Computer Graphics

7 - Hierarchical Modeling, Mesh

Yoonsang Lee
Hanyang University

Spring 2023

Notice 1 - Midterm Exam

- Date & time: **May 1**, **7:30 - 8:30 PM**

- Place: IT.BT **509** & **609**
  - **See https://learning.hanyang.ac.kr/courses/119266/discussion_topics/248733 for the list of students for each room.**

- Scope: Lecture & Lab 2~7
  - Lecture & Lab 8 is included in the final exam scope

- **You cannot leave until 30 minutes after the start of the exam** even if you finish the exam earlier.

- That means, **you cannot enter the room after 30 minutes from the start of the exam** (do not be late, never too late!).

- Please bring your **student ID card** to the exam.

Notice 2 - Next Week's Lecture

- Due to the instructor's business trip, next week's **lecture** (Apr 24) will be provided **as a recorded lecture video** that will be uploaded to the LMS.
  - If you have any questions about the lecture, please post them on the LMS Q&A board.
  - The video will be uploaded tomorrow or the day after tomorrow.

- The **lab** will be held **offline** in the classroom starting at **5:00 AM** on Apr 24.

Outline

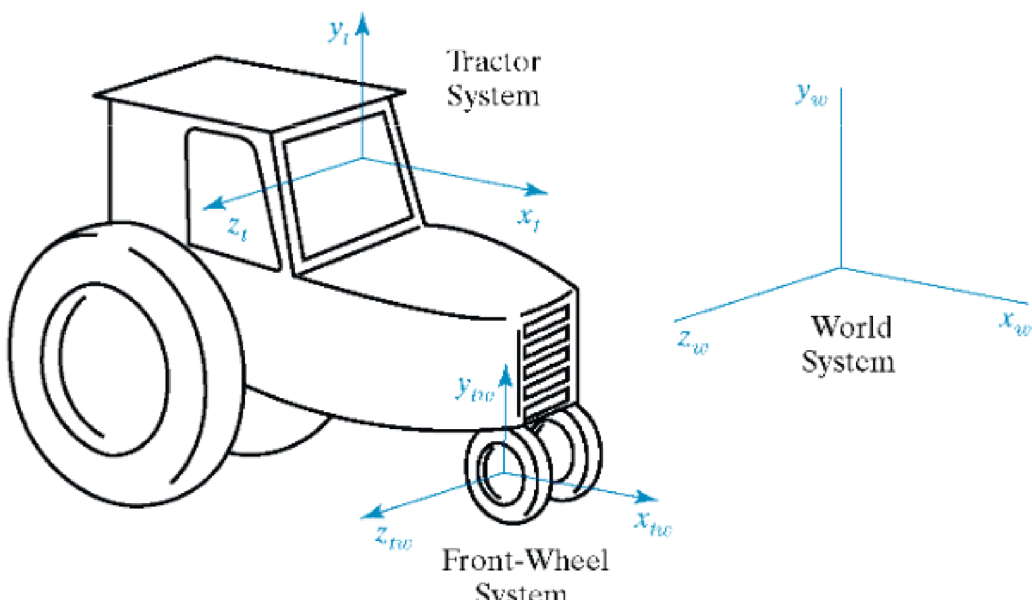
- Hierarchical Modeling
  - Concept of Hierarchical Modeling
    - Example: Human Figure
  - Rendering Hierarchical Models
  - Interpretation of a Series of Transformations

- Mesh
  - Separate triangles
  - Indexed triangle set

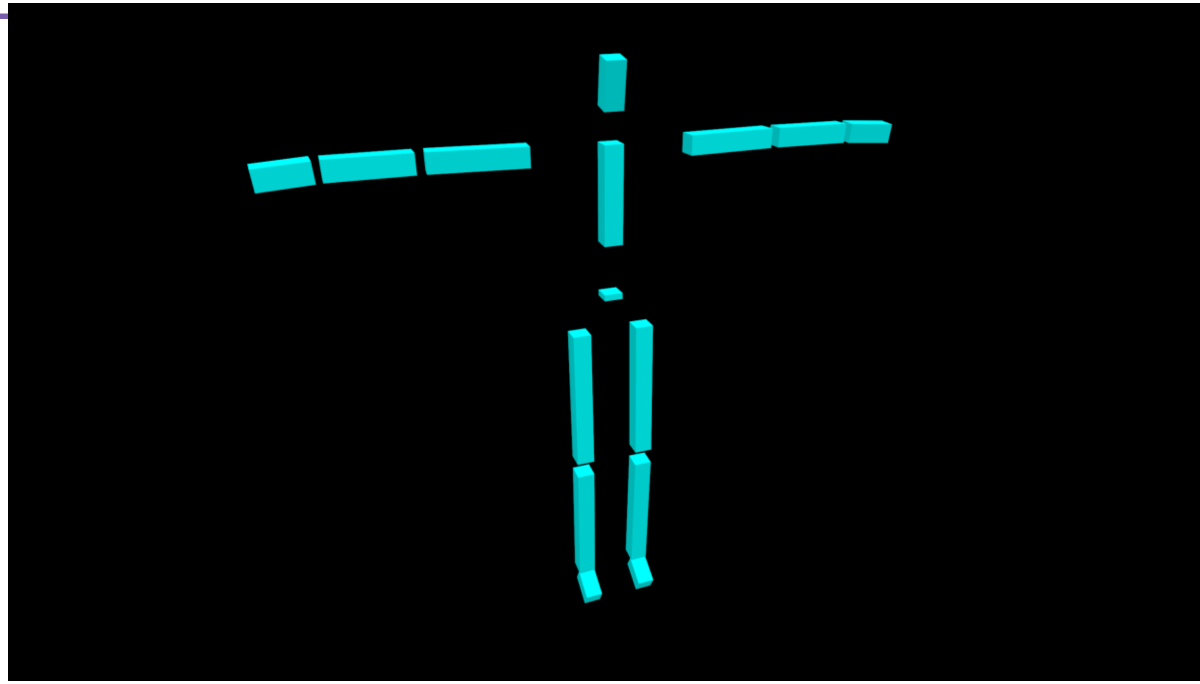
Hierarchical Modeling

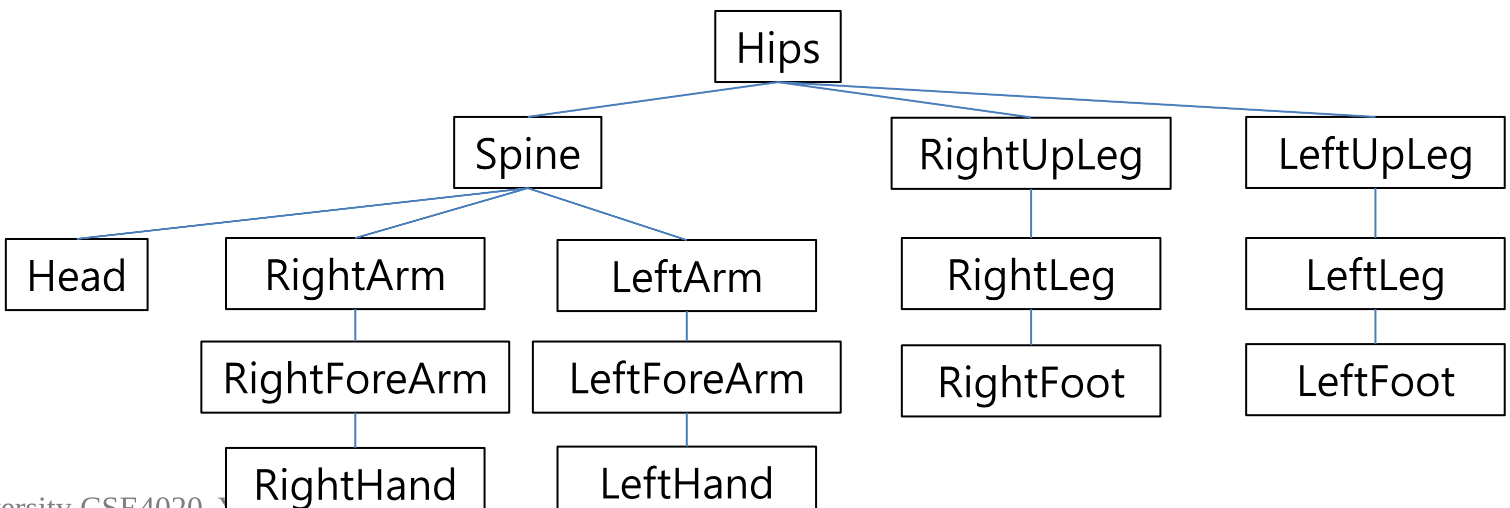
Hierarchical Modeling

- Nesting the description of subparts (child parts) into another part (parent part) to form a tree structure.
- Each part has its own reference frame (body frame).
- Each part's movement is described w.r.t. its parent's reference frame.

