3D Rotations and Complex Representations

Computer Graphics
CMU 15-462/15-662, Fall 2017
Rotations in 3D

- What is a rotation, intuitively?
- *How do you know a rotation when you see it?*
  - length/distance is preserved (no stretching/shearing)
  - lines get mapped to lines (linear)
  - orientation is preserved (e.g., text remains readable)
3D Rotations—Degrees of Freedom

- How many numbers do we need to specify a rotation in 3D?
- For instance, we could use rotations around X, Y, Z. But do we need all three?
- Well, to rotate Pittsburgh to another city (say, São Paulo), we have to specify two numbers: latitude & longitude:
- Do we really need both latitude and longitude? Or will one suffice?
- Is that the only rotation from Pittsburgh to São Paulo? (How many more numbers do we need?)

NO: We can keep São Paulo fixed as we rotate the globe.

Hence, we MUST have three degrees of freedom.
Commutativity of Rotations—2D

In 2D, order of rotations doesn’t matter:

Same result! (“2D rotations commute”)
Commutativity of Rotations—3D

- What about in 3D?

- IN-CLASS ACTIVITY:
  - Rotate 90° around Y, then 90° around Z, then 90° around X
  - Rotate 90° around Z, then 90° around Y, then 90° around X
  - (Was there any difference?)

CONCLUSION: bad things can happen if we’re not careful about the order in which we apply rotations!
Representing Rotations—2D

First things first: how do we get a rotation matrix in 2D? (Don’t just regurgitate the formula!)

Suppose I have a function $S(\theta)$ that for a given angle $\theta$ gives me the point $(x,y)$ around a circle (CCW).

- Right now, I do not care how this function is expressed!*

What’s $e_1$ rotated by $\theta$? $\tilde{e}_1 = S(\theta)$

What’s $e_2$ rotated by $\theta$? $\tilde{e}_2 = S(\theta + \pi/2)$

How about $u := a e_1 + b e_2$?

$$u := a S(\theta) + b S(\theta + \pi/2)$$

What then must the matrix look like?

$$\begin{bmatrix} S(\theta) & S(\theta + \pi/2) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos(\theta + \pi/2) \\ \sin(\theta) & \sin(\theta + \pi/2) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

*I.e., I don’t yet care about sines and cosines and so forth.*
Representing Rotations in 3D—Euler Angles

- How do we express rotations in 3D?
- One idea: we know how to do 2D rotations.
- Why not simply apply rotations around the three axes? (X,Y,Z)
- Scheme is called Euler angles
- PROBLEM: “Gimbal Lock” [DEMO]
Rotation from Axis/Angle

Alternatively, there is a general expression for a matrix that performs a rotation around a given axis \( u \) by a given angle \( \theta \):

\[
\begin{bmatrix}
\cos \theta + u_x^2 (1 - \cos \theta) & u_x u_y (1 - \cos \theta) - u_z \sin \theta & u_x u_z (1 - \cos \theta) + u_y \sin \theta \\
u_y u_x (1 - \cos \theta) + u_z \sin \theta & \cos \theta + u_y^2 (1 - \cos \theta) & u_y u_z (1 - \cos \theta) - u_x \sin \theta \\
u_z u_x (1 - \cos \theta) - u_y \sin \theta & u_z u_y (1 - \cos \theta) + u_x \sin \theta & \cos \theta + u_z^2 (1 - \cos \theta)
\end{bmatrix}
\]

Just memorize this matrix! :-(

...we’ll see a different way, later on.
Complex Analysis—Motivation

- Natural way to encode geometric transformations in 2D
- Simplifies code / notation / debugging / thinking
- Moderate reduction in computational cost/bandwidth/storage
- Fluency with complex analysis can lead into deeper/novel solutions to problems...

Truly: no good reason to use 2D vectors instead of complex numbers...
DON’T: Think of these numbers as “complex.”

