by the height and width
{
// the code written here
}

//<<<<<<<<<<< myDisplay >>>>>>>>
void myDisplay(void)
{
    GLintPoint point;
    int width, height;
// make successive calls to  parameterizedHouse
}

//<<<<<<<  main  >>>>>>>>>
void main (int argc, char ** argv)
{
            // code written here
}
```

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**EXAMPLE 2.3.4 Building a polyline drawer**

- Some applications compute and store the vertices of a polyline in a list. We have to add to our growing toolbox of routines a function that accepts the list as a parameter and draws the corresponding polyline.
- The list might be in the form of an array or a linked list.
- Here we use the array form and define the class to hold it in

```
class GLintPointArray
{
   const int MAX_NUM = 100;
   public:
   int num = 100;
   GLintPoint  pt  [MAX_NUM];
}
```

pt is an array of GLintPoint

num is the actual number of elements in the array

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```
void drawPolyLine ( GLintPointArray poly, int closed)
{
      glBegin ( closed ? GL_LINE_LOOP : GL_LINE_STRIP);
         for(int i = 0; i < poly. num; i++)
         glVertex2i(poly.pt[i].x, poly.pt[i].y);
      glEnd();
      glFlush() ;
      }

      // pt is an array of GLintPoint
      // num is the actual number of elements in the array
```

- **The routine also takes a parameter closed:**

**If closed is nonzero, the GL_LINE_LOOP passed to OpenGL**

- **The routine simply sends each vertex of the polyline to OpenGL**

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## Line Drawing using moveto () and lineto()

- We can summarize the effects of the two functions as follows:
- moveto (x, y): set CP to (x, y)
  CP **is the current position**
- lineto (x, y): draw a line from CP to *(x, y),* and then
  update CP to *(x, y)*

A line from (x1, y1) to (x2, y2) is therefore drawn using the two calls moveto (x1, y1) and lineto (x2 , y2).

A polyline based on the list of points, so it is easily drawn using the following code:

```
moveto(x[0], y [0]);
for ( int i =1; i < n; i++)
    lineto ( x[i], y[i]);
```

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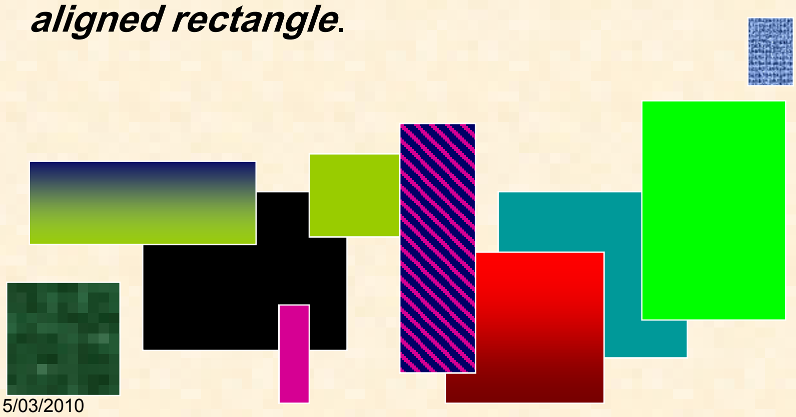
## moveto() and lineto() in OpenGL.

```
GLintPoint CP;    // global current position

//«««««« moveto »»»»»»»»
void moveto(GLint x, GLint y)
{
CP.x = x; CP.y = y; // update the CP )
}

//«««««« lineTo >»»»»»»»»»
void lineto(GLint x, GLint y)
{
glBegin(GL_LINES); // draw the line
    glVertex2i(CP.x, CP.y);
    glVertex2i(x, y);
glEnd();
glFlush() ;
CP.x = x; CP.y = y; // update the CP
}
```



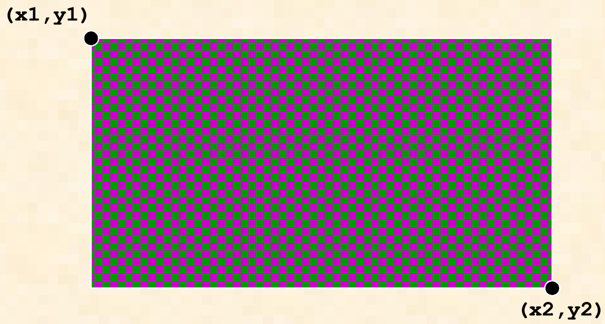
## Rectangles

- A special type of polygon with four sides and with aligned with the coordinate axis is called an ***aligned rectangle***.



