Using the Stencil Buffer

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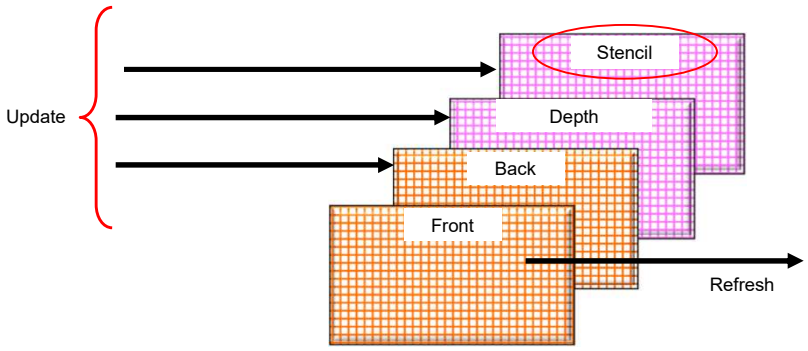
The Framebuffers



Here's what the Stencil Buffer can do for you:

1. While drawing into the Back Buffer, you can write values into the Stencil Buffer at the same time.
2. While drawing into the Back Buffer, you can do arithmetic on values in the Stencil Buffer at the same time.
3. While drawing into the Back Buffer, the Stencil Buffer can be used to write-protect certain parts of the Back Buffer.

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You Can Think of the Stencil Buffer as a Separate Framebuffer, or, You Can Think of it as being Per-Pixel

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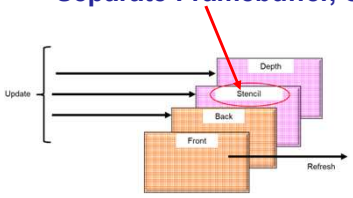

Both are correct, but I like thinking of it "per-pixel" better.

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The Stencil Buffer is Tested Per-Pixel, Very Much Like the Depth Buffer Is

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glStencilFunc(func, ref, mask)

This specifies the comparison test that is to be done per-pixel.

func can be any of GL_NEVER, GL_ALWAYS, GL_EQUAL, GL_NOTEQUAL, GL_LESS, GL_LEQUAL, GL_GREATER, GL_GEQUAL

ref is an integer reference value that is used to test the pixel's existing stencil value against using the chosen ***func***

mask is set to 1 in all these examples

The stencil test produces a *true* or *false* value at each pixel where drawing is to be done.

```
if( ref  <func>  S_existing is true )
{
        Allow the color write to the existing pixel to take place;
        Modify the pixel's existing stencil value depending on what the glStencilOp says to do;
}
```

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This Tells You What to Do with the *true* or *false* Value from the Stencil Test

glStencilOp(sfail, zfail, zpass)

This specifies how a pixel's stencil value is modified when a fragment passes or fails the stencil test depending on what combinations of *true* and *false* the stencil test and the depth buffer test produce. If the stencil test fails, then *sfail* happens. If the stencil test succeeds, then either *zfail* or *zpass* happen depending on if the depth-buffer test failed or succeeded.

The three values can be any of:

GL_KEEP	Retain the existing stencil value
GL_ZERO	Set the stencil value to zero
GL_REPLACE	Replace the stencil value with **ref** from the Stencil Func
GL_INCR	Increment the stencil value, with clamping
GL_INCR_WRAP	Increment the stencil value, without clamping
GL_DECR	Decrement the stencil value, with clamping
GL_DECR_WRAP	Decrement the stencil value, without clamping
GL_INVERT	Bitwise toggle the stencil bits: 0's → 1's, 1's → 0's


```
if( ref  <func>  S_existing is true )
{
        Allow the color write to the existing pixel to take place;
        Modify the pixel's existing stencil value depending on what the glStencilOp says to do;
}
```


Setting Up the Stencil Buffer

```
// at the top of the program:

const int STENCILBIT = 1;
const int DEFAULT_STENCIL = 0;
const float BIGX = 2.;
const float BIGY = BIGX;
const float CLOSEZ = -1.;
float Xlens, Ylens;
float Box = 0.40f;

// in InitGraphics( ):

glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE | GLUT_DEPTH | GLUT_STENCIL );

glClearColor( BACKGROUND_COLOR );
glClearStencil( DEFAULT_STENCIL );


// in Display( ):
. . .
glClear( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT | GL_STENCIL_BUFFER_BIT );
. . .
glEnable( GL_STENCIL_TEST );
. . .
```

Using the Stencil Buffer to Create a *Magic Lens*

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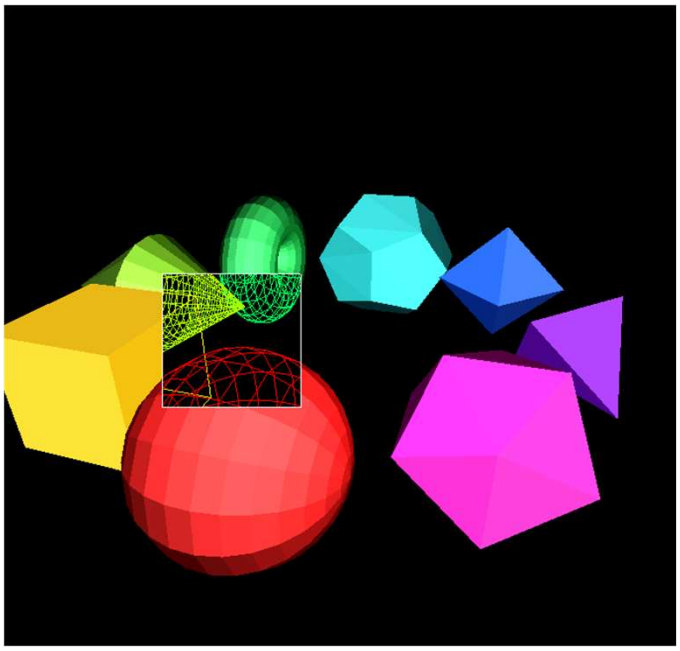

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Using the Stencil Buffer to Create a *Magic Lens*

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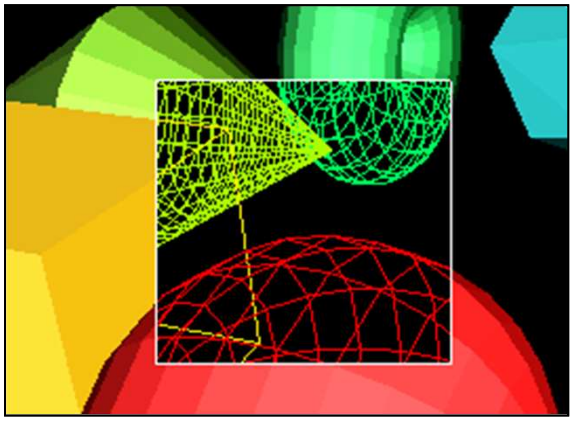
1. Clear the SB = 0
2. Enable the SB
3. Write protect the color buffer and depth buffer
4. Draw a filled square, while setting SB = 1
5. Write-enable the color buffer and depth buffer
6. Draw the solids wherever SB == 0
7. Draw the wireframes wherever SB == 1
8. Disable the SB



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Moving the Magic Lens with the Middle Mouse Button

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```
// in MouseMotion( ):

 if( ActiveButton & MIDDLE )
{
	if( Stencil == LENS )
	{
		int w = glutGet( GLUT_WINDOW_WIDTH );
		int h = glutGet( GLUT_WINDOW_HEIGHT );
		Xlens =  2.*(float)x/(float)w  - 1.;
		Ylens = -2.*(float)y/(float)h  + 1.;
	}
	else
	{
		Scale += SCLFACT * (float) ( dx - dy );
	}
}
```

x/w ranges from 0. to 1.
y/h ranges from 1. to 0
Xlens and Ylens range from -1. to 1. (NDC)

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Using the Stencil Buffer to Create a *Magic Lens*

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```
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );

glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );

glDepthMask( GL_FALSE );
glColorMask( GL_FALSE, GL_FALSE, GL_FALSE, GL_FALSE );

glStencilFunc( GL_ALWAYS, 1, STENCILBIT );
glStencilOp( GL_REPLACE, GL_REPLACE, GL_REPLACE );

glBegin( GL_QUADS );
	glVertex2f( Xlens-Box/2.,  Ylens-Box/2. );
	glVertex2f( Xlens+Box/2., Ylens-Box/2. );
	glVertex2f( Xlens+Box/2., Ylens+Box/2. );
	glVertex2f( Xlens-Box/2.,  Ylens+Box/2. );
glEnd( );

glColorMask( GL_TRUE, GL_TRUE, GL_TRUE, GL_TRUE );
glDepthMask( GL_TRUE );
```

These two identity transformation matrices cause the drawing to take place in NDC (-1 to 1.), which is what Xlens, Ylens, and Box are defined in

Write protect the depth and color buffers

Everywhere we draw, always replace the stencil value with a **1**

Draw a filled-in box

Write-enable the depth and color buffers

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Using the Stencil Buffer to Create a *Magic Lens*


```
<< set the GL_PROJECTION and GL_MODELVIEW matrices as normal >>

glEnable( GL_LIGHTING );
glStencilFunc( GL_EQUAL, 0, STENCILBIT );
glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );
glShadeModel( GL_SMOOTH );
for( int i = 0; i < 8; i++ )
{
        glCallList( SolidLists[ i ] );
}

glDisable( GL_LIGHTING );
glStencilFunc( GL_EQUAL, 1, STENCILBIT );
glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );
glShadeModel( GL_FLAT );
for( int i = 0; i < 8; i++ )
{
        glCallList( WireLists[ i ] );
}

<< set the GL_PROJECTION and GL_MODELVIEW matrices to identity again >>

glDisable( GL_LIGHTING );
glShadeModel( GL_FLAT );
glDisable( GL_DEPTH_TEST );
glColor3f( 1., 1., 1. );
glBegin( GL_LINE_LOOP );
        glVertex2f( Xlens-Box/2.,  Ylens-Box/2. );
        glVertex2f( Xlens+Box/2., Ylens-Box/2. );
        glVertex2f( Xlens+Box/2., Ylens+Box/2. );
        glVertex2f( Xlens-Box/2.,  Ylens+Box/2. );
glEnd( );
glEnable( GL_DEPTH_TEST );
```

Draw the solids everywhere *except* inside the lens

Draw the wireframes *only* inside the lens

Draw the boundary of the lens

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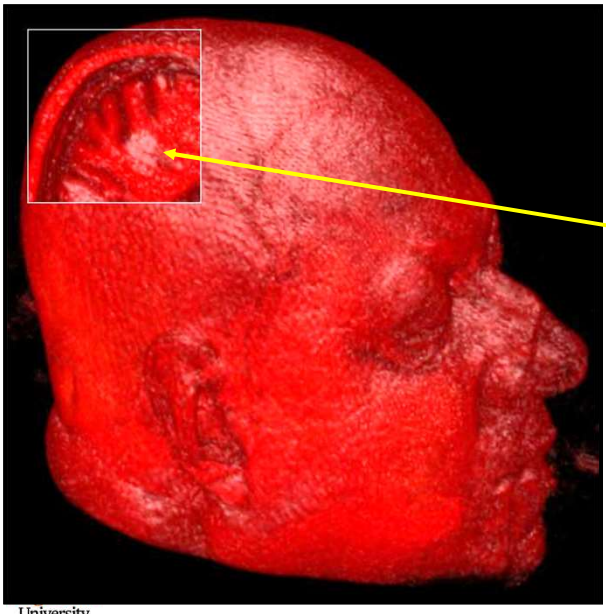
I Once Used the Stencil Buffer to Create a *Magic Lens* for Volume Data



In this case, the scene inside the lens was created by drawing the same object, but drawing it with its near clipping plane positioned partways into the data

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Using the Stencil Buffer to Perform *Polygon Capping*

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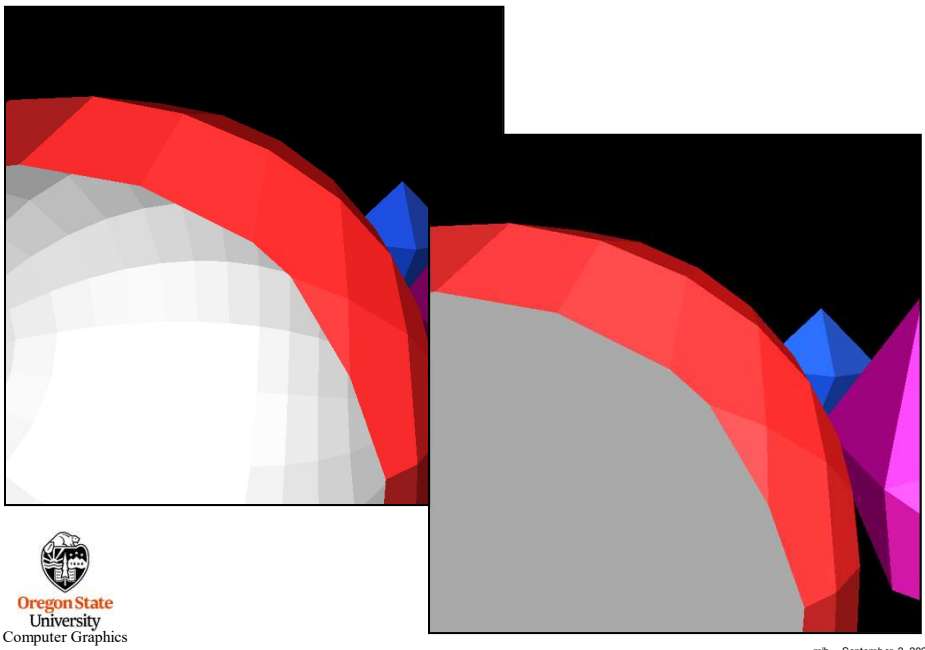

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Using the Stencil Buffer to Perform *Polygon Capping*

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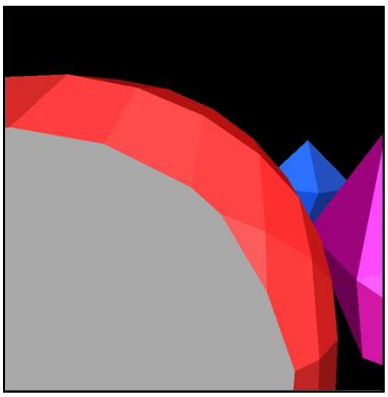
1. Clear the SB = 0
2. Enable the SB
3. Draw the polygons, setting SB = ~ SB: 0's → 1's, 1's → 0's
4. Draw a large gray polygon in front of the entire scene wherever SB != 0
5. Disable the SB



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Using the Stencil Buffer to Perform *Polygon Capping*


```
glStencilFunc( GL_ALWAYS, 0, STENCILBIT );
glStencilOp( GL_INVERT, GL_INVERT, GL_INVERT );
<< draw all objects >>
```

As we draw the ***solid*** objects, always invert the stencil bits:
0's → 1's
1's→ 0's

