

CSCI 520 Computer Animation and Simulation

Quaternions and Rotations

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Rotations

- Very important in computer animation and robotics
- Joint angles, rigid body orientations, camera parameters
- 2D or 3D

Rotations in Three Dimensions

- Orthogonal matrices:

$$RR^T = R^T R = I$$
$$\det(R) = 1$$

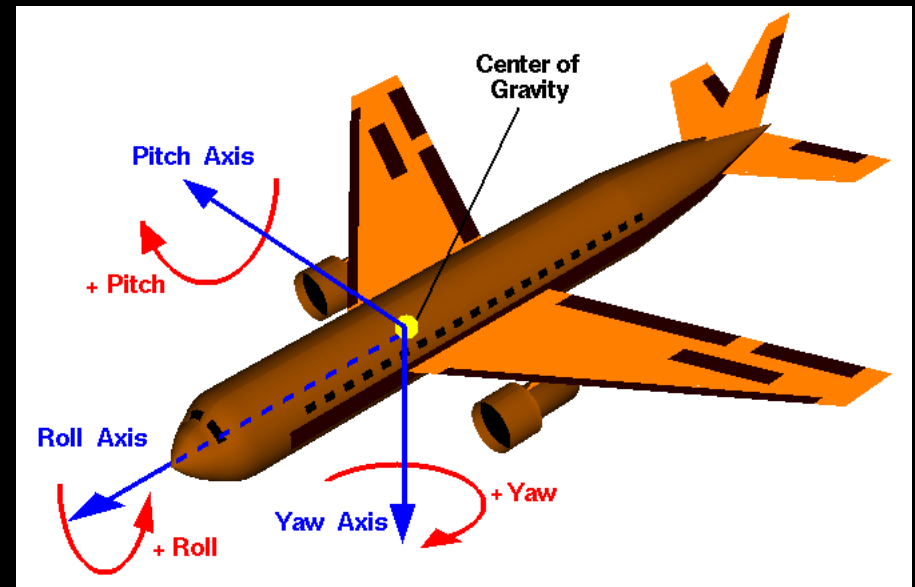
$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

Representing Rotations in 3D

- Rotations in 3D have essentially three parameters
- Axis + angle (2 DOFs + 1DOFs)
 - How to represent the axis?
Longitude / latitude have singularities
- 3x3 matrix
 - 9 entries (redundant)

Representing Rotations in 3D

- Euler angles
 - roll, pitch, yaw
 - no redundancy (good)
 - gimbal lock singularities

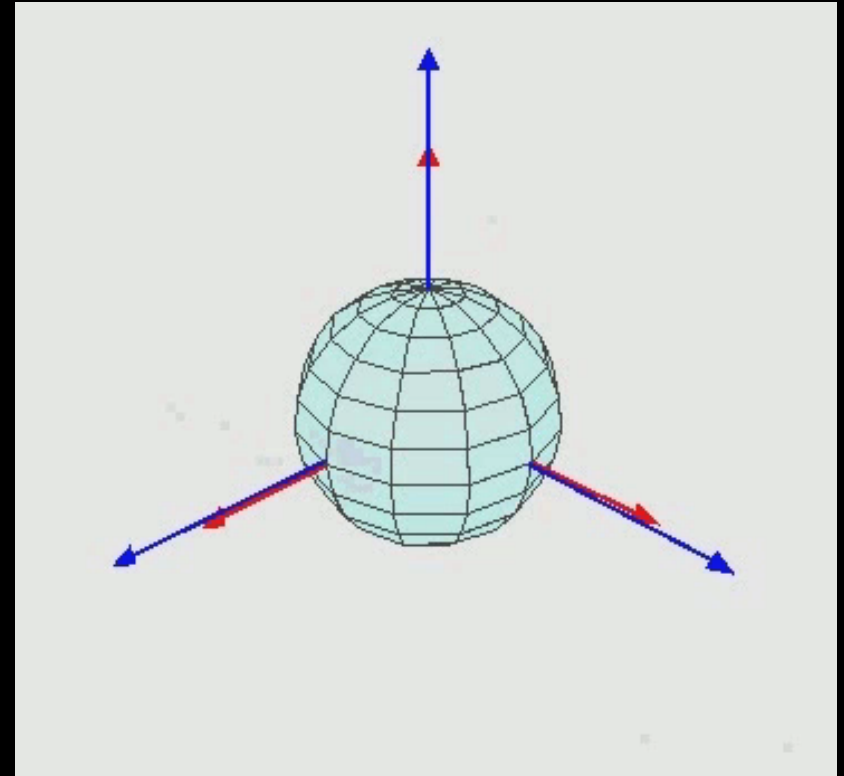


Source: Wikipedia

- Quaternions
 - generally considered the “best” representation
 - redundant (4 values), but only by one DOF (not severe)
 - stable interpolations of rotations possible

