CS686: Configuration Space I

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Course URL:
http://sgvr.kaist.ac.kr/~sungeui/MPA

Announcements

- **Make a project team of 2 or 3 persons for your project**
  - **Each student needs a clear role**
  - **Declare team members at KLMS by Sep-30; you don't need to define the topic by then**
- **Each student**
  - **Present two papers related to the project; 25 min for each talk**
  - **Declare your papers at KLMS by Oct-14**
- **Each team**
  - **Give a mid-term presentation for the project**
  - **Give the final project presentation**

Tentative schedule

- **Oct. 29, 31: Students Presentation (2 talks per each class)**
- **Nov. 5: SP3 (7th no class due to IROS presentation)**
- **Nov. 12, 14: SP5**
- **Nov. 19, 21: Mid-term presentation**

- **Nov. 26: SP6 (28th: no class due to KAIST undergraduate interview)**
- **Dec. 3, 5: SP8**
- **Dec. 10, 12: Final presentation**
- **Dec. 17, 19 reservation for now (exam period, no class for now)**

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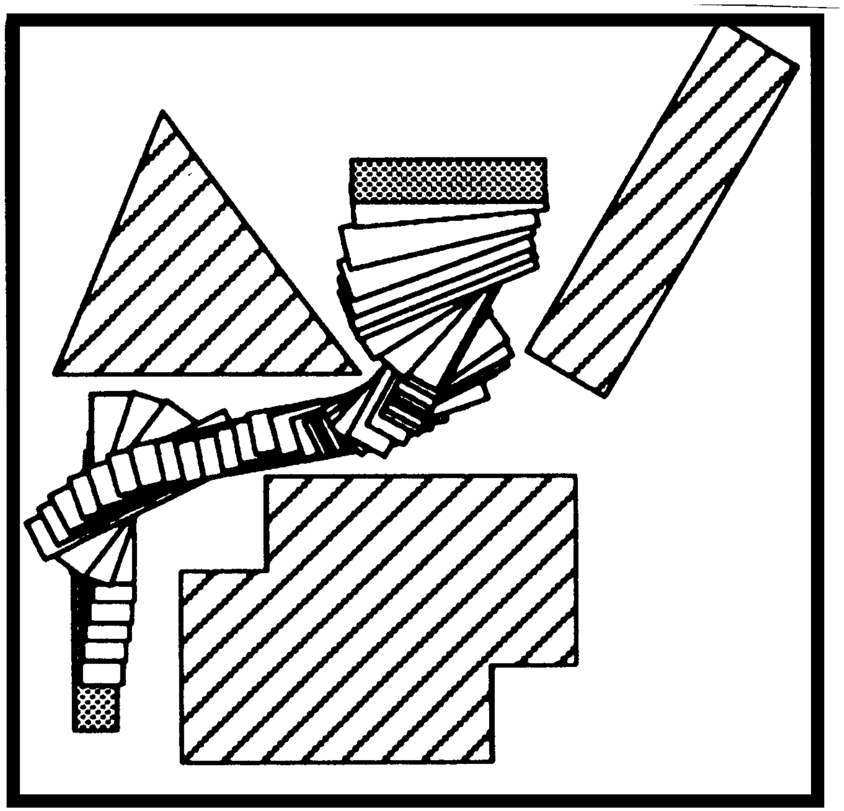
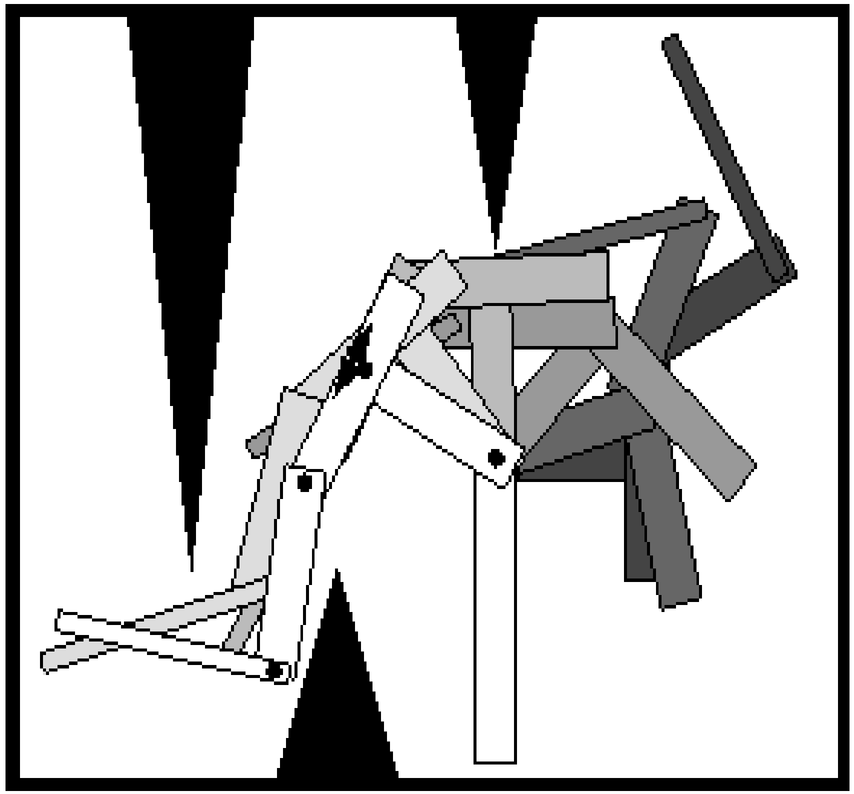
Class Objectives

- Configuration space
  - Definitions and examples
  - Obstacles
  - Paths
  - Metrics

What is a Path?