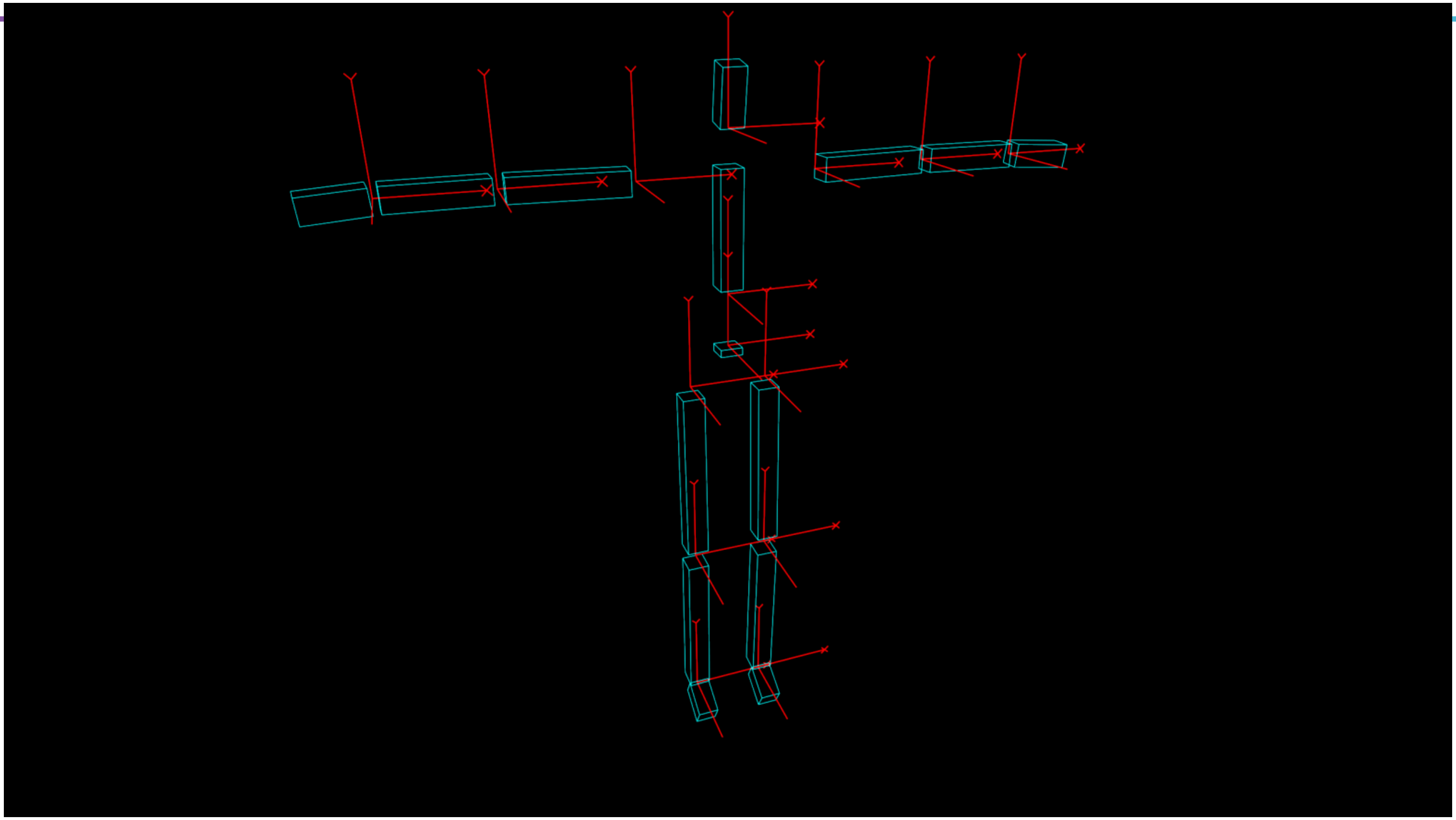


Example - Human Figure



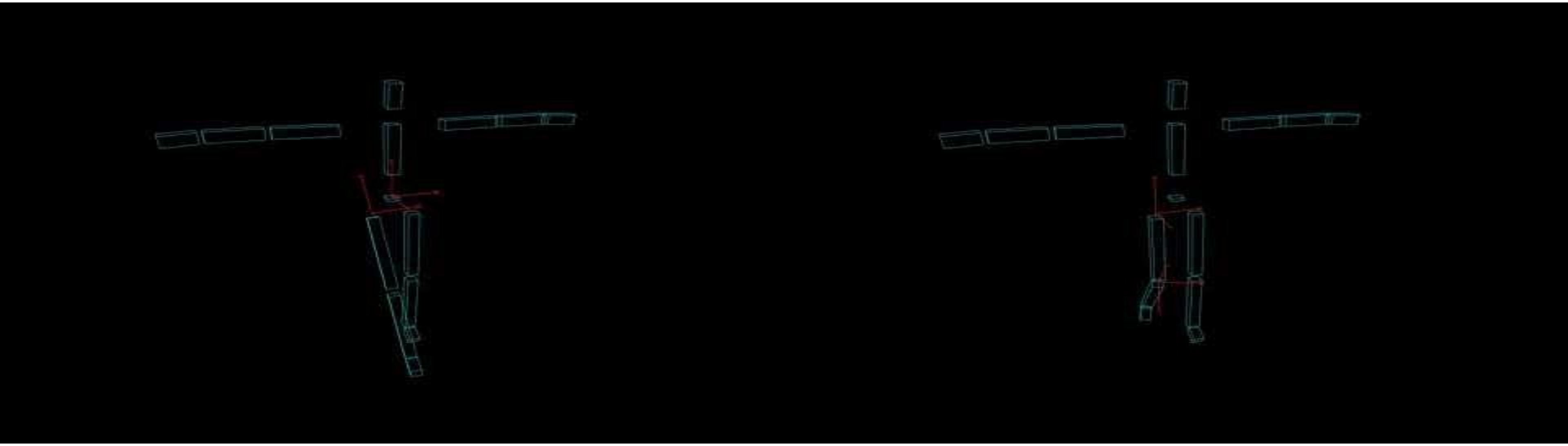


Human Figure - Frames



- Each part has its own reference frame (body frame).

Human Figure - Movement of rhip & rknee

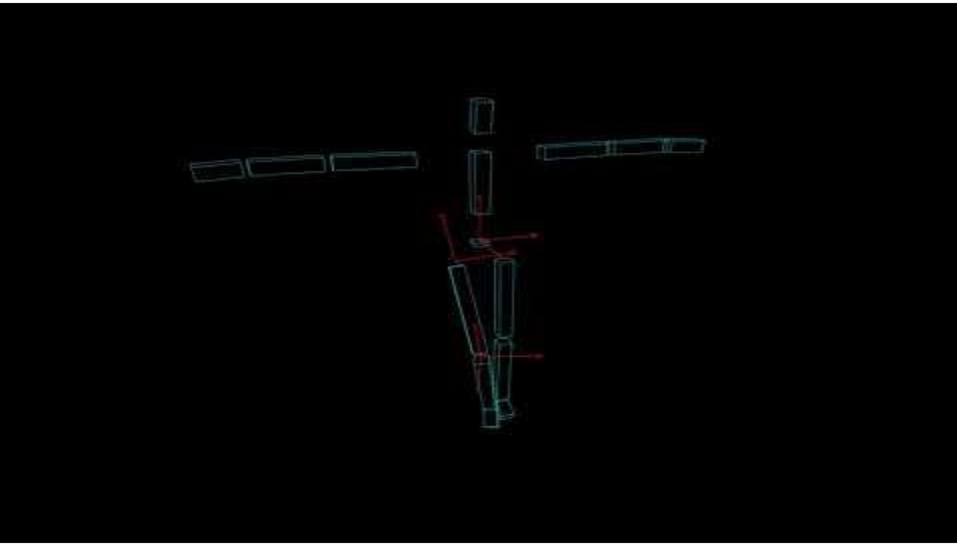


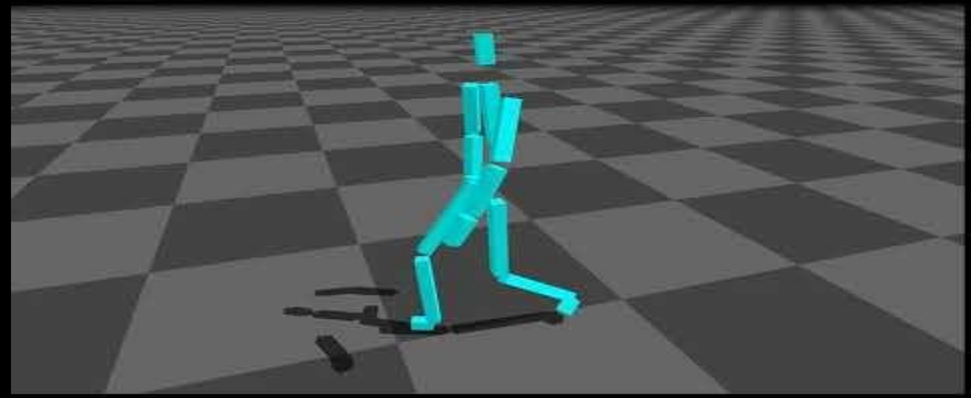
https://youtu.be/Q7lhvMkCSCg https://youtu.be/Q5R8WGUwpFU

- Each part's movement is described w.r.t. its parent's frame.
- → Each part has its **own transformation** w.r.t. parent's frame.

- This allows a part to "group" its children together.

Human Figure - Movement of more joints





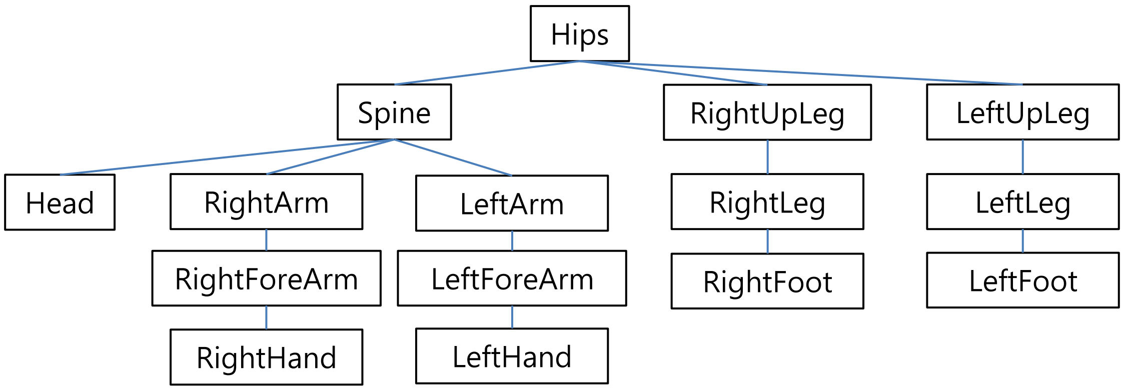
https://youtu.be/9dz8bvVK9zc

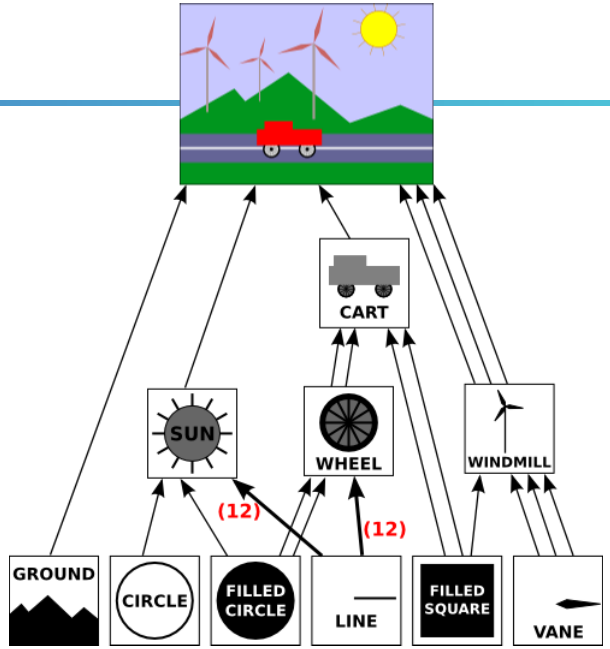
https://youtu.be/PEhyWI8LGBY

- Each part's movement is described w.r.t. its parent's frame.
- → Each part has its **own transformation** w.r.t. parent's frame.

- This allows a part to "group" its children together.

Hierarchical Model





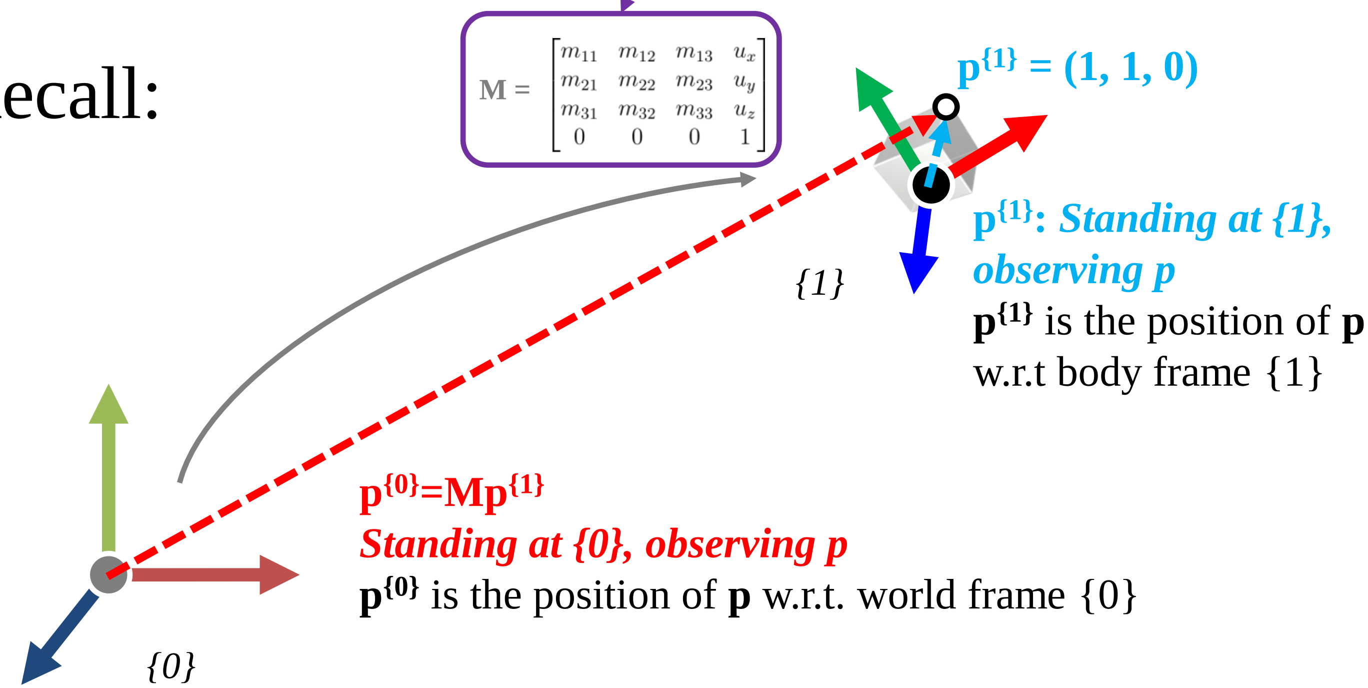
- A hierarchical model is usually represented by a **tree structure.**

- Another example of hierarchical model is *scene graph*, a graph structure that represents an entire scene.