Because these were all ***solid*** objects, they had a front face and a back face drawn. Thus, most of the time, the SB values got inverted back to 0. If they didn't, that means that the solid object penetrated the near clipping plane and now needs to be capped.

```
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );

glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );

glDisable( GL_LIGHTING );
glDisable( GL_LIGHT0 );
glStencilFunc( GL_NOTEQUAL, 0, STENCILBIT );
glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );
glShadeModel( GL_FLAT );
glColor3f( .5f, .5f, .5f );
glBegin( GL_QUADS );
        glVertex3f( -BIGX, -BIGY, CLOSEZ );
        glVertex3f(  BIGX, -BIGY, CLOSEZ );
        glVertex3f(  BIGX,  BIGY, CLOSEZ );
        glVertex3f( -BIGX,  BIGY, CLOSEZ );
glEnd( );
```

Only draw the large gray plane in front where the SB != 0

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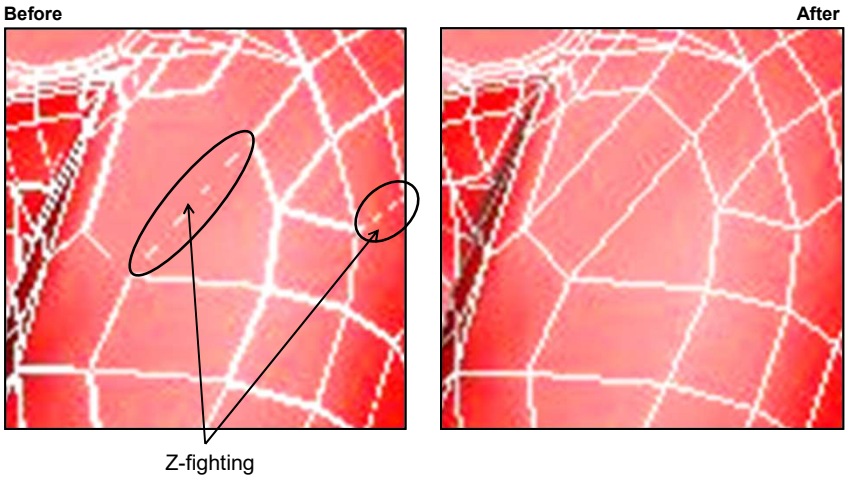
Using the Stencil Buffer to Draw Better Polygon Outlines



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Using the Stencil Buffer to Draw Better Polygon Outlines

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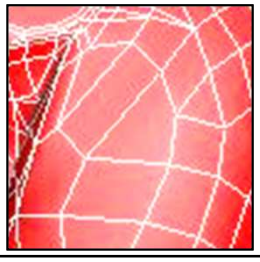
```
Clear the SB = 0

Enable the SB

for( each polygon )
{
        Draw the edges, setting SB = 1
        Draw the filled polygon wherever SB  !=  1
        Draw the edges again, setting SB = 0
}

Disable the SB
```

Before

After



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Outlining Polygons the Naïve Way Results in Z-Fighting

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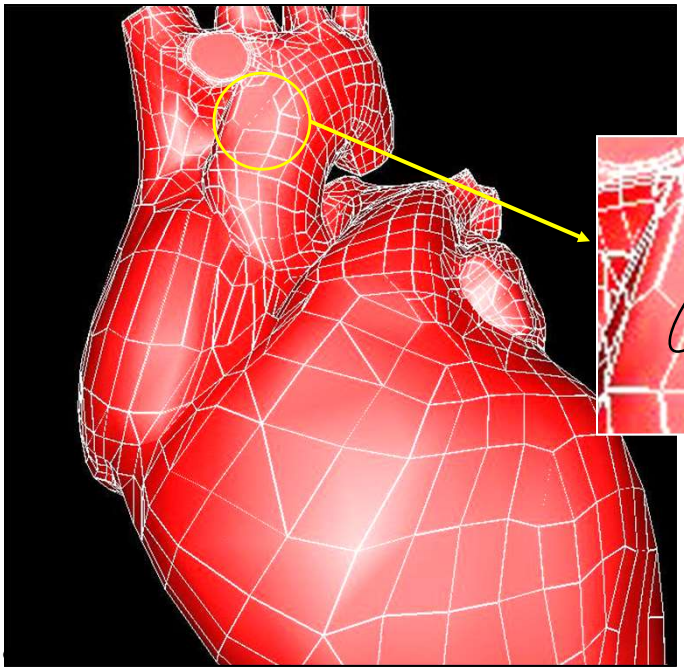

1. Draw all polygons
2. Draw all edges

Z-fighting

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Using the Stencil Buffer to Draw Better Polygon Outlines

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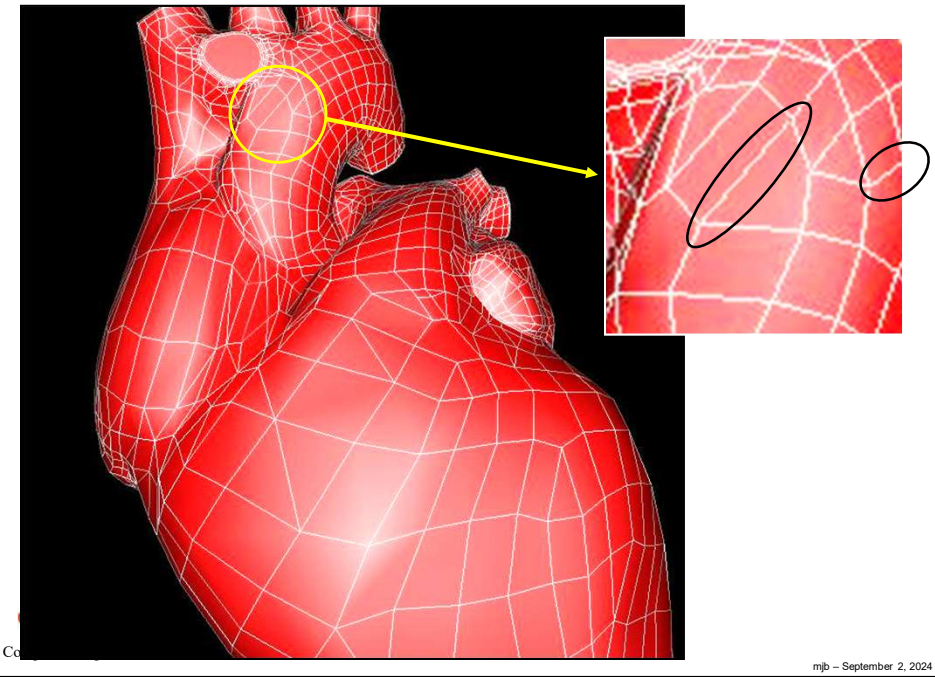

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Using the Stencil Buffer to Draw Better Polygon Outlines

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```
for( int f = 0; f < NumFaces; f++ )
{
        glStencilFunc( GL_ALWAYS, 1, STENCILBIT );
        glStencilOp( GL_REPLACE, GL_ REPLACE, GL_ REPLACE );
        glDisable( GL_LIGHTING );
        glShadeModel( GL_FLAT );
        glColor3f( 1., 1., 1. );
        glBegin( GL_LINE_LOOP );
        for( int v = FirstVertex[f];  v < FirstVertex[f+1];  v++ )
        {
                glVertex3f( Vertices[v].x, Vertices[v].y, Vertices[v].z );
        }
        glEnd( );

        glStencilFunc( GL_EQUAL, 0, STENCILBIT );
        glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );
        glEnable( GL_LIGHTING );
        glShadeModel( GL_SMOOTH );
        glMaterialfv( … );
        glBegin( GL_POLYGON );
        for( int v = FirstVertex[f];  v < FirstVertex[f+1];  v++ )
        {
                glNormal3f( Normals[v].x, Normals[v].y, Normals[v].z );
                glVertex3f( Vertices[v].x,  Vertices[v].y, Vertices[v].z );
        }
        glEnd( );

        glStencilFunc( GL_ALWAYS, 0, STENCILBIT );
        glStencilOp( GL_ REPLACE, GL_ REPLACE, GL_ REPLACE );
        glDisable( GL_LIGHTING );
        glShadeModel( GL_FLAT );
        glColor3f( 1., 1., 1. );
        glBegin( GL_LINE_LOOP );
        for( int v = FirstVertex[f];  v < FirstVertex[f+1];  v++ )
        {
                glVertex3f( Vertices[v].x, Vertices[v].y, Vertices[v].z );
        }
        glEnd( );
}
```

Put "masking tape" down on the polygon edges

Paint the polygon, which also paints the edges

Pull the "masking tape" up and paint just the polygon edges

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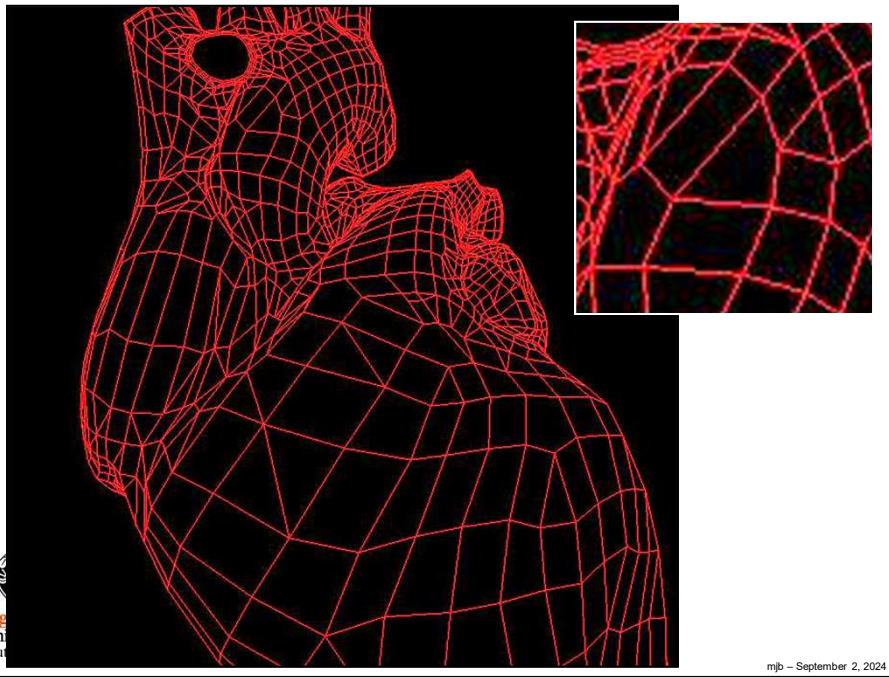
Using the Stencil Buffer to Perform *Hidden Line Removal*



Using the Stencil Buffer to Perform *Hidden Line Removal*


```
Clear the SB = 0
Enable the SB

for( each polygon )
{
        Draw the edges, setting SB = 1
        Draw the polygon, unlit and flat shaded, in the background color wherever SB  !=  1
        Draw the edges again, setting SB = 0
}

