
Computer Graphics

10 - Kinematics & Animation

Yoonsang Lee
Spring 2021

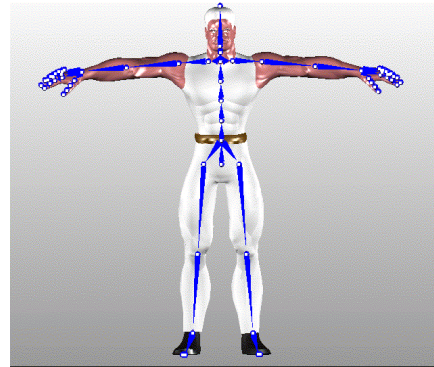
Topics Covered

- Forward Kinematics
- Introduction to Character Animation
- Motion Capture Data

Forward Kinematics

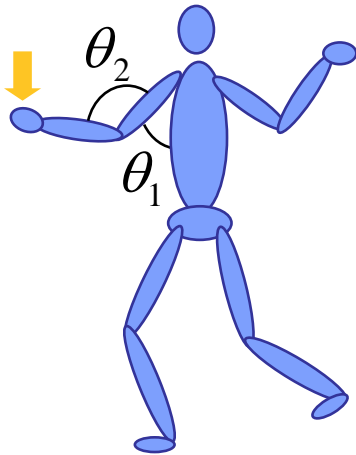
Kinematics

- *Kinematics* is
 - Study of **motion** of objects (or groups of objects), **without considering mass or forces**
 - In computer graphics, it's about how to move skeletons
 - Forward kinematics
 - Inverse kinematics



- By contrast, *Dynamics (or Kinetics)* is
 - Study of the **relationship between motion and its causes, specifically, forces and mass**

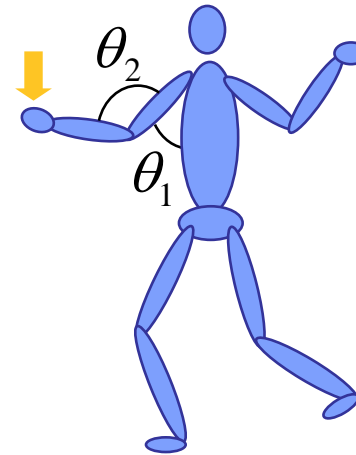
Kinematics



$$(\mathbf{p}, \mathbf{q}) = F(\theta_i)$$

Forward Kinematics

: Given joint angles,
compute the position &
orientation of end-effector

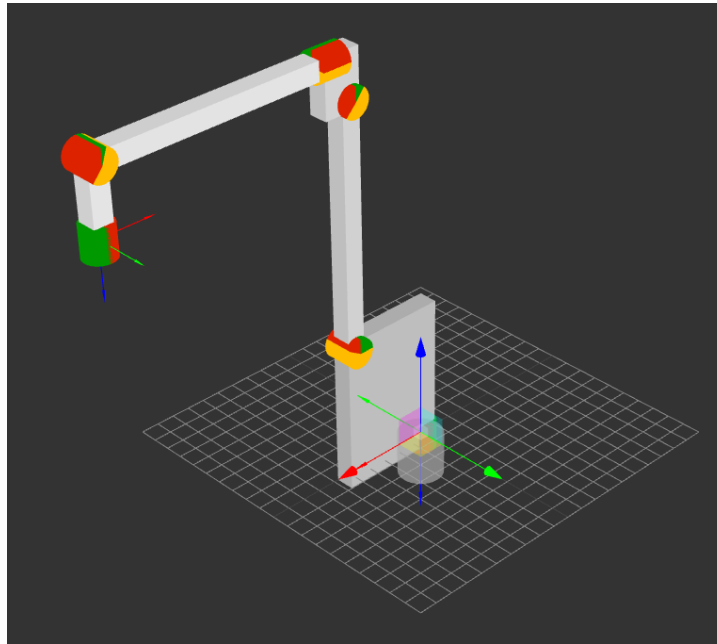


$$\theta_i = F^{-1}(\mathbf{p}, \mathbf{q})$$

Inverse Kinematics

: Given the position &
orientation of end-effector,
compute joint angles

[Practice] FK / IK Online Demo

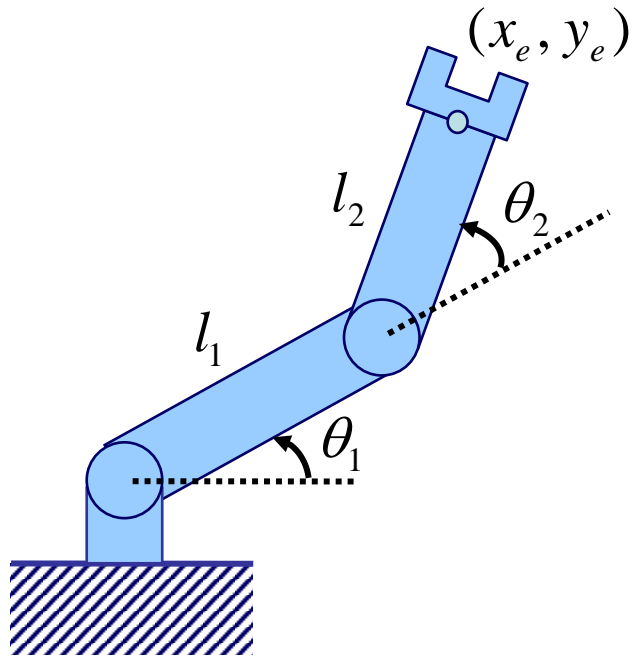


<http://robot.glumb.de/>

- Forward kinematics : Open “angles” menu and change values
- Inverse kinematics : Move the end-effector position by mouse dragging

Forward Kinematics: A Simple Example

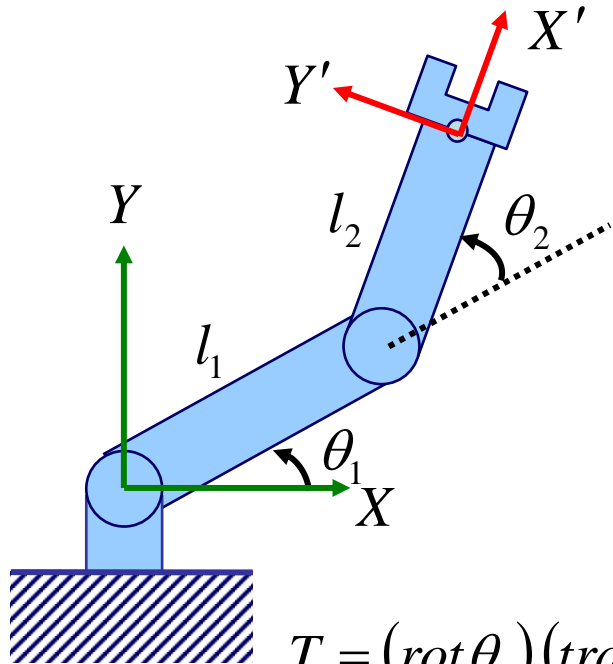
- A simple robot arm in 2-dimensional space
 - 2 revolute joints
 - Joint angles are known
 - Compute the position of the end-effector



$$x_e = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2)$$

$$y_e = l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2)$$

A Chain of Transformations



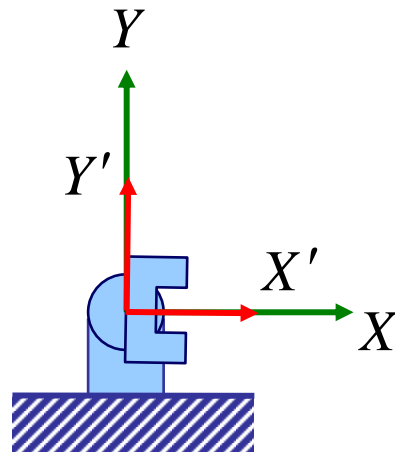
$$\begin{pmatrix} x_e \\ y_e \\ 1 \end{pmatrix} = \begin{pmatrix} & & \\ & T & \\ & & \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$T = (\text{rot } \theta_1)(\text{transl}_1)(\text{rot } \theta_2)(\text{transl}_2)$$

