Computer Graphics

8 - Hierarchical Modeling

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Topics Covered

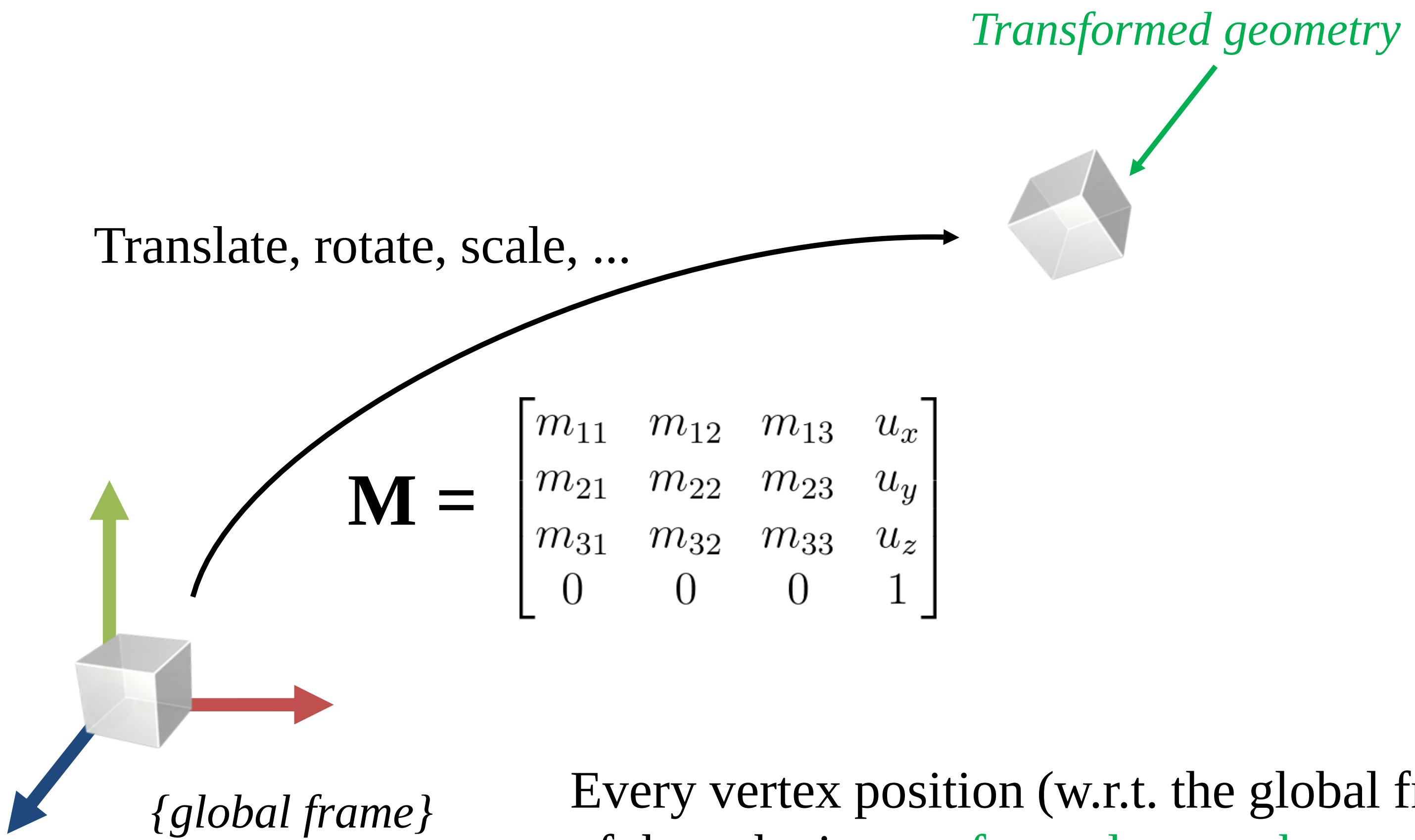
- Meanings of an Affine Transformation Matrix
- Interpretation of a Series of Transformations
- Hierarchical Modeling
  - Concept of Hierarchical Modeling
  - OpenGL Matrix Stack

Meanings of an Affine Transformation Matrix

Meanings of an Affine Transformation Matrix

- To understand hierarchical modeling, let's first take a closer look at the meaning of an affine transformation matrix.

1) A 4x4 Affine Transformation Matrix transforms a Geometry w.r.t. Global Frame

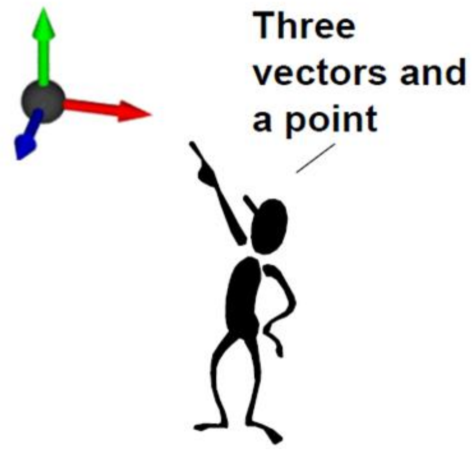


$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Every vertex position (w.r.t. the global frame) of the cube is transformed to another position (w.r.t. the global frame)

Review: Affine Frame

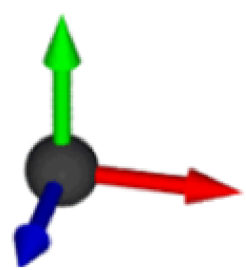
- An **affine frame** in 3D space is defined by three vectors and one point
  - Three vectors for x, y, z axes
  - One point for origin



Global Frame

- A **global frame** is usually represented by
  - Standard basis vectors for axes : $\hat{\mathbf{e}}_x, \hat{\mathbf{e}}_y, \hat{\mathbf{e}}_z$
  - Origin point : $\mathbf{0}$

global x, y, z 축



Let's transform a "global frame"

- Apply M to this "global frame", that is,
  - Multiply M with the x, y, z axis *vectors* and the origin *point* of the global frame:

x axis *vector*

벡터가 affine transform 되면 또다른 벡터가 됨

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ \boxed{0} \end{bmatrix} = \begin{bmatrix} m_{11} \\ m_{21} \\ m_{31} \\ \boxed{0} \end{bmatrix}$$

끝자리 0

y axis *vector*

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ \boxed{0} \end{bmatrix} = \begin{bmatrix} m_{12} \\ m_{22} \\ m_{32} \\ \boxed{0} \end{bmatrix}$$

homogenius coordinate로 표현하면 벡터니깐 마지막 숫자는 0이어야 함

z axis *vector*

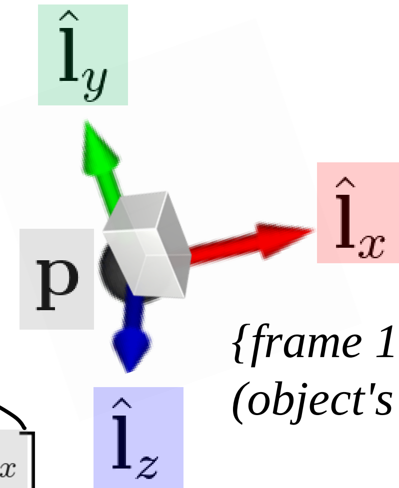
$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ \boxed{0} \end{bmatrix} = \begin{bmatrix} m_{13} \\ m_{23} \\ m_{33} \\ \boxed{0} \end{bmatrix}$$

origin *point* → 마지막 컴포넌트: 1

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ \boxed{1} \end{bmatrix} = \begin{bmatrix} u_x \\ u_y \\ u_z \\ \boxed{1} \end{bmatrix}$$

2) A 4x4 Affine Transformation Matrix defines an Affine Frame w.r.t. Global Frame

☆ global frame 상에서 표현된 벡터와 포인트이다 ☆



{frame 1}
(object's local frame)

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

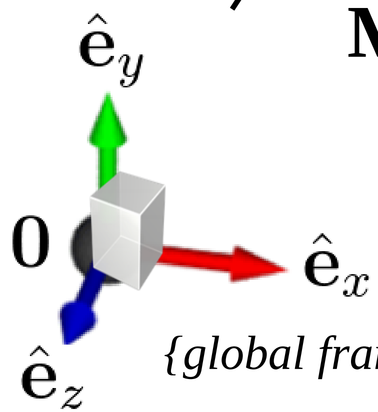
x axis *vector*

y axis *vector*

z axis *vector*

origin *point*

⇑
global frame의 x,y,z 축을 이용해 표현됨



{global frame}

→ M is **the** $\boxed{\text{새로운 frame의 } \textbf{axis vectors}}$ **and** $\boxed{\textbf{origin point}}$ **of a new frame (represented in the global frame)**

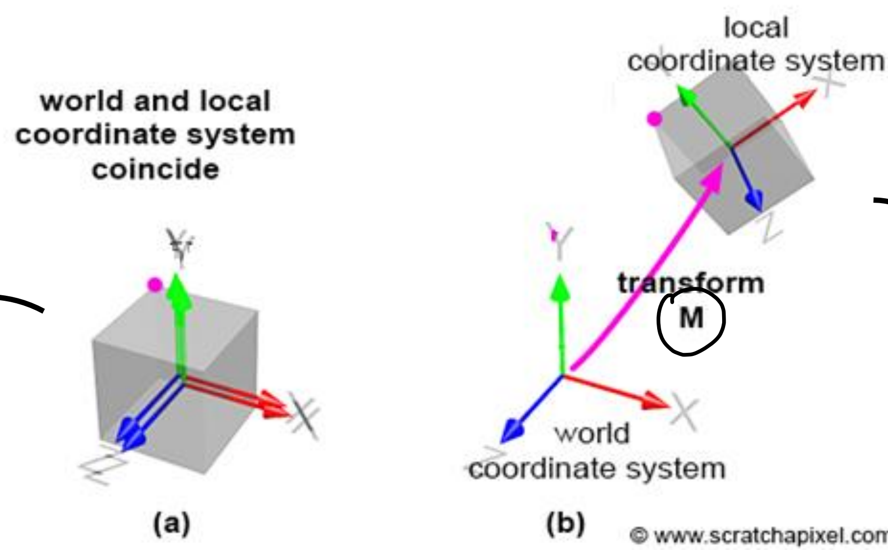
{ global frame 상에서 새로운 frame을 define 함 }

Examples

geometry를 transform 하는건 local frame도 transform 되는거다.
즉, transform matrix가 local frame 자체를 define 하기도 한다

global frame = local frame 인 경우

물체의 로컬 frame은 global frame 상에서 identity matrix로 표현됨



Matrix M 자체가 local frame을 define 함

The object's local frame is defined by:

$$I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

x axis vector, y axis vector, z axis vector, origin point

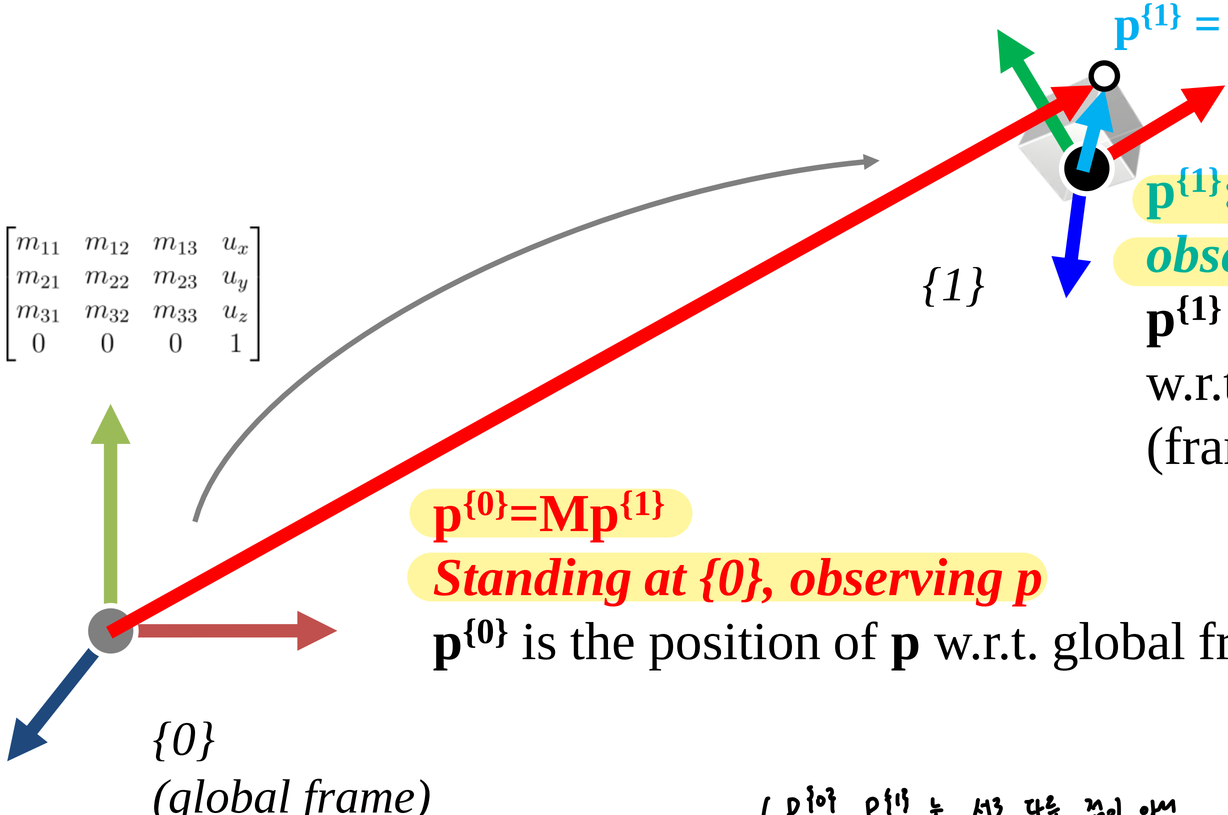
of the local frame ***represented in the global frame***

The object's local frame is defined by:

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & u_1 \\ m_{21} & m_{22} & m_{23} & u_2 \\ m_{31} & m_{32} & m_{33} & u_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

x axis vector, y axis vector, z axis vector, origin point

3) A 4x4 Affine Transformation Matrix transforms a Point Represented in an Affine Frame to (the same) Point (but) Represented in Global Frame



$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$\mathbf{p}^{\{1\}}$: ***Standing at {1}, observing p***

$\mathbf{p}^{\{1\}}$ is the position of $\mathbf{p}$ w.r.t local frame (frame {1})

$\mathbf{p}^{\{0\}} = \mathbf{M}\mathbf{p}^{\{1\}}$

Standing at {0}, observing p

$\mathbf{p}^{\{0\}}$ is the position of $\mathbf{p}$ w.r.t. global frame (frame {0})

($p^{\{0\}}$, $p^{\{1\}}$ 는 서로 다른 점이 아님.
동일 한 점을 어느 frame 에서 바라보냐를 얘기)
'global frame 상의 점을 옮긴다' 와는 조금 다른 의미.