A box robot

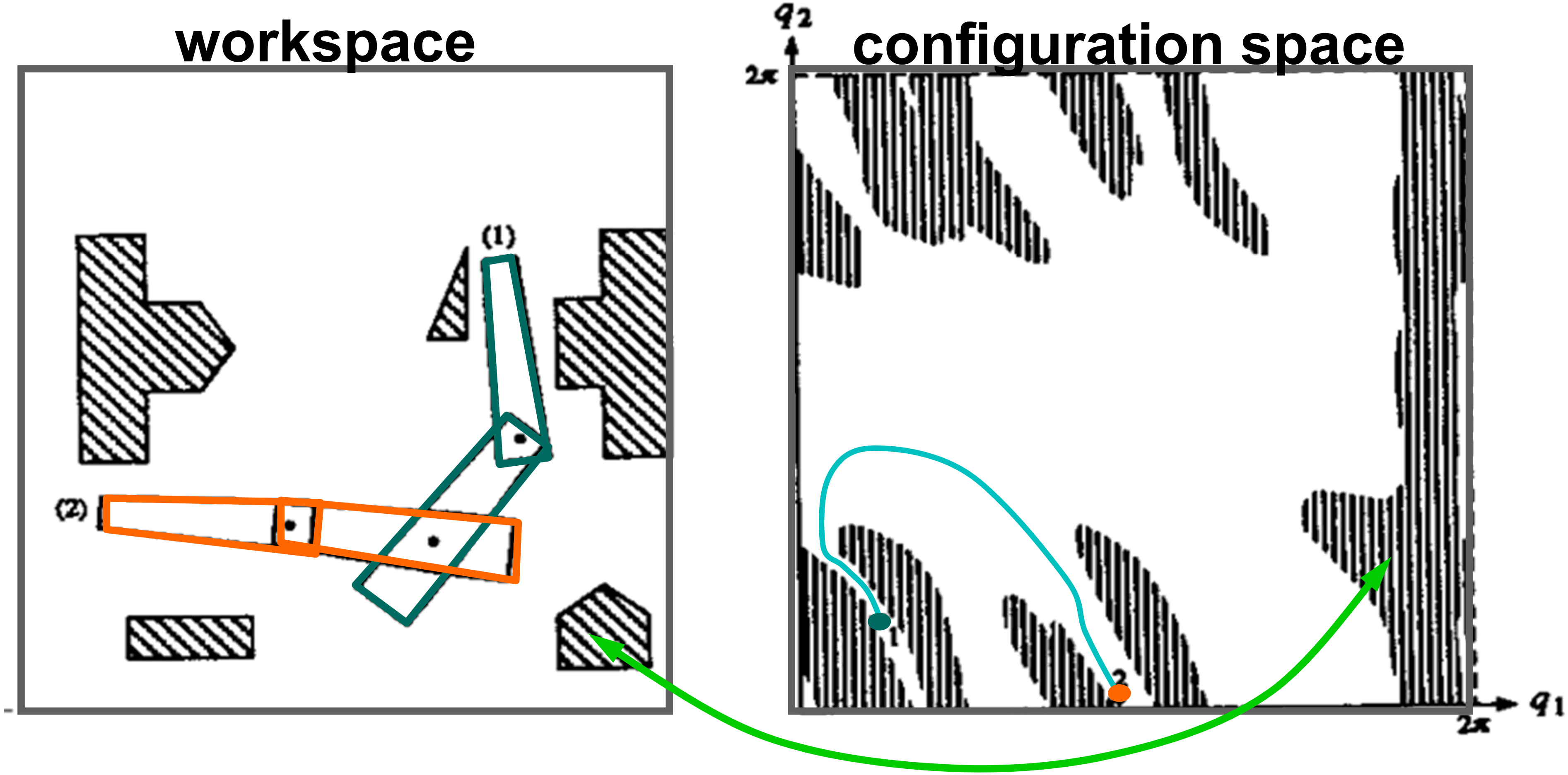


Linked robot

Rough Idea of C-Space

- **Convert rigid robots, articulated robots, *etc.* into points**
- **Apply algorithms in that space, in addition to the work space**

Mapping from the Workspace to the Configuration Space

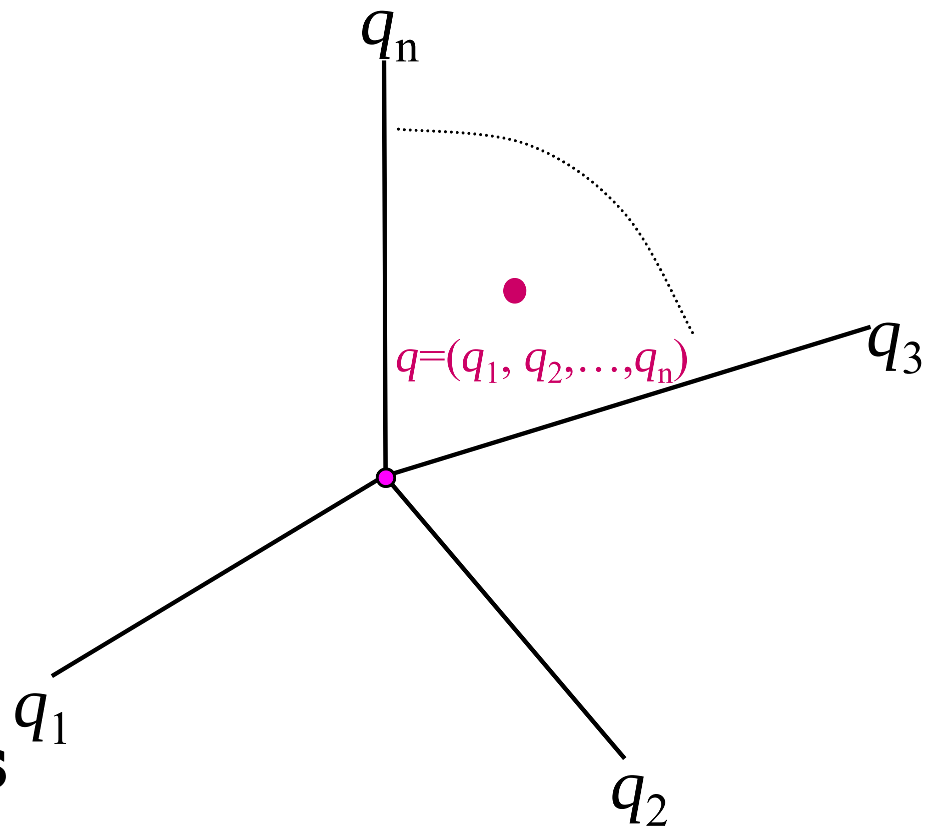


Configuration Space

- Definitions and examples
- Obstacles
- Paths
- Metrics

Configuration Space (C-space)

