CENG 477
Introduction to Computer Graphics

Graphics Hardware and OpenGL

Introduction

- Until now, we focused on graphic algorithms rather than hardware and implementation details
- But graphics, without using specialized tools and/or hardware would simply be too slow for most applications
- We will now learn about how a GPU works and how to program it using a specific API: OpenGL
- The presented ideas should apply to other APIs such as Direct3D with some modifications

Graphics Hardware (GH)

- GH is a set of components which implements the forward rendering pipeline at a chip level called GPU
- Modern GPUs are programmable
- GPUs are massively parallel (orders of magnitude more parallel than CPUs)
- GPUs change continuously mainly due to the demands of the video game industry
- Big players:
  - AMD, Nvidia, Intel, Microsoft, Apple, Qualcomm, …

Graphics Processing Unit (GPU)

- How parallel are GPUs? Let’s watch this demo:

GPGPU

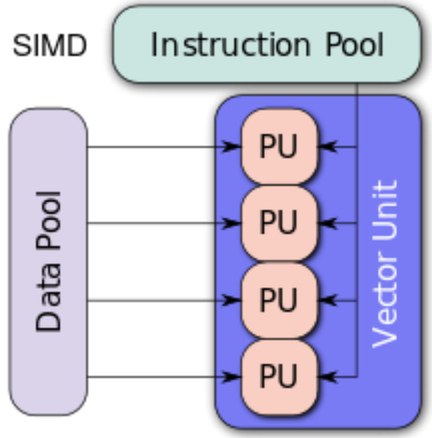
- As a result of this performance, GPUs are used in many tasks that are not related to graphics at all:
  - Called **GPGPU**: General-purpose computing on GPU
- Nvidia developed the CUDA language for GPGPU
- OpenCL is supported by AMD, Nvidia, and Intel
- Nowadays, many computational intensive tasks are performed on the GPU:
  - Image and video processing
  - Analyzing big data
  - Bioinformatics
  - Optimization
  - Machine learning, …

GPU Architecture

- GPUs are similar to CPUs in their building blocks (in fact they are somewhat simpler than CPUs):
  - Some logic to decode the instruction to be performed
  - Registers
  - Arithmetic logic units (ALUs)
  - Cache
  - Memory
- But they are massively parallel:
  - Data parallelism
  - Pipeline parallelism

GPU Parallelism

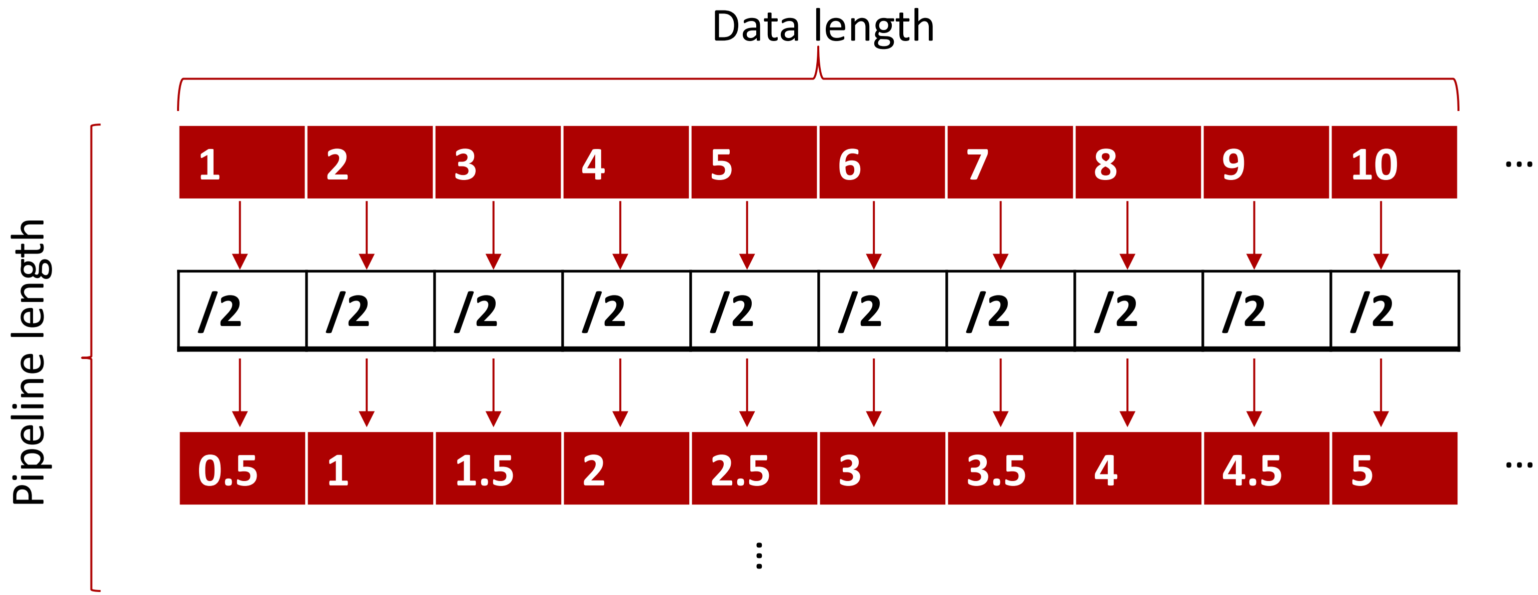
- What makes GPUs parallel?
- GPUs are SIMD architectures
  - **SIMD:** Single instruction multiple data
  - The same instruction is applied to thousands of data elements at the same time



