EGB339
Introduction to Robotics

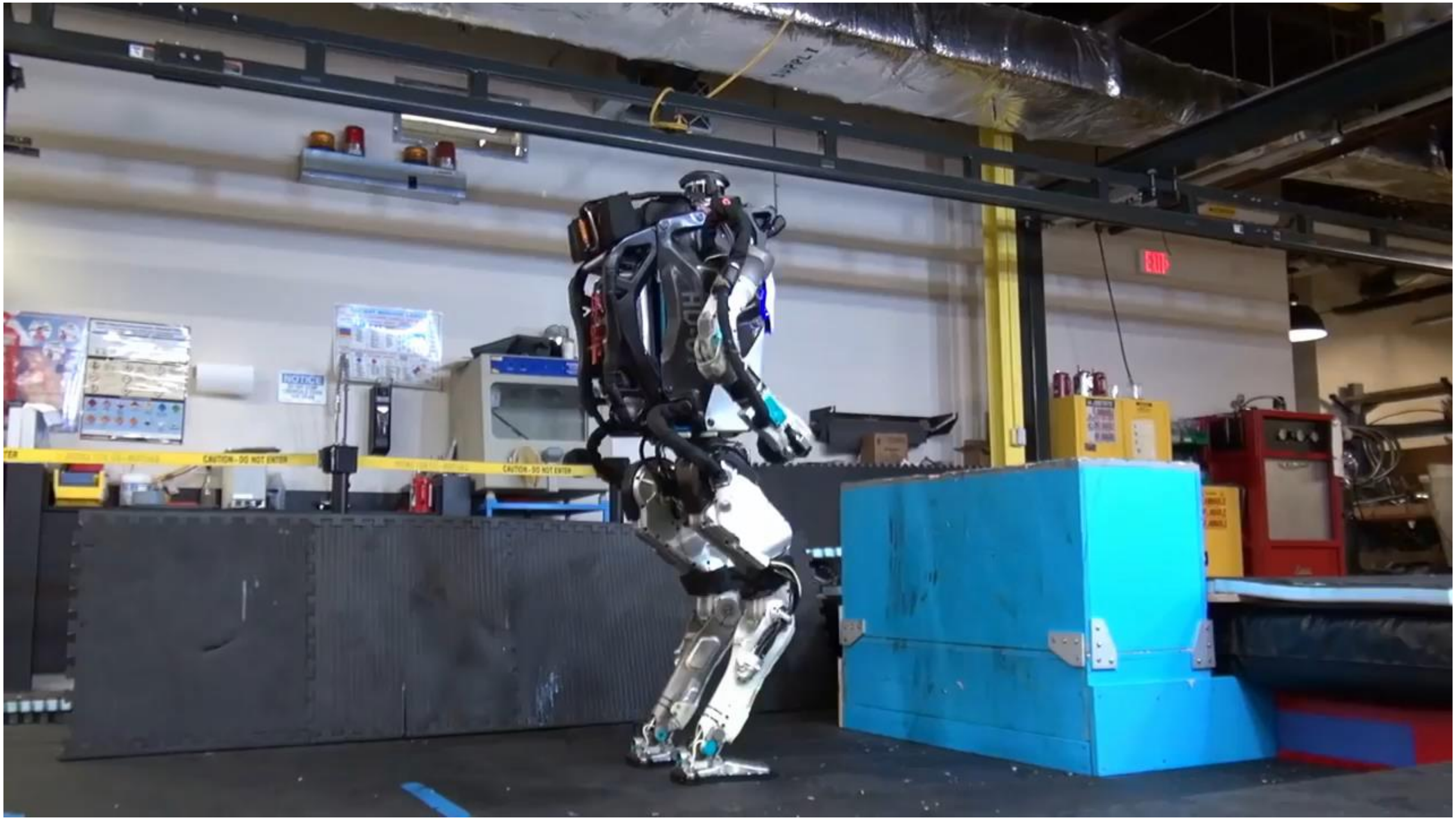
Part 2: Robotic Arms

Lecture 1:
Rigid Body Motions

Liao “Leo” Wu (Lecturer)