Euler Angles

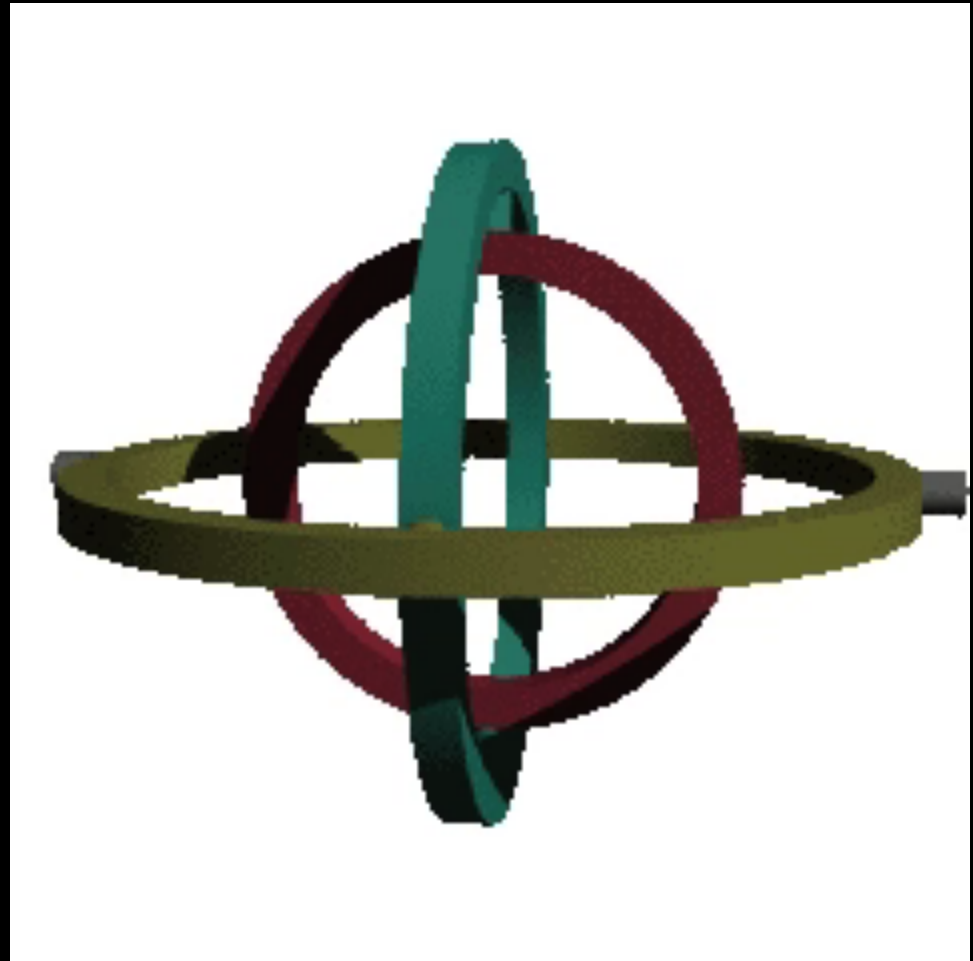
1. **Yaw**
rotate around y-axis
2. **Pitch**
rotate around (rotated) x-axis
3. **Roll**
rotate around (rotated) y-axis



Source: Wikipedia

Gimbal Lock

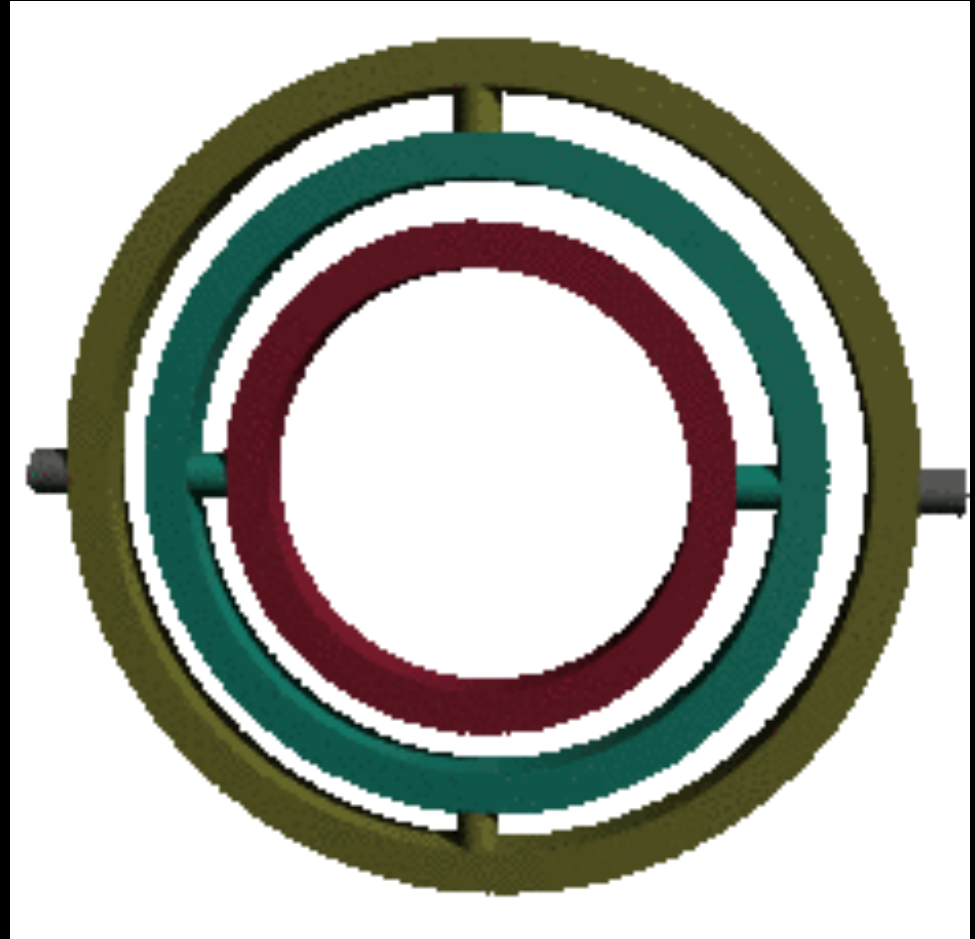
When all three gimbals are lined up (in the same plane), the system can only move in two dimensions from this configuration, not three, and is in *gimbal lock*.