3) A 4x4 Affine Transformation Matrix transforms a Point Represented in an Affine Frame to (the same) Point (but) Represented in Global Frame

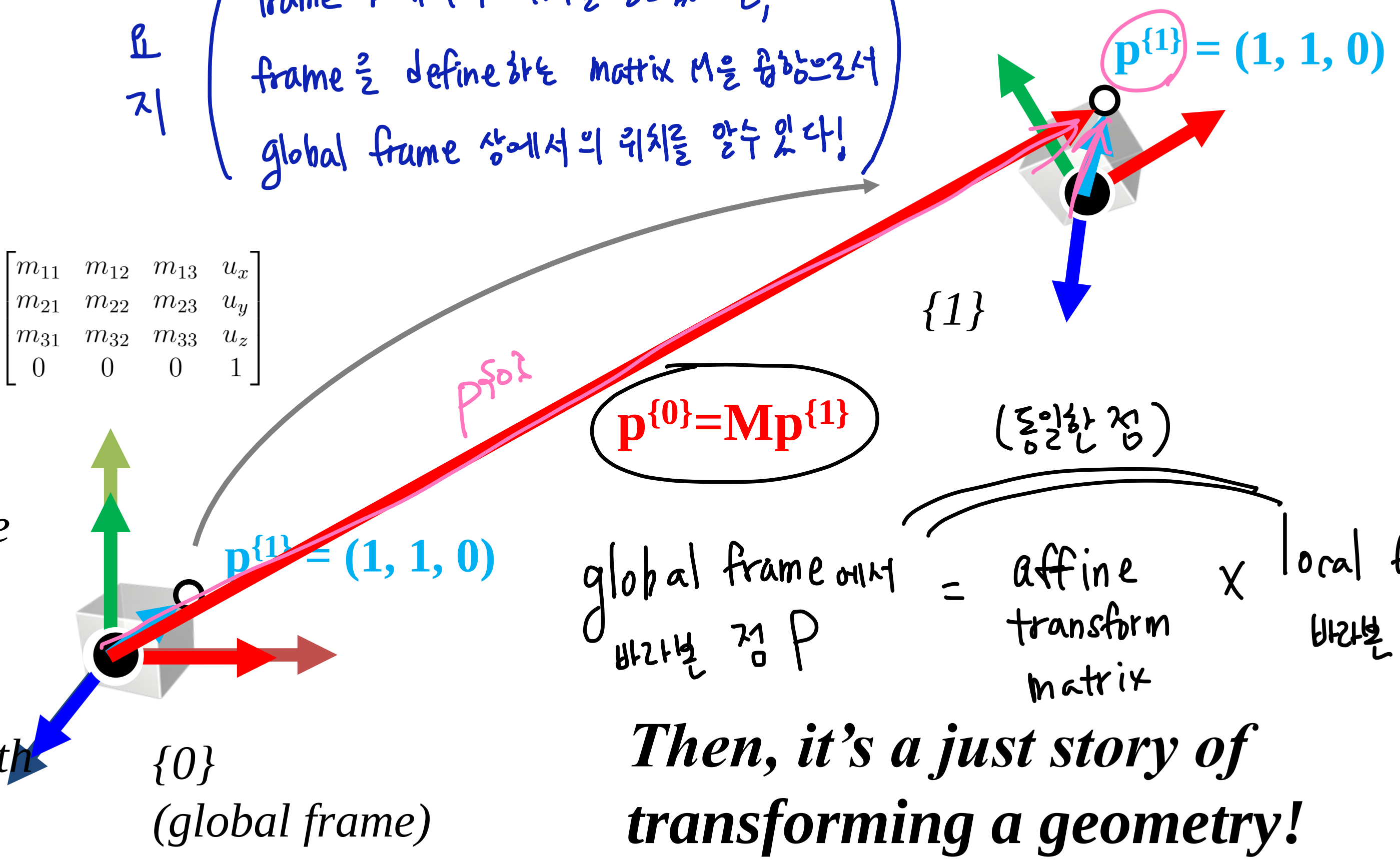
Because...

요지

(frame 1 에서의 위치를 알고있다면,
frame을 define하는 matrix M을 곱함으로서
global frame 상에서의 위치를 알수 있다!)

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & u_x \\ m_{21} & m_{22} & m_{23} & u_y \\ m_{31} & m_{32} & m_{33} & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Let's say we have the same cube object and its local frame coincident with the global frame



(동일한 점)

global frame 에서 바라본 점 P = affine transform matrix x local frame 에서 바라본 점 P

Then, it's a just story of transforming a geometry!

Quiz #1

$$\begin{bmatrix} -1 & 0 & 0 & 10 \\ 0 & 1 & 0 & 20 \\ 0 & 0 & 1 & 30 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 3 \\ 1 \end{bmatrix} = \begin{bmatrix} 9 \\ 22 \\ 33 \\ 1 \end{bmatrix}$$

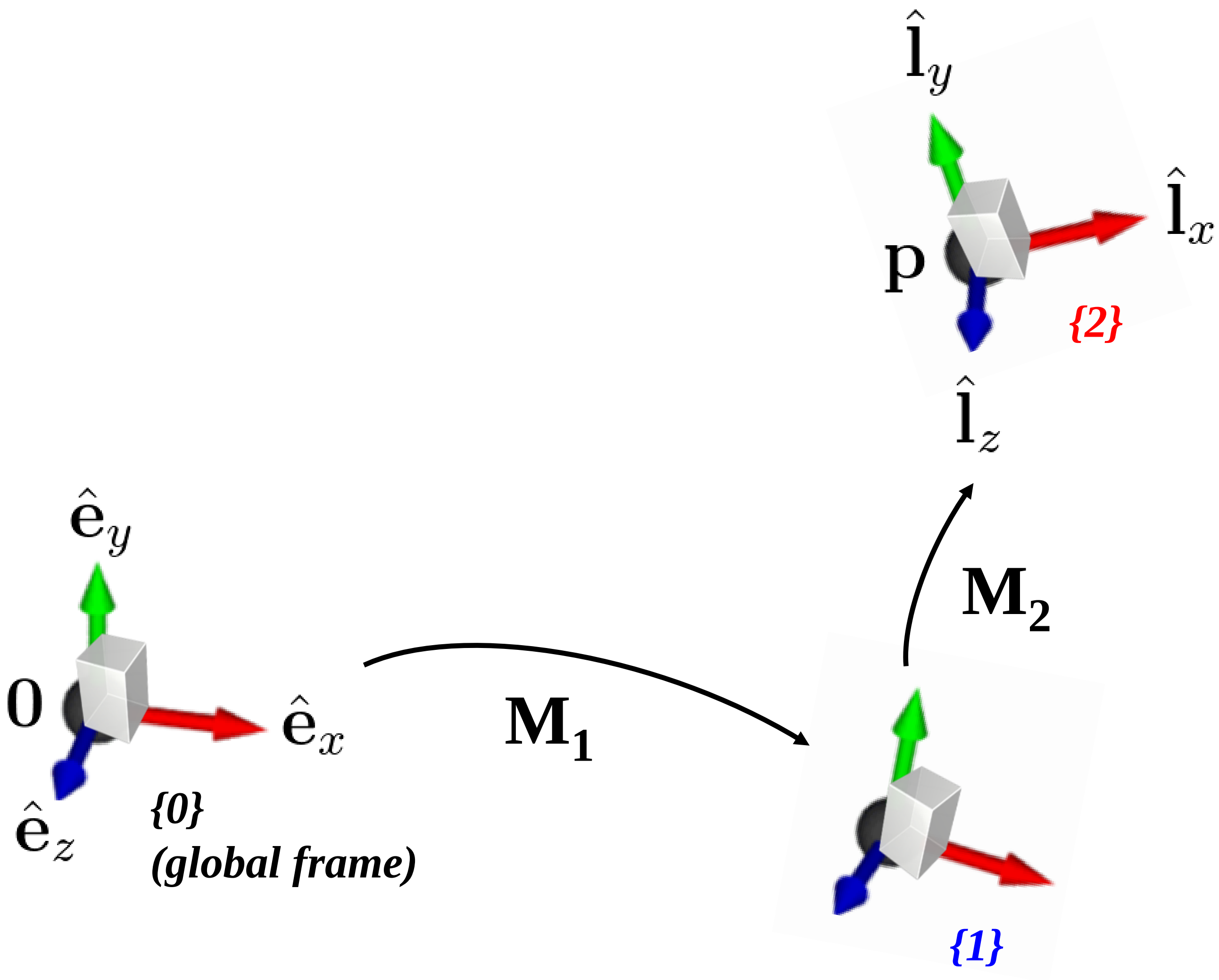
- Go to https://www.slido.com/
- Join #**cg-ys**
- Click “Polls”

homogenius coordinate 상에서 세라! 고 하면
[9, 22, 33, 1] 이 정확한 답이다.

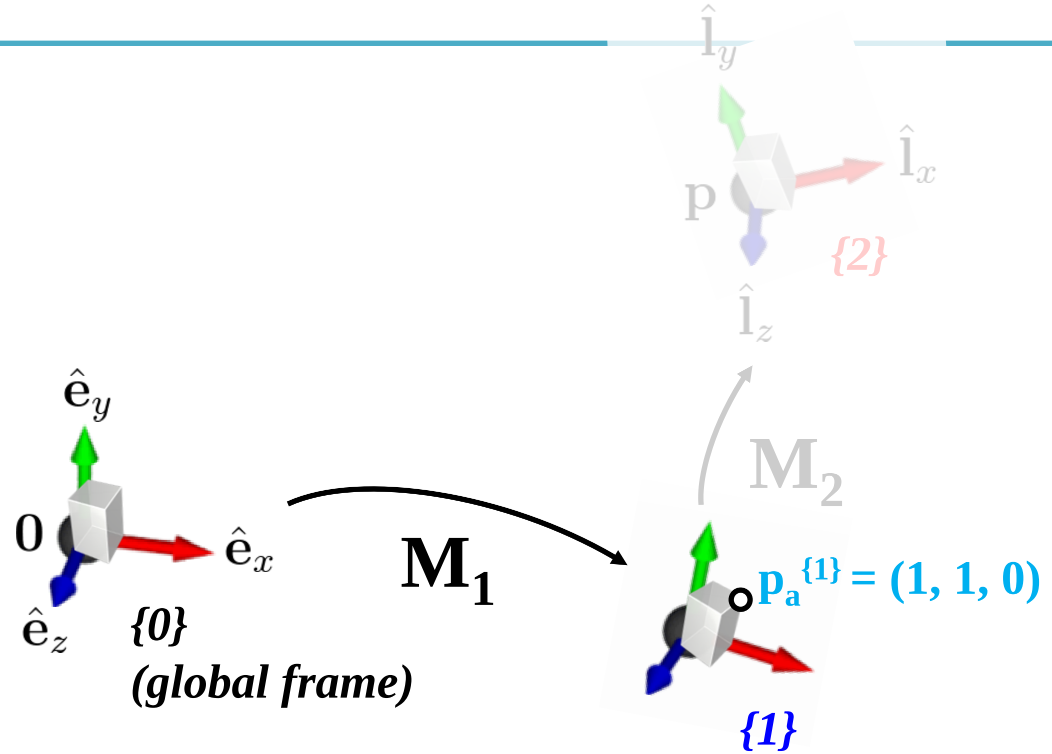
- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

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

All these concepts works even if the starting frame is not global frame!