About Part 2: Robotic Arms

What you may expect to learn



https://www.youtube.com/watch?v=fRj34o4hN4I

What you actually learn

But even just with this, you will be able to handle

https://www.youtube.com/watch?v=8_lfxPI5ObM

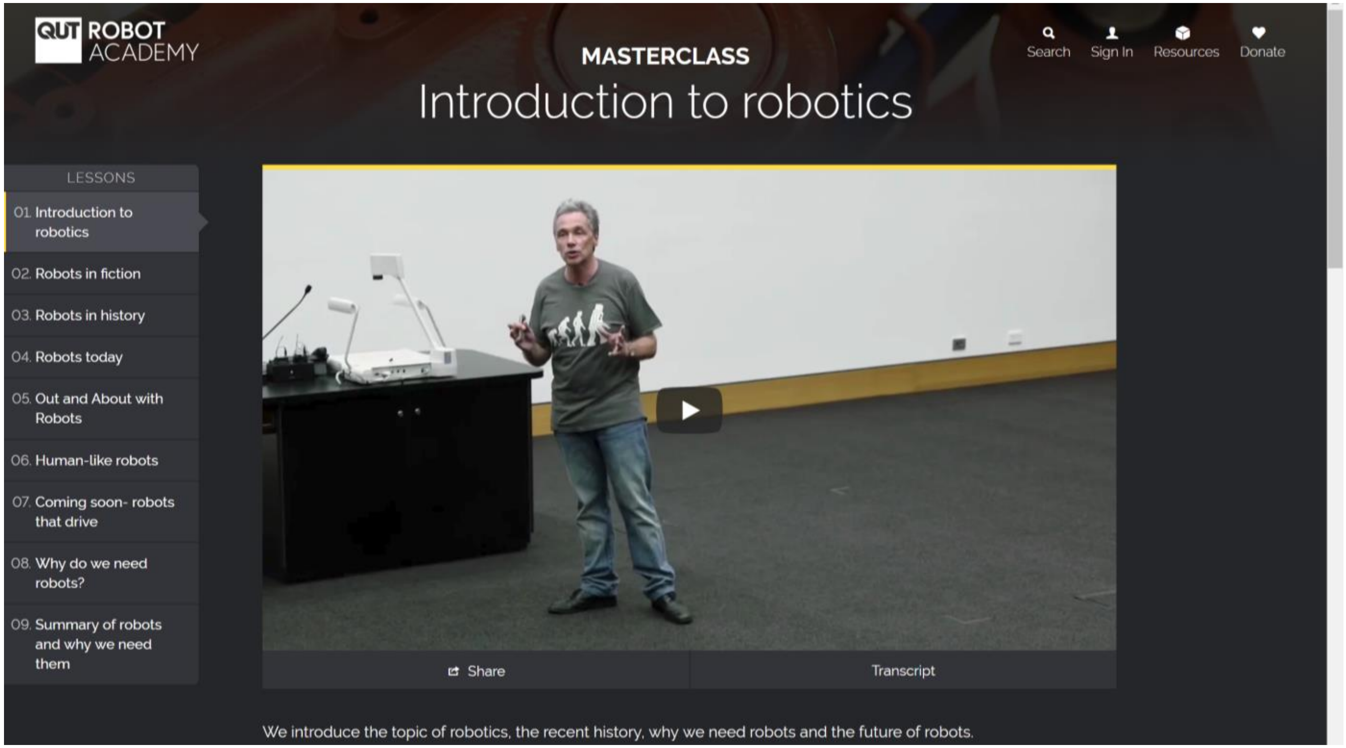
Outline

- Topics covered in this series of lectures
  - Rigid Body Motions (week 8)
  - Forward Kinematics (week 9)
  - Inverse Kinematics (week 10)
  - Velocity Kinematics (week 11)
  - Path and Trajectory Planning (week 12)
  - Revision (week 13)

- Topics not covered in this series of lectures
  - Dynamics
  - Control
  - Hardware
  - (Artificial) Intelligence
  - …

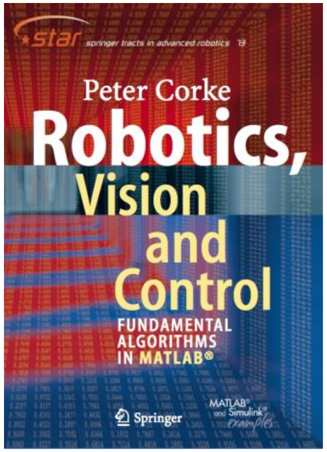
Additional Resources

- QUT Robot Academy (by Peter Corke)
  - https://robotacademy.net.au/



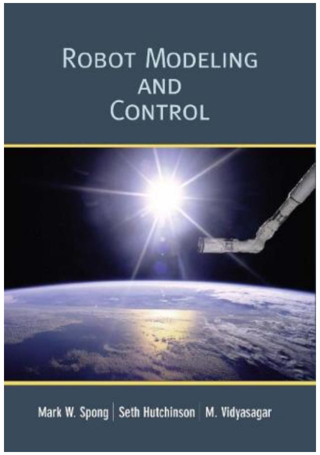
Additional Resources

- Robotics, Vision and Control (Ed2)
  - By Peter Corke
  - Electronic resources in the library
  - Hard copies in the library
  - For sale in the bookshop
  - http://petercorke.com/RVC



Additional Resources

- Robot Modeling and Control
  - By Mark W Spong; Seth Hutchinson; M Vidyasagar
  - Hard copies in the library
  - For sale in the bookshop



Additional Resources

- **Lectures:** MilfordRobotics Youtube Channel Theory Playlist (http://bit.ly/2azZacj)

- **Tutorials:** Theoretical Problems and Solutions by James Mount - Youtube Playlist (http://bit.ly/2aeZys3)