$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

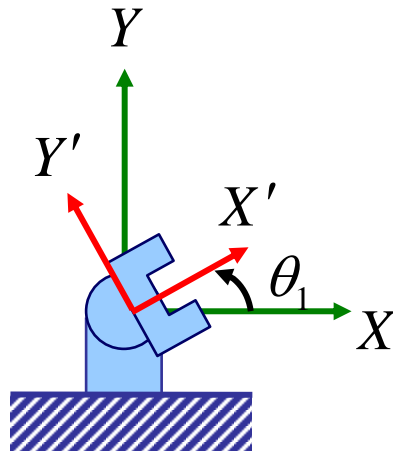
- In a view of body-attached coordinate system
(=local coordinate system of the end-effector body)



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

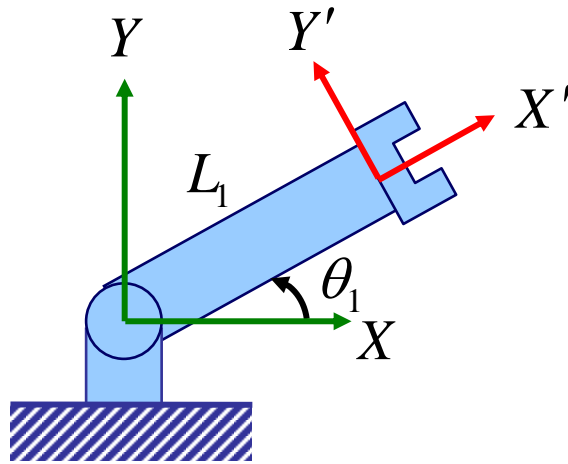
- In a view of body-attached coordinate system



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

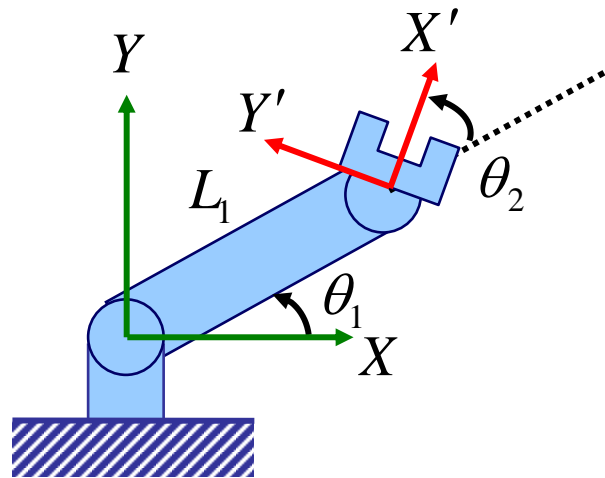
- In a view of body-attached coordinate system



$$T = (\text{rot } \theta_1)(\text{transl } l_1)(\text{rot } \theta_2)(\text{transl } l_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

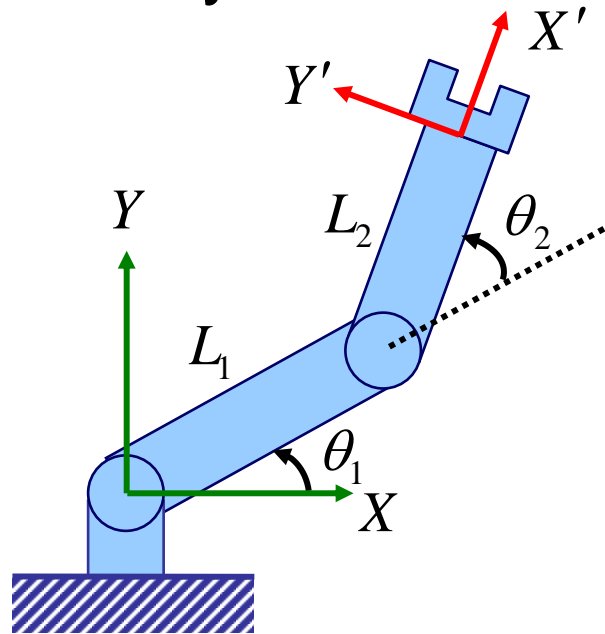
- In a view of body-attached coordinate system



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

- In a view of body-attached coordinate system

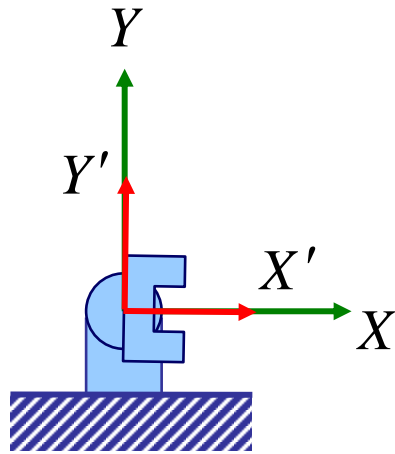


$$T = (\text{rot } \theta_1)(\text{transl}_1)(\text{rot } \theta_2)(\text{transl}_2)$$

$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

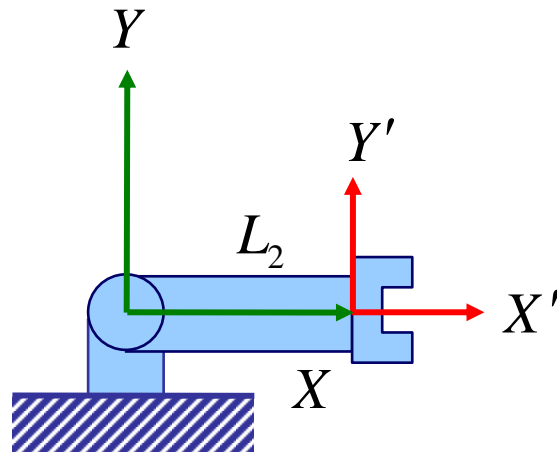
- In a view of global coordinate system



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

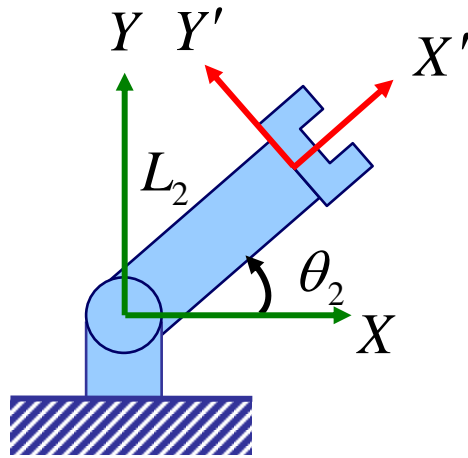
- In a view of global coordinate system



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

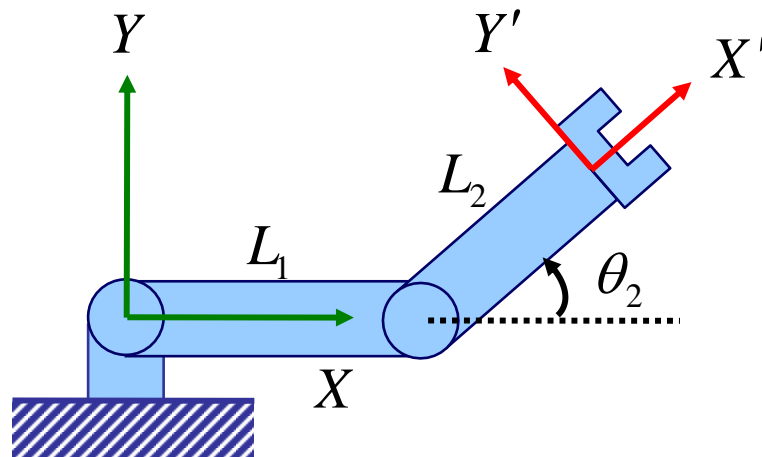
- In a view of global coordinate system



$$T = (rot \theta_1)(transl_1)(rot \theta_2)(transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

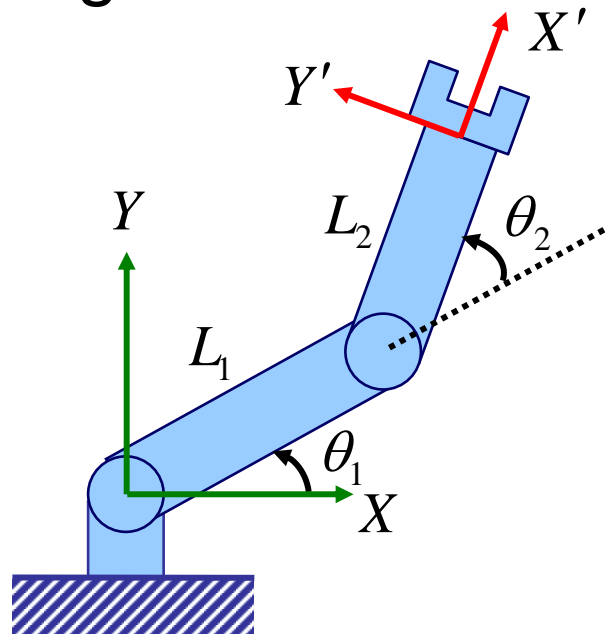
- In a view of global coordinate system



$$T = (rot \theta_1) (transl_1) (rot \theta_2) (transl_2)$$
$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thinking of Transformations

- In a view of global coordinate system



$$T = (rot\ \theta_1)(transl_1)(rot\ \theta_2)(transl_2)$$

$$= \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & l_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Quiz #1

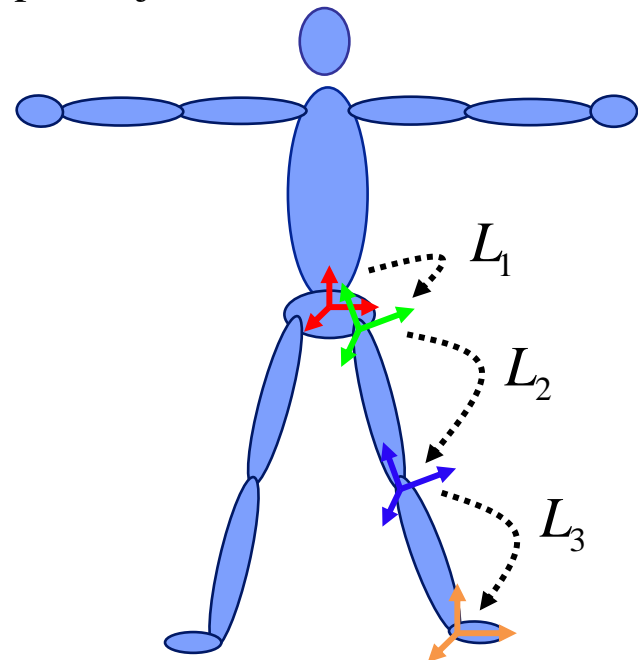
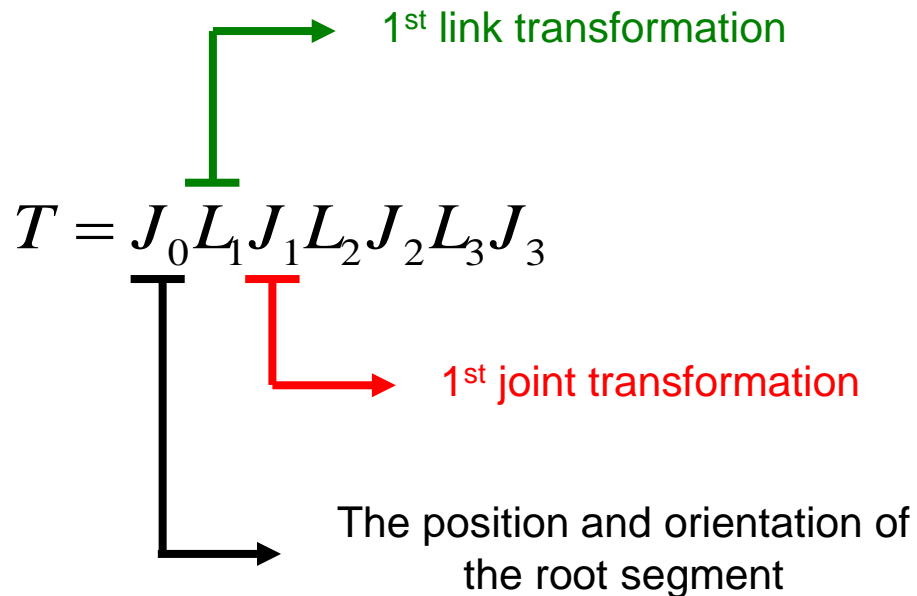
- Go to <https://www.slido.com/>
- Join #cg-ys
- Click “Polls”

- 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”.

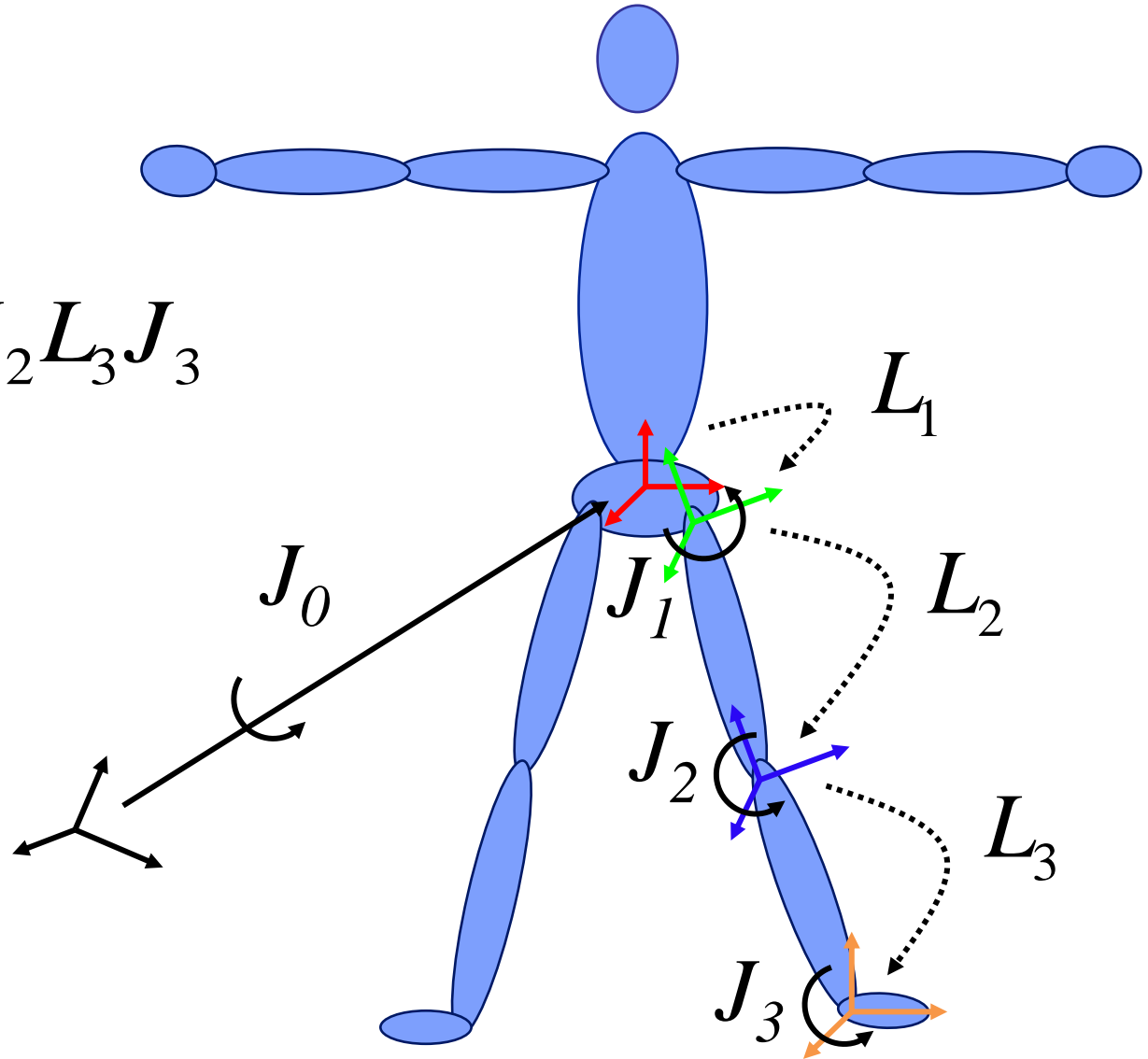
Forward Kinematics Map

- Usually, the *forward kinematics map* T is an alternating multiple of ...
 - (mapping from joint values to end effector position & orientation)
- **Joint transformations** that represents joint movement (**time-varying**)
 - Usually rotations
- **Link transformations** that defines a frame relative to its parent (**static**)
 - Usually translations (joint offset from its parent joint)



