Hierarchical Modeling

CSE 457, Autumn 2003

Graphics

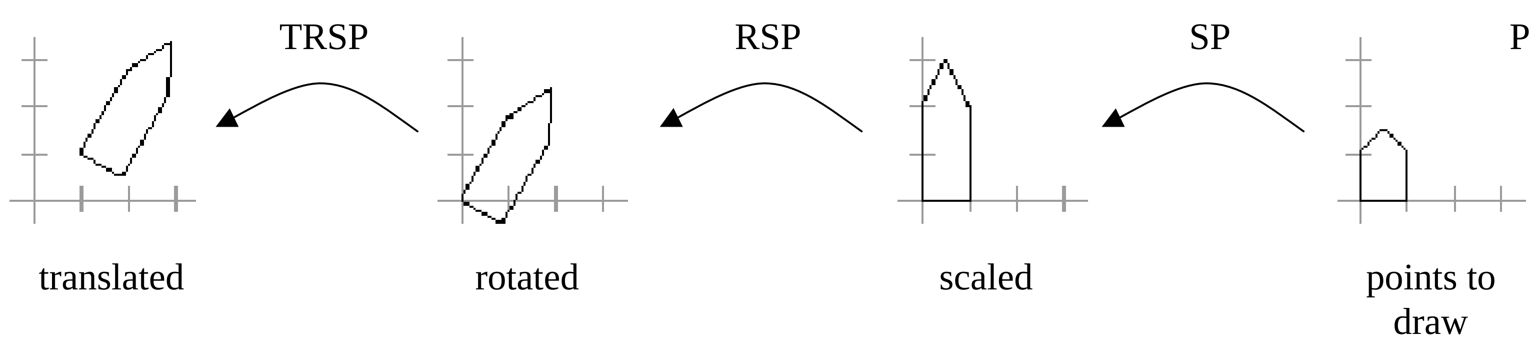
http://www.cs.washington.edu/education/courses/457/03au/

References

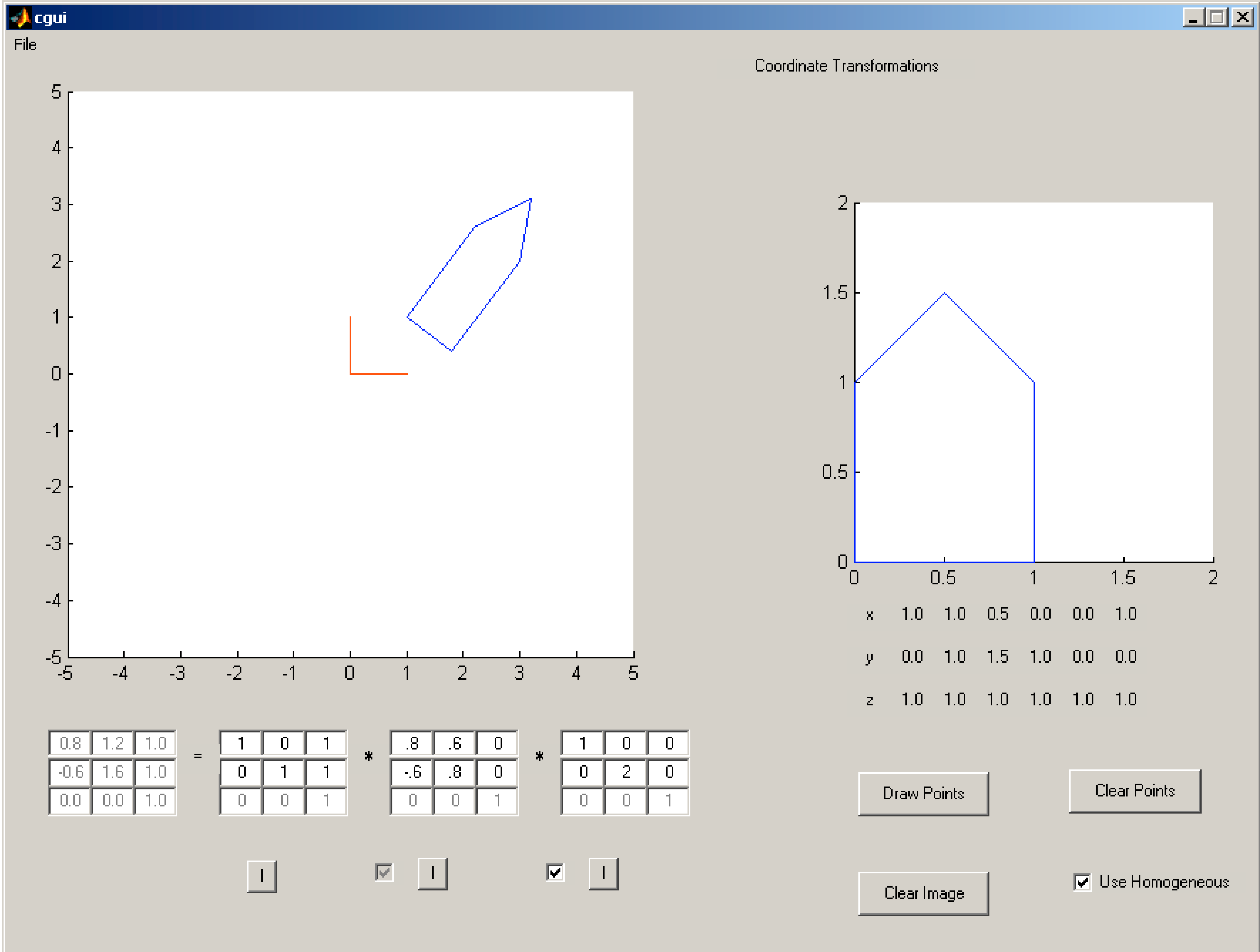
- *OpenGL Programming Guide*, The Red Book, chapter 3
- *Interactive Computer Graphics, A Top Down Approach with OpenGL*, E. Angel, sections 8.1 - 8.6