## Aligned Rectangles

```
glRecti(GLint x1, GLint y1, GLint x2, GLint y2);
```





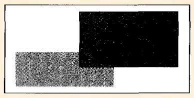

## Aligned Rectangles

```
glRecti(GLint x1, GLint y1, GLint x2, GLint y2);
```

**The rectangle will be drawn, filled with the current foreground colour.**

# Drawing Aligned Rectangles

A special case of a polygon is the **aligned rectangle,** so called because its sides are aligned with the coordinate axes. You just need two points to draw it.

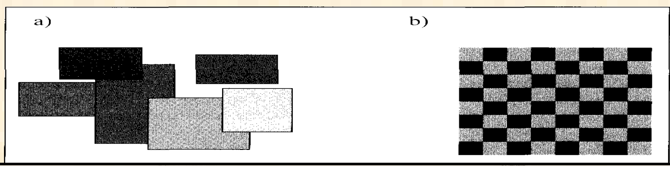


```
                     // white background
glClearColor(I.0,1.0,1.0,0.0);
                       // clear window
glClear(GL_COLOR_BUFFER_BIT); //
                   // filled color is bright gray
glColor3f(0.6,0.6,0.6);
                     // draw the rectangle
glRecti(20,20,100,70);
                   // filled color is dark gray
glColor3f(0.2,0.2,0.2);
                     // draw the rectangle
glRecti(70, 50, 150, 130) ;
glFlush();
```