Forward Kinematics Map

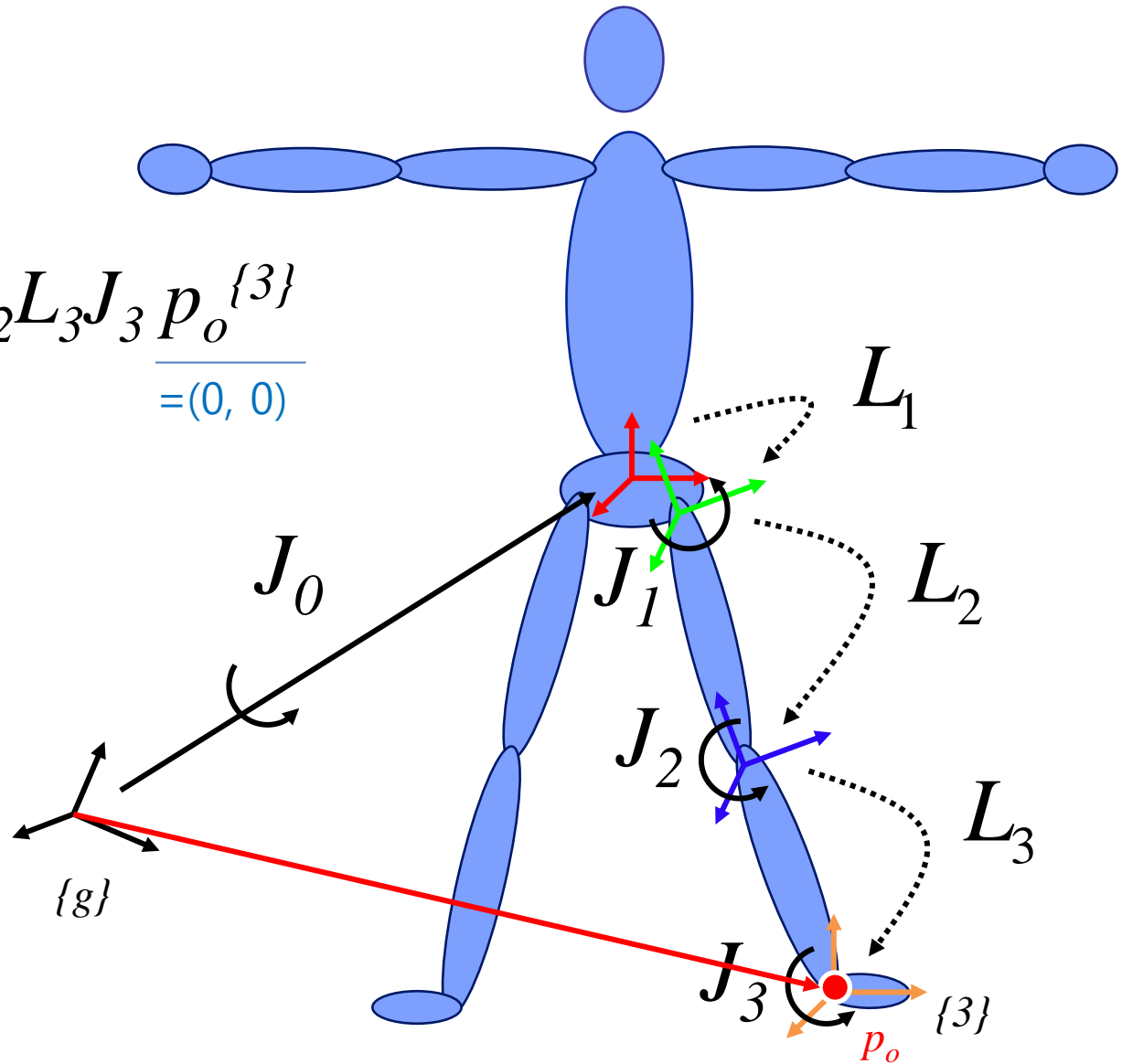
$$T = J_0 L_1 J_1 L_2 J_2 L_3 J_3$$



Forward Kinematics Map

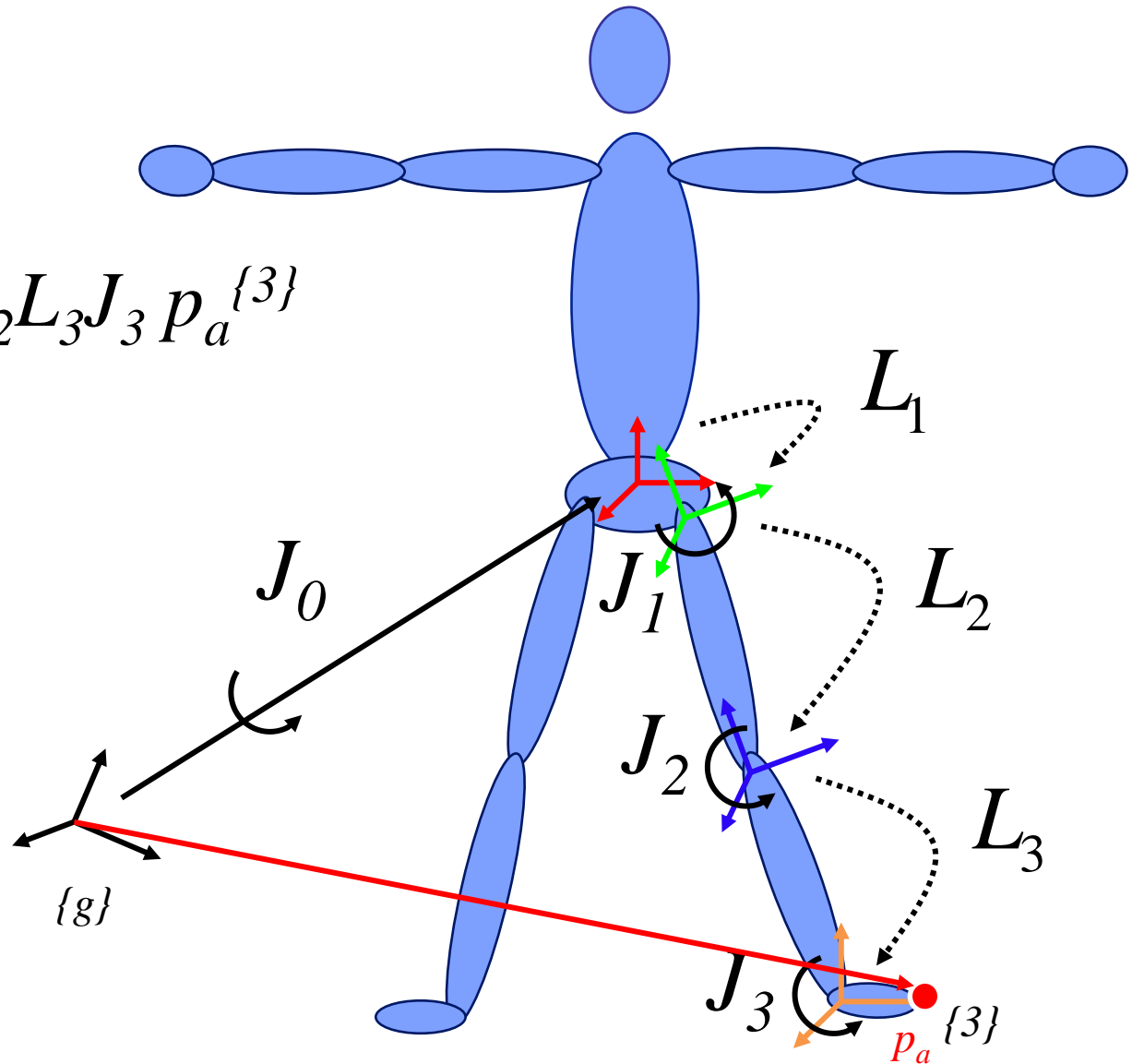
$$p_o^{\{g\}} = J_0 L_1 J_1 L_2 J_2 L_3 J_3 p_o^{\{3\}}$$

$\underbrace{\hspace{10em}}_{=(0,0)}$



Forward Kinematics Map

$$p_a^{\{g\}} = J_0 L_1 J_1 L_2 J_2 L_3 J_3 p_a^{\{3\}}$$



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 Character Animation

Traditional Hand-drawn Cel Animation

- Senior artist draws *keyframes*
- Assistant draws *inbetweens*
- Tedious / labor intensive (opportunity for technology!)

keyframe



keyframe



keyframe



inbetweens ("tweening")



Animation by Milt Kahl (Walt Disney Studios)



Animation by Marc Davis (Walt Disney Studios)



Animation by Mark Henn (Walt Disney Studios)



Animation by Milt Kahl (Walt Disney Studios)

Computer Animation

- Computers are now widely replacing labor-intensive animation processes.
 - More controllable than drawing images by hands or constructing miniatures.

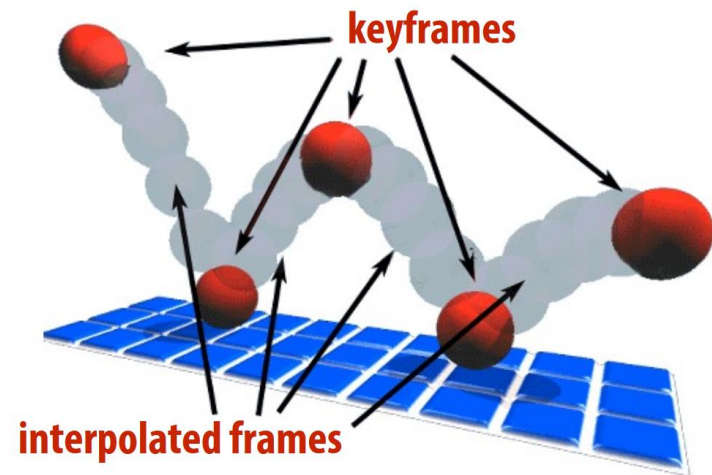
Character Animation Approaches

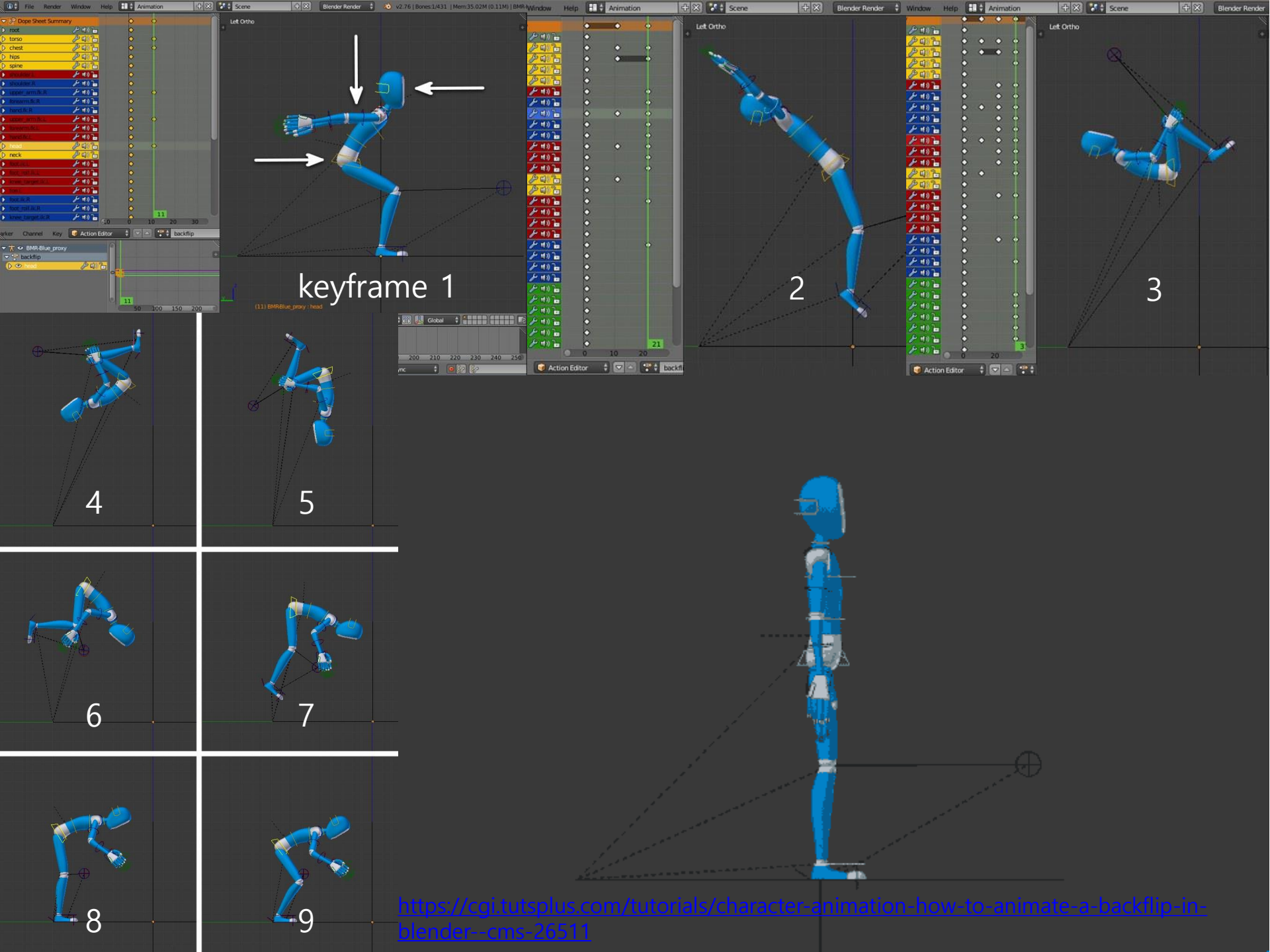
- Keyframe Animation
- Motion Capture
- Data-Driven Animation
- Physics-Based Animation

Keyframe Animation

- Idea:
 - Animators specifies important events at *keyframes*.
 - Computer fills inbetween frames using interpolation.

- Events can be
 - Positions & orientation of objects
 - Colors
 - Light intensities
 - Camera parameters
 - ...





Keyframe Animation

- One of the earliest methods used to produce computer animation.
- Difficult to create “realistic” and “physically plausible” motions.
 - The quality of the output largely depends on the skill of each artist.
- Still used a lot.

Motion Capture

- Idea: Use “real” human motion to create realistic animation.
- Motion capture system “captures” movement of people or objects.
 - Position of each marker on the skin
 - Position and orientation of each body part (or joint)

Motion Capture



<https://youtu.be/YzS73UCOk20>

Motion Capture

- Currently, widely used in movies & games
 - by major companies
- Very costly
 - Expensive devices
 - High operating cost
- Limitation: Motion captured data is very realistic **only** in the same virtual environment as capture environment.

Data-Driven Animation

- Idea: Make the most of the captured motion data by
 - reusing captured motion data with motion editing techniques
 - or learning the distribution of captured motions
- to generate new motions.
- Recently, deep learning techniques are used a lot.