Symbols and instances

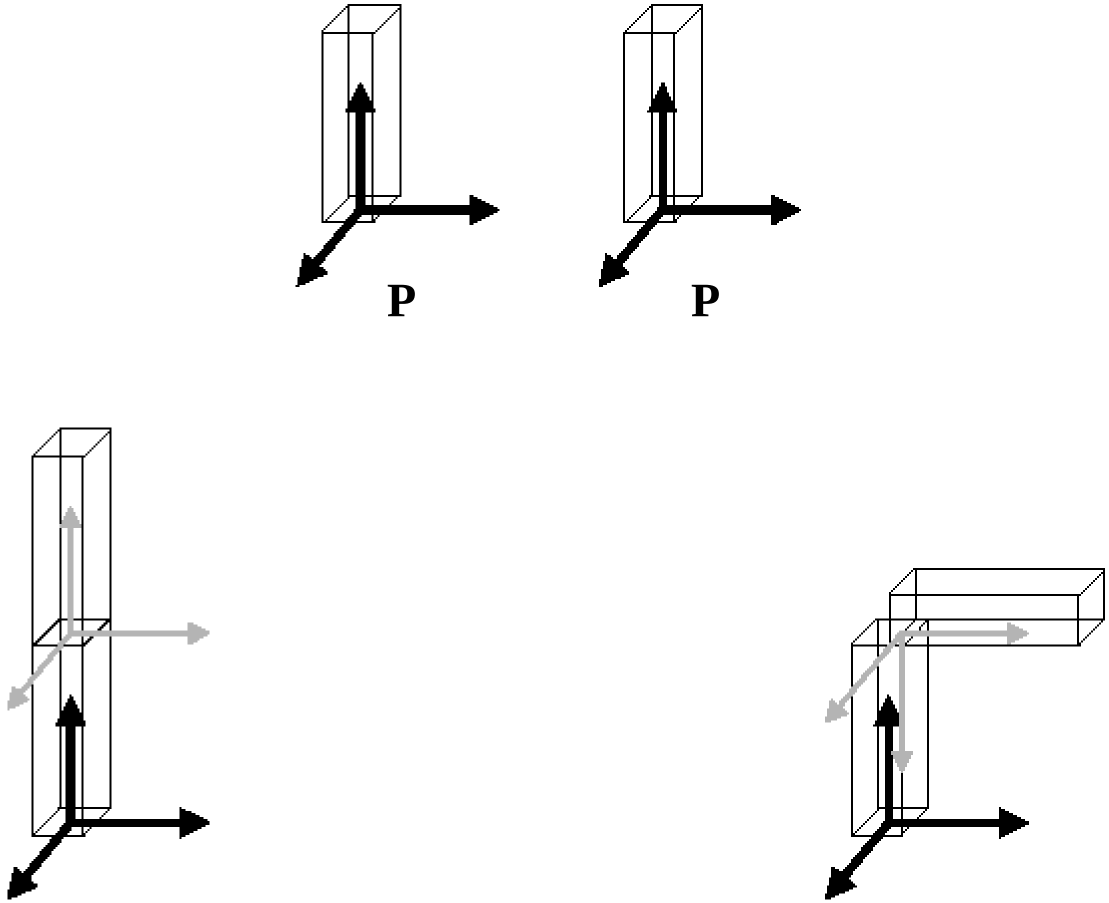
- Most graphics APIs support a few geometric **primitives**:
  - » spheres, cubes, cylinders
  - » these procedures define points for you, but they're still just points **P**
- These symbols are **instanced** using an **instance transformation**.
  - » the points are originally defined in a local coordinate system (eg, unit cube)