wikipedia.com

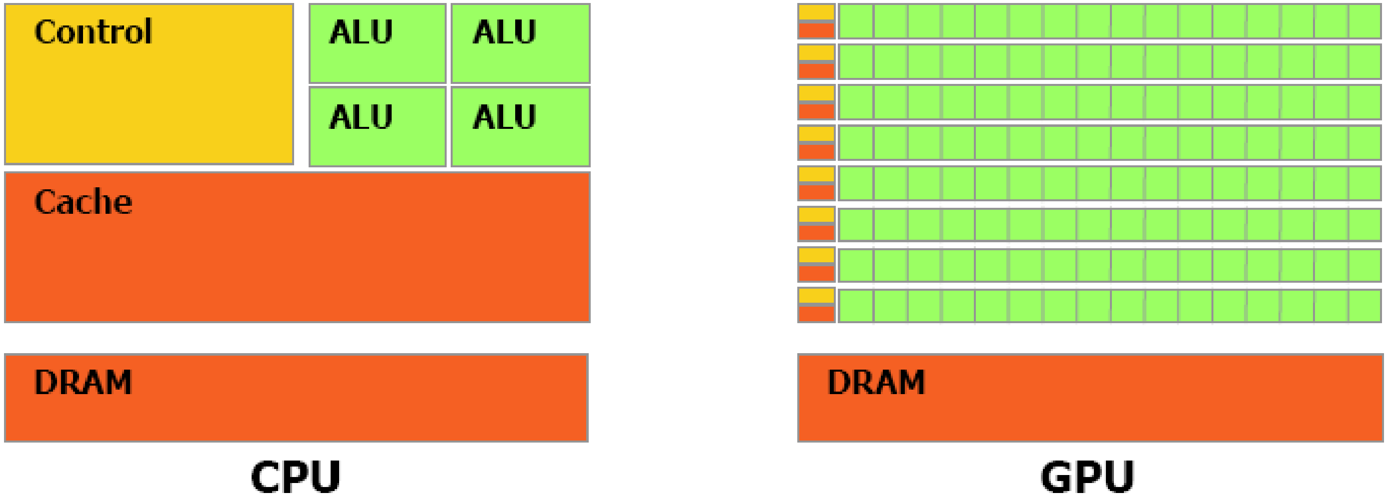
GPU Parallelism

- This works well for independent tasks such as:
  - Transforming vertices
  - Computing shading for each fragment
- Ideal if the task is the same but the data is different:



GPU vs CPU

- GPUs have a larger number of ALUs allowing for data parallelism:

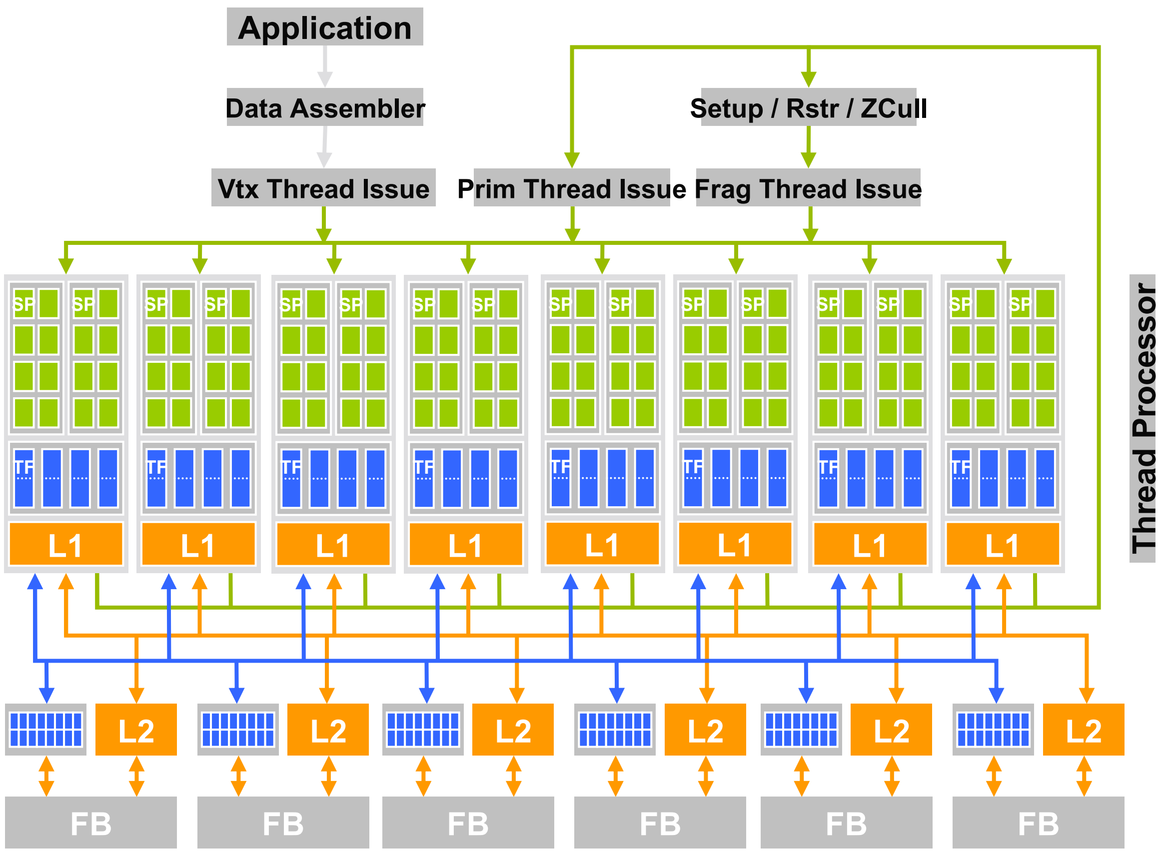


GPU vs CPU

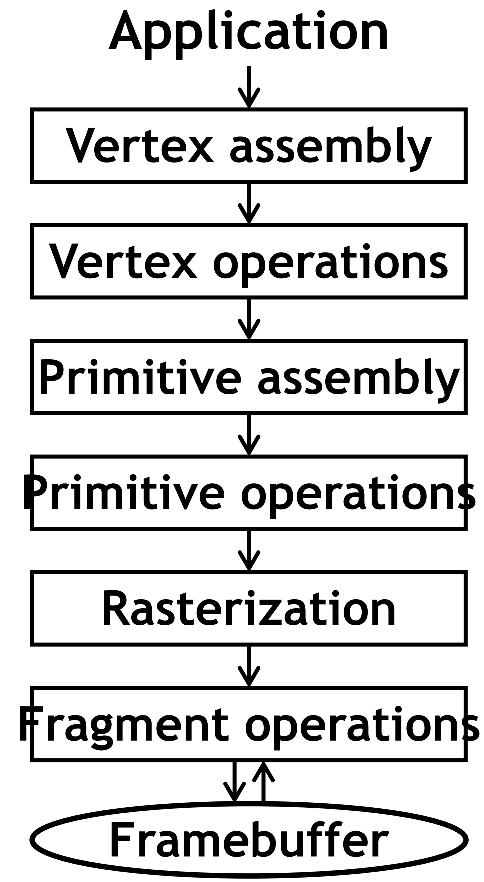
- Let’s compare a good GPU with a good CPU

Intel i7-4790K	Nvidia GTX 1060
Cores: 4 (8 threads)	Cores: 1280
Clock: 4 – 4.4 GHz	Clock: 1.5 – 1.7 GHz
Power: 88W	Power: 120W
Memory BW: 25.6 GB/s	Memory BW: 192 GB/s

Overall GPU Architecture

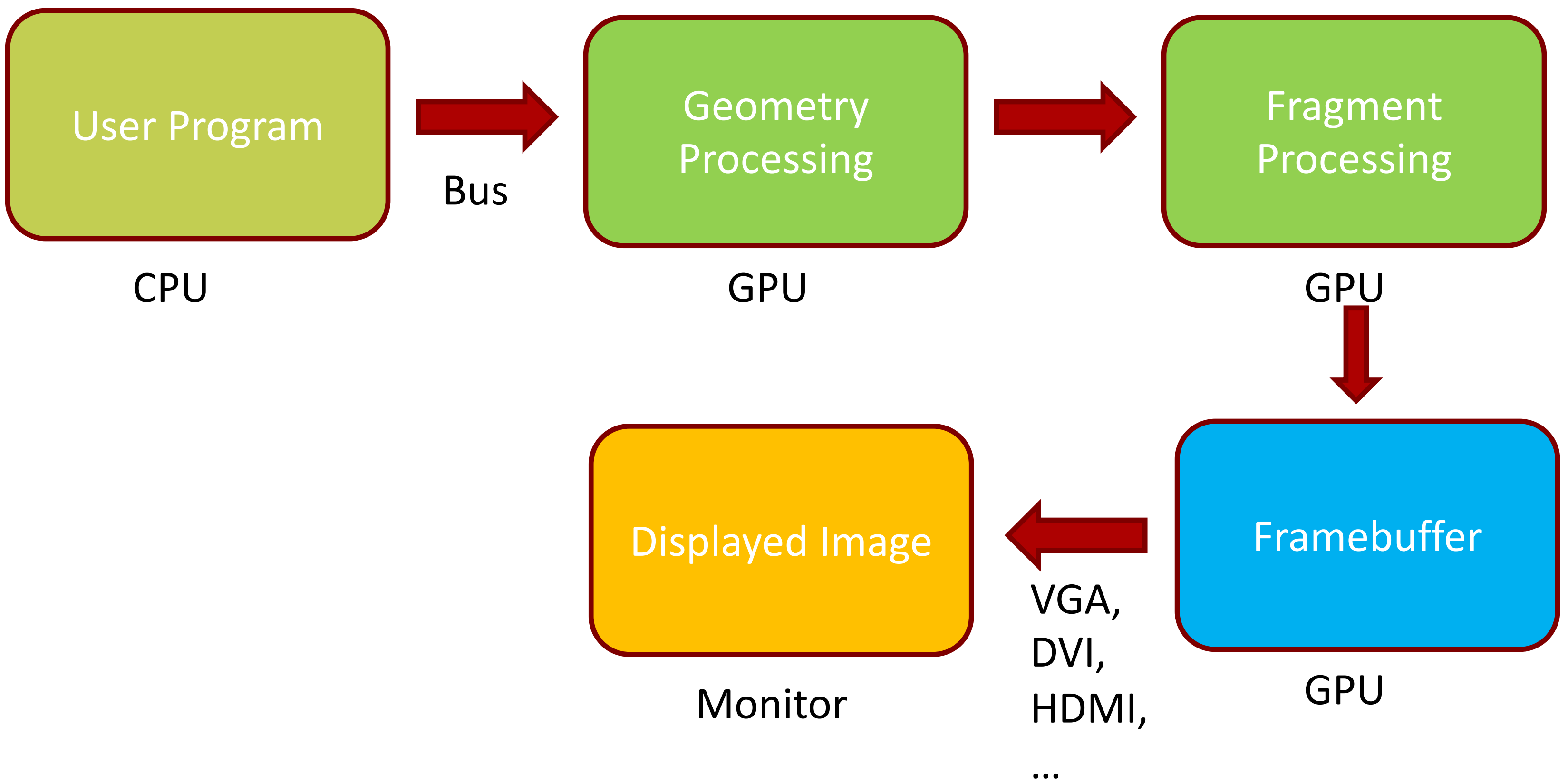


NVIDIA GeForce 8800



OpenGL Pipeline

GPU Data Flow Model



User Program

- The user program is an OpenGL (or Direct3D) program which itself runs on the CPU
- Also initially all data is in the main system memory
- The user program is responsible to arbitrate the overall flow and send data to GPU:
  - Open a window
  - Manage user interaction (mouse, keyboard, etc.)
  - Decide what to draw and when to draw
  - Ask GPU to compile shaders (programs to be later run on the GPU)