DO: Imagine we’re simply defining additional operations (like dot and cross).
Imaginary Unit

\[ i \neq \sqrt{-1} \]

*nonsense*

More importantly: obscures geometric meaning.
Imaginary unit is just a quarter-turn in the counter-clockwise direction.
Complex Numbers

- Complex numbers are then just 2-vectors
- Instead of $e_1, e_1$, use “1” and “$i$” to denote the two bases
- Otherwise, behaves exactly like a real 2-dimensional space

...except that we’re also going to get a very useful new notion of the product between two vectors.
Complex Arithmetic

- Same operations as before, plus one more:

  vector addition

  \[ z_1 + z_2 \]

  scalar multiplication

  \[ az \]

  complex multiplication

  \[ z_1z_2 \]

- Complex multiplication:
  - angles *add*
  - magnitudes *multiply*

  “POLAR FORM”*:

  \[ z_1 := (r_1, \theta_1) \]

  \[ z_2 := (r_2, \theta_2) \]

  \[ z_1z_2 = (r_1r_2, \theta_1 + \theta_2) \]

*Not quite how it really works, but basic idea is right.
Complex Product—Rectangular Form

- Complex product in “rectangular” coordinates \((1, \iota)\):

\[
z_1 = (a + b\iota)
\]

\[
z_2 = (c + d\iota)
\]

\[
z_1 z_2 = ac + ad\iota + bc\iota + bд\iota^2 = (ac - bd) + (ad + bc)\iota.
\]

- We used a lot of “rules” here. Can you justify them geometrically?

- Does this product agree with our geometric description (last slide)?
Complex Product—Polar Form

Perhaps most beautiful identity in math:

\[ e^{i\pi} + 1 = 0 \]

Specialization of Euler’s formula:

\[ e^{i\theta} = \cos(\theta) + i \sin(\theta) \]

Can use to “implement” complex product:

\[ z_1 = ae^{i\theta}, \quad z_2 = be^{i\phi} \]

\[ z_1 z_2 = abe^{i(\theta + \phi)} \]

(as with real exponentiation, exponents add)

Q: How does this operation differ from our earlier, “fake” polar multiplication?
# 2D Rotations: Matrices vs. Complex

- Suppose we want to rotate a vector $u$ by an angle $\theta$, then by an angle $\phi$.

## REAL / RECTANGULAR

<table>
<thead>
<tr>
<th>$u = (x, y)$</th>
<th>$A = \begin{bmatrix} \cos \theta &amp; -\sin \theta \ \sin \theta &amp; \cos \theta \end{bmatrix}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B = \begin{bmatrix} \cos \phi &amp; -\sin \phi \ \sin \phi &amp; \cos \phi \end{bmatrix}$</td>
<td></td>
</tr>
</tbody>
</table>

| $Au = \begin{bmatrix} x \cos \theta - y \sin \theta \\ x \sin \theta + y \cos \theta \end{bmatrix}$ |

| $BAu = \begin{bmatrix} (x \cos \theta - y \sin \theta) \cos \phi - (x \sin \theta + y \cos \theta) \sin \phi \\ (x \cos \theta - y \sin \theta) \sin \phi + (x \sin \theta + y \cos \theta) \cos \phi \end{bmatrix}$ |

| $= \cdots$ some trigonometry $\cdots = $ |

| $BAu = \begin{bmatrix} x \cos(\theta + \phi) - y \sin(\theta + \phi) \\ x \sin(\theta + \phi) + y \cos(\theta + \phi) \end{bmatrix}$ |

## COMPLEX / POLAR

<table>
<thead>
<tr>
<th>$u = re^{i\alpha}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a = e^{i\theta}$</td>
</tr>
<tr>
<td>$b = e^{i\phi}$</td>
</tr>
</tbody>
</table>

| $abu = re^{i(\alpha + \theta + \phi)}$. |

(...and simplification is not always this obvious.)
Pervasive theme in graphics:

Sure, there are often many “equivalent” representations.

...But why not choose the one that makes life easiest*?

*Or most efficient, or most accurate...
Quaternions

- **TLDR:** Kind of like complex numbers but for 3D rotations
- **Weird situation:** can’t do 3D rotations w/ only 3 components!

