ECE 4960

Prof. Kirstin Hagelskjær Petersen
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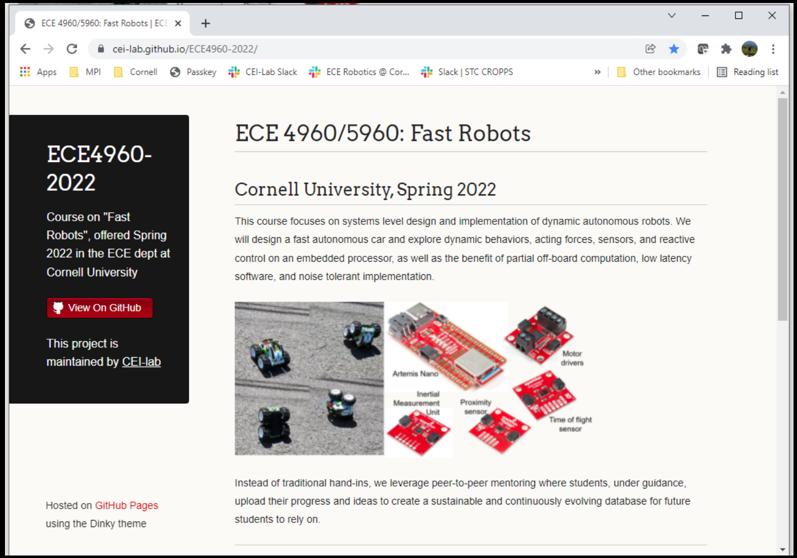
Fast Robots

Logistics (From lecture 1)

- Github page
    - Schedule
    - Lecture slides
    - Student pages
- Lab kit
    - ASML generously paid for every lab kit
    - ….Things will break, we have a small set of extra loaner components, but please be careful
    - ….Supply crisis!
- Workload
    - Average 8 hrs per lab
    - The car runs out of battery in ~10-20min
- Hand-ins
    - Github page / deadline
    - 67% technical completion, 33% write-up



ECE4960-2022

Course on "Fast Robots", offered Spring 2022 in the ECE dept at Cornell University

This project is maintained by CEI-lab

Hosted on GitHub Pages using the Dinky theme

ECE 4960/5960: Fast Robots

Cornell University, Spring 2022

This course focuses on systems level design and implementation of dynamic autonomous robots. We will design a fast autonomous car and explore dynamic behaviors, acting forces, sensors, and reactive control on an embedded processor, as well as the benefit of partial off-board computation, low latency software, and noise tolerant implementation.

Instead of traditional hand-ins, we leverage peer-to-peer mentoring where students, under guidance, upload their progress and ideas to create a sustainable and continuously evolving database for future students to rely on.

ASML

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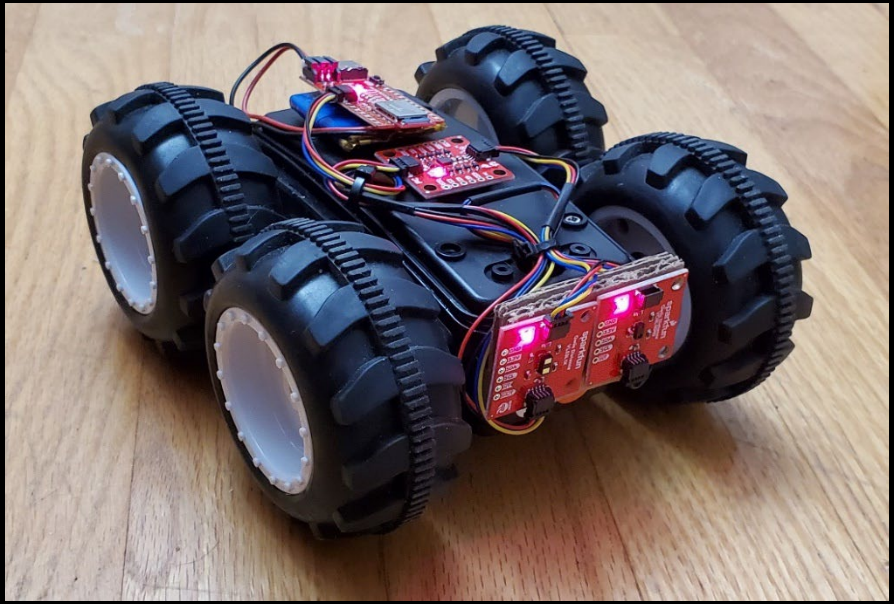
Fast Robots

Robot Configurations

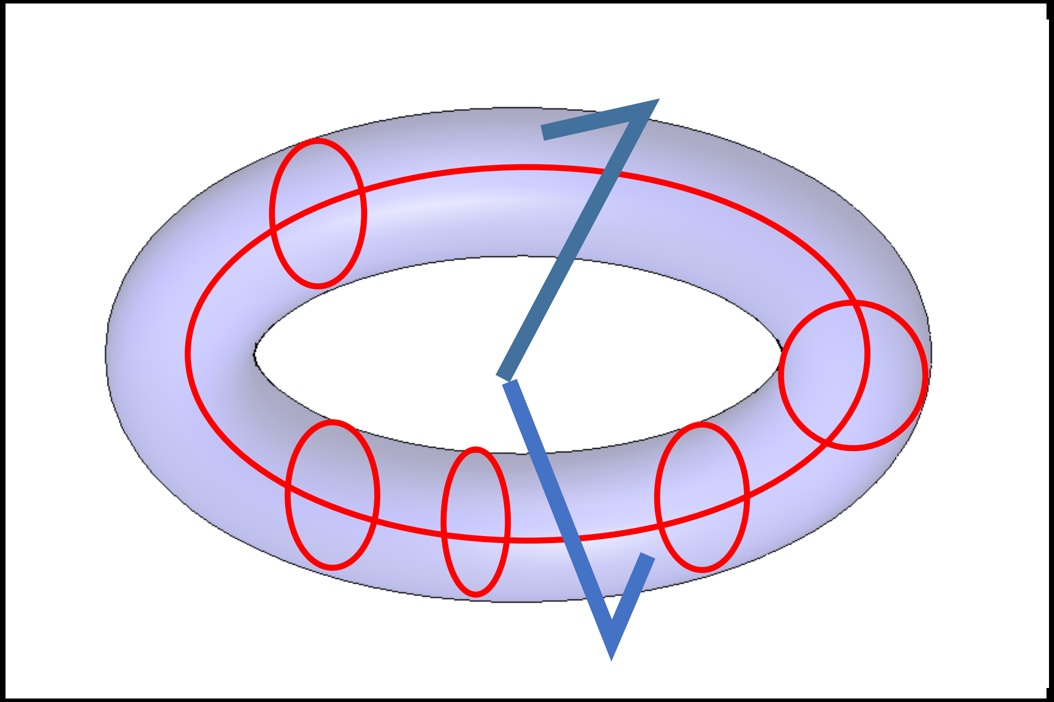
- Objective: Coordinate transformations for robotics
  - "Rigid-body kinematics"
- Robot configuration specifies all points on the robot
- The robot C-space is the space of all configurations
- The DOF is the dimension of the C-space



What is the DOF of these?

Configuration, Configuration space, Degrees of Freedom

- 2 DOF robot arm
  - C-space: 2 angles
  - J-space: Surface of a torus

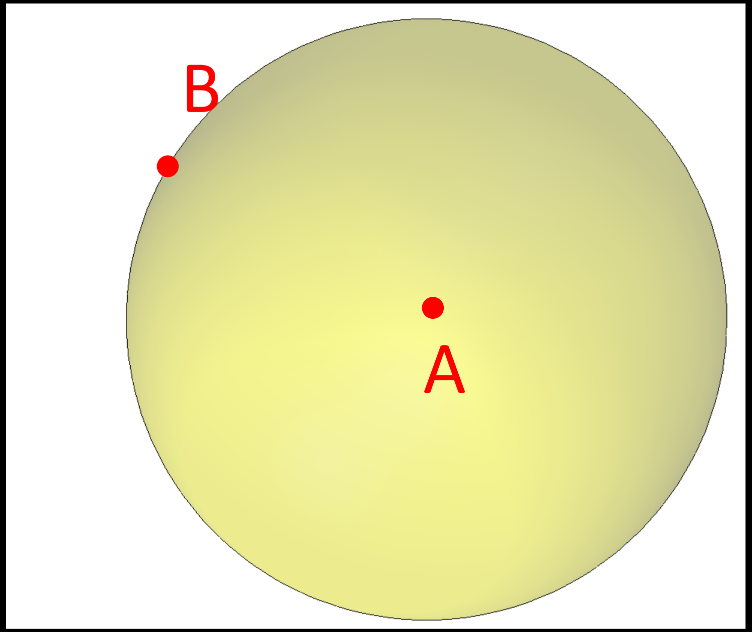


Robot Configurations

- Point A: {x, y, z}

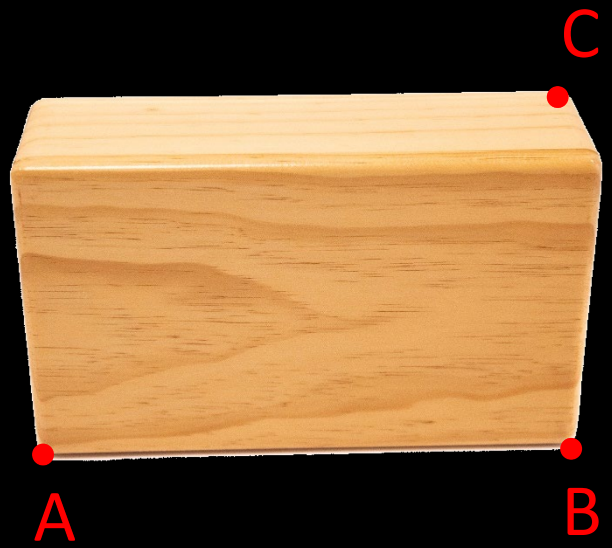
Robot Configurations

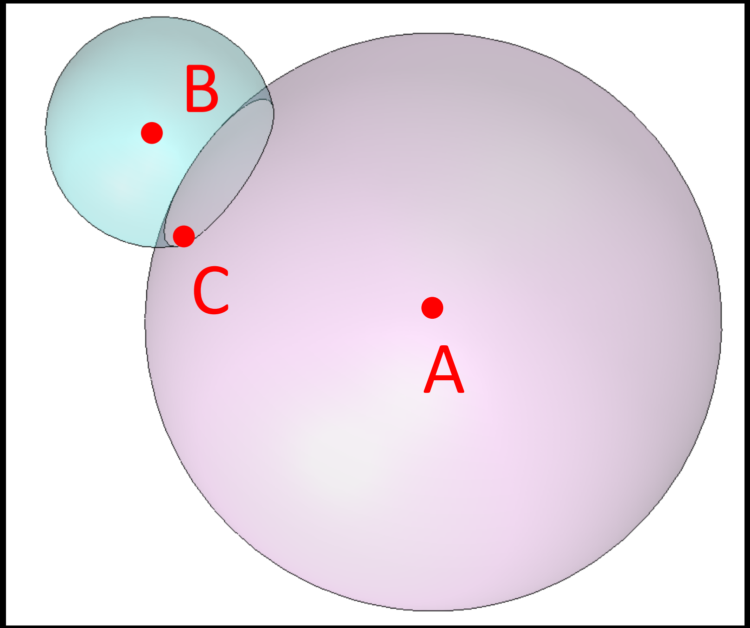
- Point A: {x, y, z}
- Point B: {θ, ϕ}



Robot Configurations

- Point A: {x, y, z}
- Point B: {θ, ϕ}
- Point C: {ψ}
- A rigid body in 3D has 6 DOF
- A rigid body in 2D has 3 DOF
- A rigid body in 4D has 10 DOF