Assessment

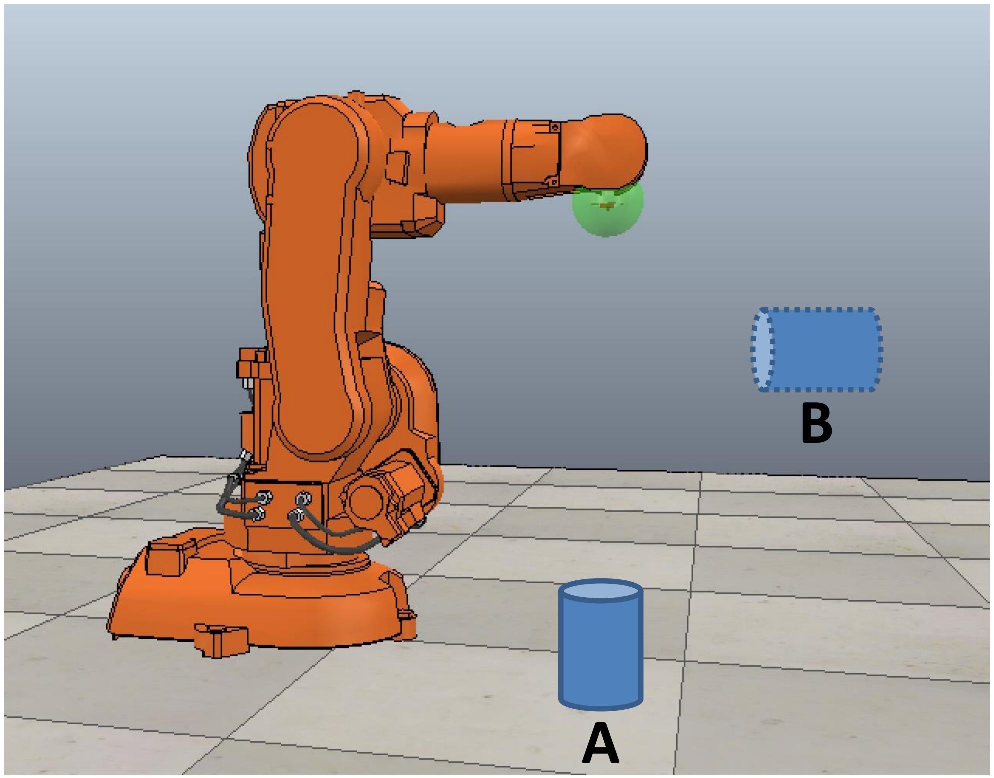
- Part 2: Robotic Arms (50%)
  - 20% prac exam Week 13
  - 30% theory exam in the final exam period
    - Open-book, but no internet or phone usage
    - You could carry the whole library with you if necessary and possible
    - Given the time limit, you'd better really master the contents than rely on the open-book
    - If you want to pass the exam, attend the tutorials!!!

Rigid Body Motions

Watch these online videos

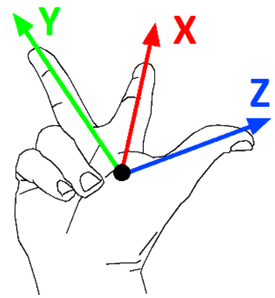
- QUT Robot Academy (by Prof Peter Corke)
  - 2D Geometry
    - https://robotacademy.net.au/masterclass/2d-geometry/
  - 3D Geometry
    - https://robotacademy.net.au/masterclass/3d-geometry/

Motivating Problem



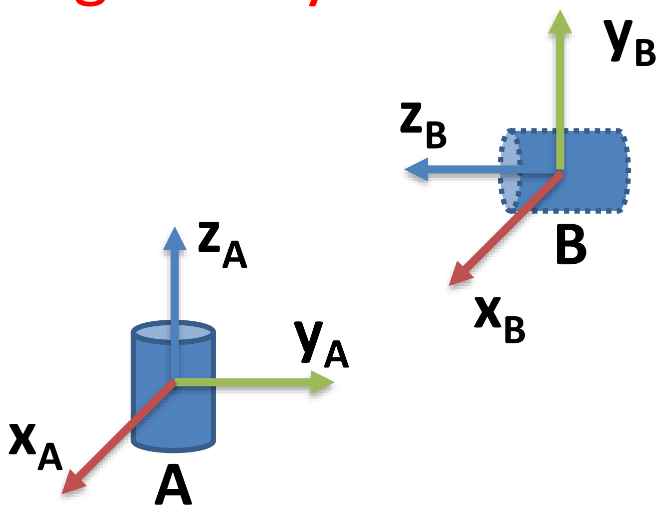
- Imagine one of your arms is replaced by a robotic arm, and you're blindfolded (you don't have sensors to detect the object in front of you).
- You are supposed to move an object from A to B.
- You want somebody to tell you where the object is and where to move it.
- How can the pose (position and orientation) of A and B be described to you?

Rigid Body Motions



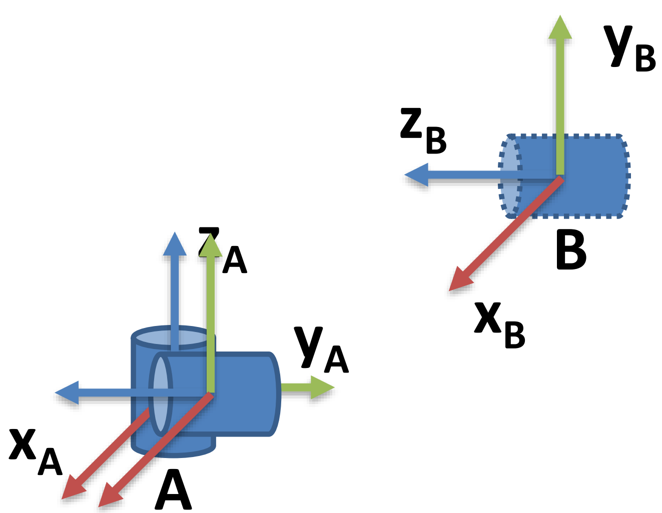
The Right-Hand Rule

- Rigid Body
  - In physics, a rigid body is a solid body in which deformation is zero or so small it can be neglected. (Wikipedia)
  - In kinematics, a rigid body is a coordinate frame. (Leo Wu)



Rigid Body Motions

- The pose of B relative to A can be described with two components:
  - A rotation matrix **R** specifying the orientation
  - And a translation vector **t** specifying the position