Source: Wikipedia

Gimbal Lock

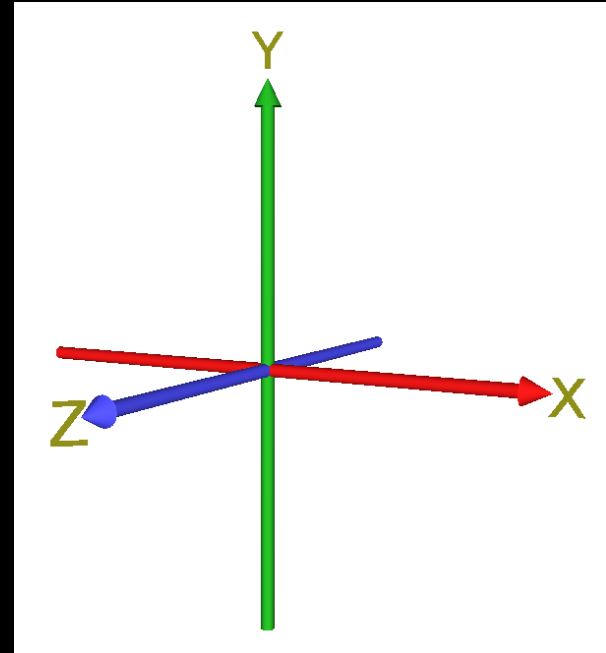
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Source: Wikipedia

Choice of rotation axis sequence for Euler Angles

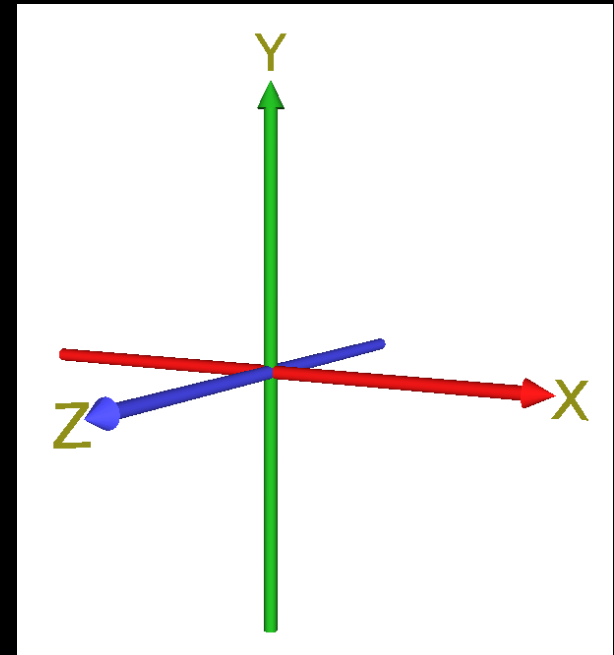
- 12 choices:
XYX, XYZ, XZX, XZY,
YXY, YXZ, YZX, YZY,
ZXY, ZXZ, ZYX, ZYZ



- Each choice can use static axes, or rotated axes, so we have a total of 24 Euler Angle versions!

Example: XYZ Euler Angles

- First rotate around X by angle θ_1 , then around Y by angle θ_2 , then around Z by angle θ_3 .
- Used in CMU Motion Capture Database AMC files
- Rotation matrix is:



$$R = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 \\ \sin(\theta_3) & \cos(\theta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta_2) & 0 & \sin(\theta_2) \\ 0 & 1 & 0 \\ -\sin(\theta_2) & 0 & \cos(\theta_2) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_1) & -\sin(\theta_1) \\ 0 & \sin(\theta_1) & \cos(\theta_1) \end{bmatrix}$$

Outline

- Rotations
- **Quaternions**
- Quaternion Interpolation

Quaternions

- Generalization of complex numbers
- Three imaginary numbers: i, j, k

$$i^2 = -1, j^2 = -1, k^2 = -1,$$

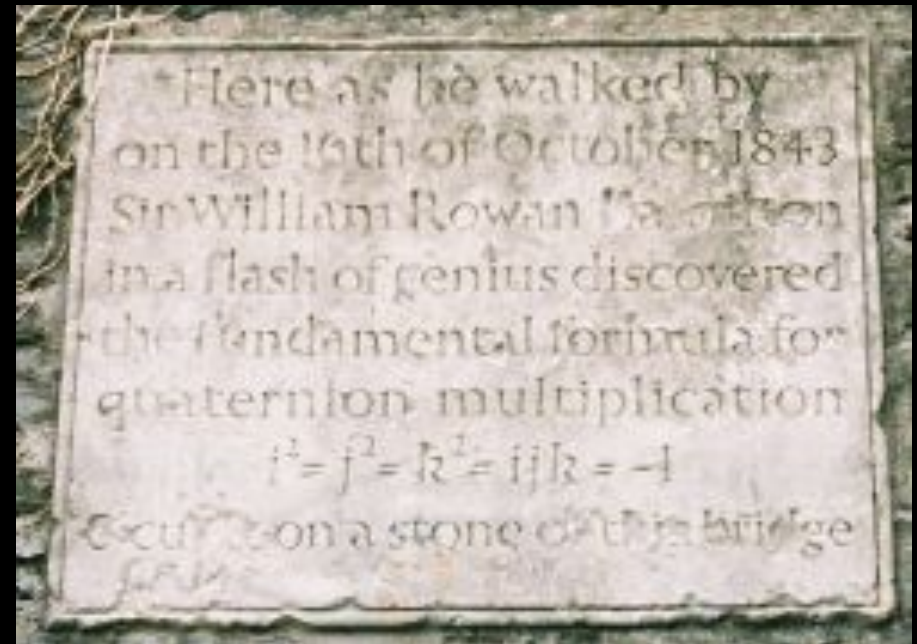
$$ij = k, jk = i, ki = j, ji = -k, kj = -i, ik = -j$$

- $q = s + x i + y j + z k,$ s, x, y, z are scalars

Quaternions

- Invented by Hamilton in 1843 in Dublin, Ireland

- Here as he walked by on the 16th of October 1843 Sir William Rowan Hamilton in a flash of genius discovered the fundamental formula for quaternion multiplication



Source: Wikipedia

$$i^2 = j^2 = k^2 = i j k = -1$$

& cut it on a stone of this bridge.