Opening a Window

- Opening a window for rendering is not part of OpenGL
  - Each OS has a different mechanism
- There are some high-level APIs that simplify this process
  - Perhaps the simplest of these APIs is GLUT
  - You will learn GLFW in the recitation, which is simpler and better

```
glutInit(&argc, argv);
glutInitDisplayMode(GLUT_RGBA |
                    GLUT_DOUBLE |
                    GLUT_DEPTH |
                    GLUT_STENCIL);
glutInitWindowPosition(100, 100);
glutInitWindowSize(640, 480);
glutCreateWindow("");
```

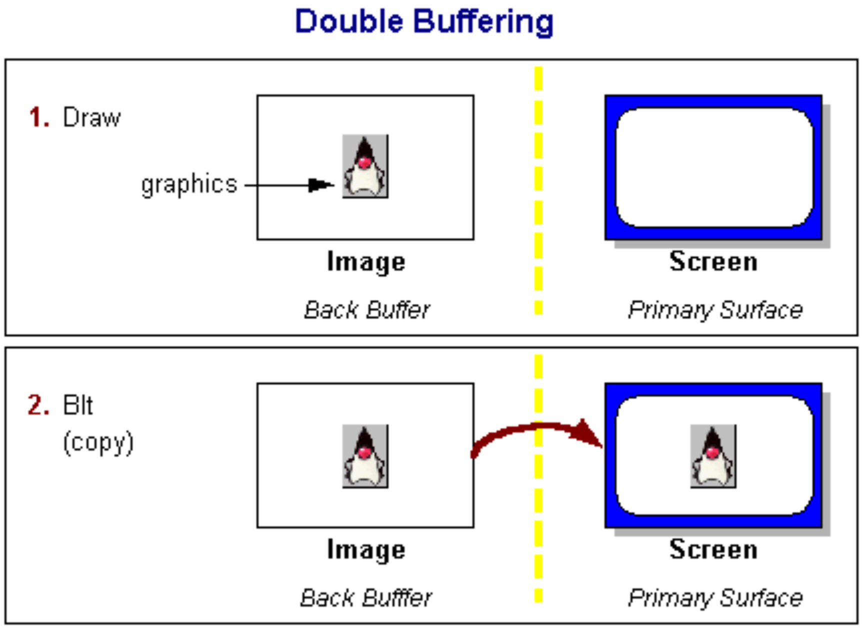
Buffers that we want

Double Buffering

- Double buffering is a technique to avoid tearing
  – Problem happens when drawing and displaying the same buffer

Double Buffering

- To avoid such artifacts, we render to a back buffer and show that buffer only when drawing is complete (usually synchronized with monitor's refresh cycle)
  - Windowed more requires a copy:



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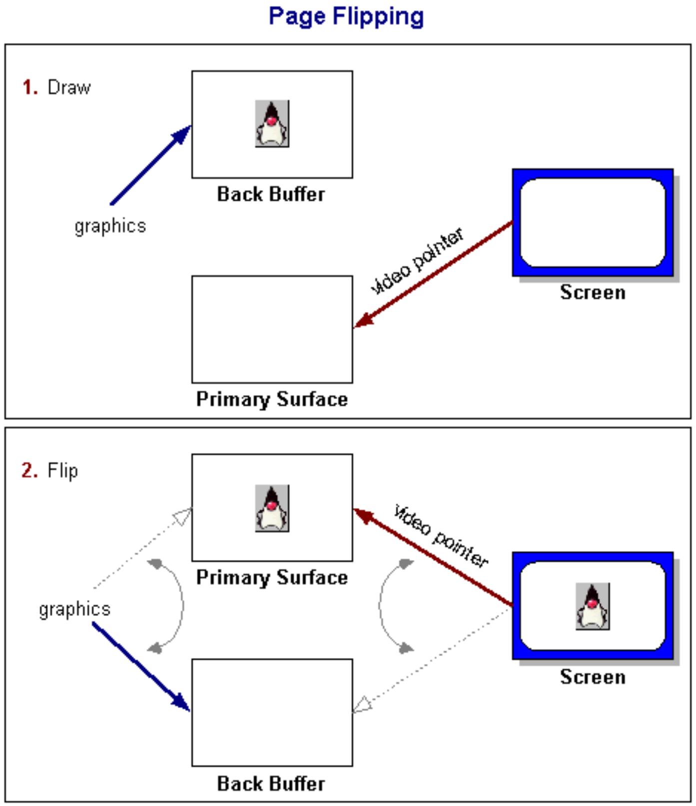
Double Buffering

- In fullscreen mode, only the video pointer is flipped:



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Managing User Interaction

- The user may interact with the program through input devices: traditionally keyboard and mouse
- GLUT also simplifies this task by registering callbacks:

```
glutReshapeFunc(reshape);
glutKeyboardFunc(keyboard);
```

Managing User Interaction

- Sample keyboard callback:

```
void keyboard(unsigned char key, int x, int y)
{
    switch (key)
    {
        case 27: // Escape
            exit(0);
            break;
        case 'q': // normal key press
            exit(0);
            break;
        default:
            break;
    }
}
```

Managing User Interaction

- Sample special key-press callback:

```
void special(int key, int x, int y)
{
    switch (key)
    {
    case GLUT_KEY_LEFT:
        break;
    case GLUT_KEY_RIGHT:
        break;
    case GLUT_KEY_UP:
        break;
    case GLUT_KEY_DOWN:
        break;
    default:
        break;
    }
}
```

Displaying/Resizing the Window

- Whenever a window is displayed or resized, certain settings (such as the viewport) may need to be updated:
- This function can also be registered by using GLUT:

```
glutReshapeFunc(reshape);
```