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

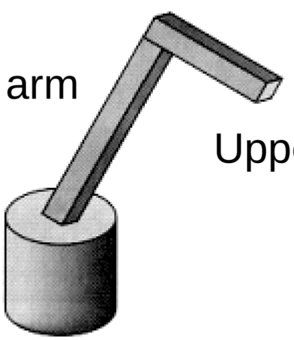

cgui
File
Coordinate Transformations
x 1.0 1.0 0.5 0.0 0.0 1.0
y 0.0 1.0 1.5 1.0 0.0 0.0
z 1.0 1.0 1.0 1.0 1.0 1.0
0.8 1.2 1.0
-0.6 1.6 1.0
0.0 0.0 1.0
=
1 0 1
0 1 1
0 0 1
*
.8 .6 0
-.6 .8 0
0 0 1
*
1 0 0
0 2 0
0 0 1
Draw Points
Clear Points
Clear Image
Use Homogeneous

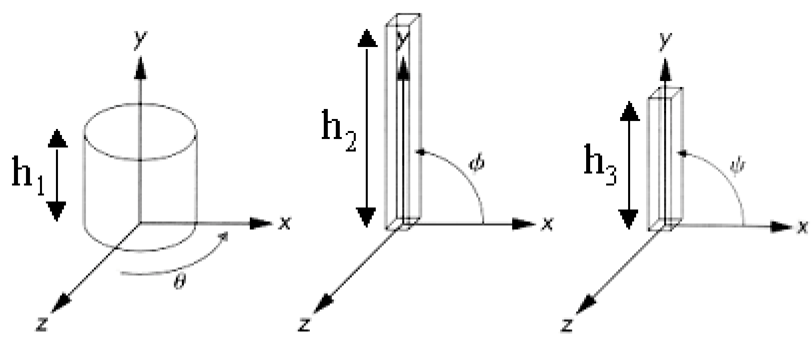
Connecting primitives



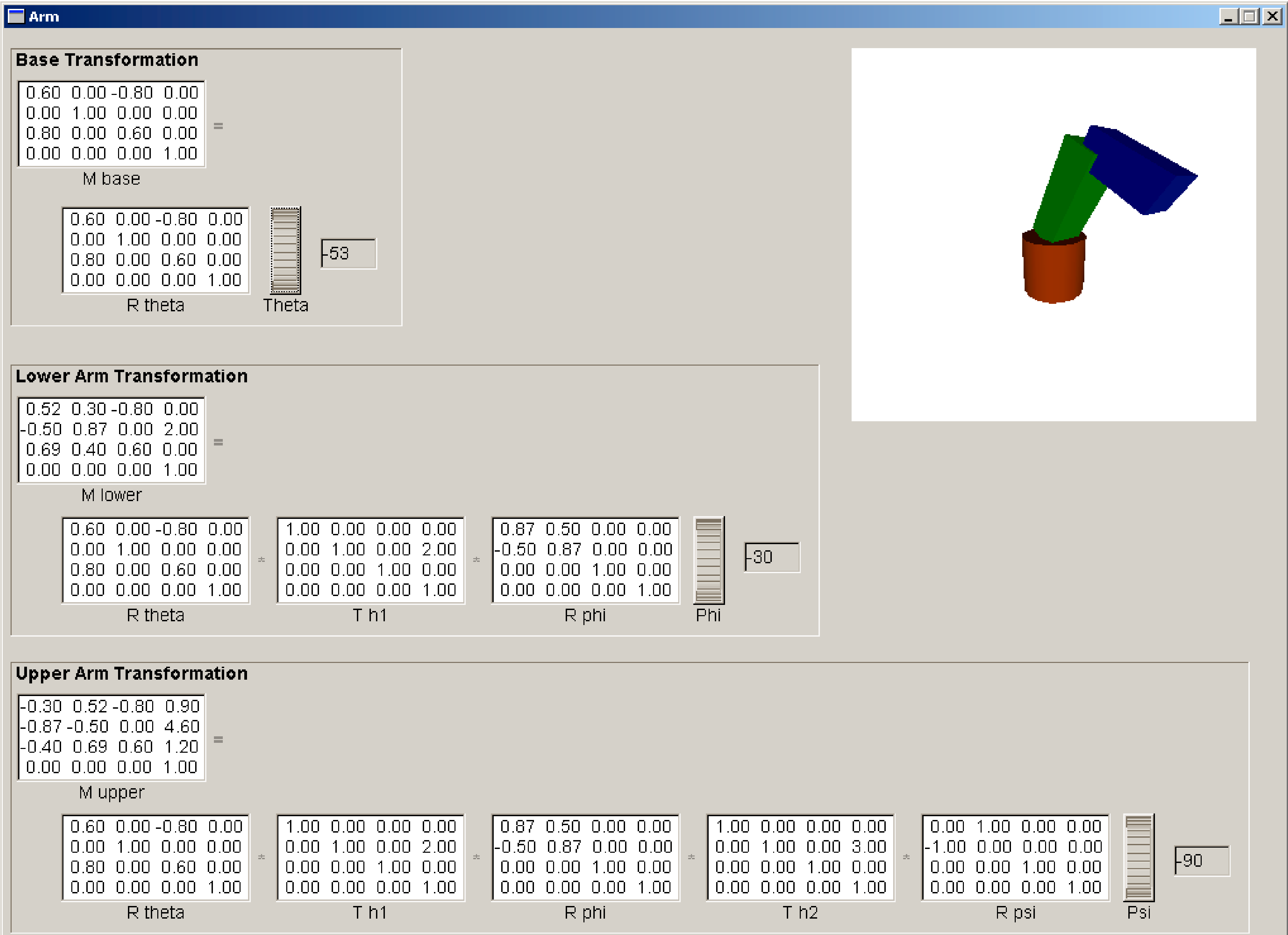
3D Example: A robot arm

- 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? the upper arm? the lower arm?


Arm
Base Transformation
0.60 0.00 -0.80 0.00
0.00 1.00 0.00 0.00
0.80 0.00 0.60 0.00
0.00 0.00 0.00 1.00
=
M base
0.60 0.00 -0.80 0.00
0.00 1.00 0.00 0.00
0.80 0.00 0.60 0.00
0.00 0.00 0.00 1.00
R theta
Theta
-53
Lower Arm Transformation
0.52 0.30 -0.80 0.00
-0.50 0.87 0.00 2.00
0.69 0.40 0.60 0.00
0.00 0.00 0.00 1.00
=
M lower
0.60 0.00 -0.80 0.00
0.00 1.00 0.00 0.00
0.80 0.00 0.60 0.00
0.00 0.00 0.00 1.00
R theta
*
1.00 0.00 0.00 0.00
0.00 1.00 0.00 2.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
T h1
*
0.87 0.50 0.00 0.00
-0.50 0.87 0.00 0.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
R phi
Phi
-30
Upper Arm Transformation
-0.30 0.52 -0.80 0.90
-0.87 -0.50 0.00 4.60
-0.40 0.69 0.60 1.20
0.00 0.00 0.00 1.00
=
M upper
0.60 0.00 -0.80 0.00
0.00 1.00 0.00 0.00
0.80 0.00 0.60 0.00
0.00 0.00 0.00 1.00
R theta
*
1.00 0.00 0.00 0.00
0.00 1.00 0.00 2.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
T h1
*
0.87 0.50 0.00 0.00
-0.50 0.87 0.00 0.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
R phi
*
1.00 0.00 0.00 0.00
0.00 1.00 0.00 3.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
T h2
*
0.00 1.00 0.00 0.00
-1.00 0.00 0.00 0.00
0.00 0.00 1.00 0.00
0.00 0.00 0.00 1.00
R psi
Psi
-90

Robot arm implementation

The robot arm could be displayed by using a global matrix and recomputing 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 just a tad wasteful?