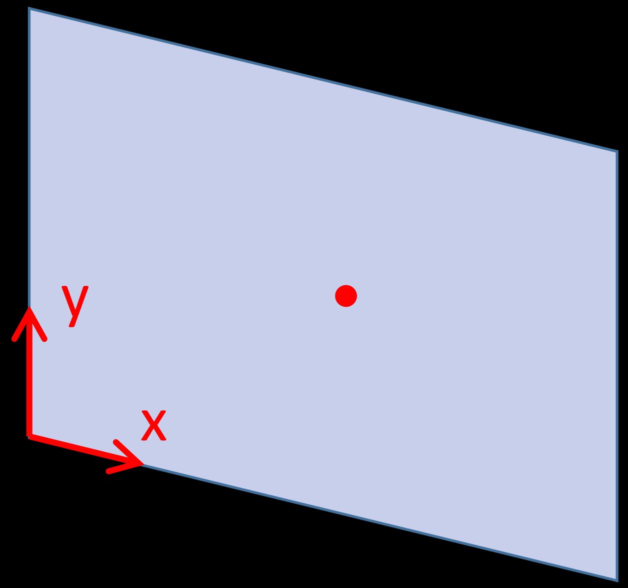
Point	Coords	Ind. constraints	Real freedoms
A	3	0	3
B	3	1	2
C	3	2	1
D	3	3	0
Total			6

DOF = Σ(freedoms of points) – no. of independent constraints

DOF = Σ(freedoms of bodies) – no. of independent constraints

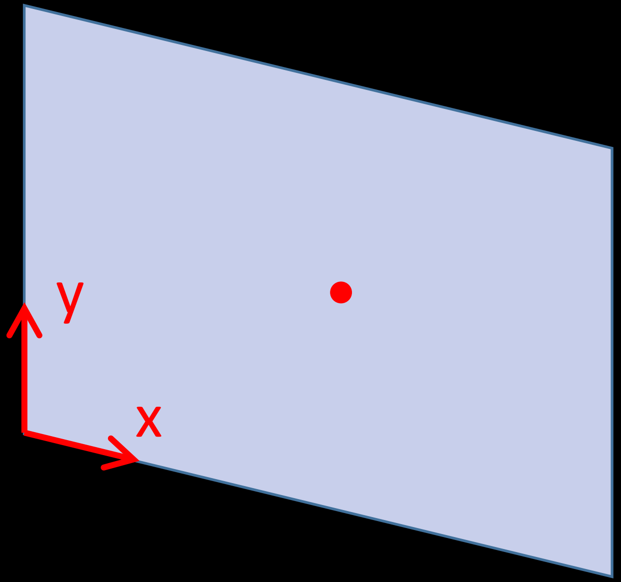
Topology Representation

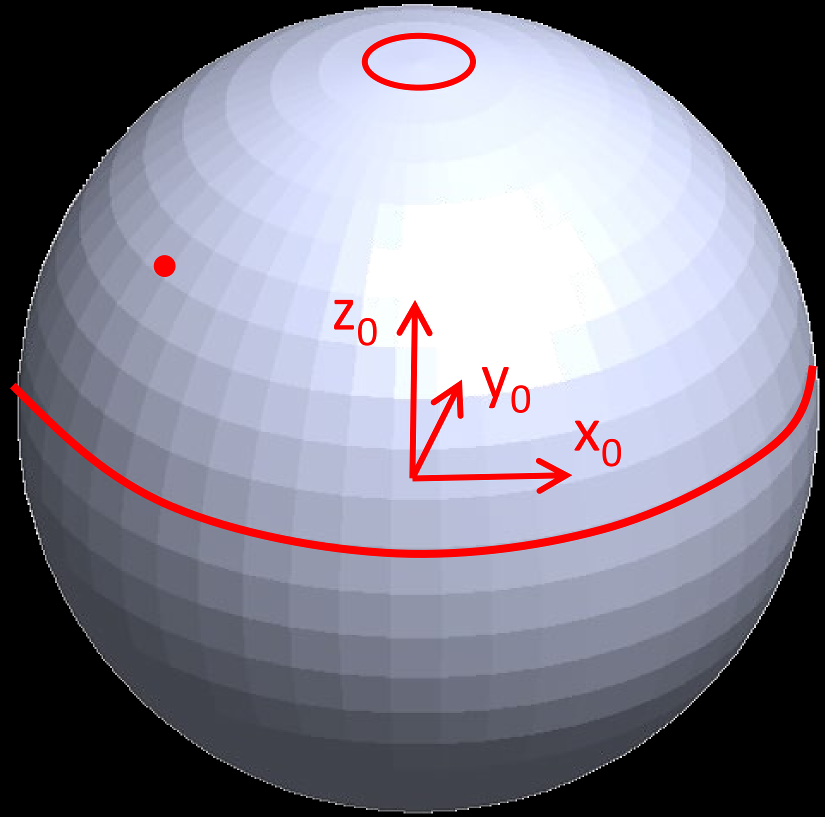
- Point on a plane
  - Origin and 2 orthogonal coordinate axis



Topology Representation

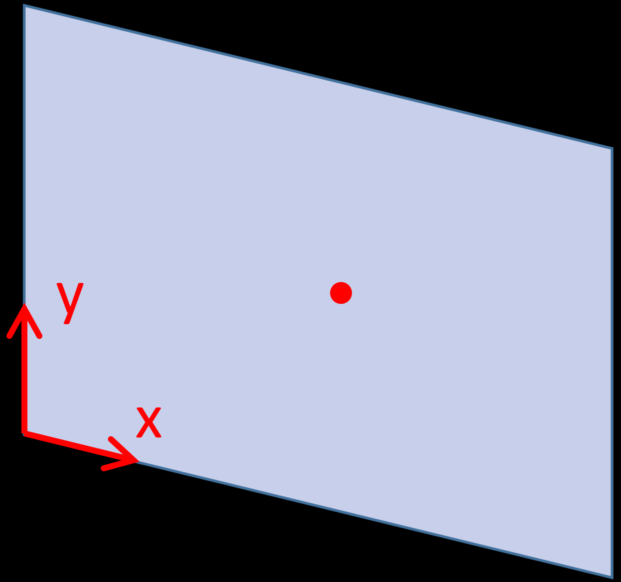
- Point on a plane
  - Origin and 2 orthogonal coordinate axis
- Points on the surface of a sphere
  - “Explicit representation”: Latitude and longitude

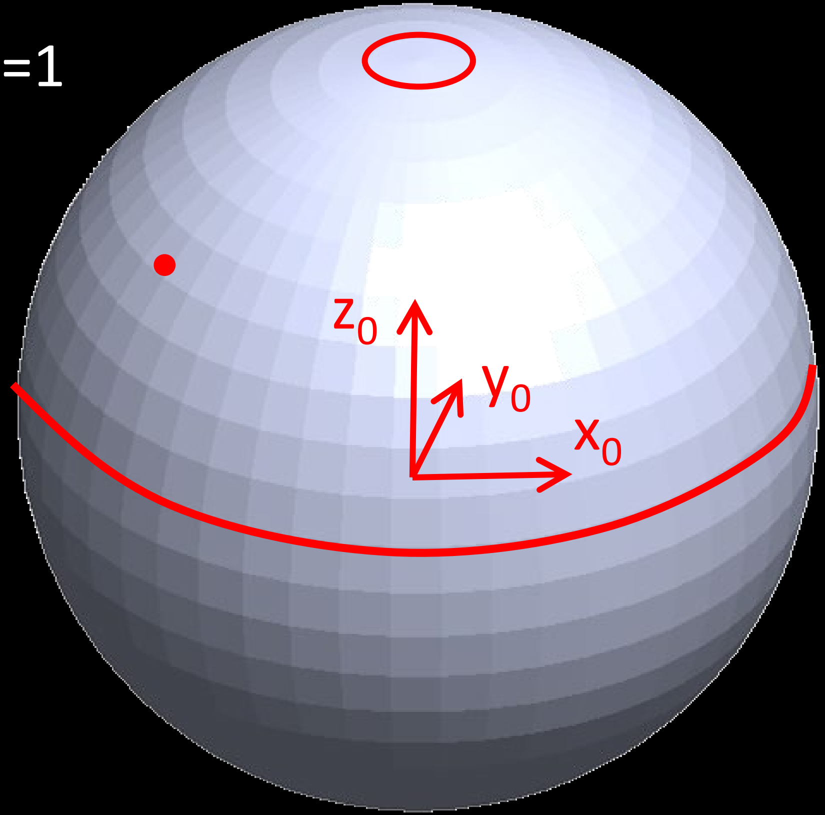




Topology Representation

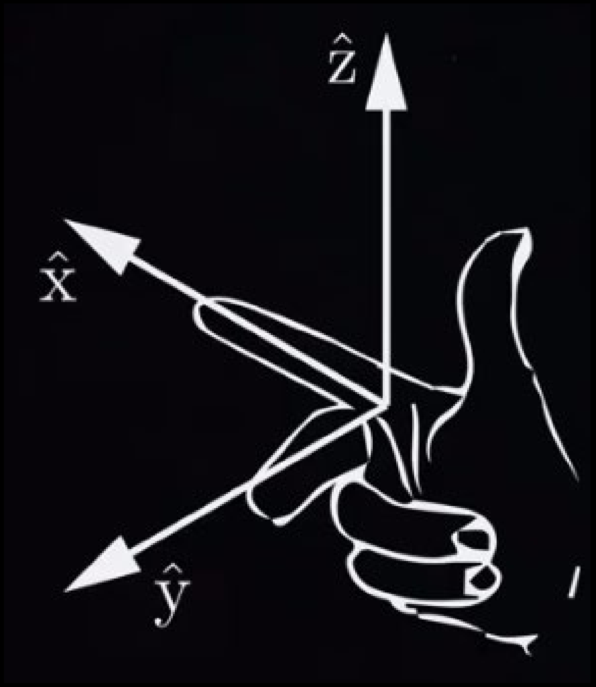
- Point on a plane
  - Origin and 2 orthogonal coordinate axis
- Points on the surface of a sphere
  - “Explicit representation”: Latitude and longitude
  - “Implicit representation”: {X, Y, Z}, such that $x^2+y^2+z^2 = 1$
    - Slightly more complex, but singularity free!
      - 3D → Rotation matrix

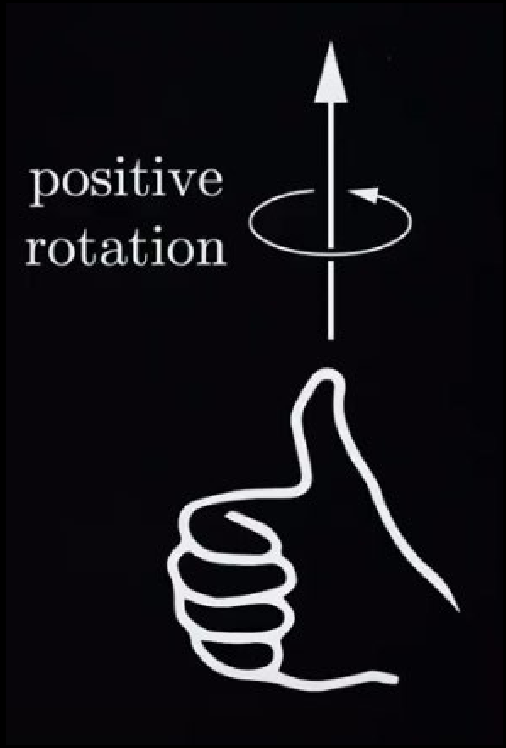




Coordinate Frames

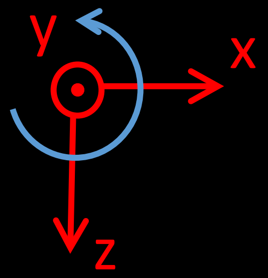
- Reference frames (origin and {x, y, z}-coordinates)
- Right hand frames and rotations



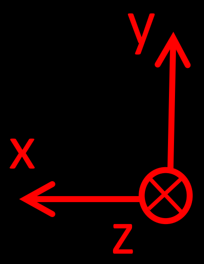


Are these right-handed or left-handed?