Displaying/Resizing the Window

- Here, we typically reset the viewport and transformation matrices:

```
void reshape(int w, int h)
{
    w = w < 1 ? 1 : w;
    h = h < 1 ? 1 : h;

    glViewport(0, 0, w, h);

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    glOrtho(-1, 1, -1, 1, -1, 1);

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

Window width and height

Projection transform can be set by *glOrtho* or *glFrustum.* It is also possible to use *gluPerspective*

Combined modeling and viewing transform

Rendering Each Frame

- **Each frame must be redrawn from scratch!**
- Again, we first register a callback for this task
- The registered function is automatically called by the windowing system whenever required:

```
glutDisplayFunc(display);
```

Rendering Each Frame

- We first clear all buffers, then render our frame, and finally swap buffers (remember double buffering):

```
void display()
{
    glClearColor(0, 0, 0, 1);
    glClearDepth(1.0f);
    glClearStencil(0);
    glClear(GL_COLOR_BUFFER_BIT |
            GL_DEPTH_BUFFER_BIT |
            GL_STENCIL_BUFFER_BIT);

    renderFrame();

    glutSwapBuffers();
}
```

Animation

- If we have animation, we must make sure that the window system calls our display function continuously
- For that purpose, we register another callback:

```
glutIdleFunc(idle);
```

- In this function, we simply ask our display function to be called during GLUT’s main loop:

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

Sets a flag so that our display function will be called

Sending Geometry Data

- The user program must communicate the geometry information to the GPU
- A simple approach:

```
glBegin(GL_LINES);
   glVertex3f(x0, y0, z0);
   glVertex3f(x1, y1, z1);
glEnd();
```

- We tell GPU that we want to draw a line from (x_0, y_0, z_0) to (x_1, y_1, z_1)

Sending Geometry Data

- Attributes besides position can be sent as well:

```
glBegin(GL_LINES);
    glColor3f(1, 0, 0); // red
    glVertex3f(x0, y0, z0);
     glColor3f(0, 1, 0); // green
    glVertex3f(x1, y1, z1);
glEnd();
```

- We tell GPU that we want to draw a line from (x_0, y_0, z_0) to (x_1, y_1, z_1)
- The endpoint colors are (1, 0, 0) and (0, 1, 0)

Sending Geometry Data

- Triangles are similar:

```
glBegin(GL_TRIANGLES);
   glVertex3f(x0, y0, z0);
   glVertex3f(x1, y1, z1);
   glVertex3f(x2, y2, z2);
glEnd();
```

- Every group of three vertices define a triangle
- Drawing two triangles:

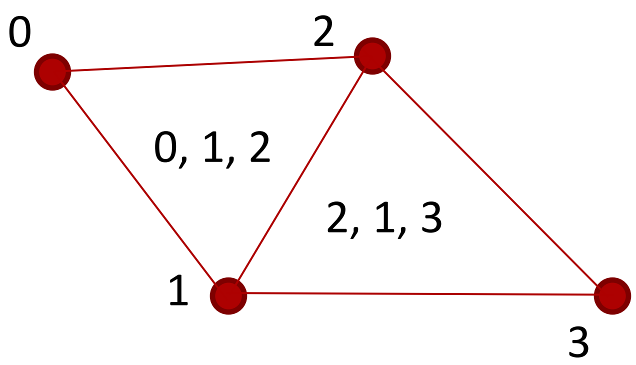
```
glBegin(GL_TRIANGLES);
   glVertex3f(x0, y0, z0); glVertex3f(x1, y1, z1); glVertex3f(x2, y2, z2);
   glVertex3f(x3, y3, z3); glVertex3f(x4, y4, z4); glVertex3f(x5, y5, z5);
glEnd();
```

Sending Geometry Data

- With this approach *m* triangles require *3m* vertex calls
- An improved method is to use triangle strips for meshes
- The first three vertices define the first triangle
- Every vertex afterwards defines a new triangle

if there is no strip keyword, 4th one is ignored

```
glBegin(GL_TRIANGLE_STRIP);
    glVertex3f(x0, y0, z0);
    glVertex3f(x1, y1, z1);
    glVertex3f(x2, y2, z2);
    glVertex3f(x3, y3, z3);
glEnd();
```

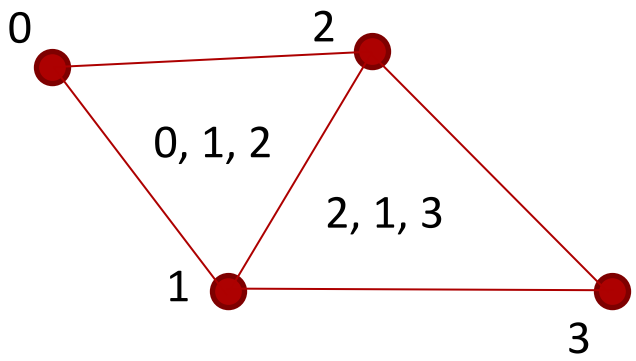


- *m* triangles require *m+2* vertex calls

Winding Order

- Winding order determines the facing of a triangle
- Here both triangles are facing toward the viewer:

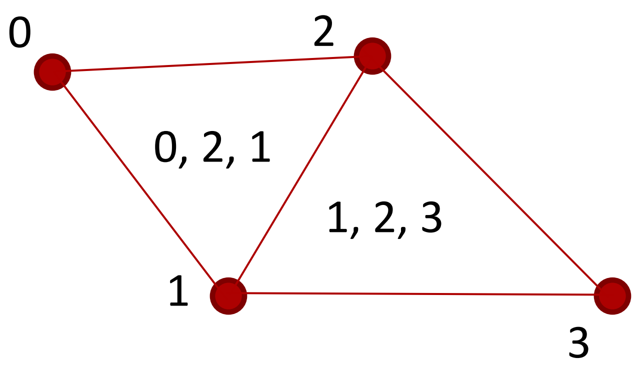
```
glBegin(GL_TRIANGLE_STRIP);
   glVertex3f(x0, y0, z0);
   glVertex3f(x1, y1, z1);
   glVertex3f(x2, y2, z2);
   glVertex3f(x3, y3, z3);
glEnd();
```



Winding Order

- Winding order determines the facing of a triangle
- Here both triangles are facing away from the viewer:

```
glBegin(GL_TRIANGLE_STRIP);
   glVertex3f(x0, y0, z0);
   glVertex3f(x2, y2, z2);
   glVertex3f(x1, y1, z1);
   glVertex3f(x3, y3, z3);
glEnd();
```



- It is important to use a consisting winding order when drawing a mesh due to backface culling

Graphics State

- OpenGL is a state machine
- Various states are preserved until we change them
- In the example below, the color of each vertex is set to (0, 1, 0), that is green:

```
glColor3f(0, 1, 0)
glBegin(GL_TRIANGLE_STRIP);
   glVertex3f(x0, y0, z0);
   glVertex3f(x1, y1, z1);
   glVertex3f(x2, y2, z2);
   glVertex3f(x3, y3, z3);
glEnd();
```

Graphics State

- Below the first three vertices have the same color and normal
- The fourth vertex has a different color and normal:

```
glColor3f(0, 1, 0)
glNormal3f(0, 0, 1)
glBegin(GL_TRIANGLE_STRIP);
   glVertex3f(x0, y0, z0);
   glVertex3f(x2, y2, z2);
   glVertex3f(x1, y1, z1);
   glColor3f(1, 0, 0)
   glNormal3f(1, 0, 1)
   glVertex3f(x3, y3, z3);
glEnd();
```

Sending Geometry Data

- Previous examples send data in immediate mode
- **Immediate mode is ineffiecient:** A large model would require too many glVertex calls
- Each glVertex call is executed on the CPU and the corresponding data is sent to the GPU
- A better approach would be to send all vertex data to the GPU using a single call
- We use vertex arrays for that purpose

Vertex Arrays

- There are several arrays such as vertex position array, vertex color array, vertex normal array, …
- Below is an example of vertex position array:

glVertexPointer(size, type, stride, pointer)

Number of coordinates per vertex

Type of each coordinate

Byte offset between consecutive vertices

Pointer to vertex position data

- You must enable an array before using it:

glEnableClientState(GL_VERTEX_ARRAY)

Vertex Arrays

- In modern OpenGL, these explicit attribute names are replaced by a generic attribute array function:

glVertexAttribPointer(index, size, type, normalized, stride, pointer)

Array index

Number of coordinates per vertex

Type of each coordinate

Whether integer data should be normalized

Byte offset between consecutive vertices

Pointer to vertex position data

- Don't forget to enable it: glEnableVertexAttribArray(index)

Drawing with Vertex Arrays

- We use a single draw call to draw using vertex arrays:

```
glDrawArrays(mode, first, count)
```

Primitive type

Starting index in the enabled arrays

Number of indices to be rendered

Drawing with Vertex Arrays

- **glDrawArrays** may still be inefficient as vertex attribute data must be repeated for each primitive
- **glDrawElements** is designed to solve this issue by using indices:

glDrawElements(mode, count, type, indices)

Primitive type

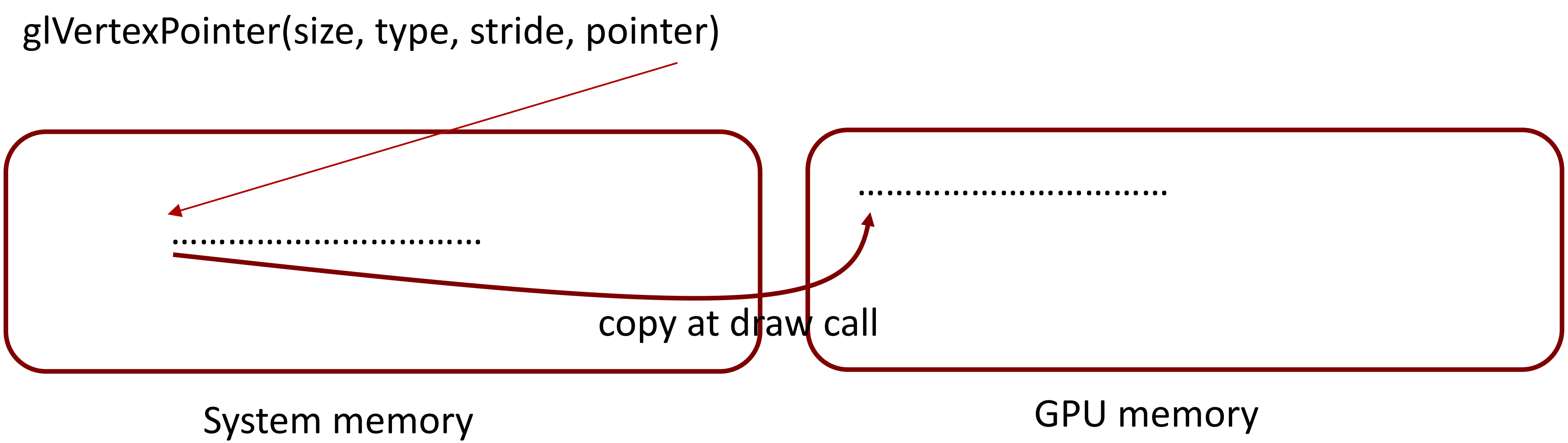
Number of indices to be rendered

Type of each index

Pointer to indices

Drawing with Vertex Arrays

- When using client-side vertex arrays, the vertex attribute data is copied from the system memory (user pointer) to the GPU memory at every draw call
- There is a better alternative, known as vertex buffers



Vertex Buffer Objects

- Previous methods required the data to be copied from the system memory to GPU memory at each draw
- Vertex Buffer Objects (VBOs) are designed to allow this copy to take place only once
- The copied data is reused at each draw

Vertex Buffer Objects

- To use VBOs, we generate two buffers:
  - Vertex attribute buffer (position, color, normal, etc.)
  - Element array buffer (indices)

