
Computer Graphics

2 - Introduction to NumPy / OpenGL

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Spring 2021

Summary of Course Intro

- Questions
 - <https://www.slido.com/> - Join #cg-ys
- Quiz & Attendance
 - <https://www.slido.com/> - Join #cg-ys - Polls
 - You must submit all quiz answers in the correct format to be checked for “attendance”.
- ~~• Language~~
 - ~~– I’ll “paraphrase” the explanation in Korean for most slides.~~
- You MUST read **1-CourseIntro.pdf** CAREFULLY.

Topics Covered

- Why Python in Computer Graphics?
- Introduction to NumPy
 - What is NumPy?
 - How to use NumPy
 - Handling vectors & matrices using NumPy
- Introduction to OpenGL
 - What is OpenGL?
 - OpenGL basics
 - GLFW input handling
 - Legacy OpenGL & Modern OpenGL
 - OpenGL as a Learning Tool

Why Python in Computer Graphics?

- Productivity
 - Easy to learn and use for beginners.
 - You can write code much faster.
 - You can focus on "logic", not language-specific issues.
- Powerful modules
 - A wide range of reliable modules are available.
 - E.g.) NumPy & SciPy for scientific computing, matplotlib for data visualization, ...
- **Python allows you to implement key computer graphics concepts in a short time.**

Why Python in Computer Graphics?

- Popular language in research & scientific community of other areas.
 - Most ML / DL framework provides Python API.
 - TensorFlow, PyTorch, Keras, Theano, ...
 - Most popular language in Data Science.
- **Python allows you to easily combine computer graphics and other techniques such as machine learning or data science.**

Python Interpreter

- Python **3.7** or later
 - <https://www.python.org/downloads/>
- Note that all submissions for assignments should work in Python **3.7**.
- You can use any OS that runs Python.

Introduction to NumPy

What is NumPy?

- NumPy is a Python module for scientific computing.
 - Written in C
 - Fast vector & matrix operations
- NumPy is **de-facto standard** for numerical computing in Python.
- Very useful for computer graphics applications, which are made of vectors & matrices.

NumPy usage

- You've already installed NumPy ~~in the last lab session~~.
 - If you haven't, see 1-Lab-EnvSetting.pdf slides and install it.
- Now, let's launch python3 interpreter in the interactive mode and import numpy like this:

```
>>> import numpy as np
```

: use 'np' as the local name for the module numpy

- The following NumPy slides come from:
 - <https://github.com/enthought/Numpy-Tutorial-SciPyConf-2017/blob/master/slides.pdf>

Introducing NumPy Arrays

SIMPLE ARRAY CREATION

```
>>> a = np.array([0, 1, 2, 3])
>>> a
array([0, 1, 2, 3])
```

CHECKING THE TYPE

```
>>> type(a)
numpy.ndarray
```

NUMERIC "TYPE" OF ELEMENTS

```
>>> a.dtype
dtype('int32')
```

NUMBER OF DIMENSIONS

```
>>> a.ndim
1
```

Array Operations

SIMPLE ARRAY MATH

```
>>> a = np.array([1, 2, 3, 4])
>>> b = np.array([2, 3, 4, 5])
>>> a + b
array([3, 5, 7, 9])

>>> a * b
array([ 2,  6, 12, 20])

>>> a ** b
array([ 1,  8, 81, 1024])
```



NumPy defines these constants:
 $\pi = 3.14159265359$
 $e = 2.71828182846$

```
# multiply entire array by
# scalar value
```

```
>>> 0.1 * a
array([0.1, 0.2, 0.3, 0.4])
```

```
# in-place operations
```

```
>>> a *= 2
>>> a
array([2, 4, 6, 8])
```

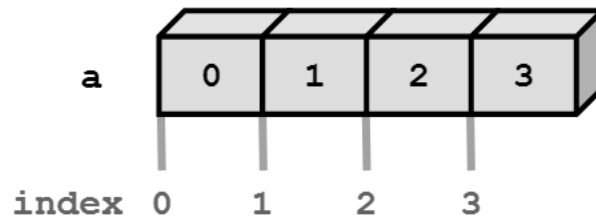
```
# apply functions to array
```

```
>>> x = 0.1*a
>>> x
array([0.2, 0.4, 0.6, 0.8])
>>> y = np.sin(x)
>>> y
array([0.19866933, 0.38941834,
0.56464247, 0.71735609])
```

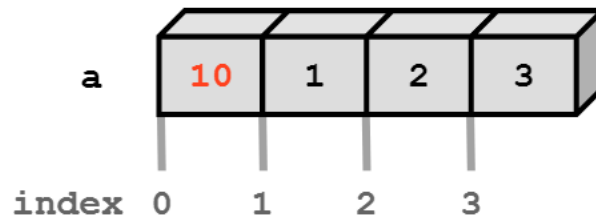
Setting Array Elements

ARRAY INDEXING

```
>>> a[0]
0
```



```
>>> a[0] = 10
>>> a
array([10, 1, 2, 3])
```



BEWARE OF TYPE COERCION

```
>>> a.dtype
dtype('int32')
```

```
# assigning a float into
# an int32 array truncates
# the decimal part
```

```
>>> a[0] = 10.6
>>> a
array([10, 1, 2, 3])
```

Numpy array: All elements have the same type and the size.

