

Hierarchical Modeling

Reading

- ◆ Angel, *Interactive Computer Graphics*, sections 8.1 - 8.6

Optional

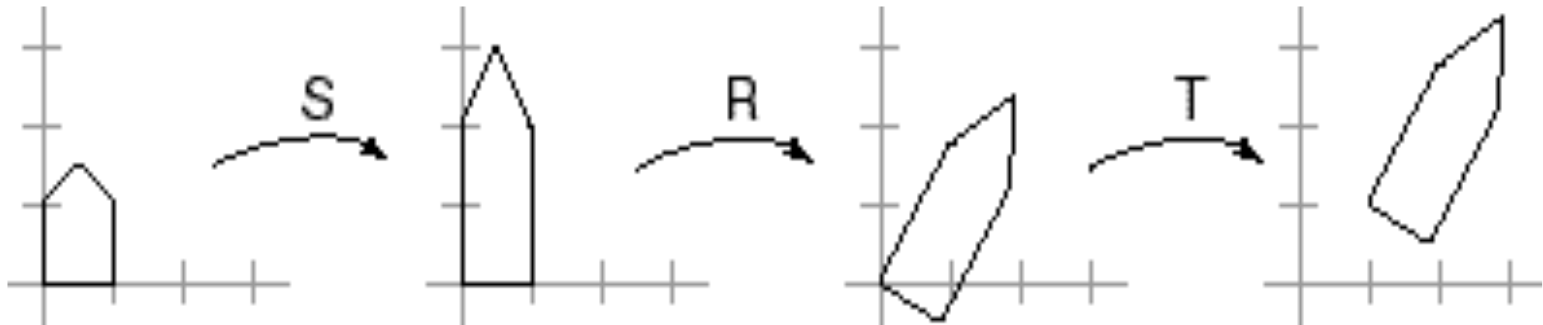
- ◆ Foley, *Computer Graphics, Chapter 5*.
- ◆ *OpenGL Programming Guide*, chapter 3

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?

Instancing in OpenGL

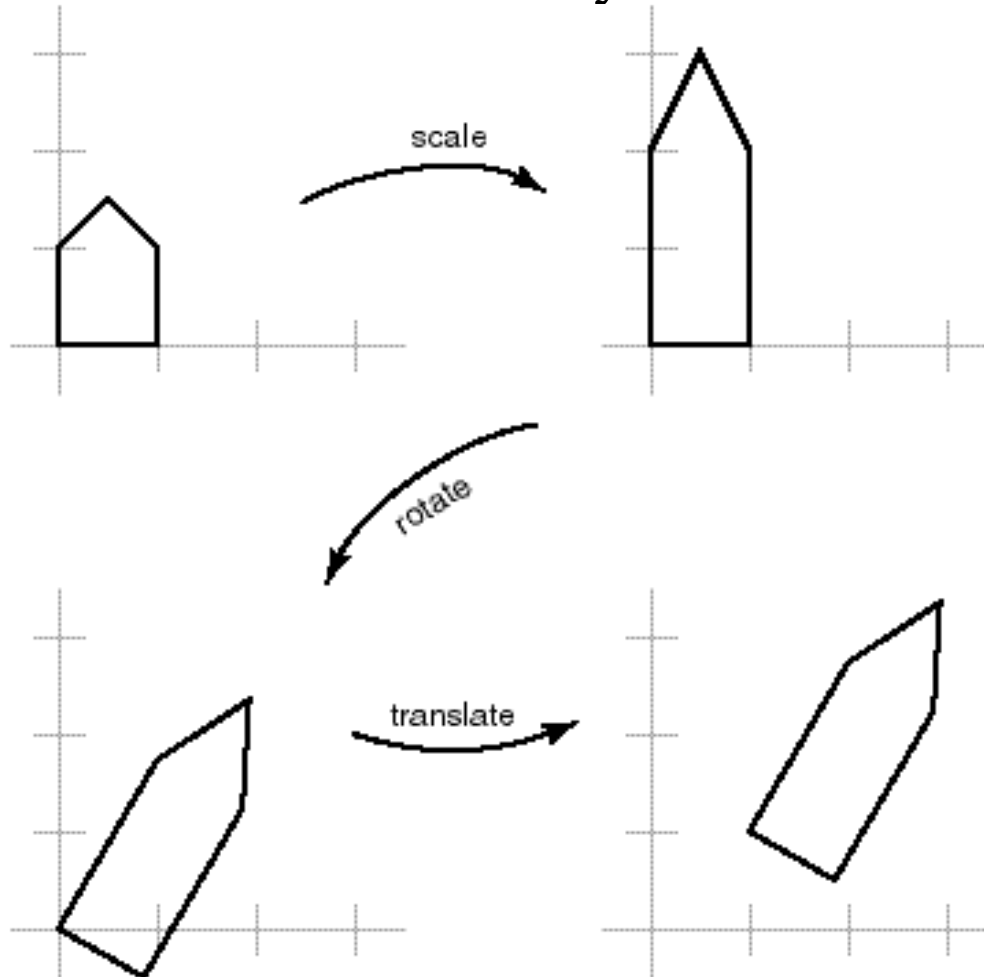
In OpenGL, instancing is created by modifying the **model-view** matrix:

