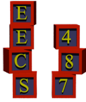
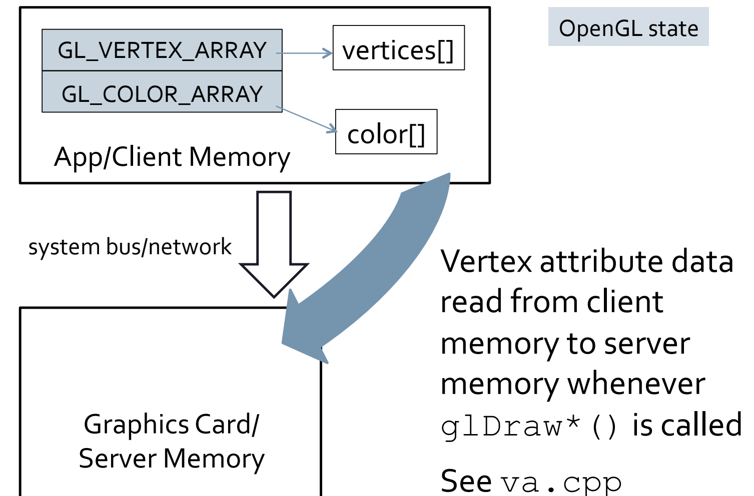


EECS 487: Interactive Computer Graphics

Lecture 17:
- Vertex Buffer Object (VBO)
- Vertex-Array Object (VAO)
- Sample code at http://web.eecs.umich.edu/~sugih/courses/eecs487/common/notes/gl3+webgl.tgz

Vertex Array



Vertex attribute data read from client memory to server memory whenever `glDraw*()` is called

See `va.cpp`

Vertex Buffer Object (VBO)

Vertex array must be copied on every draw

VBO allows data to be stored in GPU memory but still client read/write-able

Steps to set up and use a VBO:

1. Generate and bind VBO descriptor(s)
   `glGenBuffers(),glBindBuffer()`
2. Allocate space for VBO and populate it with vertex attribute(s) data
   `glBufferData(),glBufferSubData()`
3. Tell the GPU which attribute is where on the VBO
   `glEnableClientState(),glVertexPointer()`

Buffer Object Descriptor

First, generate buffer object descriptor(s)* :

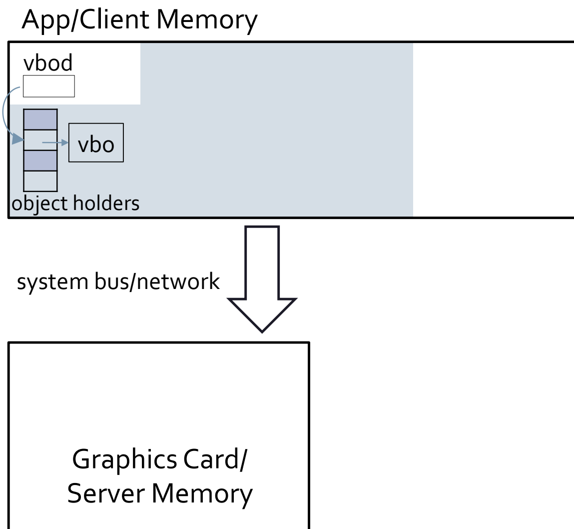
```
int vbods[N];
glGenBuffers(GLsizei N, GLuint *vbods);
```

for example, if only 1 buffer object is needed:

```
int vbod;
glGenBuffers(1, &vbod);
```

*descriptor == handle == name == id

Vertex Buffer Object



OpenGL state

`glGenBuffers()`

Current Buffer Object

Next bind each descriptor to a type of buffer

```
glBindBuffer(GLenum target, GLuint vbod);
 // target: GL_ARRAY_BUFFER,
 // GL_ELEMENT_ARRAY_BUFFER (for indices)
```

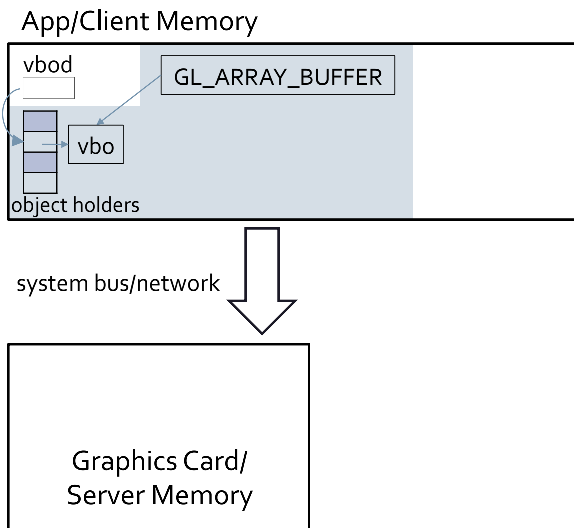
for example:

```
glBindBuffer(GL_ARRAY_BUFFER, vbod);
```

This also makes the `vbod` buffer object the "current/in-use" buffer object: all subsequent buffer object operations apply to this buffer object

If `vbod` is `NULL`, disable Buffer Object

Vertex Buffer Object



OpenGL state

`glGenBuffers()`

`glBindBuffer()`

Buffer Object Data

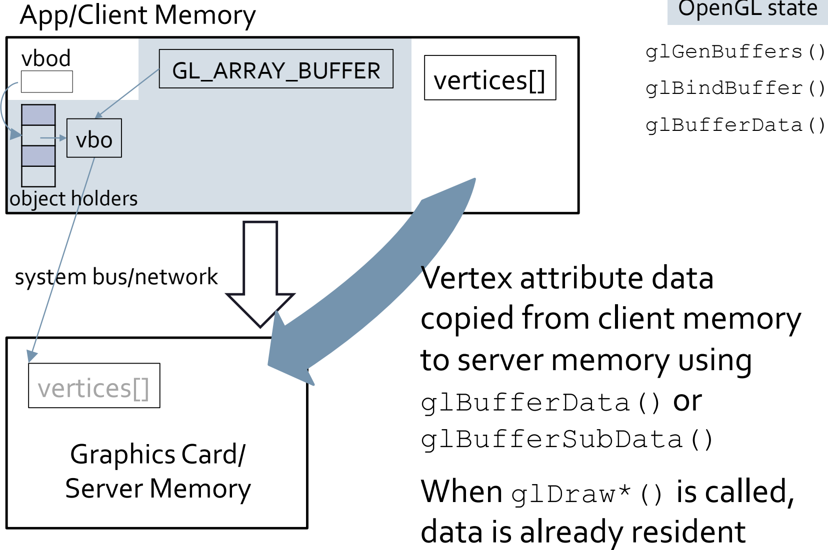
Allocated (and initialize) space for buffer object:

```
glBufferData(GLenum target, GLsizei size,
       GLvoid* data, GLenum usage);
// target: as before, size: size of data,
// data: pointer to source data array, NULL to allocate
//       memory without content initialization
// usage: will data be modified? Helps OpenGL determine
//        memory location to optimize performance
```

for example:

```
float vertices[3][2] =
  { {0.0, 0.0}, {0.0, 1.0}, {1.0, 0.0} };

glBufferData(GL_ARRAY_BUFFER, sizeof(vertices),
  vertices, GL_STATIC_DRAW);
```

Vertex Buffer Object



Vertex attribute data copied from client memory to server memory using `glBufferData()` or `glBufferSubData()`

When `glDraw*()` is called, data is already resident

Multiple Vertex Attributes

If there are multiple vertex attributes, we can put them back to back in the buffer object using:

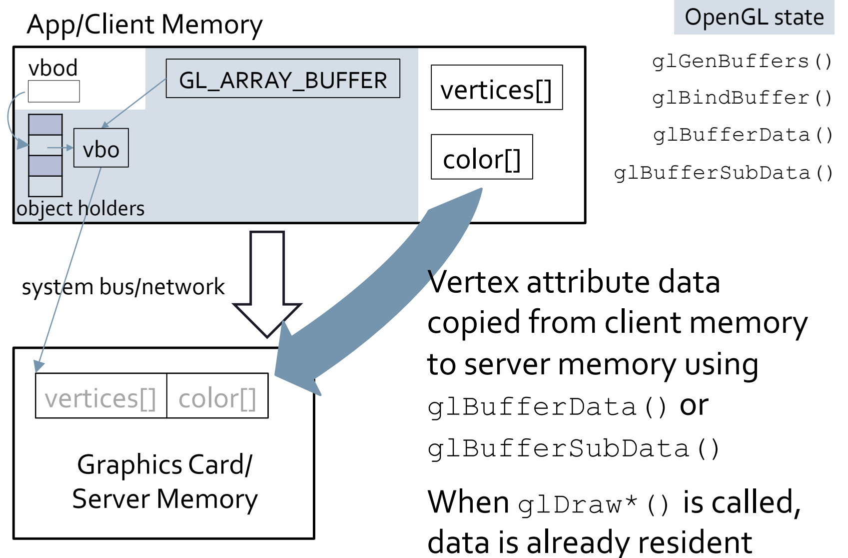
```
glBufferSubData(GLenum target, GLint
  offset, GLsizei size, GLvoid* data);
  // target: as before, offset: byte offset from the
  // start of buffer as copy target, size: size of data,
  // data: pointer to source data array
```

To avoid having two copies of `data`, client can share server memory using `glMapBuffer()`/`glUnmapBuffer()` after the call to `glBufferData()` (see Pixel Buffer Object (PBO) later)

Multiple Vertex Attributes Example

```
float vertices[3][2] =
  { {0.0, 0.0}, {0.0, 1.0}, {1.0, 0.0} };
float color[3][3]= { {1.0, 0.0, 0.0},
  {0.0, 1.0, 0.0}, {0.0, 0.0, 1.0} };
glBufferData(GL_ARRAY_BUFFER,
  sizeof(vertices)+sizeof(color), NULL,
  GL_STATIC_DRAW);  // allocate space only
glBufferSubData(GL_ARRAY_BUFFER, 0,
  sizeof(vertices), vertices); // copy data
glBufferSubData(GL_ARRAY_BUFFER,
  sizeof(vertices), sizeof(color), color);
                                // copy data
```

Vertex Buffer Object



Vertex attribute data copied from client memory to server memory using `glBufferData()` or `glBufferSubData()`

When `glDraw*()` is called, data is already resident

Common Error

`glGenBuffers()` not called before `glBindBuffer()`

Offset is given in count, not in bytes, e.g., if the first array (at offset 0) is of `N` elements of class `Vertex`, the correct offset to the second array is: `N*sizeof(Vertex)`, not just `N`

If offset is wrong, especially when using `glMapBuffer`, GPU can lock up and system must be rebooted

Vertex Buffer Object Use

All we have done so far is copied the `vertices[]` and `color[]` arrays to a buffer object

The graphics pipeline has no idea of the existence of the buffer object nor what is contained in it

We need to:
1. tell the graphics pipeline what is in the buffer object
2. pass the buffer object to the graphics pipeline

Vertex Buffer Object Use

To tell the graphics pipeline that we're passing it an array of vertices, as with vertex array, enable `GL_VERTEX_ARRAY` in client memory:
- `glEnableClientState(GL_VERTEX_ARRAY)`

Next, pass the array, specifying the data format used (different from vertex array, the last argument is a byte offset from the start of buffer)
- `glVertexPointer(GLint size, GLenum type, GLsizei stride, const GLvoid *offset);`
  `// size`: # coordinates per vertex, `type`: data type,
  `// stride=0` means coordinates are back to back,
  `// offset`: byte offset from the start of buffer object

Finally, draw as with vertex array

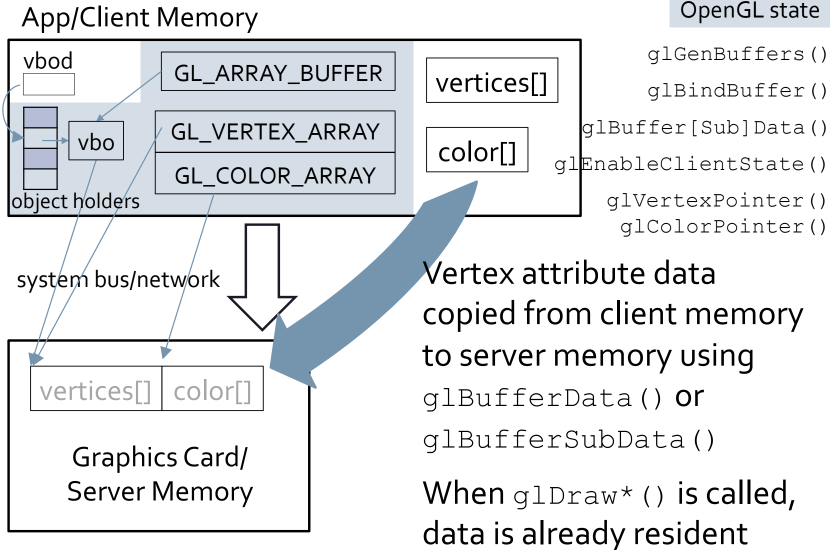
Vertex Buffer Object Use Example

```
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(2, GL_FLOAT, 0, 0);
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_FLOAT, 0,
               sizeof(vertices));

glDrawArrays(GL_TRIANGLES, 0, 3);
// start index: 0
// number of elements: 3
```

With vertex buffer object, client-side data array (`vertices[]` and `color[]`) do not need to be in scope when `glDraw*()` is called

Vertex Buffer Object

See vbo.cpp



OpenGL Object In General

OpenGL is a state machine

An OpenGL object is a container that encapsulates a particular set of states

The set of states an OpenGL object contain depends on the context it is bound to: the states that an object contains are mapped into and become the context's states, e.g., `glBindBuffer(GL_ARRAY_BUFFER, vbod);`

To read more:
http://www.opengl.org/wiki/OpenGL_Objects
http://www.opengl.org/wiki/Buffer_Objects
http://www.opengl.org/wiki/Vertex_Buffer_Object

Various OpenGL Objects

Buffer Objects: unformatted linear memory
- Vertex Buffer Objects
- Pixel Buffer Objects
- Uniform Buffer Objects

Vertex Array Objects: encapsulate sets of vertex array states including vbo bindings

Texture Objects: an OpenGL object that contains one or more images with the same image format

Framebuffer Objects
- Renderbuffer Objects

OpenGL Objects Management

All OpenGL objects are managed the same way:
- `glGen*()`
- `glBind*()`
- use
- `glDelete*()`
  - as soon as object usage is done, always call `glBind*()` with object handle 0 to unbind object and call `glDelete*()` to delete object [I'll assume you know this already and won't be mentioning it again]

Drawing Multiple Shapes

To draw different shapes, e.g., cube, sphere, cone, etc. multiple times, want to store the vertex attributes of each shape once ONLY, with re-use

Even then, with VBO alone, must make several API calls to change OpenGL state for each shape, each draw:

```
glBindBuffer(GL_ARRAY_BUFFER, vbods[i]);
glVertexPointer(2, GL_FLOAT, 0, vertex_offset);
glColorPointer(3, GL_FLOAT, 0, color_offset);
```

Vertex-Array Object

Vertex-Array Object (VAO) encapsulates vertex attribute states

- format, type, stride, storage info, and
- attached vertex buffer object if vbo is used

Enables rapid switching between sets of vertex array states and vbo bindings with a single API call, changing one OpenGL state:

```
glBindVertexArray(vaods[i]);
```

Requires OpenGL 3.0+

Vertex-Array Object

As with other OpenGL objects, first generate vertex-array object descriptor(s)/handle(s):

```
GLuint vaods[N];
glGenVertexArrays(GLsizei N, GLuint *vaods);
```

for example, if only 2 vertex-array objects are needed:

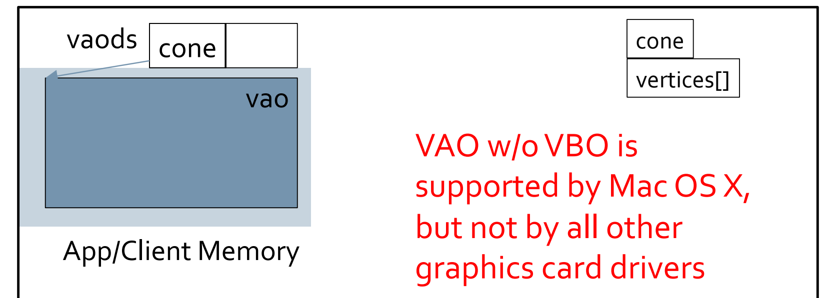
```
GLuint vaods[2];
glGenVertexArrays(2, vaods);
```

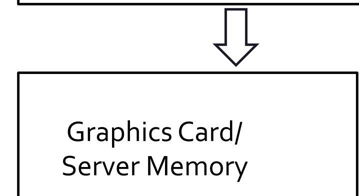
Next bind and make current each descriptor

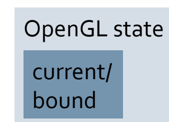
```
glBindVertexArray(GLuint vaods[int i]);
```

If `vaods` is `NULL`, disable Vertex-Array Object

Vertex Array Object without VBO







Setup Client-Side Vertex Array

For current/bound vertex-array object,
populate VAO by enabling client-side access:

```
glEnableClientState(GL_VERTEX_ARRAY);
```

then specify vertex array location:

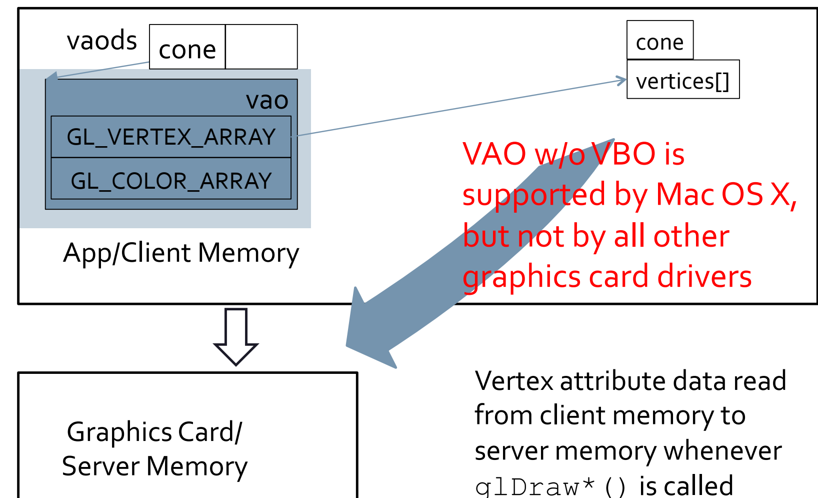
```
glVertexPointer(2, GL_FLOAT, 0, vertices);
```

Both client state and vertex array location
above are set within the context of a VAO

Then draw: VAO w/o VBO is supported by Mac OS X, but not by all other graphics card drivers

```
glDrawArrays(GL_TRIANGLES, 0, 3);
```

Vertex Array Object without VBO

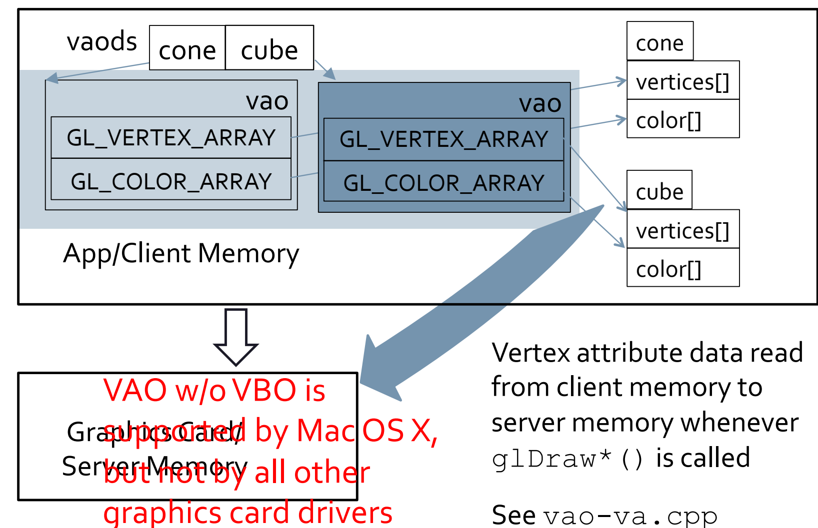


VAOs Switching Example

```
float cone[N][3], ccolors[N][3];
float cube[M][3], bcolors[M][3];

// set up: assuming vaods[] have been generated
glBindVertexArray(vaods[CONE]);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(3, GL_FLOAT, 0, cone);
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_FLOAT, 0, ccolors);

glBindVertexArray(vaods[CUBE]);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(3, GL_FLOAT, 0, cube);
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_FLOAT, 0, bcolors);

// use: cone[], ccolors[], cube[], and bcolors[] must be in scope
glBindVertexArray(vaods[CONE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, N);
glBindVertexArray(vaods[CUBE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, M);
glBindVertexArray(vaods[CONE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, N);
```