Quaternions

- Quaternions are **not** commutative!

$$q_1 q_2 \neq q_2 q_1$$

- However, the following hold:

$$(q_1 q_2) q_3 = q_1 (q_2 q_3)$$

$$(q_1 + q_2) q_3 = q_1 q_3 + q_2 q_3$$

$$q_1 (q_2 + q_3) = q_1 q_2 + q_1 q_3$$

$$\alpha (q_1 + q_2) = \alpha q_1 + \alpha q_2 \quad (\alpha \text{ is scalar})$$

$$(\alpha q_1) q_2 = \alpha (q_1 q_2) = q_1 (\alpha q_2) \quad (\alpha \text{ is scalar})$$

- I.e., all usual manipulations are valid, except cannot reverse multiplication order.

Quaternions

- Exercise: multiply two quaternions

$$(2 - i + j + 3k) (-1 + i + 4j - 2k) = \dots$$

Quaternion Properties

- $q = s + x \mathbf{i} + y \mathbf{j} + z \mathbf{k}$
- Norm: $|q|^2 = s^2 + x^2 + y^2 + z^2$
- Conjugate quaternion: $\bar{q} = s - x \mathbf{i} - y \mathbf{j} - z \mathbf{k}$
- Inverse quaternion: $q^{-1} = \bar{q} / |q|^2$
- Unit quaternion: $|q| = 1$
- Inverse of unit quaternion: $q^{-1} = \bar{q}$

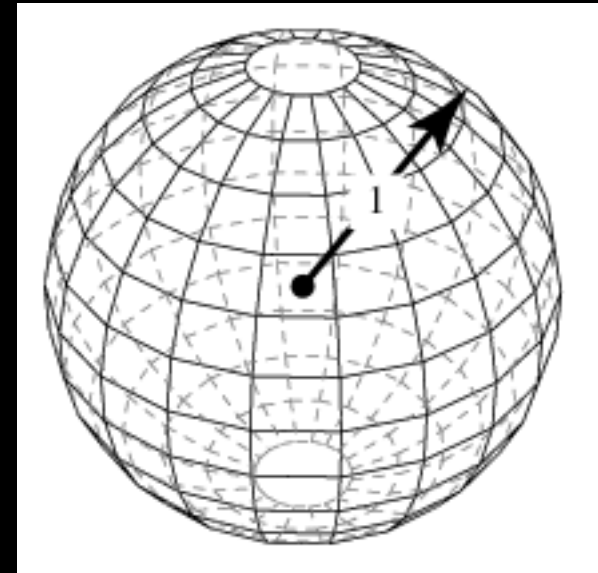
Quaternions and Rotations

- Rotations are represented by *unit* quaternions

- $q = s + x i + y j + z k$

$$s^2 + x^2 + y^2 + z^2 = 1$$

- Unit quaternion sphere
(unit sphere in 4D)



Source:
Wolfram Research

unit sphere
in 4D

Rotations to Unit Quaternions

- Let (unit) rotation axis be $[u_x, u_y, u_z]$, and angle θ
- Corresponding quaternion is

$$q = \cos(\theta/2) + \sin(\theta/2) u_x \mathbf{i} + \sin(\theta/2) u_y \mathbf{j} + \sin(\theta/2) u_z \mathbf{k}$$

- Composition of rotations q_1 and q_2 equals $q = q_2 q_1$
- 3D rotations do not commute!

Unit Quaternions to Rotations

- Let \mathbf{v} be a (3-dim) vector and let q be a unit quaternion
- Then, the corresponding rotation transforms vector \mathbf{v} to $q \mathbf{v} q^{-1}$

(\mathbf{v} is a quaternion with scalar part equaling 0, and vector part equaling \mathbf{v})

For $q = a + b \mathbf{i} + c \mathbf{j} + d \mathbf{k}$

$$R = \begin{pmatrix} a^2 + b^2 - c^2 - d^2 & 2bc - 2ad & 2bd + 2ac \\ 2bc + 2ad & a^2 - b^2 + c^2 - d^2 & 2cd - 2ab \\ 2bd - 2ac & 2cd + 2ab & a^2 - b^2 - c^2 + d^2 \end{pmatrix}$$