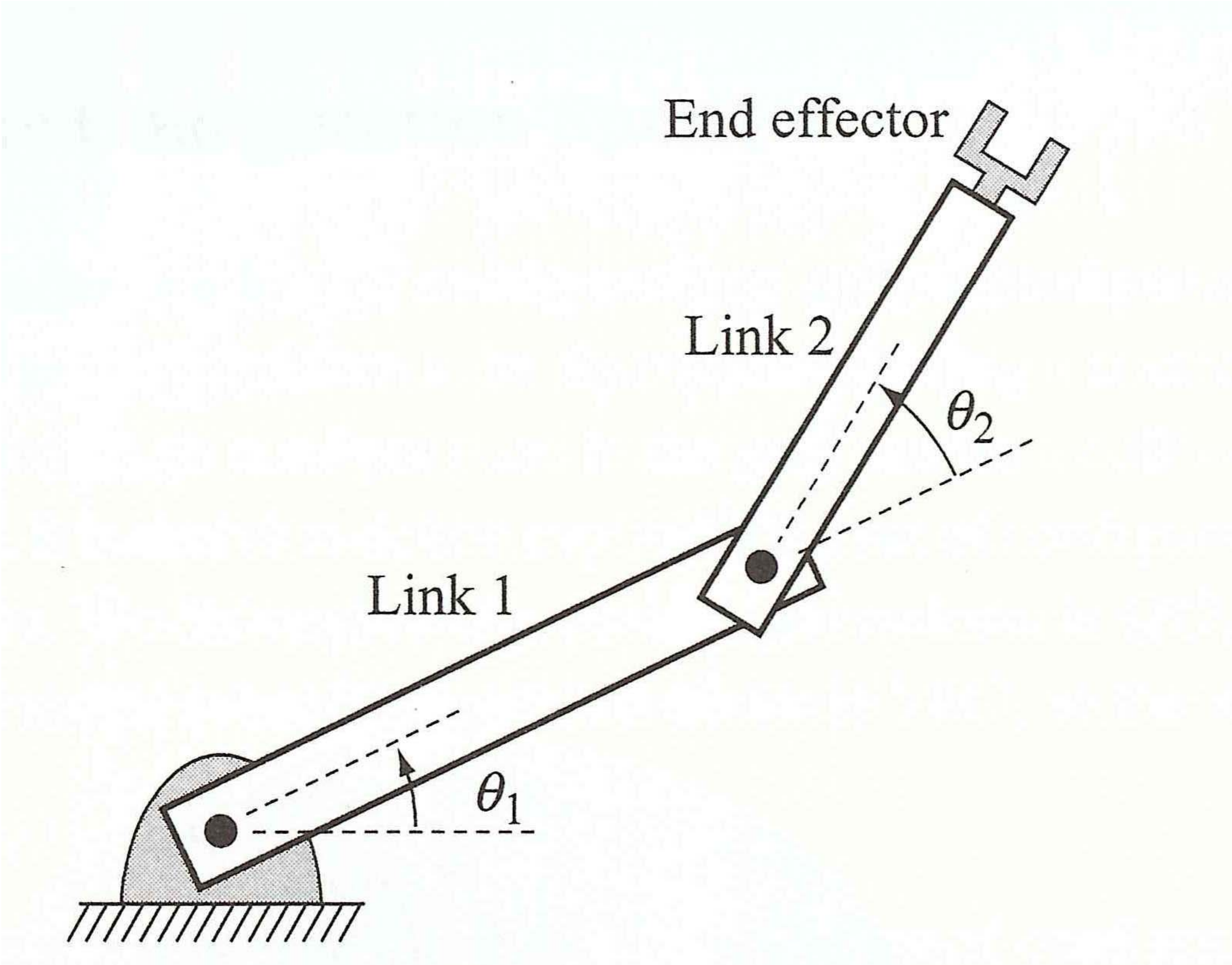
- **The configuration of an object is a complete specification of the position of every point on the object**
  - **Usually a configuration is expressed as a vector of position & orientation parameters:** $q = (q_1, q_2,\ldots,q_n)$



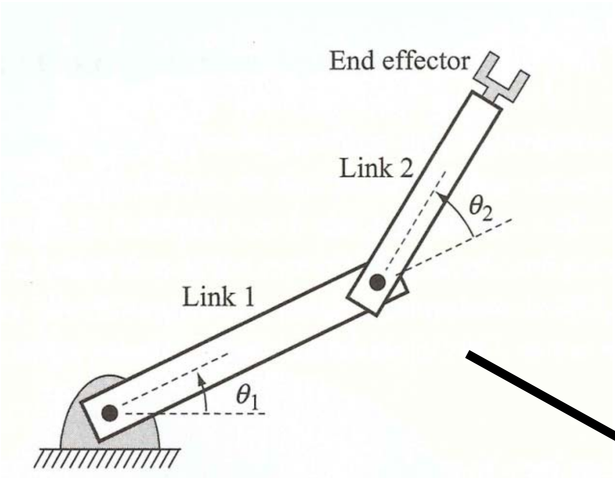
- **The configuration space C is the set of all possible configurations**
  - **A configuration is a point in C**

C-space formalism: Lozano-Perez '79

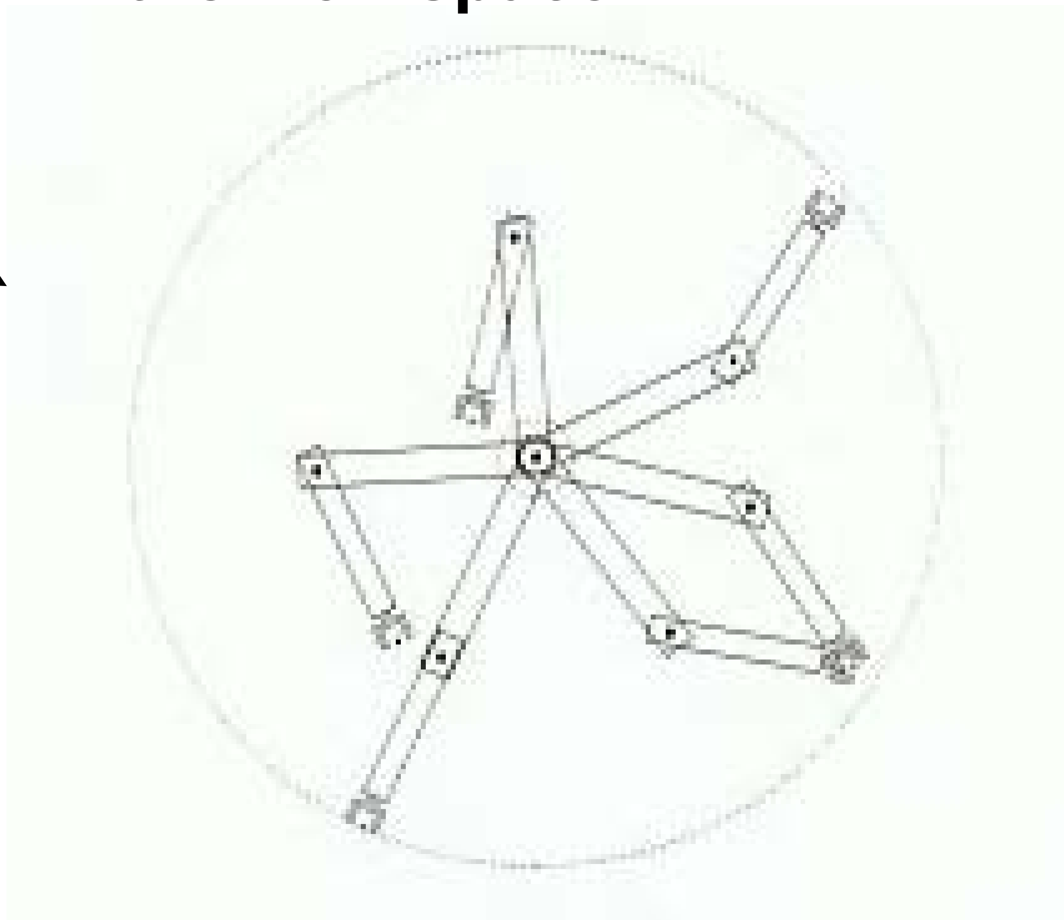
Examples of Configuration Spaces



Examples of Configuration Spaces

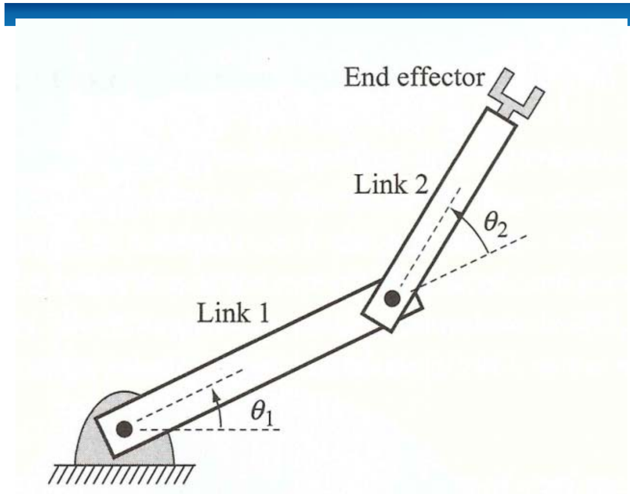


Consider the end-effector in the workspace?

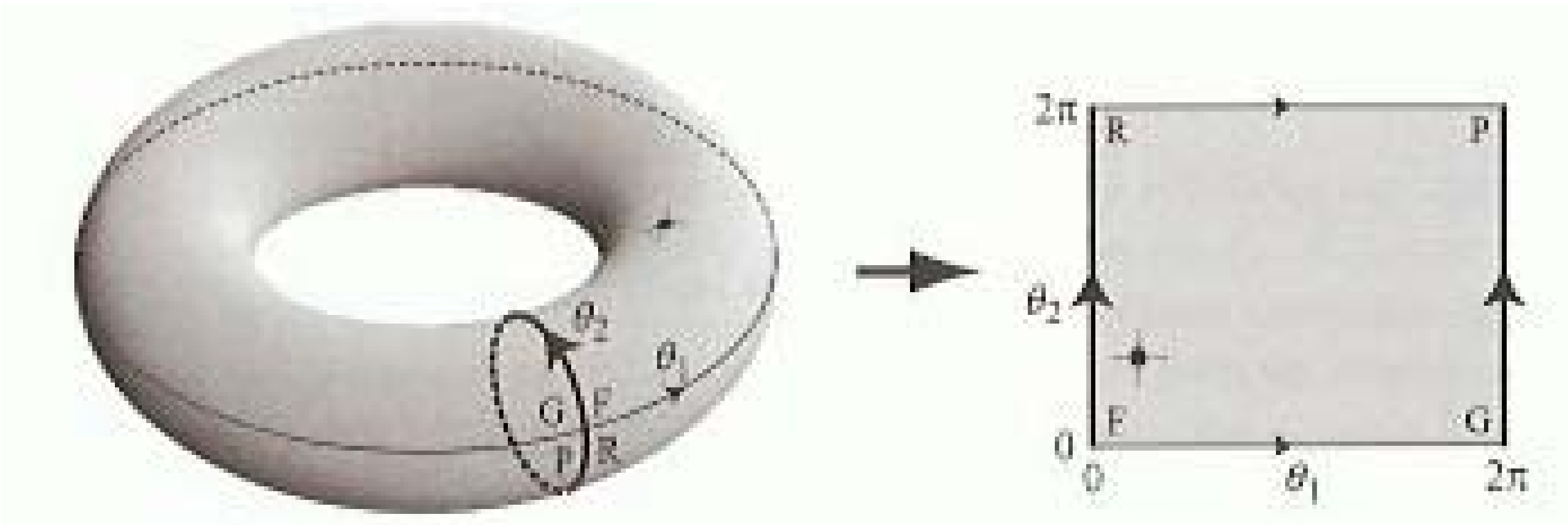


This is not a valid C-space!

Examples of Configuration Spaces

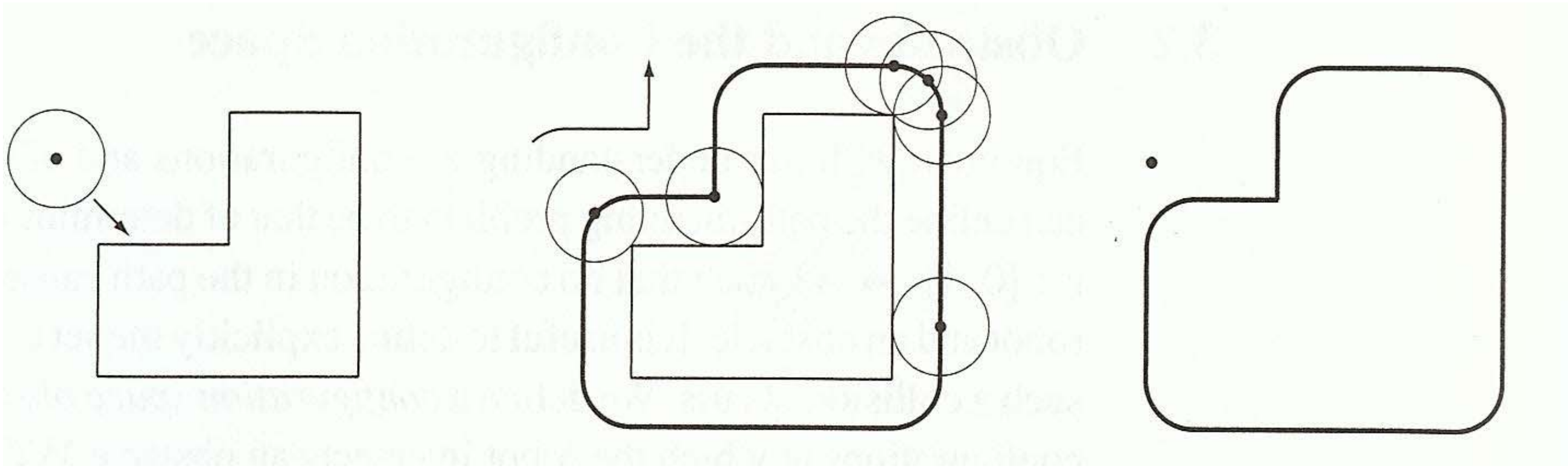


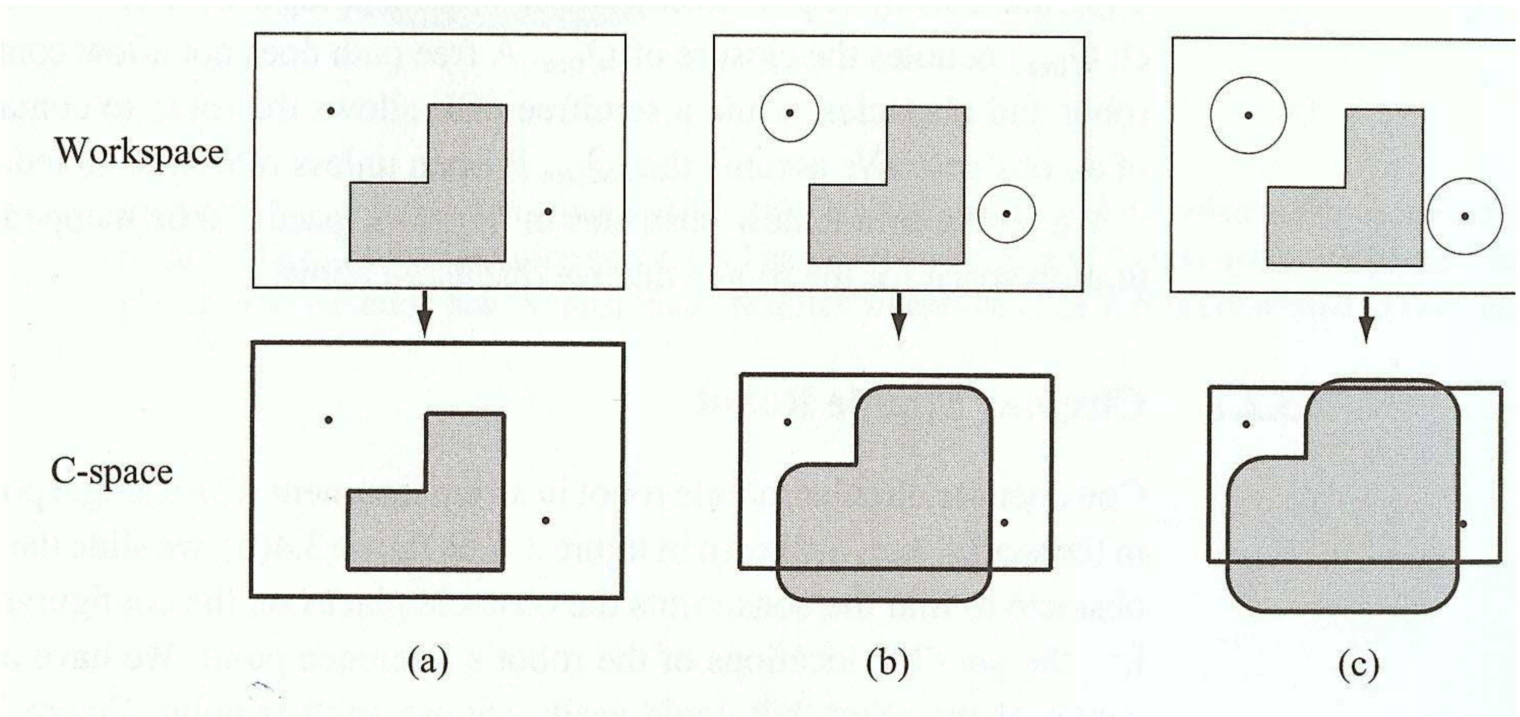
The topology of C is usually **not** that of a Cartesian space R^n.