State-of-the-Art Research Example

<https://youtu.be/fTV7sXqO6ig>



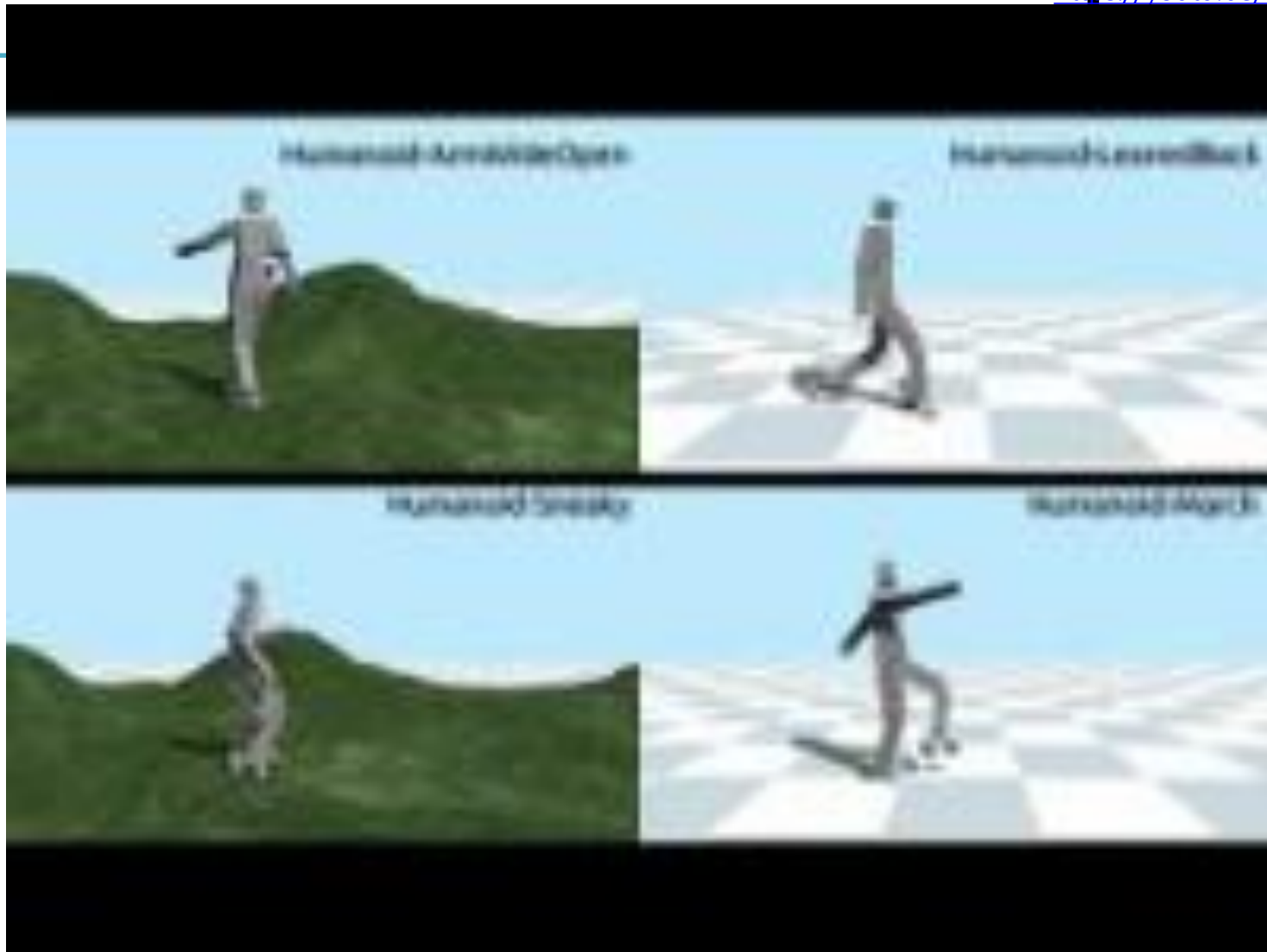
Harvey, Félix G., Mike Yurick, Derek Nowrouzezahrai, and Christopher Pal. "Robust Motion In-Betweening." ACM Transactions on Graphics 39, no. 4 (SIGGRAPH 2020)

Physics-Based Animation

- Idea: Use physics simulation to generate motion
 - Because physical reality plays a key role in creating high-quality motion.
 - Physics simulation generates a motion that is always physically plausible.
- For passive character motion, it's already in widespread use.
 - e.g. Ragdoll effect in games
- For active character motion, it requires a "controller".
 - Determines joint torques at each timestep to perform desired action while maintaining balance.
 - This problem is similar to that of robotics.
- Recently, deep learning techniques (such as deep reinforcement learning) are used a lot.

State-of-the-Art Research Example

<https://youtu.be/fGwMrRoC5bw>

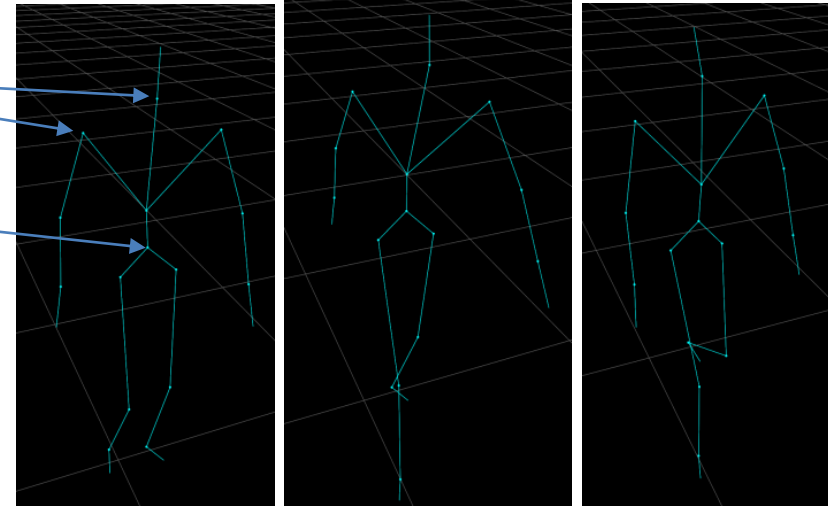
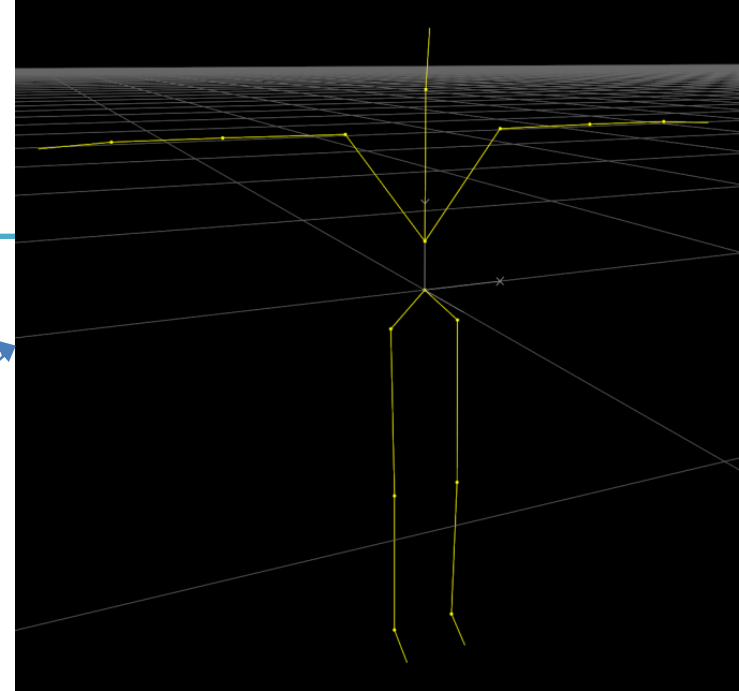


Kwon, Taesoo, Yoonsang Lee, and Michiel Van De Panne. "Fast and Flexible Multilegged Locomotion Using Learned Centroidal Dynamics." ACM Transactions on Graphics 39, no. 4 (SIGGRAPH 2020)