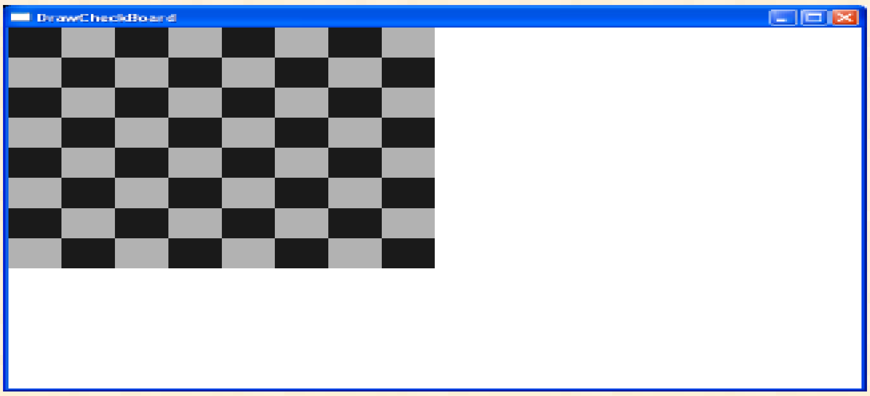
**Part (a) is a "flurry" of randomly chosen aligned rectangles that might be generated by code such as the following**

```
void drawFlurry(int num, int numColors, int Width, int Height)
// draw num random rectangles in a Width by Height rectangle
{
for (int i = 0; i < num; i++)
{
Glint  x1 = random(Width);    //  place corner randomly
GLint  y1 = random(Height);
Glint  x2 = random(Width);    //  pick the size so it fits
GLint  y2 = random(Height);

GLfloat lev = random(10)/10.0 // random value, in range 0 to 1

glColor3f(lev,lev,lev);  //set the gray level of drawing
glRecti (x1 , y1 , x2 , y2) ;  // draw the rectangle
}
glFlush();
}
```



```
void drawChessBoard(int size)
// draw num random rectangles in a Width by Height rectangle
{
    GLfloat lev1  = random(10)/10.0; //value, in range 0 to 1
    GLfloat lev2  = random(10)/10.0; // value, in range 0 to 1

    for (int i = 0; i < 8; i++)
        for (int j = 0; j < 8; j++)
    {
    GLint  x1  =  i * size ;    //       place 1st corner
    GLint  y1  =  j * size ;
    GLint  x2  =  i * size + size;    //          place 2nd corner
    GLint  y2  =  j * size  + size;

    if ((i+j) % 2 == 0) // if i+j is even
        glColor3f(lev1,lev1,lev1);
    else
        glColor3f(lev2,lev2,lev2);

    glRecti (x1 , y1 , x2 , y2) ;  // draw the rectangle
    }
glFlush();
}
```





```
//<<<<<<<<<<<<<<<< DrawDiamond >>>>>>>>>>>>>>>>>>>>>>>>>>>

void DrawDiamond(GLintPoint center, int d)
// draw num random rectangles in a Width by Height rectangle
{

	int x0 = center.x  ;     //                  calculate center
	int y0 = center.y  ;
	glBegin(GL_LINE_LOOP);
			glVertex2i(x0-d,y0);
			glVertex2i(x0,y0-d);
			glVertex2i(x0+d,y0);
			glVertex2i(x0,y0+d);
	glEnd();

glFlush();
}

//<<<<<<<<<<<<<<<< myDisplay >>>>>>>>>>>>>>>>>>>>>>>>>>>

void myDisplay(void)  // The name of this function is upto you
{
	GLintPoint CenterPoint;
	int const size  = 40;

	CenterPoint.x = screenWidth /2;
	CenterPoint.y = screenHeight /2;

	glClear(GL_COLOR_BUFFER_BIT);

	DrawDiamond(CenterPoint, size) ;

	glFlush();                                          // send all output to display
}
```

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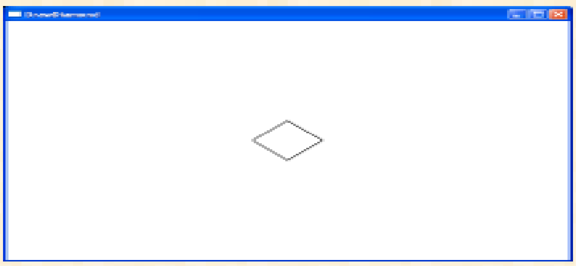

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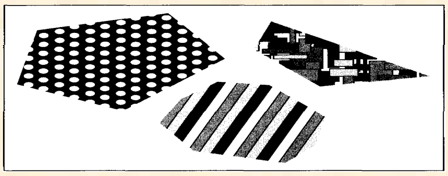
## To draw a convex polygon

based on vertices use the usual list of vertices, but place them between a glBegin(GL_POLYGON) and a glEnd ():

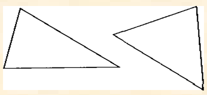
```
glBegin(GL_POLYGON);
    glVertex2f(xo, yo);
    glVertex2f(x1, y1);
    .
    .
    glVertex2f(xn, yn);
glEnd();
```

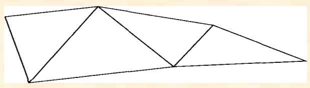


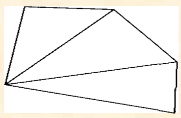
**The polygon will be filled in the current color. It cart also be filled with a stipple pattern (see Case Study 2.5),**



## Other Graphics Primitives in OpenGL





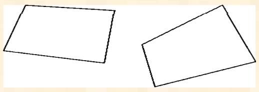


**GL_TRIANGLES** **GL_TRIANGLE_STRIP** **GL_TRIANGLE_FAN**

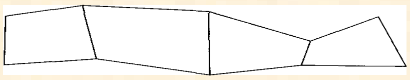
•**GL_TRIANGLES:** takes the listed vertices three at a time and draws a separate triangle for each.