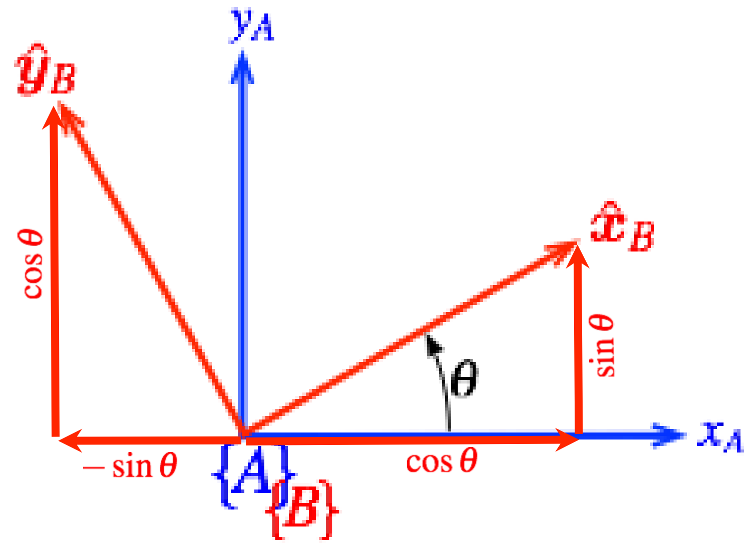


2D Rotation Matrix

- 2D rotation

$$\hat{x}_B = \cos\theta x_A + \sin\theta y_A$$
$$\hat{y}_B = -\sin\theta x_A + \cos\theta y_A$$

- 2D rotation matrix



new x-axis

new y-axis

$$\begin{pmatrix} {}^{A}x \\ {}^{A}y \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}}_{{}^{A}R_{B}} \begin{pmatrix} {}^{B}x \\ {}^{B}y \end{pmatrix}$$

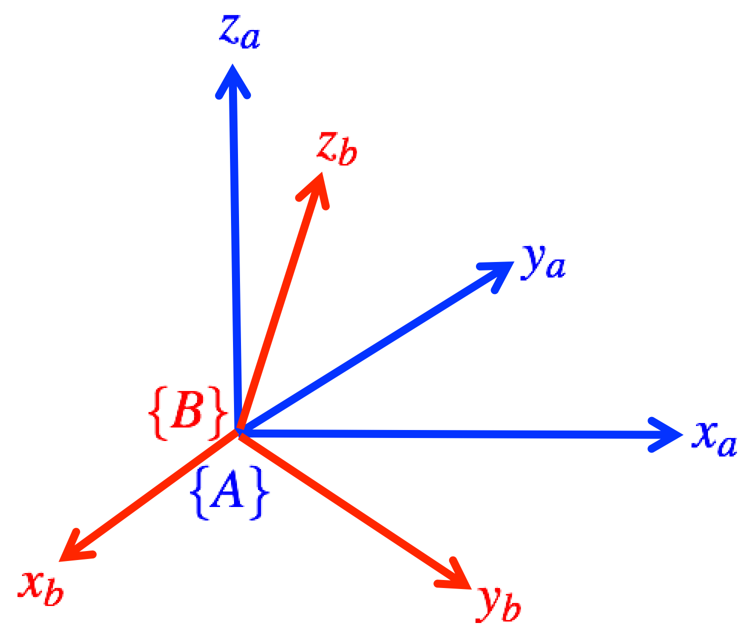
Watch https://robotacademy.net.au/masterclass/2d-geometry/?lesson=75 for the derivation

Rotation from A to B,
or rotation of B with respect to A

3D Rotation Matrix

- 3D rotation matrix

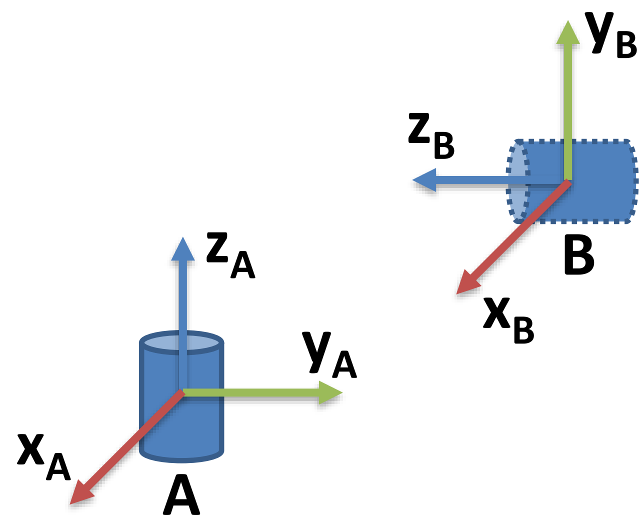
$$\begin{pmatrix} {}^A x \\ {}^A y \\ {}^A z \end{pmatrix} = \underbrace{\begin{array}{c} \begin{array}{ccc} \text{new x-axis} & \text{new y-axis} & \text{new z-axis} \end{array} \\ \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \end{array}}_{{}^A R_B} \begin{pmatrix} {}^B x \\ {}^B y \\ {}^B z \end{pmatrix}$$