Robot arm implementation, better

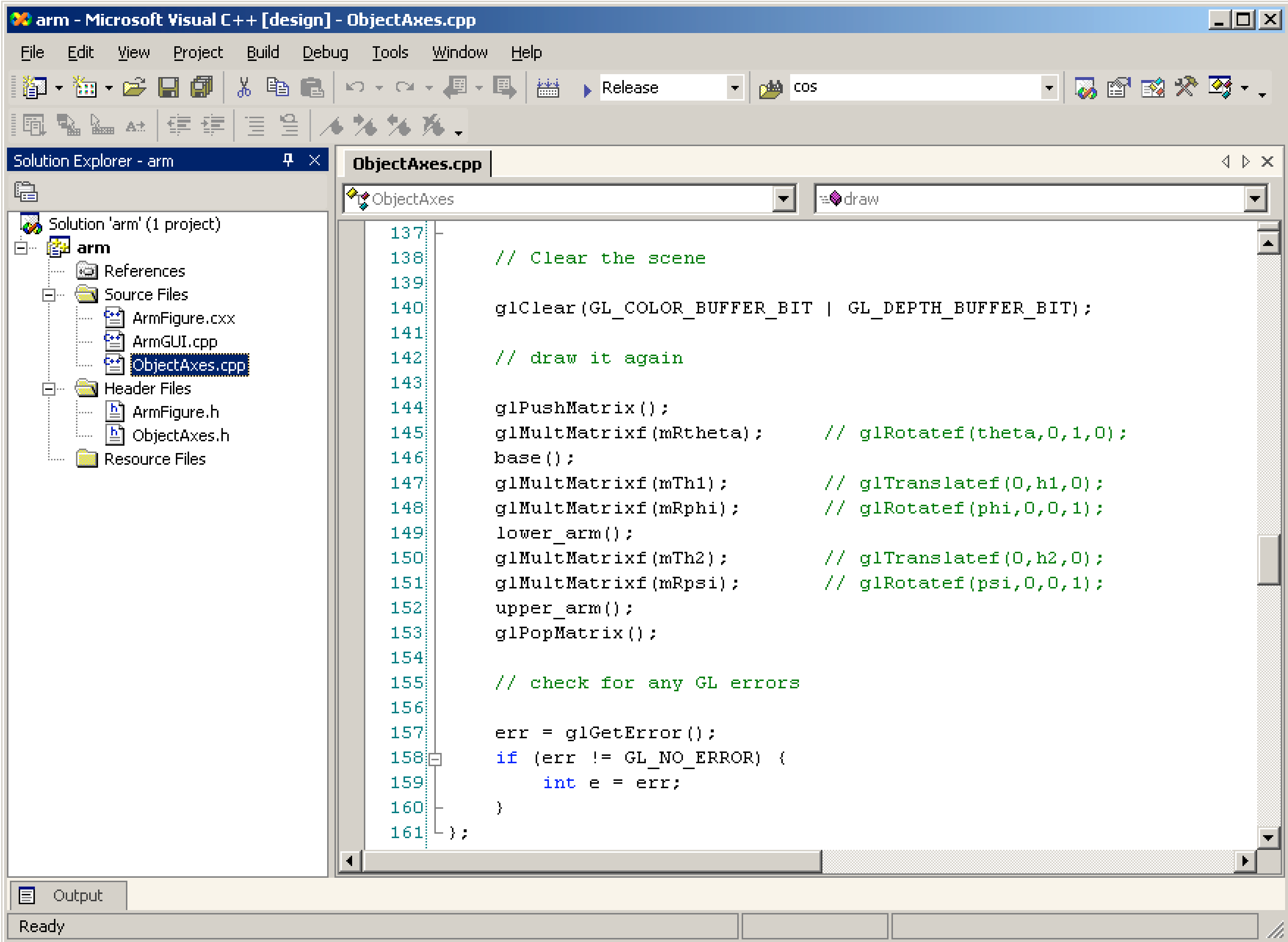
Instead of recalculating the global matrix each time, we could just update it as we go along:

```
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**.

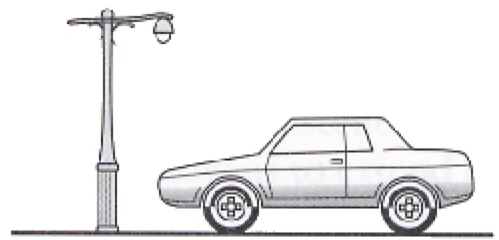
```
main() {
    . . .
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
    robot_arm();
    . . .
}