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

Do the transforms seem to be backwards?

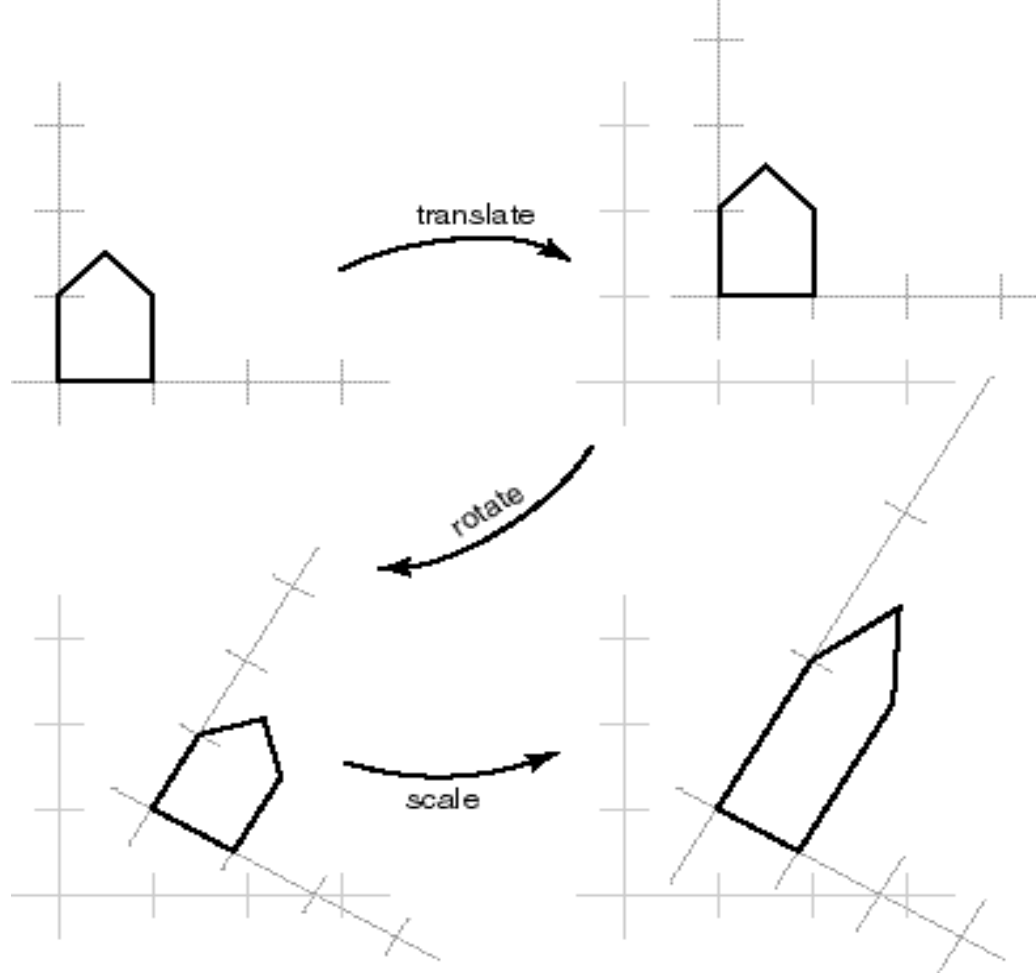
Global, fixed coordinate system

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.