$S^1 \times S^1 = T^2$

Examples of Circular Robot



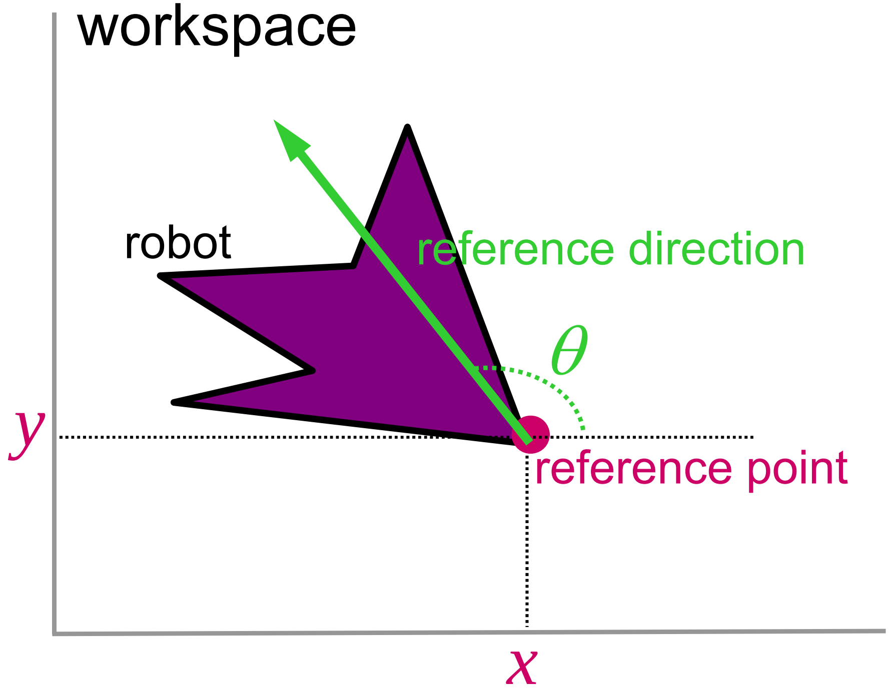


Dimension of Configuration Space

- The **dimension of the configuration space** is the **minimum** number of parameters needed to specify the configuration of the object completely

- It is also called the number of **degrees of freedom** (dofs) of a moving object

Example: Rigid Robot in 2-D Workspace



- **3-parameter specification:** $q = (x, y, \theta)$ with $\theta \in [0, 2\pi)$.
  - **3-D configuration space**

Example: Rigid Robot in 2-D workspace

- **4-parameter specification:** $q = (x, y, u, v)$ **with** $u^2+v^2 = 1$. **Note** $u = \cos\theta$ **and** $v = \sin\theta$

- **dim of configuration space = 3**
  - **Does the dimension of the configuration space (number of dofs) depend on the parametrization?**

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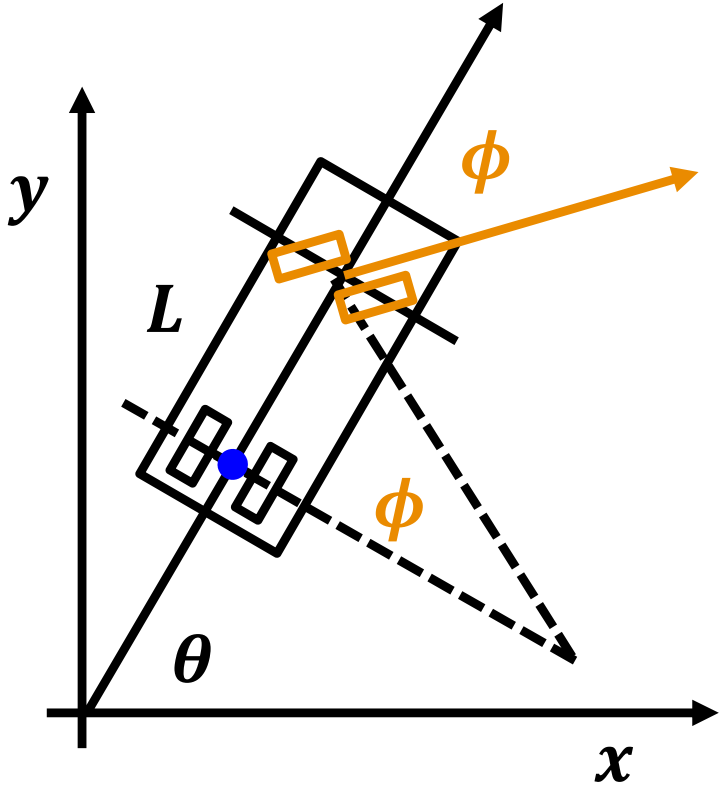
Holonomic and Non-Holonomic Contraints

- **Holonomic constraints: $g(q, t) = 0$**
- **Non-holonomic constraints**
  - **$g(q, q', t) = 0$ (or $q' = f(q, u)$, where u is an action parameter)**
  - **This is related to the kinematics of robots**
  - **To accommodate this, the C-space is extended to include the position and its velocity**
- **Dynamic constraints**
  - **Dynamic equations are represented as $G(q, q', q'') = 0$**
  - **These constraints are reduced to non-holonomic ones when we use the extended C-space such as the state space**

Example of Non-Holonomic Constraints

See Kinematic Car Model of my draft



$$\tan(\boldsymbol{\theta}) = \frac{\boldsymbol{\sin(\theta)}}{\boldsymbol{\cos(\theta)}} = \frac{\boldsymbol{dy}}{\boldsymbol{dx}}$$

$$\boldsymbol{\sin(\theta)dx - \cos(\theta)dy = 0}$$

$$\frac{\boldsymbol{dx}}{\boldsymbol{dt}} = \boldsymbol{v} \cdot \boldsymbol{\cos(\theta)}, \quad \frac{\boldsymbol{dy}}{\boldsymbol{dt}} = \boldsymbol{v} \cdot \boldsymbol{\sin(\theta)},$$

$$\frac{\boldsymbol{d\theta}}{\boldsymbol{dt}} = \frac{\boldsymbol{v}}{\boldsymbol{L}} \boldsymbol{\tan(\phi)}$$