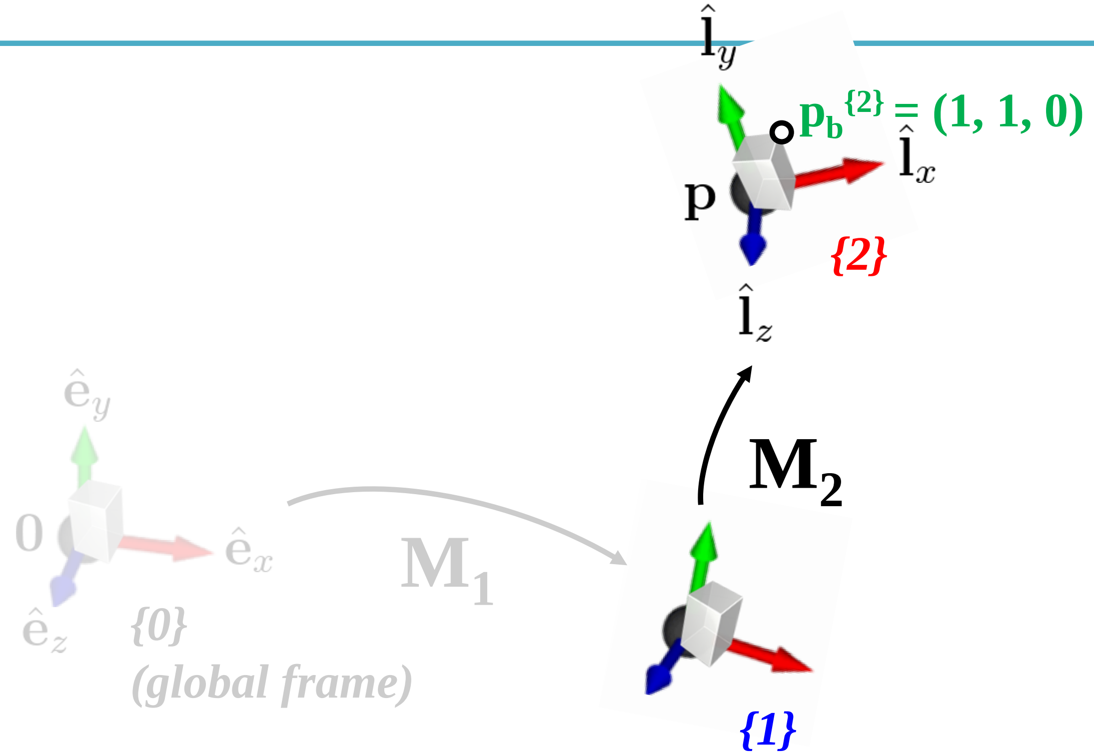


{0} to {1}



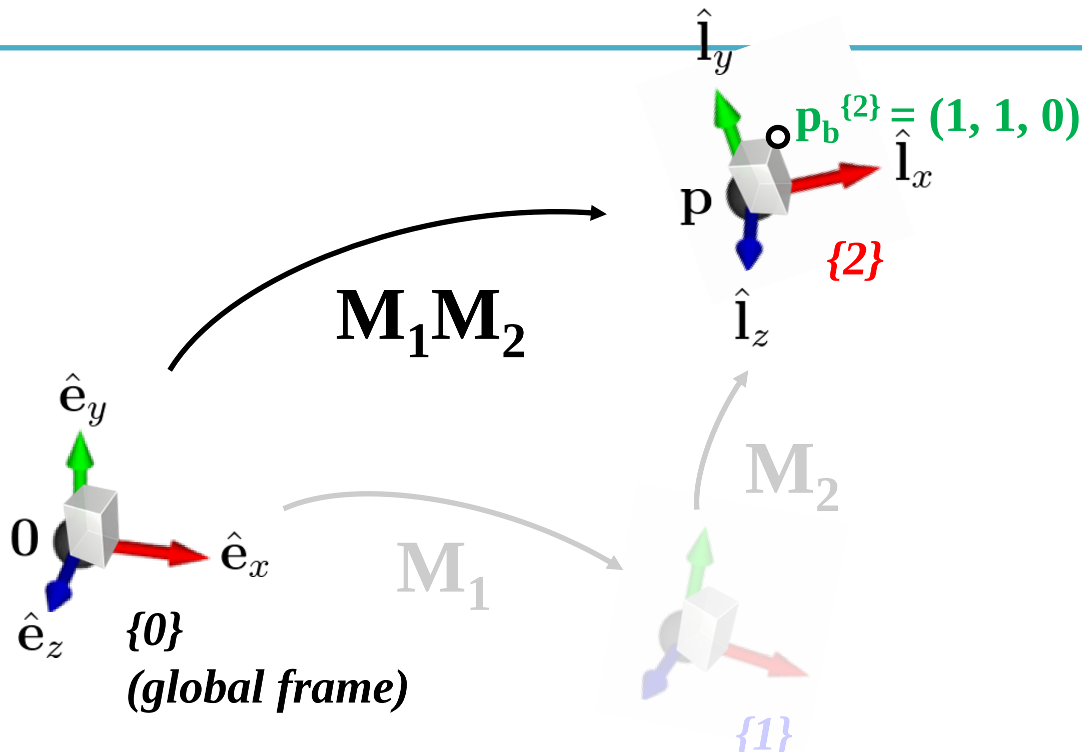
- 1) $\mathbf{M}_1$ transforms a geometry (represented in ***{0}***) w.r.t. ***{0}***
- 2) $\mathbf{M}_1$ defines an ***{1}*** w.r.t. ***{0}***
- 3) $\mathbf{M}_1$ transforms a point represented in ***{1}*** to the same point but represented in ***{0}***
  - $\mathbf{p_a}^{\{0\}}=\mathbf{M}_1\mathbf{p_a}^{\{1\}}$

{1} to {2}



- 1) $\mathbf{M}_2$ transforms a geometry (represented in *{1}*) w.r.t. *{1}*
- 2) $\mathbf{M}_2$ defines an *{2}* w.r.t. *{1}*
- 3) $\mathbf{M}_2$ transforms a point represented in *{2}* to the same point but represented in *{1}*
  - $\mathbf{p_b}^{\{1\}}=\mathbf{M}_2\mathbf{p_b}^{\{2\}}$

{0} to {2}



- 1) $\mathbf{M_1M_2}$ transforms a geometry (represented in ***{0}***) w.r.t. ***{0}***
- 2) $\mathbf{M_1M_2}$ defines an ***{2}*** w.r.t. ***{0}***
- 3) $\mathbf{M_1M_2}$ transforms a point represented in ***{2}*** to the same point but represented in ***{0}***
  - $\mathbf{p_b}^{\{1\}}=\mathbf{M_2p_b}^{\{2\}}$, $\mathbf{p_b}^{\{0\}}=\mathbf{M_1p_b}^{\{1\}}=\mathbf{M_1M_2p_b}^{\{2\}}$

global frame에 대해 표현된 변환일 경우
먼저하는 변환이 가장 오른쪽에 와야되지만,
이 경우는 local frame에 대해 표현된 변환이므로
(M2가 frame1에 대해 define 돼있음)
현재 내 프레임에 대해 변환이 적용되므로 $M_1M_2P_b$

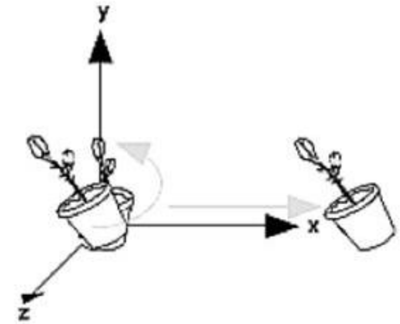
Interpretation of a Series of Transformations

Revisit: Order Matters!

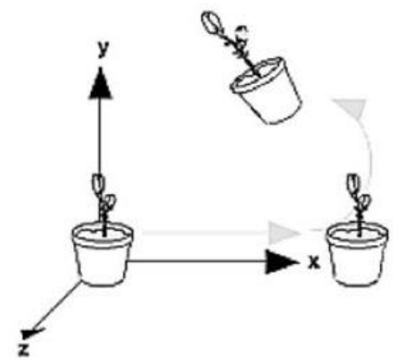
- If T and R are matrices representing affine transformations,

- **p'** = TR**p**
  - First apply transformation R to point **p**, then apply transformation T to transformed point R**p**

- **p'** = RT**p**
  - First apply transformation T to point **p**, then apply transformation R to transformed point T**p**



Rotate then Translate



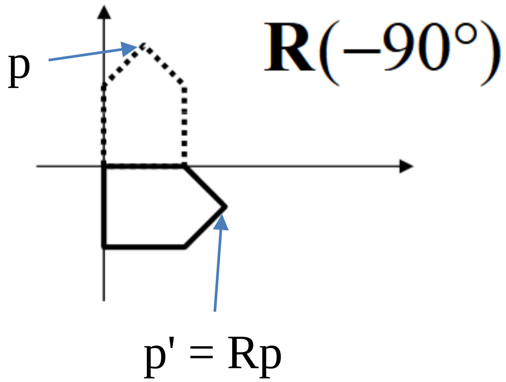
Translate then Rotate

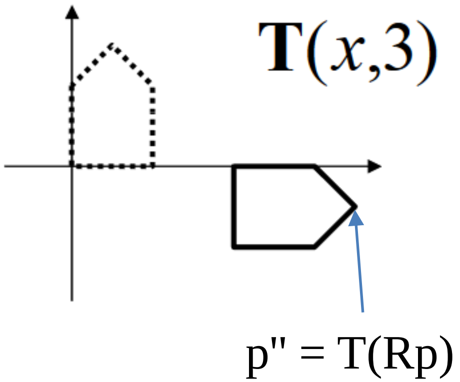
Interpretation of Composite Transformations #1

- An example transformation:

$$M = \mathbf{T}(x,3) \cdot \mathbf{R}(-90°)$$

- This is how we've interpreted so far:
  - R-to-L: Transforms ***w.r.t. global frame***



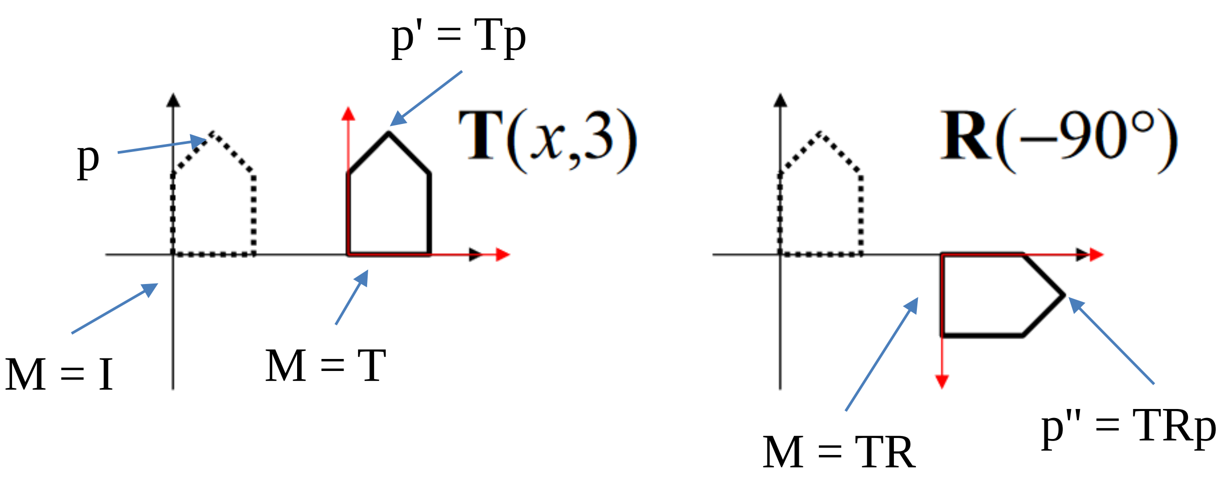


Interpretation of Composite Transformations #2

- An example transformation:

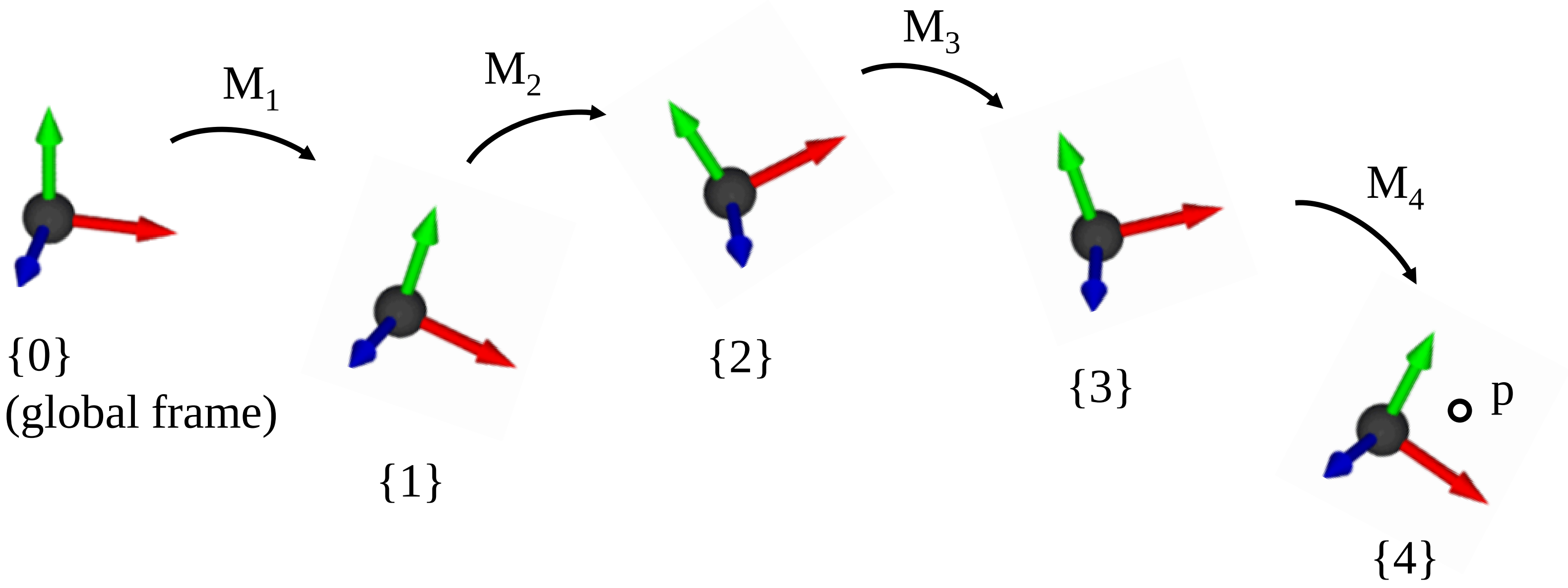
$$M = \mathbf{T}(x,3) \cdot \mathbf{R}(-90°)$$

- **Another way of interpretation:**
  - L-to-R: Transforms ***w.r.t. local frame***



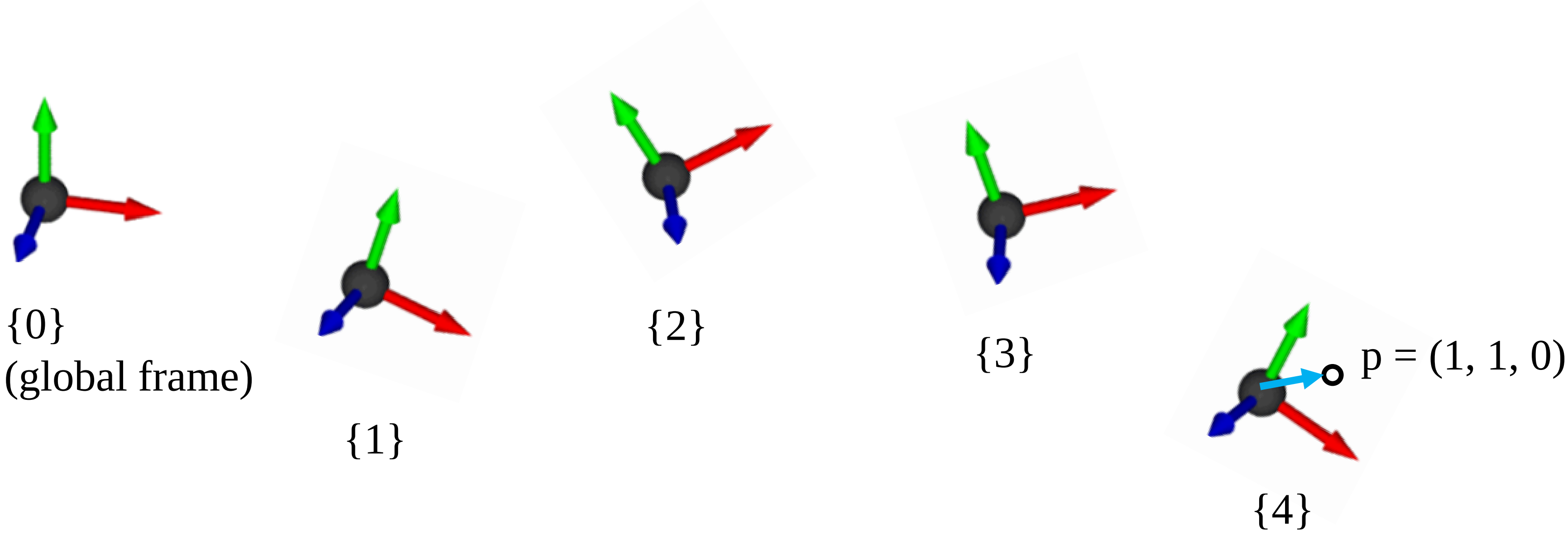
Interpretation of a Series of Transformations #1

- $p' = M_1 M_2 M_3 M_4 \; p$



Interpretation of a Series of Transformations #1

- $p' = M_1 M_2 M_3 M_4 \boxed{p}$

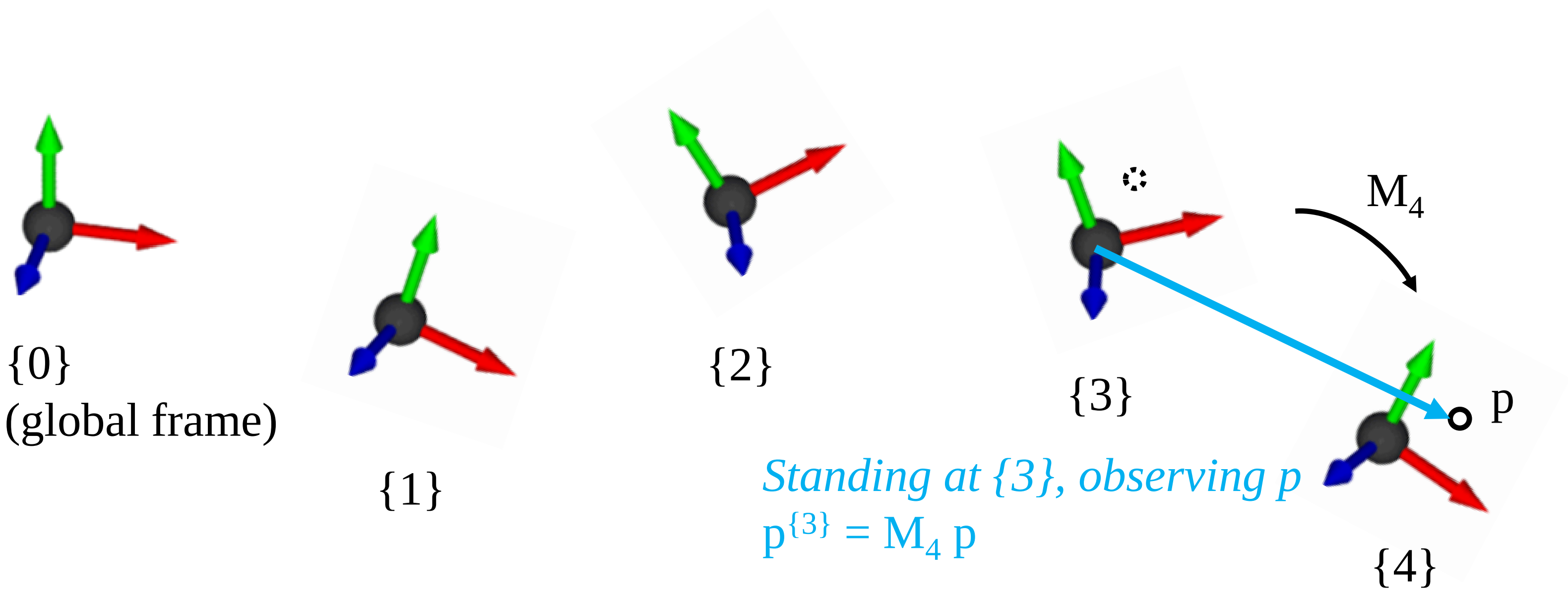


Standing at {4}, observing p

$p^{\{4\}} = p$

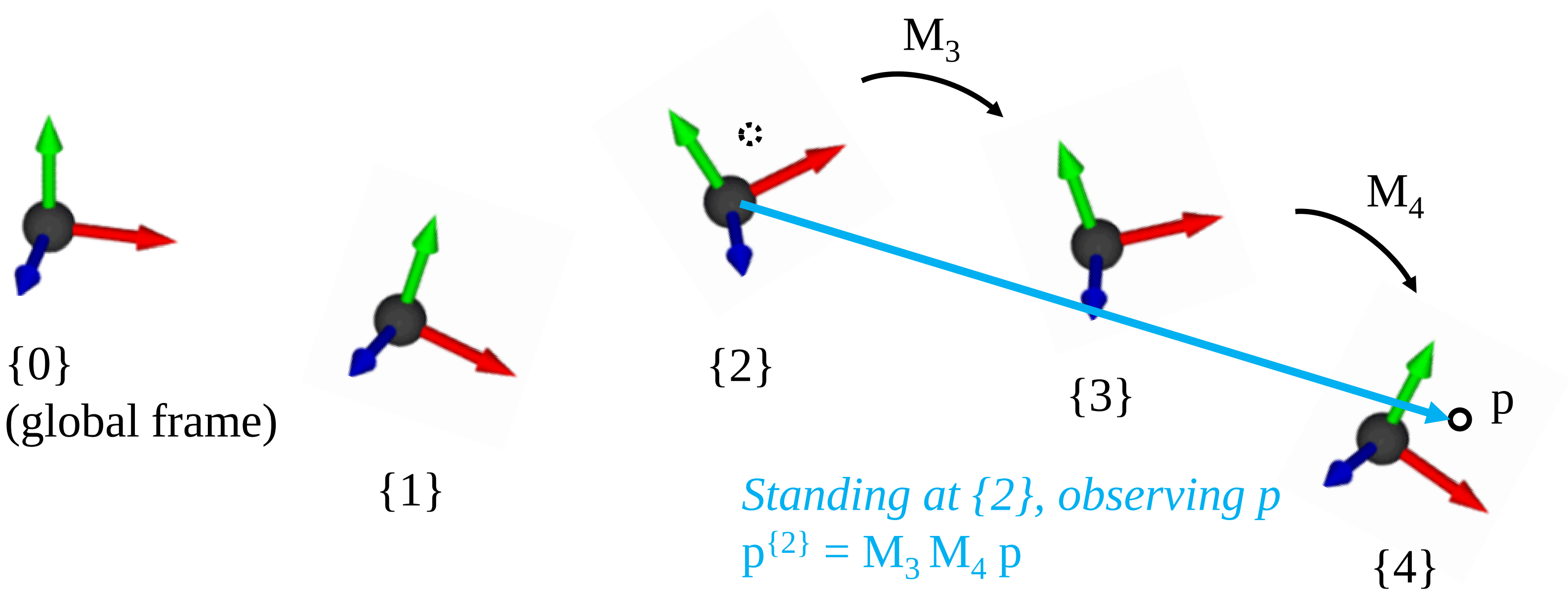
Interpretation of a Series of Transformations #1

- $p' = M_1 M_2 M_3 \boxed{M_4\ p}$



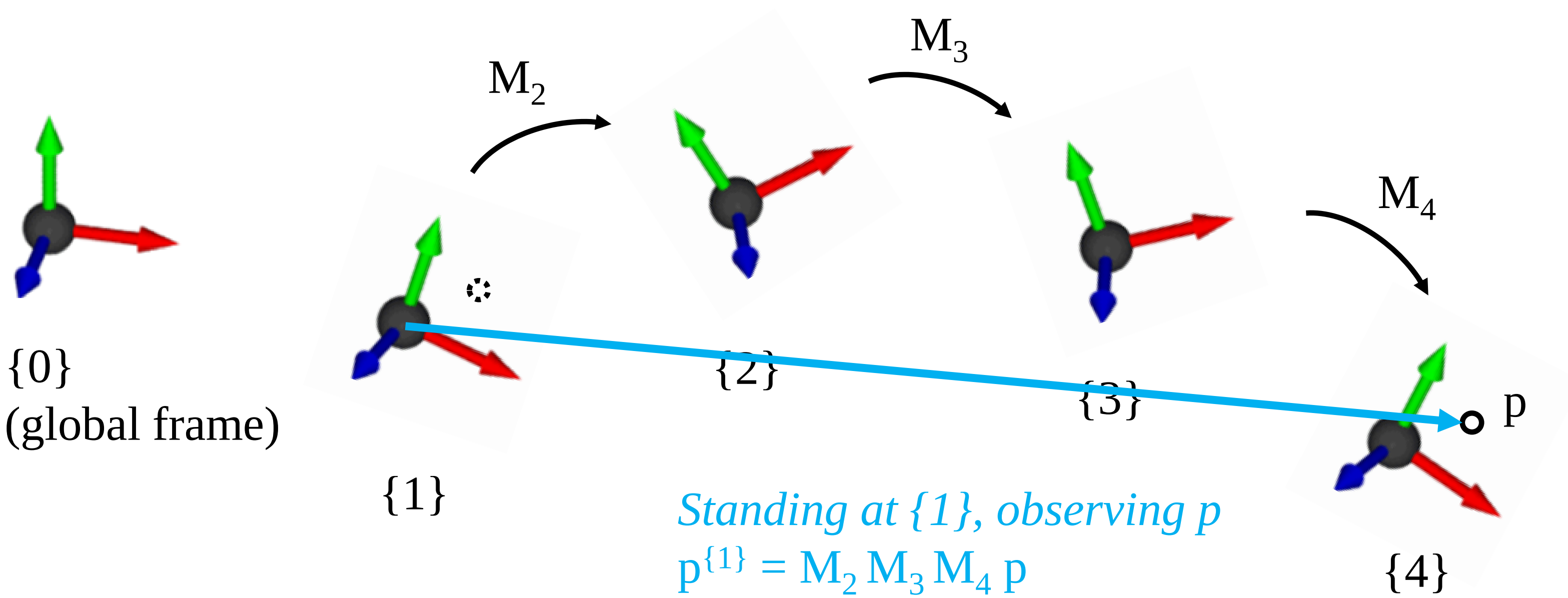
Interpretation of a Series of Transformations #1

- $p' = M_1 M_2 \boxed{M_3 M_4\ p}$



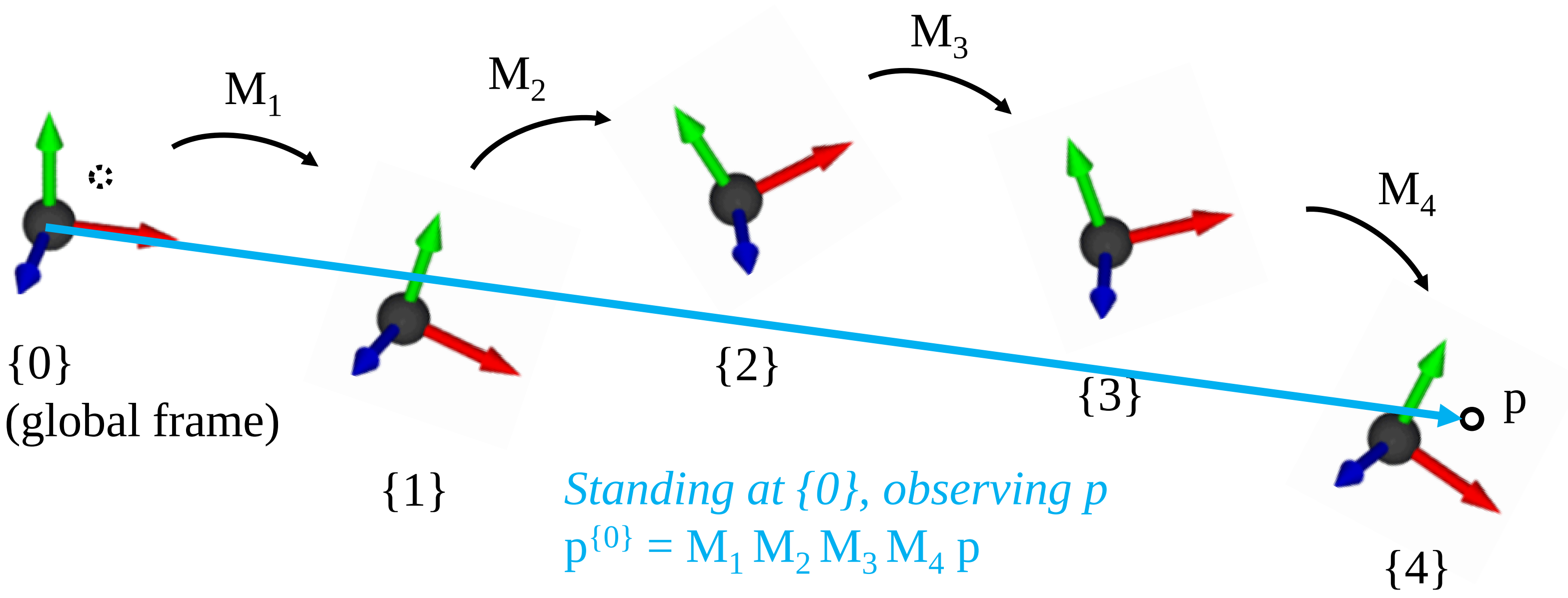
Interpretation of a Series of Transformations #1

- $p' = M_1 \boxed{M_2 M_3 M_4\ p}$



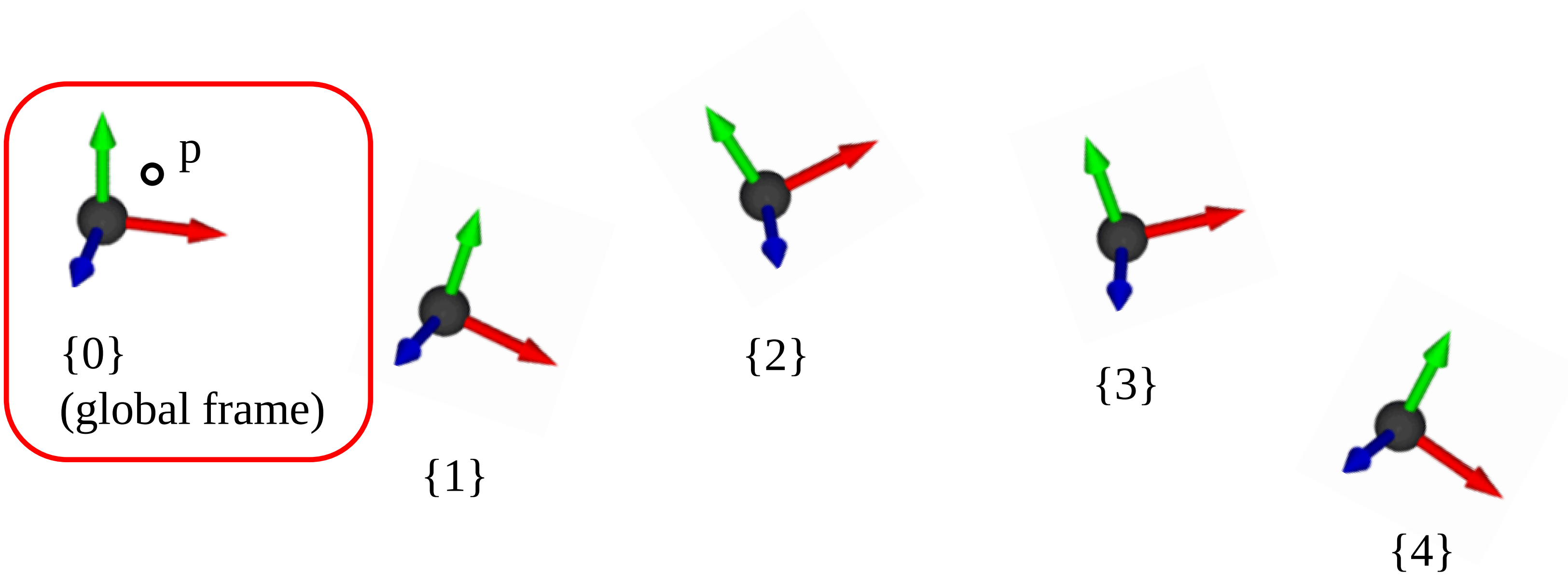
Interpretation of a Series of Transformations #1

- p' = $\boxed{M_1 M_2 M_3 M_4\ p}$



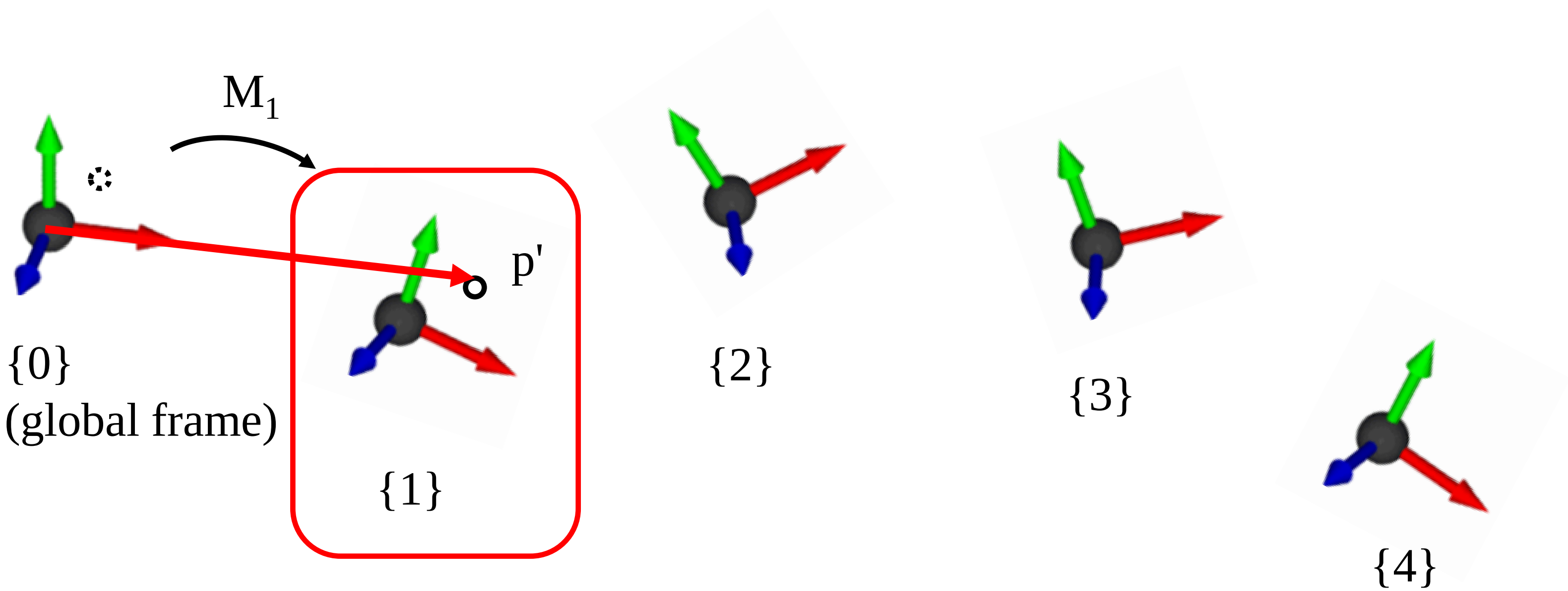
Interpretation of a Series of Transformations #2

- $p' = M_1 M_2 M_3 M_4 \, p$



Interpretation of a Series of Transformations #2

- $p' = \boxed{M_1} M_2 M_3 M_4 \, p$

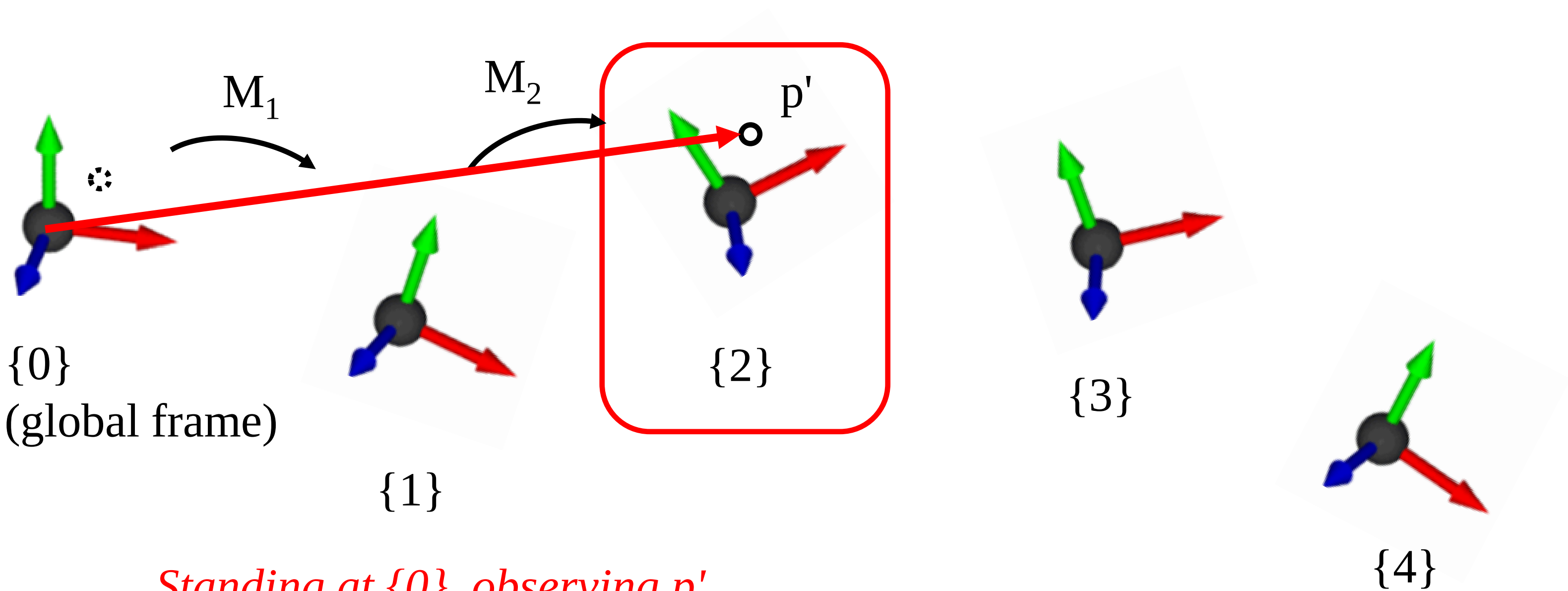


Standing at {0}, observing p'

$p' = M_1 \, p$

Interpretation of a Series of Transformations #2

- $p' = \boxed{M_1 M_2} M_3 M_4\ p$

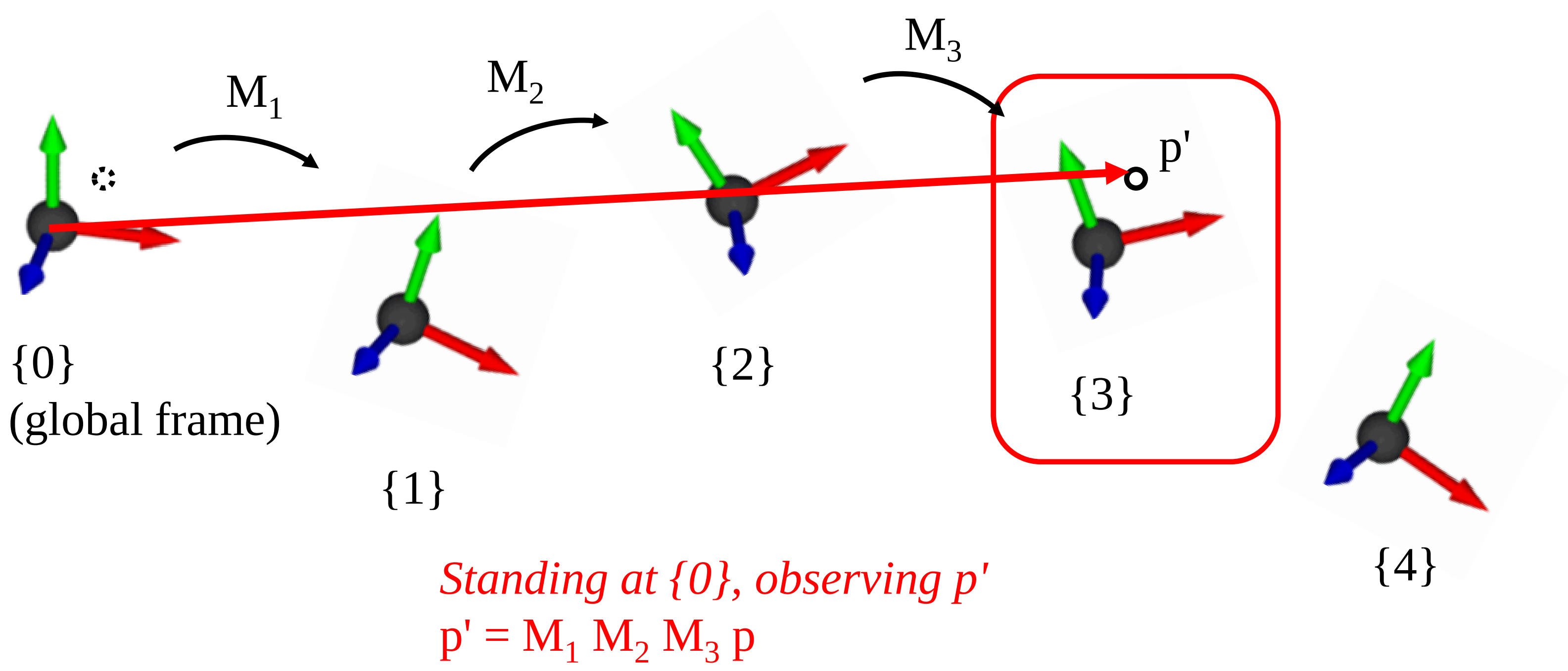


Standing at {0}, observing p'

$p' = M_1\ M_2\ p$

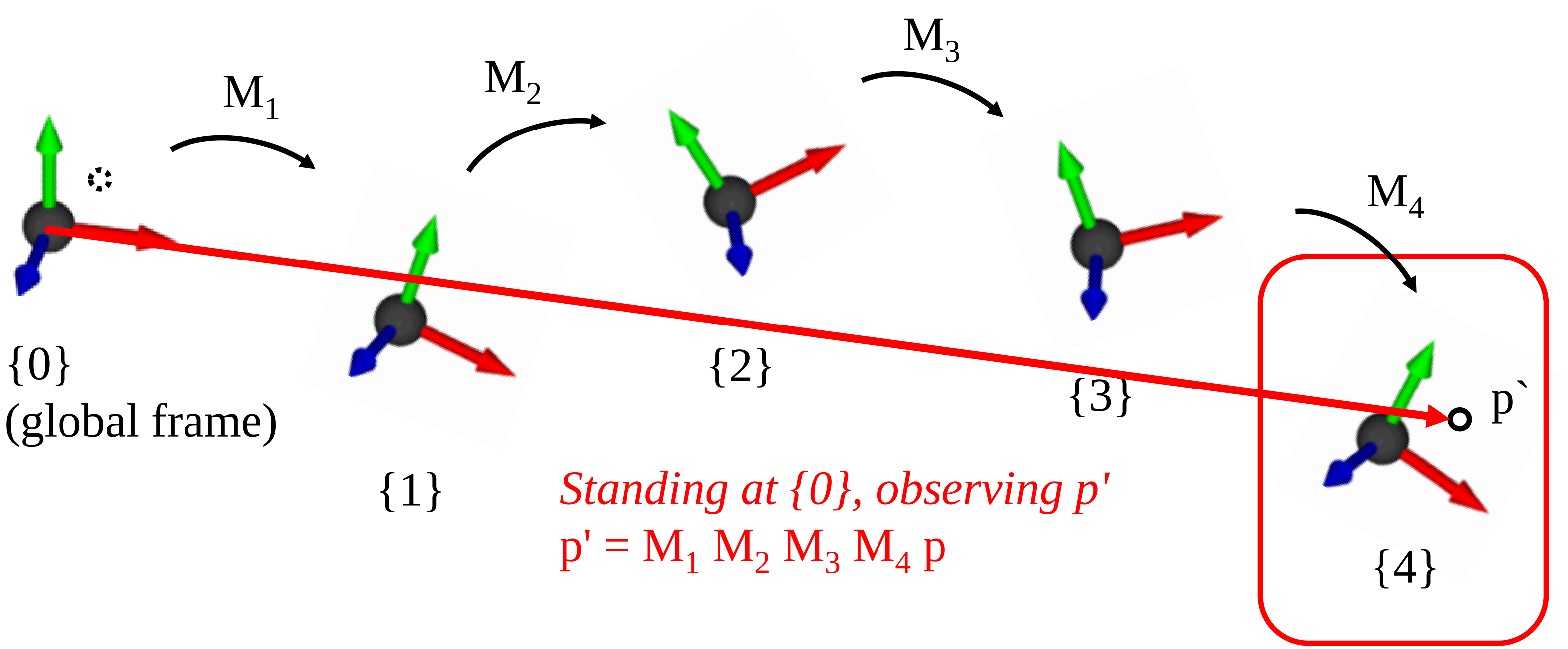
Interpretation of a Series of Transformations #2

- $p' = \boxed{M_1 M_2 M_3} M_4 \ p$



Interpretation of a Series of Transformations #2

- $p' = \boxed{M_1 M_2 M_3 M_4\ p}$



Left & Right Multiplication

- Thinking it deeper, we can see:

- **p' = RTp (left-multiplication by R)**
  - (R-to-L) Apply T to a point p w.r.t. global frame.
  - **Apply R to a point Tp w.r.t. global frame.**

- **p' = TRp (right-multiplication by R)**
  - (L-to-R) Apply T to a point p w.r.t. local frame.
  - **Apply R to a point Tp w.r.t local frame.**

[Practice] Interpretation of Composite Transformations

- Just start from the Lecture 4 practice code "[Practice] OpenGL Trans. Functions".

- Differences are:

```
def drawFrame():
    glBegin(GL_LINES)
    glColor3ub(255, 0, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([1.,0.,0.]))
    glColor3ub(0, 255, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([0.,1.,0.]))
    glColor3ub(0, 0, 255)
    glVertex3fv(np.array([0.,0.,0]))
    glVertex3fv(np.array([0.,0.,1.]))
    glEnd()
```

[Practice] Interpretation of Composite Transformations

```
def render(camAng):
    glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT)
    glEnable(GL_DEPTH_TEST)
    glLoadIdentity()
    glOrtho(-1,1, -1,1, -1,1)
    gluLookAt(.1*np.sin(camAng),.1,.1*np.cos(camAng), 0,0,0, 0,1,0)

    # draw global frame
    drawFrame()

    # 1) p'=TRp
    glTranslatef(.4, .0, 0)
    drawFrame()      # frame defined by T
    glRotatef(60, 0, 0, 1)
    drawFrame()      # frame defined by TR

    # # 2) p'=RTp
    # glRotatef(60, 0, 0, 1)
    # drawFrame()    # frame defined by R
    # glTranslatef(.4, .0, 0)
    # drawFrame()    # frame defined by RT

    drawTriangle()
```

projection transformation과
카메라 transformation이
적용된 상태
⇒ global frame

* openGL은 matrix를 current matrix의 오른쪽에 계속 곱해주는 것뿐, 그걸 어떻게 생각하는지는 생각하는 사람 자유.

Quiz #2

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

$p' = ABCp$

- 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”.

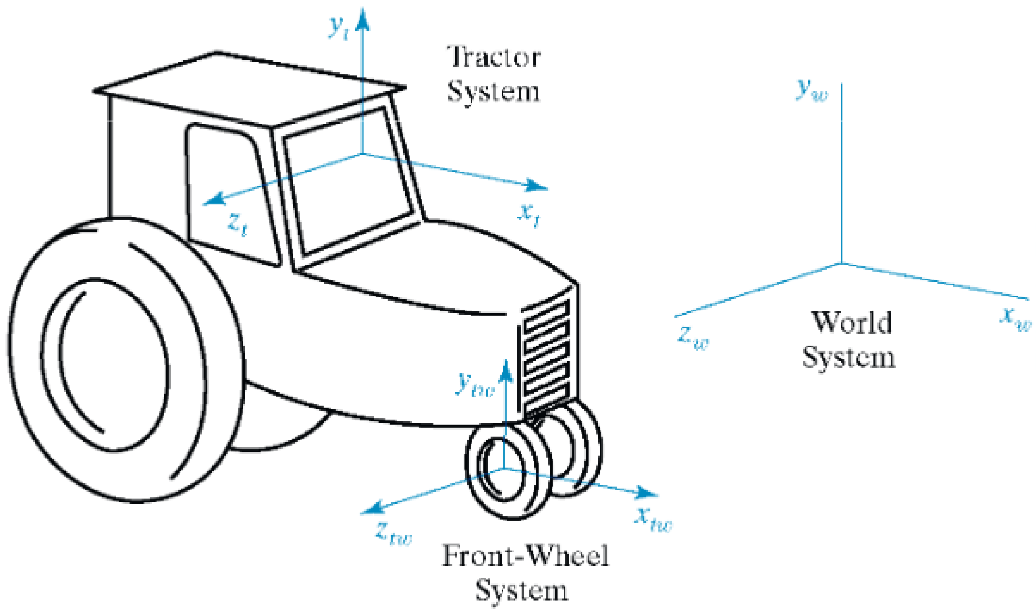
Hierarchical Modeling

Hierarchical Modeling

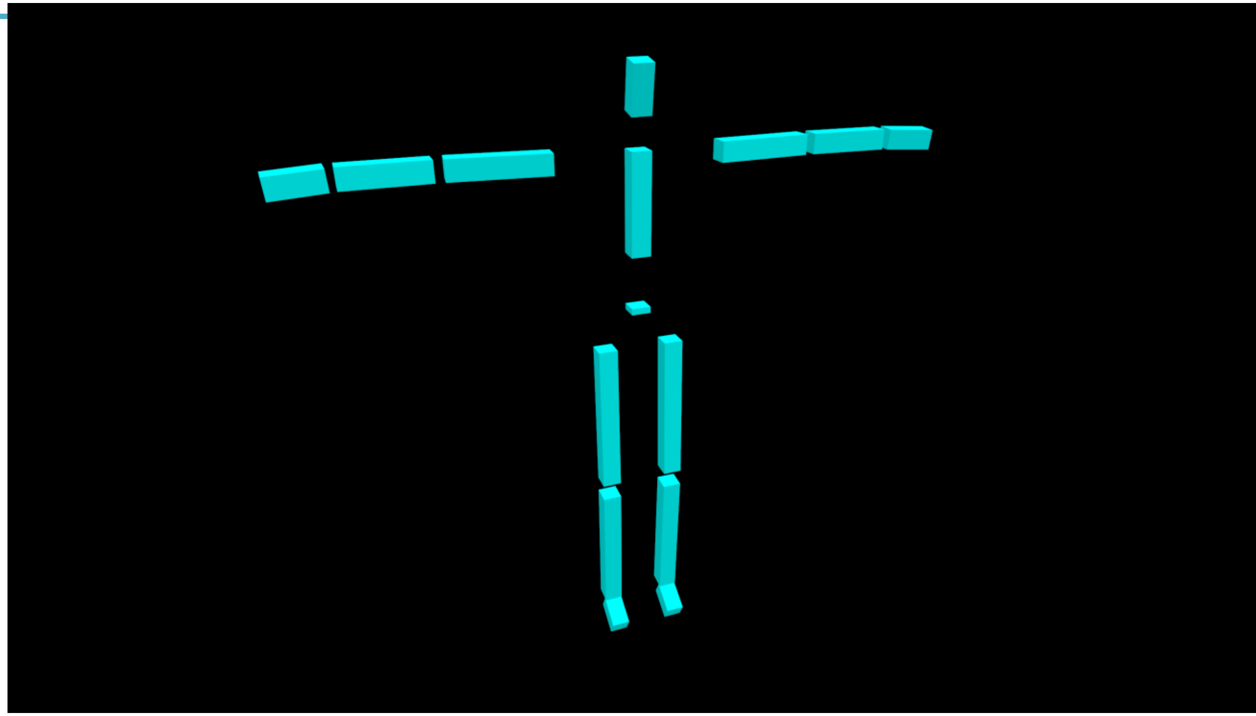
- Nesting the description of subparts (child parts) into another part (parent part) to form a tree structure

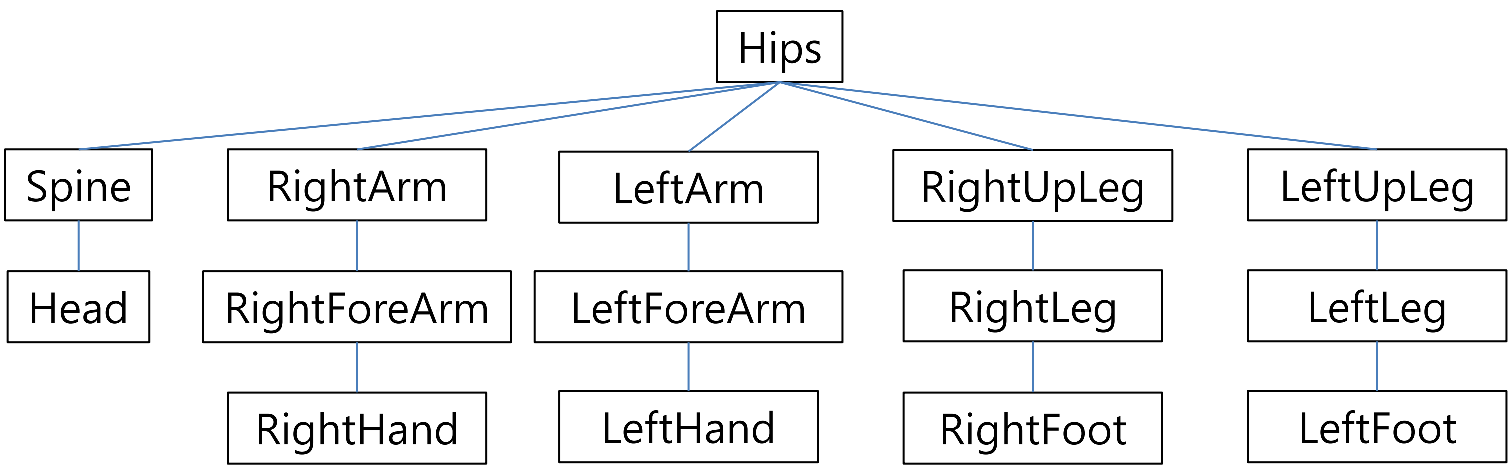
- Each part has its own reference frame (local frame).