William Rowan Hamilton (1805-1865)
Quaternions in Coordinates

- Hamilton’s insight: in order to do 3D rotations in a way that mimics complex numbers for 2D, actually need FOUR coords.
- One real, three imaginary:

\[ \mathbb{H} := \text{span}(\{1, i, j, k\}) \]

- Quaternion product determined by together w/ “natural” rules (distributivity, associativity, etc.)

\[ i^2 = j^2 = k^2 = ijk = -1 \]

- **WARNING**: product no longer commutes!

For \( q, p \in \mathbb{H} \), \( qp \neq pq \)

(Why might it make sense that it doesn’t commute?)
Quaternion Product in Components

- Given two quaternions

\[ q = a_1 + b_1 i + c_1 j + d_1 k \]
\[ p = a_2 + b_2 i + c_2 j + d_2 k \]

- Can express their product as

\[ qp = a_1 a_2 - b_1 b_2 - c_1 c_2 - d_1 d_2 \]
\[ + (a_1 b_2 + b_1 a_2 + c_1 d_2 - d_1 c_2) i \]
\[ + (a_1 c_2 - b_1 d_2 + c_1 a_2 + d_1 b_2) j \]
\[ + (a_1 d_2 + b_1 c_2 - c_1 b_2 + d_1 a_2) k \]

...fortunately there is a (much) nicer expression.
Quaternions—Scalar + Vector Form

- If we have four components, how do we talk about pts in 3D?
- Natural idea: we have three imaginary parts—why not use these to encode 3D vectors?

\[(x, y, z) \mapsto 0 + xi + yj + zj\]

- Alternatively, can think of a quaternion as a pair

\[(\text{scalar, vector}) \in \mathbb{H} \quad \cap \quad \mathbb{R} \quad \cap \quad \mathbb{R}^3\]

- Quaternion product then has simple(r) form:

\[(a, u)(b, v) = (ab - u \cdot v, au + bv + u \times v)\]

- For vectors in $\mathbb{R}^3$, gets even simpler:

\[uv = u \times v - u \cdot v\]
Main use for quaternions in graphics? *Rotations.*

Consider vector \( x \) ("pure imaginary") and *unit* quaternion \( q \):

\[
x \in \text{Im} (\mathbb{H})
\]
\[
q \in \mathbb{H}, \quad |q|^2 = 1
\]

always expresses *some* rotation
Rotation from Axis/Angle, Revisited

- Given axis $u$, angle $\theta$, quaternion $q$ representing rotation is

$$q = \cos(\theta/2) + \sin(\theta/2)u$$

- Slightly easier to remember (and manipulate) than matrix!

$$\begin{bmatrix}
\cos \theta + u_x^2 (1 - \cos \theta) & u_x u_y (1 - \cos \theta) - u_z \sin \theta & u_x u_z (1 - \cos \theta) + u_y \sin \theta \\
u_y u_x (1 - \cos \theta) + u_z \sin \theta & \cos \theta + u_y^2 (1 - \cos \theta) & u_y u_z (1 - \cos \theta) - u_x \sin \theta \\
u_z u_x (1 - \cos \theta) - u_y \sin \theta & u_z u_y (1 - \cos \theta) + u_x \sin \theta & \cos \theta + u_z^2 (1 - \cos \theta)
\end{bmatrix}$$
More Quaternions and Rotation

- Don’t have time to cover everything, but...

- Quaternions provide some very nice utility/perspective when it comes to rotations:
  - E.g., spherical linear interpolation (“slerp”)
  - Easy way to smoothly transition between orientations
  - No gimbal lock!
Where else are (hyper-)complex numbers useful in computer graphics?
Generating Coordinates for Texture Maps

Complex #s natural language for angle-preserving ("conformal") maps

Preserving angles in texture well-tuned to human perception...
Useless-But-Beautiful Example: Fractals

- Defined in terms of iteration on (hyper)complex numbers:

(Will see exactly how this works later in class.)
Quiz 4: Trees and Transformations

Last year’s student solutions: