Computer Graphics

7 - Lab - Hierarchical Modeling, Mesh

Yoonsang Lee
Hanyang University

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Outline

- Drawing a Simple Hierarchical Model Example
- Drawing a Cube using glDrawArrays() (Separate Triangles)
- Drawing a Cube using glDrawElements() (Indexed Triangle Set)

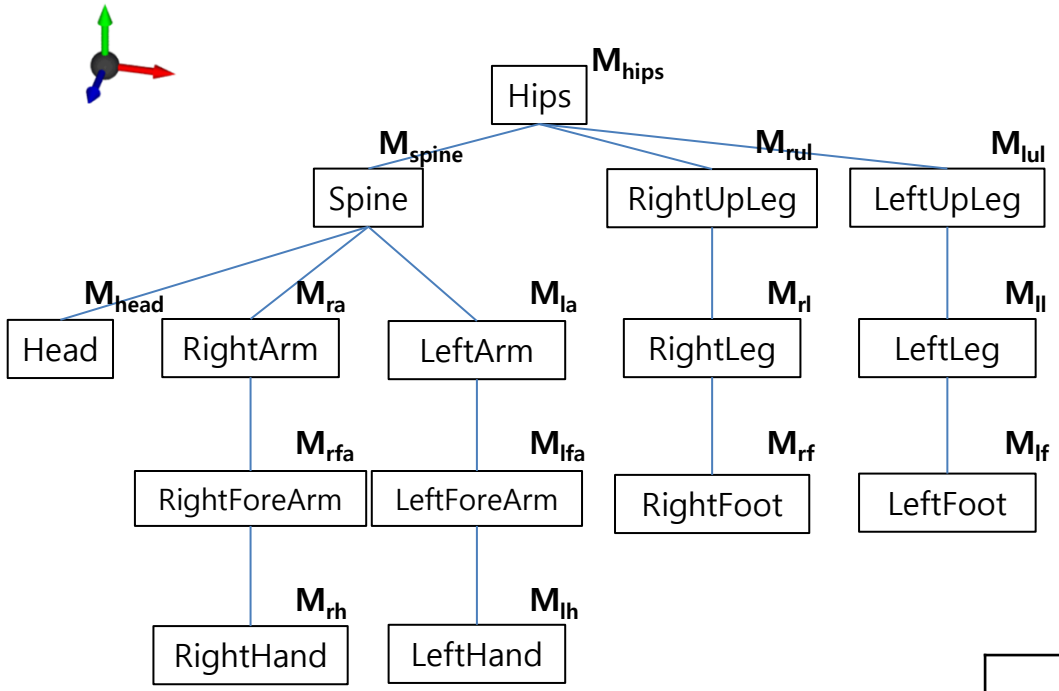
Drawing a Simple Hierarchical Model Example

Rendering Hierarchical Models - Method 1

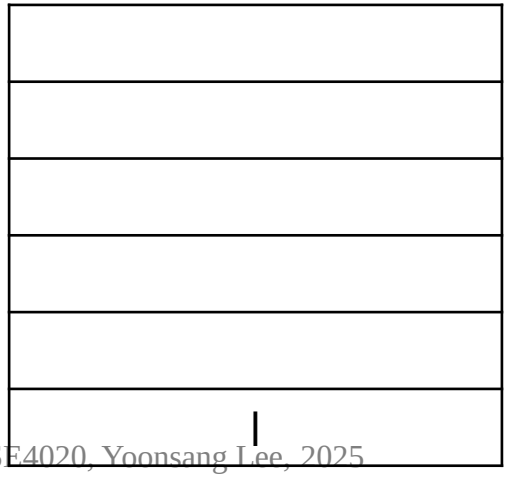
Node i	Global Transform G_i = …
Hips	M_{hips}
Spine	M_{hips} M_{spine}
Head	M_{hips} M_{spine} M_{head}
RightArm	M_{hips} M_{spine} M_{ra}
RightForeArm	M_{hips} M_{spine} M_{ra} M_{rfa}
RightHand	M_{hips} M_{spine} M_{ra} M_{rfa} M_{rh}
LeftArm	M_{hips} M_{spine} M_{la}
…	

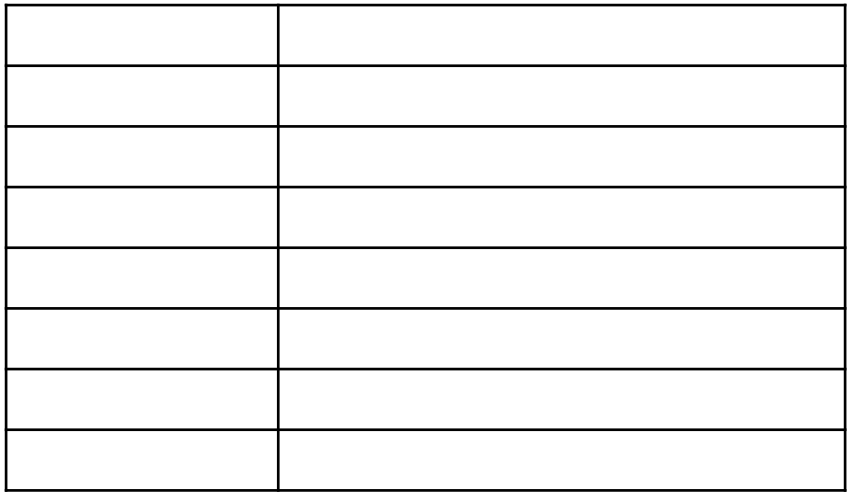
- **Method 1:** Store global transform $\mathbf{G_i}$ in each node (i-th node) *instance (object)* and use it for rendering.