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 );
    upper_arm();
    glTranslatef( 0.0, h2, 0.0 );
    glRotatef( psi, 0.0, 0.0, 1.0 );
    lower_arm();
}
```

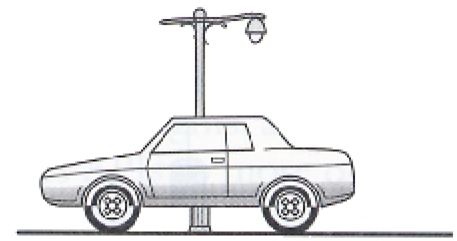

arm - Microsoft Visual C++ [design] - ObjectAxes.cpp
File Edit View Project Build Debug Tools Window Help
Release
cos
Solution Explorer - arm
Solution 'arm' (1 project)
arm
References
Source Files
ArmFigure.cxx
ArmGUI.cpp
ObjectAxes.cpp
Header Files
ArmFigure.h
ObjectAxes.h
Resource Files
ObjectAxes.cpp
ObjectAxes
draw
// Clear the scene
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
// draw it again
glPushMatrix();
glMultMatrixf(mRtheta); // glRotatef(theta,0,1,0);
base();
glMultMatrixf(mTh1); // glTranslatef(0,h1,0);
glMultMatrixf(mRphi); // glRotatef(phi,0,0,1);
lower_arm();
glMultMatrixf(mTh2); // glTranslatef(0,h2,0);
glMultMatrixf(mRpsi); // glRotatef(psi,0,0,1);
upper_arm();
glPopMatrix();
// check for any GL errors
err = glGetError();
if (err != GL_NO_ERROR) {
int e = err;
}
};
Output
Ready

Hierarchical modeling

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

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





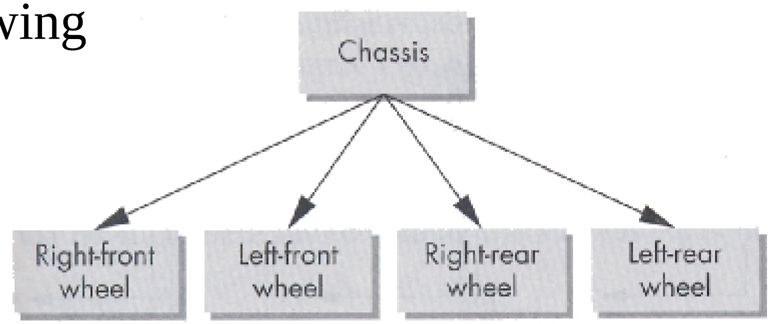


Figure 8.6 Tree structure for automobile.

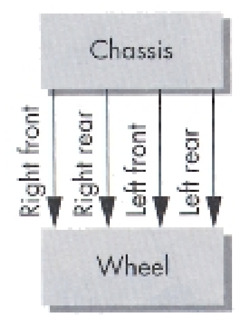
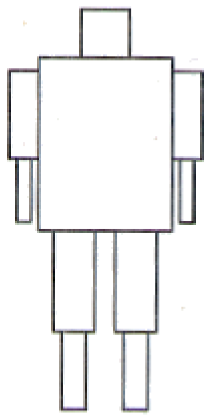


Figure 8.7 Directed-acyclic-graph (DAG) model of automobile.

figures from Angel

Another example: human figure



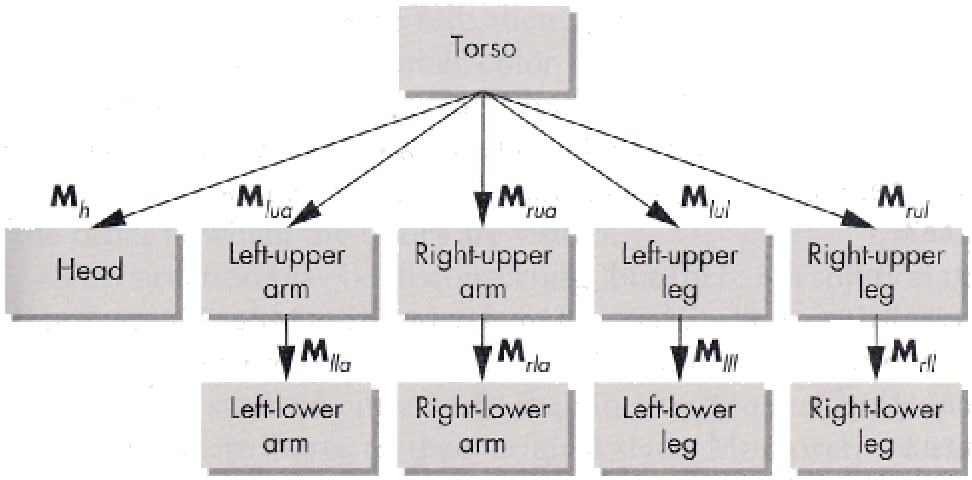


Figure 8.14 Tree with matrices.

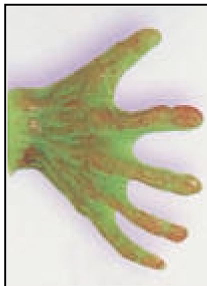
Q: What's a sensible way to traverse this tree?

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;
    ...
}
```

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?

Push and pop

```
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);
    . . .
}
```