Motion Capture Data

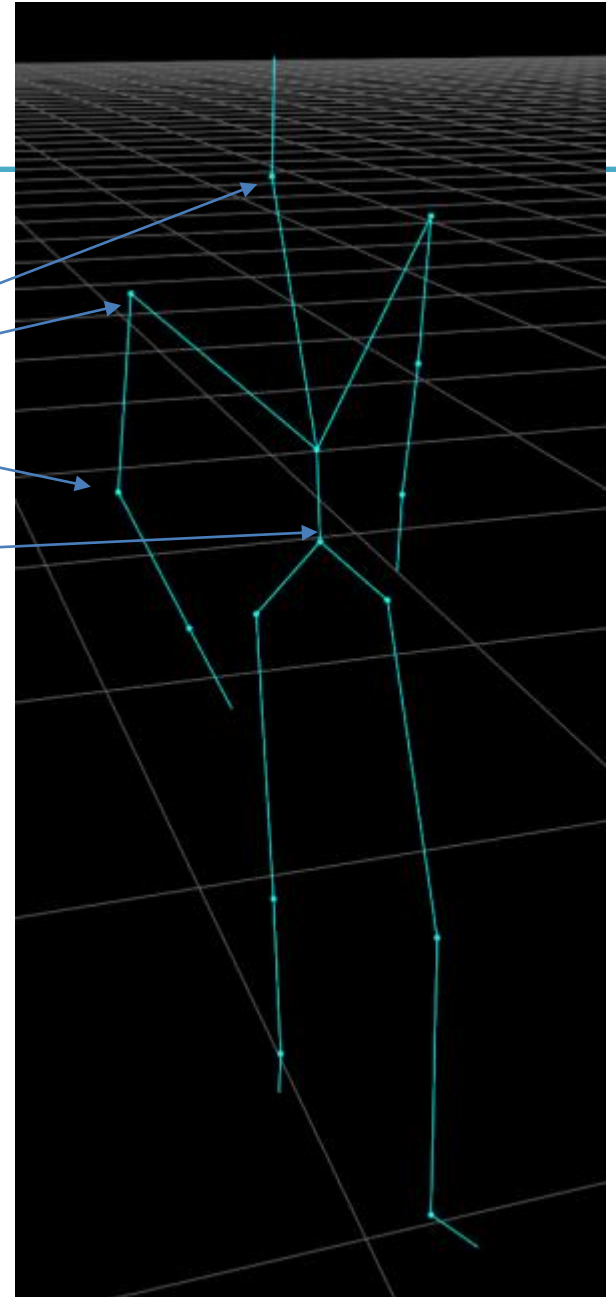
Motion Capture Data

- Motion capture data includes:
 - "Skeleton": static data
 - joint hierarchy
 - joint offset from its parent joint
 - "Motion": time-varying data
 - internal joint orientation (**w.r.t. default frame of each joint - the frame after applying link transformation for that joint**)
 - position and orientation of skeletal root (**w.r.t. global frame**)
- *Posture (pose)*: "motion" at a single frame
- *T pose*: a pose where all joint orientations are "zero" (identity matrix)



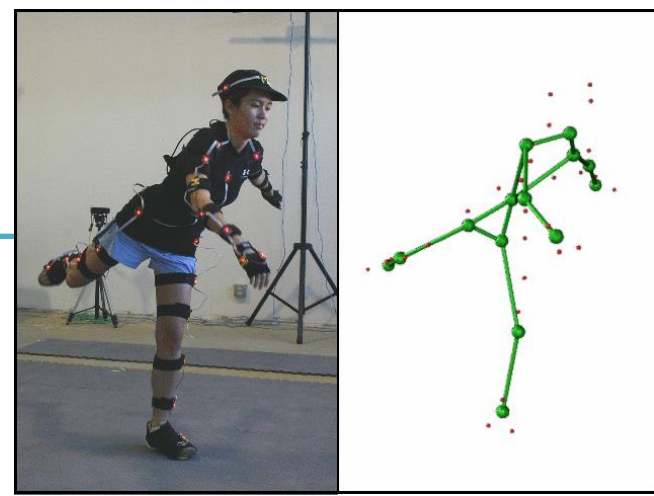
Motion Capture Data

- Generally, in motion capture data,
 - Internal joint has 3 DOFs
 - rotation only
 - Root joint has 6 DOFs
 - rotation and translation



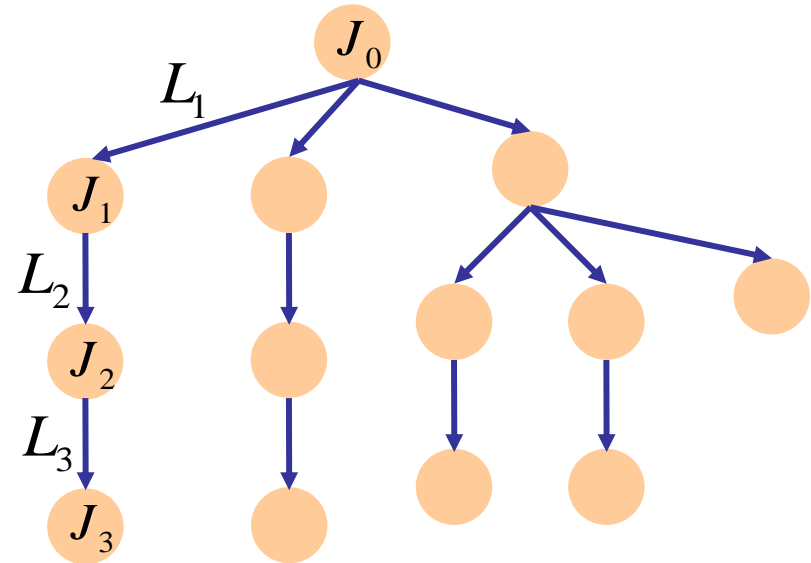
BVH File Format

- BVH (**B**io**V**ision **H**ierarchical data)
- Developed by Biovision, a motion capture company
- Has two parts:
- **Hierarchy section**
 - Describes the hierarchy and initial pose of the skeleton
- **Motion section**
 - Contains motion data
- Text file format



Hierarchy Section

- The hierarchy is a joint tree.
- Each joint has an offset and a channel list.
- For example, for Joint 1:
 - Offset: L_1
 - Channel list :a sequence of transformation types of Joint 1 motion (w.r.t. default frame of Joint 1)



Biovision BVH

■ Hierarchy section

➤ "HIERARCHY"

• "ROOT"

- followed by the name of the root
- "{ " and " } " pair
- "OFFSET"
 - » X,Y and Z offset of the segment from its parent
- "CHANNELS"
 - » the number of channels
 - » the type of each channel

• "JOINT"

- identical to the root definition except for the number of channels
- "OFFSET " , "CHANNELS"

• "End Site"

- indicates that the current segment is an end effector (no children)
- "OFFSET "

- 6 channels for the root (Tx Ty Tz Rz Rx Ry)
- 3 channels for every other object (Rz Rx Ry)

```
HIERARCHY
ROOT Hips
{
  OFFSET 0.00 0.00 0.00
  CHANNELS 6 Xposition Yposition Zposition Zrotation Xrotation Yrotation
  JOINT LeftHip
  {
    OFFSET 3.430000 0.000000 0.000000
    CHANNELS 3 Zrotation Xrotation Yrotation
    JOINT LeftKnee
    {
      OFFSET 0.000000 -18.469999 0.000000
      CHANNELS 3 Zrotation Xrotation Yrotation
      JOINT LeftAnkle
      {
        OFFSET 0.000000 -17.950001 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        End Site
        {
          OFFSET 0.000000 -3.119999 0.000000
        }
      }
    }
  }
}
...
}
```