Rotation from A to B,
or rotation of B with respect to A

Rotation Matrix - Example

- Determine the rotation matrix from {A} to {B}



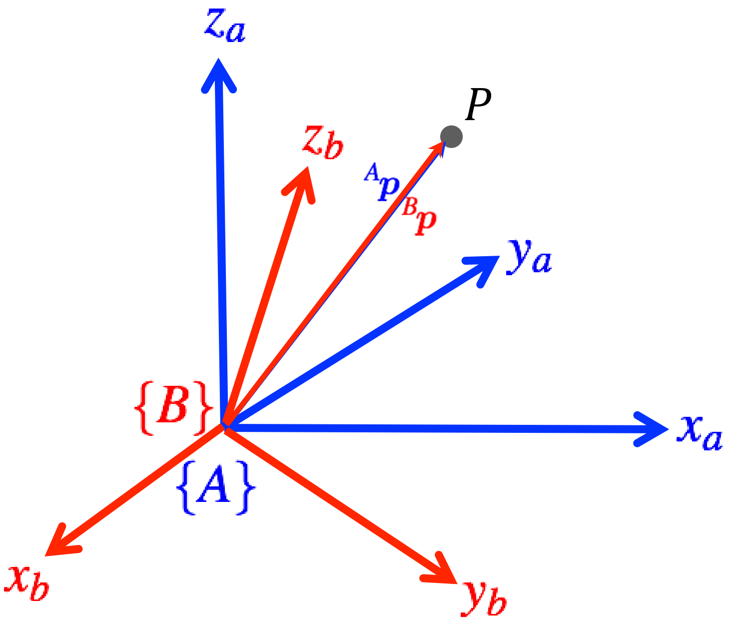
$$\begin{pmatrix} {}^{A}x \\ {}^{A}y \\ {}^{A}z \end{pmatrix} = \begin{pmatrix} \boxed{} & \boxed{} & \boxed{} \end{pmatrix} \begin{pmatrix} {}^{B}x \\ {}^{B}y \\ {}^{B}z \end{pmatrix}$$

Join at www.slido.com with code #3383 to answer this question under the POLLS tab.

Positions in Rotated Frames

- Positions of a point in rotated frames can be related by a rotation matrix (chain rule)

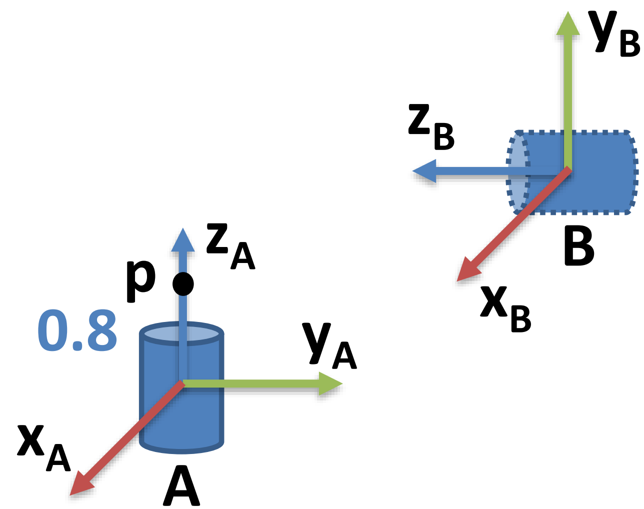
$$^{A}p = {}^{A}R_{B}\,{}^{B}p$$



Only works for frames sharing the same origin (no translation involved).

Positions in Rotated Frames - Example

- Suppose P is a 3D point.
- {A} and {B} share the same origin.
- Write down by inspection



$$ {}^{A}R_{B} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \qquad {}^{A}p = \begin{pmatrix} \quad \end{pmatrix} \qquad {}^{B}p = \begin{pmatrix} \quad \end{pmatrix} $$

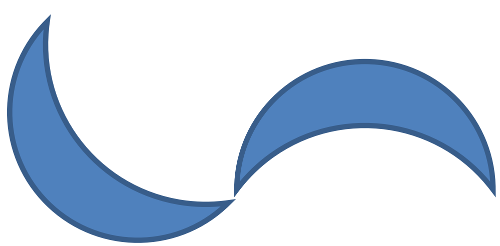
- Validate $\quad {}^{A}p = {}^{A}R_{B}\, {}^{B}p$

$$ \begin{pmatrix} 0 \\ 0 \\ 0.8 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0.8 \\ 0 \end{pmatrix} $$

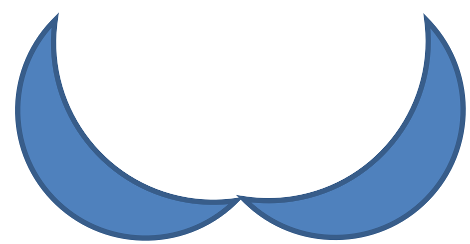
Properties of A Rotation Matrix

- Orthogonal Matrix $\boxed{R^T R = I \; or \; R^T = R^{-1}}$
  - Because the length of a vector remains the same after rotation. $(Rp)^T Rp = p^T R^T Rp = p^T p$

- Special Orthogonal Matrix $\boxed{\det(R) = 1}$
  - Otherwise it is a rotary reflection.



Rotation
$\det(R) = 1$



Rotary reflection
$\det(R) = -1$

Parameterisation of A Rotation

- How many parameters at least are required to parameterise a 3D rotation?

