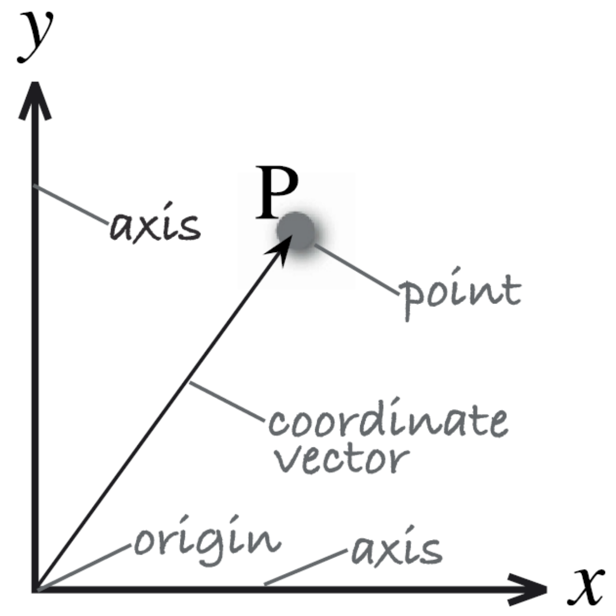
CS 3630

Pose in the Plane

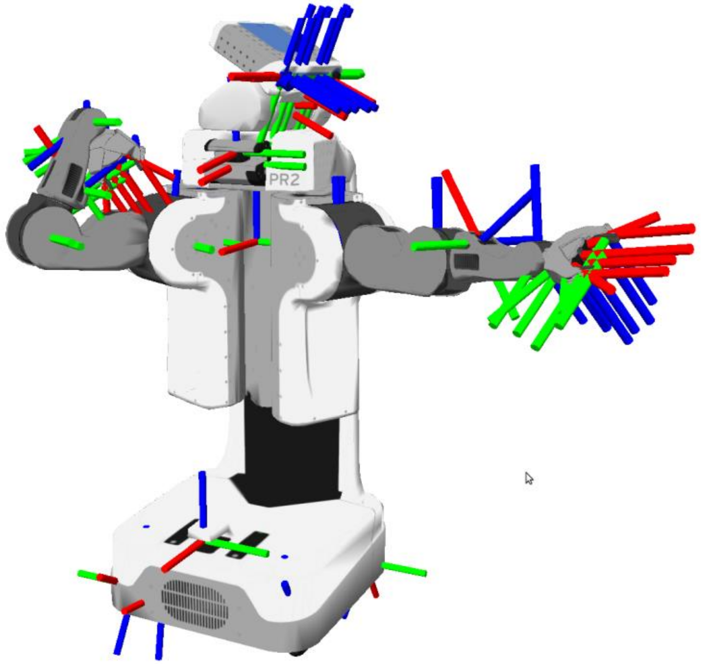
Reference Frames

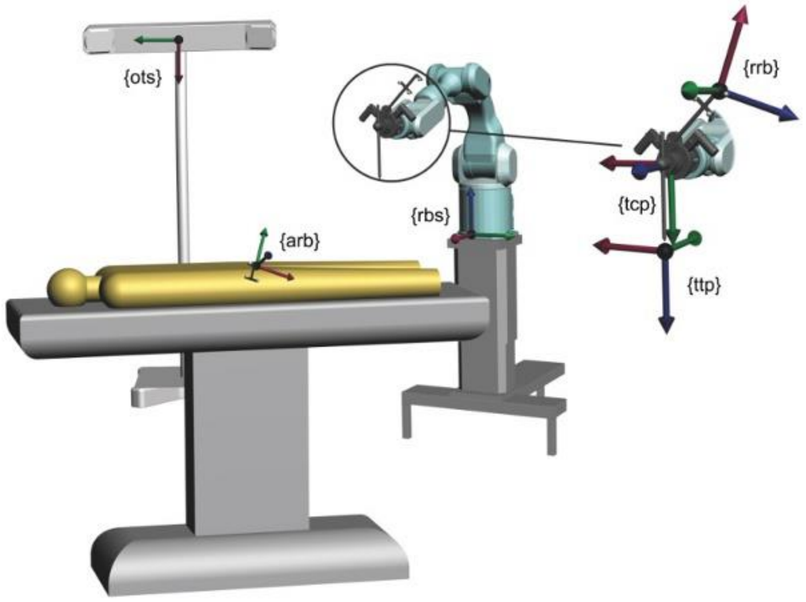
- Robotics is all about management of reference frames
  - **Perception** is about estimation of reference frames
  - **Planning** is how to move reference frames
  - **Control** is the implementation of trajectories for reference frames
- The relation between references frames is essential to a successful system

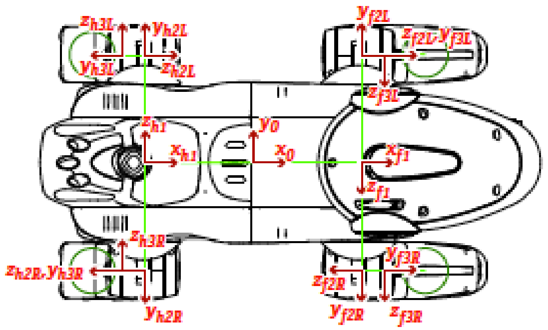


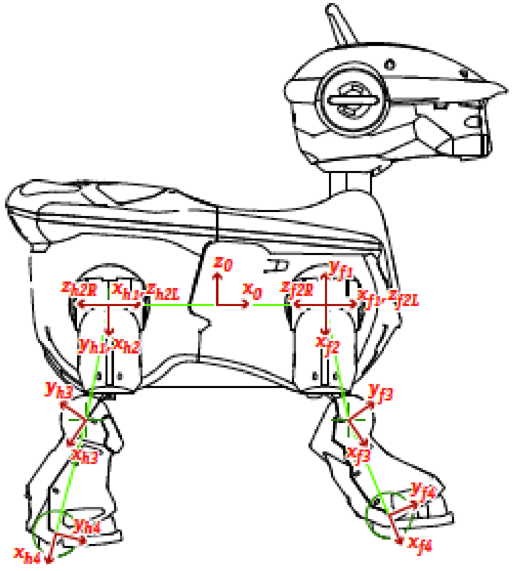
Examples of the types of reference frames we're talking about

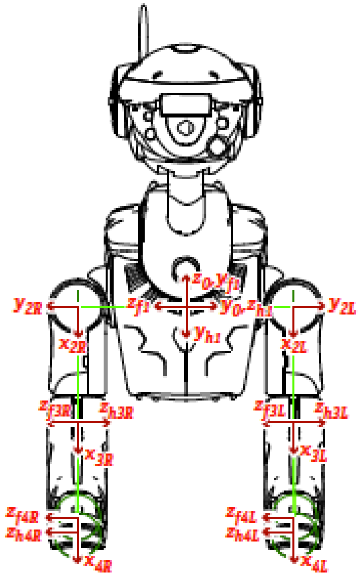
We rigidly attach coordinate frames to objects of interest. To specify the position and orientation of the object, we merely specify the position and orientation of the attached coordinate frame.

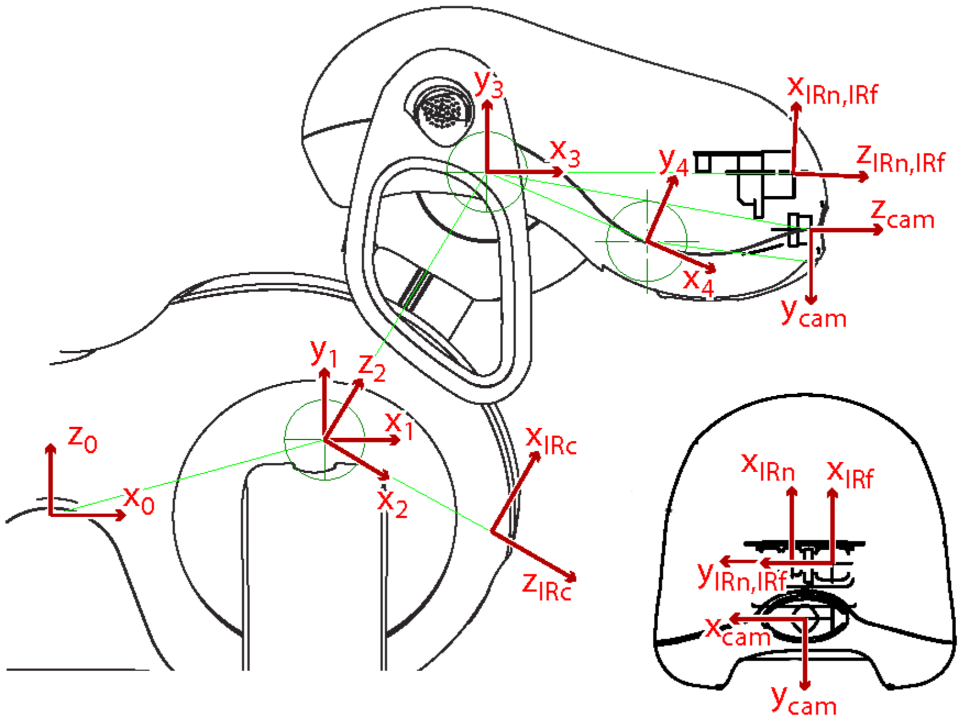










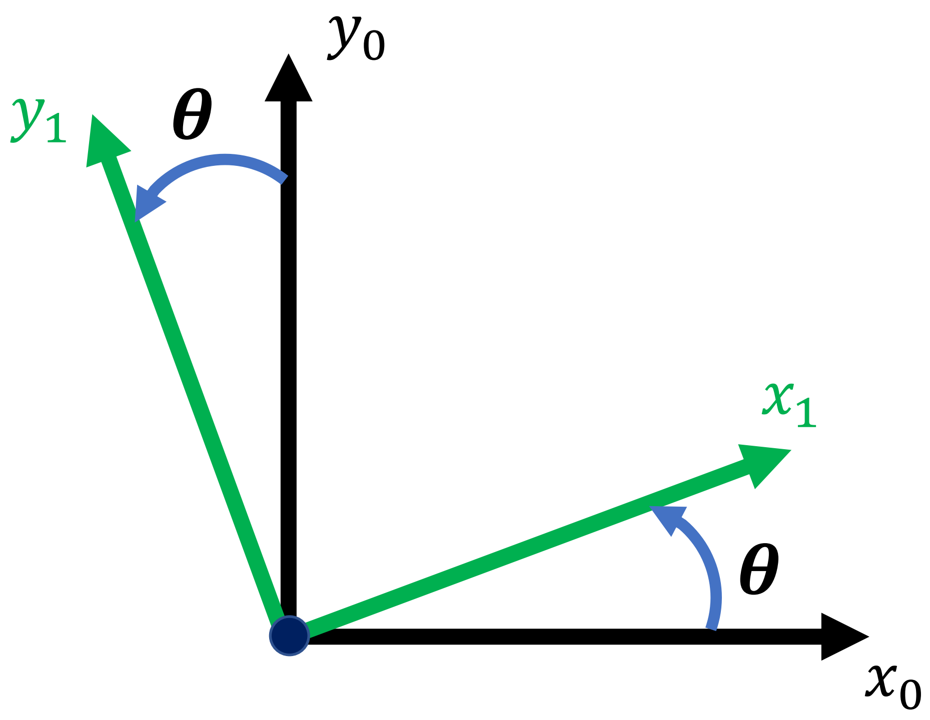


- The relationship between frames is often very simple to define, as in the case when two frames are related by the motion of a single joint/motor.
- For example the upper and lower leg of the dog robot are related by a single motor at the knee.

Today – we consider only the case of 2D reference frames, corresponding to mobile robots moving in the plane.

Specifying Orientation in the Plane

Given two coordinate frames with a common origin, how should we describe the orientation of Frame 1 w.r.t. Frame 0?



The obvious choice is to merely use the angle θ. This isn't a great idea for two reasons:

- We have problems at $\theta = 2\pi - \epsilon$. For ϵ near 0, we approach a discontinuity: for small change in ϵ, we can have a large change in θ.
- This approach does not generalize to rotations in three dimensions (and not all robots live in the plane).

Specifying Orientation in the Plane

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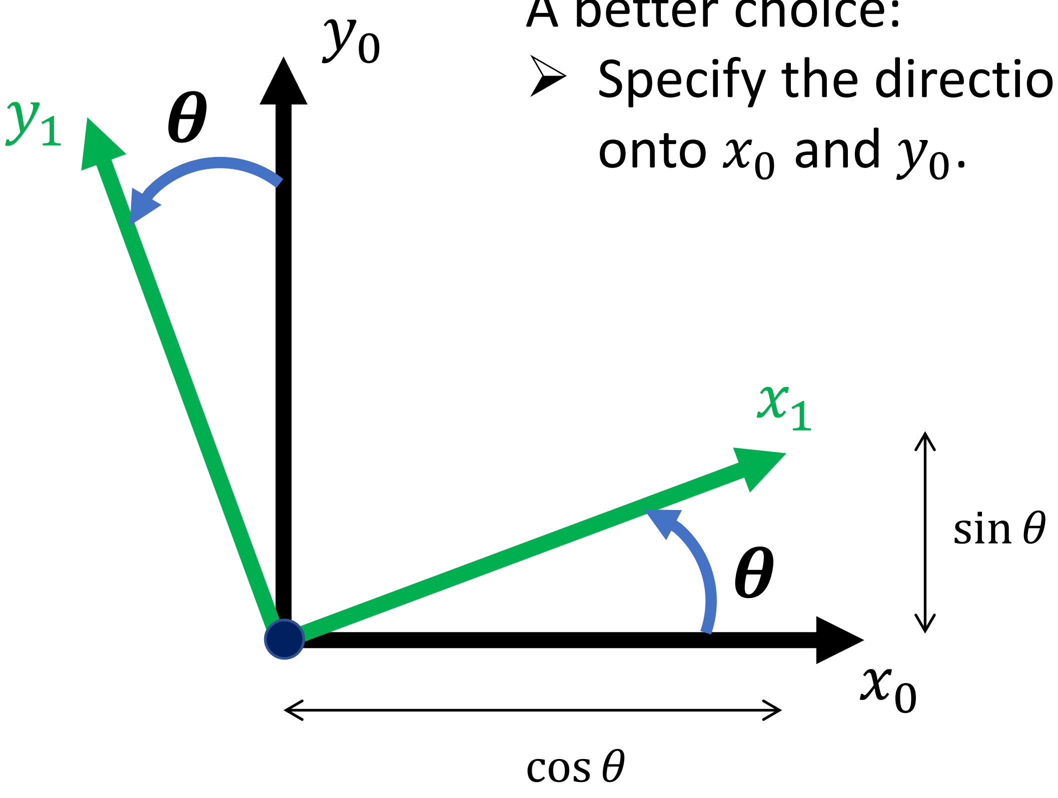


A better choice:

- Specify the directions of x_1 and y_1 with respect to Frame 0 by projecting onto x_0 and y_0.

$$x_1^0 = \begin{bmatrix} x_1 \cdot x_0 \\ x_1 \cdot y_0 \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$$

Notation: x_1^0 denotes the x-axis of Frame 1, specified w.r.t Frame 0.

$$y_1^0 = \begin{bmatrix} y_1 \cdot x_0 \\ y_1 \cdot y_0 \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

We obtain y_1^0 in the same way.

Rotation Matrices (rotation in the plane)

We combine these two vectors to obtain a ***rotation matrix***: $R_1^0 = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

All rotation matrices have certain properties:

1. The two columns are each unit vectors.
2. The two columns are orthogonal, i.e., $c_1 \cdot c_2 = 0$.
3. $\det R = +1$

For such matrices $R^{-1} = R^T$

- The first two properties imply that the matrix R is ***orthogonal***.
- The third property implies that the matrix is ***special***! (After all, there are plenty of orthogonal matrices whose determinant is -1, not at all special.)

The collection of 2×2 rotation matrices is called the ***Special Orthogonal Group of order 2***, or, more commonly $\boldsymbol{SO(2)}$.

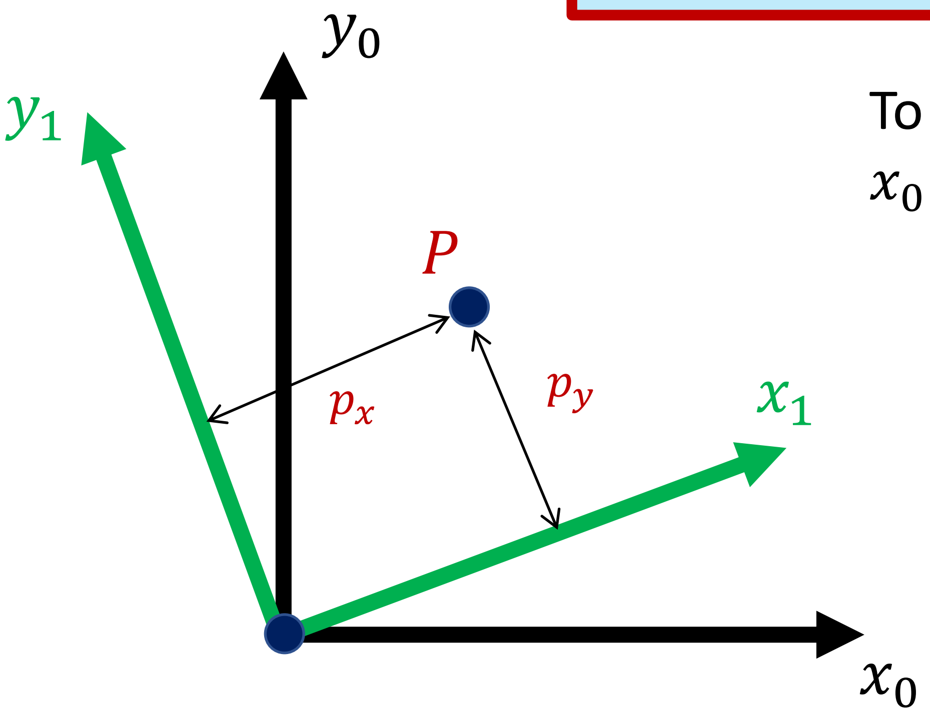
This concept generalizes to $\boldsymbol{SO(n)}$ for $n \times n$ rotation matrices.

Coordinate Transformations (rotation only)

Suppose a point P is rigidly attached to coordinate Frame 1, with coordinates given by $P^1 = \begin{bmatrix} p_x \\ p_y \end{bmatrix}$.

We can express the location of the point P in terms of its coordinates

$$P = p_x x_1 + p_y y_1$$



To obtain the coordinates of P w.r.t. Frame 0, we project P onto the x_0 and y_0 axes:

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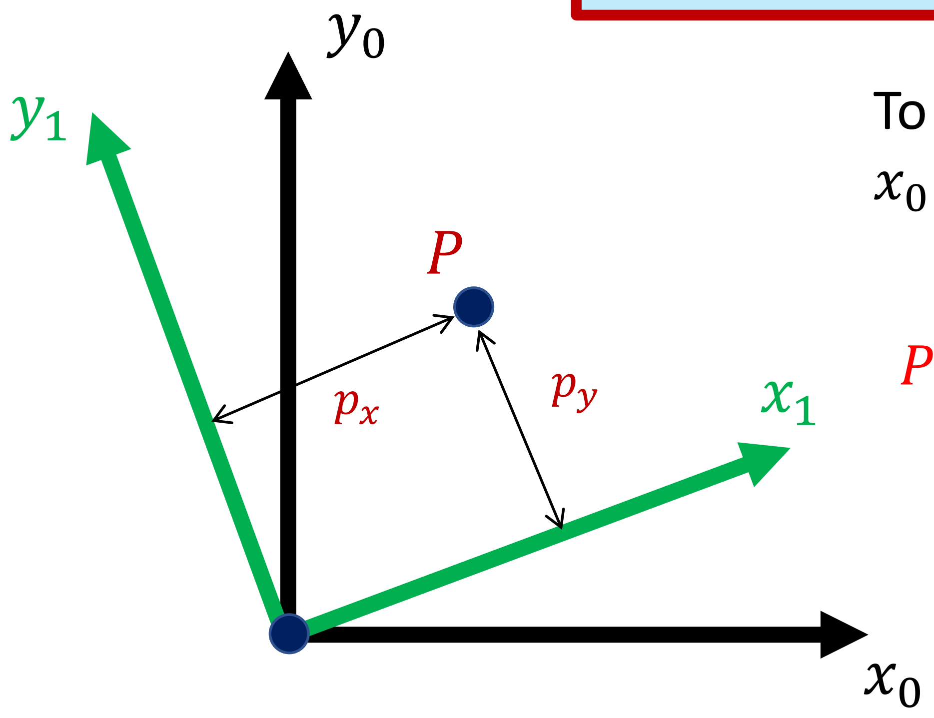

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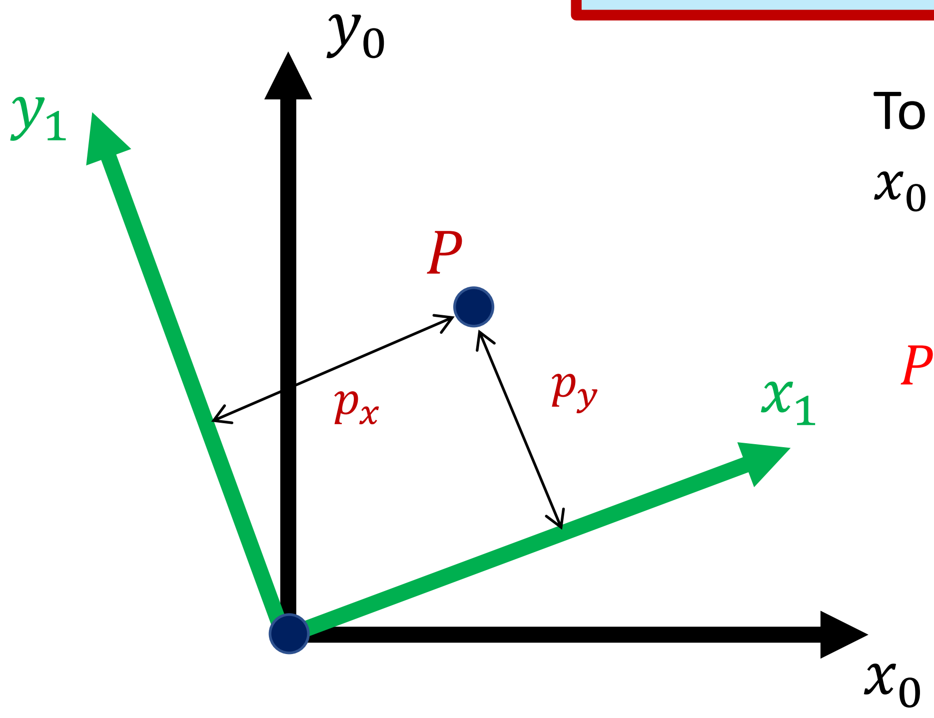

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$$P^0 = \begin{bmatrix} P \cdot x_0 \\ P \cdot y_0 \end{bmatrix} = \begin{bmatrix} (p_x x_1 + p_y y_1) \cdot x_0 \\ (p_x x_1 + p_y y_1) \cdot y_0 \end{bmatrix} =$$

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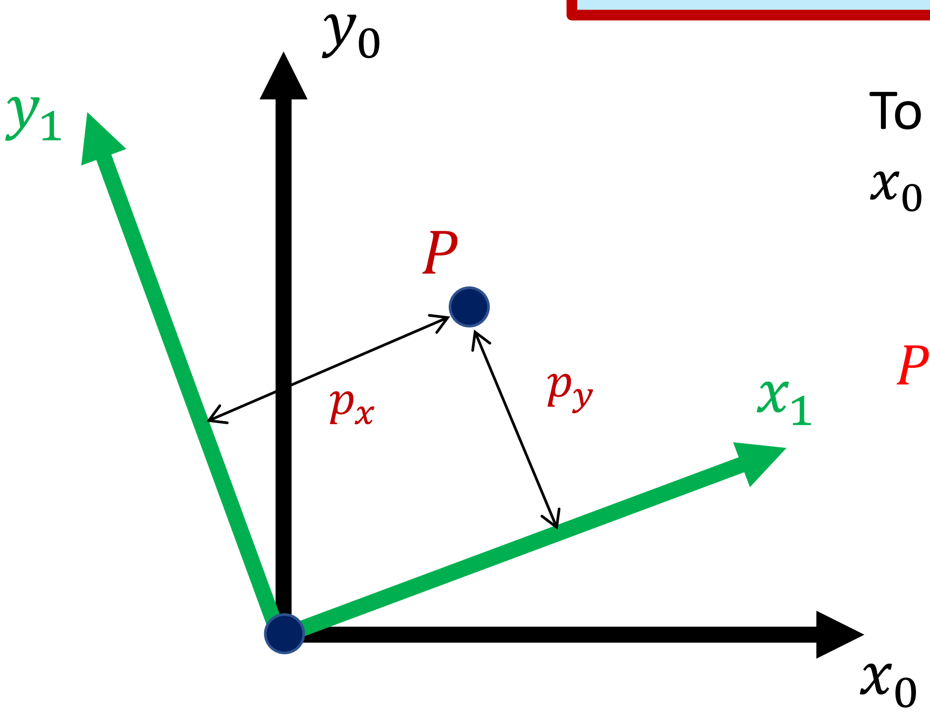

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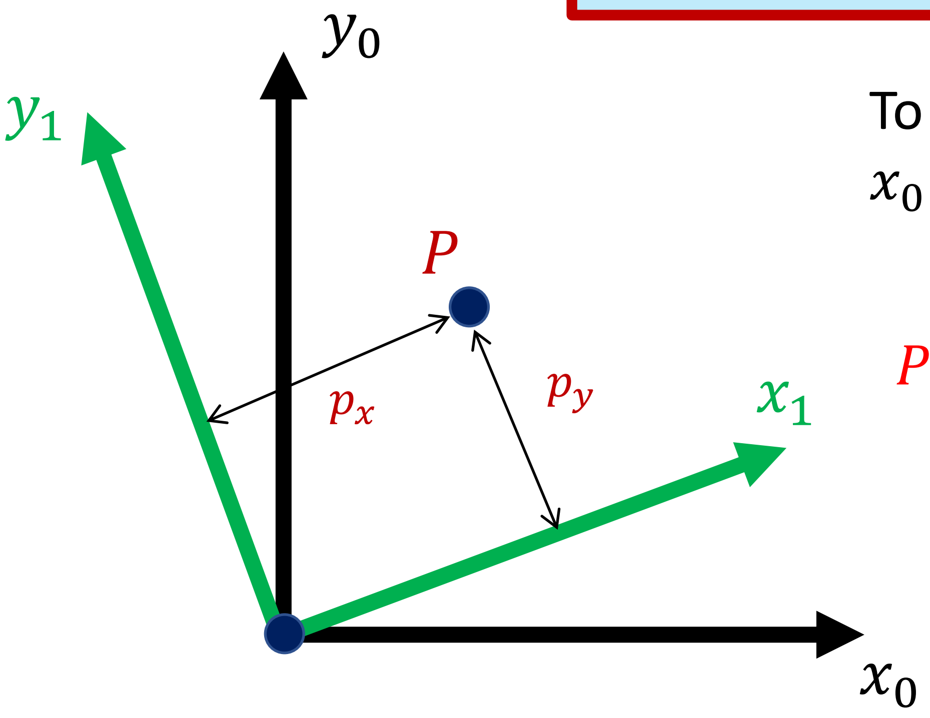

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$$= \begin{bmatrix} x_1 \cdot x_0 & y_1 \cdot x_0 \\ x_1 \cdot y_0 & y_1 \cdot y_0 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \end{bmatrix}$$

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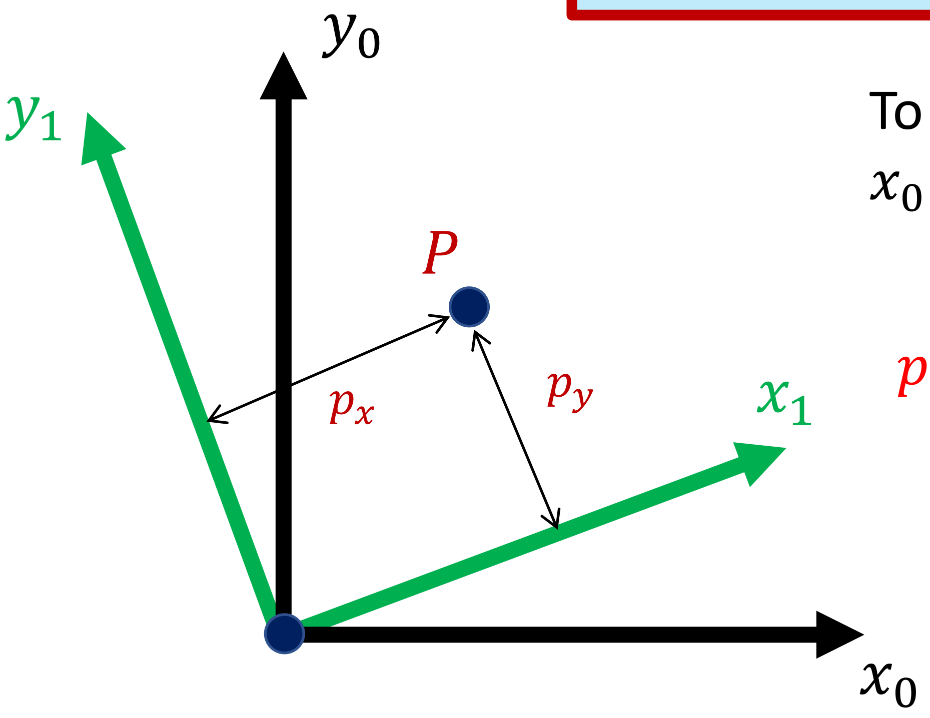

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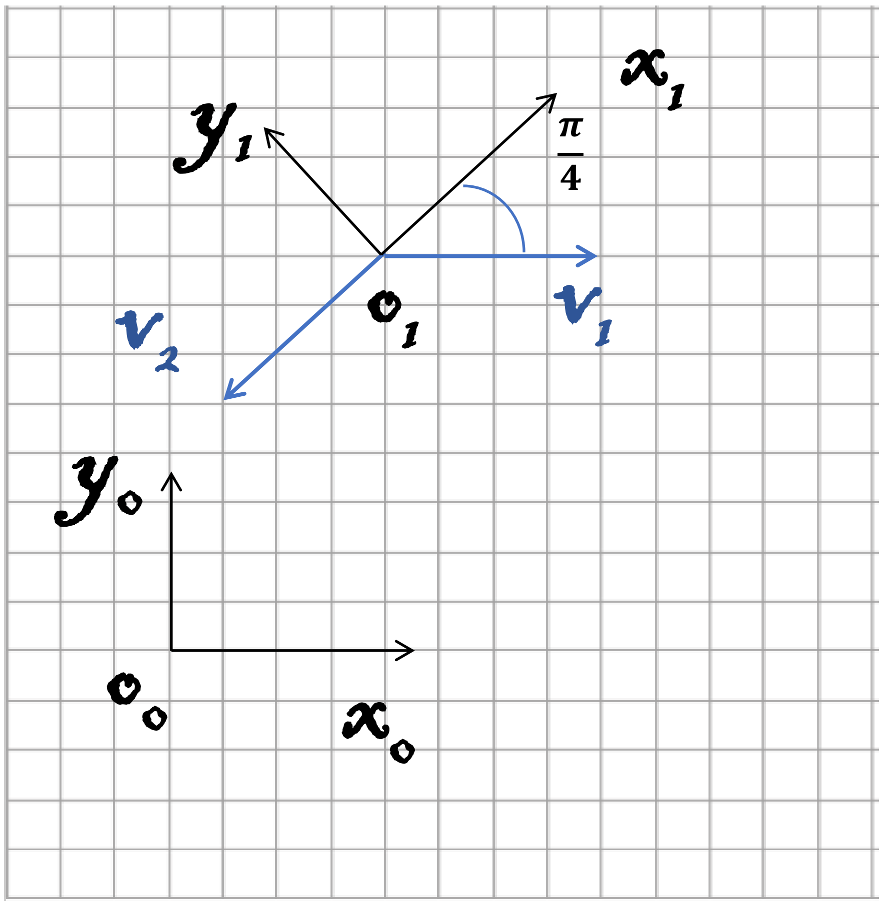
$$= \begin{bmatrix} x_1 \cdot x_0 & y_1 \cdot x_0 \\ x_1 \cdot y_0 & y_1 \cdot y_0 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \end{bmatrix} = \boldsymbol{R_1^0} \, \boldsymbol{P^1}$$

$$\boldsymbol{P^0} = \boldsymbol{R_1^0} \, \boldsymbol{P^1}$$

Lets practice…



- Two coordinate frames: o_0 and o_1
- Two free vectors: v_1 and v_2

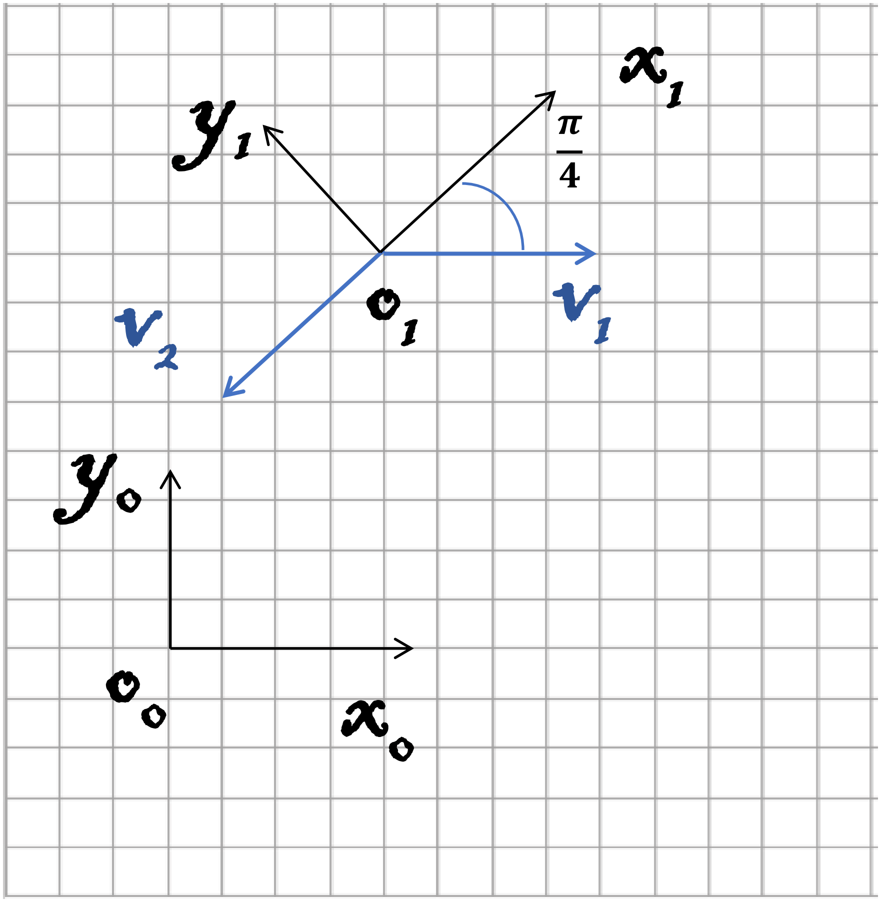
$v_1^0 = [\quad]$ $v_1^1 = [\quad]$

$v_2^0 = [\quad]$ $v_2^1 = [\quad]$

Recall: $\cos\frac{\pi}{4} = 0.5\sqrt{2}$, $\sin\frac{\pi}{4} = 0.5\sqrt{2}$

Lets practice...

Note: $\|v_1\| = 4,\ \|v_2\| = 3\sqrt{2},$



- Two coordinate frames: o_0 and o_1
- Two free vectors: v_1 and v_2

$$v_1^0 = \begin{bmatrix} 4 \\ 0 \end{bmatrix} \qquad v_1^1 = \begin{bmatrix} 2\sqrt{2} \\ -2\sqrt{2} \end{bmatrix}$$

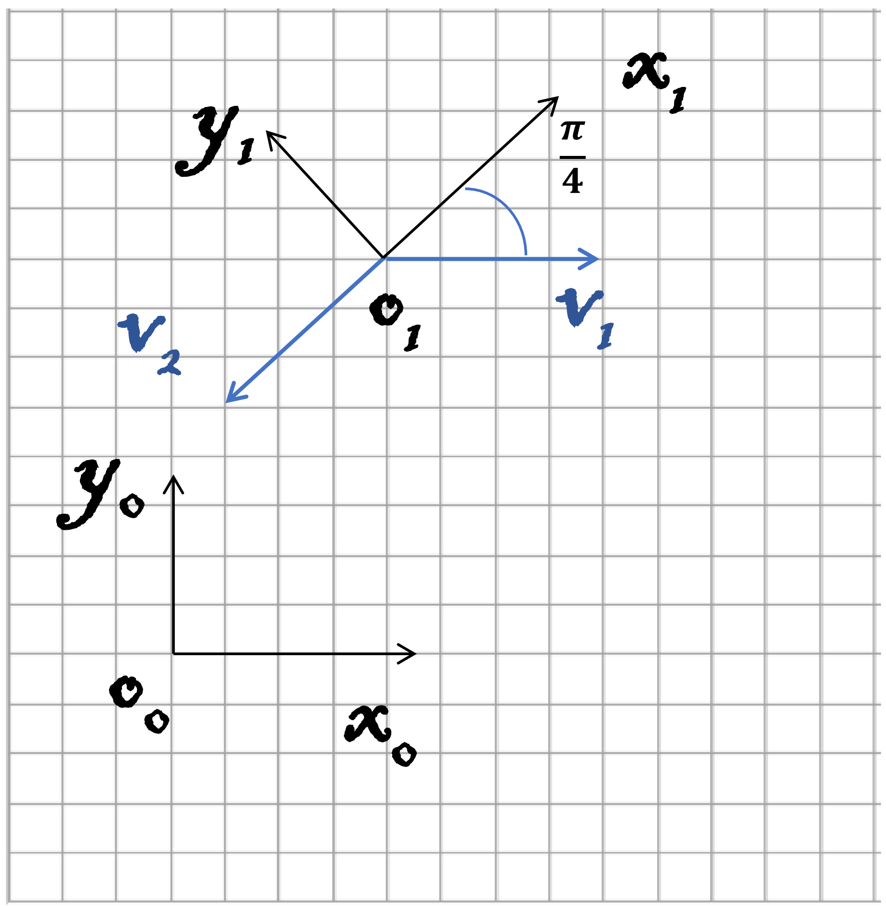
$$v_2^0 = \begin{bmatrix} -3 \\ -3 \end{bmatrix} \qquad v_2^1 = \begin{bmatrix} -3\sqrt{2} \\ 0 \end{bmatrix}$$

Recall: $\cos\frac{\pi}{4} = 0.5\sqrt{2}, \qquad \sin\frac{\pi}{4} = 0.5\sqrt{2}$

We can do this with simple geometry.

More Practice…

$$v_1^0 = \begin{bmatrix} 4 \\ 0 \end{bmatrix} \quad v_2^0 = \begin{bmatrix} -3 \\ -3 \end{bmatrix} \quad v_1^1 = \begin{bmatrix} 2\sqrt{2} \\ -2\sqrt{2} \end{bmatrix} \quad v_2^1 = \begin{bmatrix} -3\sqrt{2} \\ 0 \end{bmatrix}$$



$$R_1^0 = \begin{bmatrix} 0.5\sqrt{2} & -0.5\sqrt{2} \\ 0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix} \qquad R_0^1 = \begin{bmatrix} 0.5\sqrt{2} & 0.5\sqrt{2} \\ -0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix}$$

$$v_1^0 = R_1^0 v_1^1 = \begin{bmatrix} 0.5\sqrt{2} & -0.5\sqrt{2} \\ 0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix} \begin{bmatrix} 2\sqrt{2} \\ -2\sqrt{2} \end{bmatrix} = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$

$$v_2^0 = R_1^0 v_2^1 = \begin{bmatrix} 0.5\sqrt{2} & -0.5\sqrt{2} \\ 0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix} \begin{bmatrix} -3\sqrt{2} \\ 0 \end{bmatrix} = \begin{bmatrix} -3 \\ -3 \end{bmatrix}$$

$$v_1^1 = R_0^1 v_1^0 = \begin{bmatrix} 0.5\sqrt{2} & 0.5\sqrt{2} \\ -0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix} \begin{bmatrix} 4 \\ 0 \end{bmatrix} = \begin{bmatrix} 2\sqrt{2} \\ -2\sqrt{2} \end{bmatrix}$$

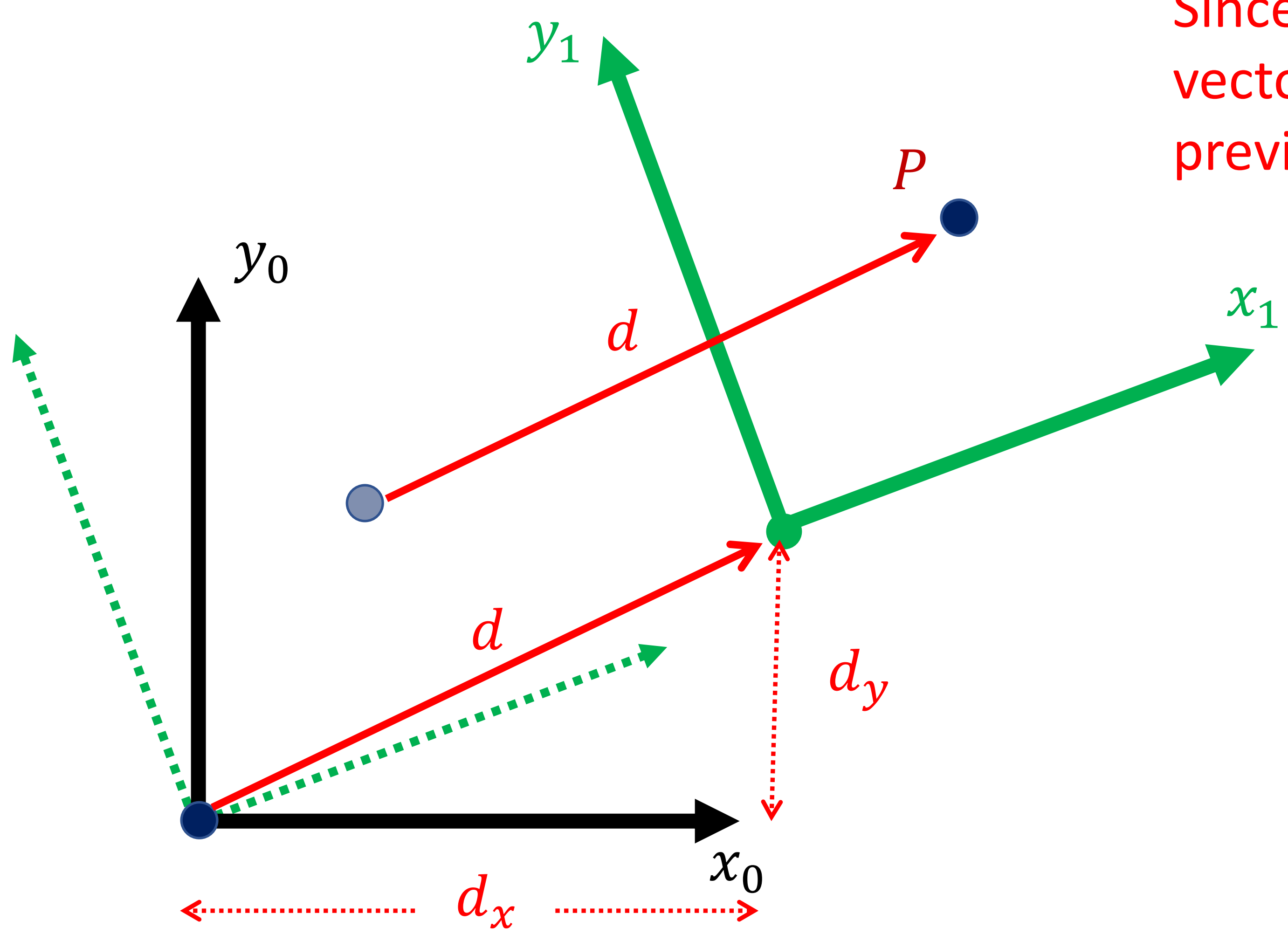
$$v_2^1 = R_0^1 v_2^0 = \begin{bmatrix} 0.5\sqrt{2} & 0.5\sqrt{2} \\ -0.5\sqrt{2} & 0.5\sqrt{2} \end{bmatrix} \begin{bmatrix} -3 \\ -3 \end{bmatrix} = \begin{bmatrix} -3\sqrt{2} \\ 0 \end{bmatrix}$$

OR, we can use coordinate transformations!

Specifying Pose in the Plane

Suppose we now translate Frame 1 (*no new rotatation*).
What are the coordinates of P w.r.t. Frame 0?

Since we merely translated P by a fixed vector d, simply add the offset to our previous result!



$$\boldsymbol{P}^0 = \boldsymbol{R}_1^0\, \boldsymbol{P}^1 + \boldsymbol{d}^0$$

$$\boldsymbol{d}^0 = \begin{bmatrix} \boldsymbol{d}_x \\ \boldsymbol{d}_y \end{bmatrix}$$

Homogeneous Transformations

We can simplify the equation for coordinate transformations by augmenting the vectors and matrices with an extra row:

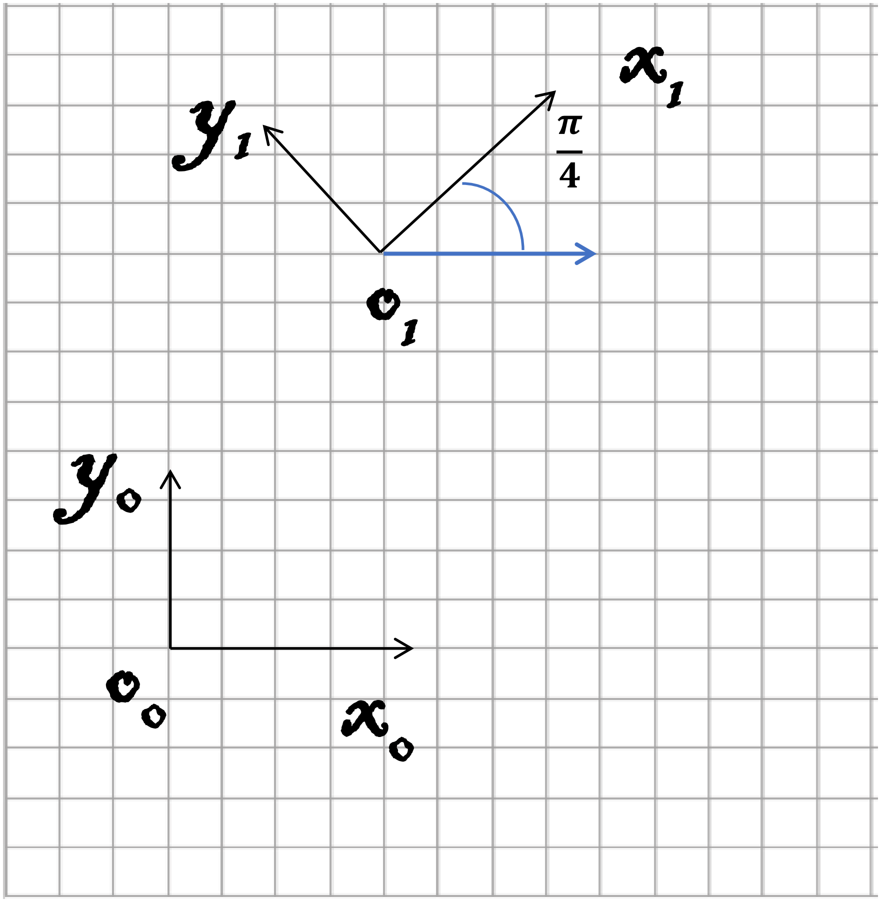
This is just our eqn from the previous page

$$\begin{bmatrix} \boldsymbol{P}^0 \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}_1^0 \boldsymbol{P}^1 + \boldsymbol{d}^0 \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}_1^0 & \boldsymbol{d}^0 \\ 0_2 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{P}^1 \\ 1 \end{bmatrix}$$

in which $0_2 = [0 \quad 0]$

The set of matrices of the form $\begin{bmatrix} R & d \\ 0_n & 1 \end{bmatrix}$, where $R \in SO(n)$ and $d \in \mathbb{R}^n$ is called the ***Special Euclidean Group of order n***, or $SE(n)$.

Lets practice…

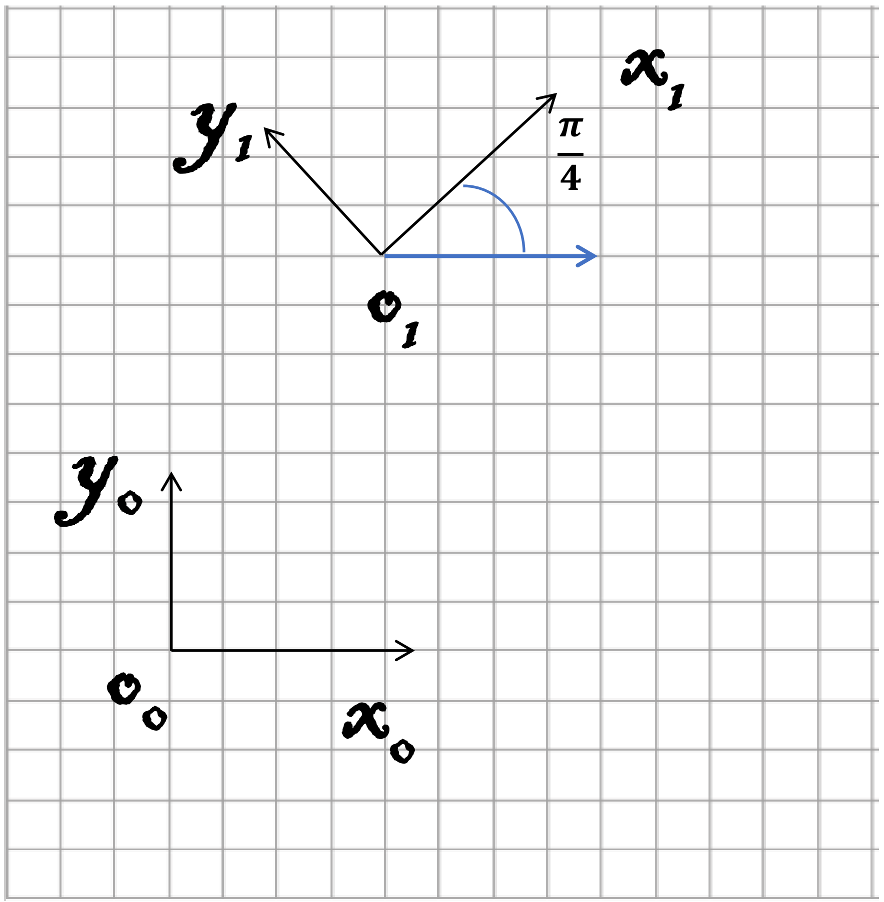


$$T_1^0 = \begin{bmatrix} & & \end{bmatrix}$$

$$T_0^1 = \begin{bmatrix} & & \end{bmatrix}$$

Recall: $\cos\frac{\pi}{4} = 0.5\sqrt{2}$, $\sin\frac{\pi}{4} = 0.5\sqrt{2}$

Lets practice…



$$T_1^0 = \begin{bmatrix} 0.5\sqrt{2} & -0.5\sqrt{2} & 4 \\ 0.5\sqrt{2} & 0.5\sqrt{2} & 8 \\ 0 & 0 & 1 \end{bmatrix}$$

$$T_0^1 = \begin{bmatrix} 0.5\sqrt{2} & 0.5\sqrt{2} & -6\sqrt{2} \\ -0.5\sqrt{2} & 0.5\sqrt{2} & -2\sqrt{2} \\ 0 & 0 & 1 \end{bmatrix}$$

Recall: $\cos\frac{\pi}{4} = 0.5\sqrt{2}$, $\sin\frac{\pi}{4} = 0.5\sqrt{2}$

Inverse of a Homogeneous Transformation

What is the relationship between T_1^0 and T_0^1?

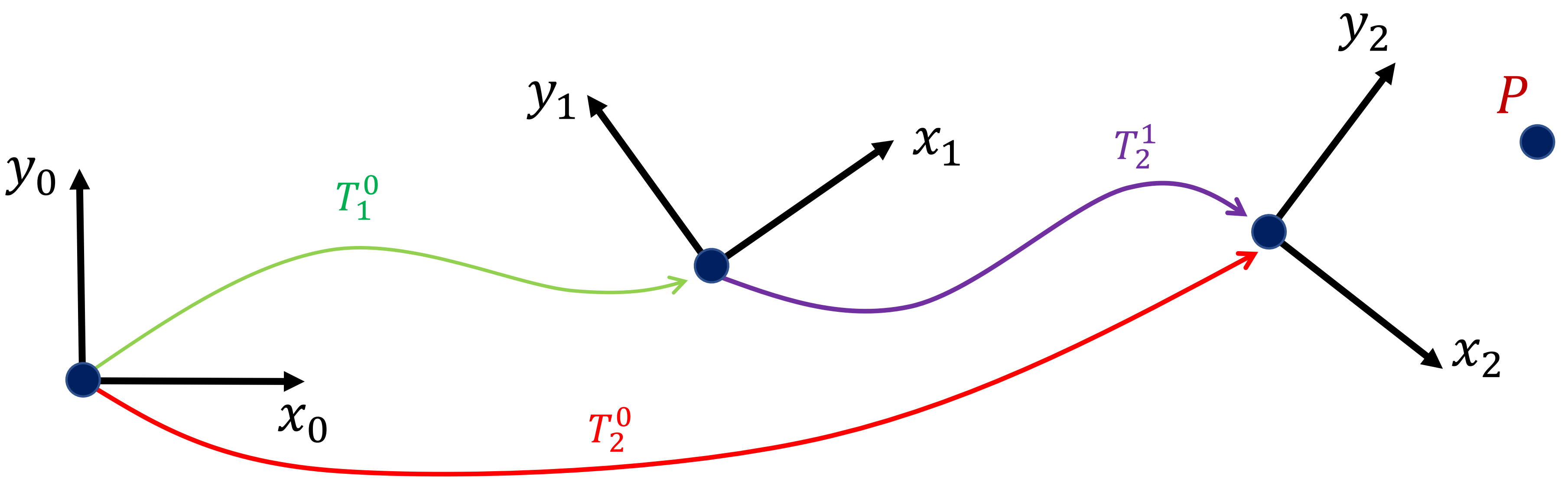
$$T_1^0 T_0^1 = \begin{bmatrix} 0.5\sqrt{2} & -0.5\sqrt{2} & 4 \\ 0.5\sqrt{2} & 0.5\sqrt{2} & 8 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0.5\sqrt{2} & 0.5\sqrt{2} & -6\sqrt{2} \\ -0.5\sqrt{2} & 0.5\sqrt{2} & -2\sqrt{2} \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In general, $T_k^j = \left(T_j^k\right)^{-1}$ and $\begin{bmatrix} \boldsymbol{R} & \boldsymbol{d} \\ 0_n & 1 \end{bmatrix}^{-1} = \begin{bmatrix} \boldsymbol{R}^{\boldsymbol{T}} & -\boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{d} \\ 0_n & 1 \end{bmatrix}$

This is easy to verify:

$$\begin{bmatrix} \boldsymbol{R} & \boldsymbol{d} \\ 0_n & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{R}^{\boldsymbol{T}} & -\boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{d} \\ 0_n & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}\boldsymbol{R}^{\boldsymbol{T}} & -\boldsymbol{R}\boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{d} + \boldsymbol{d} \\ 0_n & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_{n\times n} & \boldsymbol{0}_n \\ 0_n & 1 \end{bmatrix} = I_{(n+1)\times(n+1)}$$

Composition of Transformations



From our previous results, we know:

$$P^0 = T_1^0 P^1$$
$$P^1 = T_2^1 P^2$$

$\Rightarrow$ $P^0 = T_1^0 T_2^1 P^2$

But we also know: $P^0 = T_2^0 P^2$

$\Rightarrow$ $T_2^0 = T_1^0 T_2^1$

This is the composition law for homogeneous transformations.

CS 3630

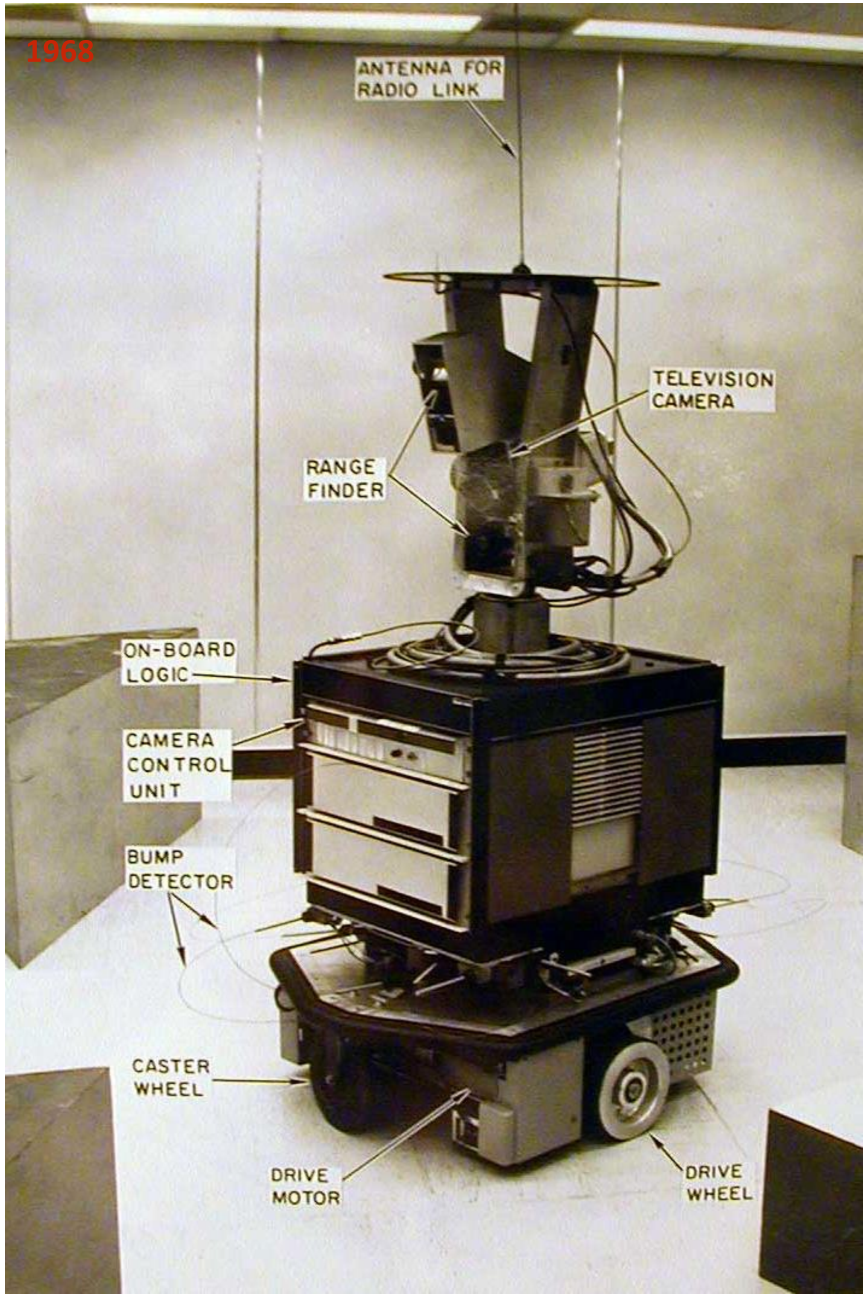
Differential Drive Robots

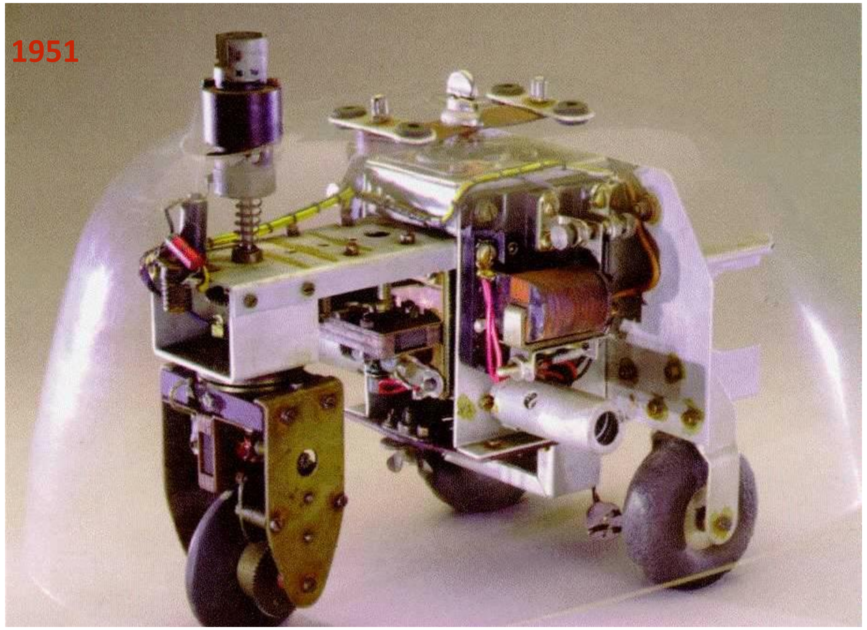
Mobile Robots

- There are many kinds of wheeled mobile robots.
- In this class, we primarily study *differential drive robots.*
- The Duckiebot is a differential drive robot.

Mobile Robot Kinematics

- Relationship between input commands (e.g., wheel velocity) and pose of the robot, not considering forces. *If the wheels turn at a certain rate, what is the resulting robot motion?*
- No direct way to measure pose (unless we sensorize the environment), but we can integrate velocity (odometry) to obtain a good estimate.





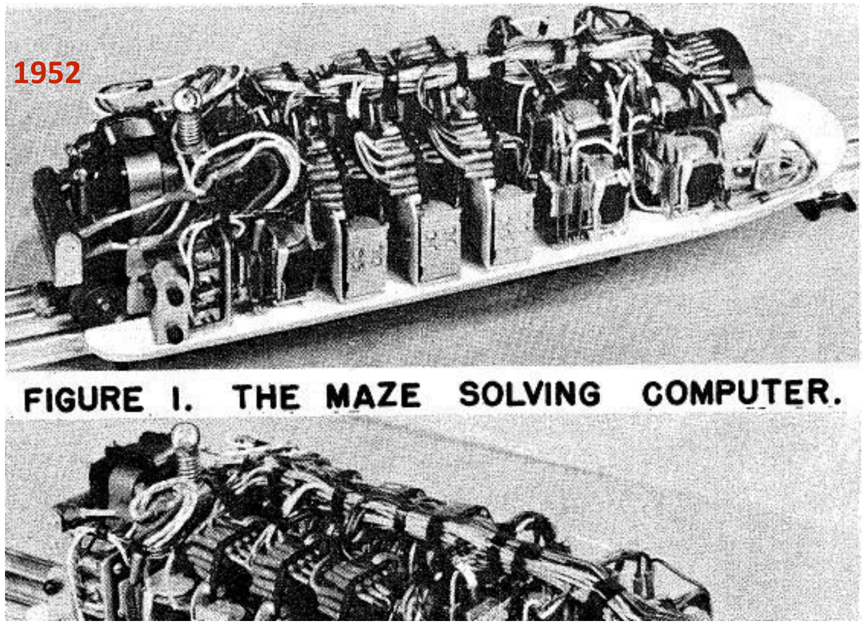
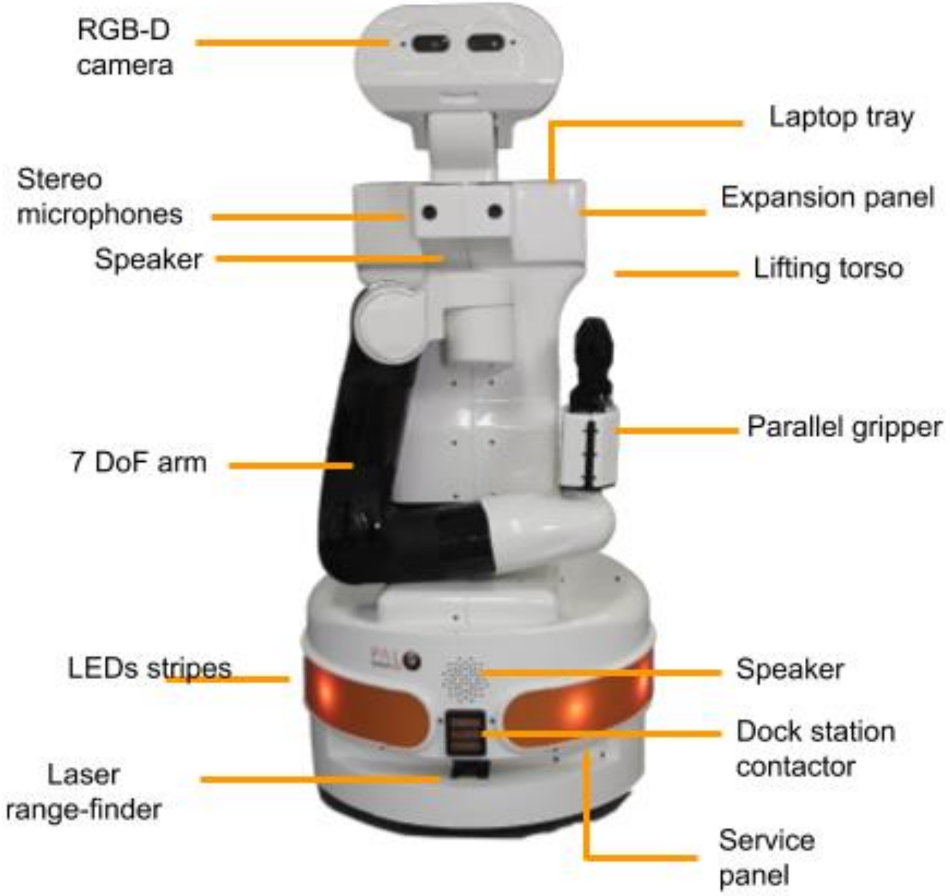
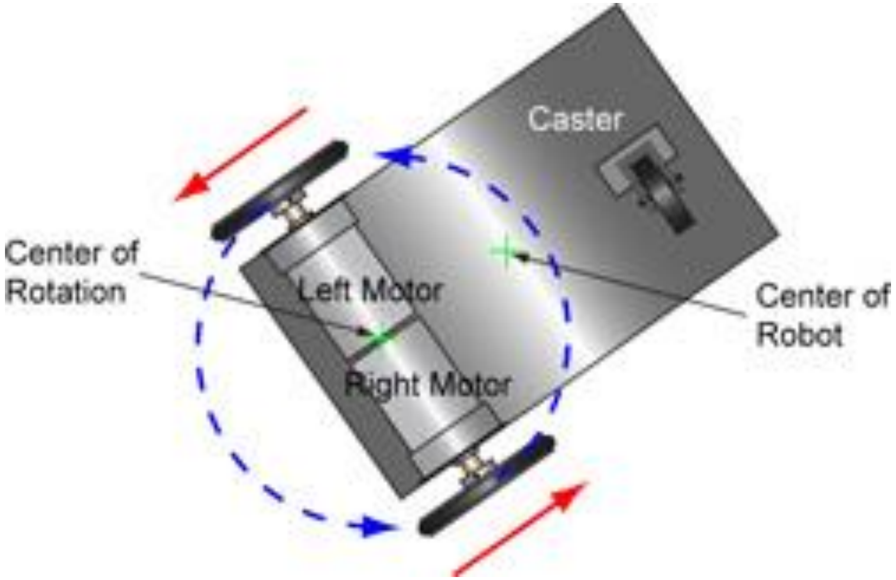


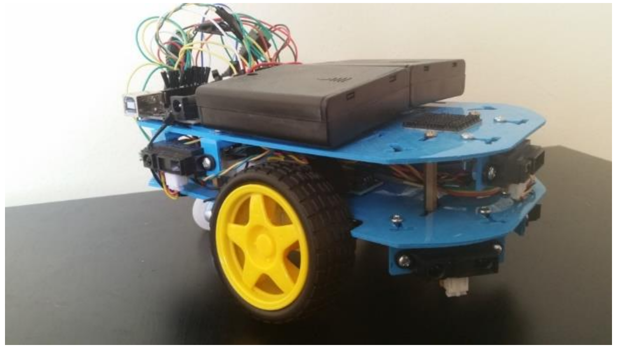
FIGURE I. THE MAZE SOLVING COMPUTER.

More Modern AGVs

Differential Drive Robots

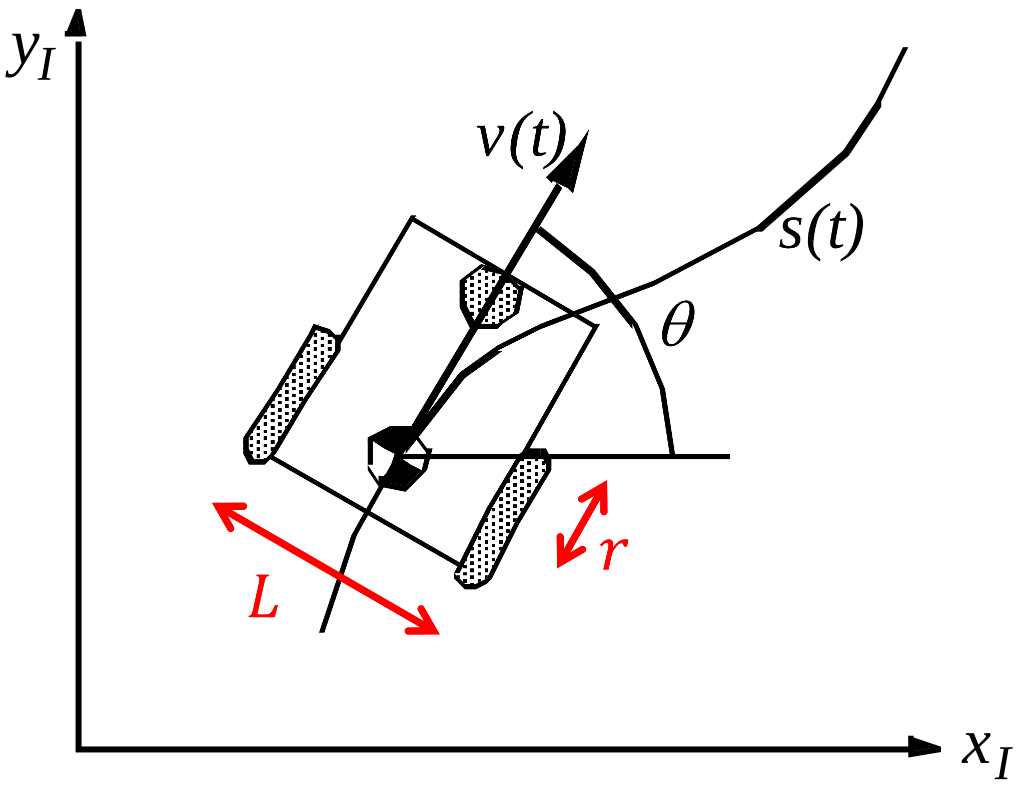






Two wheels with a common axis, and that can spin independently

Differential Drive Robots



The configuration of the robot can be specified by

$$q = (x, y, \theta)$$

At any moment in time, the instantaneous velocity of the robot is given by

$$v(t) = \begin{bmatrix} v_x \\ v_y \end{bmatrix}, \qquad \dot{\theta} = \omega$$

This robot cannot move instantaneously in the direction perpendicular to the forward velocity: $v_y = 0$

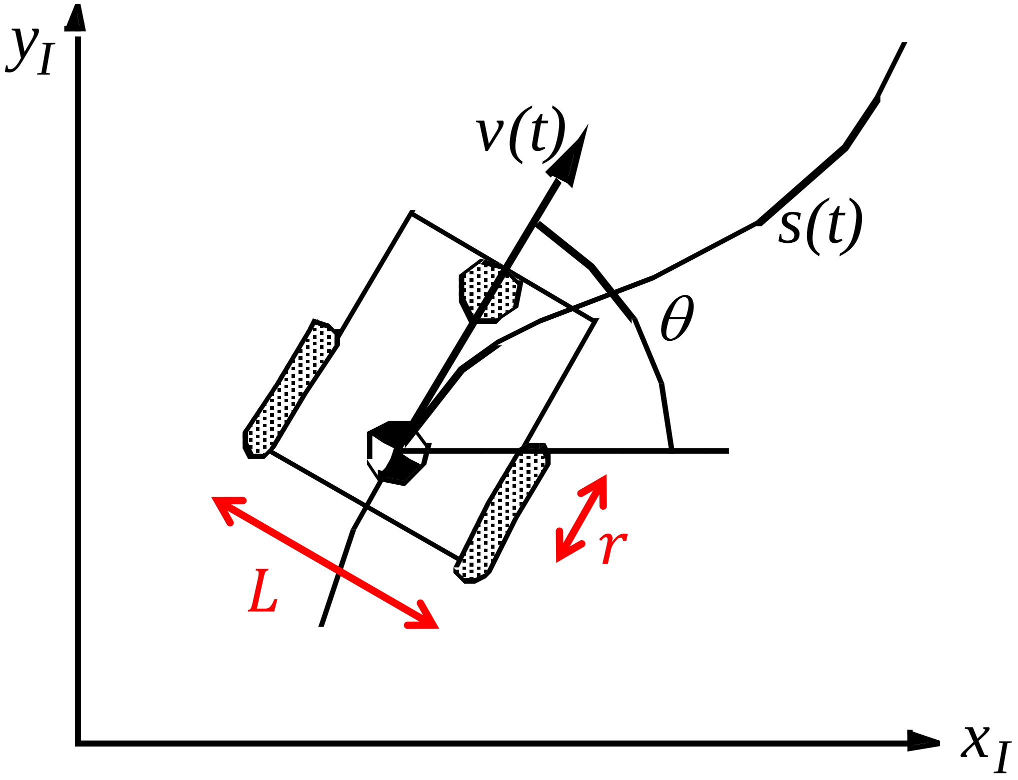
Wheel radius is r

Baseline distance between wheels is L

NOTE: These velocities are specified w.r.t. the robot's coordinate frame.

Differential Drive Robots

$\dot{\phi}$ = speed of wheel rotation



When both wheels turn with the same velocity and same direction, we have pure forward motion:

$$\dot{\phi}_R = \frac{v_x}{r}, \qquad \dot{\phi}_L = \frac{v_x}{r}$$

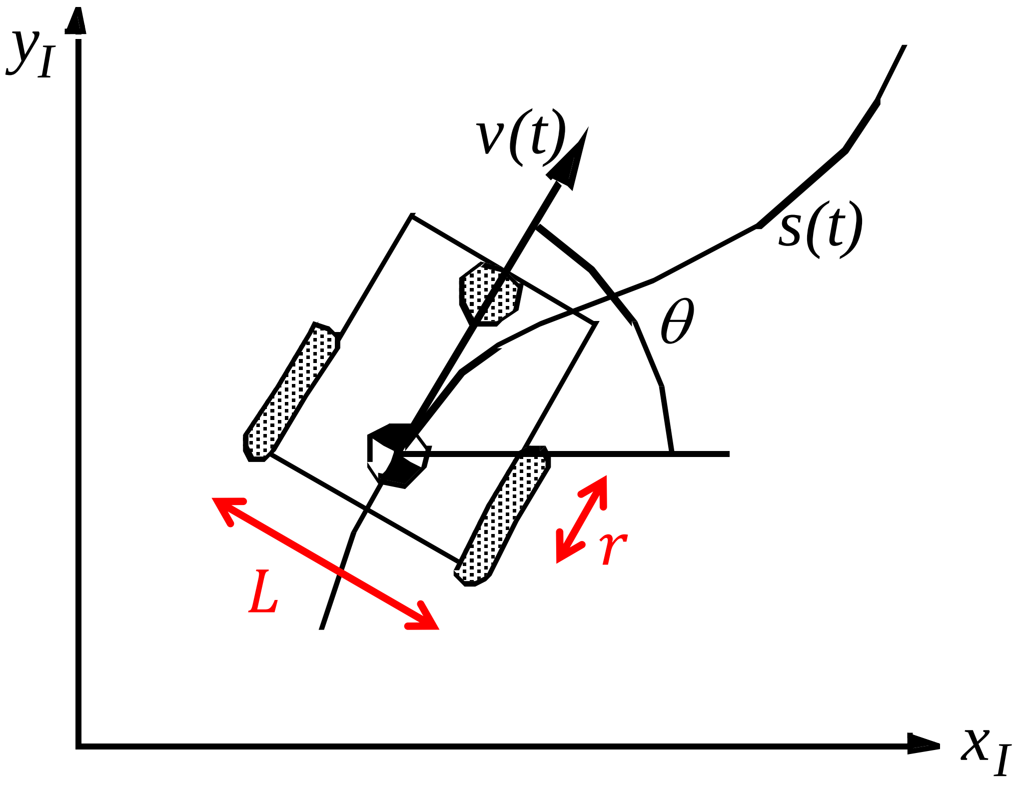
When the wheels turn in opposite directions with the same velocity, we have pure rotation:

$$\dot{\phi}_R = \frac{\omega L}{2r}, \qquad \dot{\phi}_L = -\frac{\omega L}{2r}$$

Combining the two (velocities are linear, so superposition applies) we obtain:

$$\dot{\phi}_R = \frac{\omega L}{2r} + \frac{v_x}{r}, \qquad \dot{\phi}_L = -\frac{\omega L}{2r} + \frac{v_x}{r}$$

Differential Drive Robots



We have equations that define wheel angular velocity in terms of linear and angular velocity of the robot:

$$\dot{\phi}_R = \frac{\omega L}{2r} + \frac{v_x}{r}, \qquad \dot{\phi}_L = -\frac{\omega L}{2r} + \frac{v_x}{r}$$

A bit of algebra gives the desired relationship between input (wheel velocity) and output (linear and angular velocity of the robot):

$$\frac{r}{2}(\dot{\phi}_R + \dot{\phi}_L) = v_x, \qquad \frac{r}{L}(\dot{\phi}_R - \dot{\phi}_L) = \omega = \dot{\theta}$$

$$\begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2}(\dot{\phi}_R + \dot{\phi}_L) \\ 0 \\ \frac{r}{L}(\dot{\phi}_R - \dot{\phi}_L) \end{bmatrix}$$

Motion relative to the world frame

We transform the robot velocity to world coordinates using our usual coordinate transformation:

$$v^0 = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_x \\ 0 \end{bmatrix} = \begin{bmatrix} v_x \cos\theta \\ v_x \sin\theta \end{bmatrix}$$

$$\dot{\theta} = \omega$$

$$\begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2}(\dot{\phi}_R + \dot{\phi}_L) \\ 0 \\ \frac{r}{L}(\dot{\phi}_R - \dot{\phi}_L) \end{bmatrix}$$

We typically think of the robot as a device with linear and angular velocity input, rather than think about wheel RMPs.

We typically write the equations of motion as:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} v_x \cos\theta \\ v_x \sin\theta \\ \omega \end{bmatrix}$$

or as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$