Disable the SB
```

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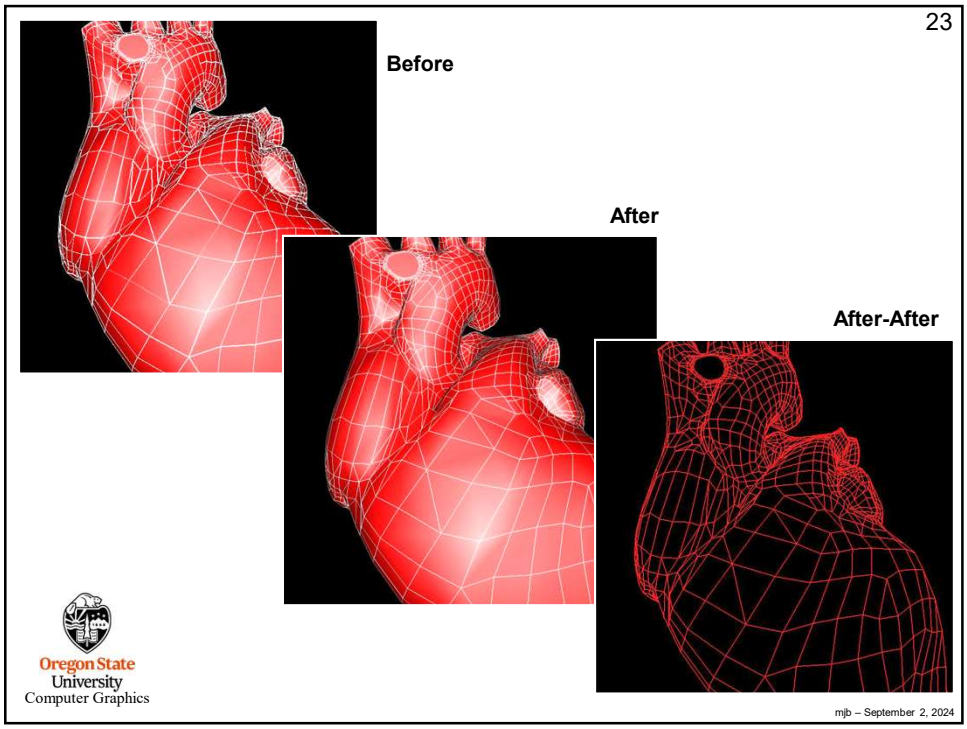
23
Before
After
After-After
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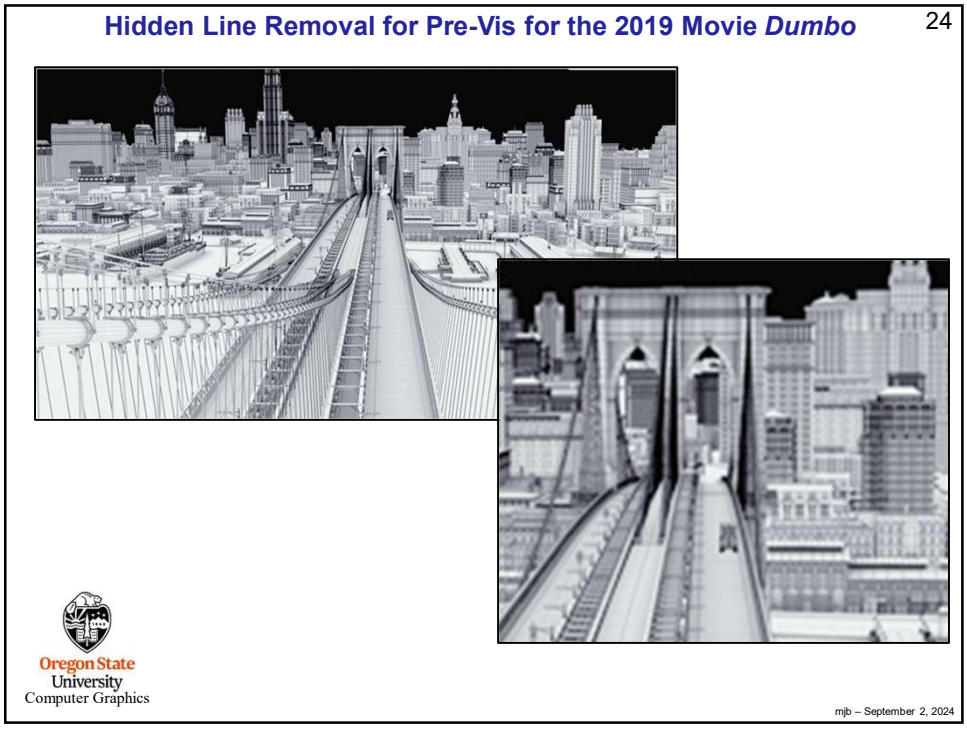
Hidden Line Removal for Pre-Vis for the 2019 Movie *Dumbo*
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Hidden Line Removal in Construction Shows

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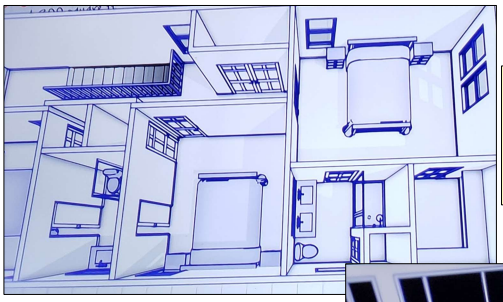

I've noticed that some of the construction reality TV shows use hidden line removal like this, presumably to create a blueprint-ish effect. This came from the show *Good Bones*.

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Stencil Buffers can be used to Create Portals

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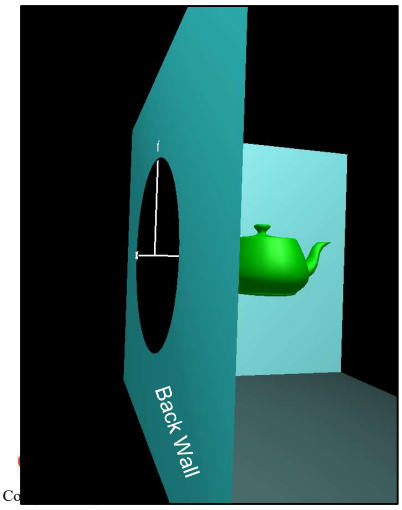
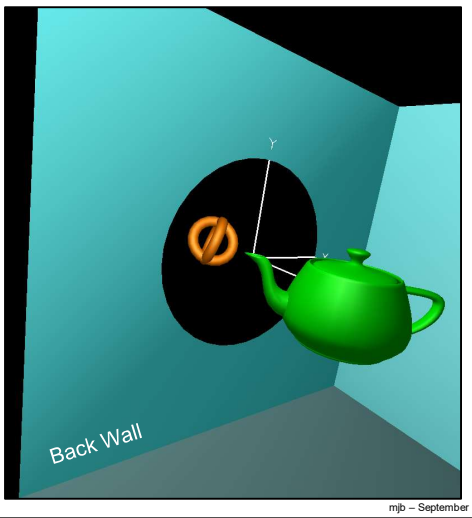
Here we have a room with a teapot in it and a hole in the Back Wall. You can tell that it is a hole because the axes obviously go through it. Clearly there is nothing behind the Back Wall.



But if we look at the scene from within the room, there is indeed a 3D object (the orange torii) seen through the hole. The hole is acting like a "portal" to another 3D space.



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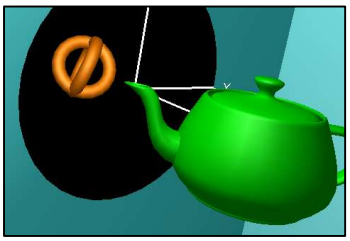
Stencil Buffers can be used to Create Portals

Here's the process:

1. Draw the teapot and the axes like normal
2. Turn off writing into the depth and color framebuffers
3. Draw an invisible large square behind the Back Wall setting SB=1
4. Draw an invisible circle on that wall setting SB=0
5. Draw an invisible large square behind the back Wall between there and the viewer setting SB=1
6. Draw the cyan room walls and the orange torii only where SB=0 – this makes the portal

The first large square (SB=1) plus circle (SB=0) ends up making the Stencil Buffer look like this:

1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0	1	1	1	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1	1
1	1	1	1	0	0	0	0	0	0	0	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1	1
1	1	1	1	1	1	1	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1



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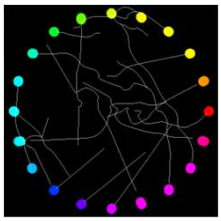
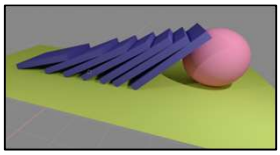
Animation





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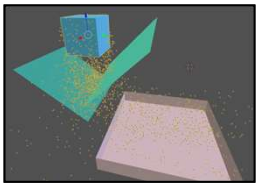

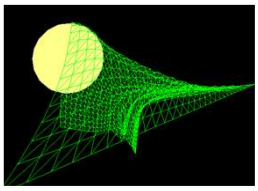

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Animation

Animation is the process of giving motion to your geometric models. Before animating, there are questions you need to ask first:

- Why am I doing this?
- Do I want the animation to obey the real laws of physics? Partially? Which elements?
- Am I willing to "fake" the physics to get the objects to *want* to move in a way that I tell it?
- Do I have specific key positions I want the objects to pass through no matter what?
- Do I want to simply record the motion of a real person, animal, etc., and then play it back?

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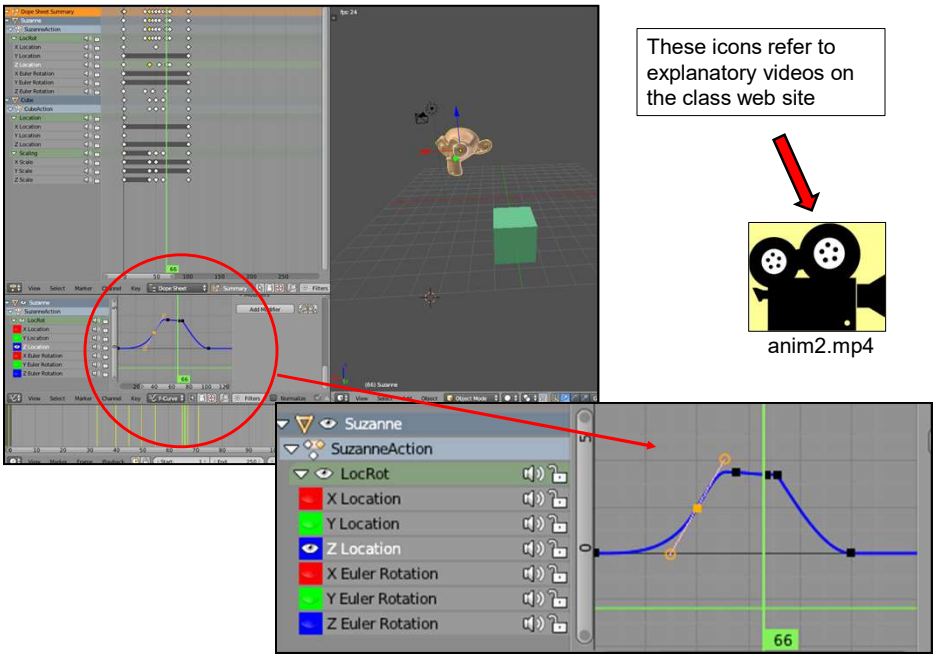
Keyframe Animation



These icons refer to explanatory videos on the class web site

anim2.mp4

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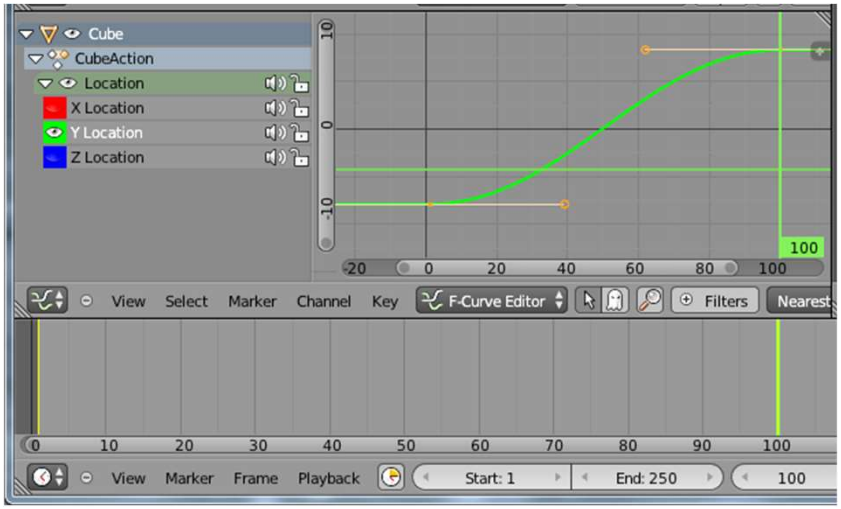
Keyframe Animation

Blender:



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Here's Some Code that Lets You Create DIY Keyframe Animations

For my own work, instead of *Key Frames*, I like specifying *Key Times* better. And, so, I created a C++ class to do it for you.

```
class Keytimes:

        void    AddTimeValue( float time, float value );
        float   GetFirstTime( );
        float   GetLastTime( );
        int     GetNumKeytimes( );
        float   GetValue( float time );
        void    Init( );
        void    PrintTimeValues( );
```

Instead of Key *Frames*, I Like Specifying Key *Times* Better

```
Keytimes Xpos;

int
main( int argc, char *argv[ ] )
{
        Xpos.Init( );
        Xpos.AddTimeValue(  0.0,  0.000 );
        Xpos.AddTimeValue(  2.0,  0.333 );
        Xpos.AddTimeValue(  1.0,  3.142 );
        Xpos.AddTimeValue(  0.5,  2.718 );
        fprintf( stderr, "%d time-value pairs:\n", Xpos.GetNumKeytimes( ) );
        Xpos.PrintTimeValues( );

        fprintf( stderr, "Time runs from %8.3f to %8.3

        for( float t = 0.; t <= 2.0; t += 0.1 )
        {
                float v = Xpos.GetValue( t );
                fprintf( stderr, "%8.3f\t%8.3f\n", t, v );
        }
}
```

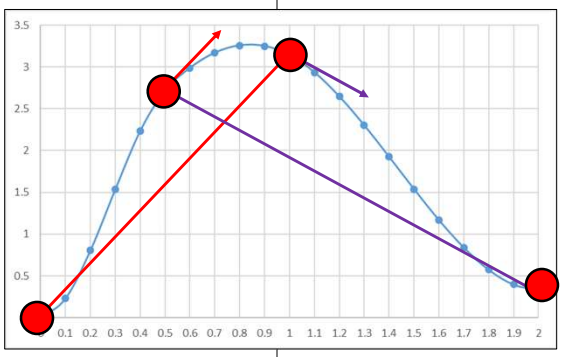
Declare one class per parameter you are animating. Here it wants to interpolate and animate the x-location of something.

Key-Time pairs (Time and Xlocation) can be specified in any order

Just to demonstrate, this for-loop runs through a collection of time values and looks up the interpolate x-location at those values. Normally you would get the time from the system clock.

Instead of Key *Frames*, I Like Specifying Key *Times* Better

```
( 0.00,  0.000)
( 0.00,  0.000)  ( 2.00,  0.333)
( 0.00,  0.000)  ( 1.00,  3.142)  ( 2.00,  0.333)
( 0.00,  0.000)  ( 0.50,  2.718)  ( 1.00,  3.142)  ( 2.00,  0.333)
4 time-value pairs
Time runs from   0.000 to   2.000
  0.000         0.000
  0.100         0.232
  0.200         0.806
  0.300         1.535
  0.400         2.234
  0.500         2.718
  0.600         2.989
  0.700         3.170
  0.800         3.258
  0.900         3.250
  1.000         3.142
  1.100         2.935
  1.200         2.646
  1.300         2.302
  1.400         1.924
  1.500         1.539
  1.600         1.169
  1.700         0.840
  1.800         0.574
  1.900         0.397
  2.000         0.333
```



= the originally-specified key-time pairs

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Using the System Clock in Display( ) for Timing

```
#define MSEC       10000                    // i.e., 10 seconds
Keytimes Xpos, Ypos, Zpos;
Keytimes ThetaX, ThetaY, ThetaZ;

. . .

if( AnimationIsOn )
{
      // # msec into the cycle ( 0 - MSEC-1 ):
      int msec = glutGet( GLUT_ELAPSED_TIME )  %  MSEC;

      // turn that into a time in seconds:
      float nowTime = (float)msec  / 1000.;
      glPushMatrix( );
            glTranslatef( Xpos.GetValue( nowTime ), Ypos.GetValue( nowTime ), Zpos.GetValue( nowTime )
);
            glRotatef( ThetaX.GetValue( nowTime ),  1., 0., 0. );
            glRotatef( ThetaY.GetValue( nowTime ),  0., 1., 0. );
            glRotatef( ThetaZ.GetValue( nowTime ),  0., 0., 1. );
            << draw the object >>
      glPopMatrix( );
}
```

Number of msec in the animation cycle

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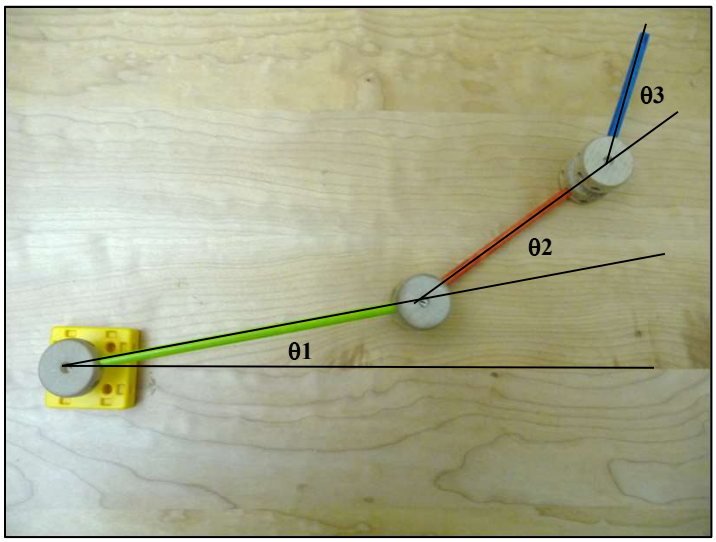
Forward Kinematics:
Change Parameters – Connected Things Move
(All children understand this)



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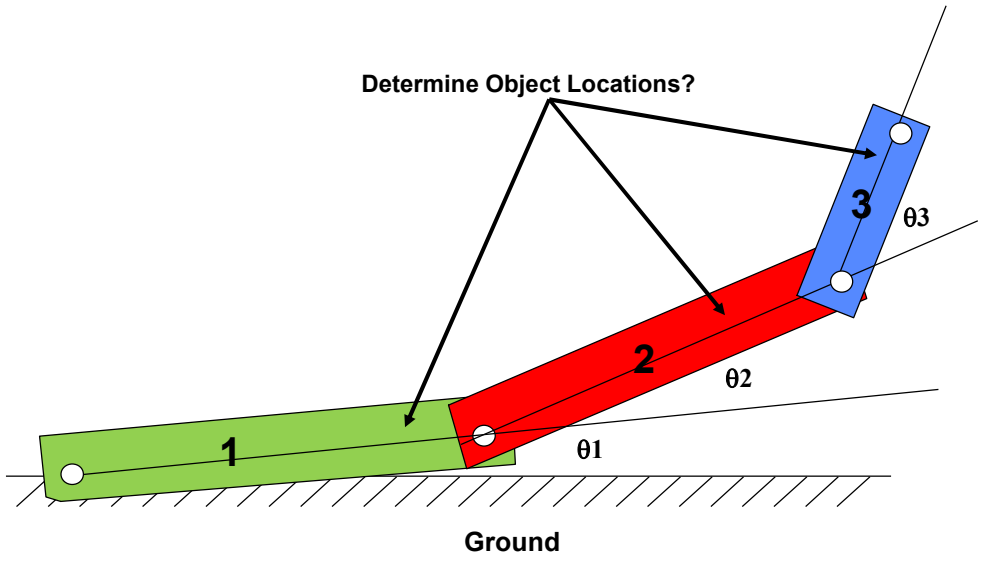
Forward Kinematics: Transformation Hierarchies



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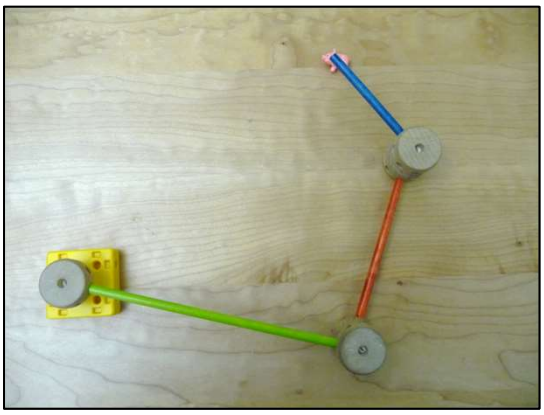
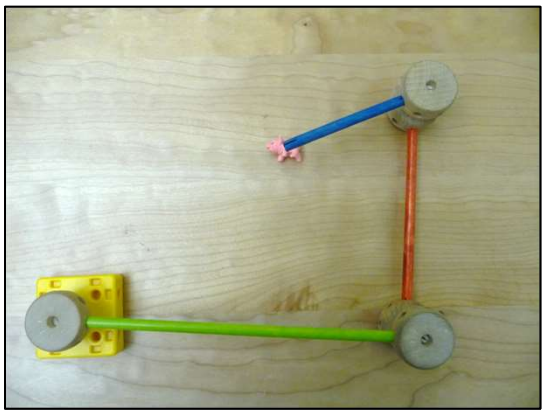
Inverse Kinematics (IK):
Things Need to Move to a Particular Location – What Parameters Will Make Them Do That?



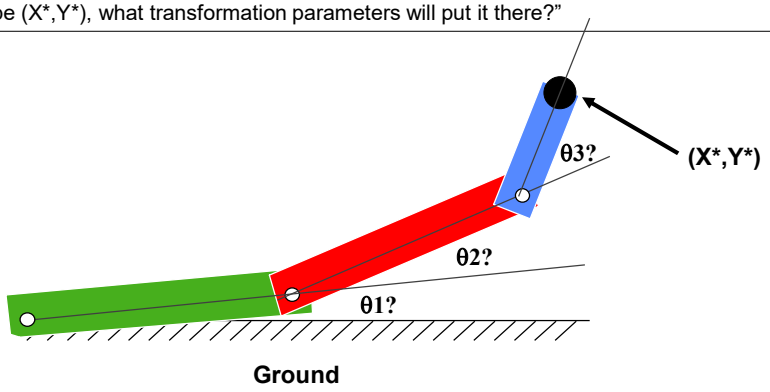


Of course, there will always be target locations that can *never* be reached.
Think about that spot in the middle of your back that you can never scratch! ☺

Inverse Kinematics (IK)

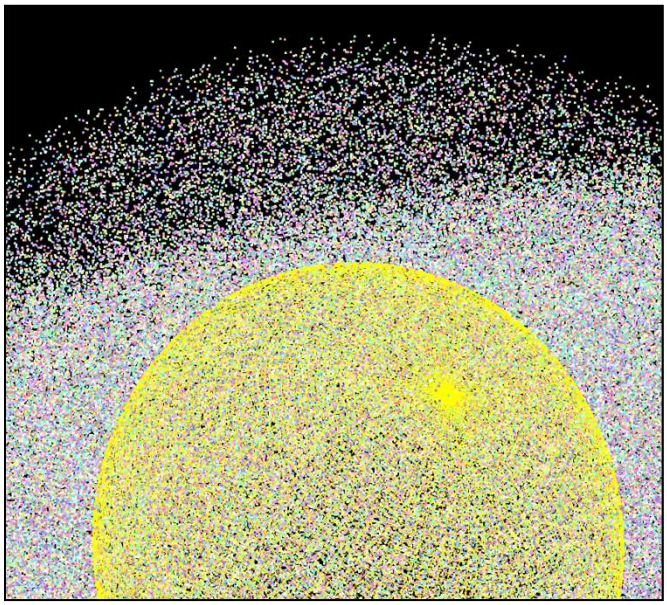
Forward Kinematics solves the problem "if I know the link transformation parameters, where are the links?".

Inverse Kinematics (IK) solves the problem "If I know where I want the end of the chain to be (X*,Y*), what transformation parameters will put it there?"



Particle Systems:
A Cross Between Modeling and Animation?

13



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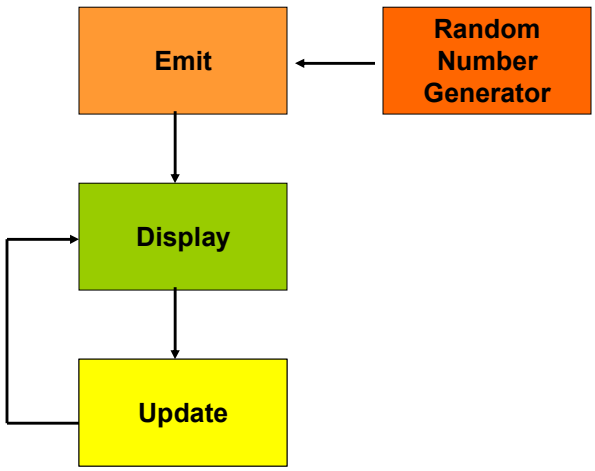
Particle Systems:
A Cross Between Modeling and Animation?

14

The basic process is:



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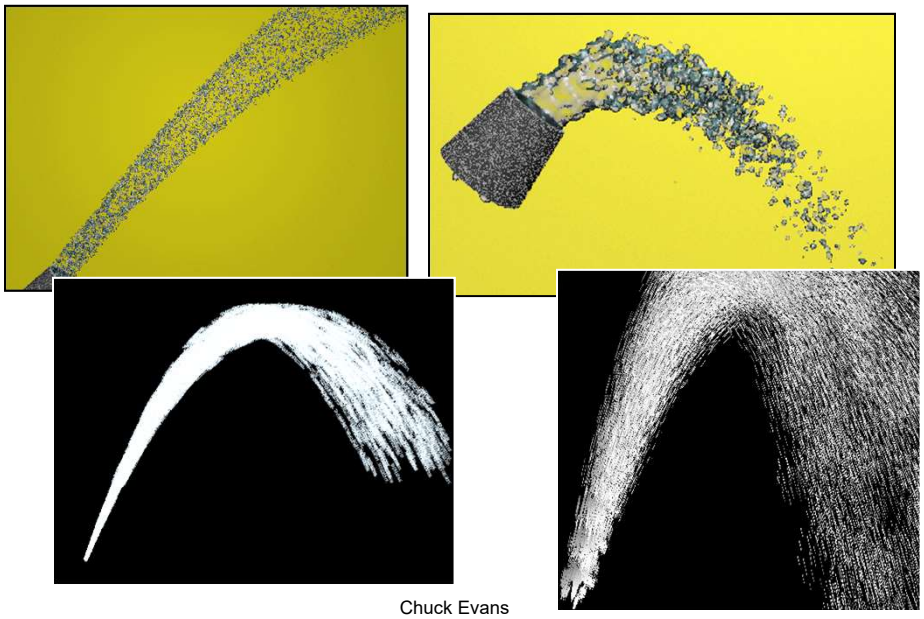
Particle Systems Examples



Chuck Evans

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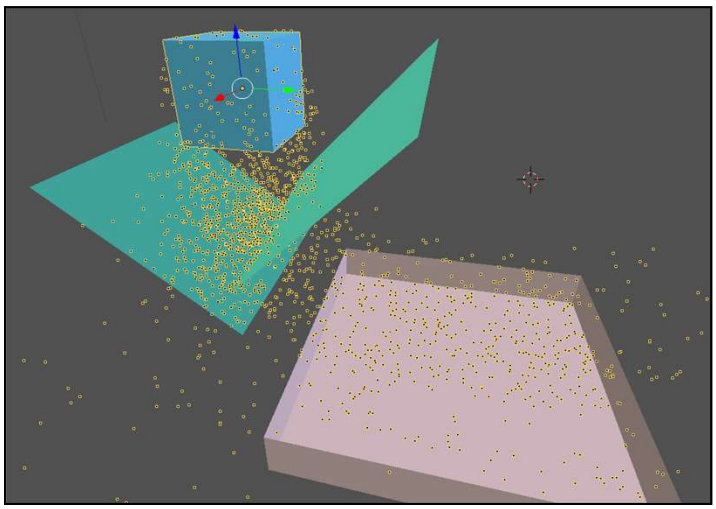
Particle Systems Examples



particles.mp4

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Particle Systems Examples

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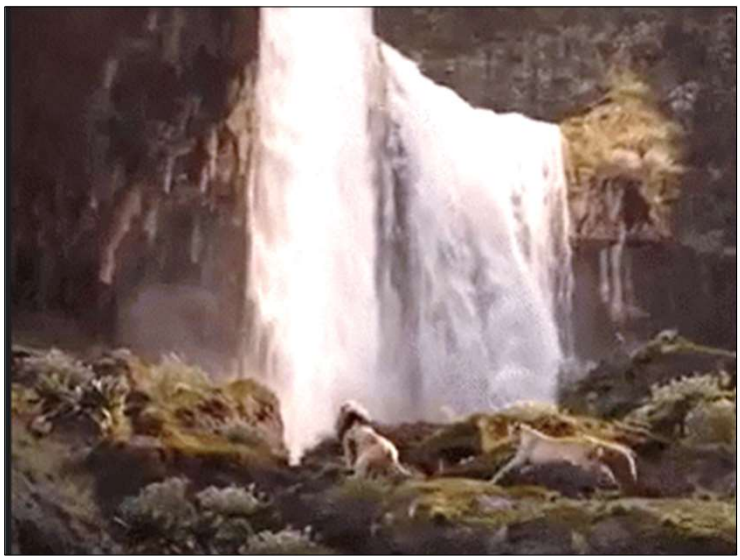
Particle Systems Examples



The Lion King (2019) -- Disney

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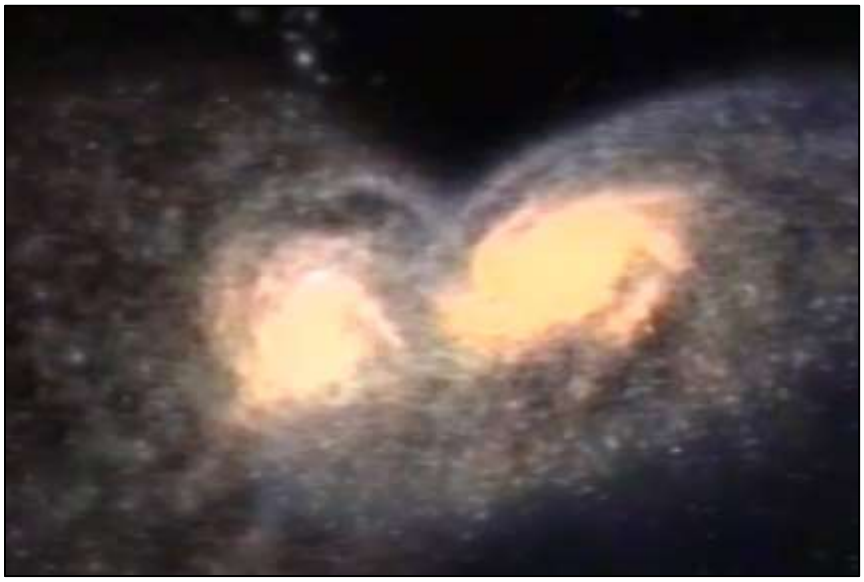
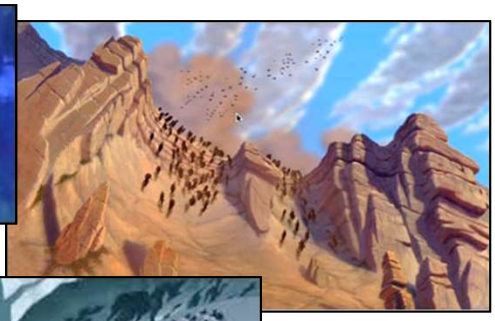
A Particle System to Simulate Colliding Galaxies in *Cosmic Voyage*



Cosmic Voyage

Particles Don't Actually Have to Be "Particles"

Avatar

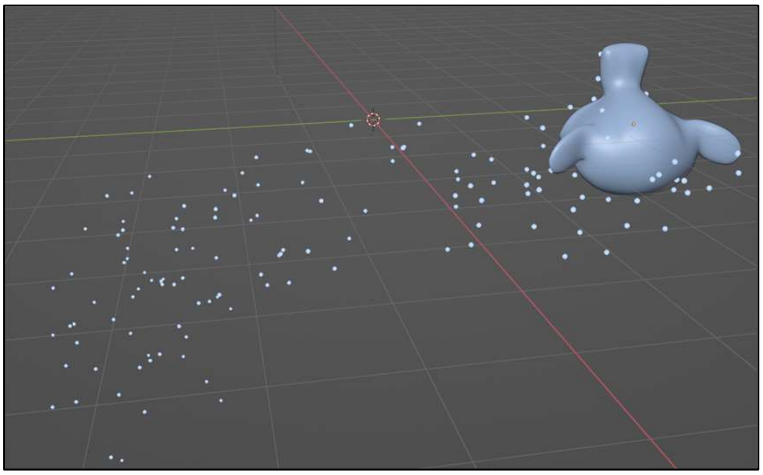


The Lion King

Mulan

Multiple Animation Techniques Can Be Combined

A Particle System coming from a moving keyframed object in Blender:



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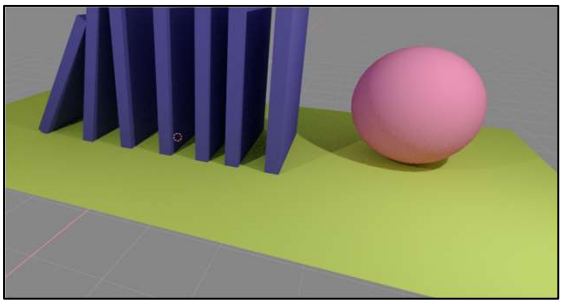
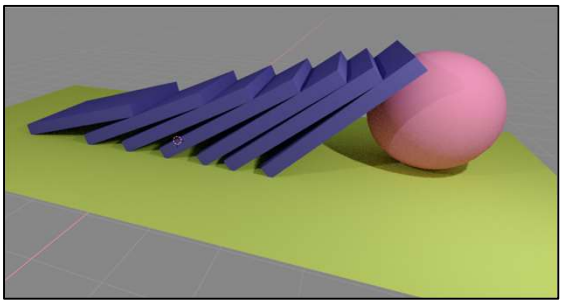
Animating using Rigid-body Physics





Newton's second law:

force = mass * acceleration

or

$\ddot{x}$ = acceleration = force / mass

$$x(T) = \iint_{t=0}^{t=T} \ddot{x}\,dt \approx \sum \sum \ddot{x}\,\Delta t$$

dominos.mp4

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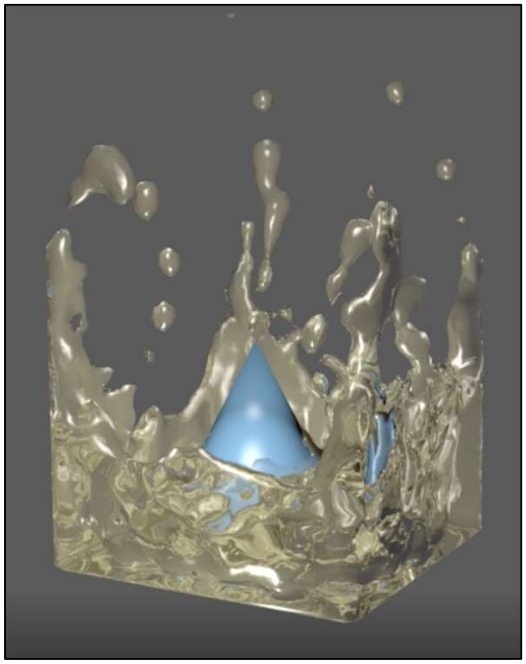
In order to make this work, you need to supply physical properties such as mass, center of mass, moment of inertia, coefficients of friction, coefficients of restitution, etc.

Animating using Fluid Physics



fluid.avi

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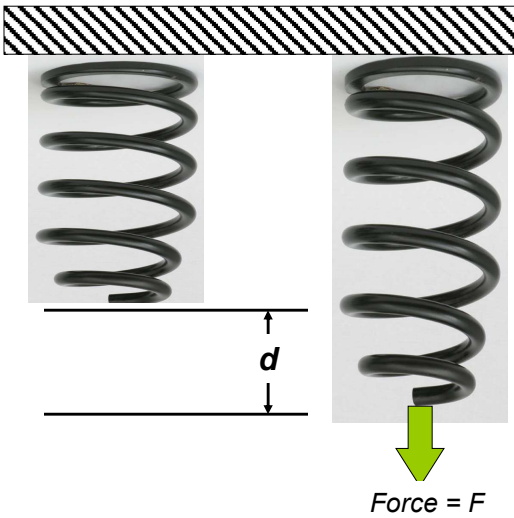
Animating using Physics



$$d = \frac{-F}{k}$$

d = ***spring displacement*** in inches

k = ***spring stiffness*** in pounds/inch

Or, if you know the displacement, the force exerted by the spring is:

$$F = -kd$$

This is known as **Hooke's Law**

Why the minus sign? Because a spring's force acts in a direction opposite the displacement. In other words, a spring's force tries to correct its displacement.

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Animating using the Physics of a Mesh of Springs

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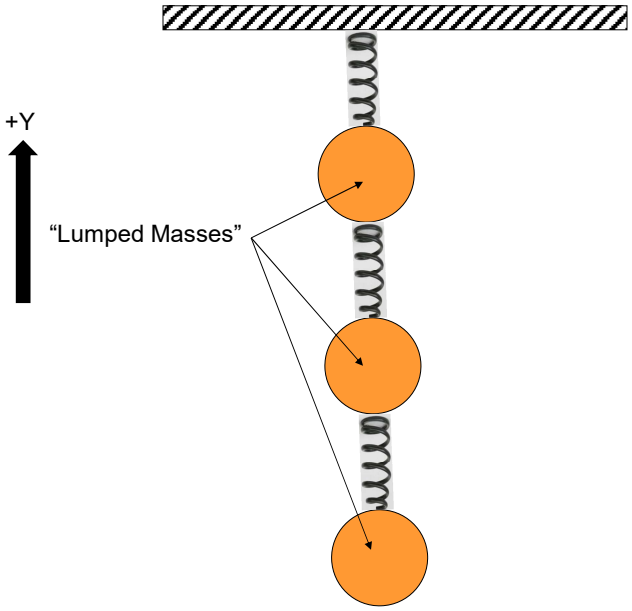

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Simulating a Bouncy String or a Chain

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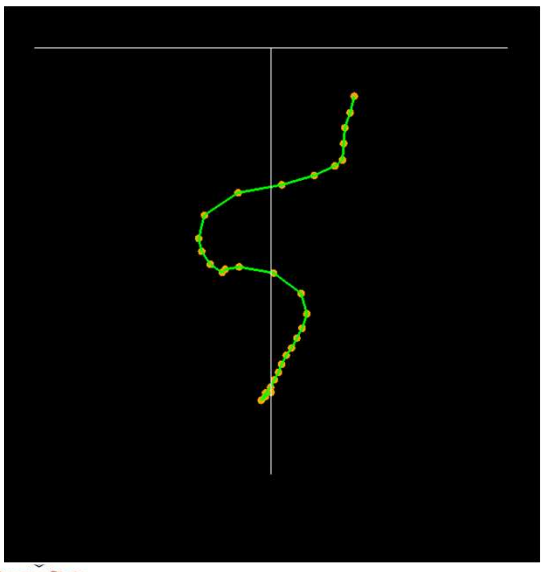

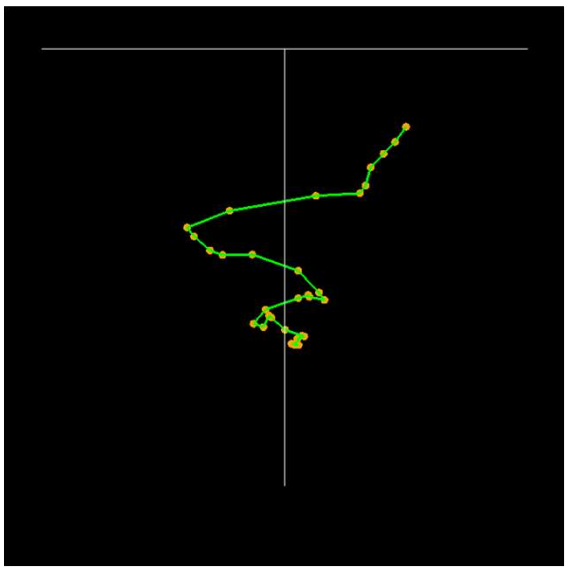

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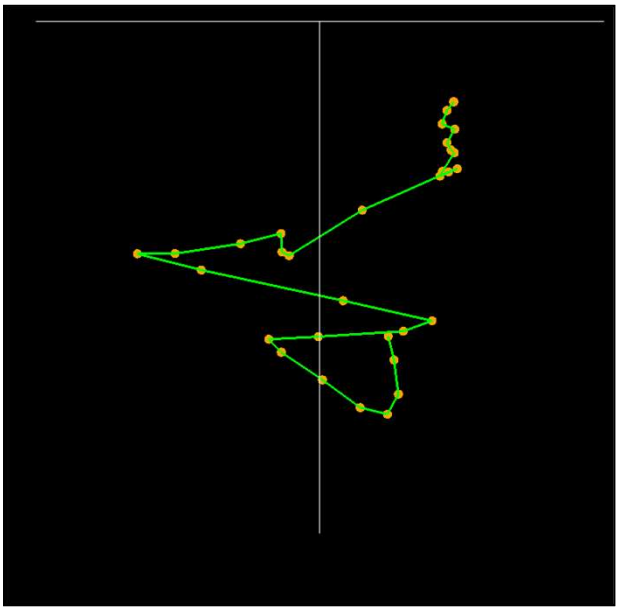
Simulating a Bouncy String or a Chain



string.mp4

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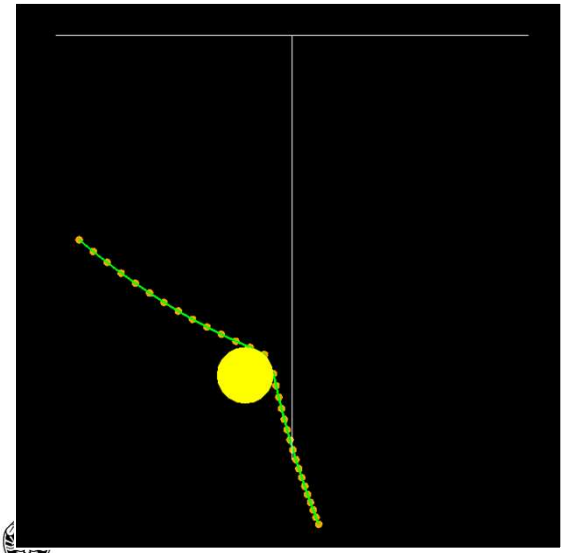
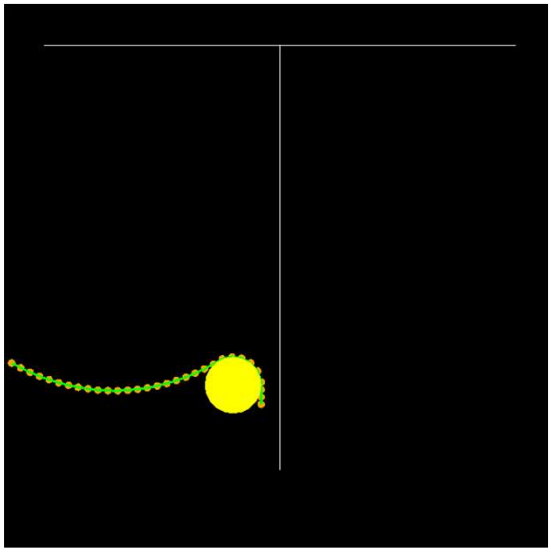
Placing a Physical Barrier in the Scene





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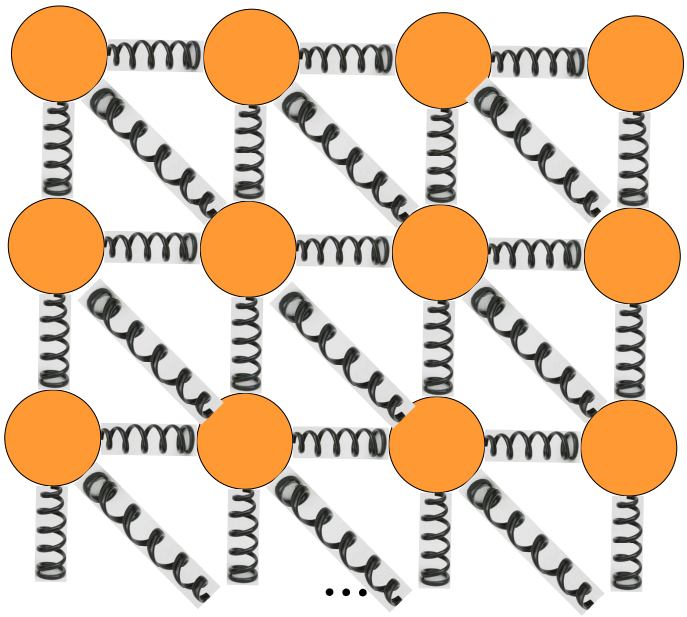
Animating Cloth



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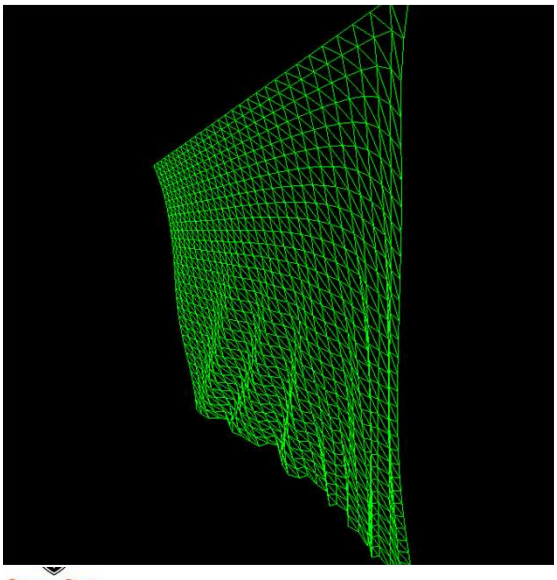
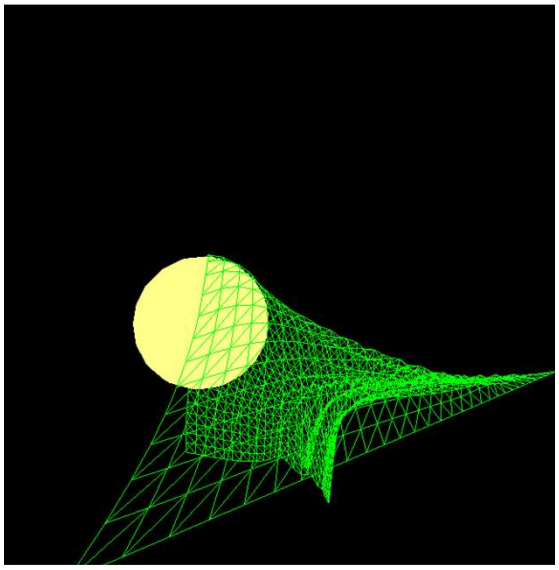
Cloth Examples





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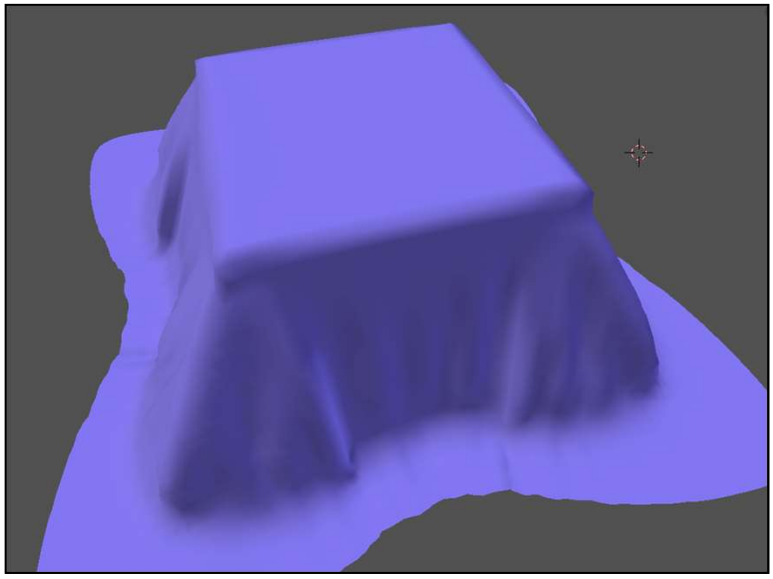
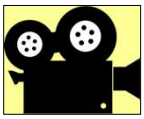
Cloth Example





cloth.mp4

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Cloth Example

Geri's Game, Pixar

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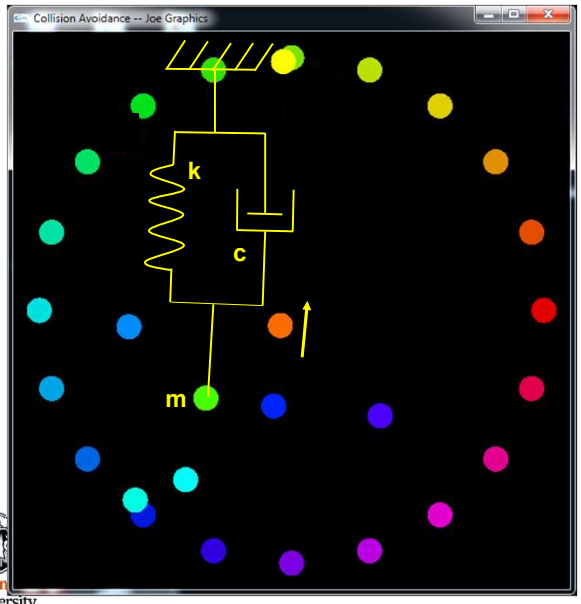
Functional Animation:
Setup Imaginary Physics to Make the Object *Want* to Move Towards a Goal Position



Newton's second law:

force = mass * acceleration

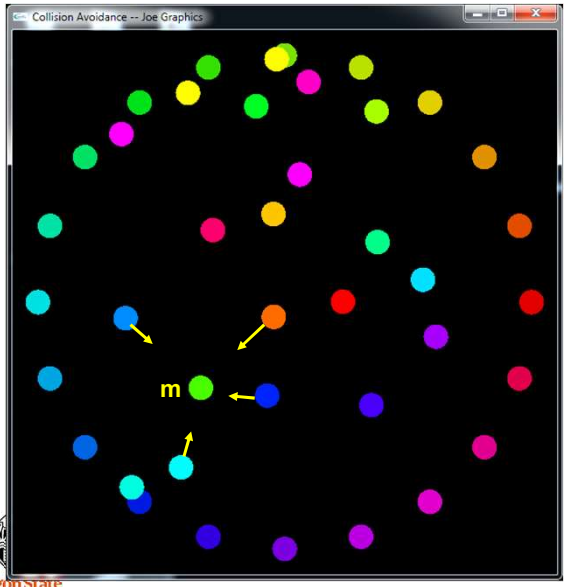
or

$\ddot{x}$ = acceleration = force / mass

$$\ddot{x} = \frac{-c\dot{x} - kx}{m}$$

- The ***k*** is an imaginary spring.
- The ***c*** is an imaginary "damper", which you can think of as a shock absorber which absorbs energy. (Your car has these to soften bouncing.)

Functional Animation:
Setup Imaginary Physics to Make the Object *Want* to Move Away from all other Objects



Newton's second law:

force = mass * acceleration

or

$\ddot{x}$ = acceleration = force / mass

$$\ddot{x} = \frac{F_{repulsive}}{m}$$

Repulsion Coefficient

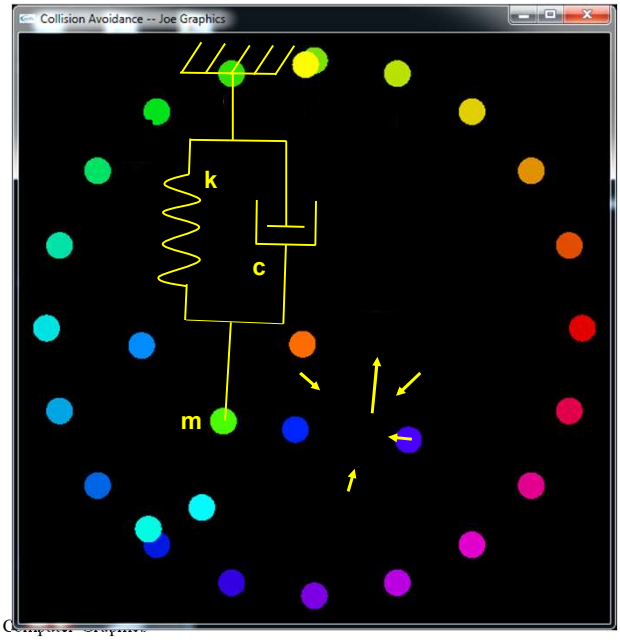
$$F_{repulsive} = \frac{C_{repulse}}{d^{Power}}$$

Distance between the boundaries of the 2 bodies

Repulsion Exponent

This isn't from a book. I just made this up. It seemed like a good idea.

Total Goal – Make the Free Body Move Towards its Final Position While Being Repelled by the Other Bodies



Newton's second law:

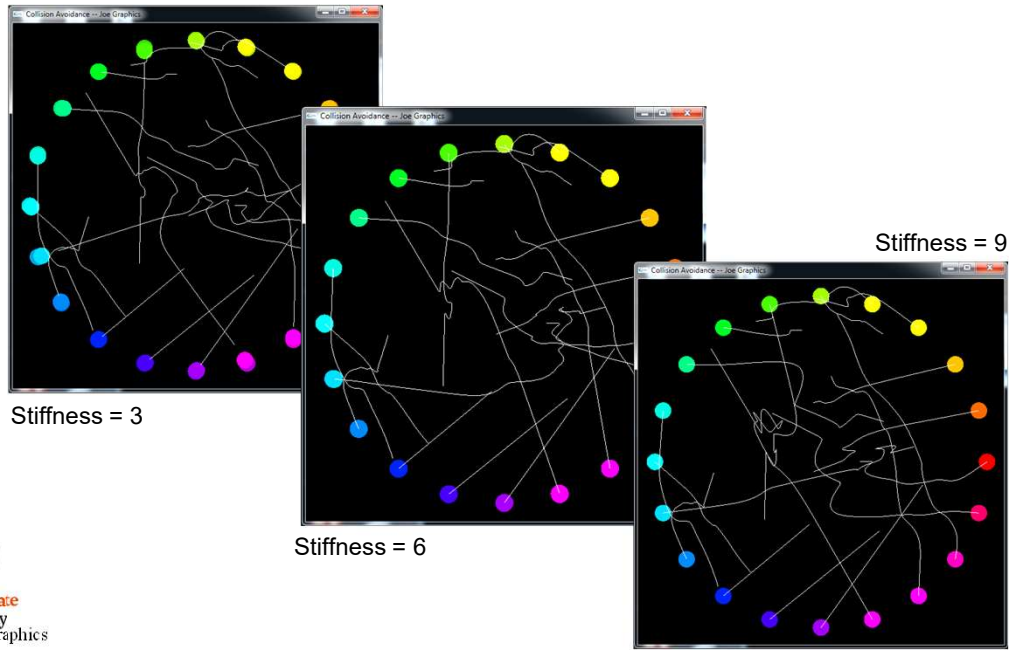
force = mass * acceleration

or

$\ddot{x}$ = acceleration = force / mass

$$\ddot{x} = \frac{-c\dot{x} - kx + \sum F_{repulsive}}{m}$$

Increasing the Stiffness



Stiffness = 3

Stiffness = 6

Stiffness = 9

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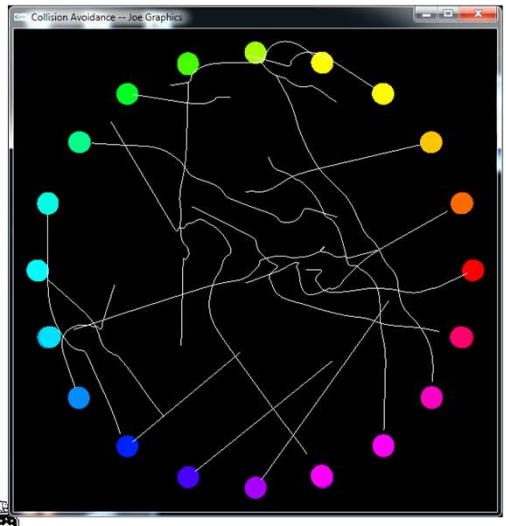
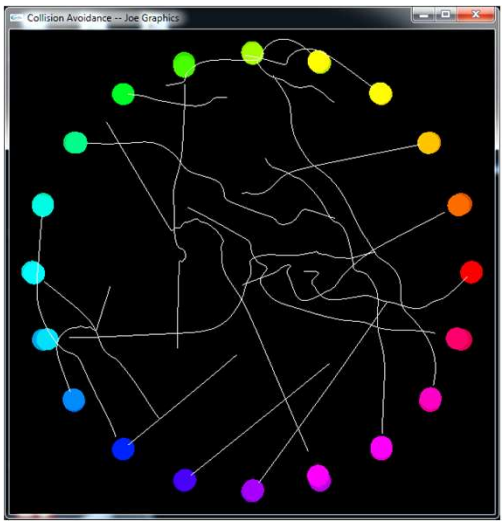
Increasing the Repulsion Coefficient



Repulse = 10



Repulse = 30

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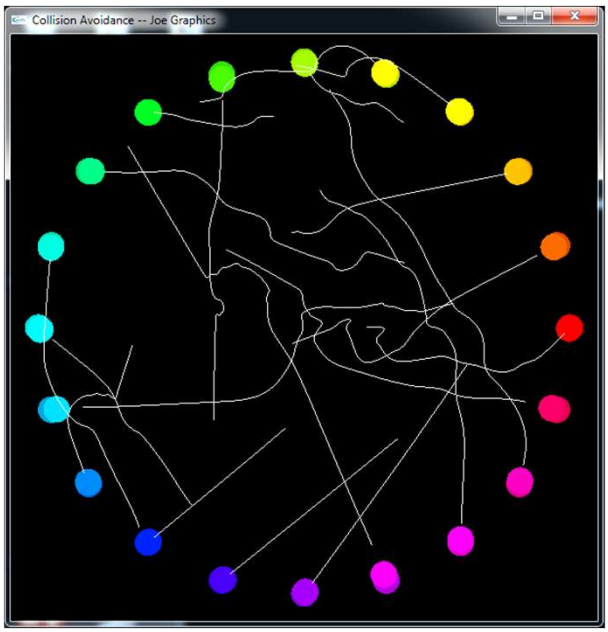
Functional Animation:
Setup Imaginary Physics to Make the Object *Want* to Move Like We Want it To



avoid.mp4

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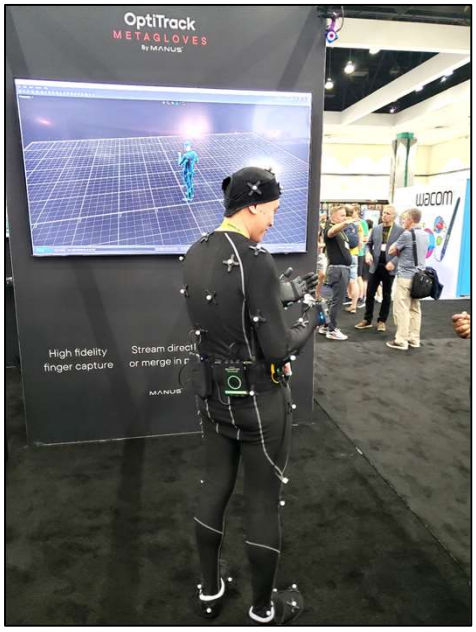
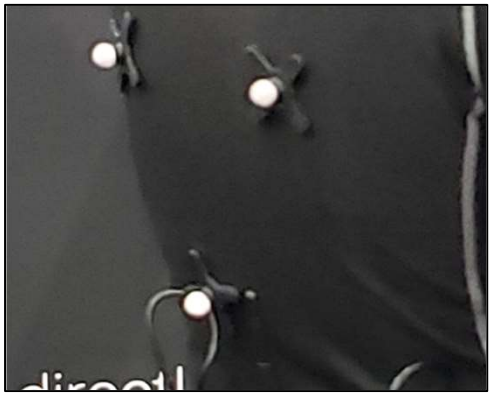
39

Motion Capture ("MoCap") as an Input for Animation





Natural Point

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39

40

Motion Capture is for Hands and Faces Too

Natural Point

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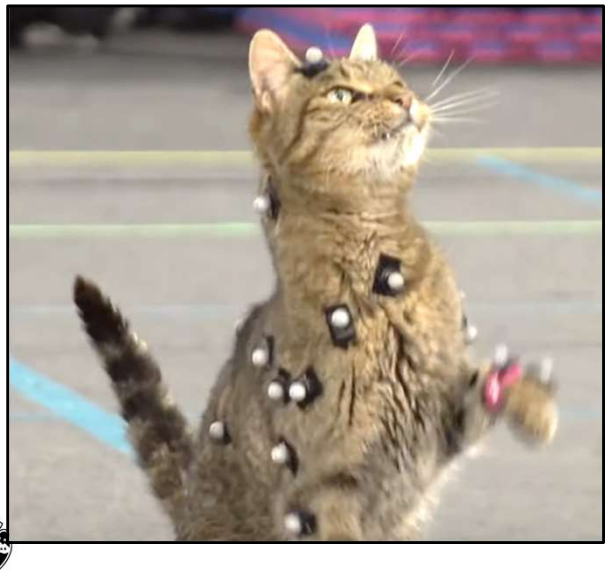
41

Even Animals can be MoCapped



My cats would never have put up with this…

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https://www.youtube.com/watch?v=zyq_LQrHpoo

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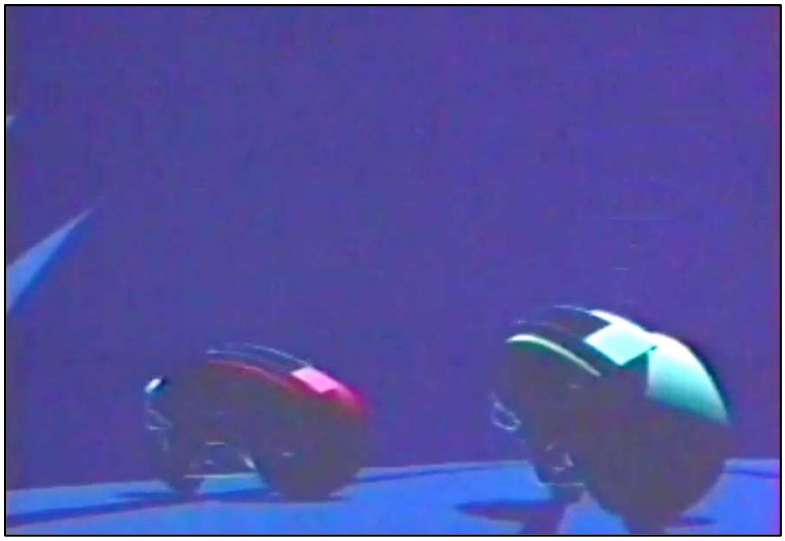
41

42

Tron I –
They probably should have used physics, but didn't



MAGI

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Card Trick

Rob Russ

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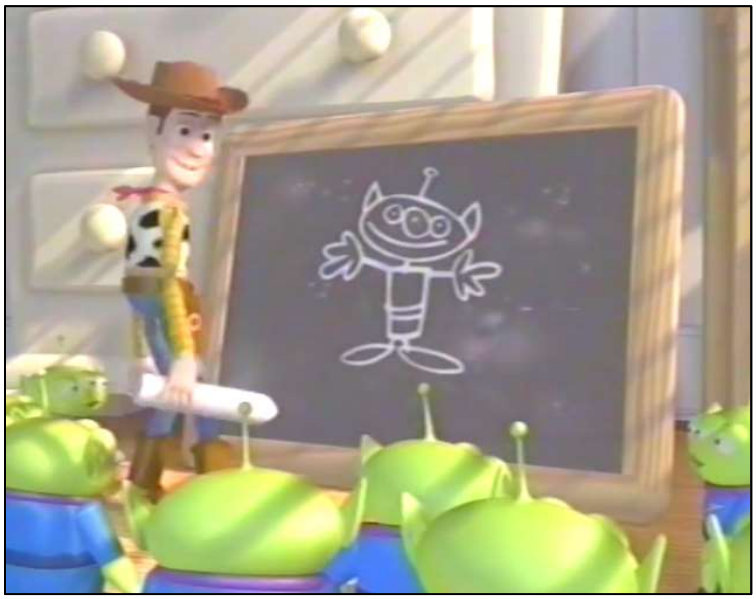
Pixar Animated Shorts



Pixar

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3D Printing

(which I consider to be a legitimate form of Computer Graphics display…)

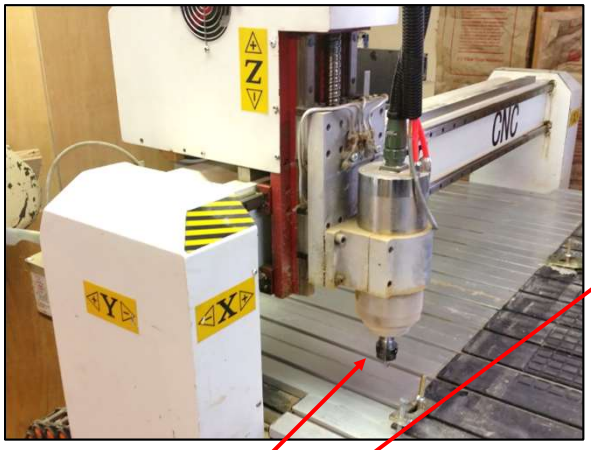
1

Mike Bailey

mjb@cs.oregonstate.edu

In the Beginning, All Manufacturing was "Subtractive"

2



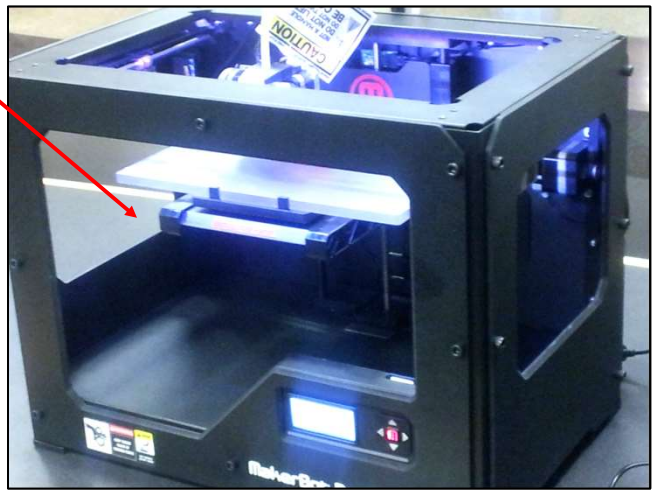
1. The whirling drill bit follows a 3D path around a block of metal, wax, or wood
2. Chips fly
3. A block of metal becomes a part

Today's 3D Printing Process

3

"3D Printing" is generally considered to be some sort of **"Additive**" process in which layers of material get deposited on previous layers. (Additive manufacturing is also sometimes called *Stereolithography*.)

The current frenzy in 3D Printing consists mostly of desktop systems that deposit layers of molten plastic, like this one. But there are many others.



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3

Examples of 3D Printing using a Variety of Materials

4

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4

Portland's Laika uses Color 3D Printing to Make Faces for Stop-motion Movies

5

From *Kubo and the Two Strings*

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5

The 3D Printing Geometry File

6

3D Printers are fed a file called an "STL File", which lists all the triangles in the object. All 3D CAD-ish systems (as well as TinkerCad, Thingiverse, and Blender) can produce this type of file for you.