```
GLuint vertexAttribBuffer, indexBuffer;

glGenBuffers(1, &vertexAttribBuffer);
glGenBuffers(1, &indexBuffer);
```

Vertex Buffer Objects

- Next, we bind these buffers to locations that are meaningful for the GPU:

```
glBindBuffer(GL_ARRAY_BUFFER, vertexAttribBuffer);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, indexBuffer)
```

don’t forget to bind array and element buffer to 0.
glBindBuffer(GL_ARRAY_BUFFER, 0);

Vertex Buffer Objects

- We then ask the GPU to allocate memory for us and copy our data into this memory

Attribute data size in bytes

Attribute data pointer

```
glBufferData(GL_ARRAY_BUFFER, aSize, aPtr, GL_STATIC_DRAW);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, iSize, iPtr, GL_STATIC_DRAW);
```

Index data size in bytes

Index data pointer

Vertex Buffer Objects

- Once this is done, the CPU data can safely be deleted:

Attribute data size in bytes

Attribute data pointer

```
glBufferData(GL_ARRAY_BUFFER, aSize, aPtr, GL_STATIC_DRAW);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, iSize, iPtr, GL_STATIC_DRAW);
```

Index data size in bytes

Index data pointer

```
delete[] aPtr;
delete[] iPtr;
```

Vertex Buffer Objects

- Before drawing, we can specifying an offset into our buffers
- It is accomplished by the same function as before
- But this time, pointer indicates a byte offset into our buffer (similar for glColorPointer, etc.)

glVertexPointer(size, type, stride, pointer)

Number of coordinates per vertex

Type of each coordinate

Byte offset between consecutive vertices

Offset to vertex position data

Vertex Buffer Objects

- Drawing is the same as before where index pointer is now also an offset to the element array buffer:

glDrawElements(mode, count, type, indices)

- mode: Primitive type
- count: Number of indices to be rendered
- type: Type of each index
- indices: Offset to indices

Vertex Buffer Objects

- The relevant buffers must still be enabled:

```
glEnableClientState(GL_VERTEX_ARRAY)
glEnableClientState(GL_COLOR_ARRAY)
…
```

- Unfortunately, this is a very bad naming as it suggests client-side data is being used
- In modern OpenGL, these are replaced with:

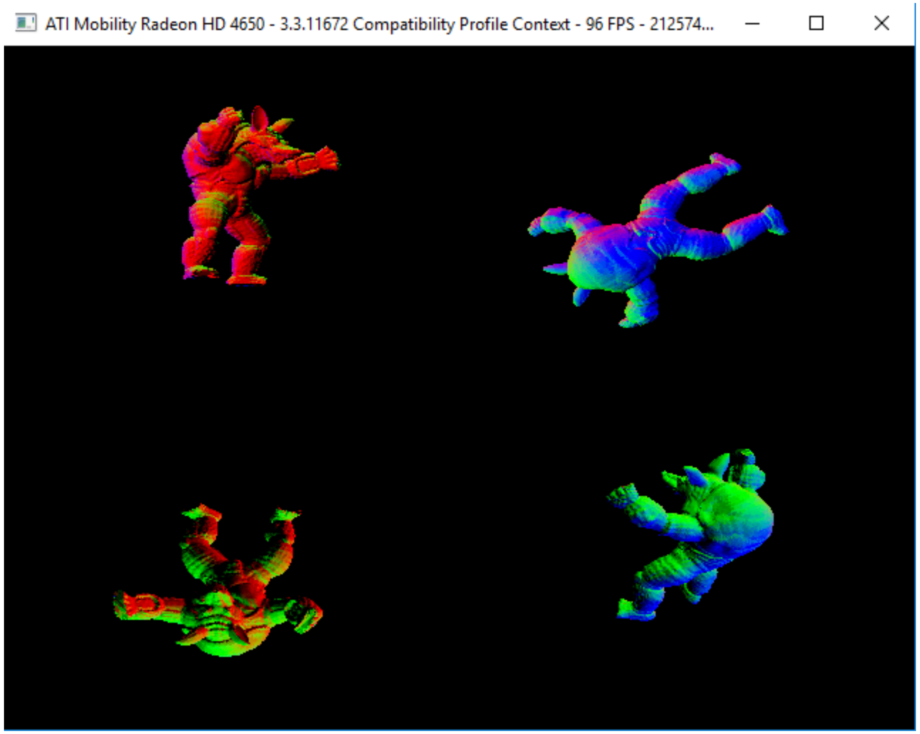
```
glEnableVertexAttribArray(0);
glEnableVertexAttribArray(1);
…
```

Vertex Buffer Objects

- Note that in **glVertexPointer** and **glDrawElements** the last parameter is sometimes treated as pointer and sometimes offset
- OpenGL makes this decision as follows:
  - If a non-zero name is bound to **GL_ARRAY_BUFFER**, the last parameter glVertexPointer is treated as offset (otherwise pointer)
  - If a non-zero name is bound to **GL_ELEMENT_ARRAY_BUFFER**, the last parameter glDrawElements is treated as offset (otherwise pointer)

Performance Comparison

- Drawing an Armadillo model comprised of 212574 triangles at four distinct locations (resulting in a total of 850296 triangles):



Performance Comparison

- On AMD Mobility Radeon HD4650 and at resolution 640x480:
  - Using VBOs the frame rate was about 100 FPS
  - Using client-side glDrawElements, the frame rate was about 20 FPS
- Therefore, almost all modern games use VBOs for drawing complex models

Transformations in OpenGL

- In classic OpenGL, transformations are performed using three commands:

```
glTranslatef(deltaX, deltaY, deltaZ);
glRotatef(angle, axisX, axisY, axisZ);
glScalef(scaleX, scaleY, scaleZ);
```

- These commands effect the current matrix
- Therefore the current matrix should be set as **GL_MODELVIEW** before calling these commands
- Note that angle is in degrees (not radians)!

Transformations in OpenGL

- Transformations apply in the reverse order
- The command closest to the *draw* call takes effect first