VAO w/o VBO is supported by Mac OS X, but not by all other graphics card drivers

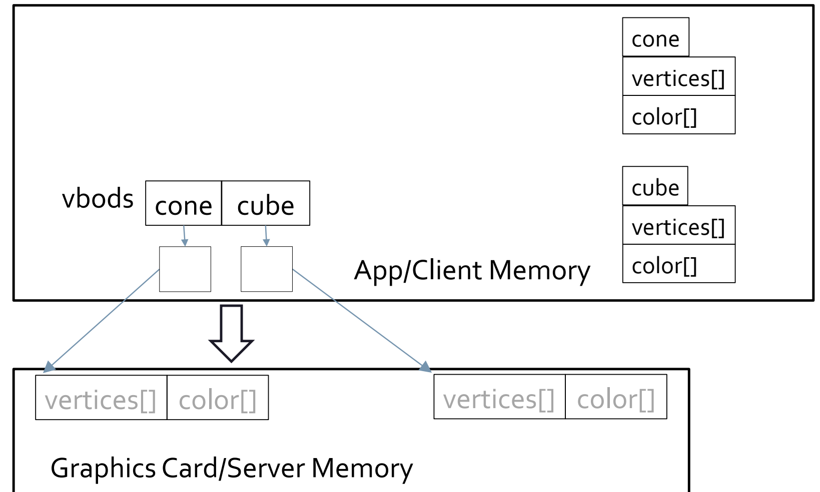
Vertex Array Object without VBO



VAO with VBO
First, Setup VBO

```
float cone[N][3], ccolors[N][3];
float cube[M][3], bcolors[M][3];
enum {CONE=0, CUBE, NSHAPES};

GLuint vbods[NSHAPES];
glGenBuffers(NSHAPES, vbods);

// set up the two vertex buffer objects
glBindBuffer(GL_ARRAY_BUFFER, vbods[CONE]);
glBufferData(GL_ARRAY_BUFFER, sizeof(cones)+sizeof(ccolors),
             0, GL_STATIC_DRAW));
glBufferSubData(GL_ARRAY_BUFFER, 0, sizeof(cone), cone);
glBufferSubData(GL_ARRAY_BUFFER,
                sizeof(cone), sizeof(ccolors), ccolors);

glBindBuffer(GL_ARRAY_BUFFER, vbods[CUBE]);
glBufferData(GL_ARRAY_BUFFER, sizeof(cube)+sizeof(bcolors),
             0, GL_STATIC_DRAW));
glBufferSubData(GL_ARRAY_BUFFER, 0, sizeof(cube), cube);
glBufferSubData(GL_ARRAY_BUFFER,
                sizeof(cube), sizeof(bcolors), bcolors);
```

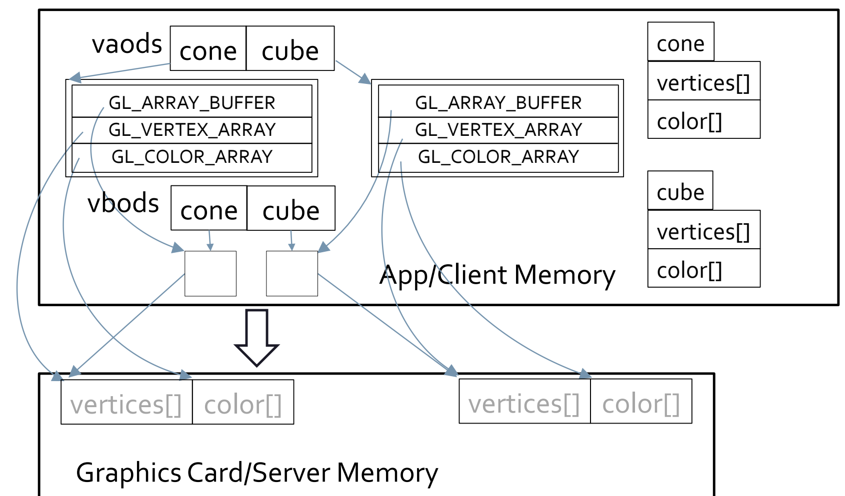
Vertex-Array Object with VBO



Next, Setup VAOs

```
GLuint vaods[NSHAPES];
glGenVertexArrays(NSHAPES, vaods);

// set up the two vertex-array objects
glBindVertexArray(vaods[CONE]);
glBindBuffer(GL_ARRAY_BUFFER, vbods[CONE]);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(3, GL_FLOAT, 0, 0 /* buffer byte offset */);
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_FLOAT, 0, sizeof(cone) /* byte offset */);

glBindVertexArray(vaods[CUBE]);
glBindBuffer(GL_ARRAY_BUFFER, vbods[CONE]);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(3, GL_FLOAT, 0, 0 /* byte offset */);
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_FLOAT, 0, sizeof(cube) /* byte offset */);
```

Vertex-Array Object with VBO



Finally, Use VAOs to Switch Shapes

```
// use, same as client-side, but cone[], ccolors[],
// cube[], and bcolors[] don't need to be in scope
glBindVertexArray(vaods[CONE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, N);

glBindVertexArray(vaods[CUBE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, M);

glBindVertexArray(vaods[CONE]);
glDrawArrays(GL_TRIANGLE_STRIP, 0, N);
```

See `vao-vbo.cpp`

Next: VBO and VAO with shaders