Note that v, ϕ are action parameters

Example of Non-Holonomic Constraints

- **Point-mass robot with dynamics in a 2D plane**
  - **Its state is defined with its position and velocity (x, y, v_x, v_y)**
  - **To control the robot, we can apply forces in x- and y-directions**
  - **Then the equations of motions:**

$$x' = v_x \qquad v'_x = u_x / m$$
$$y' = v_y \qquad v'_y = u_y / m,$$

Where u_x and u_y are applied forces, and m is its mass

Computation of Dimension of C-Space

- Suppose that we have a rigid body that can translate and rotate in 2D workspace
  - Start with three points: A, B, C (6D space)

- We have the following (holonomic) constraints
  - Given A, we know the dist to B: d(A,B) = |A-B|
  - Given A and B, we have similar equations: d(A,C) = |A-C|, d(B,C) = |B-C|

- Each holonomic constraint reduces one dim.
  - Not for non-holonomic constraint

Example: Rigid Robot in 3-D Workspace

- **We can represent the positions and orientations of such robots with matrices (i.e., SO (3) and SE (3))**

SO (n) and SE (n)

- **Special orthogonal group, SO(n),** of n x n matrices R,

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

that satisfy:

$r_{1i}^2 + r_{2i}^2 + r_{3i}^2 = 1$ for all i ,
$r_{1i}\, r_{1j} + r_{2i}\, r_{2j} + r_{3i}\, r_{3j} = 0$ for all $i \neq j$,
$\det(R) = +1$

Refer to the 3D Transformation at the undergraduate computer graphics.

- **Given the orientation matrix R of SO (n) and the position vector p, special Euclidean group, SE (n), is defined as:**

$$\begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix}$$

Example: Rigid Robot in 3-D Workspace

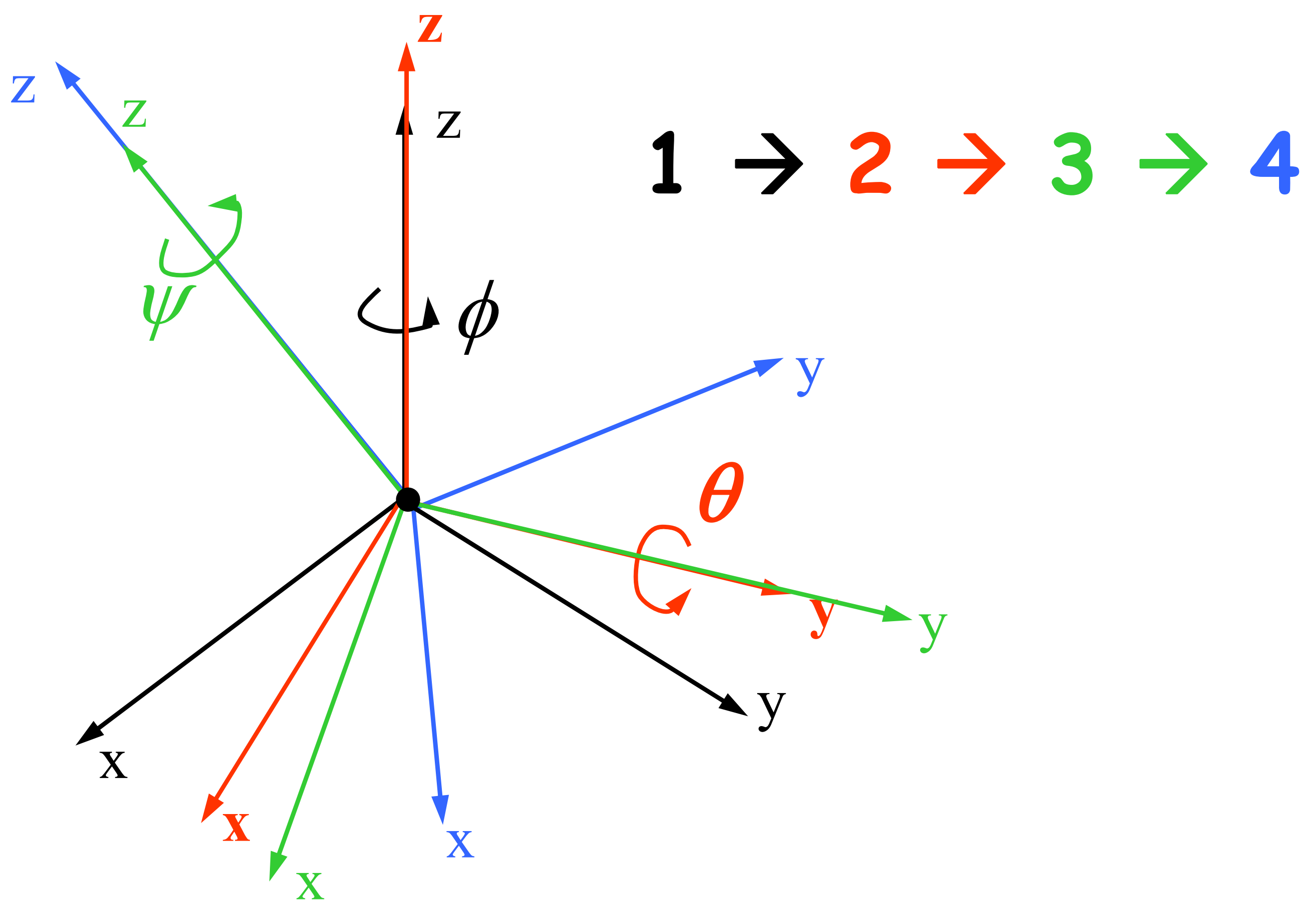
- q = (**position, orientation**) = $(x, y, z, ???)$