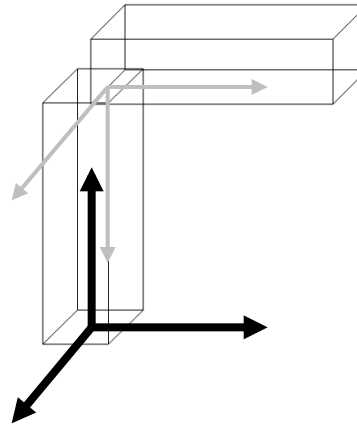
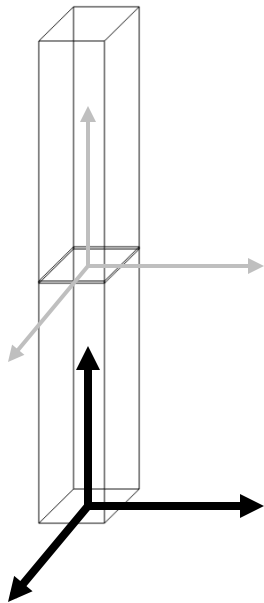
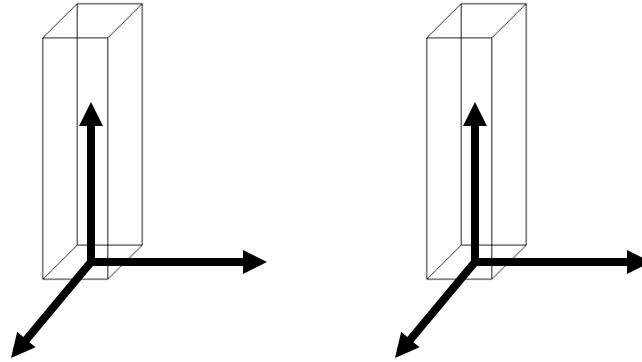
Instancing in real OpenGL

The advantage of right-multiplication is that it places the *earlier* transforms *closer* to the primitive.

```
glPushMatrix();  
glTranslate( ... );  
glRotate( ... );  
house();  
glPopMatrix();
```

```
glPushMatrix();  
glTranslate( ... );  
glRotate( ... );  
house();  
glPopMatrix();
```