- Each node has its **own transformation** w.r.t. parent node's frame.

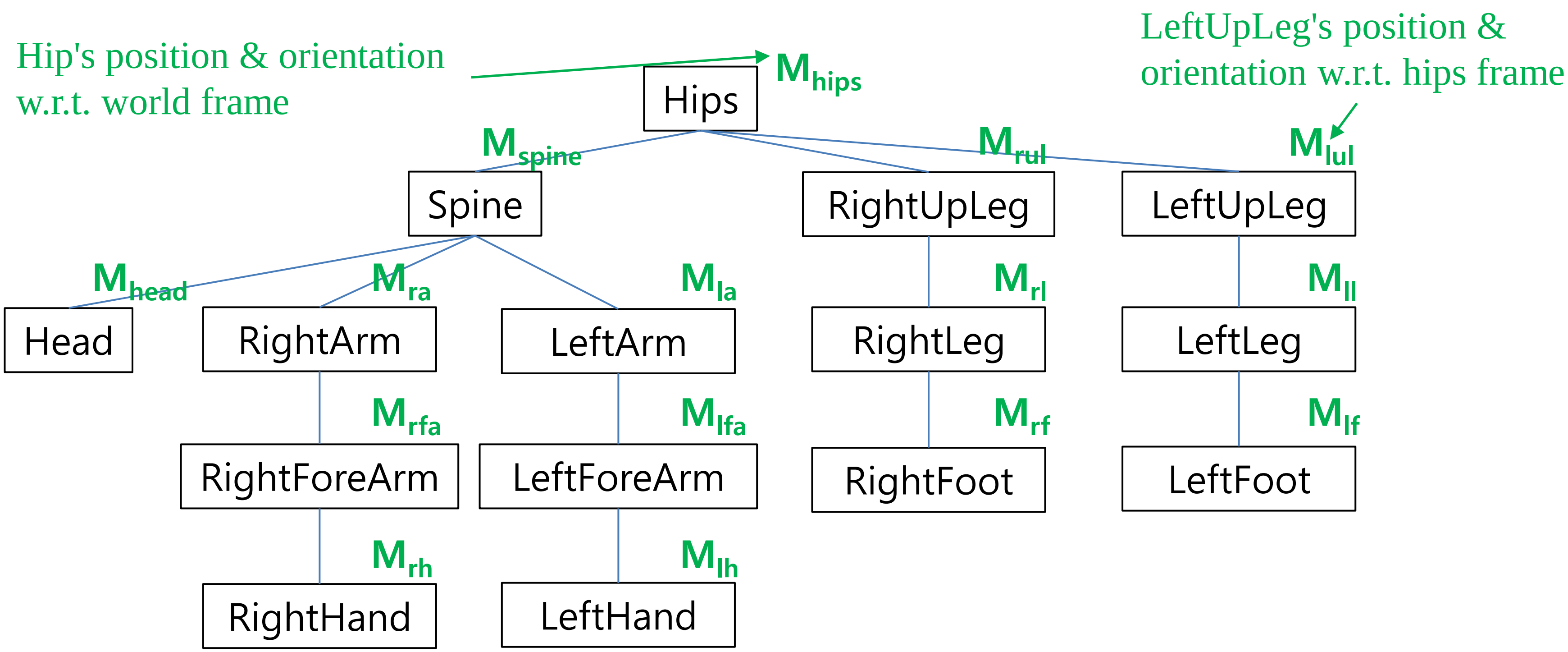
Rendering Hierarchical Models

- To render a hierarchical model, we need each node's frame represented w.r.t. world frame, to compute the global position of each vertex.
- Recall:



Rendering Hierarchical Models

- Each node has its own transformation w.r.t. parent node's frame.
  → **Local transformation**



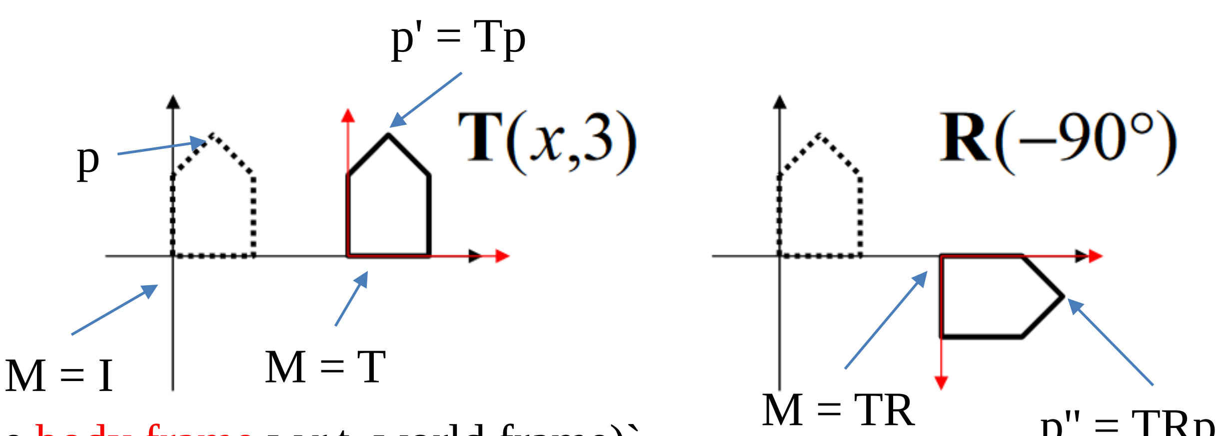
Rendering Hierarchical Models

- We need each node's frame represented w.r.t. world frame to render a hierarchical model.
  → **Global transformation**

- How can we compute the global transform of a node using the local transforms of other nodes?

Recall: Right Multiplication

- **$p' = M_1 M_2 p$ (right-multiplication by M_2)**
  – (L-to-R)
  – 1') Apply $\mathbf{M_1}$ w.r.t. body frame **I** (world frame) to update body frame to $\mathbf{M_1}$
  – 2') Apply $\mathbf{M_2}$ w.r.t. body frame $\mathbf{M_1}$ to update body frame to $\mathbf{M_1 M_2}$
  – 3') Locate **p** in body frame $\mathbf{M_1 M_2}$

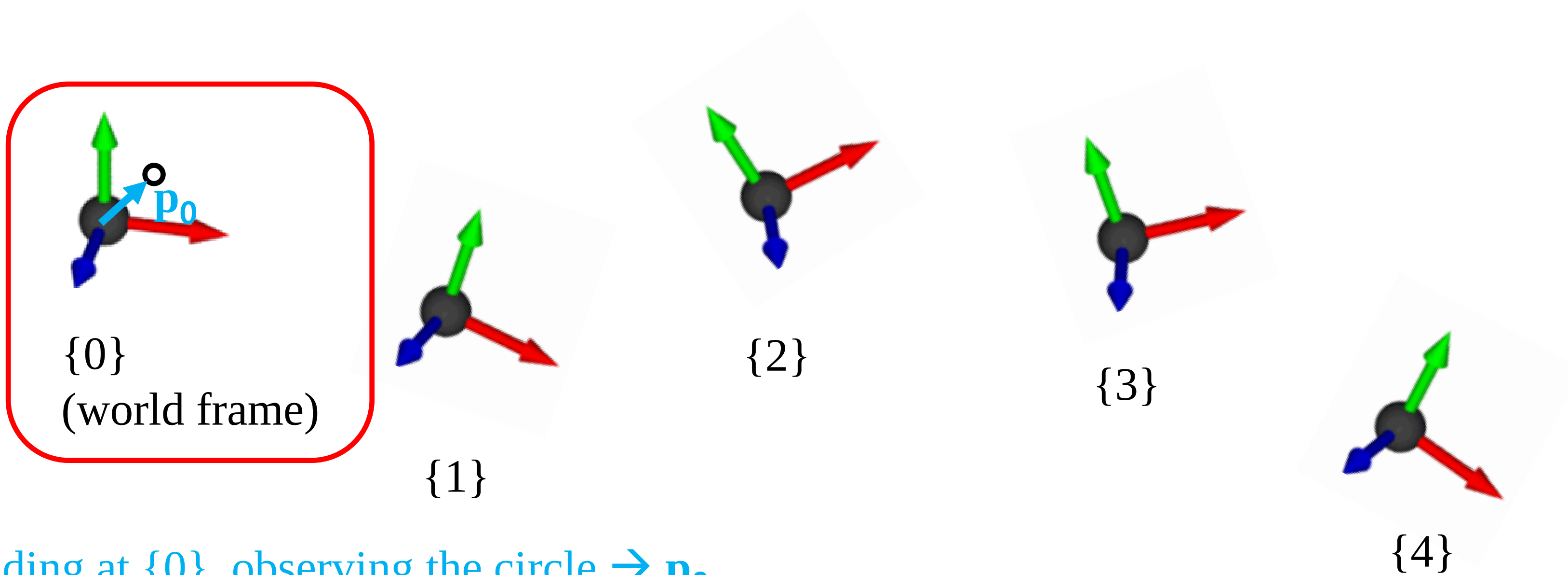


(M defines the body frame w.r.t. world frame)`

Interpretation of a Series of Transformations

- $\mathbf{p_0} = \underline{\mathbf{I}}\ \mathbf{p_0}$

  body frame ({0})



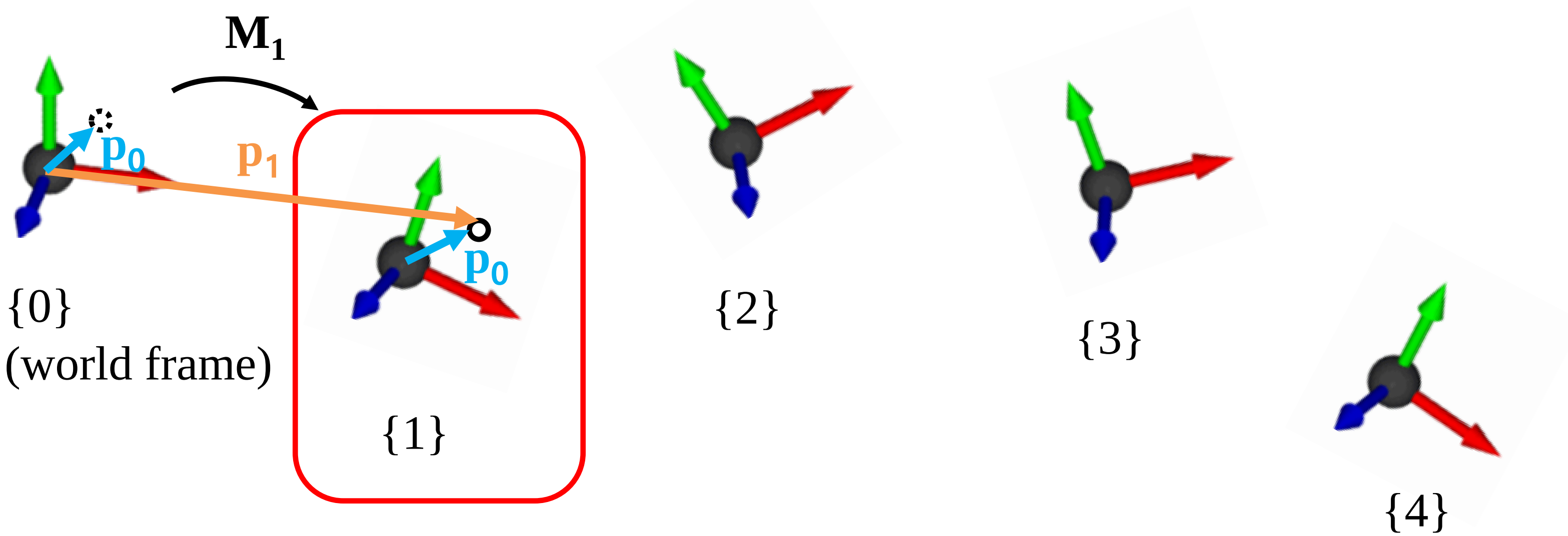
Standing at {0}, observing the circle → $\mathbf{p_0}$