```
solid

 facet normal   0.00   0.00   -1.00
  outer loop
    vertex   -2.000000   -2.000000   0.250000
    vertex   -1.980000   -1.980000   0.250000
    vertex   -1.980000   -2.000000   0.250000
  endloop
 endfacet

 facet normal   0.00   0.00   -1.00
  outer loop
    vertex   -2.000000   -2.000000   0.250000
    vertex   -2.000000   -1.980000   0.250000
    vertex   -1.980000   -1.980000   0.250000
  endloop
 endfacet

       . . .

endsolid
```

In this particular file, these coordinates were in units of inches.

Some 3D Printers still use **inches**, but most now seem to use **millimeters**.

Check! It matters!

Note: there are 25.4 mm/inch

If you sent this file to a millimeter-based 3D printer, the part would come out very, very tiny! ☺

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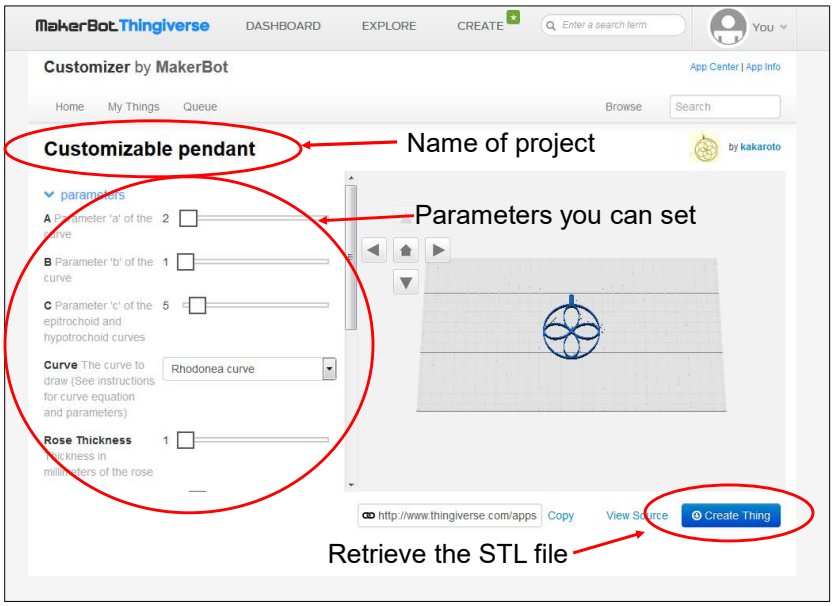
6

thingiverse.com

7



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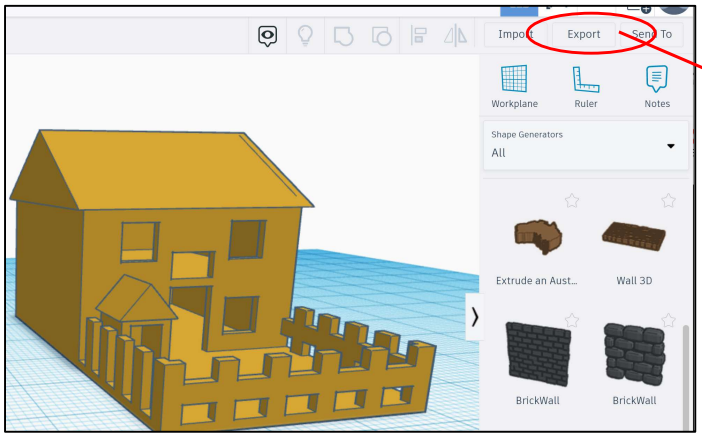
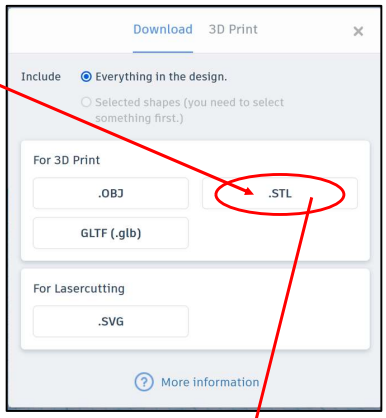
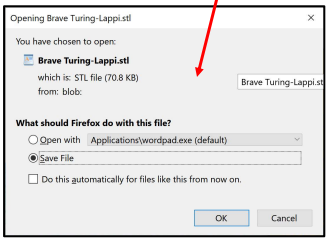
TinkerCad

8







Click on **Import→STL**

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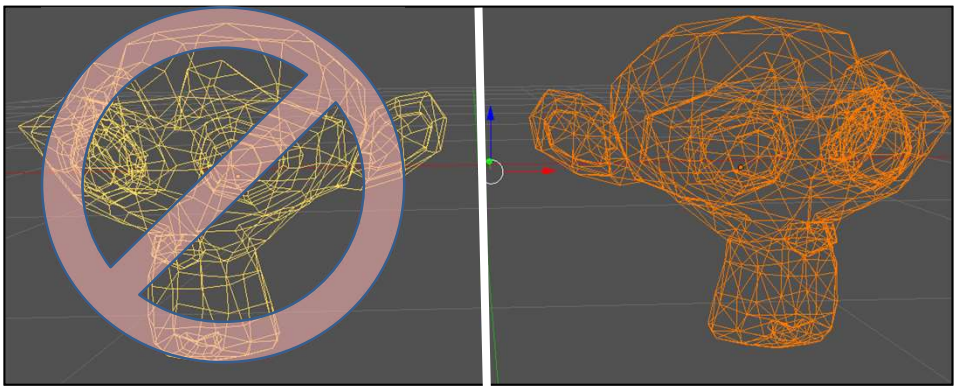
Object Rules for 3D Printing

9

1. The object must be a mesh and ***consist only of triangles***.



Quads and triangles **Triangles only**

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In Blender: Modifiers → Add Modifier → Triangulate

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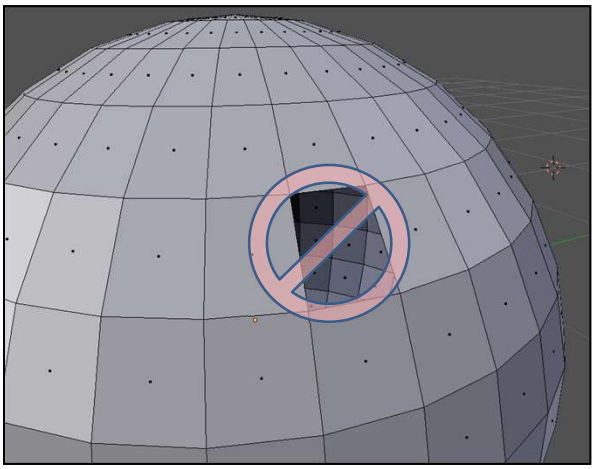
9

Object Rules for 3D Printing

10

2. The object *must* be a legal solid. It *must* have a definite inside and a definite outside. It can't have any missing face pieces.



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"Definite inside and outside" is sometimes called "Two-manifold" or "Watertight"

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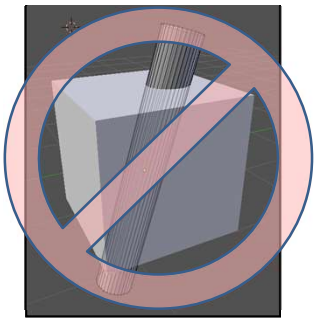
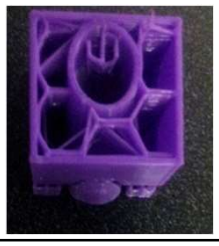
10

Object Modeling Rules for 3D Printing

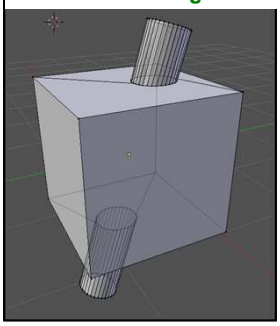
3. You can't make a compound object by simply overlapping two objects in 3D. If you want both shapes together, do a Boolean union on them so that they become one complete, legal object.

Overlapped in 3D -- bad





Boolean union -- good



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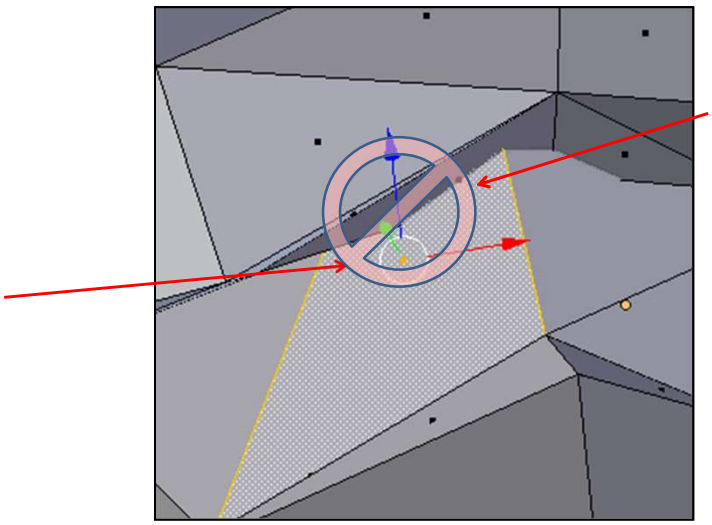
Object Rules for 3D Printing

4. Each edge in the mesh must bound 2 and only 2 triangles (this is known as the **Vertex-to-Vertex Rule**)



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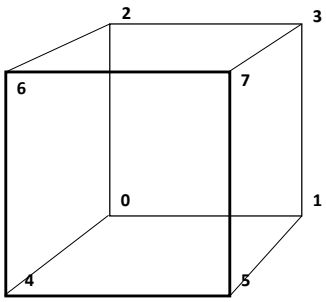
The Simplified Euler's Formula* for Legal Solids

13

$$F - E + V = 2$$

F	Faces
E	Edges
V	Vertices



For a cube: 6 – 12 + 8 = 2

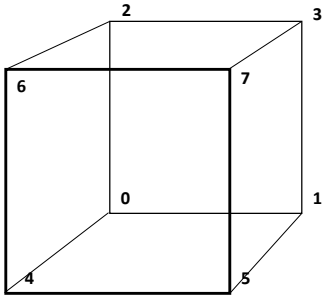
*sometimes called the Euler-Poincaré formula

The Full Euler's Formula* for Legal Solids

14

$$F - E + V - L = 2(B - G)$$

F	Faces
E	Edges
V	Vertices
L	Inner Edge Loops (within faces)
B	Bodies
G	Genus (number of through-holes)



For a cube: 6 – 12 + 8 – 0 = 2(1 – 0)

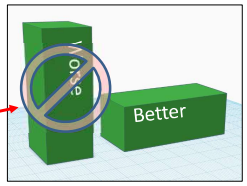
*sometimes called the Euler-Poincaré formula

Advice on 3D Printing

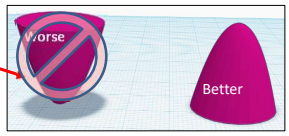
15