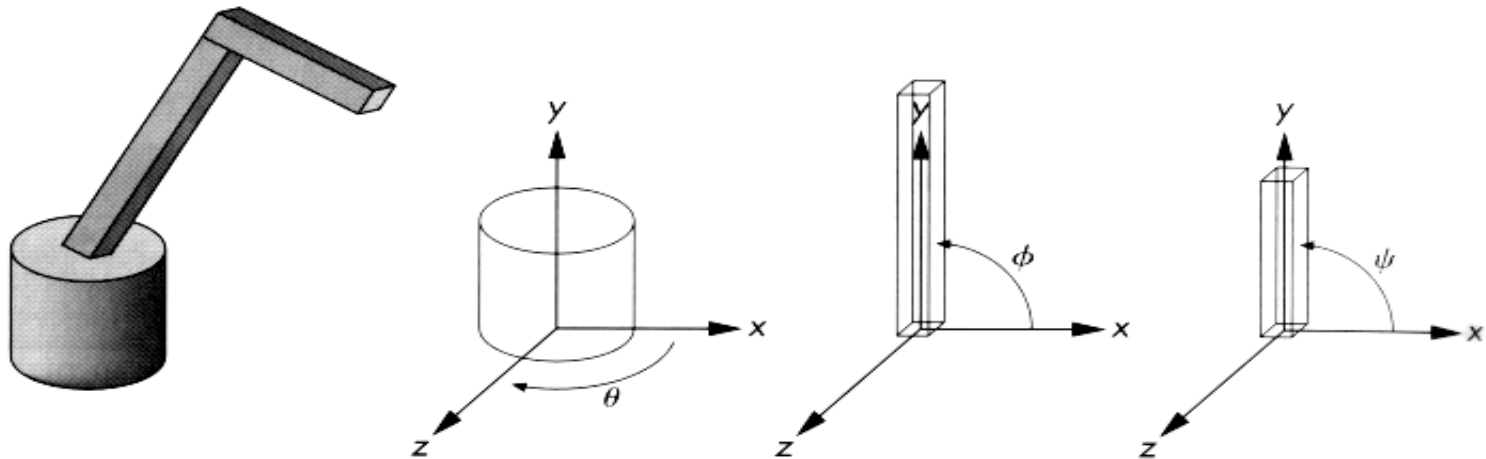
Connecting Primitives



3D Example: A robot arm

Consider this robot arm with 3 degrees of freedom:

- ◆ Base rotates about its vertical axis by θ
- ◆ Lower arm rotates in its xy -plane by ϕ
- ◆ Upper arm rotates in its xy -plane by ψ



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

Q: What matrix for the lower arm?

Q: What matrix for the upper arm?



Robot arm implementation

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

```
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*:

```
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();
}
```

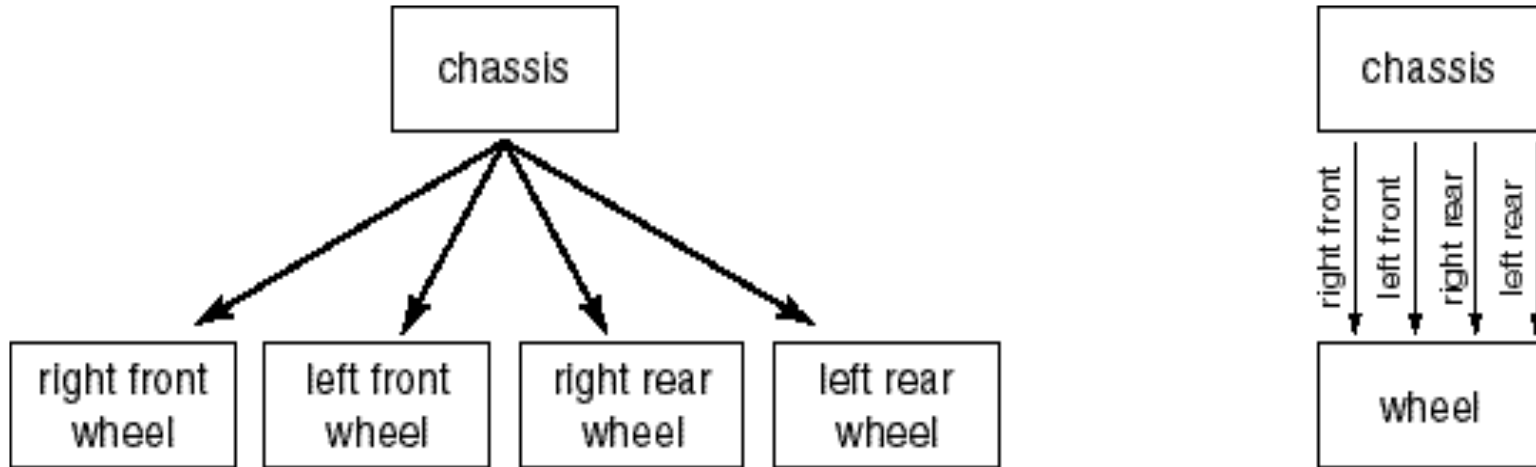
Robot arm implementation, OpenGL

OpenGL maintains a global state matrix called the **model-view matrix**.