Quaternions

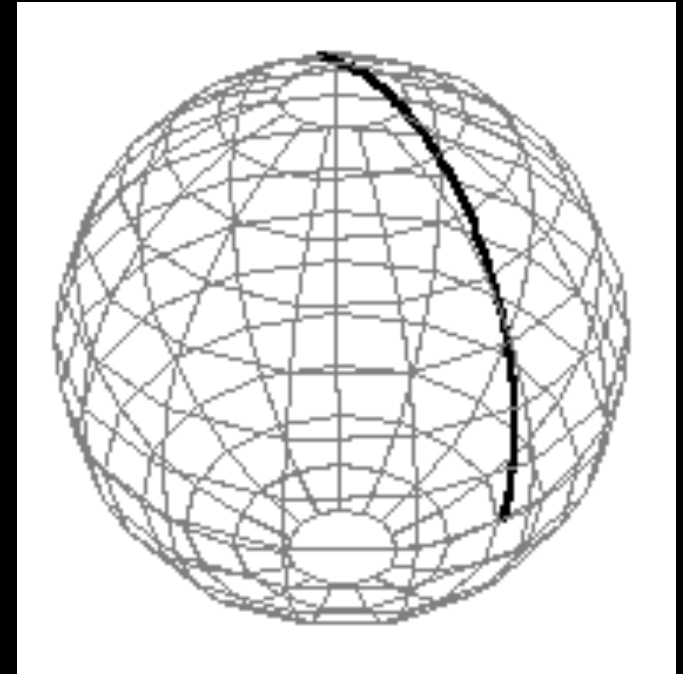
- Quaternions q and $-q$ give the same rotation!
- Other than this, the relationship between rotations and quaternions is unique

Outline

- Rotations
- Quaternions
- Quaternion Interpolation

Quaternion Interpolation

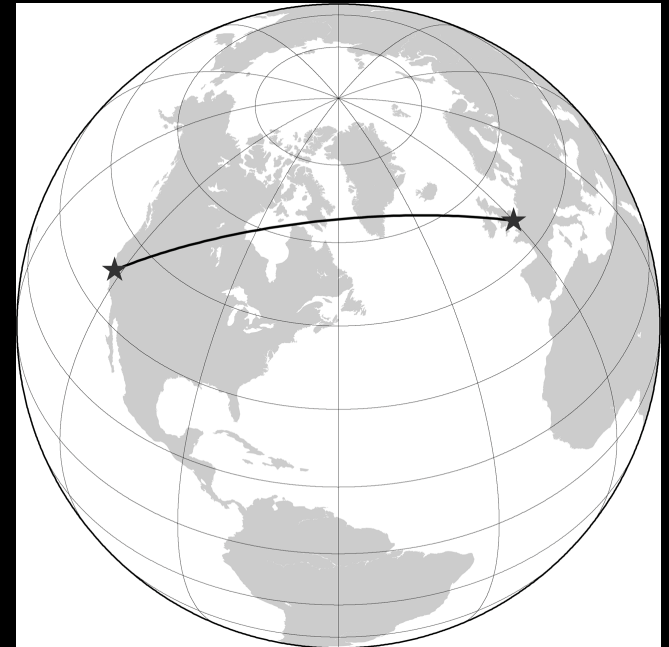
- Better results than Euler angles
- A quaternion is a point on the 4-D unit sphere
- Interpolating rotations corresponds to curves on the 4-D sphere



Source:
Wolfram Research

Spherical Linear intERPolation (SLERPing)

- Interpolate along the great circle on the 4-D unit sphere
- Move with constant angular velocity along the great circle between the two points
- Any rotation is given by two quaternions, so there are two SLERP choices; pick the shortest



San Francisco
to London

SLERP

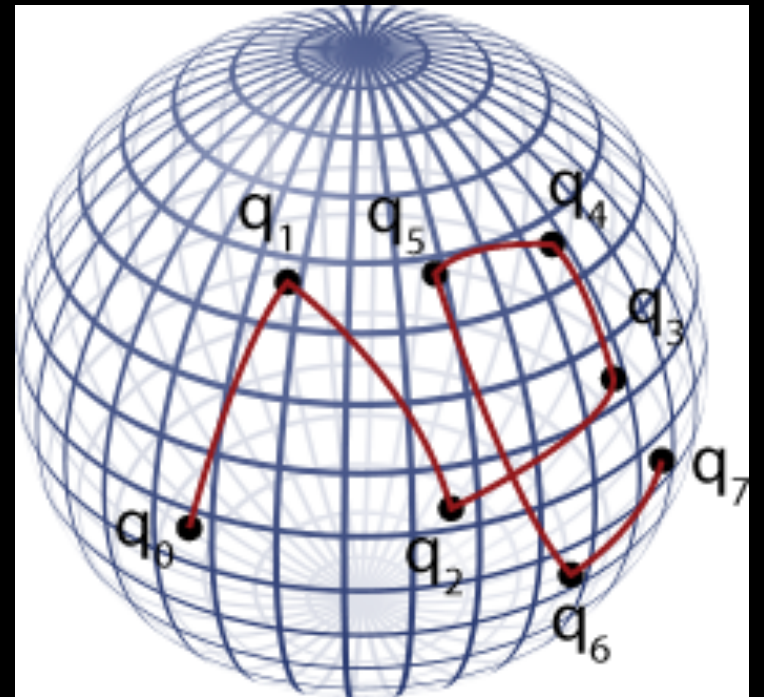
$$\text{Slerp}(q_1, q_2, u) = \frac{\sin((1-u)\theta)}{\sin(\theta)} q_1 + \frac{\sin(u\theta)}{\sin(\theta)} q_2$$

$$\begin{aligned} \cos(\theta) &= q_1 \cdot q_2 = \\ &= s_1 s_2 + x_1 x_2 + y_1 y_2 + z_1 z_2 \end{aligned}$$

- u varies from 0 to 1
- $q_m = s_m + x_m \mathbf{i} + y_m \mathbf{j} + z_m \mathbf{k}$, for $m = 1, 2$
- The above formula does not produce a unit quaternion and must be normalized; replace q by $q / |q|$