HIERARCHY

ROOT Hips

{

OFFSET 0.0 0.0 0.0

CHANNELS 6 XPOSITION YPOSITION ZPOSITION ZROTATION XROTATION YROTA

JOINT chest

{

OFFSET 0.096536 3.475309 -0.289609

CHANNELS 3 Xrotation Zrotation Yrotation

JOINT neck

{

OFFSET -0.096536 13.901242 -2.027265

CHANNELS 3 Xrotation Zrotation Yrotation

JOINT head

{

OFFSET -0.166775 1.448045 0.482682

CHANNELS 3 Xrotation Zrotation Yrotation

JOINT leftEye

-

HIERARCHY

ROOT Hips

```
{  
  OFFSET 0.0 0.0 0.0 J0 channels  
  CHANNELS 6 XPOSITION YPOSITION ZPOSITION ZROTATION XROTATION YROTA  
  JOINT chest  
  {  
    OFFSET 0.096536 3.475309 -0.289609 L1  
    CHANNELS 3 Xrotation Zrotation Yrotation J1 channels  
    JOINT neck  
    {  
      OFFSET -0.096536 13.901242 -2.027265 L2  
      CHANNELS 3 Xrotation Zrotation Yrotation J2 channels  
      JOINT head  
      {  
        OFFSET -0.166775 1.448045 0.482682 L3  
        CHANNELS 3 Xrotation Zrotation Yrotation  
        JOINT leftEye J3 channels  
        -
```

HIERARCHY

ROOT Hips **Root Hips Joint**

```
{  
  OFFSET 0.0 0.0 0.0 Root offset is generally zero (or ignored even if it's not zero)  
  CHANNELS 6 XPOSITION YPOSITION ZPOSITION ZROTATION XROTATION YROTA
```

```
  JOINT chest Chest Joint
```

```
  {  
    OFFSET 0.096536 3.475309 -0.289609  
    CHANNELS 3 Xrotation Zrotation Yrotation
```

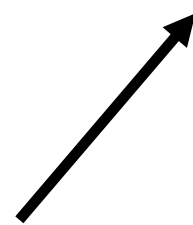
```
    JOINT neck Neck Joint
```

```
    {  
      OFFSET -0.096536 13.901242 -2.027265  
      CHANNELS 3 Xrotation Zrotation Yrotation
```

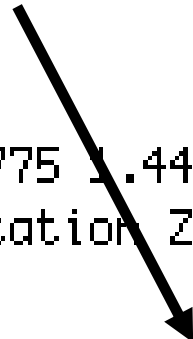
```
      JOINT head
```

```
      {  
        OFFSET -0.166775 1.448045 0.482682  
        CHANNELS 3 Xrotation Zrotation Yrotation
```

```
        JOINT leftEye
```



Neck's offset from chest



Channel list:

Transformation from chest coordinate system to neck coordinate system


```
MOTION
Frames:    20
Frame Time: 0.033333
0.00 39.68 0.00 0.65 ...
...
```

■ Motion Section

➤ "MOTION"

- followed by a line indicating the number of frames
- **"Frames:"**
 - the number of frames
- **"Frame Time:"**
 - the sampling rate of the data
 - Ex) 0.033333 → 30 frames a second
- The rest of the file contains the actual motion data
 - The numbers appear in the order of the channel specifications as the skeleton hierarchy was parsed
- **Each line has motion data for a single frame**
- **Each number in a line is a value for a single channel**
- **The unit of rotation channel values is degree**

HIERARCHY

ROOT Hips

```
{
  OFFSET 0.0 0.0 0.0
  CHANNELS 6 XPOSITION YPOSITION ZPOSITION ZROTATION XROTATION YROTATION
  JOINT chest Column 1 Column 2 Column 3 Column 4 Column 5 Column 6
  {
    OFFSET 0.096536 3.475309 -0.289609
    CHANNELS 3 Xrotation Zrotation Yrotation
    JOINT neck Column 7 Column 8 Column 9
    {
      OFFSET -0.096536 13.901242 -2.027265
      CHANNELS 3 Xrotation Zrotation Yrotation
      JOINT head Column 10 Column 11 Column 12
      {
        OFFSET -0.166775 1.448045 0.482682
        CHANNELS 3 Xrotation Zrotation Yrotation
          Column 13 Column 14 Column 15
      }
    }
  }
}
```

MOTION

Frames: 199

Frame Time: 0.033333

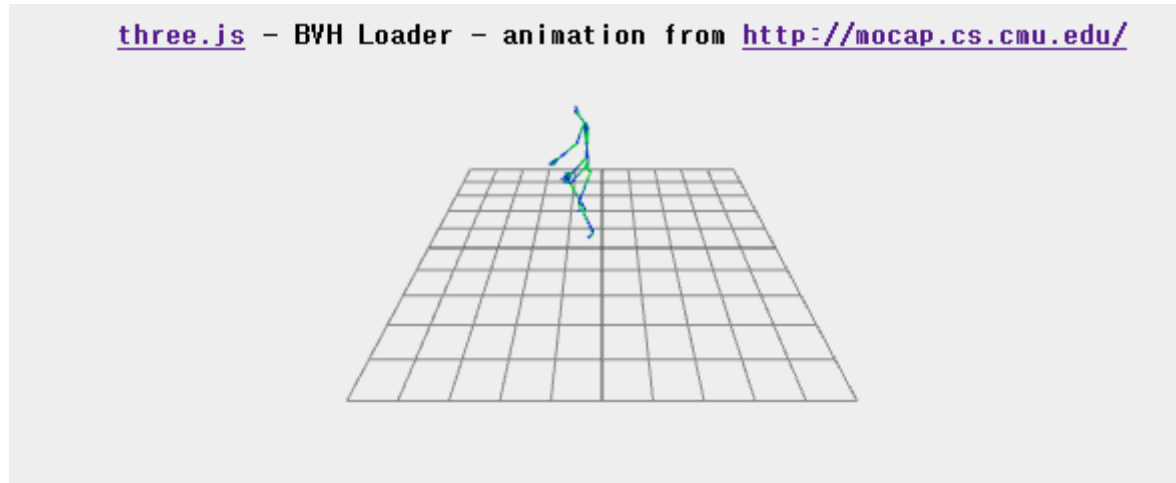
```
1.95769 0.989769479321 0.039193 -4.11275998891 -0.490682977769 -91.3519974695 0.45458697547 ...
1.95769 0.989769479321 0.0392908 -4.11760985011 -0.48626597981 -91.3734989051 0.513819016282 ...
1.95769 0.989769479321 0.039424 -4.12004011679 -0.488125979059 -91.387002189 0.592700017233 ...
1.95771 0.989769479321 0.0395518 -4.0961698863 -0.500940000911 -91.3840993586 0.61126399115 ...
1.95779 0.989759479321 0.0396999 -4.05799980101 -0.510696019006 -91.3839969058 0.58299101005 ...
1.9579 0.989719479321 0.0398625 -4.0423300664 -0.503295989288 -91.3842018115 0.57718001317 ...
```

...

■ Interpreting the data

- To calculate the position of a segment
 - Translation information
 - For any joint segment
 - » the translation information will simply be the **offset** as defined in the hierarchy section
 - For the root object
 - » The translation data will be the sum of the **offset data** and the **translation data** from the motion section
 - Rotation information
 - comes from the **motion section**
 - If the order is “ZROTATION XROTATION YROTATION”
 - Apply transformation in order of rotation about z, rotation about x, rotation about y w.r.t. local frame
 - → ZXY Euler angles
 - Usually ZXY order is used, but other orders can be used

[Practice] BVH Online Demo



<http://motion.hahasoha.net/>

- Select other motions from the list.
- Download corresponding BVH files and open them in a text editor.

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”.

Next Time

- Lab in this week:
 - Lab assignment 10
- Next lecture:
 - 11 - Curve
- **Class Assignment #3**
 - **Due: 23:59, May 30, 2021**
- Acknowledgement: Some materials come from the lecture slides of
 - Prof. Kayvon Fatahalian and Prof. Keenan Crane, CMU, <http://15462.courses.cs.cmu.edu/fall2015/>
 - Prof. Jinxiang Chai, Texas A&M Univ., http://faculty.cs.tamu.edu/jchai/csce441_2016spring/lectures.html
 - 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>