```
main()
{
    . . .
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
    robot_arm(a, b, c);
    . . .
}
robot_arm(theta, phi, psi)
{
    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();
}
```

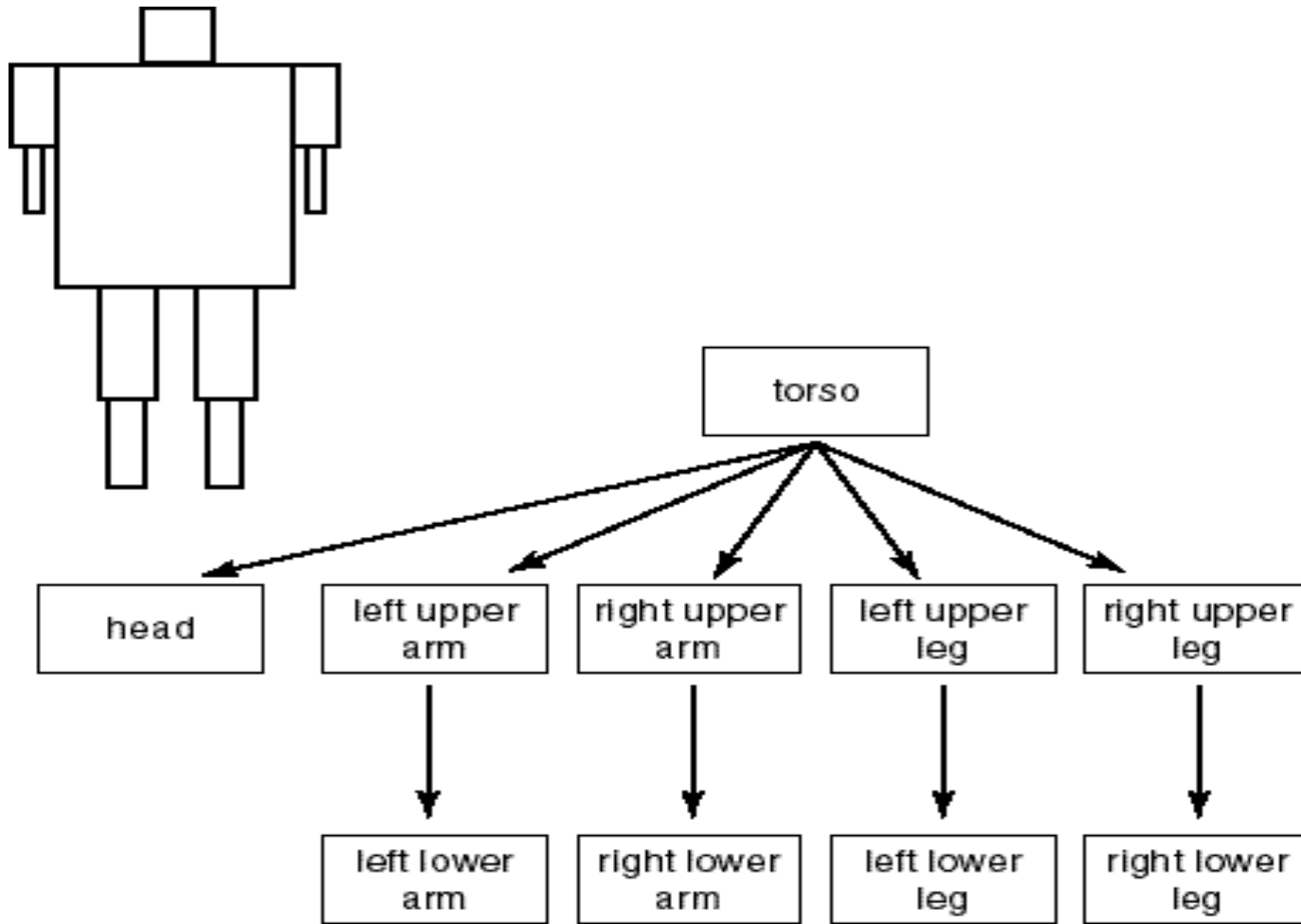
Hierarchical modeling

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



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

A complex example: human figure



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

Human figure implementation

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

```
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?

```
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 *= T(. . .)*R(. . .);
  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

```
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

```
figure() {  
    torso();  
    glPushMatrix();  
        glTranslate( ... );  
        glRotate( ... );  
        head();  
    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);  
glPopMatrix();
```