A)

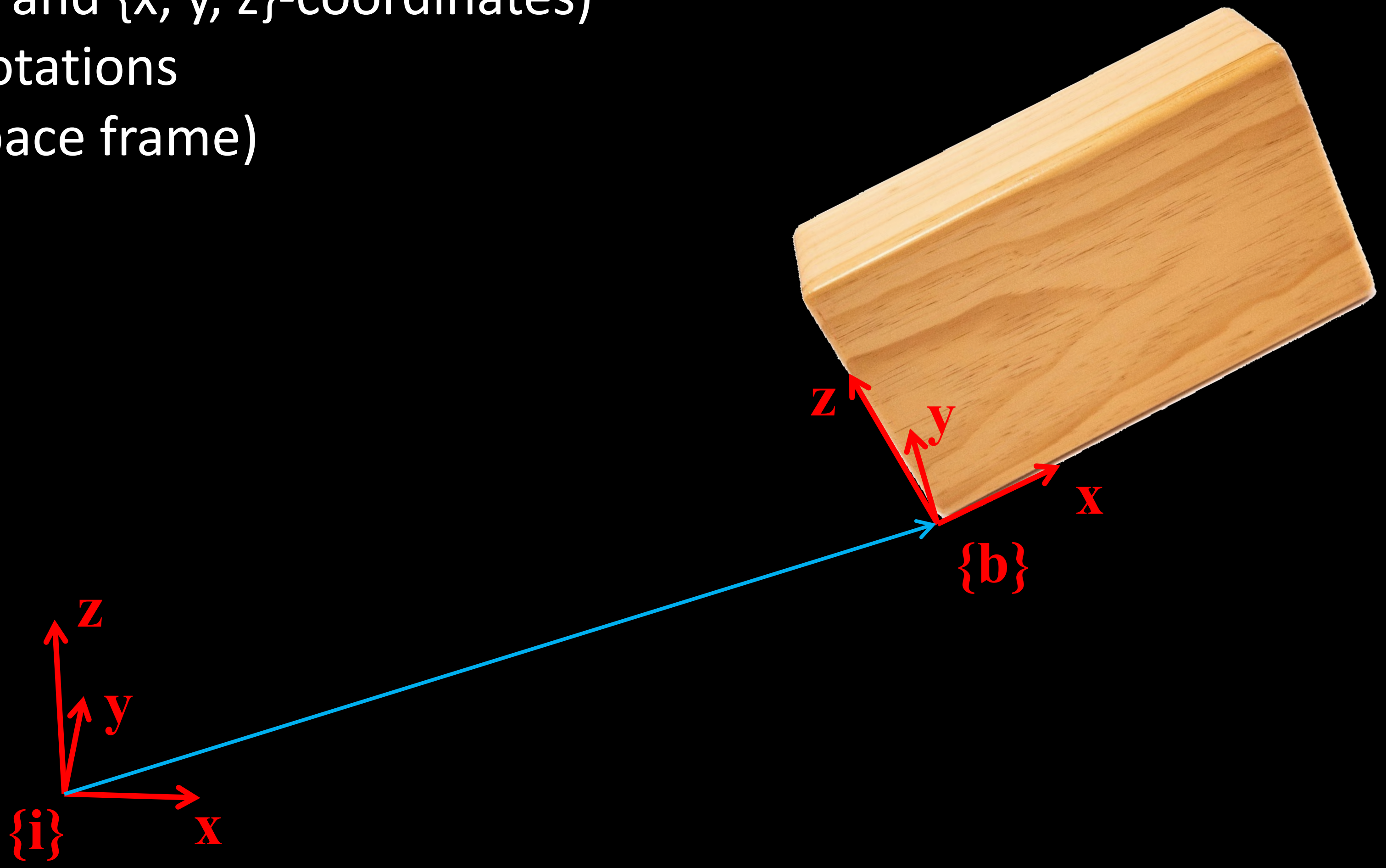


B)



Coordinate Frames

- Reference frames (origin and {x, y, z}-coordinates)
- Right hand frames and rotations
- Inertial frame (/world/space frame)
- Body frame



Coordinate Frames

- Reference frames (origin and {x, y, z}-coordinates)
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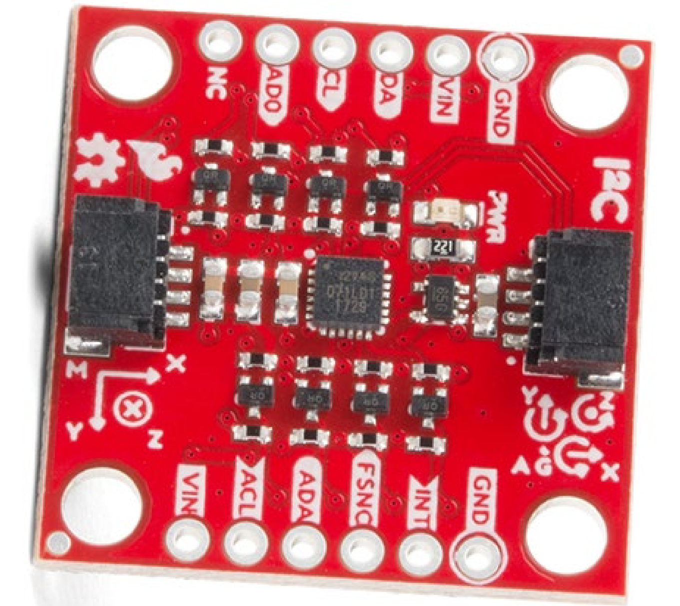
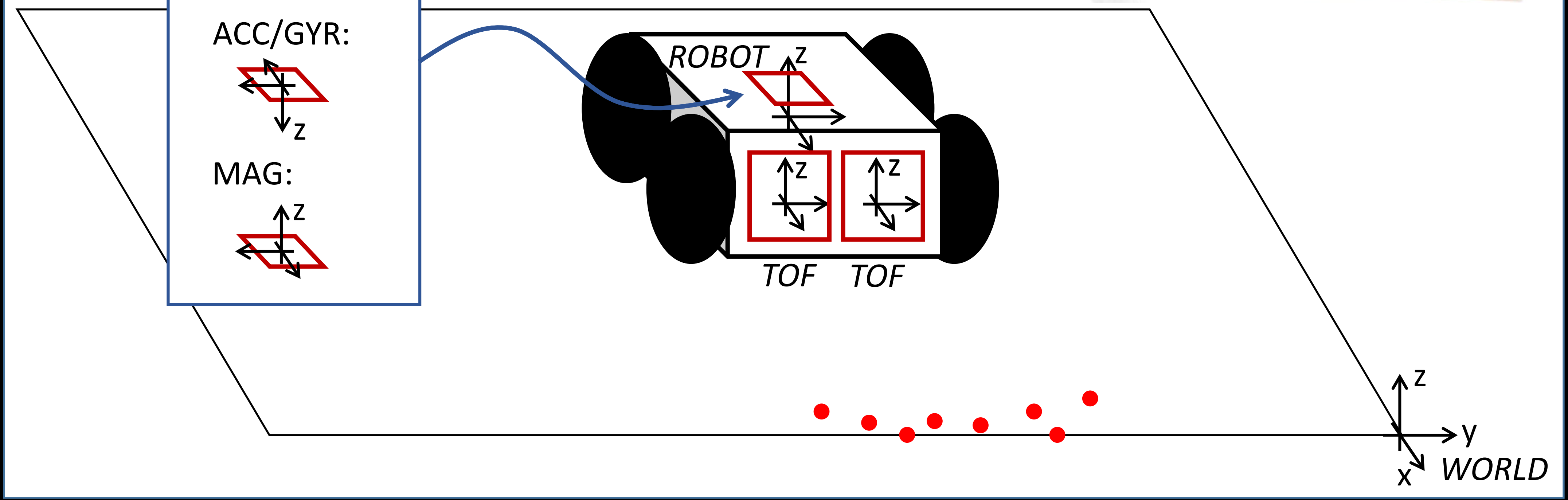
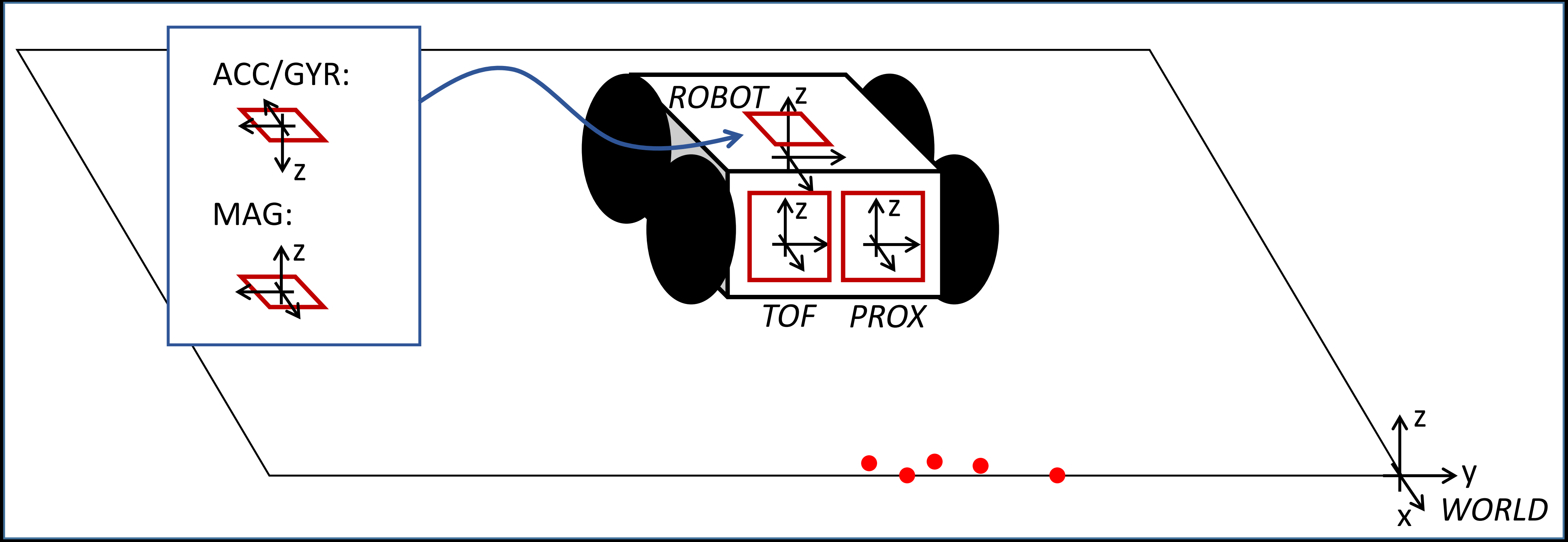




Homogeneous Transformation Matrix

rotation translation

$$T = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} \boxed{\begin{matrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{matrix}} & \boxed{\begin{matrix} x \\ y \\ z \end{matrix}} \\ \begin{matrix} 0 & 0 & 0 \end{matrix} & 1 \end{bmatrix}$$