- Each part's movement is described w.r.t. its parent's reference frame.

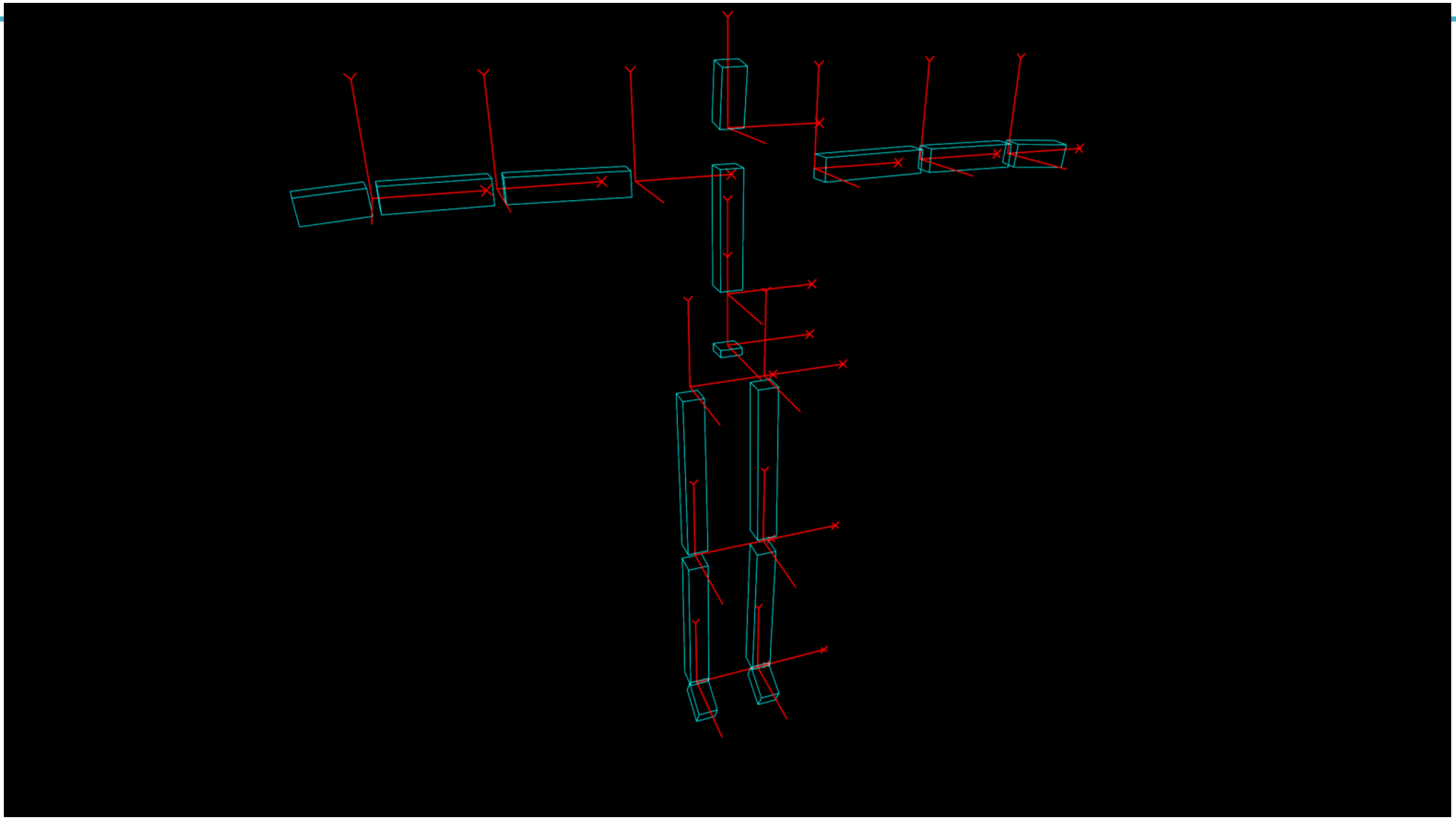


Another Example - Human Figure



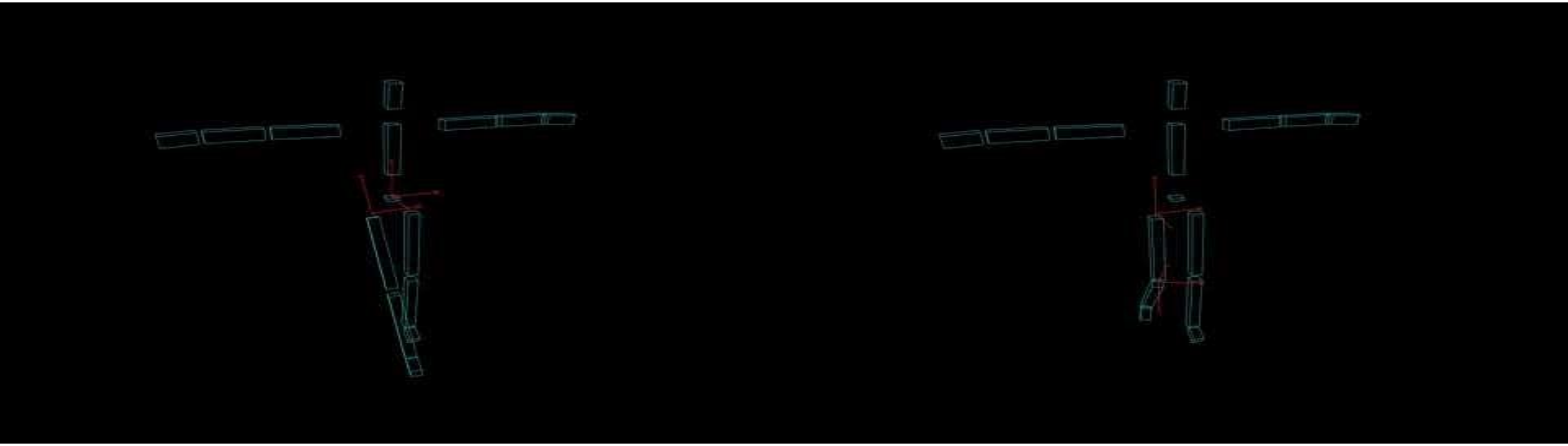


Human Figure - Frames



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

Human Figure - Movement of rhip & rknee

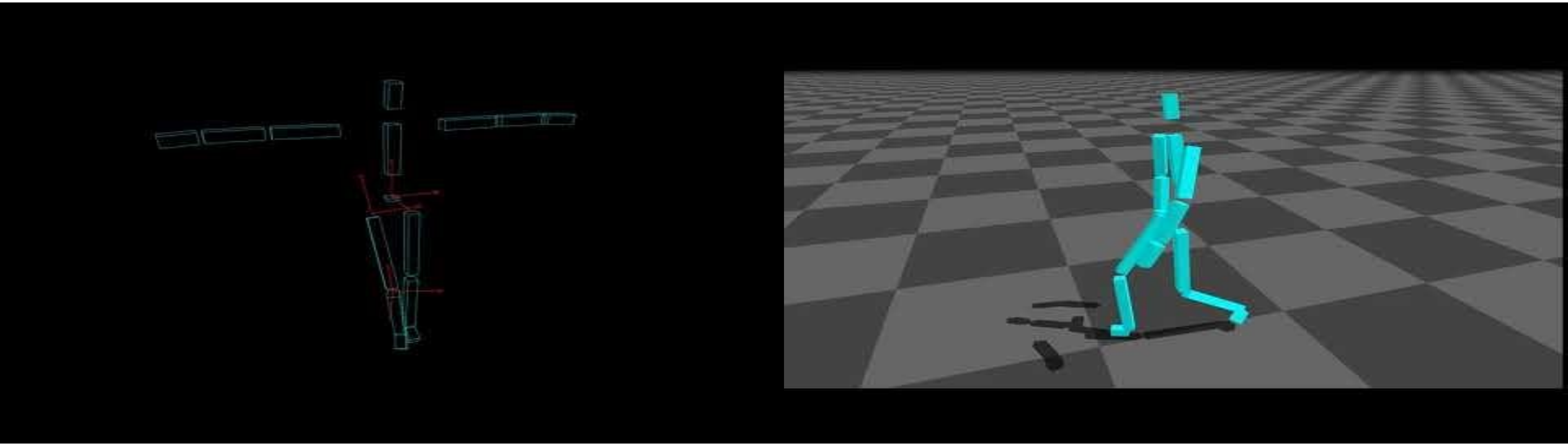


https://youtu.be/Q7lhvMkCSCg https://youtu.be/Q5R8WGUwpFU

hierarchical model에서는 parent 모델에 대한 상대적인 움직임으로 모든움직임을 표현함

- Each part's movement is described w.r.t. its parent's reference frame.
  - Each part has its own transformation w.r.t. parent part's frame
  - "Grouping"

Human Figure - Movement of more joints

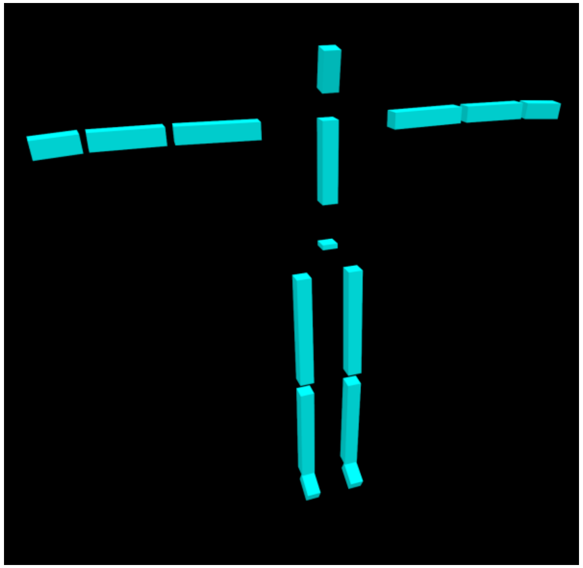


https://youtu.be/9dz8bvVK9zc https://youtu.be/PEhyWI8LGBY

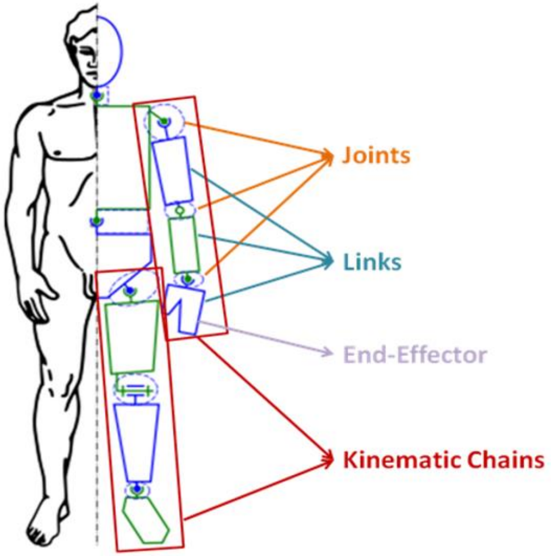
- Each part's movement is described w.r.t. its parent's reference frame.
  - Each part has its own transformation w.r.t. parent part's frame
  - "Grouping"

Articulated Body

- A common type of hierarchical model used in CG is an *articulated body*
  - that has objects that are connected end to end to form multibody jointed chains.
  - a.k.a. *kinematic chain*, *linkage* (robotics)

