7. 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?

3D Example: A robot arm

Consider this robot arm with 3 degrees of freedom:

- Base rotates about its vertical axis by $\theta$
- Lower arm rotates in its $xy$-plane by $\phi$
- Upper arm rotates in its $xy$-plane by $\psi$

Q: What matrix do we use to transform the base?

Q: What matrix for the lower arm?

Q: What matrix for the 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?

Robot arm implementation

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

```cpp
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?
Instead of recalculating the global matrix each time, we can just update it in place:

```c
Matrix M_model;

main()
{
    ...
    M_model = Identity();
    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.

```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();
}
```

### Human figure implementation

We can also design code for drawing the human figure, with a slight modification due to the branches in the tree:

```c
figure()
{
    torso();
    M_save = M_model;
    M_model *= T(. . .)*R(. . .);
    head();
    M_model = M_save;
    M_model *= T(. . .)*R(. . .);
    left_upper_arm();
    M_model *= T(. . .)*R(. . .);
    left_lower_arm();
    M_model = M_save;
    ..
    ..
}
```

### Human figure with hand

What if we add a hand?

```c
figure()
{
    torso();
    M_save = M_model;
    M_model *= T(. . .)*R(. . .);
    head();
    M_model = M_save;
    M_model *= T(. . .)*R(. . .);
    left_upper_arm();
    M_model *= T(. . .)*R(. . .);
    left_lower_arm();
    M_model = M_save;
    left_hand();
    M_save2 = M_model;
    M_model *= T(. . .)*R(. . .);
    left_thumb();
    M_model = M_save2;
    M_model *= T(. . .)*R(. . .);
    left_forefinger();
    M_model = M_save2;
    ..
}
```

Is there a better way to keep track of piles of matrices that need to be saved, modified, and restored?
Human figure implementation, better

```cpp
figure()
{
    torso();
    push(M_model);
    M_model *= T(...)*R(...);
    head();
    M_model = pop(M_model);
    push(M_model);
    M_model *= T(...)*R(...);
    left_upper_arm();
    M_model *= T(...)*R(...);
    left_lower_arm();
    M_model *= T(...)*R(...);
    left_hand();
    push(M_model);
    M_model *= T(...)*R(...);
    left_thumb();
    M_model = pop(M_model);
    push(M_model);
    M_model *= T(...)*R(...);
    left_forefinger();
    M_model = pop(M_model);
    push(M_model);
    ...
}
```

Human figure implementation, OpenGL

```cpp
figure()
{
    torso();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    glPopMatrix();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    left_upper_arm();
    glTranslate(...);
    glRotate(...);
    left_lower_arm();
    glTranslate(...);
    glRotate(...);
    left_hand();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    left_thumb();
    glPopMatrix();
    glPushMatrix();
    glTranslate(...);
    glRotate(...);
    left_forefinger();
    glPopMatrix();
    ...
}
```

The Matrix Stack

Trace of OpenGL calls
- `glLoadIdentity();`
- `glPushMatrix();`
- `glTranslatef(Tx,Ty,0);`
- `glRotatef(u,0,0,1);`
- `glTranslatef(-px,-py,0);`
- `glPushMatrix();`
- `glTranslatef(qx,qy,0);`
- `glRotatef(v,0,0,1);`
- `glTranslatef(-rx,-ry,0);`
- `Draw(A);`
- `glPopMatrix();`
- `Draw(B);`

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.
Kinematics and dynamics

Definitions:
- **Kinematics**: how the positions of the parts vary as a function of the joint angles.
- **Dynamics**: how the positions of the parts vary as a function of applied forces.

Questions:
- Q: What do the terms inverse kinematics and inverse dynamics mean?
- Q: Why are these problems more difficult?

Key-frame animation

One way to get around these problems is to use 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

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**.

The peculiarity of OpenGL ordering

Let’s revisit the very first simple example in this lecture.

To draw the transformed house, we would write OpenGL code like:

```c
glMatrixMode( GL_MODELVIEW );
glLoadIdentity();
glTranslatef( ... );
glRotatef( ... );
glScalef( ... );
house();
```

Is there something a little funny about the order of operations?

Why was OpenGL designed this way?
Global, fixed coordinate system

OpenGL’s transforms, logical as they may be, still seem backwards. They are, if you think of them as transforming the object in a fixed coordinate system.

Local, changing coordinate system

Another way to view transformations is as affecting a local coordinate system that the primitive is drawn in. Now the transforms appear in the “right” order.

Summary

Here’s what you should take home from this lecture:

- All the boldfaced terms.
- How primitives can be instanced and composed to create hierarchical models using geometric transforms.
- How the notion of a model tree or DAG can be extended to entire scenes.
- How keyframe animation works.
- How transforms can be thought of as affecting either the geometry, or the coordinate system which it is drawn in.