Interpretation of a Series of Transformations

- $\mathbf{p_1} = \underline{\mathbf{M_1}}\ \mathbf{p_0}$

  body frame ({1})

  apply w.r.t. {0}



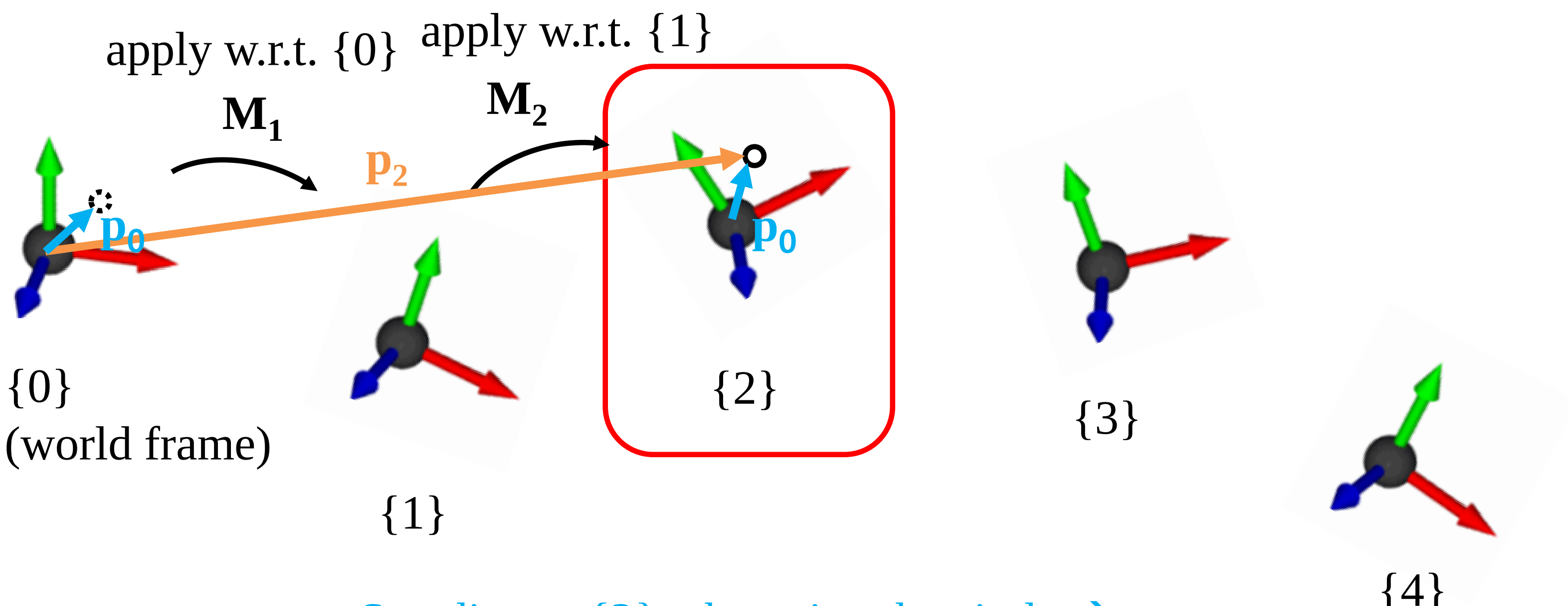
Standing at {1}, observing the circle → $\mathbf{p_0}$

Standing at {0}, observing the circle → $\mathbf{p_1}$

Interpretation of a Series of Transformations

- $\mathbf{p}_2 = \underline{\mathbf{M}_1\mathbf{M}_2}\ \mathbf{p}_0$

  body frame ({2})

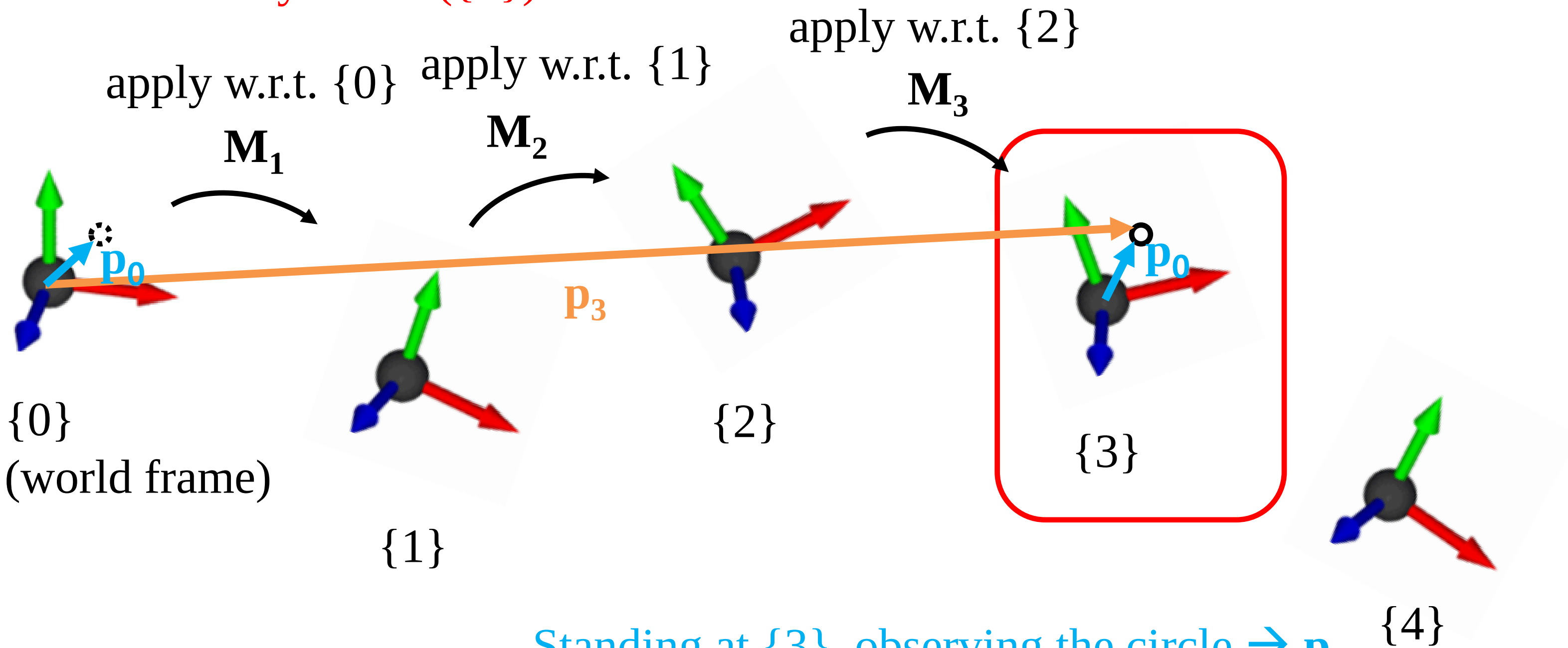


Standing at {2}, observing the circle → $\mathbf{p}_0$

Standing at {0}, observing the circle → $\mathbf{p}_2$

Interpretation of a Series of Transformations

- $\mathbf{p}_3 = \underbrace{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}_{\text{body frame (\{3\})}}\ \mathbf{p}_0$

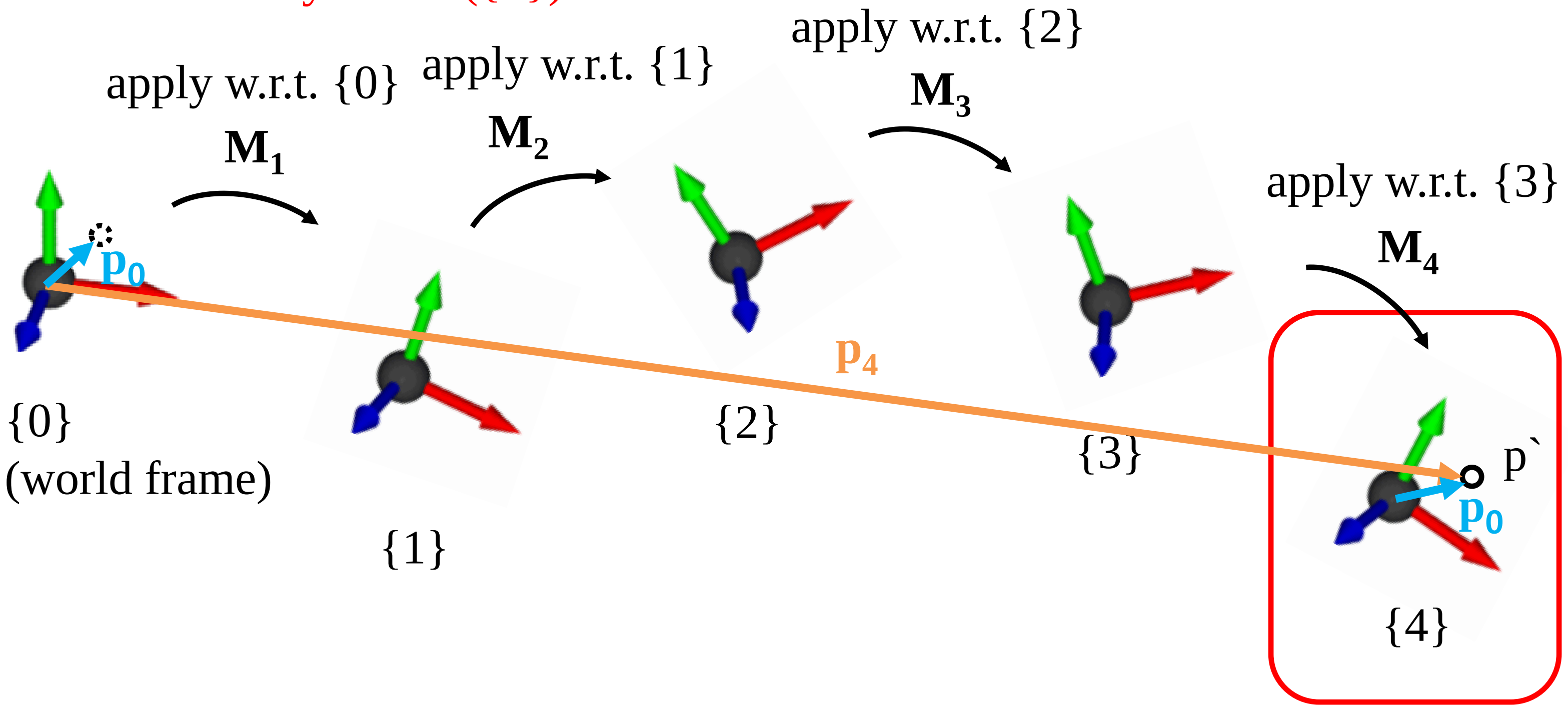


Standing at {3}, observing the circle → $\mathbf{p}_0$

Standing at {0}, observing the circle → $\mathbf{p}_3$

Interpretation of a Series of Transformations

- $\mathbf{p_4} = \underbrace{\mathbf{M_1 M_2 M_3 M_4}}_{\text{body frame (\{4\})}} \mathbf{p_0}$