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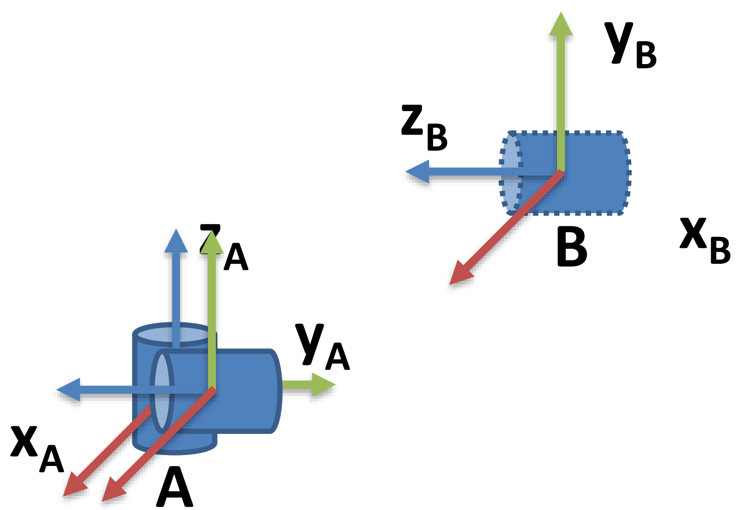
- …

Join at www.slido.com with code #3383 to answer this question under the POLLS tab.

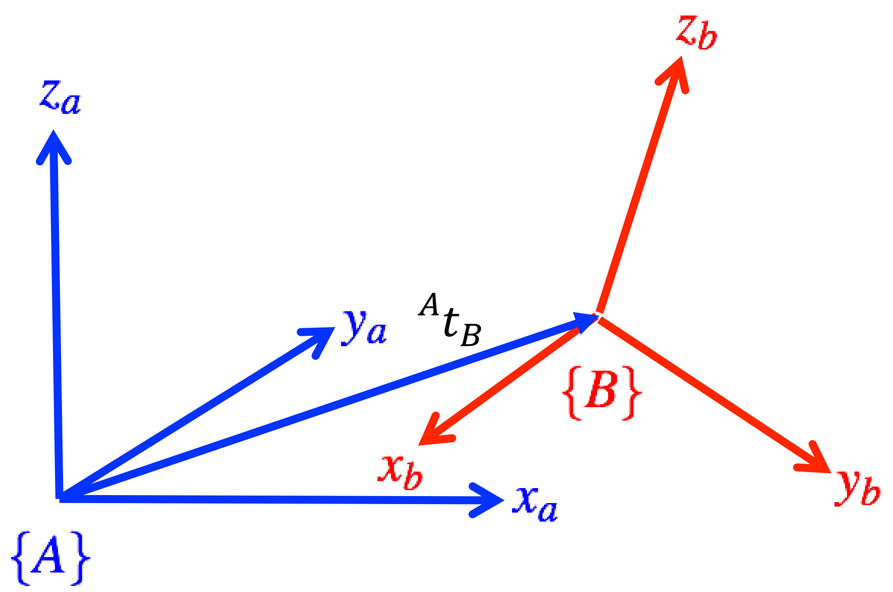
Recall: Rigid Body Motions

- The pose of B relative to A can be described with two components:
  - A rotation matrix **R** specifying the orientation
  - And a translation vector **t** specifying the position



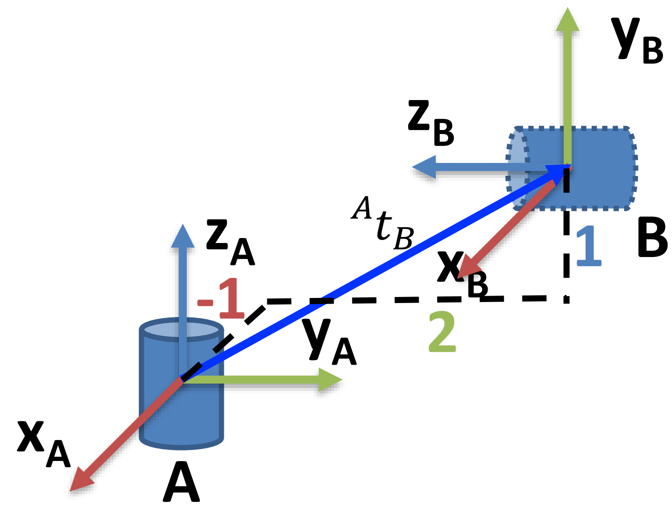
Translation Vector

- Translation vector ${}^{A}t_{B}$ is a vector pointing from the origin of {A} to the origin of {B} evaluated in {A}.



Translation Vector - Example

- Determine the translation vector from {A} to {B}



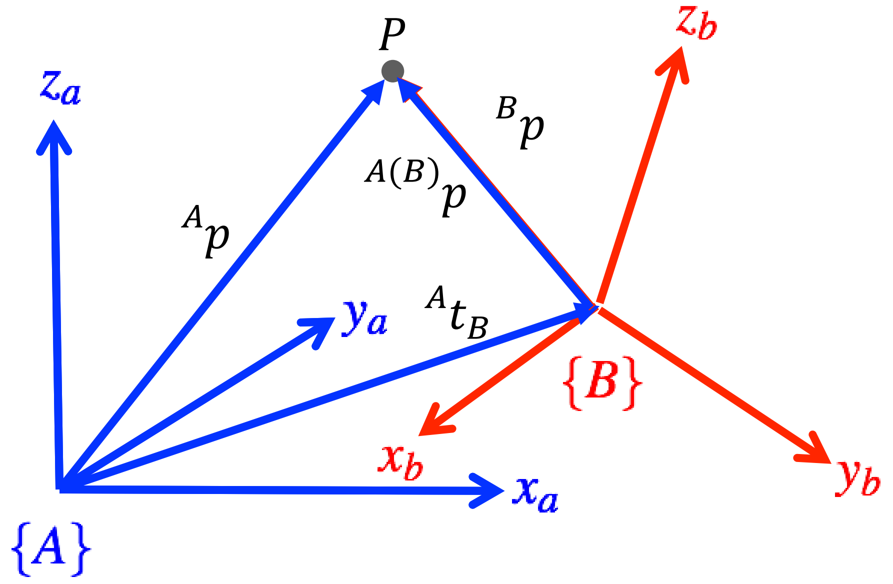
$${}^{A}t_B = \left(\boxed{}\right)$$

Homogeneous Transformation

- Suppose P is a 3D point.