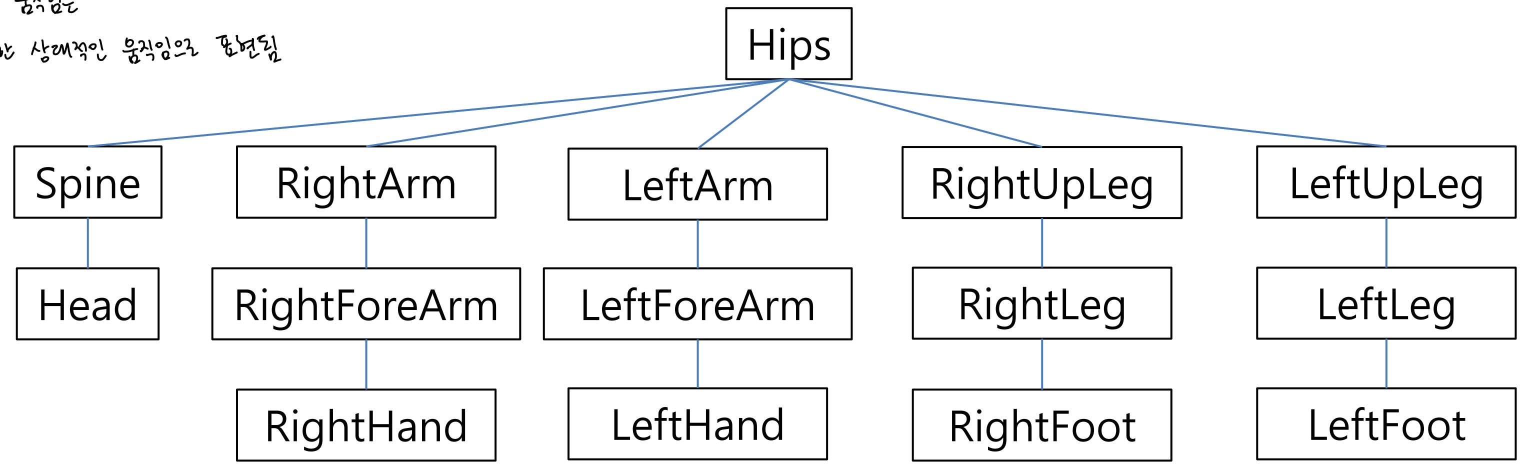


- Terminologies
  - *Joint* - a connection between two objects which allows some motion
  - *Link* - a rigid object between joints
  - *End effector* - a free end of a kinematic chain



Articulated Body

모든 부분의 움직임은
부모에 대한 상대적인 움직임으로 표현됨

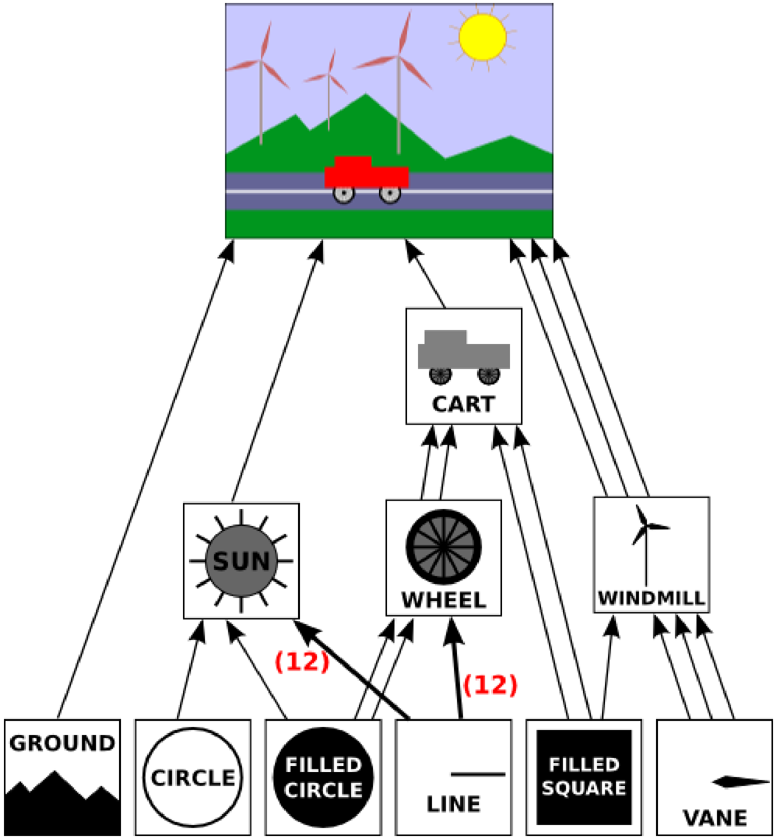


- An articulated body is represented by a graph structure.
  - A tree structure is most commonly used.

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

Scene Graph

- A graph structure that represents an entire scene.



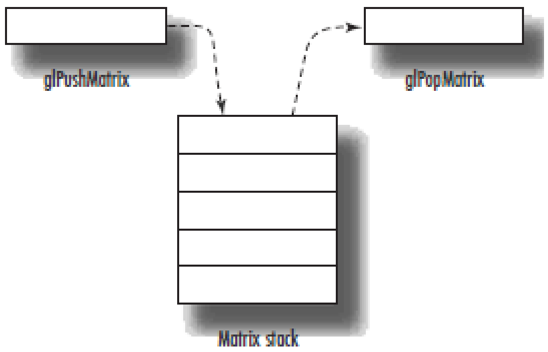
Rendering Hierarchical Models in OpenGL

- OpenGL provides a useful way of drawing objects in a hierarchical structure.

- → **Matrix stack**

OpenGL Matrix Stack

- A *stack* for transformation matrices
  - Last In First Outs

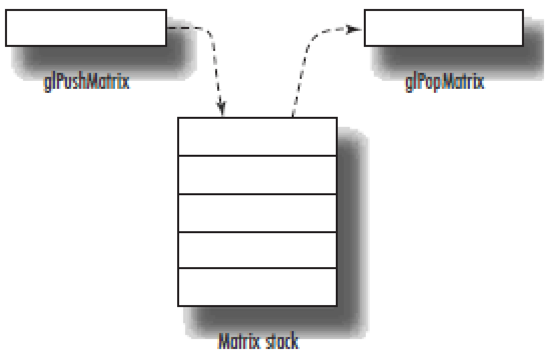


- You can **save** the **current transformation matrix** and then **restore** it after some objects have been drawn

- Useful for traversing hierarchical data structures (i.e. scene graph or tree)

OpenGL Matrix Stack

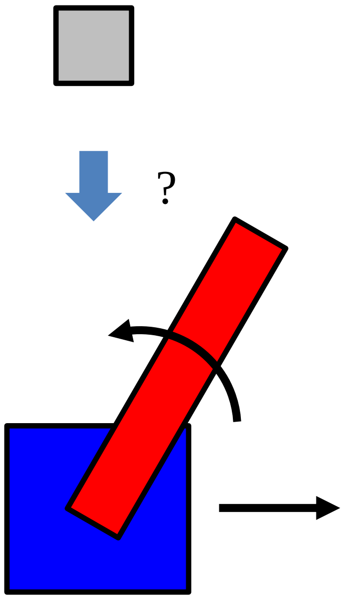
- glPushMatrix()
  - Pushes **the current matrix** onto the stack.



- glPopMatrix()
  - Pops the matrix off the stack.
- The **current matrix** is the matrix **on the top of the stack!**
- Keep in mind that the **numbers of glPushMatrix() calls and glPopMatrix() calls must be the same.**

A simple example

drawBox(): draw a unit box



Bold text is the **current transformation matrix** (the one at the top of the matrix stack)

Start with identity matrix

I

glPushMatrix()

I
I

glTranslate(T) # to translate base

T
I

glPushMatrix()

T
T
I

glScale(S) # scaling for drawing

TS
T
I

drawBox() **p'=TSp**

glPopMatrix()

T
I

glPushMatrix()

T
T
I

glRotate(R) # to rotate arm

TR
T
I

glPushMatrix()

TR
TR
T
I

glScale(U) # scaling for drawing

TRU
TR
T
I

drawBox() **p'=TRUp**

glPopMatrix()

TR
T
I

glPopMatrix()

T
I

glPopMatrix()

I

[Practice] Matrix Stack

```python
import glfw
from OpenGL.GL import *
import numpy as np
from OpenGL.GLU import *

gCamAng = 0

def render(camAng):
    # enable depth test (we'll see
details later)
    glClear(GL_COLOR_BUFFER_BIT |
GL_DEPTH_BUFFER_BIT)
    glEnable(GL_DEPTH_TEST)

    glLoadIdentity()

    # projection transformation
    glOrtho(-1,1, -1,1, -1,1)

    # viewing transformation
    gluLookAt(.1*np.sin(camAng),.1,
.1*np.cos(camAng), 0,0,0, 0,1,0)

    drawFrame()

    t = glfw.get_time()
```

```python
    # modeling transformation

    # blue base transformation
    glPushMatrix()
    glTranslatef(np.sin(t), 0, 0)

    # blue base drawing
    glPushMatrix()
    glScalef(.2, .2, .2)
    glColor3ub(0, 0, 255)
    drawBox()
    glPopMatrix()

    # red arm transformation
    glPushMatrix()
    glRotatef(t*(180/np.pi), 0, 0, 1)
    glTranslatef(.5, 0, .01)

    # red arm drawing
    glPushMatrix()
    glScalef(.5, .1, .1)
    glColor3ub(255, 0, 0)
    drawBox()
    glPopMatrix()

    glPopMatrix()
    glPopMatrix()
```

```
def drawBox():
    glBegin(GL_QUADS)
    glVertex3fv(np.array([1,1,0.]))
    glVertex3fv(np.array([-1,1,0.]))
    glVertex3fv(np.array([-1,-1,0.]))
    glVertex3fv(np.array([1,-1,0.]))
    glEnd()

def drawFrame():
    # draw coordinate: x in red, y in
green, z in blue
    glBegin(GL_LINES)
    glColor3ub(255, 0, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([1.,0.,0.]))
    glColor3ub(0, 255, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([0.,1.,0.]))
    glColor3ub(0, 0, 255)
    glVertex3fv(np.array([0.,0.,0]))
    glVertex3fv(np.array([0.,0.,1.]))
    glEnd()<
```

```
def key_callback(window, key, scancode, action,
mods):
    global gCamAng, gComposedM
    if action==glfw.PRESS or
action==glfw.REPEAT:
        if key==glfw.KEY_1:
            gCamAng += np.radians(-10)
        elif key==glfw.KEY_3:
            gCamAng += np.radians(10)

def main():
    if not glfw.init():
        return
    window =
glfw.create_window(640,640,"Hierarchy",
None,None)
    if not window:
        glfw.terminate()
        return
    glfw.make_context_current(window)
    glfw.set_key_callback(window, key_callback)
    glfw.swap_interval(1)

    while not glfw.window_should_close(window):
        glfw.poll_events()
        render(gCamAng)
        glfw.swap_buffers(window)

    glfw.terminate()

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

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. 2017123456: 4)**

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

OpenGL Matrix Stack Types

- Actually, OpenGL maintains four different types of matrix stacks:

- **Modelview matrix stack (GL_MODELVIEW)**
  - Stores model view matrices.
  - This is the default type (what we've just used)
- **Projection matrix stack (GL_PROJECTION)**
  - Stores projection matrices
- Texture matrix stack (GL_TEXTURE)
  - Stores transformation matrices to adjust texture coordinates. Mostly used to implement texture projection (like an image projected by a beam projector)
- Color matrix stack (GL_COLOR)
  - Rarely used. Just ignore it.

- You can switch the current matrix stack type using glMatrixMode()
  - e.g. glMatrixMode(GL_PROJECTION) to select the projection matrix stack

OpenGL Matrix Stack Types

- A common guide is something like:

```
/* Projection Transformation */
glMatrixMode(GL_PROJECTION);    /* specify the projection matrix */
glLoadIdentity();               /* initialize current value to identity */
gluPerspective(...);            /* or glOrtho(...) for orthographic */
                                /* or glFrustrum(...), also for perspective */

/* Viewing And Modelling Transformation */
glMatrixMode(GL_MODELVIEW);     /* specify the modelview matrix */
glLoadIdentity();               /* initialize current value to identity */
gluLookAt(...);                 /* specify the viewing transformation */

glTranslate(...);               /* various modelling transformations */
glScale(...);
glRotate(...);
...
```

- **Projection transformation** functions (gluPerspective(), glOrtho(), …) should be called with **glMatrixMode(GL_PROJECTION).**

- **Modeling & viewing transformation** functions (gluLookAt(), glTranslate(), …) should be called with **glMatrixMode(GL_MODELVIEW).**

- Otherwise, you'll get wrong lighting results.

[Practice] With Correct Matrix Stack Types

```
def render(camAng):
    # enable depth test (we'll see 
details later)
    glClear(GL_COLOR_BUFFER_BIT | 
GL_DEPTH_BUFFER_BIT)
    glEnable(GL_DEPTH_TEST)

    glMatrixMode(GL_PROJECTION)
    glLoadIdentity()

    # projection transformation
    glOrtho(-1,1, -1,1, -1,1)

    glMatrixMode(GL_MODELVIEW)
    glLoadIdentity()

    # viewing transformation
    gluLookAt(.1*np.sin(camAng),.1, 
.1*np.cos(camAng), 0,0,0, 0,1,0)

    drawFrame()
    t = glfw.get_time()
```

```
    # modeling transformation

    # blue base transformation
    glPushMatrix()
    glTranslatef(np.sin(t), 0, 0)

    # blue base drawing
    glPushMatrix()
    glScalef(.2, .2, .2)
    glColor3ub(0, 0, 255)
    drawBox()
    glPopMatrix()

    # red arm transformation
    glPushMatrix()
    glRotatef(t*(180/np.pi), 0, 0, 1)
    glTranslatef(.5, 0, .01)

    # red arm drawing
    glPushMatrix()
    glScalef(.5, .1, .1)
    glColor3ub(255, 0, 0)
    drawBox()
    glPopMatrix()

    glPopMatrix()
    glPopMatrix()
```

Next Time

- Lab in this week:
  - Lab assignment 8

- Next lecture:
  - 9 - Orientation & Rotation

- Acknowledgement: Some materials come from the lecture slides of
  - Prof. Jehee Lee, SNU, http://mrl.snu.ac.kr/courses/CourseGraphics/index_2017spring.html
  - Prof. Taesoo Kwon, Hanyang Univ., http://calab.hanyang.ac.kr/cgi-bin/cg.cgi
  - Prof. Kayvon Fatahalian and Keenan Crane, CMU, http://15462.courses.cs.cmu.edu/fall2015/