10. Hierarchical Modeling

Symbols and instances

Most graphics APIs support a few geometric primitives:
- spheres
- cubes
- cylinders

These symbols are instanced using an instance transformation.

Q: What is the matrix for the instance transformation above?

Connecting primitives
3D Example: A robot arm

Consider this robot arm with 3 degrees of freedom:
- Base rotates about its vertical axis by $\theta$
- Upper arm rotates in its $xy$-plane by $\phi$
- Lower arm rotates in its $xy$-plane by $\psi$

Q: What matrix do we use to transform the base?
Q: What matrix for the upper arm?
Q: What matrix for the lower arm?

Robot arm implementation

The robot arm can be displayed by keeping a global matrix and computing it at each step:

```c
Matrix M_model;
main()
{
    
    robot_arm();
    
}

robot_arm()
{
    M_model = R_y(theta);
    base();
    M_model = R_y(theta)*T(0,h1,0)*R_z(phi);
    upper_arm();
    M_model = R_y(theta)*T(0,h1,0)*R_z(phi)*T(0,h2,0)*R_z(psi);
    lower_arm();
}
```

Do the matrix computations seem wasteful?

Robot arm implementation, better

Instead of recalculating the global matrix each time, we can just update it in place by concatenating matrices on the right:

```c
Matrix M_model;
main()
{
    
    robot_arm();
    
}

robot_arm()
{
    M_model *= R_y(theta);
    base();
    M_model *= T(0,h1,0)*R_z(phi);
    upper_arm();
    M_model *= T(0,h2,0)*R_z(psi);
    lower_arm();
}
```

Robot arm implementation, OpenGL

OpenGL maintains a global state matrix called the model-view matrix, which is updated by concatenating matrices on the right.

```c
main()
{
    
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
    robot_arm();
    
}

robot_arm()
{
    glRotatef( theta, 0.0, 1.0, 0.0 );
    base();
    glTranslatef( 0.0, h1, 0.0 );
    glRotatef( phi, 0.0, 0.0, 1.0 );
    lower_arm();
    glTranslatef( 0.0, h2, 0.0 );
    glRotatef( psi, 0.0, 0.0, 1.0 );
    upper_arm();
}
```
Hierarchical modeling

Hierarchical models can be composed of instances using trees or DAGs:

- edges contain geometric transformations
- nodes contain geometry (and possibly drawing attributes)

How might we draw the tree for the robot arm?

A complex example: human figure

Q: What’s the most sensible way to traverse this tree?

Human figure implementation, OpenGL

```c
figure()
{
    torso();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    head();
    glPopMatrix();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    left_upper_arm();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    left_lower_arm();
    glPopMatrix();
    glPopMatrix();
    . . .
}
```

Animation

The above examples are called **articulated models**:
- rigid parts
- connected by joints

They can be animated by specifying the joint angles (or other display parameters) as functions of time.
**Key-frame animation**

The most common method for character animation in production is **key-frame animation**.

- Each joint specified at various **key frames** (not necessarily the same as other joints)
- System does interpolation or **in-betweening**

Doing this well requires:

- A way of smoothly interpolating key frames: **splines**
- A good interactive system
- A lot of skill on the part of the animator

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**Scene graphs**

The idea of hierarchical modeling can be extended to an entire scene, encompassing:

- many different objects
- lights
- camera position

This is called a **scene tree** or **scene graph**.

[Scene graph diagram]