Rendering Hierarchical Models - Method 2

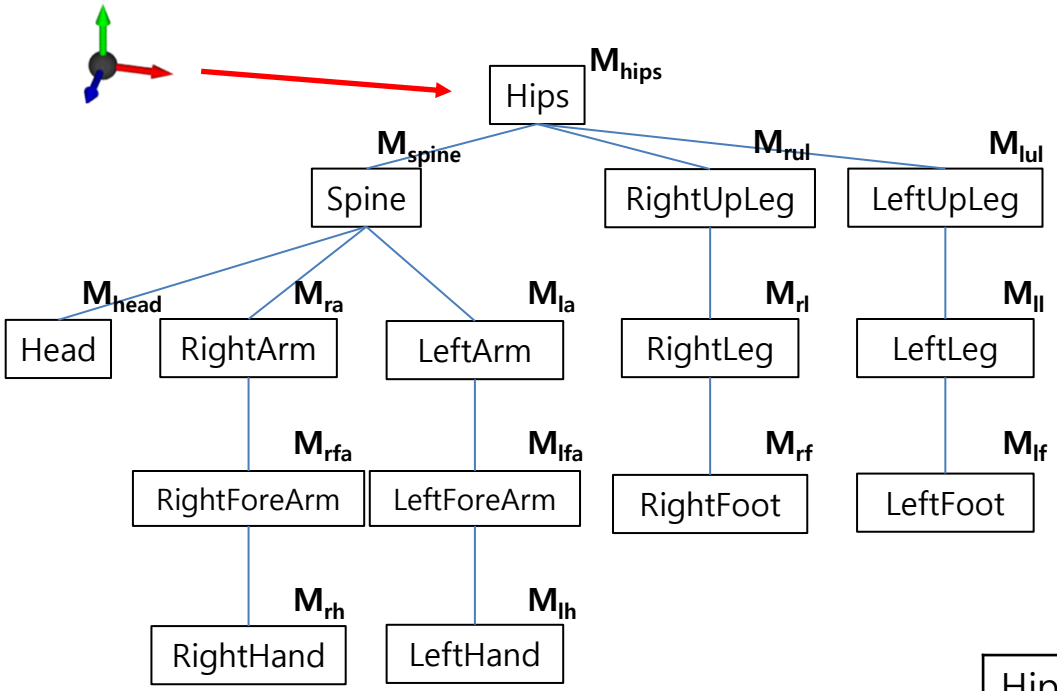


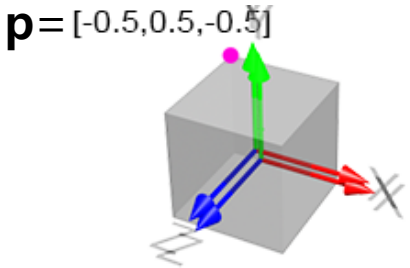
- **Method 2:**
  Use *stack* for *depth-first traversal* to compute global transform $\mathbf{G_i}$ when rendering.



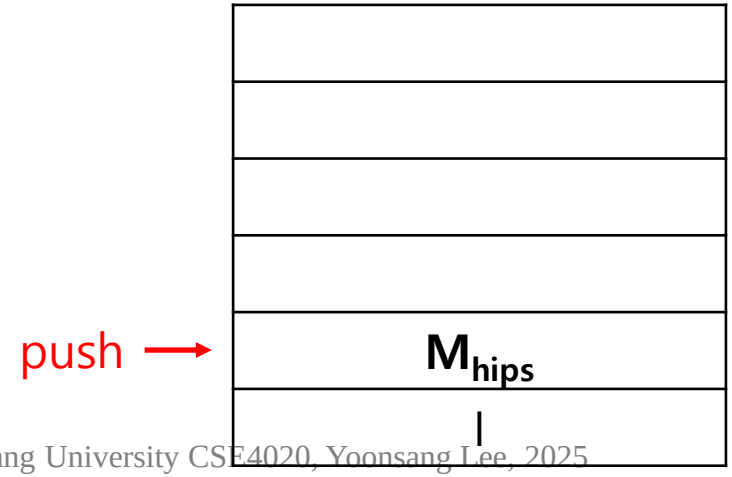


Rendering Hierarchical Models - Method 2



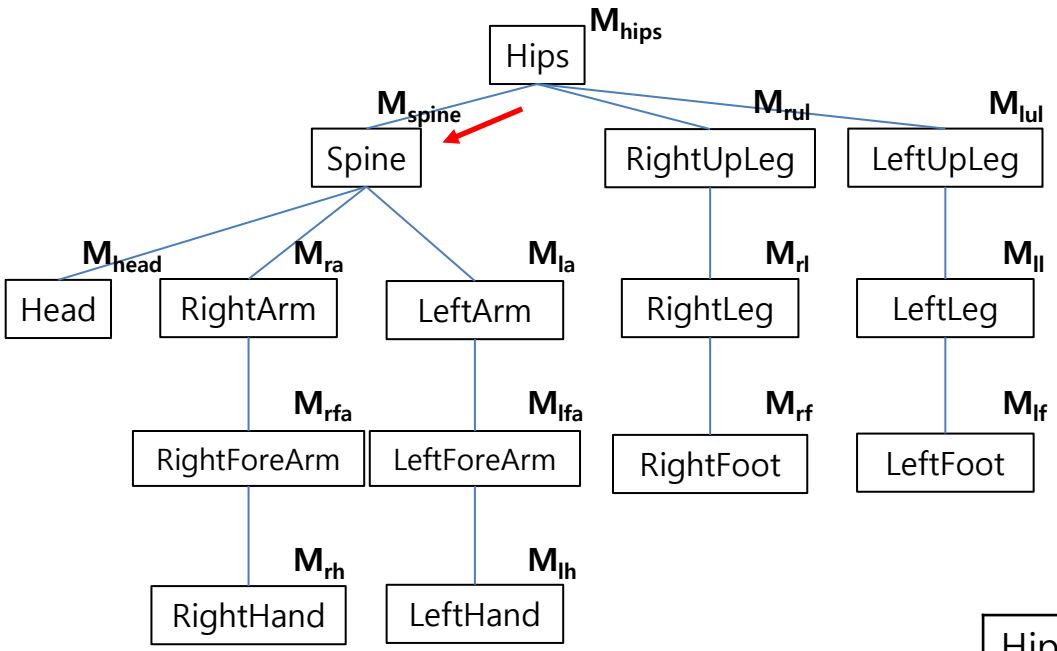


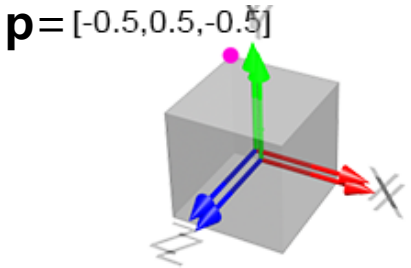
Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…



Hips	$\mathbf{p'} = M_{hips}\,\mathbf{p}$

Rendering Hierarchical Models - Method 2





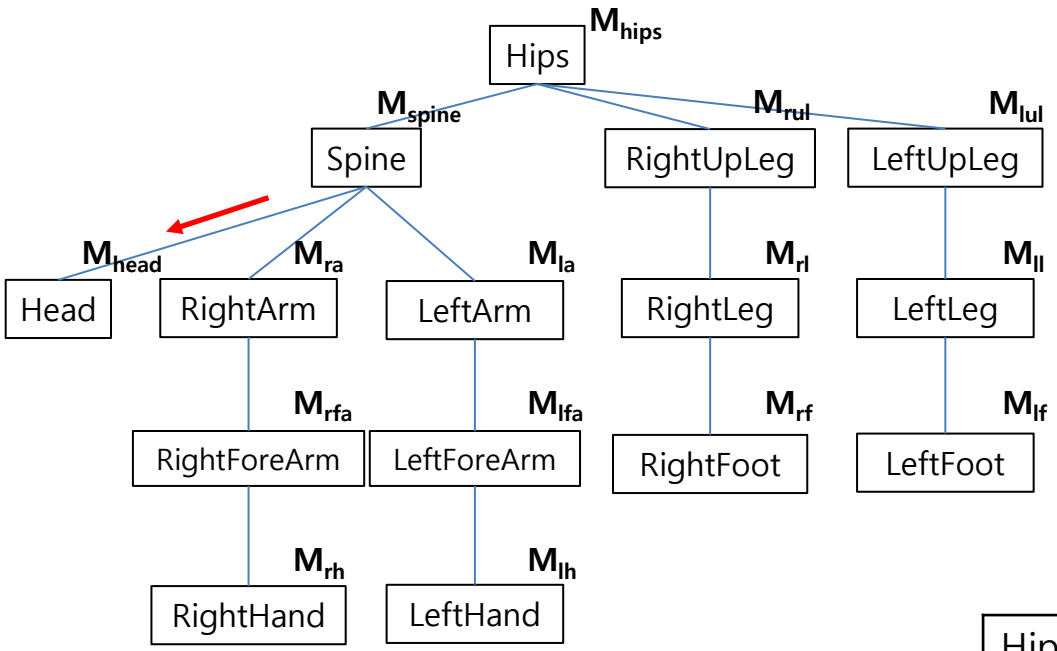
Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…

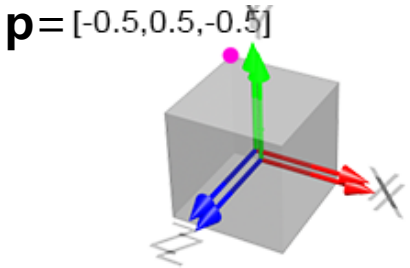
push →

$\mathbf{M_{hips}}\ \mathbf{M_{spine}}$
$\mathbf{M_{hips}}$

Hips	$\mathbf{p'} = \mathbf{M_{hips}}\ \mathbf{p}$
Spine	$\mathbf{p'} = \mathbf{M_{hips}}\ \mathbf{M_{spine}}\ \mathbf{p}$