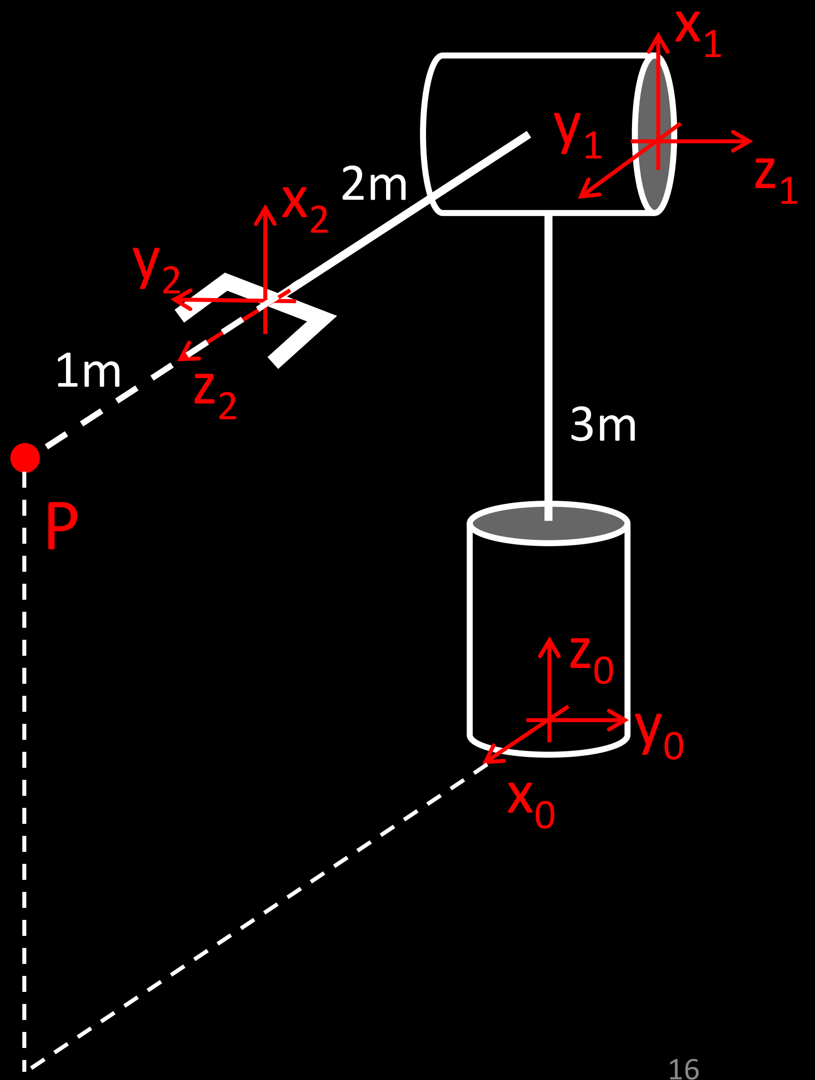
Homogeneous Transformation Matrix

- What is the location of the point P in reference frame 2?

$$P^2 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

- What is the location of point P in reference frame 0?

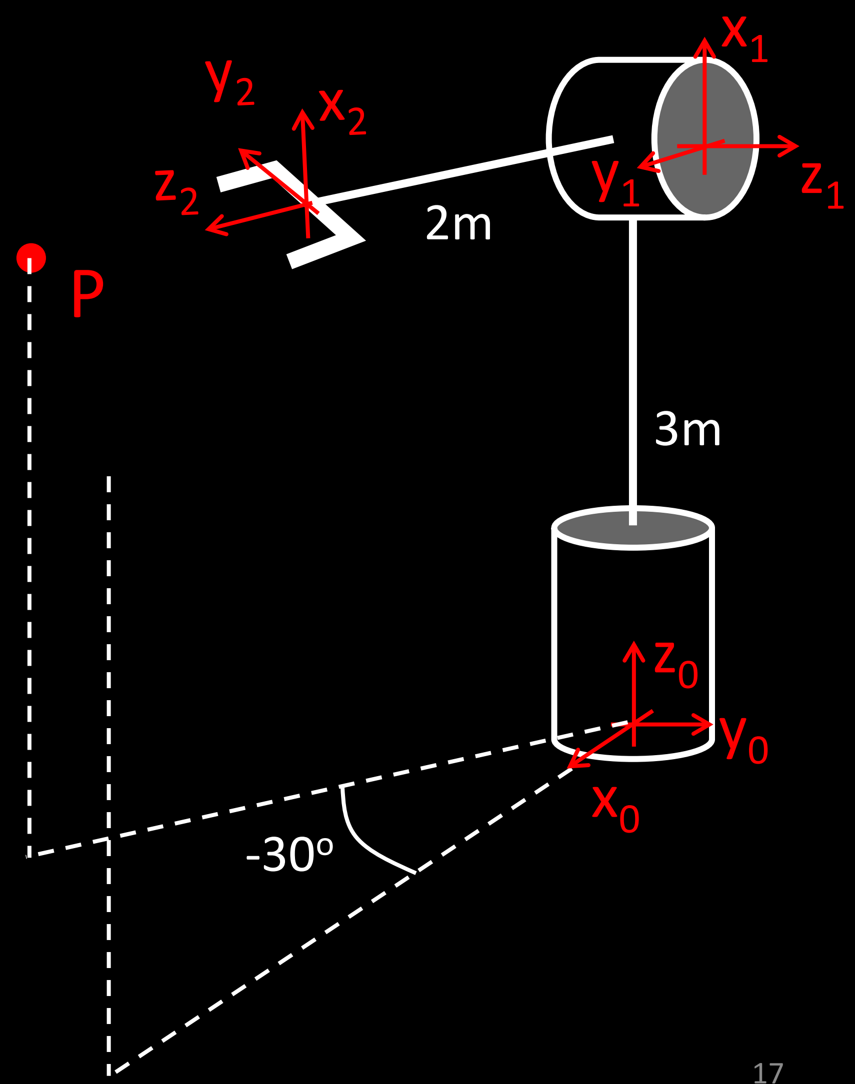
$$P^0 = \begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix}$$



Homogeneous Transformation Matrix

- What is the location of the point P in reference frame 2?

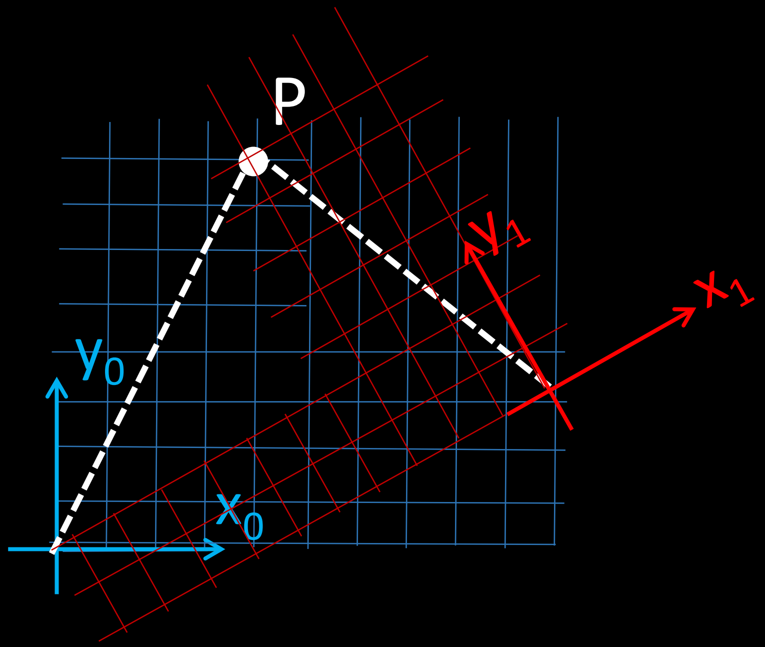
- What is the location of point P in reference frame 0?



Homogeneous Transformation Matrix

- The change in position and orientation between frames is described using transformation matrices

$$P^0 = \begin{bmatrix} 4 \\ 8 \end{bmatrix} \qquad P^1 = \begin{bmatrix} -3 \\ 7 \end{bmatrix} \qquad O_1^0 = \begin{bmatrix} 10 \\ 3.3 \end{bmatrix} \qquad O_0^1 = \begin{bmatrix} -10.3 \\ 2 \end{bmatrix}$$



How do we express P^0 if we know P^1 and the relative location of O_1^0?

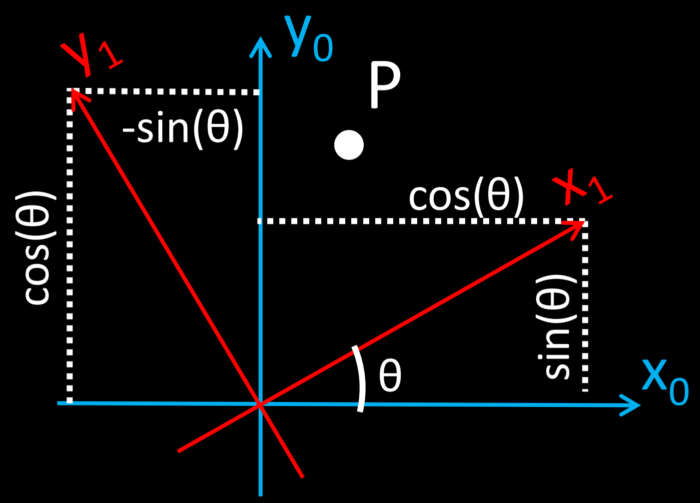
$$P^0 \cancel{=} P^1 + O_1^0$$

Homogeneous Transformation Matrix

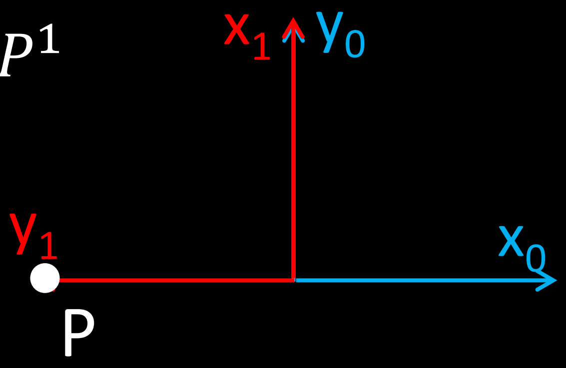
- We need both translation and rotation!

$$R_1^0 = [x_1^0 \quad y_1^0] \qquad x_1^0 = \begin{bmatrix} cos(\theta) \\ sin(\theta) \end{bmatrix} \qquad y_1^0 = \begin{bmatrix} -sin(\theta) \\ cos(\theta) \end{bmatrix} \qquad R_1^0 = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}$$

$$P^0 = R_1^0 P^1 = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} P^1$$



e.g. if $P^1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and $\theta = 90^{o}$:



$$P^0 = R_1^0 P^1 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -1 \\ 0 \end{bmatrix}$$

Homogeneous Transformation Matrix

- We need both translation and rotation!

$$R_1^0 = [x_1^0 \quad y_1^0] \qquad x_1^0 = \begin{bmatrix} cos(\theta) \\ sin(\theta) \end{bmatrix} \quad y_1^0 = \begin{bmatrix} -sin(\theta) \\ cos(\theta) \end{bmatrix}$$