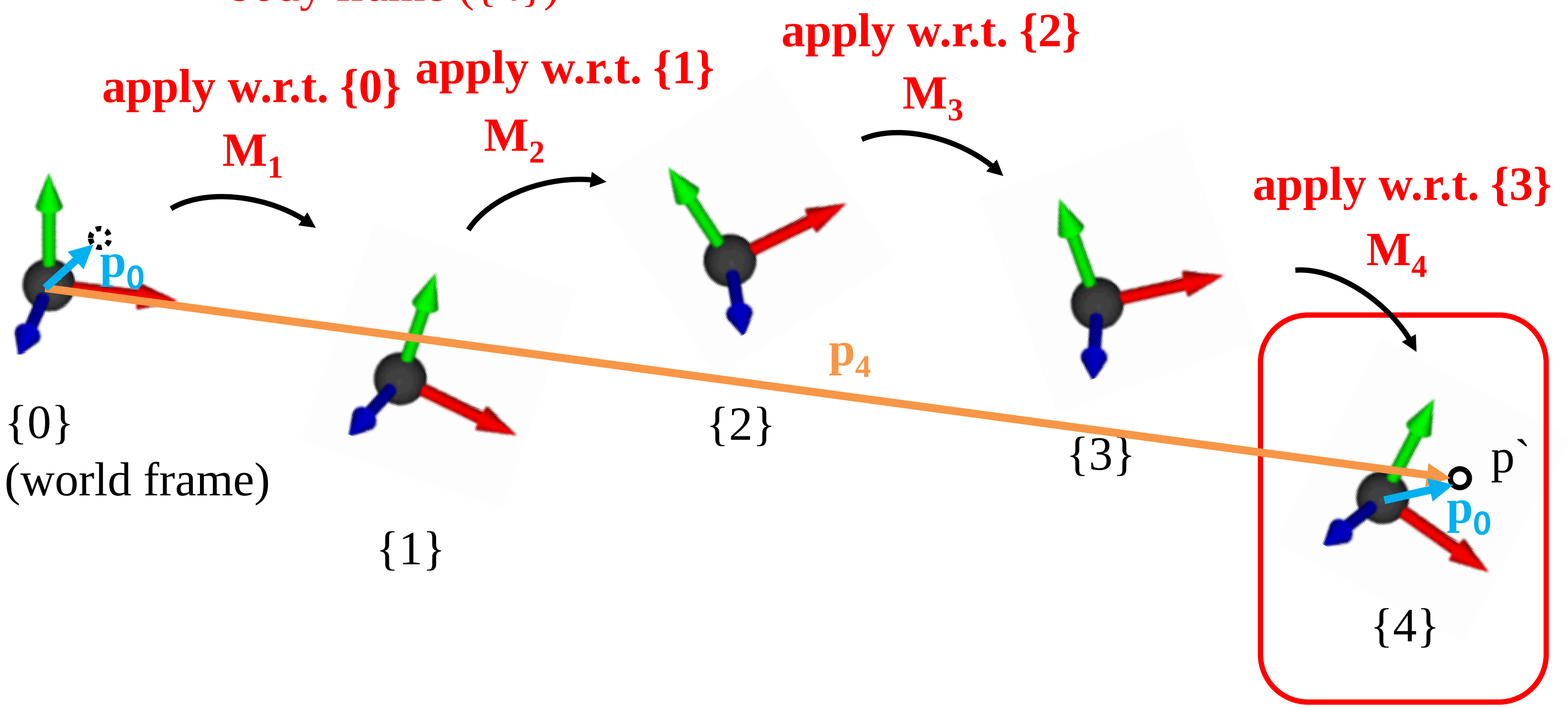


Standing at {4}, observing the circle → $\mathbf{p_0}$

Standing at {0}, observing the circle → $\mathbf{p_4}$

Interpretation of a Series of Transformations

- $\mathbf{p_4} = \underbrace{\mathbf{M_1 M_2 M_3 M_4}}_{\text{body frame (\{4\})}} \mathbf{p_0}$

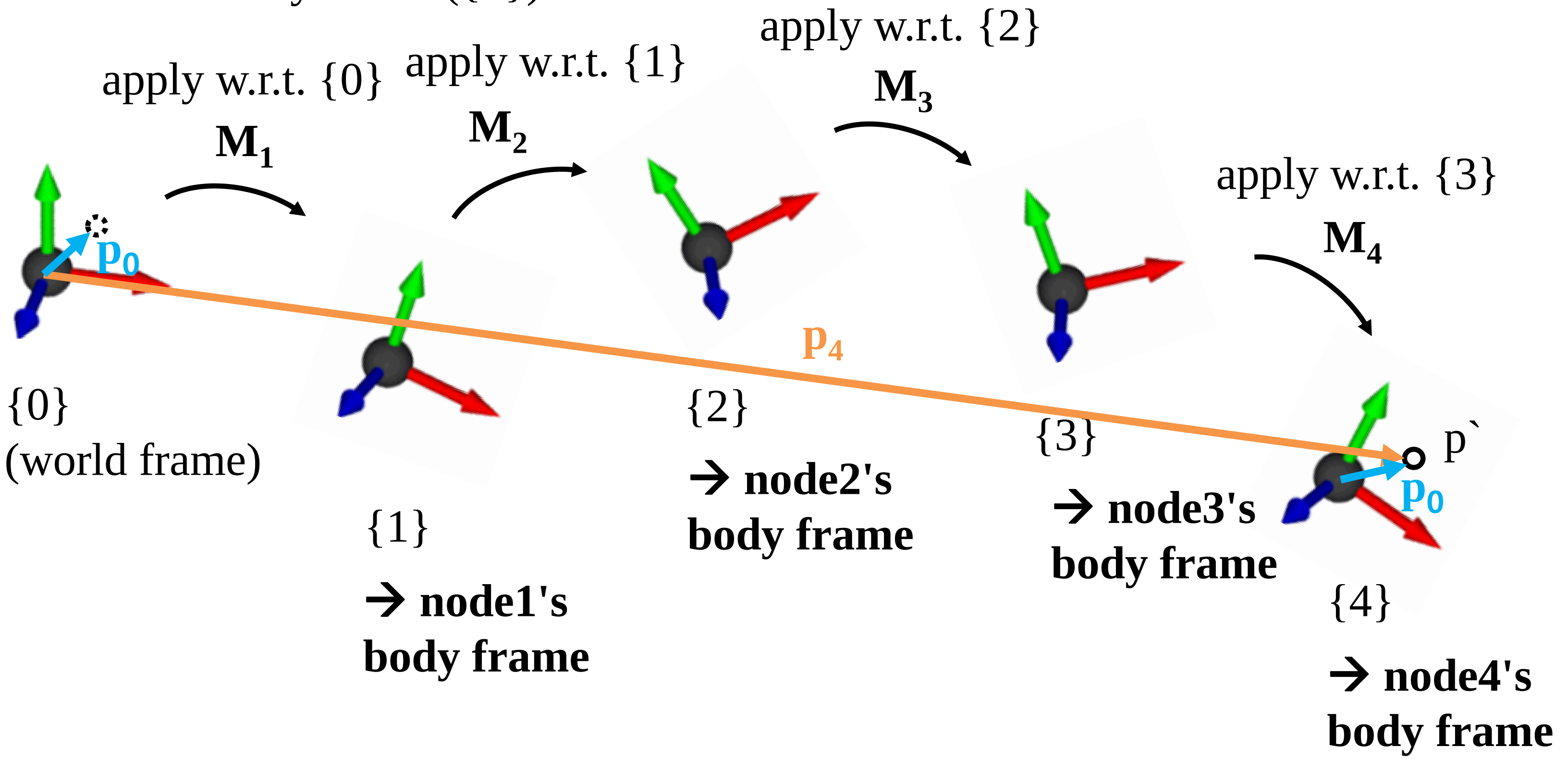


Standing at {4}, observing the circle → $\mathbf{p_0}$

Standing at {0}, observing the circle → $\mathbf{p_4}$

Interpretation of a Series of Transformations

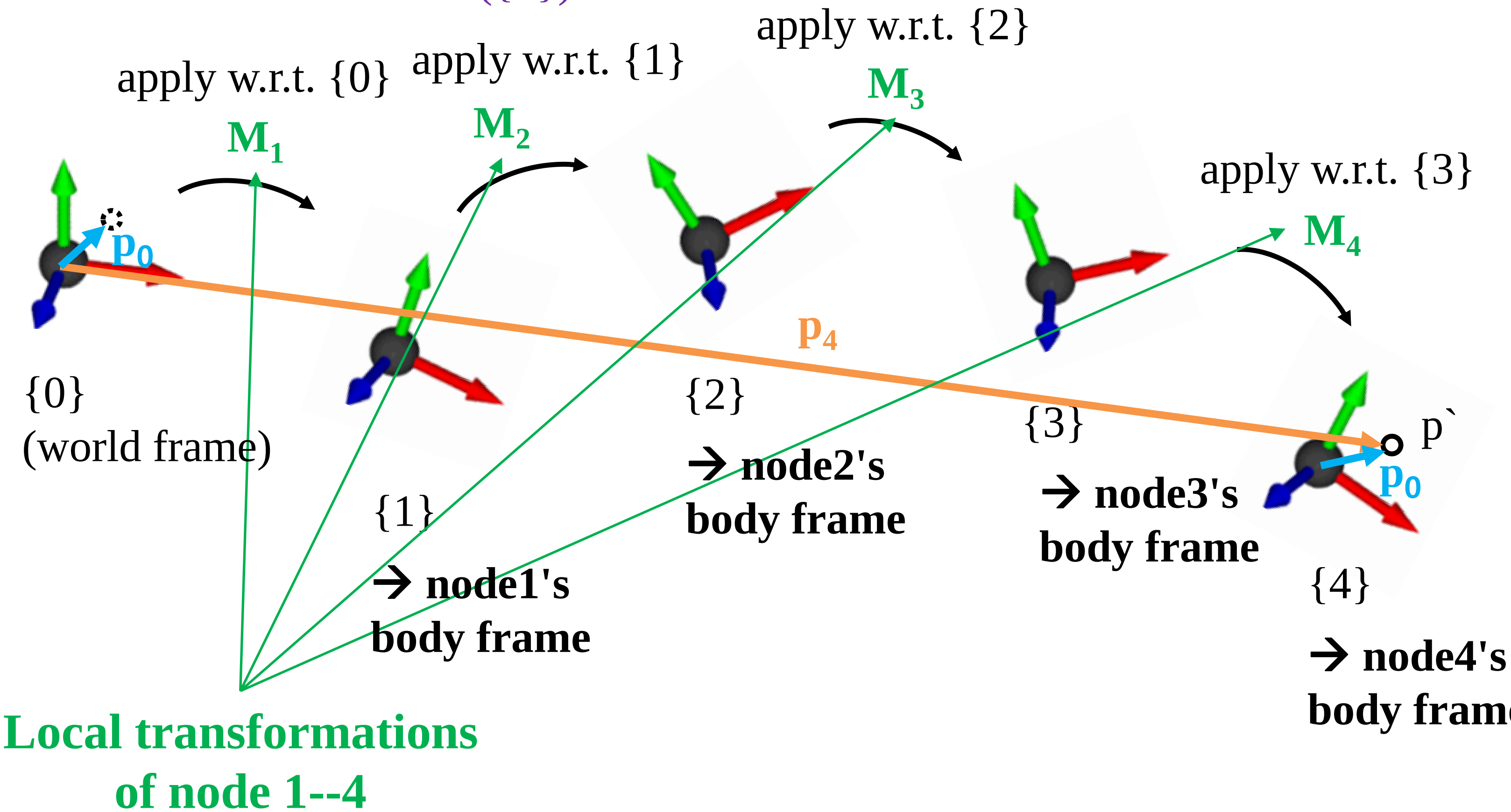
- $\mathbf{p_4} = \underbrace{\mathbf{M_1 M_2 M_3 M_4}}_{\text{body frame (\{4\})}} \mathbf{p_0}$



Computing Global Transform from Series of Local Transforms

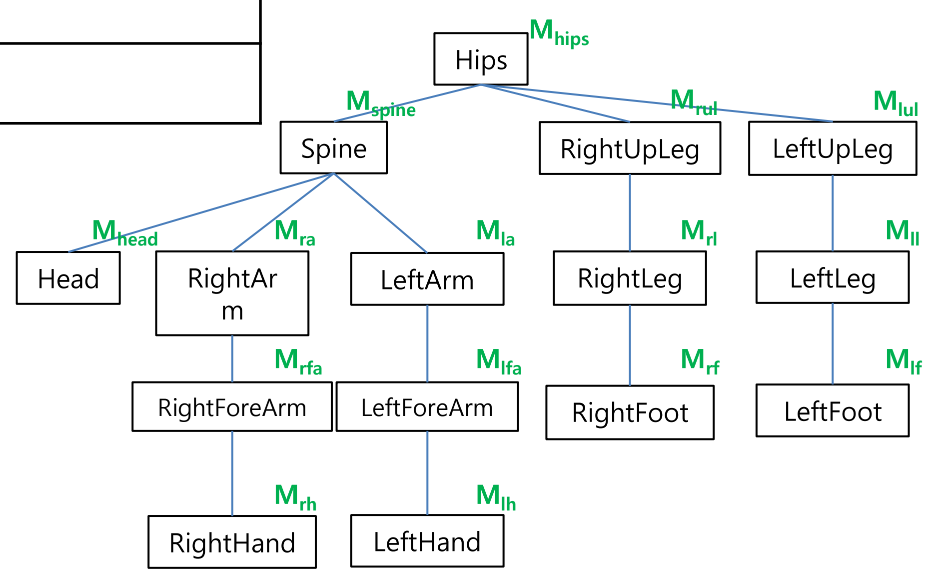
- $\mathbf{p_4} = \underbrace{\mathbf{M_1 M_2 M_3 M_4}}_{\text{node 4's frame (\{4\})}}\ \mathbf{p_0}$

Global transformation of node 4



Computing Global Transform from Series of Local Transforms

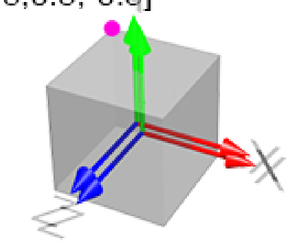
Node i	**Global Transform G_i = …**
Hips	M_{hips}
Spine	$M_{hips}\ M_{spine}$
Head	$M_{hips}\ M_{spine}\ M_{head}$
RightArm	$M_{hips}\ M_{spine}\ M_{ra}$
RightForeArm	$M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}$
RightHand	$M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}\ M_{rh}$
LeftArm	$M_{hips}\ M_{spine}\ M_{la}$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



Rendering Hierarchical Models

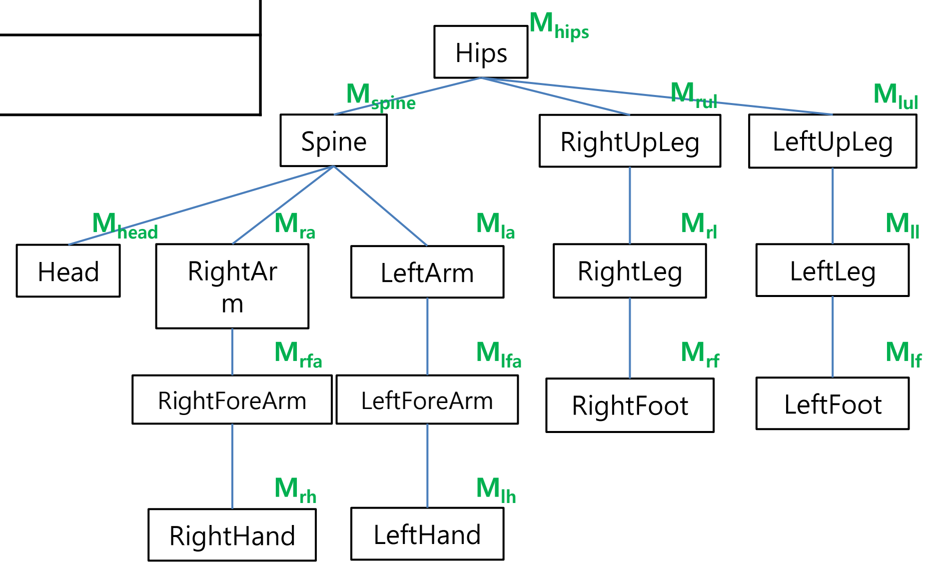
Node i	Global Transform G_i = ...
Hips	M_{hips}
Spine	$M_{hips}\ M_{spine}$
Head	$M_{hips}\ M_{spine}\ M_{head}$
RightArm	$M_{hips}\ M_{spine}\ M_{ra}$
RightForeArm	$M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}$
RightHand	$M_{hips}\ M_{spine}\ M_{ra}\ M_{rfa}\ M_{rh}$
LeftArm	$M_{hips}\ M_{spine}\ M_{la}$
...	

$\mathbf{p}_0$=[-0.5,0.5,-0.5]



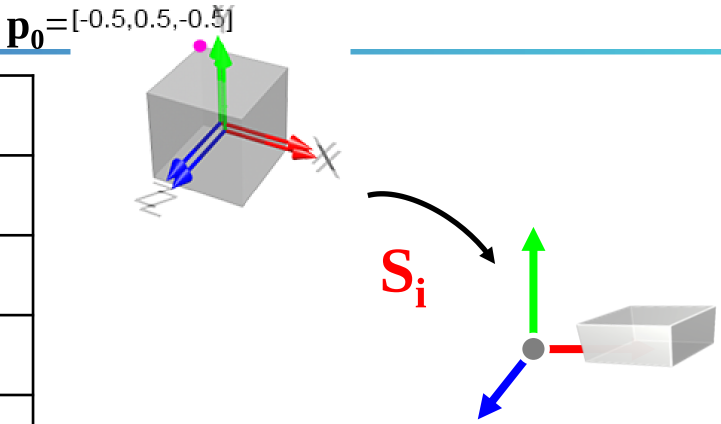
Let's say i-th node is rendered **as a unit cube** above (without scaling), its vertex position $\mathbf{p}_i'$ w.r.t. world frame is…

$$\mathbf{p}_i' = \mathbf{G}_i\ \mathbf{p}_0$$



Rendering Hierarchical Models

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	$M_{hips}\ M_{spine}\ M_{la}$
…	



Let's say i-th node is rendered **as a cuboid transformed by** S_i **from the unit cube**, its vertex position $\mathbf{p}_i'$ w.r.t. world frame is…

$$\mathbf{p}_i' = \mathbf{G}_i\ \mathbf{S}_i\ \mathbf{p}_0$$

- You might want to use "shape transformation" $\mathbf{S}_{ij}$ for j-th shape of i-th node.

Rendering Hierarchical Models

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	$M_{hips}\ M_{spine}\ M_{la}$
…	

- To render a hierarchical model, store global transform $\mathbf{G_i}$ in each node (i-th node) object and use it when rendering.

Quiz 1

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

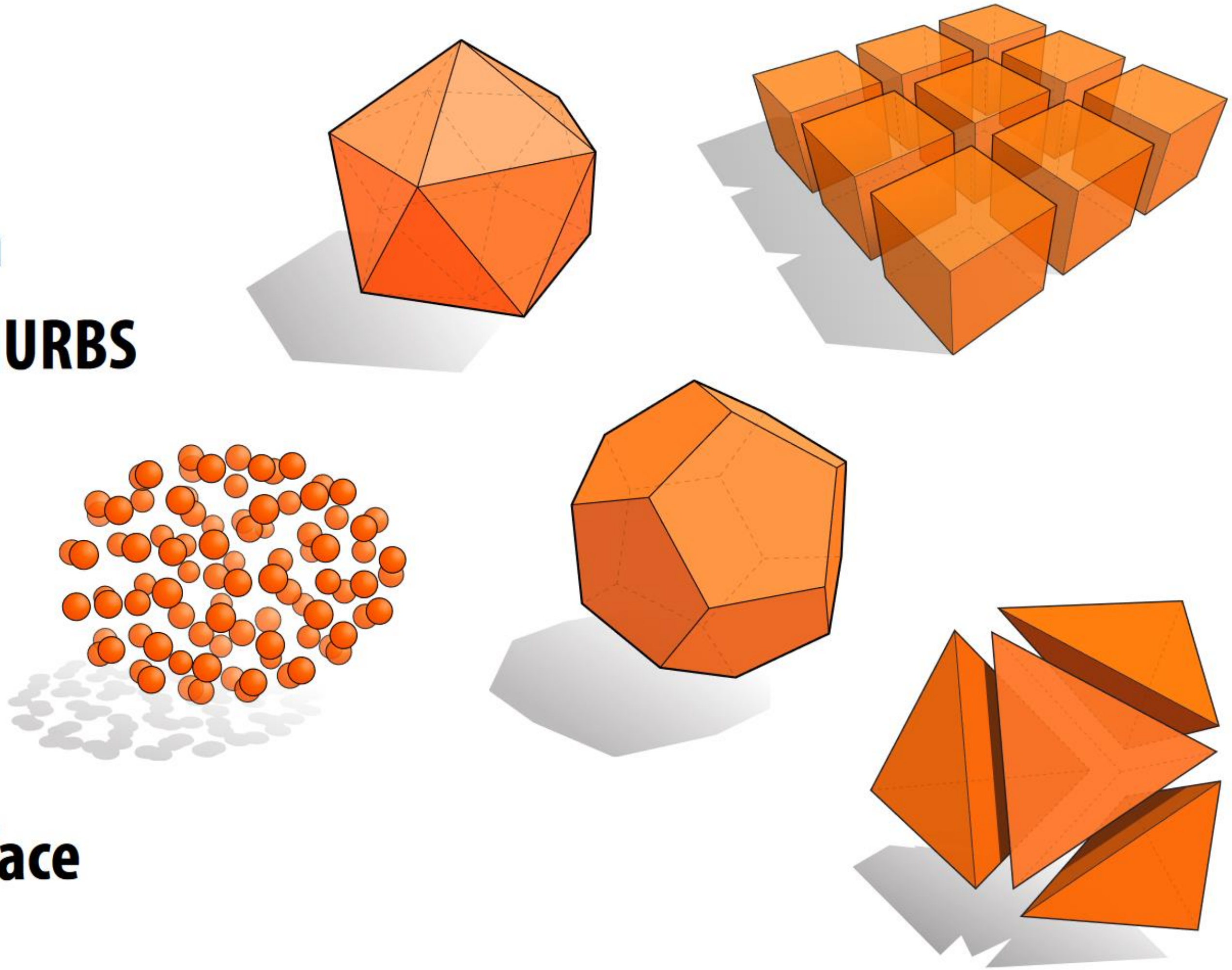
- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2021123456: 4.0**

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

Mesh

Many ways to digitally encode geometry

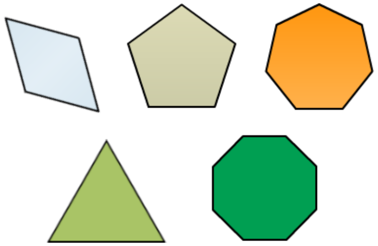
- EXPLICIT
  - point cloud
  - polygon mesh
  - subdivision, NURBS
  - L-systems
  - ...
- IMPLICIT
  - level set
  - algebraic surface
  - ...
- Each choice best suited to a different task/type of geometry



* This slide is from http://15462.courses.cs.cmu.edu/fall2015/lecture/introgeometry

The Most Popular Representation : Polygon Mesh

- Because this can model any arbitrary complex shapes with relatively simple representations and can be rendered fast.



- **Polygon**: a “closed” shape with straight sides

- **Polygon mesh**: a bunch of polygons in 3D space that are connected together to form a surface
  - Usually use *triangles* or *quads* (4 side polygon)

Triangle Mesh

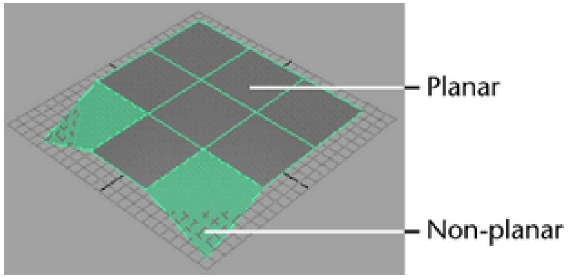
- A general N-polygon can be
  - Non-planar
  - Non-convex
- , which are not desirable for fast rendering.

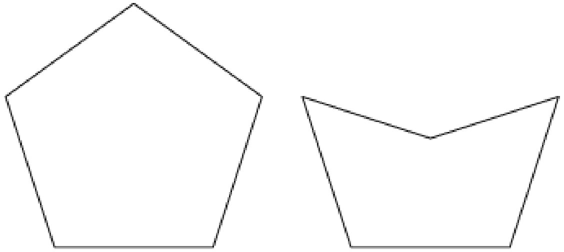
- A triangle does not have such problems. It’s always planar & convex.

- and N-polygons can be composed of multiple triangles.

- That's why modern GPUs draw everything as a set of triangles.

- So, we'll focus on triangle meshes.

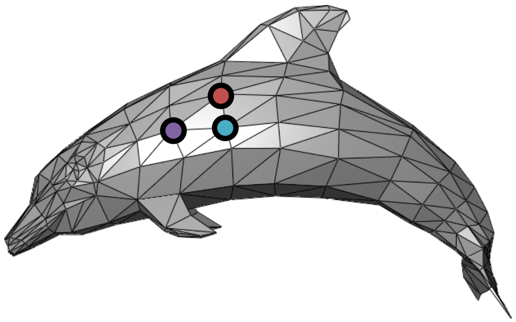




convex polygon *concave polygon*

Representation for Triangle Mesh

- It's about how to store
  - vertex positions
  - relationship between vertices (to make triangles)
- on memory.

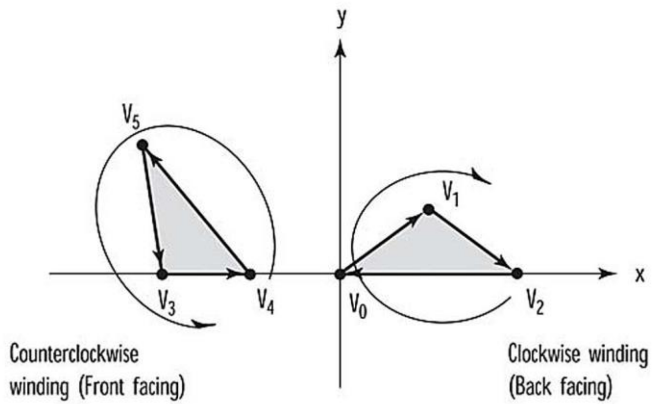


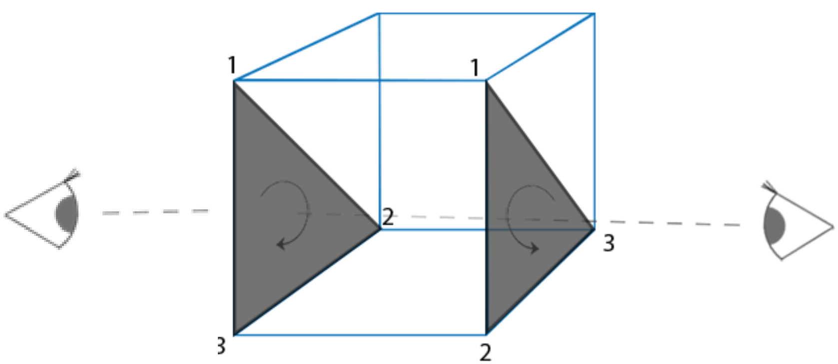
- Two basic representations:
  - Separate triangles
  - Indexed triangle set

Vertex Winding Order

- *Vertex winding order* is the order in which the vertices of a polygon are listed in a representation of a polygon.

- Determines which side of the polygon is "front".
  - In OpenGL, by default, polygons whose vertices appear in counterclockwise (CCW) order on the screen is front-facing.
  - In Direct3D, the default front-facing winding order is clockwise (CW).

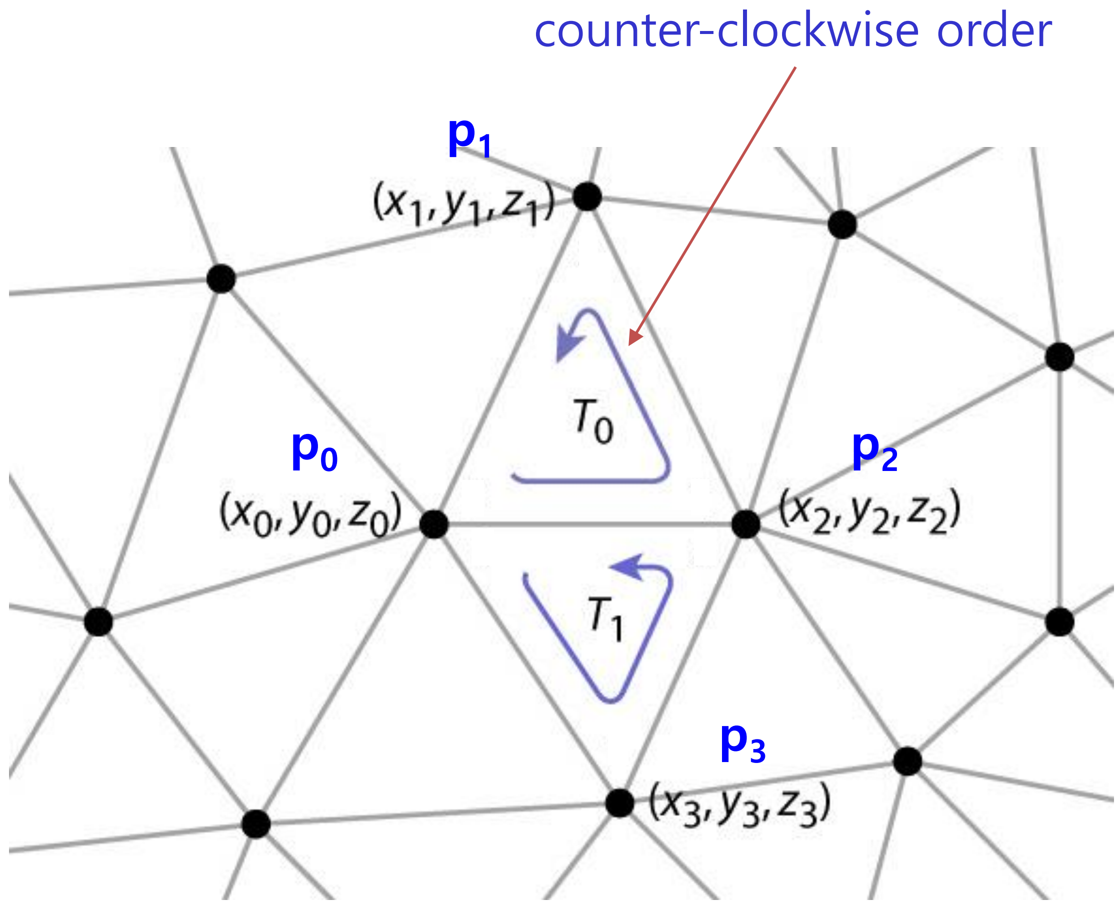




Separate triangles

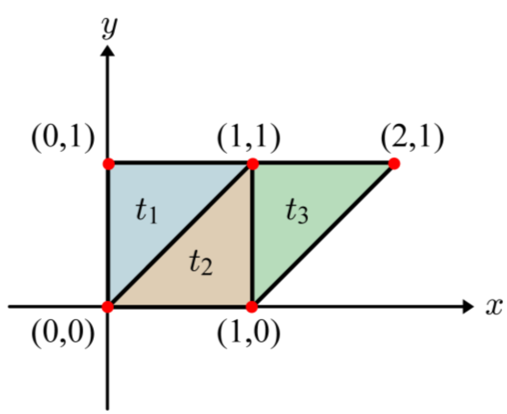
vertex array

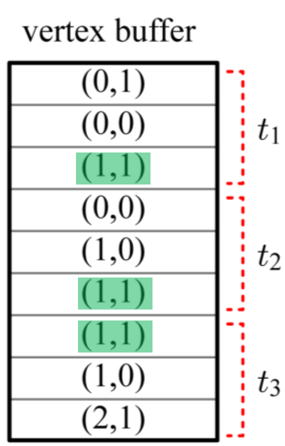
	[0]	[1]	[2]
tris[0]	x_0, y_0, z_0	x_2, y_2, z_2	x_1, y_1, z_1
tris[1]	x_0, y_0, z_0	x_3, y_3, z_3	x_2, y_2, z_2
⋮	⋮	⋮	⋮



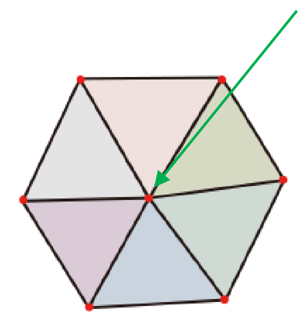
Separate Triangles

- Various problems
  - Wastes memory space
  - Cracks due to roundoff
  - Difficulty of finding neighbor triangles
    - If you want find "neighbor" triangles of t2, you have to find all "zero-distance" vertices from t2's each vertex.



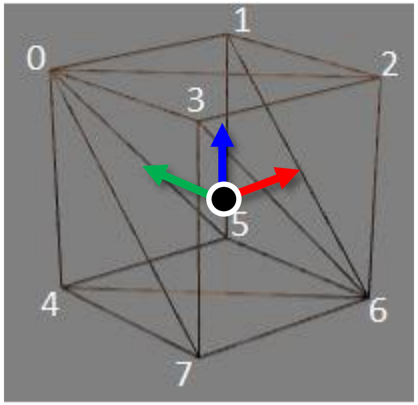


stored 6 times!



(1,1) is stored 3 times!

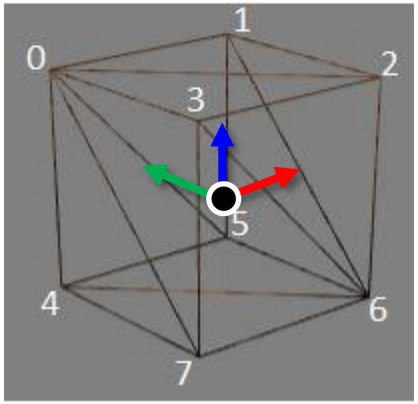
Example: a cube of length 2



vertex index	position
0	(-1 , 1 , 1)
1	(1 , 1 , 1)
2	(1 , -1 , 1)
3	(-1 , -1 , 1)
4	(-1 , 1 , -1)
5	(1 , 1 , -1)
6	(1 , -1 , -1)
7	(-1 , -1 , -1)

Example Cube in Separate Triangles

- In separate triangles scheme, the cube is represented by the **positions of the 36 vertices that make up its 12 triangles.**

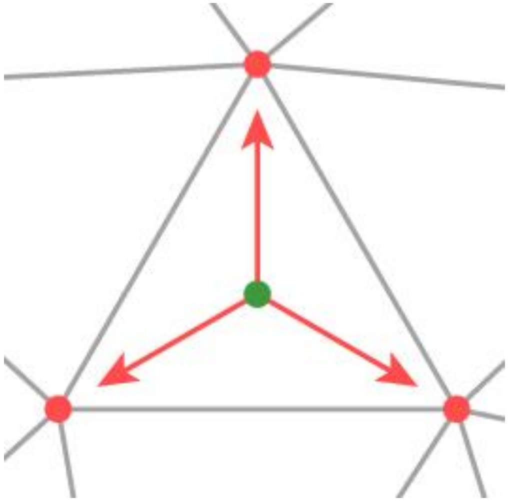



```
# vertex array
# triangle 0
-1 ,  1 ,  1, # v0
 1 , -1 ,  1, # v2
 1 ,  1 ,  1, # v1
# triangle 1
-1 ,  1 ,  1, # v0
-1 , -1 ,  1, # v3
 1 , -1 ,  1, # v2
# triangle 2
-1 ,  1 , -1, # v4
 1 ,  1 , -1, # v5
 1 , -1 , -1, # v6
# triangle 3
-1 ,  1 , -1, # v4
 1 , -1 , -1, # v6
-1 , -1 , -1, # v7
# triangle 4
-1 ,  1 ,  1, # v0
 1 ,  1 ,  1, # v1
 1 ,  1 , -1, # v5
# triangle 5
-1 ,  1 ,  1, # v0
 1 ,  1 , -1, # v5
-1 ,  1 , -1, # v4
```

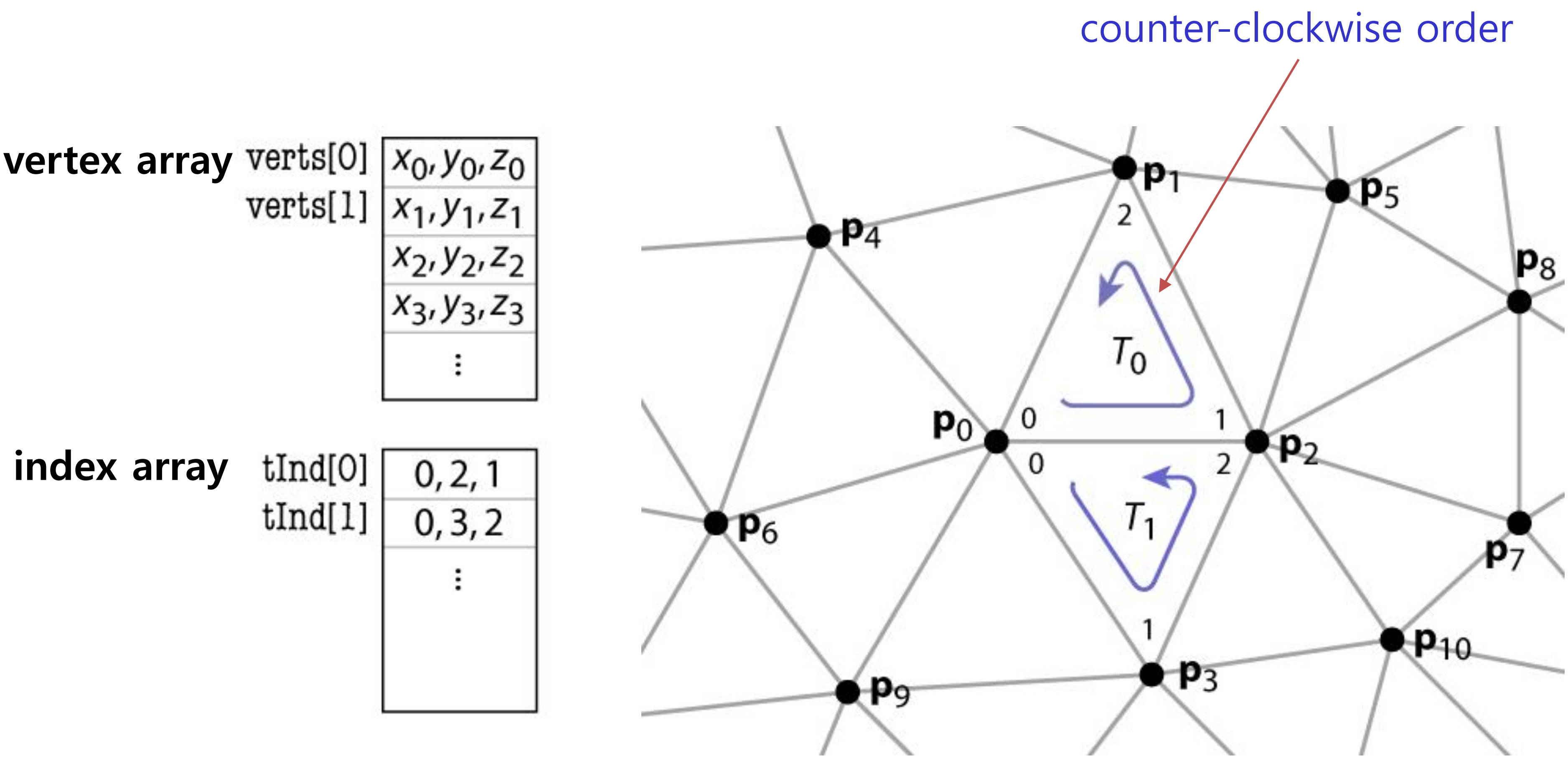
```
# triangle 6
-1 , -1 ,  1, # v3
 1 , -1 , -1, # v6
 1 , -1 ,  1, # v2
# triangle 7
-1 , -1 ,  1, # v3
-1 , -1 , -1, # v7
 1 , -1 , -1, # v6
# triangle 8
 1 ,  1 ,  1, # v1
 1 , -1 ,  1, # v2
 1 , -1 , -1, # v6
# triangle 9
 1 ,  1 ,  1, # v1
 1 , -1 , -1, # v6
 1 ,  1 , -1, # v5
# triangle 10
-1 ,  1 ,  1, # v0
-1 , -1 , -1, # v7
-1 , -1 ,  1, # v3
# triangle 11
-1 ,  1 ,  1, # v0
-1 ,  1 , -1, # v4
-1 , -1 , -1, # v7
```

Indexed triangle set

- Store each vertex once
- Each triangle points to its three vertices



Indexed triangle set

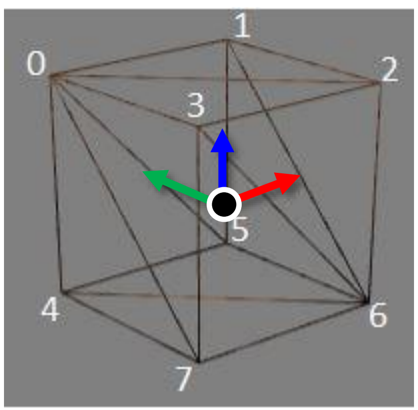


Indexed Triangle Set

- Memory efficient: each vertex position is stored only once.
- Represents topology and geometry separately.
- Finding neighbor triangles is at least well defined.
  - Neighbor triangles share same vertex indices.

Example Cube in Indexed Triangle Set

- In indexed triangle set scheme, the cube is represented by the **positions of its 8 vertices** and the **vertex indices of its 12 triangles**.




```
# vertex array
-1 ,  1 ,  1, # v0
 1 ,  1 ,  1, # v1
 1 , -1 ,  1, # v2
-1 , -1 ,  1, # v3
-1 ,  1 , -1, # v4
 1 ,  1 , -1, # v5
 1 , -1 , -1, # v6
-1 , -1 , -1, # v7
```

```
# index array
0,2,1, # t0
0,3,2, # t1
4,5,6, # t2
4,6,7, # t3
0,1,5, # t4
0,5,4, # t5
3,6,2, # t6
3,7,6, # t7
1,2,6, # t8
1,6,5, # t9
0,7,3, # t10
0,4,7, # t11
```

Quiz 2

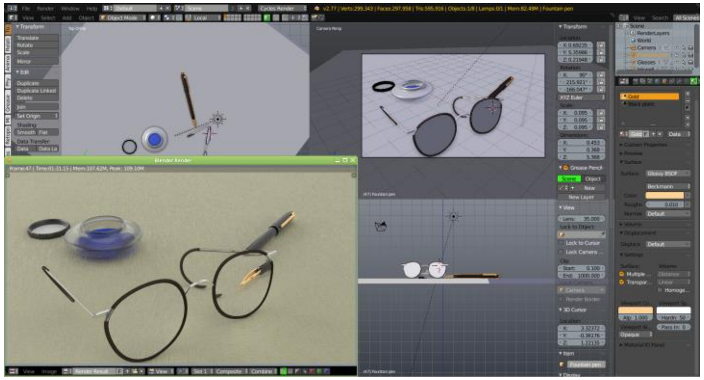
- Go to https://www.slido.com/
- Join #**cg-ys**
- Click "Polls"

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

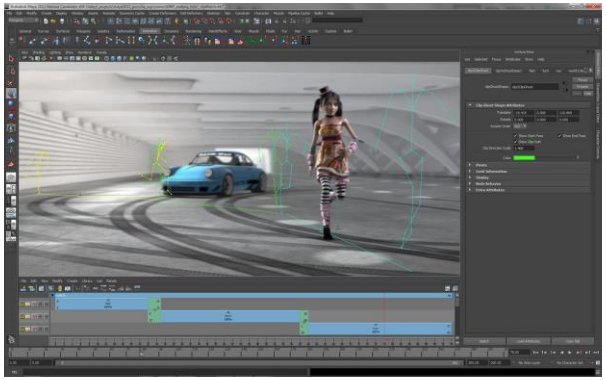
- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

Creating Polygon Meshes

- Usually, polygon meshes are created using 3D modeling programs.
  - A file that stores polygon mesh data is called an *object file* or *model file*.



Blender



Maya

- Applications (such as games) usually load vertex and index data from an *object file* and draw the object using the loaded data.

3D Model File Formats

- DXF – AutoCAD
  - Supports 2-D and 3-D; binary
- 3DS – 3DS MAX
  - Flexible; binary
- VRML – Virtual reality modeling language
  - ASCII – Human readable (and writeable)
- **OBJ – Wavefront OBJ format**
  - ASCII – Human readable (and writeable)
  - Extremely simple
  - Widely supported
- Let's take a closer look at OBJ format!

OBJ File Format

```
# this is a comment

# List of vertex positions, in (x, y, z) form.
v 0.123 0.234 0.345
v 0.2 0.5 0.3
v ...
...

# List of vertex normals, in (x,y,z) form; normals
might not be unit vectors.
vn 0.707 0.000 0.707
vn ...
...

# List of vertex texture coordinates, in (u, v) form.
vt 0.500 1
vt ...
...
```

OBJ File Format

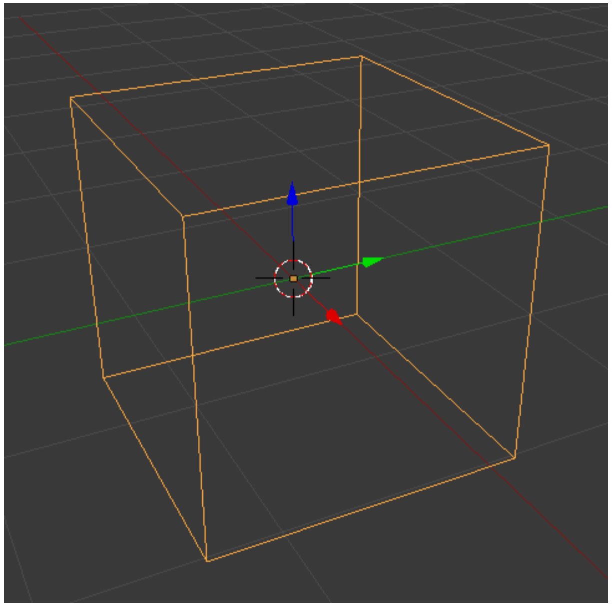
```
# List of faces (all argument indices are 1-based indices!)

# with vertex positions only - vertex_position_index
f 1 2 3
f 2 3 4
...

#
vertex_position_index/texture_coordinates_index/vertex_normal_
index
f 6/4/1 3/5/3 7/6/5

# vertex_position_index//vertex_normal_index
f 7//1 8//2 9//3
...

# vertex_position_index/texture_coordinates_index
f 3/1 4/2 5/3
...
```

OBJ File Format

- Other supported features:
  - for polyline
    - `l 5 8 1 2 4 9`
  - for materials
    - `mtllib [external .mtl file name]`
    - `usemtl [material name]`
  - ...

- You don't need to use these features in this class.

An OBJ Example



```
# A simple cube
v 1.000000 -1.000000 -1.000000
v 1.000000 -1.000000 1.000000
v -1.000000 -1.000000 1.000000
v -1.000000 -1.000000 -1.000000
v 1.000000 1.000000 -1.000000
v 1.000000 1.000000 1.000000
v -1.000000 1.000000 1.000000
v -1.000000 1.000000 -1.000000
f 1 2 3 4
f 5 8 7 6
f 1 5 6 2
f 2 6 7 3
f 3 7 8 4
f 5 1 4 8
```

OBJ Sources

- https://free3d.com/
- https://www.cgtrader.com/free-3d-models

- You can download any .obj model files from these sites and open them in Blender.

- OBJ file format is very popular:
  - Most modeling programs will export OBJ files
  - Most rendering packages will read in OBJ files

Lab Session

- Now, let's start the lab today.