Push and pop, 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();
    . . .
}
```

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

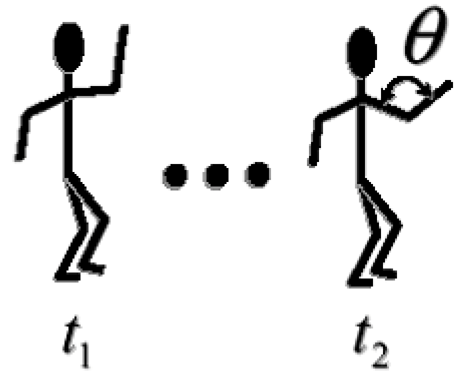
- Definitions:
  - » **Kinematics:** how the positions of the parts vary as a function of the joint angles.
  - » **Dynamics:** how the positions of the parts vary as a function of applied forces.

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

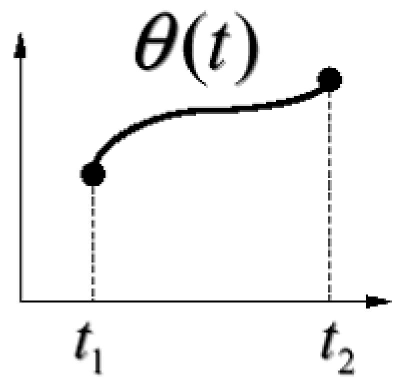
Key-frame animation

- 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**

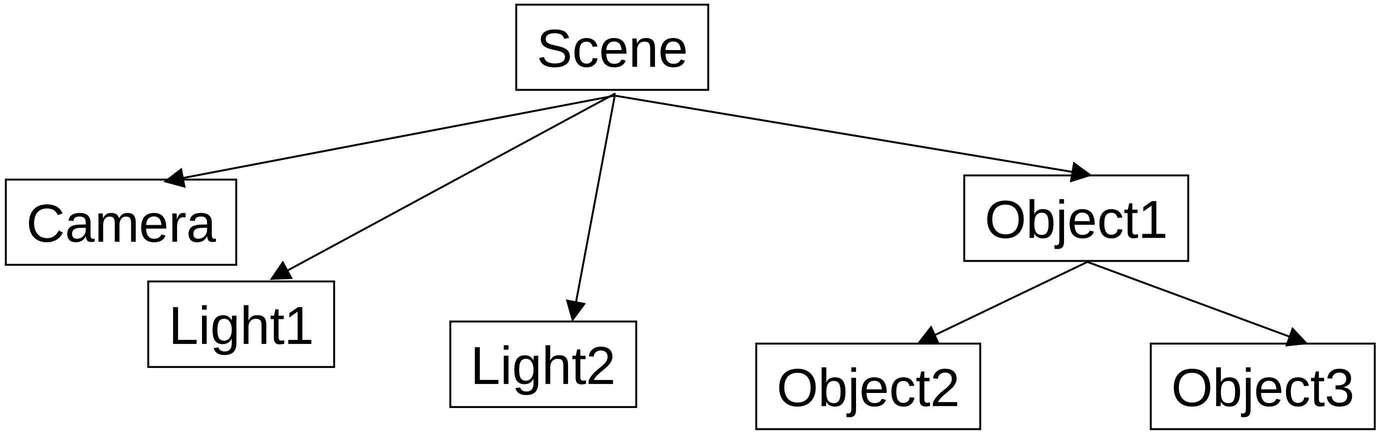


- Doing this well requires:
  A way of smoothly interpolating key frames: **splines**
  A good interactive system
  A lot of skill on the part of the animator



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**.



Order of transformations

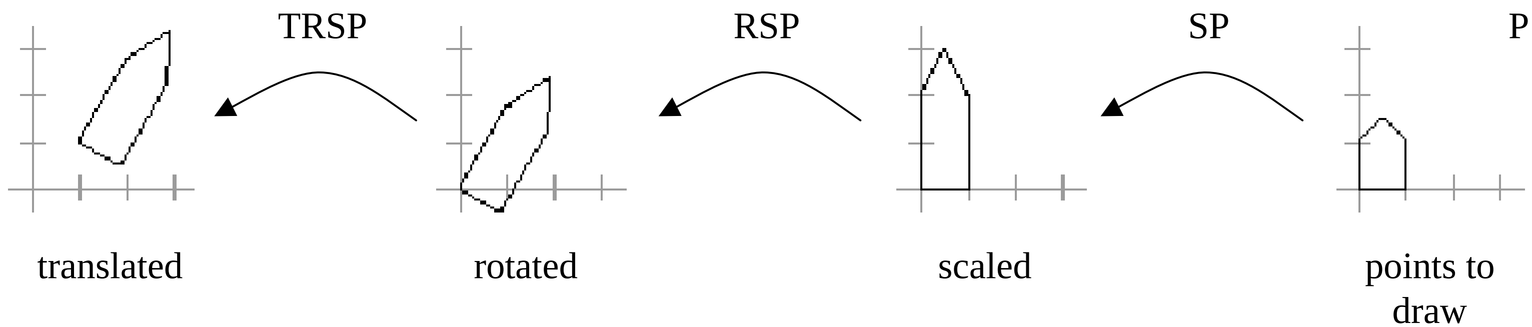
- Let's revisit the very first simple example in this lecture.
- To draw the transformed house, we would write OpenGL code like:

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

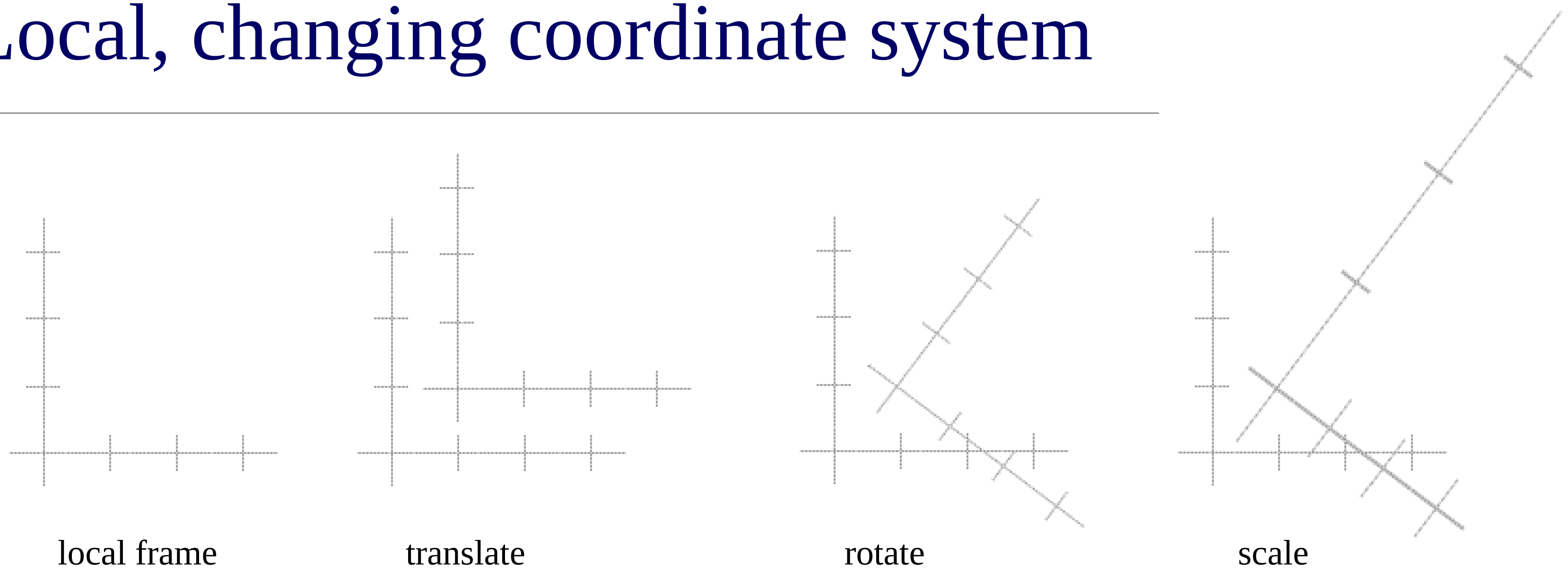
Note that we are building the composite transformation matrix by starting from the left and postmultiplying each additional matrix

Global, fixed coordinate system

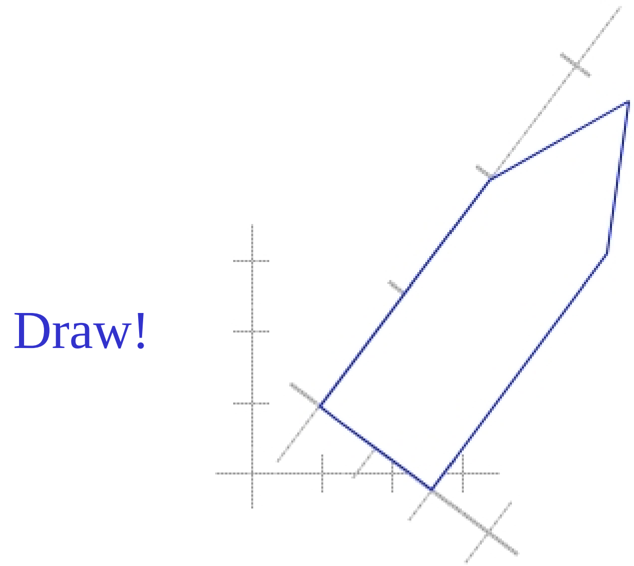
- One way to think of transformations is as movement of points in a *global, fixed coordinate system*
  - » Build the transformation matrix sequentially from left to right: T, then R, then S
  - » Then apply the transformation matrix to the object points: multiply all the points in P by the composite matrix TRS
    - this transformation takes the points from original to final positions



Local, changing coordinate system



- Another way to think of transformations is as affecting a *local coordinate system* that the primitive is eventually drawn in.
  - » This is EXACTLY the same transformation as on the previous page, it's just how you look at it.



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.