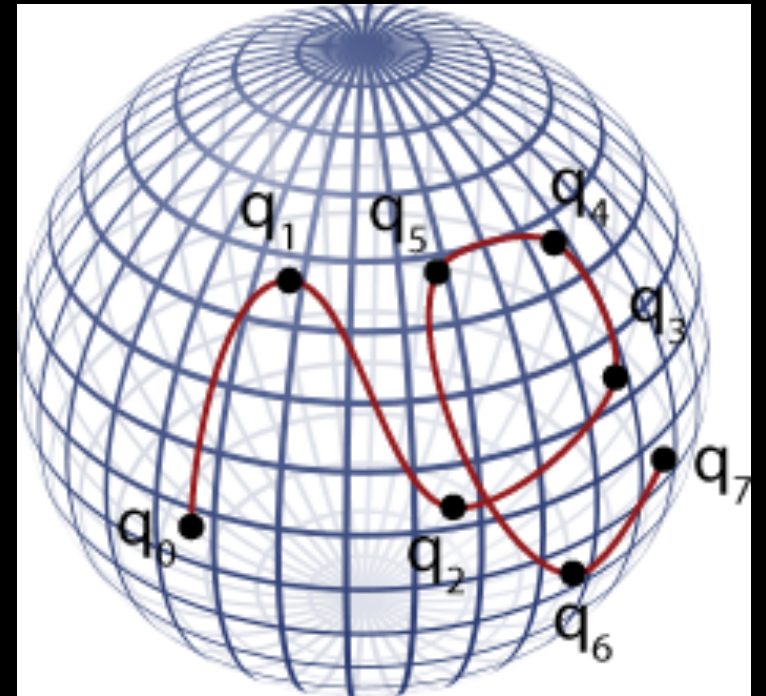
Interpolating more than two rotations

- Simplest approach: connect consecutive quaternions using SLERP
- Continuous rotations
- Angular velocity not smooth at the joints



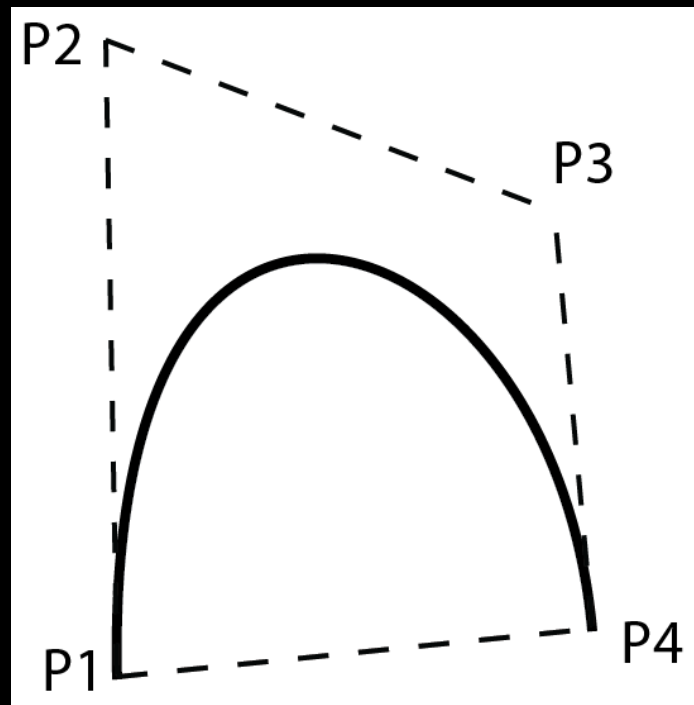
Interpolation with smooth velocities

- Use splines on the unit quaternion sphere
- Reference: Ken Shoemake in the SIGGRAPH '85 proceedings (Computer Graphics, V. 19, No. 3, P. 245)



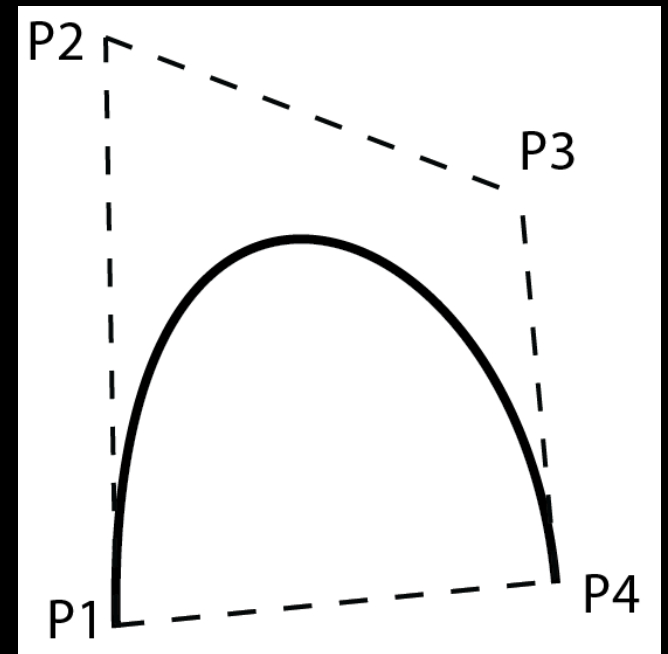
Bezier Spline

- Four control points
 - points P1 and P4 are on the curve
 - points P2 and P3 are off the curve; they give curve tangents at beginning and end



Bezier Spline

- $p(0) = P1, p(1) = P4,$
- $p'(0) = 3(P2-P1)$
- $p'(1) = 3(P4 - P3)$
- Convex Hull property:
curve contained within the
convex hull of control points
- Scale factor “3” is chosen to
make “velocity” approximately
constant