I

$I T(tx, ty) Rz(u) T(-px, -py)$

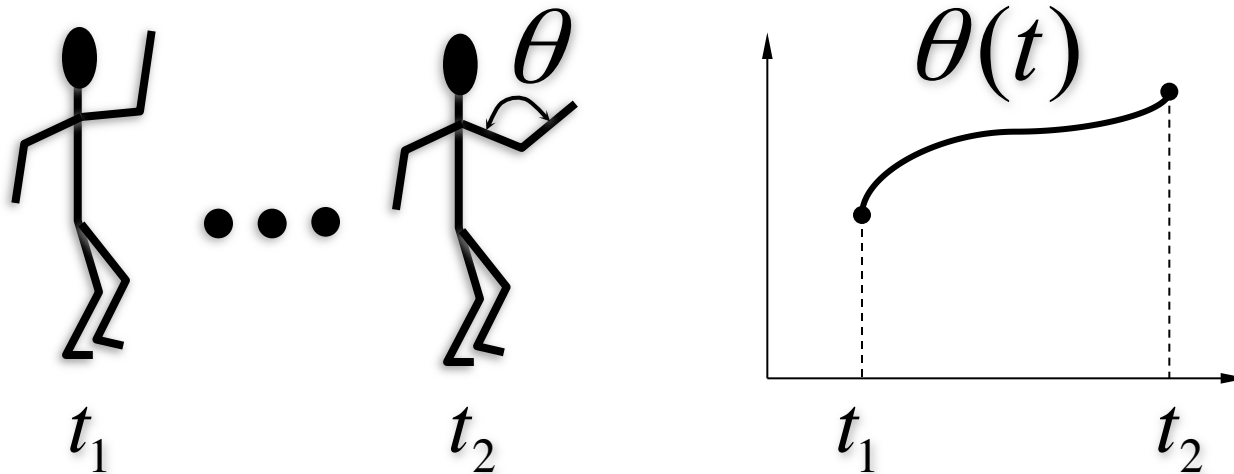
$I T(tx, ty) Rz(u) T(-px, -py) T(qx, qy) Rz(v) T(-rx, -ry)$

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

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

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:

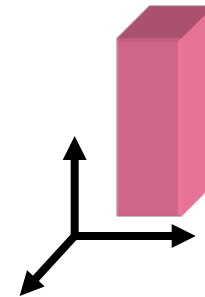
Q: What do the terms **inverse kinematics** and **inverse dynamics** mean?

Q: Why are these problems more difficult?

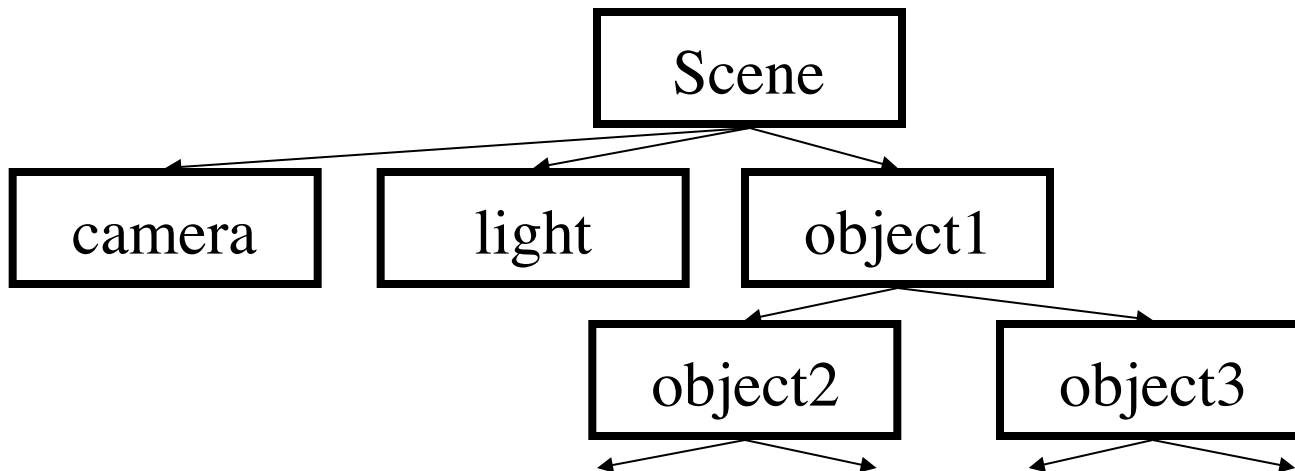
Scene graphs

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**.



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.