Rendering Hierarchical Models - Method 2

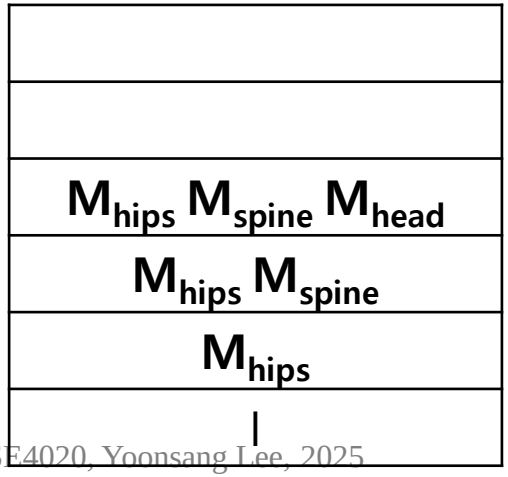




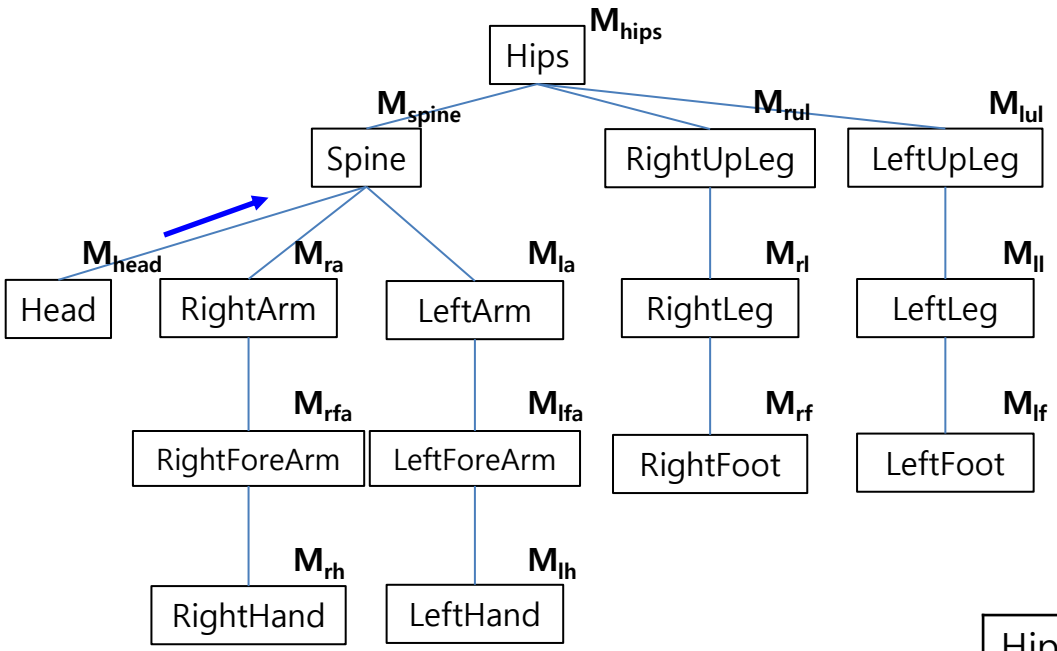
Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…

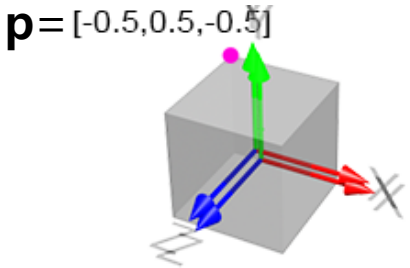
Hips	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{p}$
Spine	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{p}$
Head	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{M}_{head}\,\mathbf{p}$

push →



Rendering Hierarchical Models - Method 2

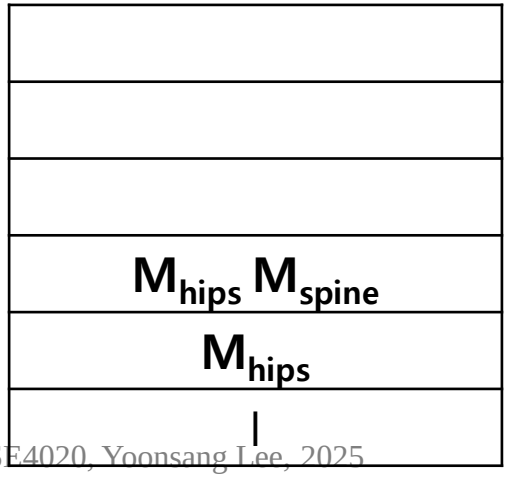




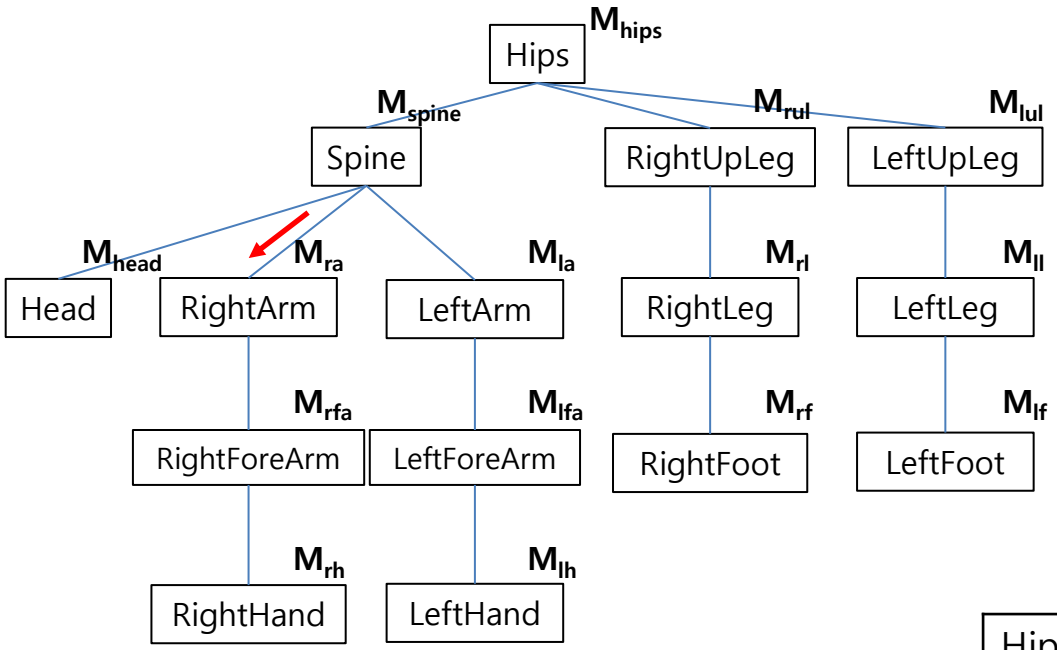
Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…

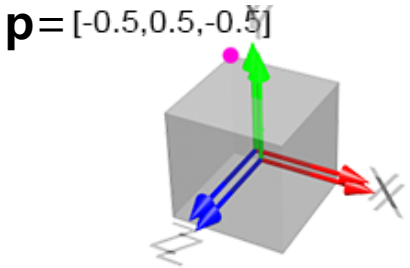
Hips	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{p}$
Spine	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{p}$
Head	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{M}_{head}\,\mathbf{p}$

pop ←



Rendering Hierarchical Models - Method 2

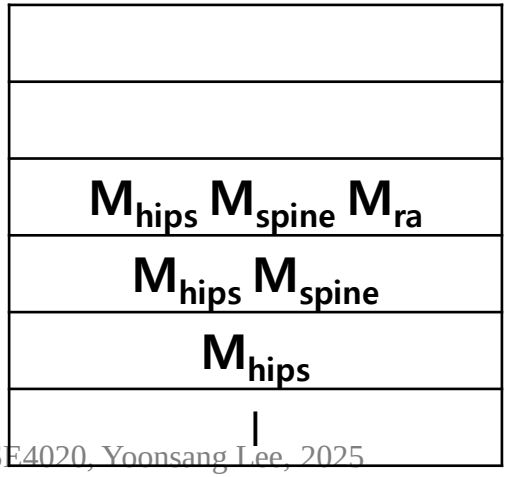




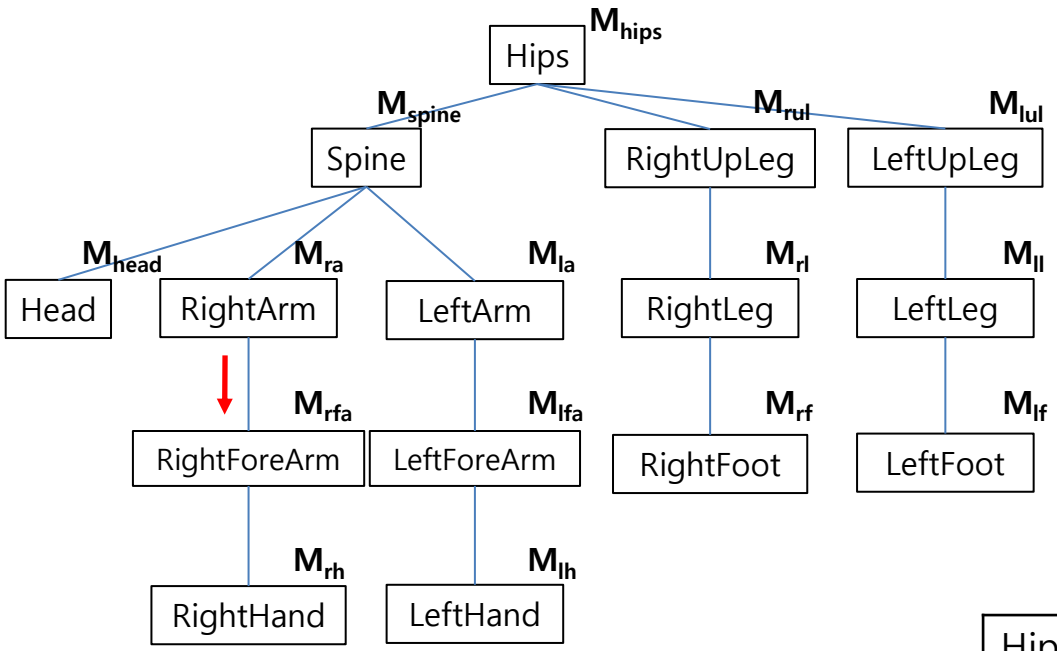
Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…

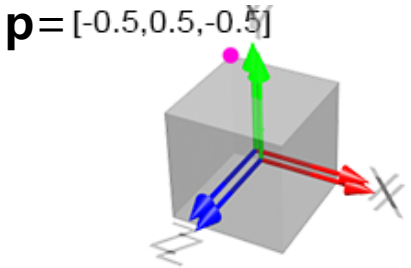
Hips	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{p}$
Spine	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{p}$
Head	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{M}_{head}\,\mathbf{p}$
RightArm	$\mathbf{p'} = \mathbf{M}_{hips}\,\mathbf{M}_{spine}\,\mathbf{M}_{ra}\,\mathbf{p}$

push →



Rendering Hierarchical Models - Method 2





Let's say each part is rendered as a unit cube above (without scaling), its vertex position **p'** w.r.t. world frame is…

push →

$M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}$
$M_{hips}\ M_{spine}\ M_{ra}$
$M_{hips}\ M_{spine}$
M_{hips}

Hips	$\mathbf{p'} = M_{hips}\ \mathbf{p}$
Spine	$\mathbf{p'} = M_{hips}\ M_{spine}\ \mathbf{p}$
Head	$\mathbf{p'} = M_{hips}\ M_{spine}\ M_{head}\ \mathbf{p}$
RightArm	$\mathbf{p'} = M_{hips}\ M_{spine}\ M_{ra}\ \mathbf{p}$
RightForeArm	$\mathbf{p'} = M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}\ \mathbf{p}$
…	

Two Methods for Rendering Hierarchical Models

- Method 1: Store global transform $\mathbf{G_i}$ in the node_i instance (object).
- Method 2: Use stack to compute global transform $\mathbf{G_i}$

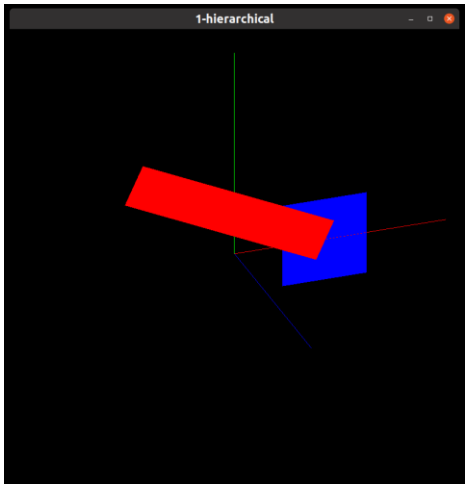
- Method 2 is the legacy OpenGL way.
  - In legacy OpenGL, a built-in matrix stack (glPushMatrix() / glPopMatrix()) was provided for managing transformations, but it has been removed in modern OpenGL.

- In modern OpenGL, you would typically calculate transformation matrices on the CPU and pass them as uniforms to shader programs. You can directly manage them without using a stack. → Method 1

- It is possible to use your own matrix stack if you prefer, but it is not necessary for modern OpenGL applications.

[Code] 1-hierarchical

- This example does not use a stack. It just stores global transform $\mathbf{G_i}$ in i-th node object.



- Translating "base" + rotating "arm"
- Three things to render, each moving differently:
  - World frame
  - Blue base
  - Red arm

[Code] 1-hierarchical

- Two VAOs
  - Frame VAO
  - Box VAO (for base and arm)
- Two shader programs
  - Shader for frame: use vertex color specified as a vertex attribute
  - Shader for box: use vertex color passed as a uniform variable
- "Node" class that represents a node and builds a tree structure
  - 2 Node instances: base, arm
- Each node instance has:
  - `parent` (parent node), `children` (child nodes)
  - `transform` (local transform)
  - `global_transform`
  - `shape_transform`
  - `color`

[Code] 1-hierarchical

Vertex shader for frame

```
#version 330 core

layout (location = 0) in vec3 vin_pos;
layout (location = 1) in vec3 vin_color;

out vec4 vout_color;

uniform mat4 MVP;

void main()
{
    // 3D points in homogeneous
coordinates
    vec4 p3D_in_hcoord =
vec4(vin_pos.xyz, 1.0);

    gl_Position = MVP * p3D_in_hcoord;

    vout_color = vec4(vin_color, 1.);
}
```

Vertex shader for box

```
#version 330 core

layout (location = 0) in vec3 vin_pos;

out vec4 vout_color;

uniform mat4 MVP;
uniform vec3 color;

void main()
{
    // 3D points in homogeneous
coordinates
    vec4 p3D_in_hcoord =
vec4(vin_pos.xyz, 1.0);

    gl_Position = MVP * p3D_in_hcoord;

    vout_color = vec4(color, 1.);
}
```

- Fragment shaders are the same for both frame and box.

[Code] 1-hierarchical

```
def prepare_vao_box():
    # prepare vertex data (in main
memory)
    # 6 vertices for 2 triangles
    vertices = glm.array(glm.float32,
        # position
        -1 ,  1 ,  0 , # v0
         1 , -1 ,  0 , # v2
         1 ,  1 ,  0 , # v1

        -1 ,  1 ,  0 , # v0
        -1 , -1 ,  0 , # v3
         1 , -1 ,  0 , # v2
    )
ss     ...

    # configure vertex positions
    glVertexAttribPointer(0, 3, GL_FLOAT,
GL_FALSE, 3 * glm.sizeof(glm.float32),
None)
    glEnableVertexAttribArray(0)

    return VAO
```

```
def prepare_vao_frame():
    # prepare vertex data (in main
memory)
    vertices = glm.array(glm.float32,
        # position # color
        0, 0, 0,  1, 0, 0, # x-axis start
        1, 0, 0,  1, 0, 0, # x-axis end
        0, 0, 0,  0, 1, 0, # y-axis start
        0, 1, 0,  0, 1, 0, # y-axis end
        0, 0, 0,  0, 0, 1, # z-axis start
        0, 0, 1,  0, 0, 1, # z-axis end
    )
    ...
    # configure vertex positions
    glVertexAttribPointer(0, 3, GL_FLOAT,
GL_FALSE, 6 * glm.sizeof(glm.float32),
None)
    glEnableVertexAttribArray(0)

    # configure vertex colors
    glVertexAttribPointer(1, 3, GL_FLOAT,
GL_FALSE, 6 * glm.sizeof(glm.float32),
ctypes.c_void_p(3*glm.sizeof(glm.float32)
))
    glEnableVertexAttribArray(1)

    return VAO
```

[Code] 1-hierarchical

```
class Node:
    def __init__(self, parent, shape_transform, color):
        # hierarchy
        self.parent = parent
        self.children = []
        if parent is not None:
            parent.children.append(self)

        # transform
        self.transform = glm.mat4()
        self.global_transform = glm.mat4()

        # shape
        self.shape_transform = shape_transform
        self.color = color

    def set_transform(self, transform):
        self.transform = transform
    def update_tree_global_transform(self):
        if self.parent is not None:
            self.global_transform = self.parent.get_global_transform() * self.transform
        else:
            self.global_transform = self.transform
        for child in self.children:
            child.update_tree_global_transform()

    def get_global_transform(self):
        return self.global_transform
    def get_shape_transform(self):
        return self.shape_transform
    def get_color(self):
        return self.color
```

[Code] 1-hierarchical

```
def draw_frame(vao, MVP, loc_MVP):
    glBindVertexArray(vao)
    glUniformMatrix4fv(loc_MVP, 1, GL_FALSE, glm.value_ptr(MVP))
    glDrawArrays(GL_LINES, 0, 6)

def draw_node(vao, node, VP, loc_MVP, loc_color):
    MVP = VP * node.get_global_transform() * node.get_shape_transform()
    color = node.get_color()

    glBindVertexArray(vao)
    glUniformMatrix4fv(loc_MVP, 1, GL_FALSE, glm.value_ptr(MVP))
    glUniform3f(loc_color, color.r, color.g, color.b)
    glDrawArrays(GL_TRIANGLES, 0, 6)
```

[Code] 1-hierarchical

```
def main():
    ...
    # load shaders
    shader_for_frame = load_shaders(g_vertex_shader_src_color_attribute,
g_fragment_shader_src)
    shader_for_box = load_shaders(g_vertex_shader_src_color_uniform,
g_fragment_shader_src)

    # get uniform locations
    loc_MVP_frame = glGetUniformLocation(shader_for_frame, 'MVP')
    loc_MVP_box = glGetUniformLocation(shader_for_box, 'MVP')
    loc_color_box = glGetUniformLocation(shader_for_box, 'color')

    # prepare vaos
    vao_box = prepare_vao_box()
    vao_frame = prepare_vao_frame()

    # create a hirarchical model - Node(parent, shape_transform, color)
    base = Node(None, glm.scale((.2,.2,0.)), glm.vec3(0,0,1))
    arm = Node(base, glm.translate((.5,0,.01)) * glm.scale((.5,.1,0.)),
glm.vec3(1,0,0))
```

[Code] 1-hierarchical

```
...
while not glfwWindowShouldClose(window):
     # projection matrix
    P = glm.ortho(-1,1,-1,1,-10,10)

    # view matrix
    V = glm.lookAt(...)

    # draw world frame
    glUseProgram(shader_for_frame)
    draw_frame(vao_frame, P*V*glm.mat4(), MVP_loc_frame)


    t = glfwGetTime()

    # set local transformations of each node
    base.set_transform(glm.translate((glm.sin(t),0,0)))
    arm.set_transform(glm.translate((.2, 0, 0)) * glm.rotate(t, (0,0,1)))

    # recursively update global transformations of all nodes
    base.update_tree_global_transform()

    # draw nodes
    glUseProgram(shader_for_box)
    draw_node(vao_box, base, P*V, MVP_loc_box, color_loc_box)
    draw_node(vao_box, arm, P*V, MVP_loc_box, color_loc_box)
```

Quiz 3

- Go to https://www.slido.com/
- Join #**cg-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2021123456: 4.0**

- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

Drawing a Cube

Using glDrawArrays() (Separate Triangles)

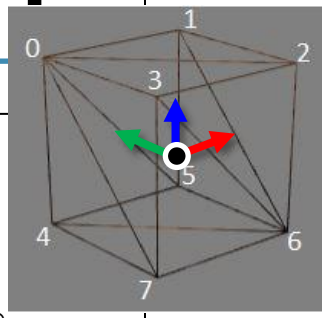
- This is what we've done to draw a cube in the previous lab.

```
def prepare_vao_cube():
# 36 vertices for 12 triangles
    vertices = glm.array(glm.float32,
        # position              color
        -0.5 ,  0.5 ,  0.5 ,  1, 1, 1, # v0
         0.5 , -0.5 ,  0.5 ,  1, 1, 1, # v2
         0.5 ,  0.5 ,  0.5 ,  1, 1, 1, # v1

        -0.5 ,  0.5 ,  0.5 ,  1, 1, 1, # v0
        -0.5 , -0.5 ,  0.5 ,  1, 1, 1, # v3
         0.5 , -0.5 ,  0.5 ,  1, 1, 1, # v2
        ...
)
    ...

def draw_cube(vao, MVP, MVP_loc):
    glBindVertexArray(vao)
    glUniformMatrix4fv(MVP_loc, 1, GL_FALSE, glm.value_ptr(MVP))
    glDrawArrays(GL_TRIANGLES, 0, 36)
```

[Code] 2-cube-separate

- Same as "2-frustum-perspective.py" in the previous lab except the size of the cube.
  - Cube edge length: 1 → 2

[Code] 2-cube-separate




```
def prepare_vao_cube():
    # prepare vertex data (in main memory)
    # 36 vertices for 12 triangles
    vertices = glm.array(glm.float32,
        # position      color
        -1 ,  1 ,  1 ,  1, 1, 1, # v0
         1 , -1 ,  1 ,  1, 1, 1, # v2
         1 ,  1 ,  1 ,  1, 1, 1, # v1

        -1 ,  1 ,  1 ,  1, 1, 1, # v0
        -1 , -1 ,  1 ,  1, 1, 1, # v3
         1 , -1 ,  1 ,  1, 1, 1, # v2

        -1 ,  1 , -1 ,  1, 1, 1, # v4
         1 ,  1 , -1 ,  1, 1, 1, # v5
         1 , -1 , -1 ,  1, 1, 1, # v6

        -1 ,  1 , -1 ,  1, 1, 1, # v4
         1 , -1 , -1 ,  1, 1, 1, # v6
        -1 , -1 , -1 ,  1, 1, 1, # v7

        -1 ,  1 ,  1 ,  1, 1, 1, # v0
         1 ,  1 ,  1 ,  1, 1, 1, # v1
         1 ,  1 , -1 ,  1, 1, 1, # v5

        -1 ,  1 ,  1 ,  1, 1, 1, # v0
         1 ,  1 , -1 ,  1, 1, 1, # v5
        -1 ,  1 , -1 ,  1, 1, 1, # v4

        -1 , -1 ,  1 ,  1, 1, 1, # v3
         1 , -1 , -1 ,  1, 1, 1, # v6
         1 , -1 ,  1 ,  1, 1, 1, # v2

        -1 , -1 ,  1 ,  1, 1, 1, # v3
        -1 , -1 , -1 ,  1, 1, 1, # v7
         1 , -1 , -1 ,  1, 1, 1, # v6

         1 ,  1 ,  1 ,  1, 1, 1, # v1
         1 , -1 ,  1 ,  1, 1, 1, # v2
         1 , -1 , -1 ,  1, 1, 1, # v6

         1 ,  1 ,  1 ,  1, 1, 1, # v1
         1 , -1 , -1 ,  1, 1, 1, # v6
         1 ,  1 , -1 ,  1, 1, 1, # v5

        -1 ,  1 ,  1 ,  1, 1, 1, # v0
        -1 , -1 , -1 ,  1, 1, 1, # v7
        -1 , -1 ,  1 ,  1, 1, 1, # v3

        -1 ,  1 ,  1 ,  1, 1, 1, # v0
        -1 ,  1 , -1 ,  1, 1, 1, # v4
        -1 , -1 , -1 ,  1, 1, 1, # v7
    )
```

Using glDrawElements()(Indexed Triangles)

- Using glDrawElements(), we can specify triangles in the indexed triangle set scheme.

- Indices are provided using an **EBO** (element buffer object).

Using glDrawElements()(Indexed Triangles)

- Preparation (at initialization):
  - 1. Create vertex data **and index data** (in main memory)
  - 2. Create and activate VAO
  - 3. Create and activate VBO
  - **3.5 Create and activate EBO**
  - 4. Copy vertex data to VBO
  - **4.5 Copy index data to EBO**
  - 5. Configure vertex attributes

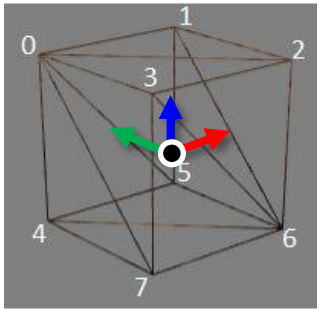
- Drawing (at every rendering frame):
  - 1. Activate VAO
  - **2. Call glDrawElements()**

P1. Create vertex data and index data

- In this method, the vertex data **should not have duplicate vertex.**

```
# prepare vertex data
# 8 vertices
vertices = glm.array(glm.float32,
    # position      color
    -1 ,  1 ,  1 ,  1, 1, 1, # v0
     1 ,  1 ,  1 ,  1, 1, 1, # v1
     1 , -1 ,  1 ,  1, 1, 1, # v2
    -1 , -1 ,  1 ,  1, 1, 1, # v3
    -1 ,  1 , -1 ,  1, 1, 1, # v4
     1 ,  1 , -1 ,  1, 1, 1, # v5
     1 , -1 , -1 ,  1, 1, 1, # v6
    -1 , -1 , -1 ,  1, 1, 1, # v7
)
```

```
# prepare index data
# 12 triangles
indices = glm.array(glm.uint32,
    0,2,1,
    0,3,2,
    4,5,6,
    4,6,7,
    0,1,5,
    0,5,4,
    3,6,2,
    3,7,6,
    1,2,6,
    1,6,5,
    0,7,3,
    0,4,7,
```



P3.5 Create and activate EBO

- Element Buffer Object (EBO):
  - A type of buffer that is used to store indices that define the vertices of geometric primitives such as triangles.

- Creation and activation are similar to VBOs except the `target` parameter.

```
EBO = glGenBuffers(1)    # create a buffer object
ID and store it to EBO variable
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, EBO)   #
activate EBO as an element buffer object
```

P4.5 Copy index data to EBO

- Copying data to EBO is also similar to VBOs except the `target` parameter.

```
glBufferData(GL_ELEMENT_ARRAY_BUFFER,
indices.nbytes, indices.ptr, GL_STATIC_DRAW) #
allocate GPU memory for and copy index data to the
currently bound element buffer
```

D2. Call glDrawElements()

- `glDrawElements(GL_TRIANGLES, 36, GL_UNSIGNED_INT, None)`

- `glDrawElements(mode, count, type, indices)`
  - Render primitives from vertex & index data in VBO & EBO referred by currently bounded VAO.
  - `mode`: Primitive type to render.
  - `count`: Number of **elements (indices)** to be rendered.
  - `type`: Type of the values in `indices`.
  - `indices`: Byte offset of the beginning index ('None' for 0)

[Code] 3-cube-indexed

```
def prepare_vao_cube():
    # prepare vertex data (in main memory)
    # 8 vertices
    vertices = glm.array(glm.float32,
        # position      color
        -1 ,  1 ,  1 ,  1, 1, 1, # v0
         1 ,  1 ,  1 ,  1, 1, 1, # v1
         1 , -1 ,  1 ,  1, 1, 1, # v2
        -1 , -1 ,  1 ,  1, 1, 1, # v3
        -1 ,  1 , -1 ,  1, 1, 1, # v4
         1 ,  1 , -1 ,  1, 1, 1, # v5
         1 , -1 , -1 ,  1, 1, 1, # v6
        -1 , -1 , -1 ,  1, 1, 1, # v7
    )

    # prepare index data
    # 12 triangles
    indices = glm.array(glm.uint32,
        0,2,1,
        0,3,2,
        4,5,6,
        4,6,7,
        0,1,5,
        0,5,4,
        3,6,2,
        3,7,6,
        1,2,6,
        1,6,5,
        0,7,3,
        0,4,7,
    )
```

```
    # create and activate VAO & VBO
    VAO = glGenVertexArrays(1)
    glBindVertexArray(VAO)
    VBO = glGenBuffers(1)
    glBindBuffer(GL_ARRAY_BUFFER, VBO)

    # create and activate EBO
    EBO = glGenBuffers(1)
    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, EBO)

    # copy vertex & index data to VBO & EBO
    glBufferData(GL_ARRAY_BUFFER, vertices.nbytes,
vertices.ptr, GL_STATIC_DRAW)
    glBufferData(GL_ELEMENT_ARRAY_BUFFER,
indices.nbytes, indices.ptr, GL_STATIC_DRAW)

    # configure vertex positions
    glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE,
6 * glm.sizeof(glm.float32), None)
    glEnableVertexAttribArray(0)

    # configure vertex colors
    glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE,
6 * glm.sizeof(glm.float32),
ctypes.c_void_p(3*glm.sizeof(glm.float32)))
    glEnableVertexAttribArray(1)

    return VAO
```

[Code] 3-cube-indexed

```
def draw_cube(vao, MVP, MVP_loc):
    glBindVertexArray(vao)
    glUniformMatrix4fv(MVP_loc, 1, GL_FALSE, glm.value_ptr(MVP))
    # glDrawArrays(GL_TRIANGLES, 0, 36)
    glDrawElements(GL_TRIANGLES, 36, GL_UNSIGNED_INT, None)
```

Time for Assignment

- Let's start today's assignment.
- TA will guide you.