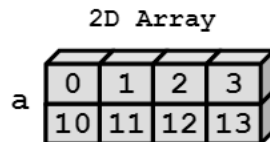


Python list: Elements can have various sizes and types.

Multi-Dimensional Arrays

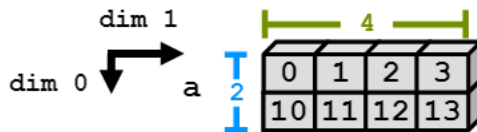
MULTI-DIMENSIONAL ARRAYS

```
>>> a = np.array([[ 0, 1, 2, 3],
...               [10,11,12,13]])
>>> a
array([[ 0,  1,  2,  3],
       [10, 11, 12, 13]])
```



SHAPE = (ROWS, COLUMNS)

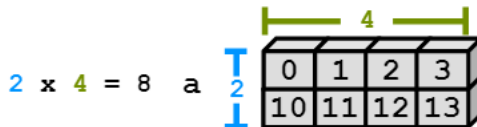
```
>>> a.shape
(2, 4)
```



```
# Shape returns a tuple
# listing the length of the
# array along each dimension.
```

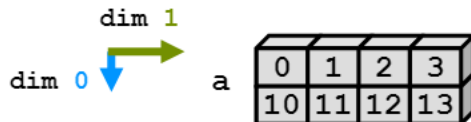
ELEMENT COUNT

```
>>> a.size
8
```



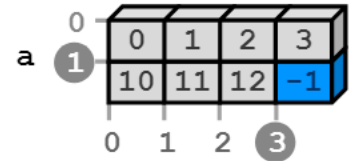
NUMBER OF DIMENSIONS

```
>>> a.ndim
2
```



GET / SET ELEMENTS

```
>>> a[1, 3]
13
>>> a[1, 3] = -1
>>> a
array([[ 0,  1,  2,  3],
       [10, 11, 12, -1]])
```



```
var [lower:upper:step]
```

Extracts a portion of a sequence by specifying a lower and upper bound. The lower-bound element is included, but the upper-bound element is **not** included. Mathematically: [lower, upper). The step value specifies the stride between elements.

SLICING ARRAYS

```
#           -5 -4 -3 -2 -1
# indices:   0  1  2  3  4
>>> a = np.array([10,11,12,13,14])

# [10, 11, 12, 13, 14]
>>> a[1:3]
array([11, 12])

# negative indices work also
>>> a[1:-2]
array([11, 12])
>>> a[-4:3]
array([11, 12])
```

OMITTING INDICIES

```
# omitted boundaries are
# assumed to be the beginning
# (or end) of the list

# grab first three elements
>>> a[:3]
array([10, 11, 12])

# grab last two elements
>>> a[-2:]
array([13, 14])

# every other element
>>> a[::2]
array([10, 12, 14])
```

Array Slicing

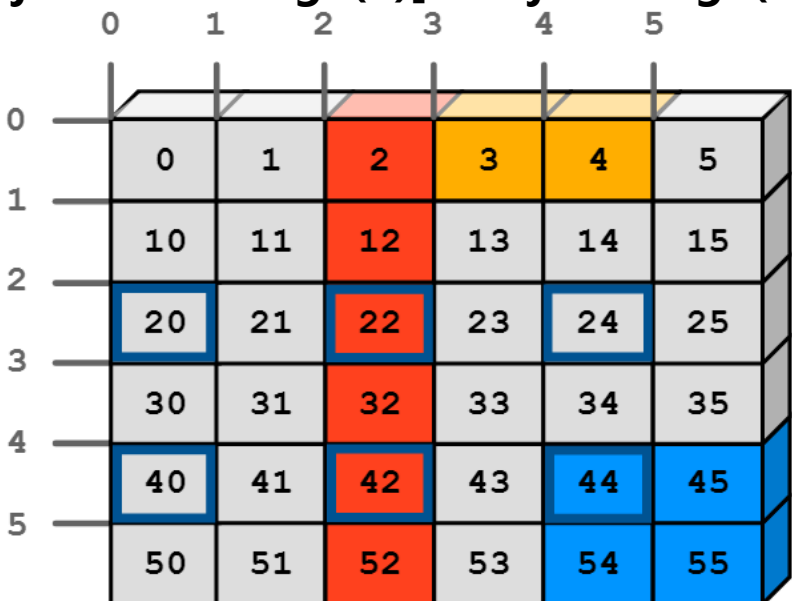
SLICING WORKS MUCH LIKE STANDARD PYTHON SLICING

```
>>> a[0, 3:5]
array([3, 4])
```

```
>>> a[4:, 4:]
array([[44, 45],
       [54, 55]])
```

```
>>> a[:, 2]
array([2, 12, 22, 32, 42, 52])
```

```
a = np.array([[i+10*j for i in range(6)] for j in range(6)])
```



	0	1	2	3	4	5
0	0	1	2	3	4	5
1	10	11	12	13	14	15
2	20	21	22	23	24	25
3	30	31	32	33	34	35
4	40	41	42	43	44	45
5	50	51	52	53	54	55

STRIDED ARE ALSO POSSIBLE

```
>>> a[2::2, ::2]
array([[20, 22, 24],
       [40, 42, 44]])
```

Array Constructor Examples

FLOATING POINT ARRAYS

```
# Default to double precision
>>> a = np.array([0,1.0,2,3])
>>> a.dtype
dtype('float64')
>>> a.nbytes
32
```

REDUCING PRECISION

```
>>> a = np.array([0,1.,2,3],
...               dtype='float32')
>>> a.dtype
dtype('float32')
>>> a.nbytes
16
```


Array Creation Functions

IDENTITY

$n \times n$ square matrix with ones on the main diagonal and zeros elsewhere.

```
# Generate an n by n identity
# array. The default dtype is
# float64.
```

```
>>> a = np.identity(4)
>>> a
array([[ 1.,  0.,  0.,  0.],
       [ 0.,  1.,  0.,  0.],
       [ 0.,  0.,  1.,  0.],
       [ 0.,  0.,  0.,  1.]])
```

```
>>> a.dtype
dtype('float64')
```

```
>>> np.identity(4, dtype=int)
array([[ 1,  0,  0,  0],
       [ 0,  1,  0,  0],
       [ 0,  0,  1,  0],
       [ 0,  0,  0,  1]])
```

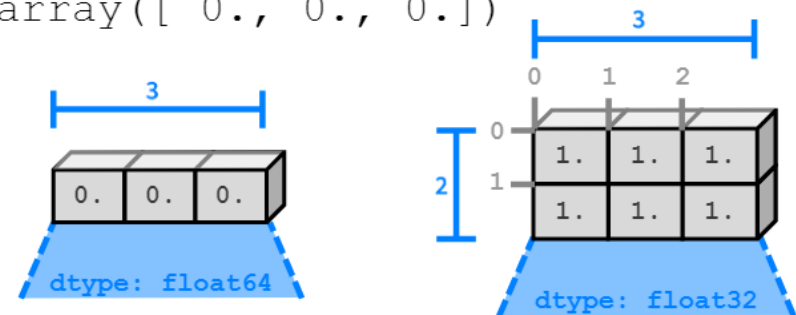
ONES, ZEROS

```
ones(shape, dtype='float64')
zeros(shape, dtype='float64')
```

shape is a number or sequence specifying the dimensions of the array. If **dtype** is not specified, it defaults to **float64**.

```
>>> np.ones((2, 3),
...         dtype='float32')
array([[ 1.,  1.,  1.],
       [ 1.,  1.,  1.]],
      dtype=float32)
```

```
>>> np.zeros(3)
array([ 0.,  0.,  0.]])
```



`zeros(3)` is equivalent to `zeros((3,))`

Array Creation Functions (cont'd)

Linspace

```
# Generate N evenly spaced
# elements between (and including)
# start and stop values.
>>> np.linspace(0, 1, 5)
array([0., 0.25., 0.5, 0.75, 1.0])
```

ARANGE

```
arange([start,] stop[, step],
       dtype=None)
```

- Nearly identical to Python's range()
- Creates an array of the interval including *start* but **excluding stop**
- When using a **non-integer step**, the results will **often not be consistent due to finite machine precision**. It is **better to use linspace()** for this case.

```
>>> np.arange(4)
array([0, 1, 2, 3])
```

```
>>> np.arange(1.5, 2.1, 0.3)
array([ 1.5, 1.8, 2.1])
```

Transpose

TRANSPOSE

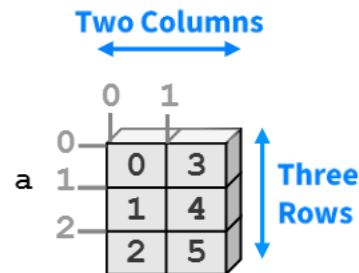
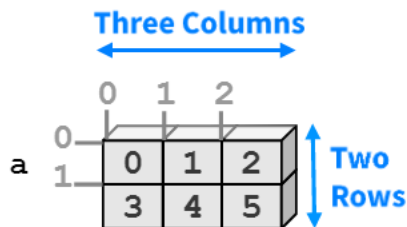
```
>>> a = np.array([[0,1,2],  
...               [3,4,5]])
```

```
>>> a.shape  
(2,3)
```

Transpose swaps the order
of axes.

```
>>> a.T  
array([[0, 3],  
       [1, 4],  
       [2, 5]])
```

```
>>> a.T.shape  
(3,2)
```



Reshaping Arrays

RESHAPE

```
>>> a = np.array([[0,1,2],  
...               [3,4,5]])
```

Return a new array with a
different shape (a view
where possible)

```
>>> a.reshape(3,2)  
array([[0, 1],  
       [2, 3],  
       [4, 5]])
```

Reshape cannot change the
number of elements in an
array

```
>>> a.reshape(4,2)
```

ValueError: total size of new
array must be unchanged

Quiz #1

- Go to <https://www.slido.com/>
- Join #cg-ys
- Click “Polls”

- Submit your answer in the following format:
 - **Student ID: Your answer**
 - e.g. **2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for “attendance”.

Vector & Matrix with NumPy

- Vectors are just 1D arrays:

```
>>> v = np.arange(3)
>>> v
array([0, 1, 2])
```

- Matrices are just 2D arrays:

```
>>> M = np.arange(9).reshape(3,3)
>>> M
array([[0, 1, 2],
       [3, 4, 5],
       [6, 7, 8]])
```

Matrix & Vector Multiplication

- `*` is an element-wise multiplication operator.

```
>>> v * v
array([0, 1, 4])
>>> M * M
array([[ 0,  1,  4],
       [ 9, 16, 25],
       [36, 49, 64]])
```

- Not so much used in computer graphics.

Matrix & Vector Multiplication

- Matrix multiplication requires "dot product" (inner product in Euclidian space)

$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \times \begin{bmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{bmatrix} = \begin{bmatrix} 58 \\ \end{bmatrix}$$

The "Dot Product" is where we **multiply matching members**, then sum up:

$$\begin{aligned} (1, 2, 3) \cdot (7, 9, 11) &= 1 \times 7 + 2 \times 9 + 3 \times 11 \\ &= 58 \end{aligned}$$

Matrix & Vector Multiplication

- **@** is a **matrix multiplication operator**.

```
>>> v @ v
5
>>> M @ M
array([[ 15,  18,  21],
       [ 42,  54,  66],
       [ 69,  90, 111]])
>>> M @ v
array([ 5, 14, 23])
```

- Very often used in computer graphics!

Quiz #2

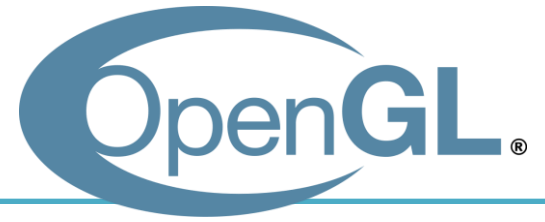
- Go to <https://www.slido.com/>
- Join #cg-ys
- Click “Polls”

- Submit your answer in the following format:
 - **Student ID: Your answer**
 - e.g. **2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for “attendance”.

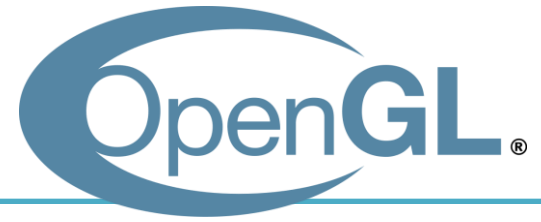
Introduction to OpenGL

What is OpenGL?



- **Open Graphics Library**
- OpenGL is an **API** (Application Programming Interface) for graphics programming.
 - Unlike its name, OpenGL is not a library.

What is OpenGL?



- **API is a specification.**
 - API describes **interfaces** and **expected behavior**.
- As for OpenGL API,
 - OS vendors provide OpenGL interface (e.g. `opengl32.dll` on Windows)
 - GPU vendors provide OpenGL implementation, the graphics card driver (e.g. Nvidia drivers)

Characteristics of OpenGL

- Cross platform
 - You can use OpenGL on Windows, OS X, Linux, iOS, Android, ...
- Language independent
 - OpenGL has many language bindings (C, Python, Java, Javascript, ...)
 - We'll use its Python binding in this class - PyOpenGL

So, what can we do with OpenGL?

- **Just only drawing things**
 - Provides small, but powerful set of low-level drawing operations
 - No functions for creating windows & OpenGL contexts, handling events (we'll see the "context" later)
- Thus, additional utility libraries are required to use OpenGL
 - GLFW, FreeGLUT : Simple utility libraries for OpenGL
 - Fltk, wxWidgets, Qt, Gtk : General purpose GUI framework

Utility Libraries for Learning OpenGL

- General GUI frameworks(e.g. Qt) are powerful, but too heavy for just learning OpenGL.
- GLUT “was” most popular for this purpose.
 - But it’s outdated and unmaintained.
 - Its open-source clone FreeGLUT is mostly concerned with providing a stable clone of GLUT.
- Now, GLFW is getting more popular.
 - Provides much fine control for managing windows and events.
 - So GLFW is our choice for this class.

[Practice] First OpenGL Program

```
import glfw
from OpenGL.GL import *

def render():
    pass

def main():
    # Initialize the library
    if not glfw.init():
        return
    # Create a windowed mode window and its OpenGL context
    window = glfw.create_window(640, 480, "Hello World", None, None)
    if not window:
        glfw.terminate()
        return

    # Make the window's context current
    glfw.make_context_current(window)

    # Loop until the user closes the window
    while not glfw.window_should_close(window):
        # Poll events
        glfw.poll_events()

        # Render here, e.g. using pyOpenGL
        render()

        # Swap front and back buffers
        glfw.swap_buffers(window)

    glfw.terminate()

if __name__ == "__main__":
    main()
```

import X
: access X's attribute or method using X.attribute, X.method()

from X import *
: access X's attribute or method just using attribute, method()

If the python interpreter is running this source file as the main program, it sets the special `__name__` variable to have a value `"__main__"`.

If this file is being imported from another module, `__name__` will be set to the module's name.

[Practice] Draw a Triangle

```
def render():  
    glClear(GL_COLOR_BUFFER_BIT)  
    glLoadIdentity()  
    glBegin(GL_TRIANGLES)  
    glVertex2f(0.0, 1.0)  
    glVertex2f(-1.0, -1.0)  
    glVertex2f(1.0, -1.0)  
    glEnd()
```

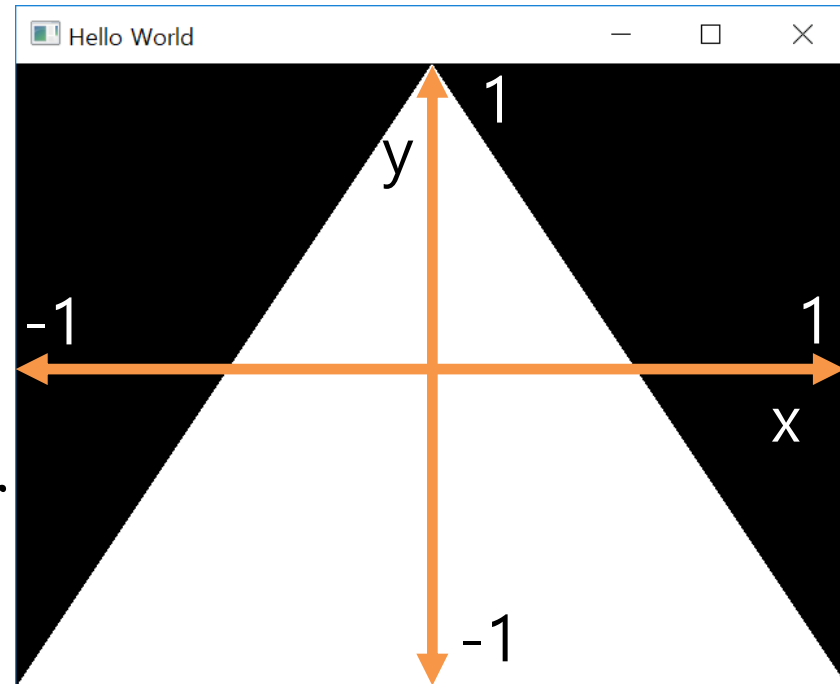
Vertex

- In OpenGL, geometry is specified by **vertices**.
- To draw something, vertices have to be listed between *glBegin(primitive_type)* and *glEnd()* calls.
- *glVertex*()* specifies the coordinate values of a vertex.

```
glBegin(GL_TRIANGLES)
glVertex2f(0.0, 1.0)
glVertex2f(-1.0, -1.0)
glVertex2f(1.0, -1.0)
glEnd()
```

Coordinate System

- You can draw the triangle anywhere in a 2D square ranging from $(-1, -1)$ to $(1, 1)$.
- Called “Normalized Device Coordinate” (NDC).
- We’ll see how objects are transformed to NDC in later classes.

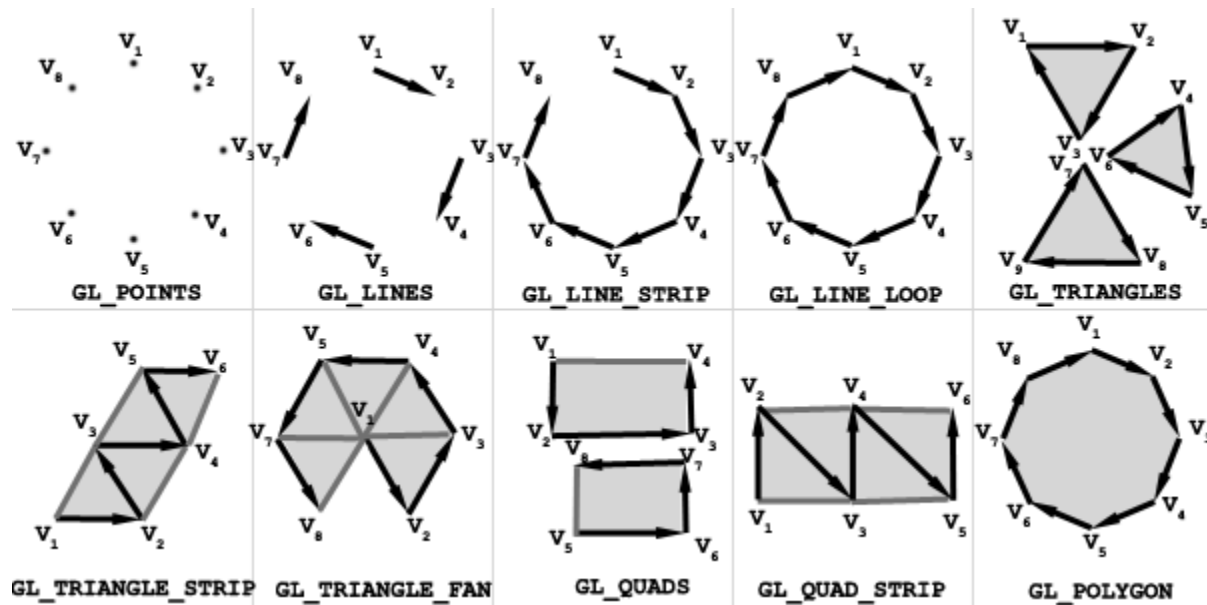


[Practice] Resize the Triangle

```
def render():  
    glClear(GL_COLOR_BUFFER_BIT)  
    glLoadIdentity()  
    glBegin(GL_TRIANGLES)  
    glVertex2f(0.0, 0.5)  
    glVertex2f(-0.5, -0.5)  
    glVertex2f(0.5, -0.5)  
    glEnd()
```

Primitive Types

- Primitive types in $glBegin(\textit{primitive_type})$:



- They represent how vertices are to be connected.

[Practice] Change the Primitive Type

```
def render():
    glClear(GL_COLOR_BUFFER_BIT)
    glLoadIdentity()
    glBegin(GL_POINTS)
    # glBegin(GL_LINES)
    # glBegin(GL_LINE_STRIP)
    # glBegin(GL_LINE_LOOP)
    # ...
    glVertex2f(0.0, 0.5)
    glVertex2f(-0.5, -0.5)
    glVertex2f(0.5, -0.5)
    glEnd()
```

Vertex Attributes

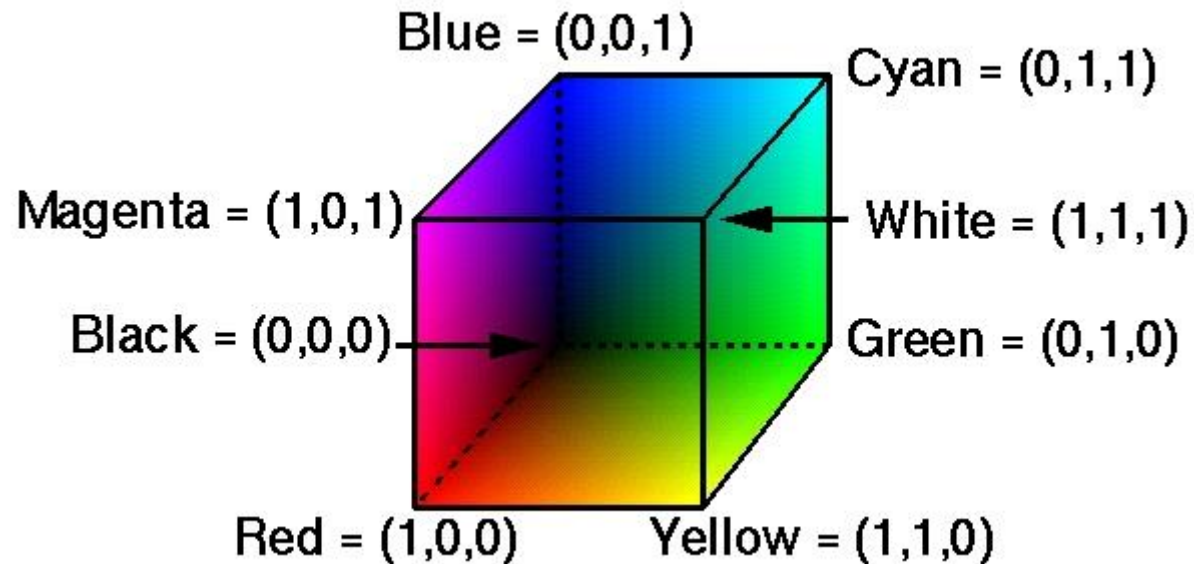
- In OpenGL, a vertex has these attributes:
 - **Vertex coordinate** : specified by glVertex*()
 - **Vertex color** : specified by glColor*()
 - **Normal vector** : specified by glNormal*()
 - **Texture coordinate** : specified by glTexCoord*()
- We'll see normal vector and texture coord. attributes in later classes.
- Now, let's have a look at the **vertex color**.

[Practice] Colored Triangle

```
def render():  
    glClear(GL_COLOR_BUFFER_BIT)  
    glLoadIdentity()  
    glBegin(GL_TRIANGLES)  
    glColor3f(1.0, 0.0, 0.0)  
    glVertex2f(0.0, 1.0)  
    glColor3f(0.0, 1.0, 0.0)  
    glVertex2f(-1.0, -1.0)  
    glColor3f(0.0, 0.0, 1.0)  
    glVertex2f(1.0, -1.0)  
    glEnd()
```


Color

- OpenGL uses the RGB color model.



- Colors in interior are interpolated.

Then, how to draw a just “red” triangle?

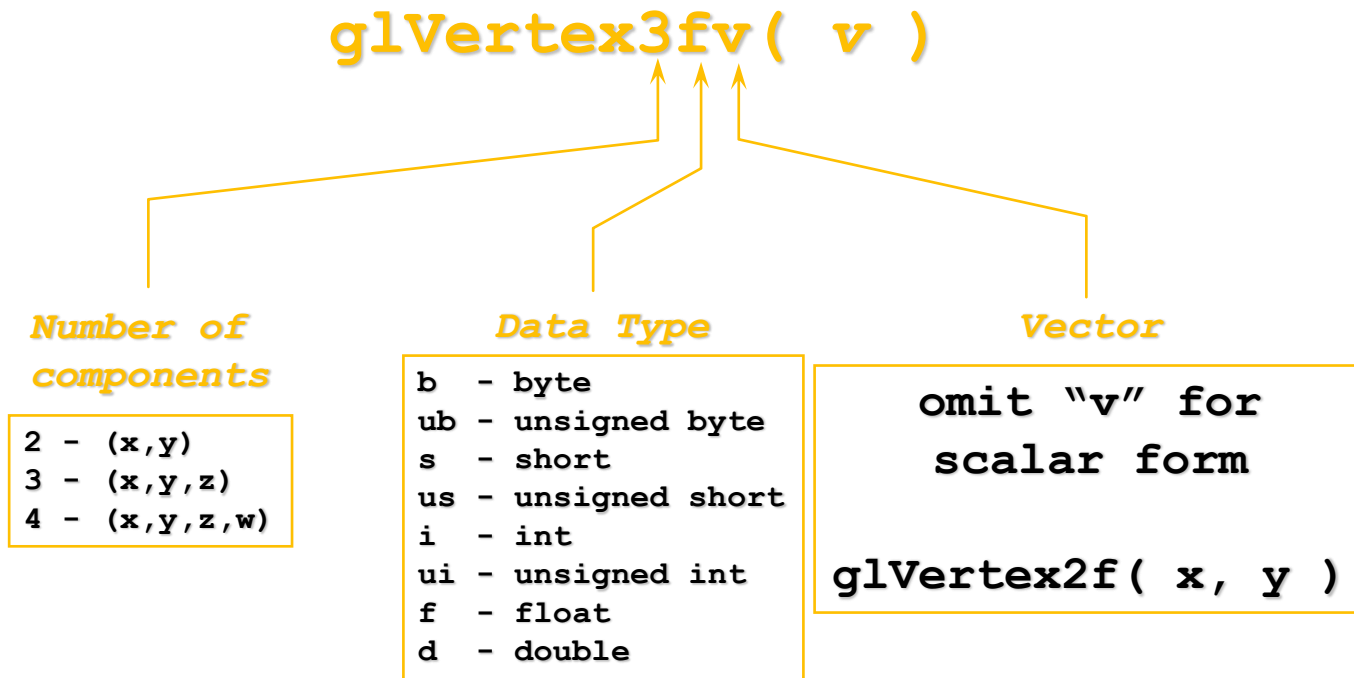
- Set red color for each vertex?
- You can do it just by:

```
def render():  
    glClear(GL_COLOR_BUFFER_BIT)  
    glLoadIdentity()  
    glBegin(GL_TRIANGLES)  
    glColor3f(1.0, 0.0, 0.0)  
    glVertex2f(0.0, 1.0)  
    glVertex2f(-1.0, -1.0)  
    glVertex2f(1.0, -1.0)  
    glEnd()
```

OpenGL is a State Machine

- If you set a value for a state (or mode), **it remains in effect until you change it.**
 - E.g. “current” color
 - Others states:
 - “current” viewing and projection transformations
 - “current” polygon drawing modes
 - “current” positions and characteristics of lights
 - “current” material properties of the objects
 - ...
- **OpenGL context** stores all of the state associated with this instance of OpenGL.

OpenGL Functions



[Practice] Using other forms of OpenGL Functions

```
import numpy as np

def render():
    glClear(GL_COLOR_BUFFER_BIT)
    glLoadIdentity()
    glBegin(GL_TRIANGLES)
    glColor3ub(255, 0, 0)
    glVertex2fv((0.0, 1.0))
    glVertex2fv([-1.0, -1.0])
    glVertex2fv(np.array([1.0, -1.0]))
    glEnd()
```

Quiz #3

- Go to <https://www.slido.com/>
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- Click “Polls”

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GLFW Input Handling

- *glfw.poll_events()*
 - Processes events that have already been received and then returns immediately.
 - Calls a user-registered callback function for each type of events.

Event type	Set a callback using...
Key input	<code>glfw.set_key_callback()</code>
Mouse cursor position	<code>glfw.set_cursor_pos_callback()</code> or just poll the position using <code>glfw.get_cursor_pos()</code>
Mouse button	<code>glfw.set_mouse_button_callback()</code>
Mouse scroll	<code>glfw.set_scroll_callback()</code>

```
import glfw
from OpenGL.GL import *

def render():
    pass

def key_callback(window, key, scancode, action, mods):
    if key==glfw.KEY_A:
        if action==glfw.PRESS:
            print('press a')
        elif action==glfw.RELEASE:
            print('release a')
        elif action==glfw.REPEAT:
            print('repeat a')
    elif key==glfw.KEY_SPACE and action==glfw.PRESS:
        print ('press space: (%d, %d)'%glfw.get_cursor_pos(window))

def cursor_callback(window, xpos, ypos):
    print('mouse cursor moving: (%d, %d)'%(xpos, ypos))

def button_callback(window, button, action, mod):
    if button==glfw.MOUSE_BUTTON_LEFT:
        if action==glfw.PRESS:
            print('press left btn: (%d, %d)'%glfw.get_cursor_pos(window))
        elif action==glfw.RELEASE:
            print('release left btn: (%d, %d)'%glfw.get_cursor_pos(window))

def scroll_callback(window, xoffset, yoffset):
    print('mouse wheel scroll: %d, %d'%(xoffset, yoffset))
```



```
def main():
    # Initialize the library
    if not glfw.init():
        return

    # Create a windowed mode window and its OpenGL context
    window = glfw.create_window(640, 480, "Hello World", None, None)
    if not window:
        glfw.terminate()
        return

    glfw.set_key_callback(window, key_callback)
    glfw.set_cursor_pos_callback(window, cursor_callback)
    glfw.set_mouse_button_callback(window, button_callback)
    glfw.set_scroll_callback(window, scroll_callback)

    # Make the window's context current
    glfw.make_context_current(window)

    # Loop until the user closes the window
    while not glfw.window_should_close(window):
        # Poll for and process events
        glfw.poll_events()
        # Render here, e.g. using pyOpenGL
        render()
        # Swap front and back buffers
        glfw.swap_buffers(window)

    glfw.terminate()

if __name__ == "__main__":
    main()
```

Documentation for glfw

- <http://www.glfw.org/documentation.html>
- Note there are changes in the python binding:
 - function names use the pythonic **words_with_underscores** notation instead of camelCase
 - **GLFW_ and glfw prefixes have been removed**, as their function is replaced by the module namespace
 - functions like glfwGetMonitors **return a list instead of a pointer and an object count**
 - see <https://pypi.python.org/pypi/glfw> for more information

Legacy OpenGL & Modern OpenGL

- Legacy OpenGL (OpenGL 1.x)
 - Invented when “fixed-function” hardware was standard
 - No shaders
 - Easier to learn & good for rapid prototyping
 - Deprecated since OpenGL 3.0
- Modern OpenGL (OpenGL 2.x~)
 - Now programmable hardware is the common industry practice
 - Use of programmable shaders
 - More difficult to program but far more flexible & powerful

OpenGL as a Learning Tool

- My focus is on fundamental computer graphics ideas, not on concrete implementation.
- So I choose the legacy OpenGL as a basic learning tool, thanks to its simplicity.
- Note that legacy OpenGL is **just one implementation example** of fundamental computer graphics ideas we'll learn.
- Other implementations:
 - Graphics libraries: Modern OpenGL, DirectX, Vulkan, Nvidia Optix, ...
 - Game engines: Unreal, Unity, ...
 - Authoring tools: Maya, Blender, ...

Next Time

- Lab in this week:
 - 1-Lab-EnvSetting: Environment settings for lectures & assignments
 - 2-Lab-Gitlab
 - Lab assignment 1
 - Lab assignment 2
- Next lecture:
 - 3 - Transformation 1