```
glTranslatef(deltaX, deltaY, deltaZ);
glRotatef(angle, axisX, axisY, axisZ);
glScalef(scaleX, scaleY, scaleZ);

drawCube();
```

- Here, the cube is first scaled, then rotated, and finally translated

Transformations in OpenGL

- Transformations keep effecting the current matrix
- If you want to draw an object at the same position at each frame you need to reset the matrix to identity:

```
glLoadIdentity();

glTranslatef(deltaX, deltaY, deltaZ);
glRotatef(angle, axisX, axisY, axisZ);
glScalef(scaleX, scaleY, scaleZ);

drawCube();
```

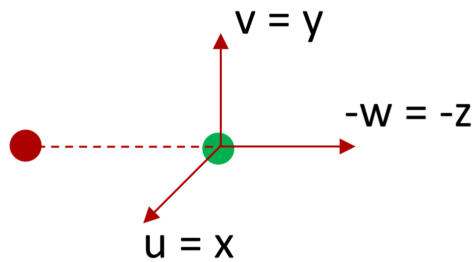
- Otherwise your object will quickly disappear!

Transformations in OpenGL

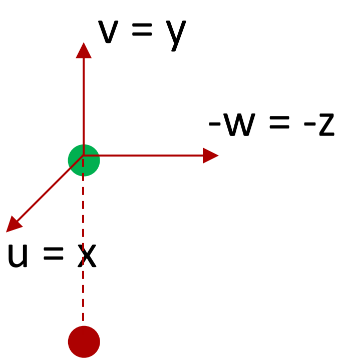
- In OpenGL, we do not specify a camera position
- It is assumed that the camera is at **(0, 0, 0)** and looking down the **negative z** axis
- You can view a modelview transformation in two ways:
  - Transform all objects drawn after the transformation by keeping the camera fixed
  - Transform the camera (i.e. coordinate system) by the opposite transformations by keeping the objects fixed
- In reality, objects are transformed but both would produce the same result

Transformations in OpenGL

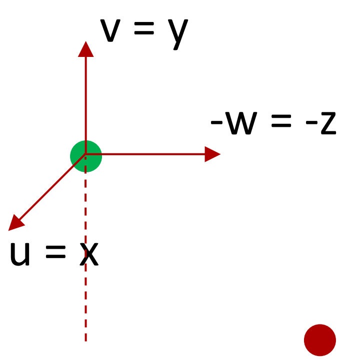
- Assume we have an object at (0, 0, 4):



Apply glRotatef(90, 1, 0, 0)

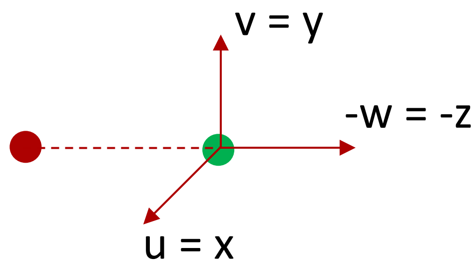


Apply glTranslatef(0, 0, -5)

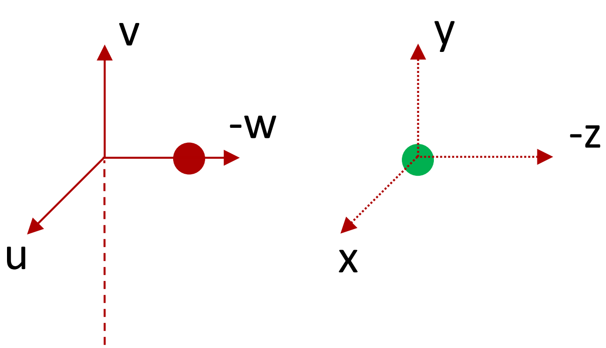


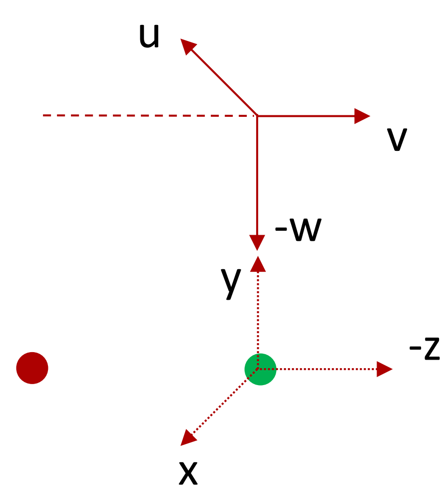
Transformations in OpenGL

- Now imagine applying the opposite to the camera:



Apply glTranslatef(0, 0, 5)

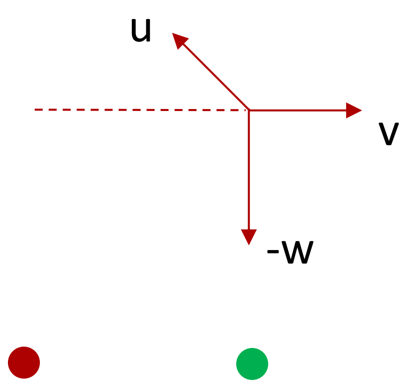




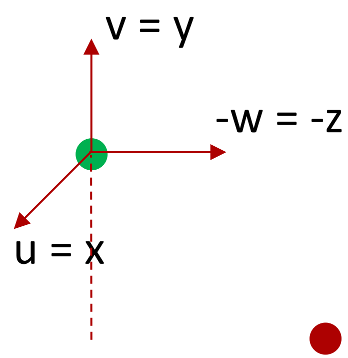
Apply glRotatef(-90, 1, 0, 0)

Transformations in OpenGL

- Now imagine applying the opposite to the camera:



New result



Original result

The object position w.r.t. the camera
is exactly the same in these two cases