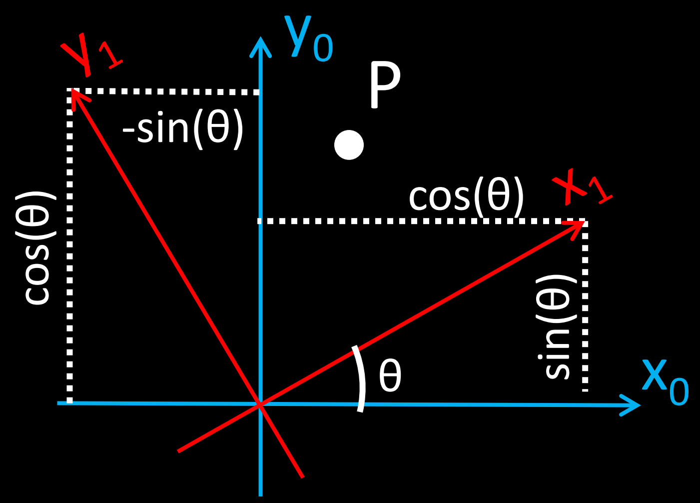
$$R_1^0 = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}$$

$$\Downarrow$$

$$R_1^0 = \begin{bmatrix} x_0 \cdot x_1 & y_0 \cdot x_1 \\ x_0 \cdot y_1 & y_0 \cdot y_1 \end{bmatrix}$$

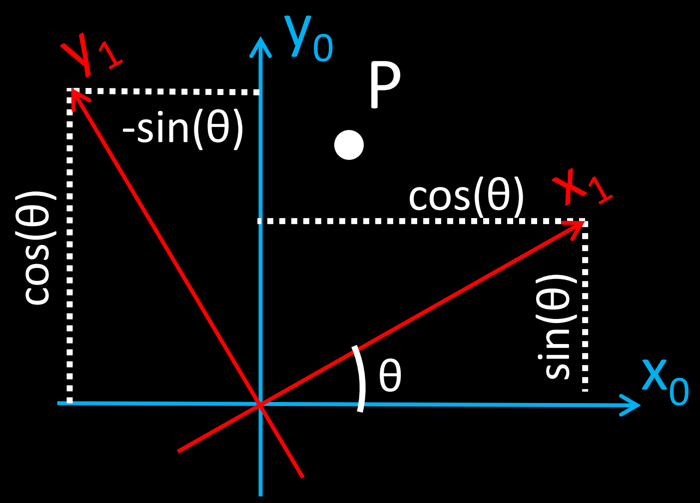
…$Properties\ of\ rotation\ matrices$:

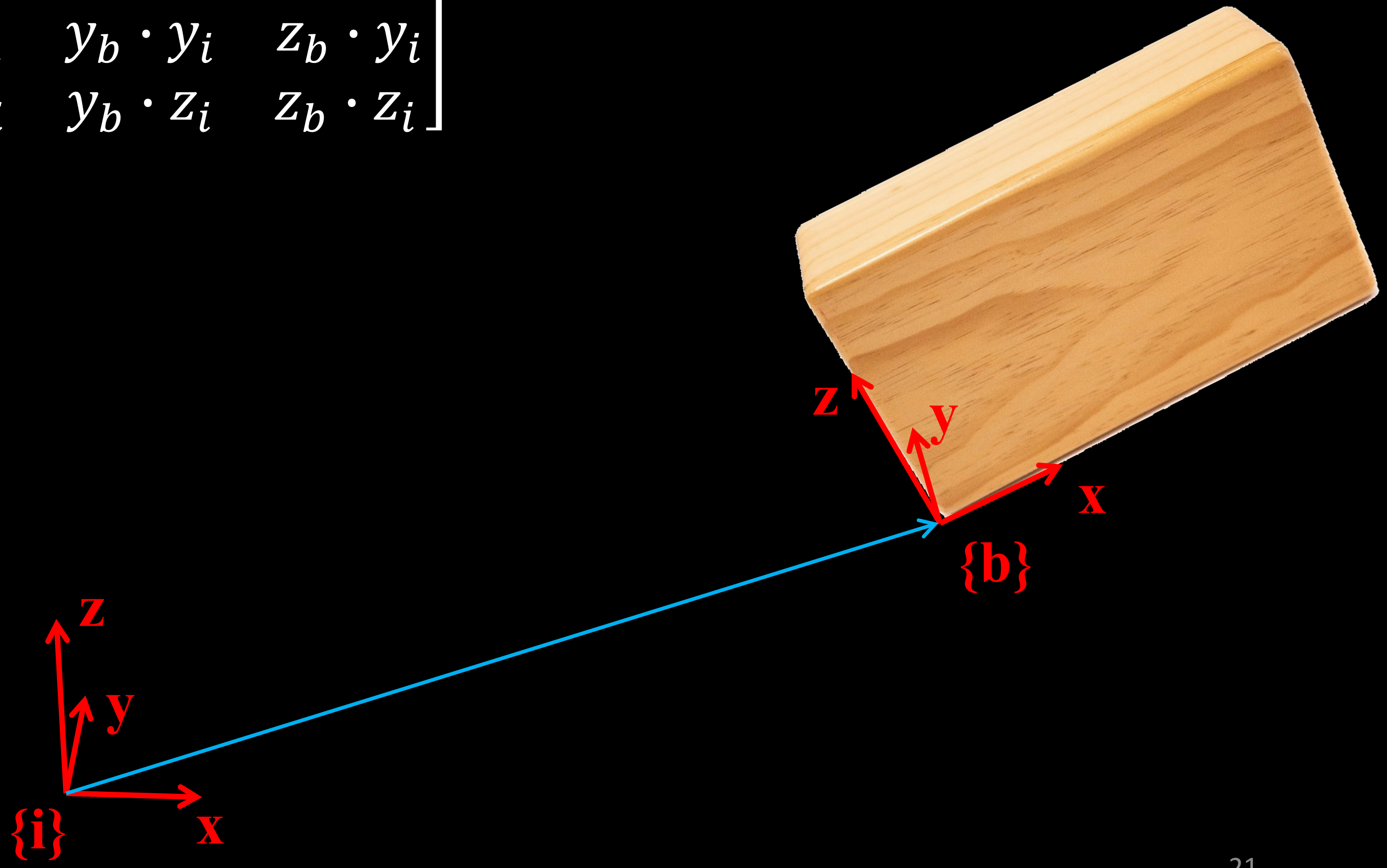
$R_0^1 = (R_1^0)^T = (R_1^0)^{-1}$ and det(R) =1



Rotation Matrix in 3D

$$R_b^i = \begin{bmatrix} x_b^i & y_b^i & z_b^i \end{bmatrix} = \begin{bmatrix} x_b \cdot x_i & y_b \cdot x_i & z_b \cdot x_i \\ x_b \cdot y_i & y_b \cdot y_i & z_b \cdot y_i \\ x_b \cdot z_i & y_b \cdot z_i & z_b \cdot z_i \end{bmatrix}$$



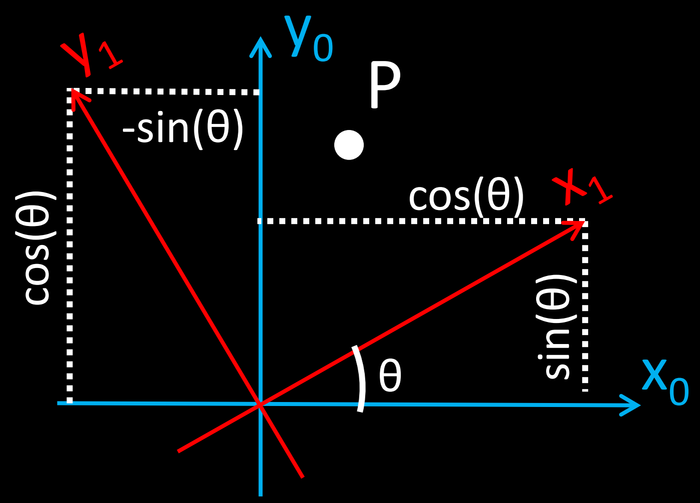


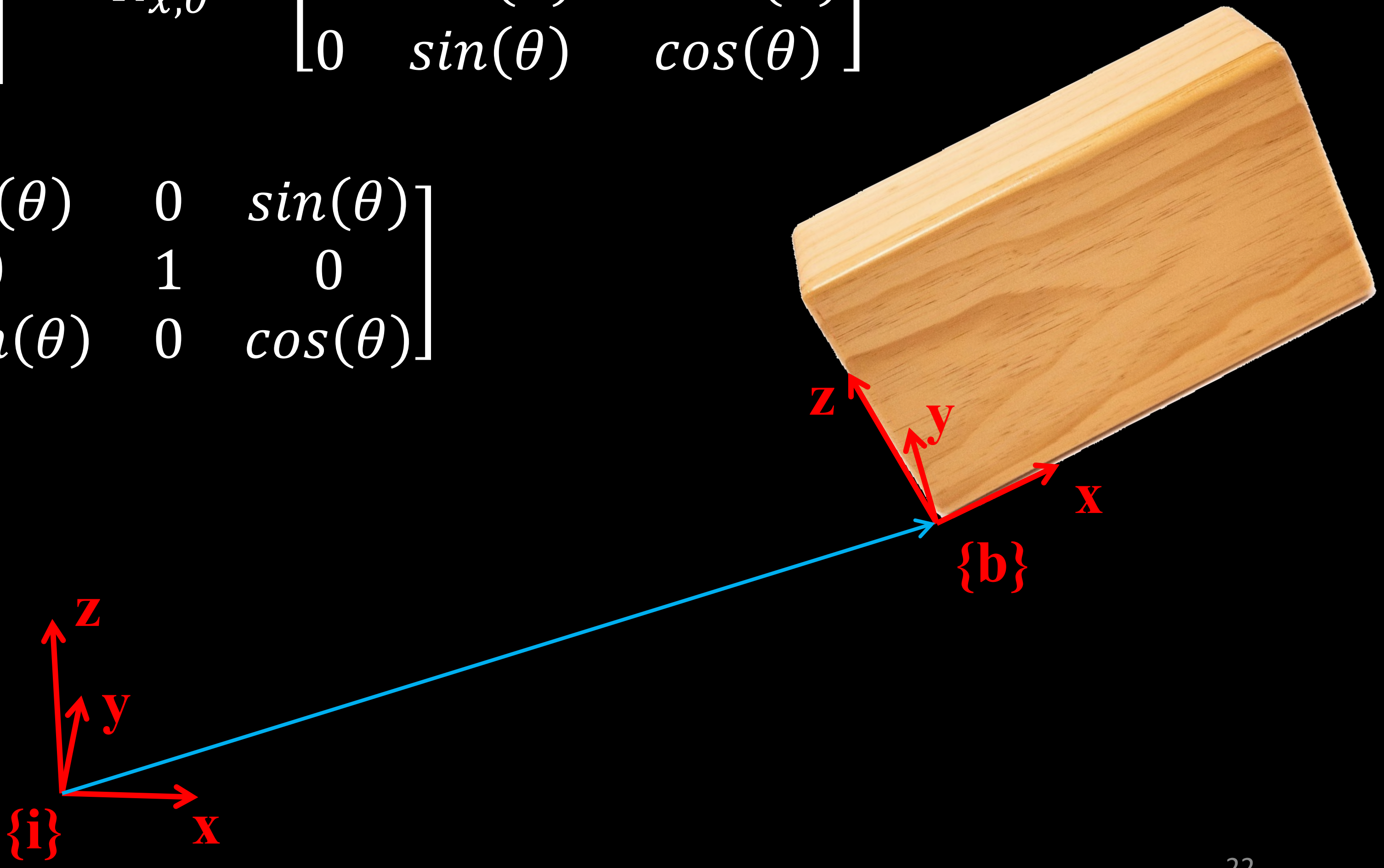
Rotation Matrix in 3D

- Find the rotation matrix $R_{z,\theta}$ for a rotation θ about z

$$R_{z,\theta} = \begin{bmatrix} cos(\theta) & -sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad R_{x,\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\theta) & -sin(\theta) \\ 0 & sin(\theta) & cos(\theta) \end{bmatrix}$$

$$R_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$



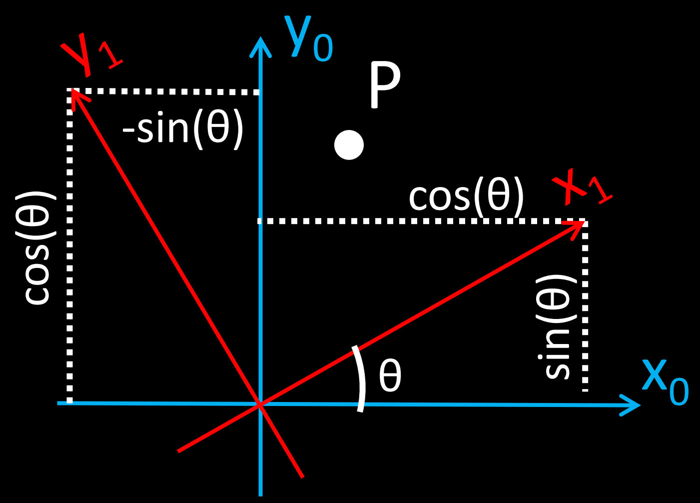


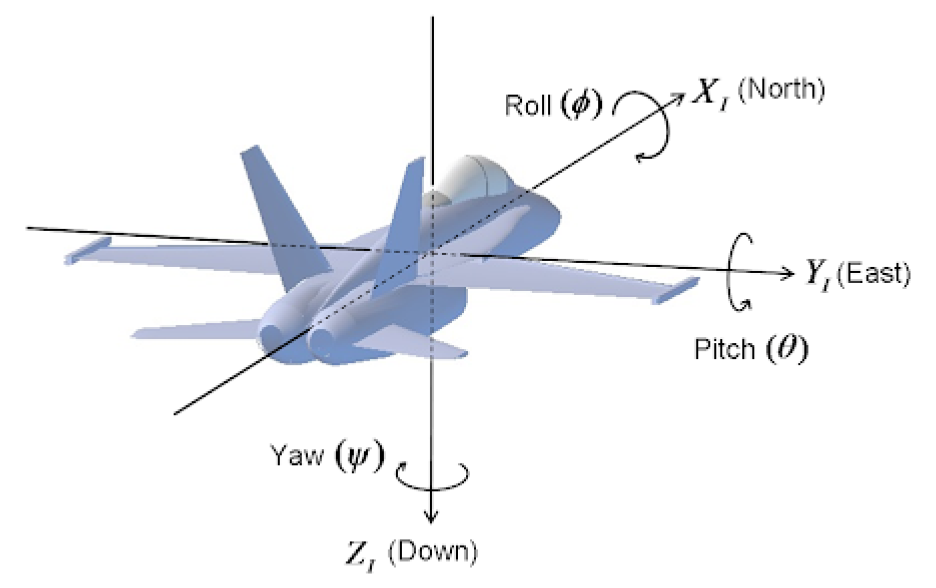
Rotation Matrix in 3D

- Find the rotation matrix $R_{z,\psi}$ for a rotation ψ about Z

$$R_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix}$$

$$R_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$



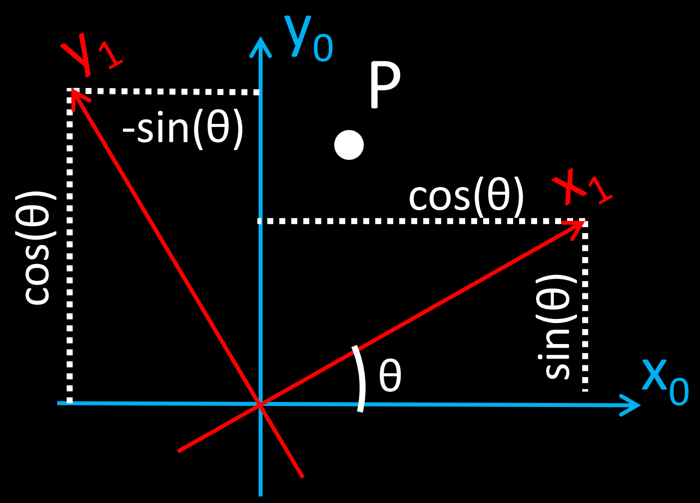


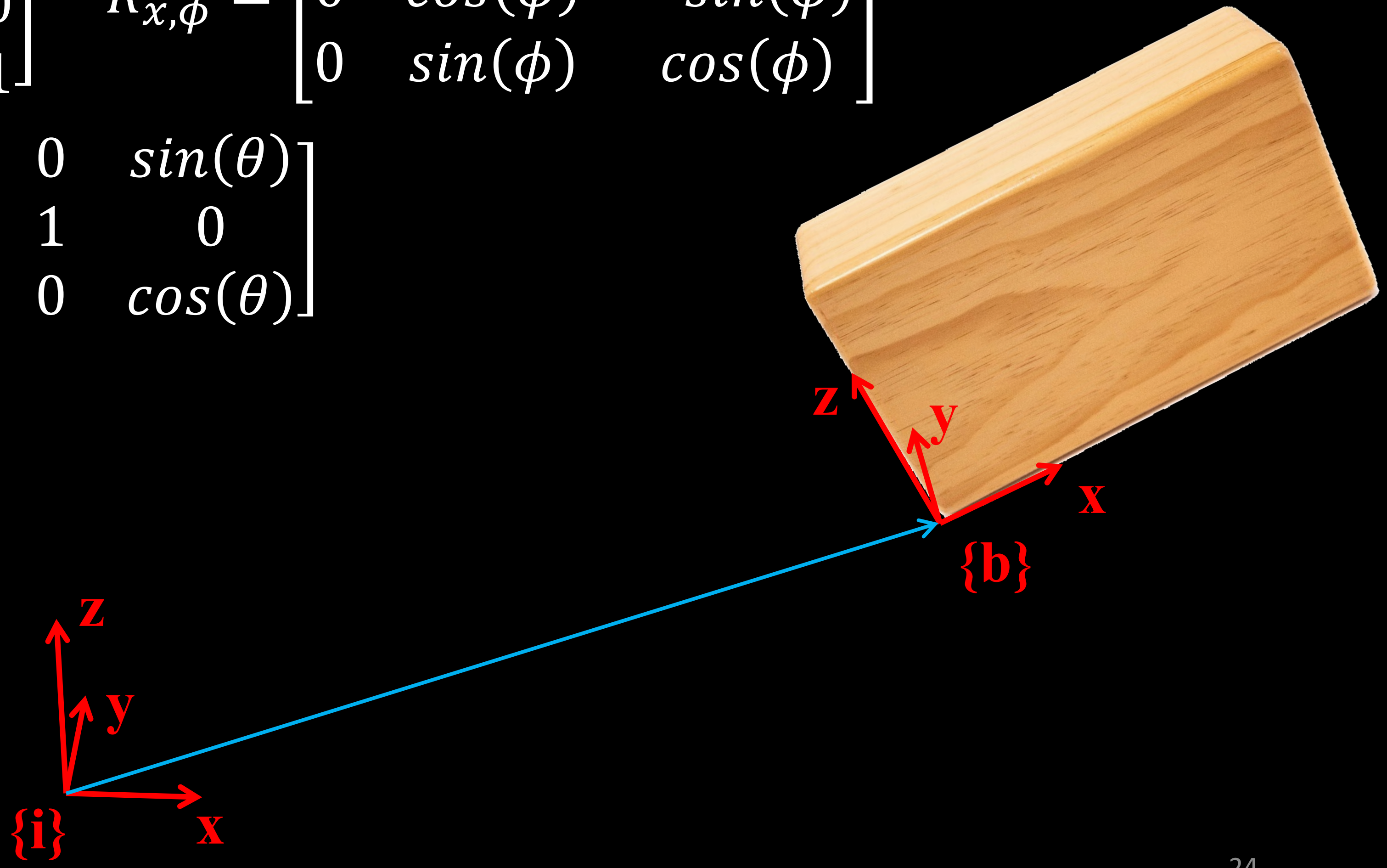
Rotation Matrix in 3D

- Find the rotation matrix $R_{z,\psi}$ for a rotation ψ about Z

$$R_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix}$$

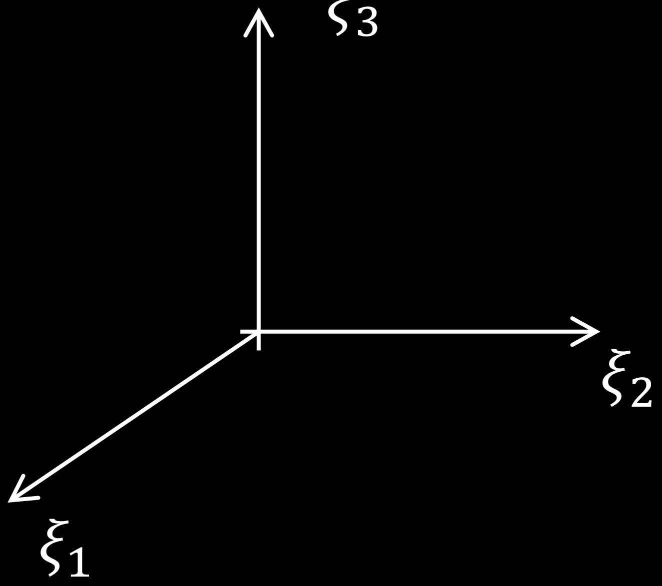
$$R_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$





Euler

- *"Any rotation can be described by three successive rotations about linearly independent axis."*
  - **Proper Euler angles**
    - *z-x-z, x-y-x, y-z-y, z-y-z, x-z-x, y-x-y*
  - **Tait–Bryan angles**
    - *x-y-z, y-z-x, z-x-y, x-z-y, z-y-x, y-x-z*
  - Most commonly z-y-z or *x-y-z*

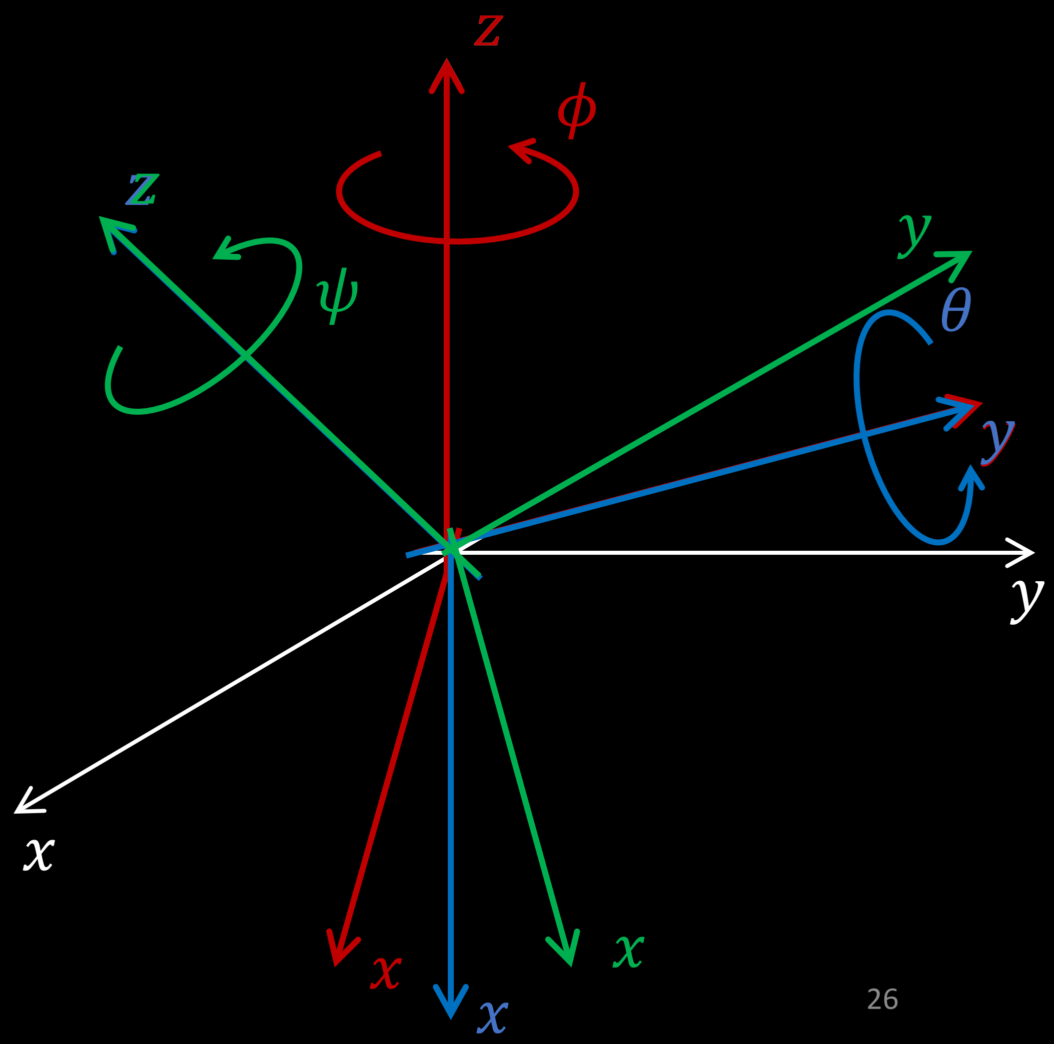


Rotation Matrix using ZYZ

$$R_{ZYZ} = R_{z,\phi} R_{y,\theta} R_{z,\psi}$$

$$= \begin{bmatrix} c_\phi & -s_\phi & 0 \\ s_\phi & c_\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} c_\psi & -s_\psi & 0 \\ s_\psi & c_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_\phi c_\theta c_\psi - s_\phi s_\psi & -c_\phi c_\theta s_\psi - s_\phi c_\psi & c_\phi s_\theta \\ s_\phi c_\theta c_\psi + c_\phi s_\psi & -s_\phi c_\theta s_\psi + c_\phi c_\psi & s_\phi s_\theta \\ -s_\phi s_\psi & s_\phi s_\psi & c_\theta \end{bmatrix}$$



Rotation Matrix using Roll-Pitch-Yaw (X-Y-Z)

$$R_{XYZ} = R_{x,\phi} R_{y,\theta} R_{z,\psi}$$

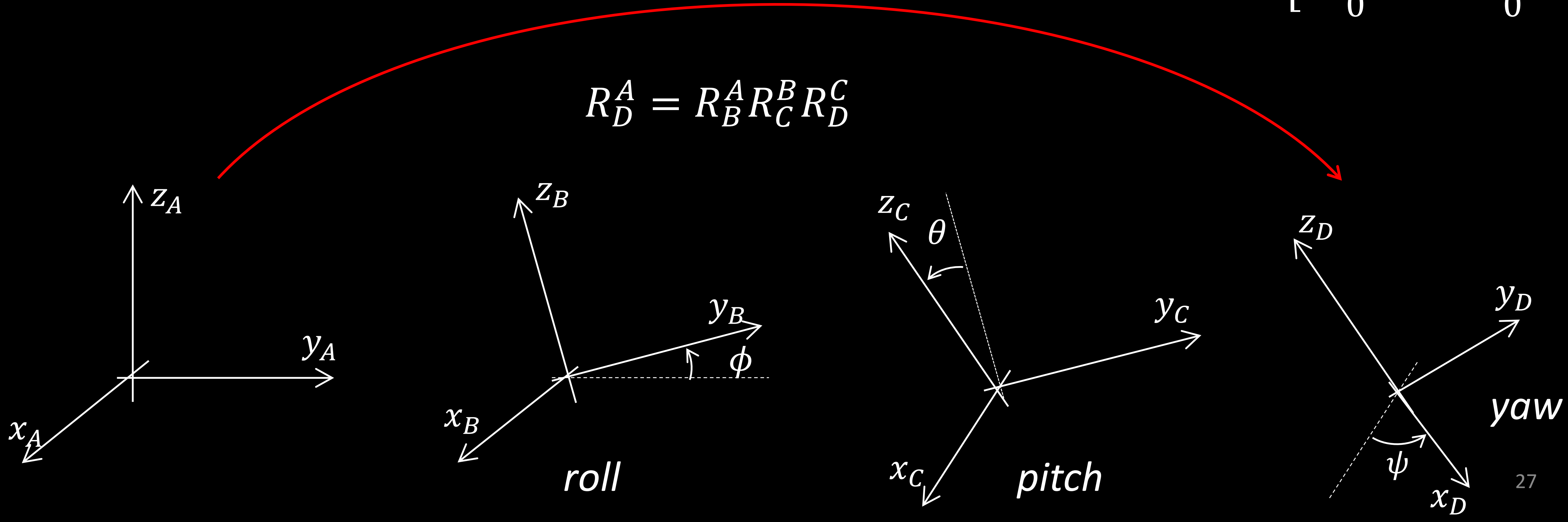
$$= \begin{bmatrix} c_\theta c_\psi & -c_\theta s_\psi & s_\theta \\ c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi - s_\phi s_\theta s_\psi & -s_\phi c_\theta \\ s_\phi s_\psi - c_\phi s_\theta c_\psi & s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{bmatrix}$$

$$R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix}$$

$$R_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$

$$R_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_D^A = R_B^A R_C^B R_D^C$$



Rotation Matrix using Roll-Pitch-Yaw (X-Y-Z)

$$R_{XYZ} = R_{x,\phi} R_{y,\theta} R_{z,\psi}$$

$$= \begin{bmatrix} c_\theta c_\psi & -c_\theta s_\psi & s_\theta \\ c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi - s_\phi s_\theta s_\psi & -s_\phi c_\theta \\ s_\phi s_\psi - c_\phi s_\theta c_\psi & s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{bmatrix}$$

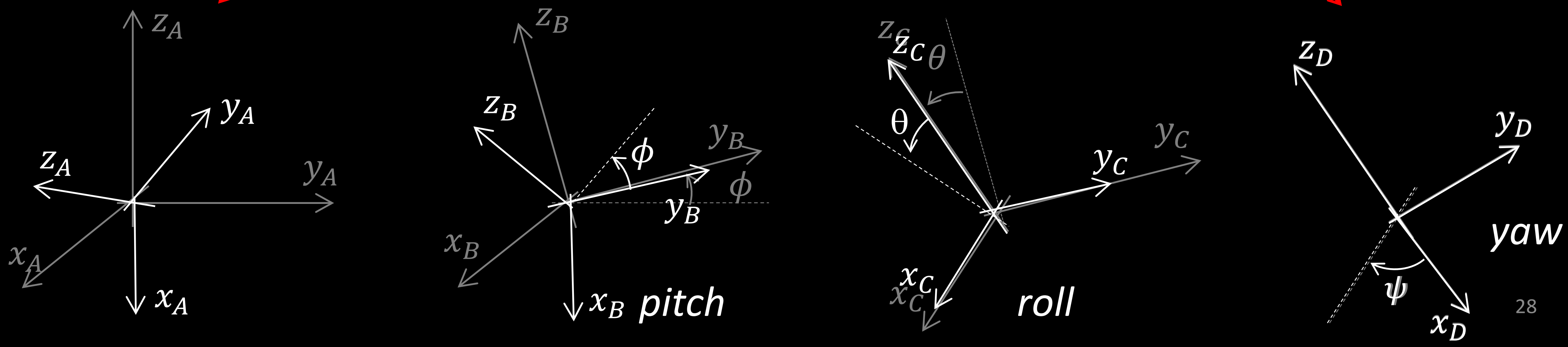
$$R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix}$$

$$R_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$

$$R_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Does the order matter? YES!

R_D^A ~~$= R_D^C R_C^B R_B^A$?~~



Rotation Matrix using Roll-Pitch-Yaw (X-Y-Z) – *How to back out angles?*

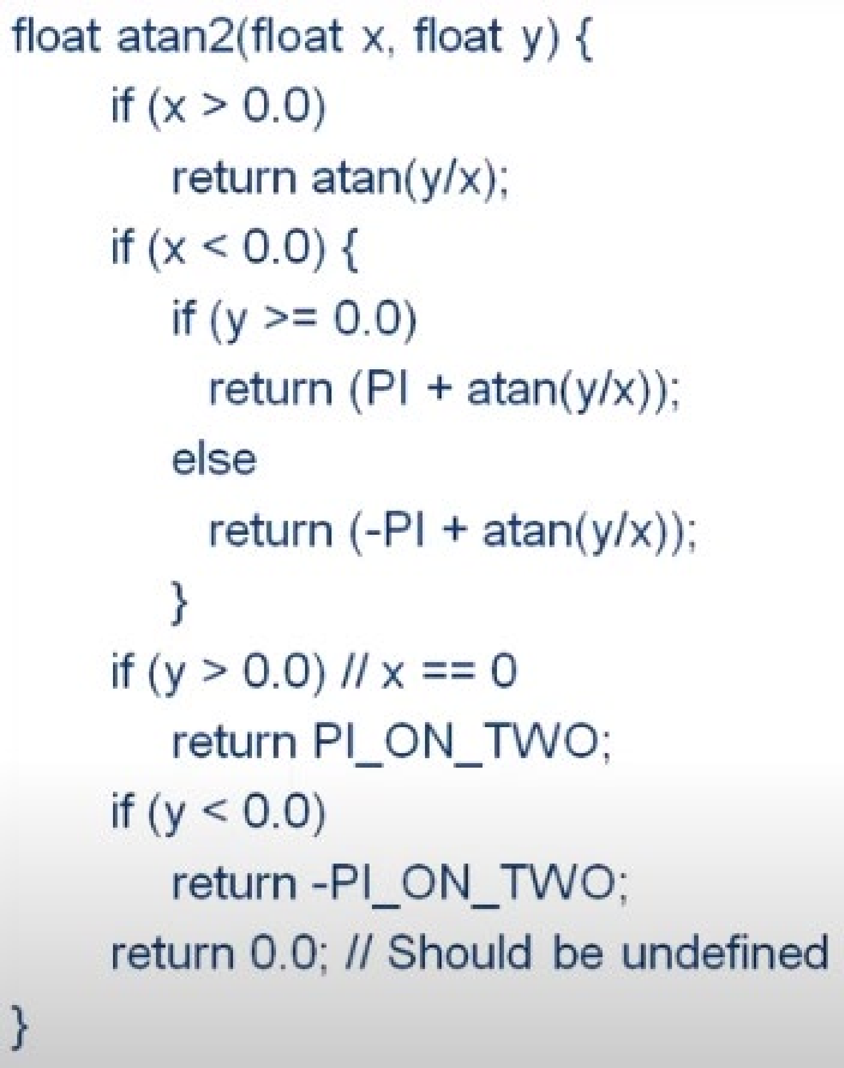
$$R_{XYZ} = R_{x,\phi} R_{y,\theta} R_{z,\psi}$$

$$= \begin{bmatrix} c_\theta c_\psi & -c_\theta s_\psi & s_\theta \\ c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi - s_\phi s_\theta s_\psi & -s_\phi c_\theta \\ s_\phi s_\psi - c_\phi s_\theta c_\psi & s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{bmatrix}$$

- But the solution to acos is not unique
- atan(x) returns [- $\pi/2, \pi/2$]
- Instead use atan2(adj,opp)* which returns [- π, π]
  - $\theta =$ asin(r_{13})
  - $\phi =$ atan2(-r_{23}, r_{33})
  - ψ = atan2(-r_{12}, r_{11})

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

- Special case if r_{13}=1 (the z' axis is parallel to the x-axis)
  - $\theta = 90^o$, ψ = atan2(r_{21}, r_{22}), $\phi = 0^o$

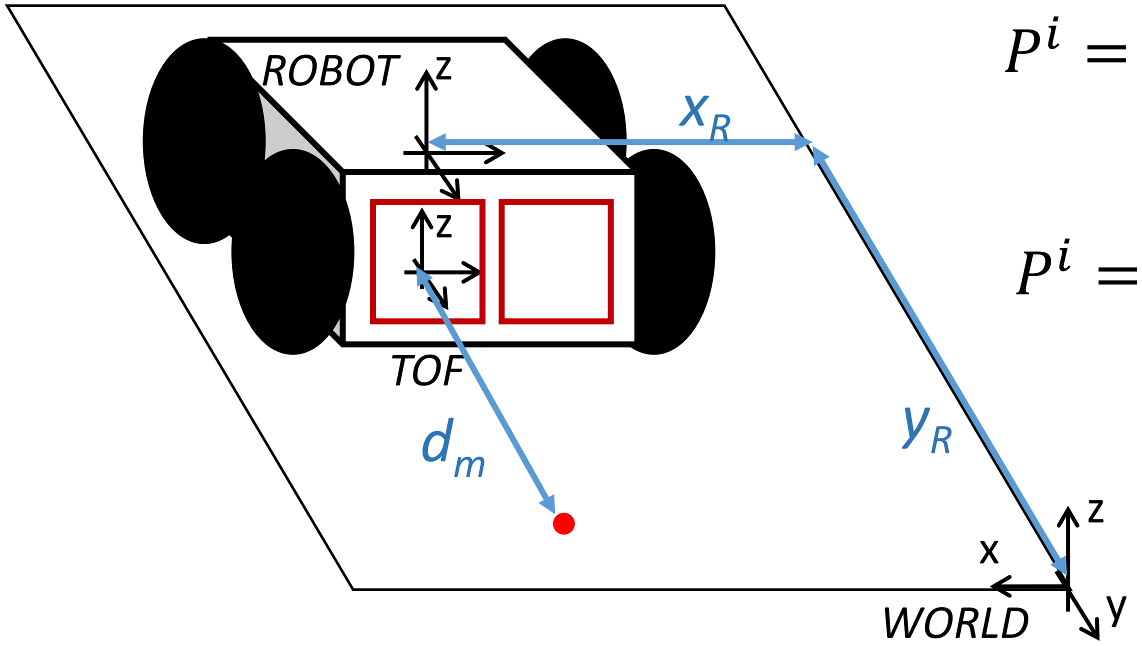


```
float atan2(float x, float y) {
    if (x > 0.0)
        return atan(y/x);
    if (x < 0.0) {
        if (y >= 0.0)
          return (PI + atan(y/x));
        else
          return (-PI + atan(y/x));
        }
    if (y > 0.0) // x == 0
        return PI_ON_TWO;
    if (y < 0.0)
        return -PI_ON_TWO;
    return 0.0; // Should be undefined
}
```

**These are not consistent across platforms!*

Homogeneous Transformation Matrix

$$T = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \left[\begin{array}{cc} \overbrace{\boxed{\begin{matrix} c_\theta c_\psi & -c_\theta s_\psi & s_\theta \\ c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi - s_\phi s_\theta s_\psi & -s_\phi c_\theta \\ s_\phi s_\psi - c_\phi s_\theta c_\psi & s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{matrix}}}^{\text{rotation}} & \overbrace{\boxed{\begin{matrix} d_x \\ d_y \\ d_z \end{matrix}}}^{\text{translation}} \\ \begin{matrix} 0 & \qquad\qquad 0 & \qquad\qquad 0 \end{matrix} & 1 \end{array} \right]$$

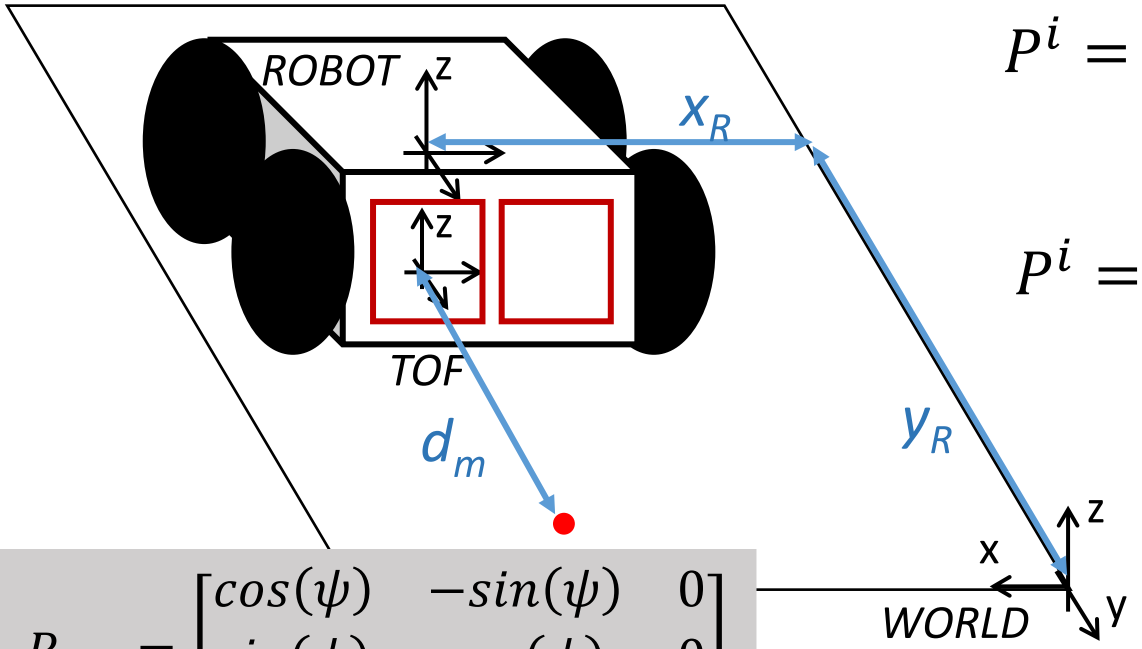


$$P^i = T_R^i T_{TOF}^R \boxed{P^{TOF}}$$

$$P^i = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} & & & \\ & & & \\ & & & \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d_m \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Homogeneous Transformation Matrix

$$T = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \overset{\text{rotation}}{\boxed{\begin{matrix} c_\theta c_\psi & -c_\theta s_\psi & s_\theta \\ c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi - s_\phi s_\theta s_\psi & -s_\phi c_\theta \\ s_\phi s_\psi - c_\phi s_\theta c_\psi & s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{matrix}}} & \overset{\text{translation}}{\boxed{\begin{matrix} d_x \\ d_y \\ d_z \end{matrix}}} \\ \begin{matrix} 0 & \qquad 0 & \qquad 0 \end{matrix} & 1 \end{bmatrix}$$



$$R_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$P^i = T_R^i T_{TOF}^R P^{TOF}$$

$$P^i = \begin{bmatrix} & & & \\ & & & \\ & & & \\ & & & \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0.08 \\ 0 & 1 & 0 & -0.015 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d_m \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

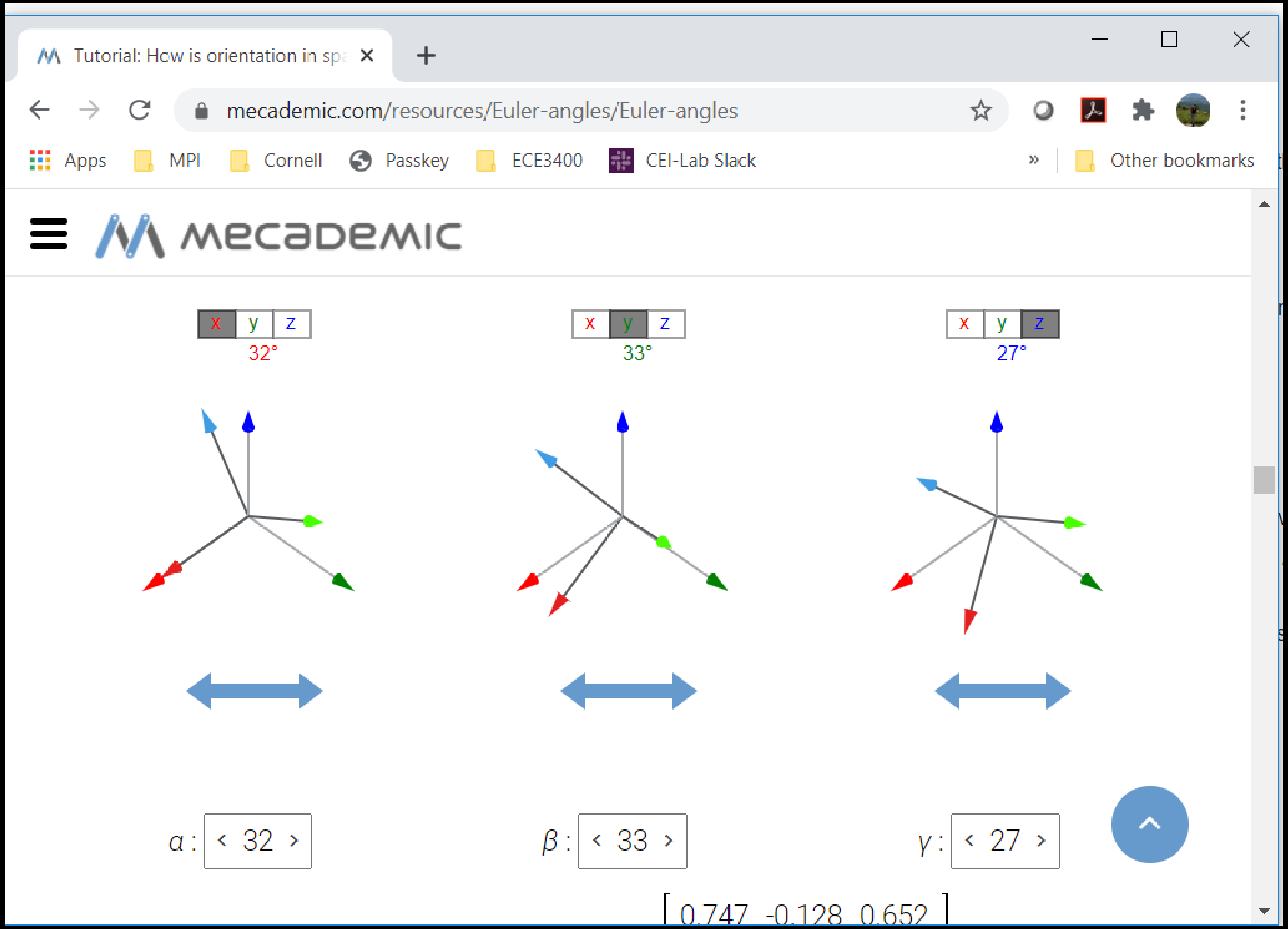
if $X_R = 1$, $y_R = 1$, $d_m = 1$:

$=[1.015 \quad 0.08 \quad 0 \quad 1]^T$

Moving Frame versus Fixed Frame Rotation

- Equivalent, BUT the order matters
- Mobile frame
  - Post-multiply
- Fixed frame
  - Pre-multiply

https://www.mecademic.com/resources/Euler-angles/Euler-angles



α : 32

β : 33

γ : 27

[0.747 -0.128 0.652]

Sources and References

- Northwestern University, course on Modern Robotics
- Upenn Coursera course on Aerial Robotics
- MilfordRobotics youtube stream
- Mecademic