The Bezier Spline Formula

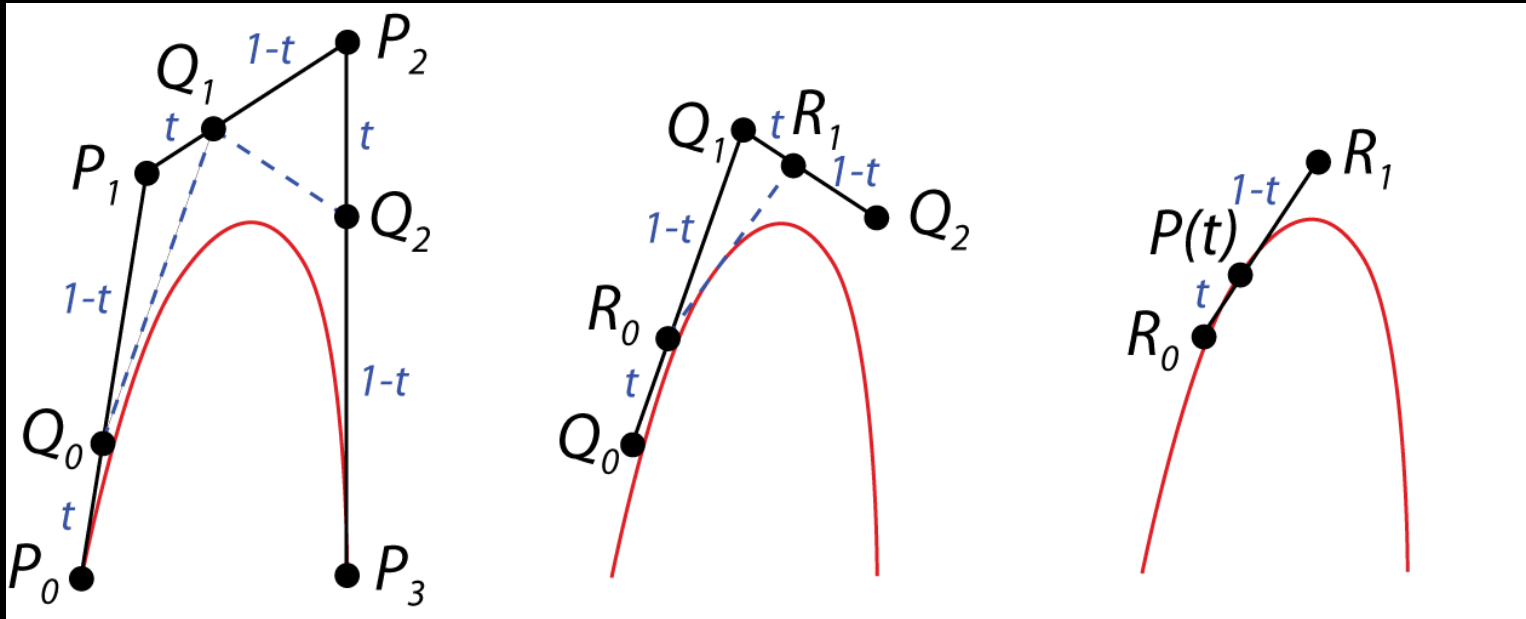
$$[x \ y \ z] = [u^3 \ u^2 \ u \ 1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \\ x_4 & y_4 & z_4 \end{bmatrix}$$

Bezier basis

Bezier
control matrix

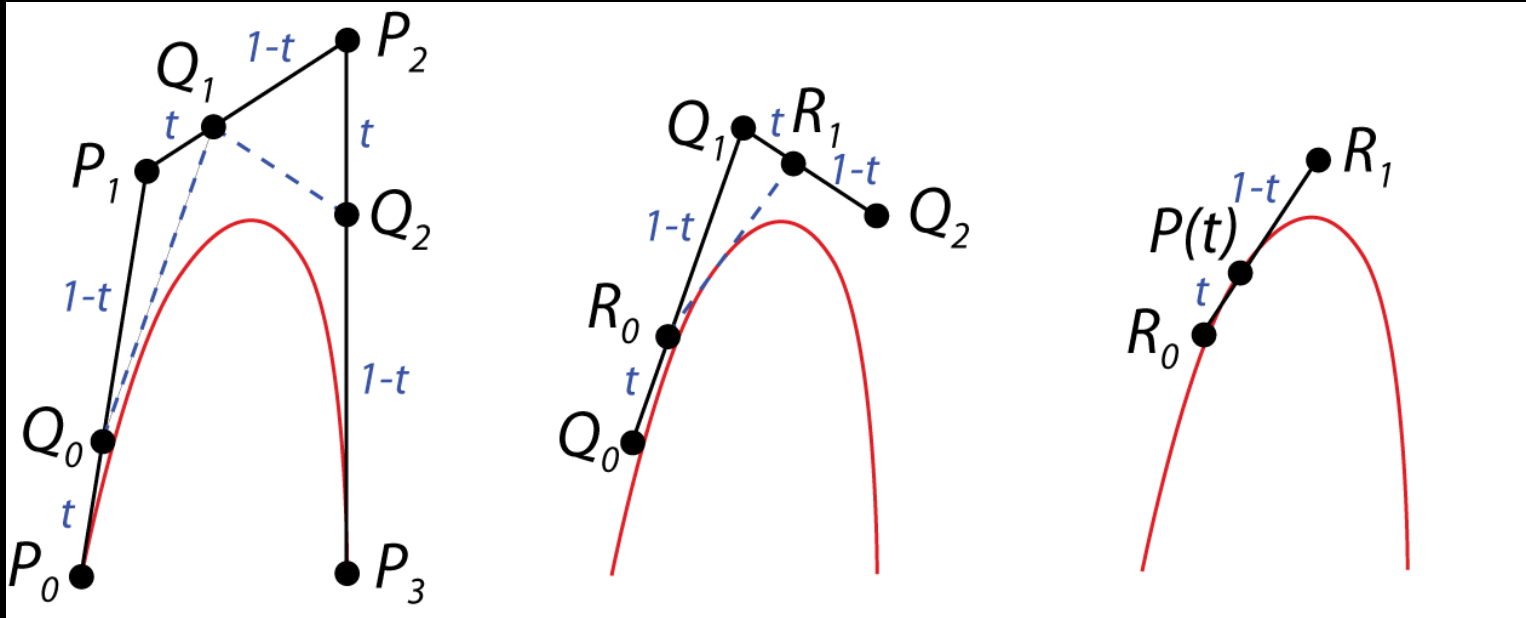
- $[x,y,z]$ is point on spline corresponding to u
- u varies from 0 to 1
- $P1 = [x_1 \ y_1 \ z_1]$ $P2 = [x_2 \ y_2 \ z_2]$
- $P3 = [x_3 \ y_3 \ z_3]$ $P4 = [x_4 \ y_4 \ z_4]$