$$^{A}p = {}^{A}t_B + {}^{A(B)}p$$

$$^{A(B)}p = {}^{A}R_B \, {}^{B}p$$



$$^{A}p = {}^{A}t_B + {}^{A}R_B \, {}^{B}p$$

$$\begin{pmatrix} ^{A}p \\ 1 \end{pmatrix} = \begin{pmatrix} & {}^{A}R_B & & {}^{A}t_B \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ^{B}p \\ 1 \end{pmatrix}$$

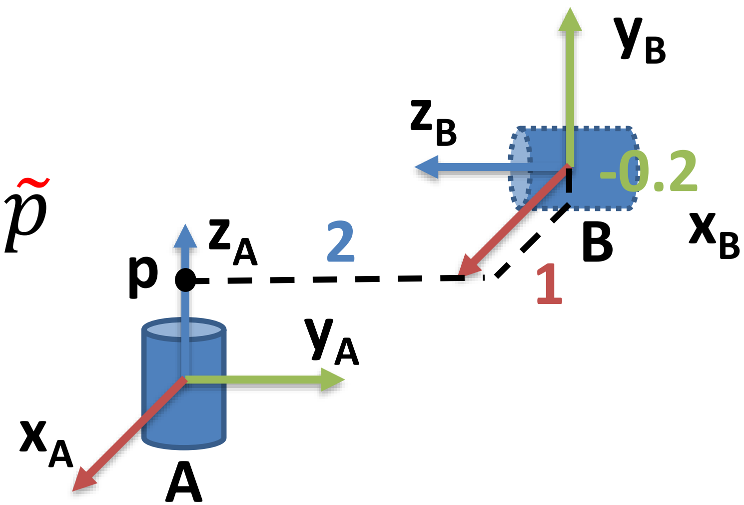
Homogeneous Transformation

$$\underbrace{{}^A\tilde{p}}_{\text{Homogeneous Vector}} = \underbrace{{}^AT_B}_{\text{Homogeneous Transformation}} \underbrace{{}^B\tilde{p}}_{\text{Homogeneous Vector}}$$

$$\begin{pmatrix} {}^Ap \\ 1 \end{pmatrix} = \begin{pmatrix} & {}^AR_B & & {}^At_B \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} {}^Bp \\ 1 \end{pmatrix}$$

Homogeneous Transformation - Example

- Suppose P is a 3D point.
- Given ${}^{A}T_{B}$ and ${}^{B}\tilde{p}$, find ${}^{A}\tilde{p}$



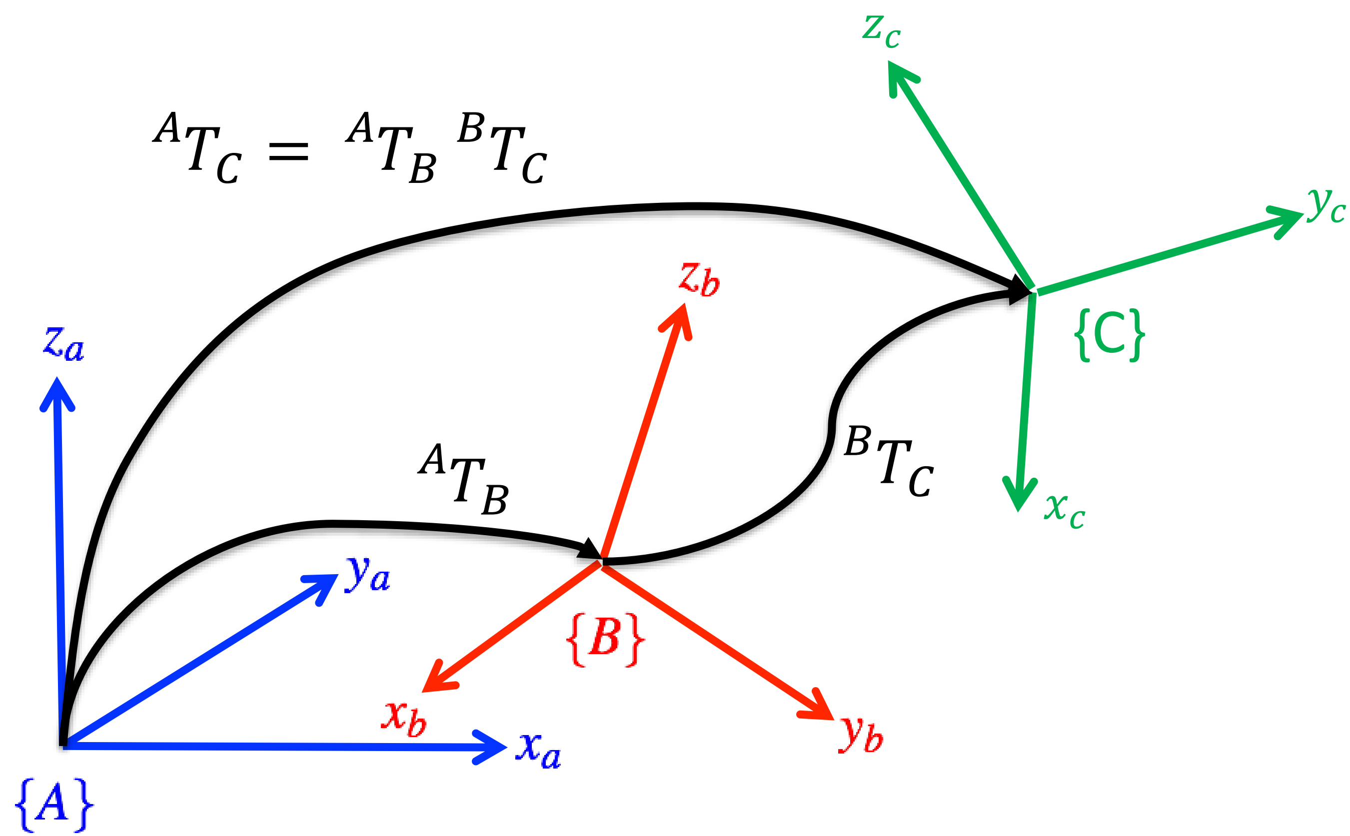
$$ {}^{A}T_{B} = \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & -1 & 2 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