- **Parametrization of orientations by matrix:**
  $q = (r_{11}, r_{12}, \ldots, r_{33}, r_{33})$ **where** $r_{11}, r_{12}, \ldots, r_{33}$ **are the elements of rotation matrix**

$$R = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \in SO(3)$$

Example: Rigid Robot in 3-D Workspace

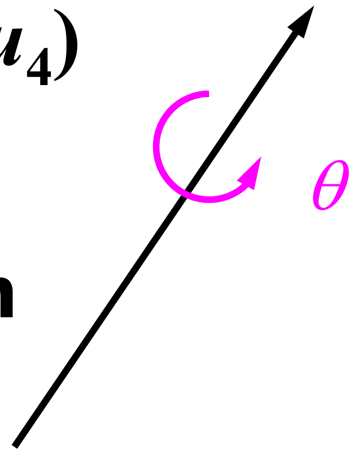
- **Parametrization of orientations by Euler angles:** (ϕ,θ,ψ)



Example: Rigid Robot in 3-D Workspace

- **Parametrization of orientations by unit quaternion:** $u = (u_1, u_2, u_3, u_4)$ **with** $u_1^2 + u_2^2 + u_3^2 + u_4^2 = 1.$
  - **Note** $(u_1, u_2, u_3, u_4) = (\cos\theta/2, n_x\sin\theta/2, n_y\sin\theta/2, n_z\sin\theta/2)$ **with** $n_x^2 + n_y^2 + n_z^2 = 1$
  - **Compare with representation of orientation in 2-D:** $(u_1, u_2) = (\cos\theta, \sin\theta)$

$\mathbf{n} = (n_x, n_y, n_z)$

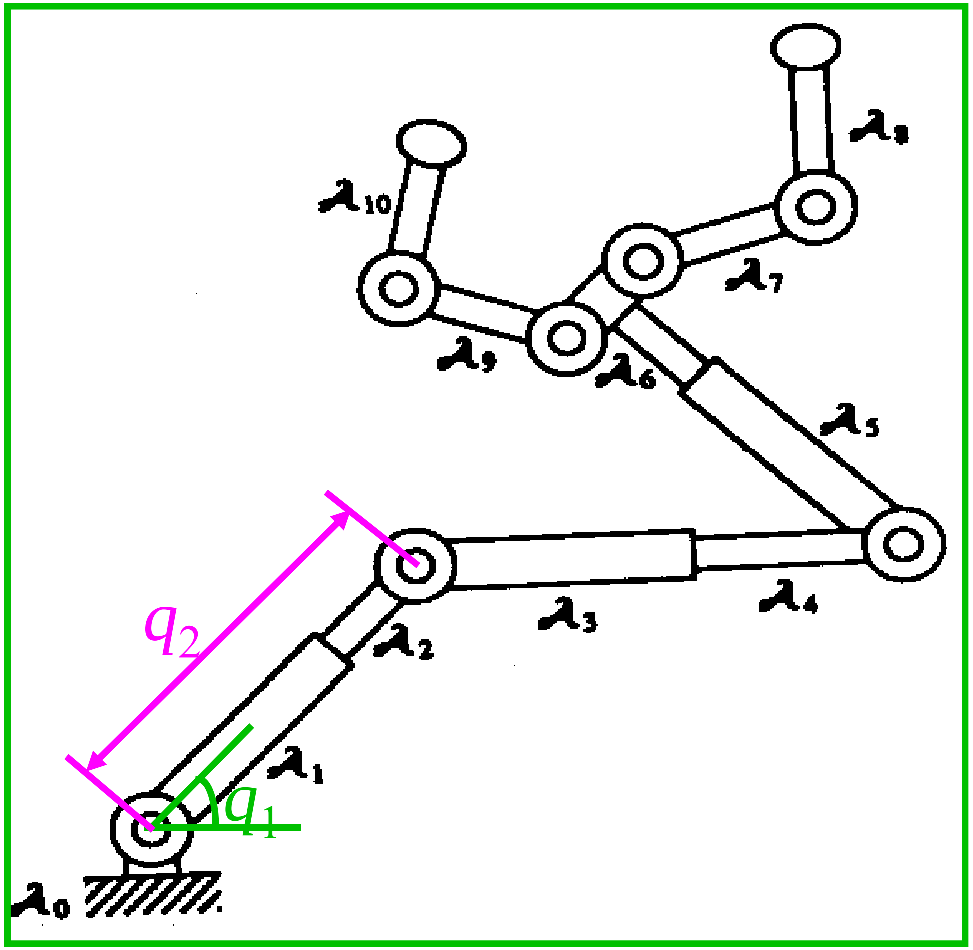


Example: Rigid Robot in 3-D Workspace

- **Advantage of unit quaternion representation**
  - **Compact**
  - **No singularity (no gimbal lock indicating two axises are aligned)**
  - **Naturally reflect the topology of the space of orientations**

- **Number of dofs = 6**
- **Topology:** $R^3 \times SO(3)$

Example: Articulated Robot



An articulated object is a set of rigid bodies connected at the joints.

- $q = (q_1,q_2,\ldots,q_{2n})$
- **Number of dofs** = $2n$
- **What is the topology?**

Class Objectives were:

- Configuration space
  - Definitions and examples
  - Obstacles
  - Paths
  - Metrics

Next Time….

- Configuration space
  - Definitions and examples
  - Obstacles
  - Paths
  - Metrics

Homework

- Browse 2 ICRA/IROS/RSS/CoRL/TRO/IJRR papers
  - Submit it online before the Tue. Class

- Example of a summary (just a paragraph)

Title: XXX XXXX XXXX
Conf./Journal Name: ICRA, 2016
Summary: this paper is about accelerating the performance of collision detection. To achieve its goal, they design a new technique for reordering nodes, since by doing so, they can improve the coherence and thus improve the overall performance.

Homework for Every Class

- **Go over the next lecture slides**
- **Come up with one question on what we have discussed today and submit at the end of the class**
  - **1 for typical questions**
  - **2 for questions with thoughts or that surprised me**

- **Write a question 3 times before the mid-term exam**