DeCasteljau Construction



Efficient algorithm to evaluate Bezier splines.
Similar to Horner rule for polynomials.
Can be extended to interpolations of 3D rotations.

DeCasteljau on Quaternion Sphere

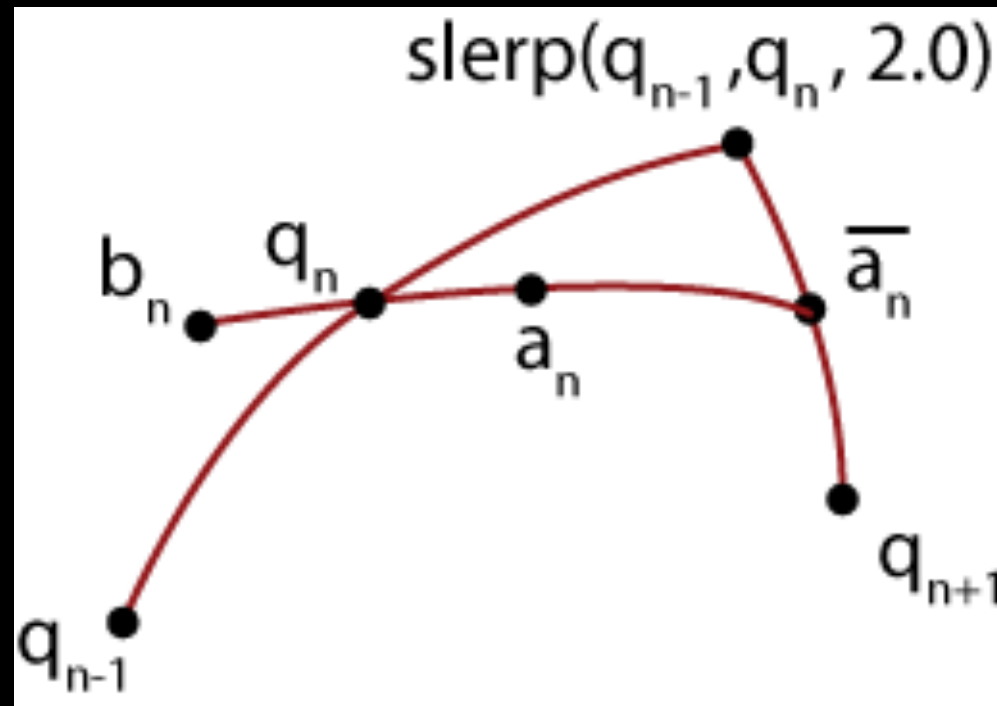


Given t , apply DeCasteljau construction:

$$\begin{aligned} Q_0 &= \text{Slerp}(P_0, P_1, t) & Q_1 &= \text{Slerp}(P_1, P_2, t) \\ Q_2 &= \text{Slerp}(P_2, P_3, t) & R_0 &= \text{Slerp}(Q_0, Q_1, t) \\ R_1 &= \text{Slerp}(Q_1, Q_2, t) & P(t) &= \text{Slerp}(R_0, R_1, t) \end{aligned}$$

Bezier Control Points for Quaternions

- Given quaternions q_{n-1} , q_n , q_{n+1} , form:
 $\bar{a}_n = \text{Slerp}(\text{Slerp}(q_{n-1}, q_n, 2.0), q_{n+1}, 0.5)$
 $a_n = \text{Slerp}(q_n, \bar{a}_n, 1.0 / 3)$
 $b_n = \text{Slerp}(q_n, \bar{a}_n, -1.0 / 3)$



Interpolating Many Rotations on Quaternion Sphere

- Given quaternions q_1, \dots, q_N , form Bezier spline control points (previous slide)
- Spline 1: q_1, a_1, b_2, q_2
- Spline 2: q_2, a_2, b_3, q_3 etc.
- Need a_1 and b_N ; can set
 $a_1 = \text{Slerp}(q_1, \text{Slerp}(q_3, q_2, 2.0), 1.0 / 3)$
 $b_N = \text{Slerp}(q_N, \text{Slerp}(q_{N-2}, q_{N-1}, 2.0), 1.0 / 3)$
- To evaluate a spline at any t , use DeCasteljau construction