• **GL_TRIANGLE_STRIP**: draws a series of triangles based on triplets of vertices: *vo, v1, v2,*, then *v1, v2, v3,* then *v2, v3, v4.*, etc. (in an order such that all triangles are "traversed" in the same way, e.g., counterclockwise).

•**GL_TRIANGLE_FAN:** draws a series of connected triangles based on triplets of vertices: *vo, v1, v2,* then *vo, v2, v3,* then *vo, v3, v4.*, etc.



GL_QUADS



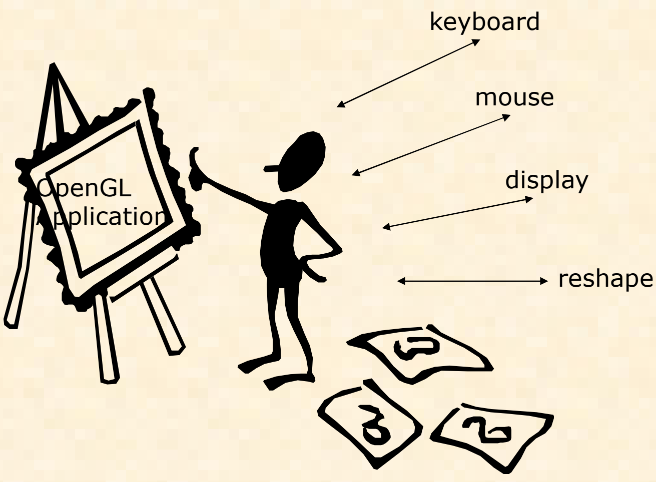
GL_QUAD_STRIP

- **GL_QUADS**: takes the vertices four at a time and draws a separate quadrilateral for each.

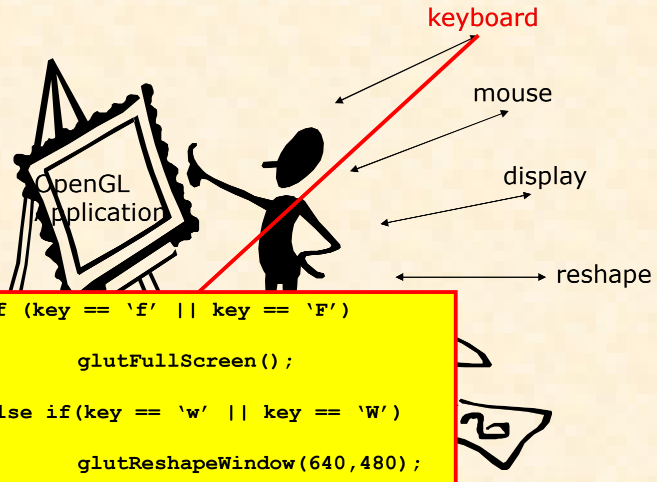
- **GL_QUAD_STRIP**: draws a series of quadrilaterals based on foursomes of vertices: first *vo, v1, v2,v3,* then *v2, v3 , v4, v5,* then *v4, v5, v6, v7, .,*etc. (in an order such that all quadrilaterals are "traversed" in the same way, e.g., counterclockwise).



# Anatomy of GLUT



# Anatomy of GLUT




```
if (key == 'f' || key == 'F')
{
        glutFullScreen();
}
else if(key == 'w' || key == 'W')
{
        glutReshapeWindow(640,480);
}
```



# Anatomy of GLUT

**`void myKeyboard(unsigned char key, int mouseX, int mouseY)`**

Runs whenever a keyboard event occurs (e.g. user presses a key)

**`void myMouse(int button, int state, int x, int y)`**

Runs whenever a mouse event occurs (e.g. user presses a mouse button, mouse moves)

**`void myDisplay(void)`**

Runs whenever the system determines that the window must be redrawn (e.g. window comes to the front, window has been moved)

**`void myReshape(void)`**

Runs whenever a window changes size