$$ {}^{A}\tilde{p} = \begin{pmatrix} \boxed{} \end{pmatrix} \qquad {}^{B}\tilde{p} = \begin{pmatrix} 1 \\ -0.2 \\ 2 \\ 1 \end{pmatrix} $$

- Validate

Join at www.slido.com with code #3383 to answer this question under the POLLS tab.

Chain Rule



Inverse of Homogeneous Transformation

$$T = \begin{pmatrix} & R & & t \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad T^{-1} = \begin{pmatrix} & R^T & & -R^T t \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$${}^{A}T_{C} = {}^{A}T_{B}\, {}^{B}T_{C} \qquad {}^{\mathrm{A}}p = {}^{A}T_{B}\, {}^{B}p$$

$${}^{A}T_{B}^{-1}\, {}^{A}T_{C} = {}^{B}T_{C} \qquad {}^{A}T_{B}^{-1}\, {}^{\mathrm{A}}p = {}^{B}p$$

Summary

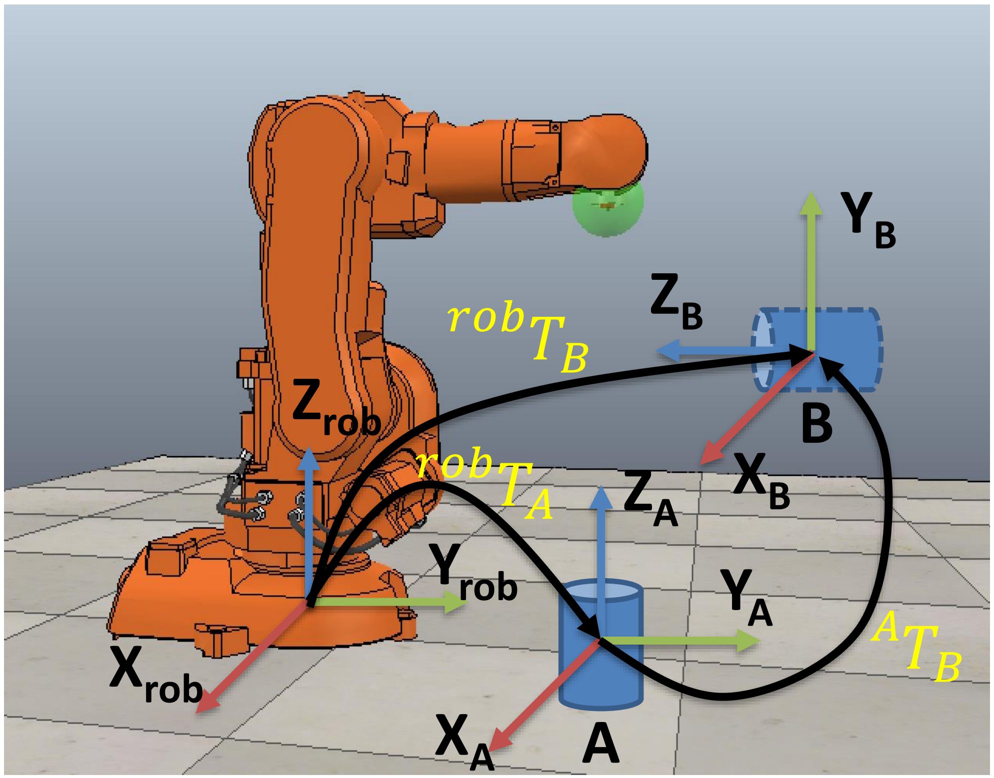
- A rigid body can be represented by a coordinate frame

- Rigid body motions have two components
  - A rotational component (rotation matrix)
  - And a translational component (translation vector)

- Rigid body motions can be represented by homogeneous transformations

- Homogeneous transformations conform to chain rules and are invertible

Motivating Problem - Revisit



- Imagine one of your arms is replaced by a robotic arm, and you are blindfolded (you don't have sensors to detect the object in front of you).
- You are supposed to move the object from A to B.
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Final Remarks

- Acknowledgements
  - Some material of the slides was developed by the previous lecturers of EGB339 - Introduction to Robotics (Michael Milford, Peter Corke, and Chris Lehnert)

- Feedback
  - Please send your (anonymous) feedback through www.slido.com with code #3383 under the QUESTIONS tab (only active for three days).
  - I will try to incorporate the feedback into the next lecture.