Don't make the part too big to start – it will take a long time to 3D print. It's nice if you can fit several models in a single run.

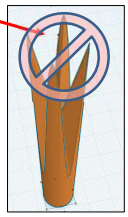
Try to rotate the part so the smallest dimension is vertical. It's stronger that way, and it builds faster.



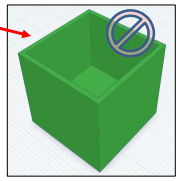
The 3D Printer will like it better if the part gets smaller as it goes up, not the other way around.



Don't design the part with long, thin edges. They will snap right off.



Don't make walls too thin – they will break.



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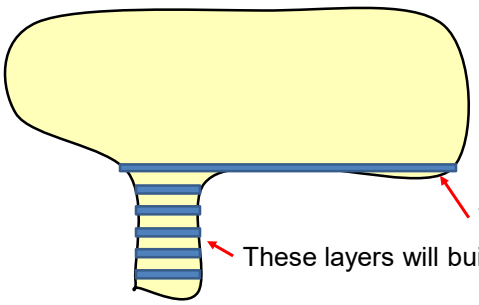
15

Watch Out for Overhangs!

16



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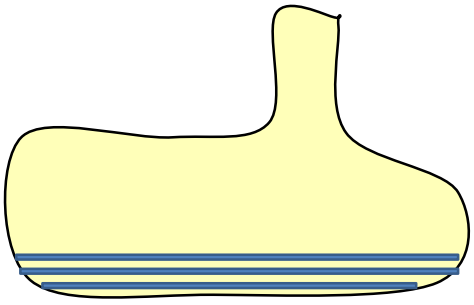
16

Note that, if you build this object upside-down, it will probably be fine

17



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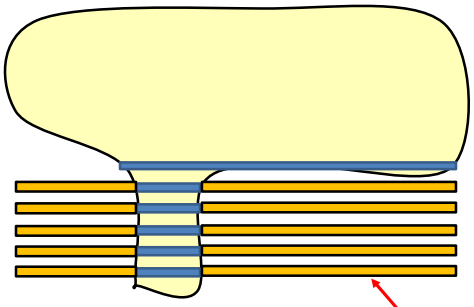
17

Watch Out for Overhangs!

18



Some 3D printers handle overhangs by leaving unused material in place to support the overhangs

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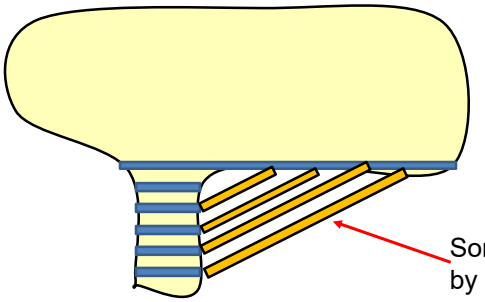
Watch Out for Overhangs!

19



Some 3D printers handle overhangs by using software to add “support structures” to the overhangs

Some 3D printers handle this better than others…

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19

What Happens if You Don’t Follow the Rules?

20

Check here:
http://twistedsifter.com/2013/08/when-3d-printing-goes-wrong/

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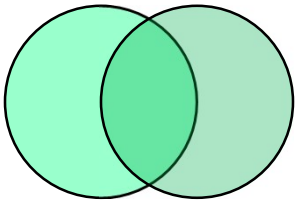
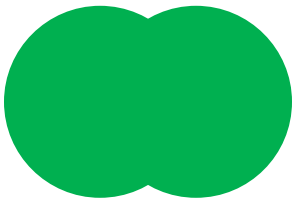
20

How Can You Guarantee That You Are Modeling With Legal Solids? Remember the "3D Venn Diagrams"

21



Two Overlapping Shapes



Union

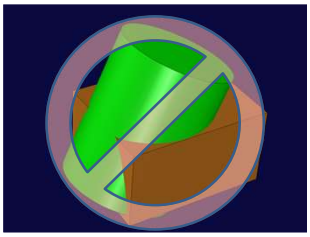
Intersection

Difference

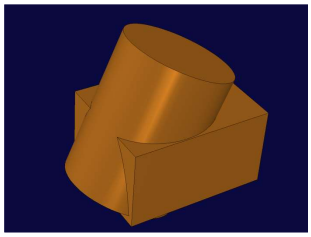
21

How Can You Guarantee That You Are Modeling With Legal Solids? Remember the "3D Venn Diagrams"

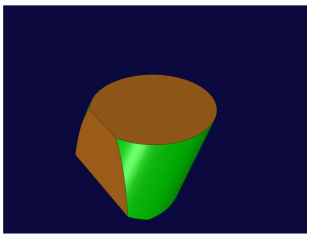
22



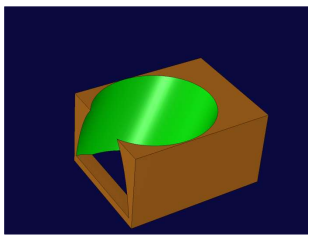
Two Overlapping Solids



Union



Intersection



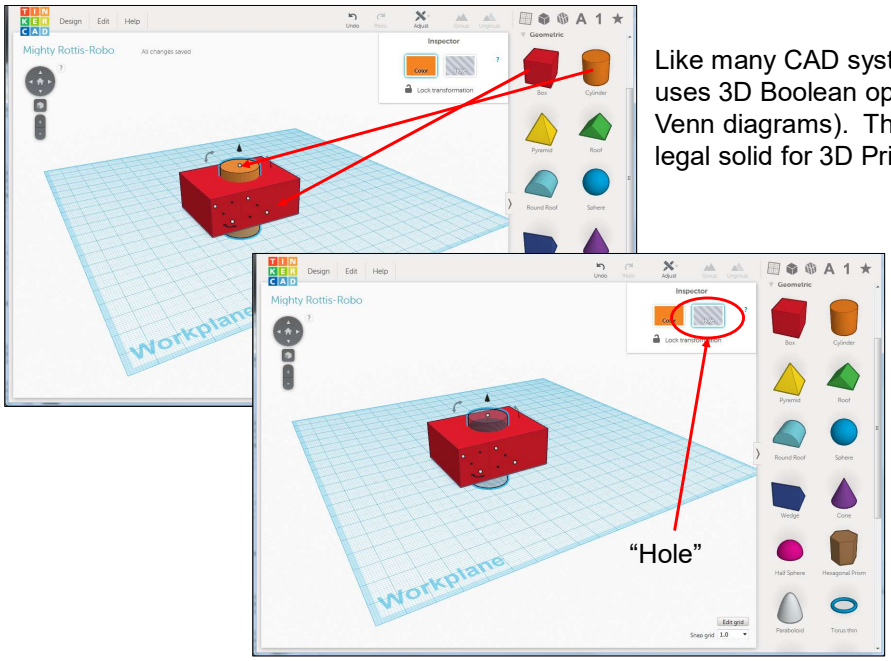
Difference

This is often called Constructive Solid Geometry (CSG)

22

TinkerCad: http://www.tinkercad.com

23



Like many CAD systems, TinkerCad uses 3D Boolean operators (3D Venn diagrams). This guarantees a legal solid for 3D Printing.

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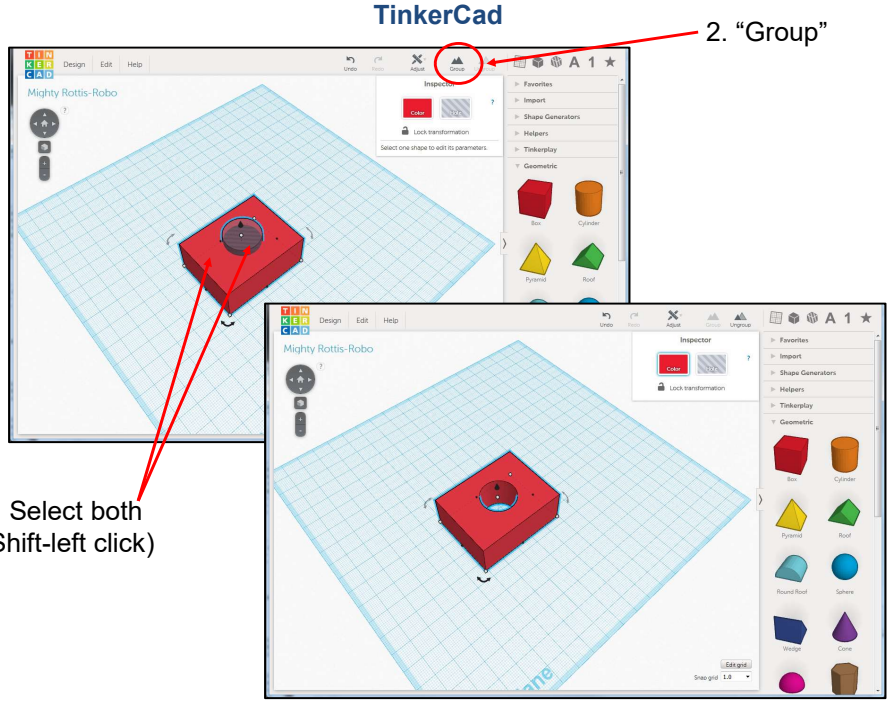
TinkerCad

24



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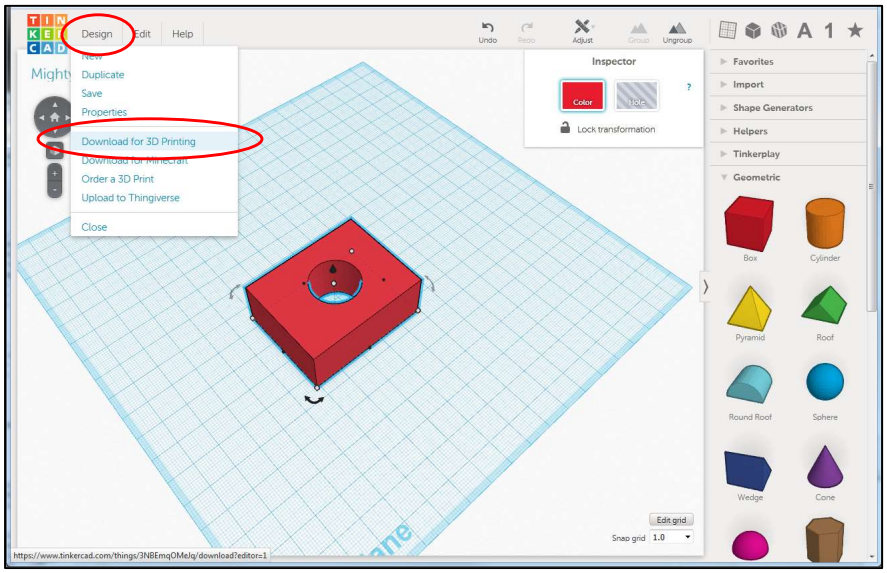
TinkerCad

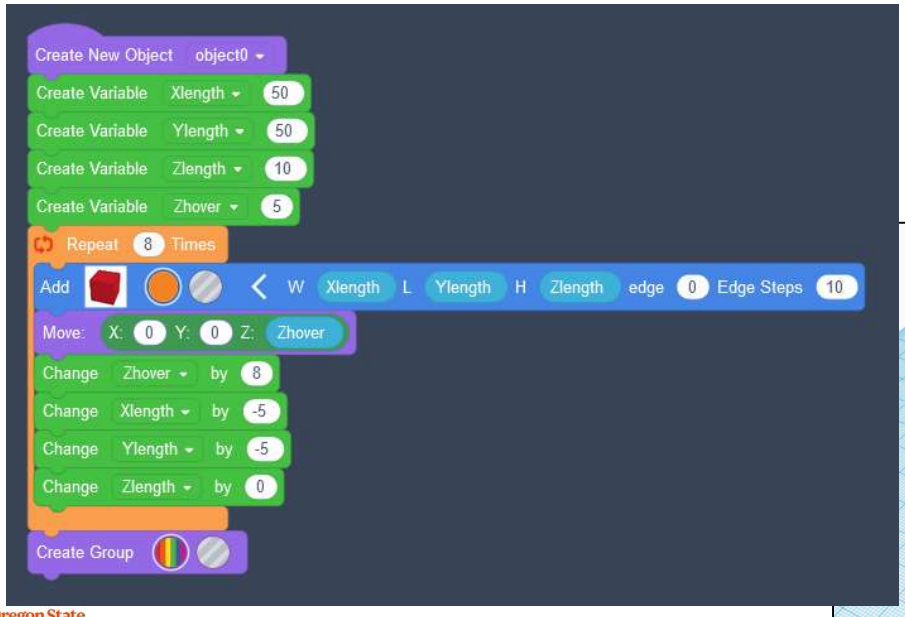
25

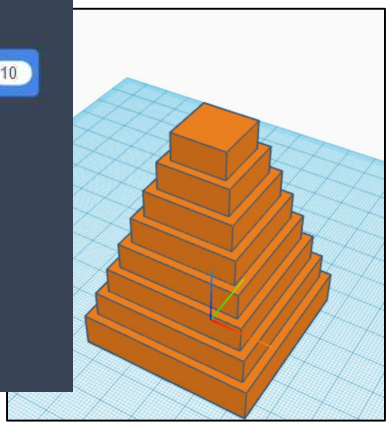


25

Procedural CSG Using TinkerCad/Codeblocks

26





26

Blender's 3D Printing Utility isn't there by Default

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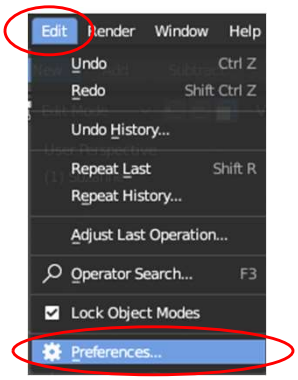

By default, Blender doesn't let you see its 3D Printing utility. You need to tell Blender to turn it on.

1. Click **Edit** → **Preferences**

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Blender's 3D Printing Options aren't there by Default

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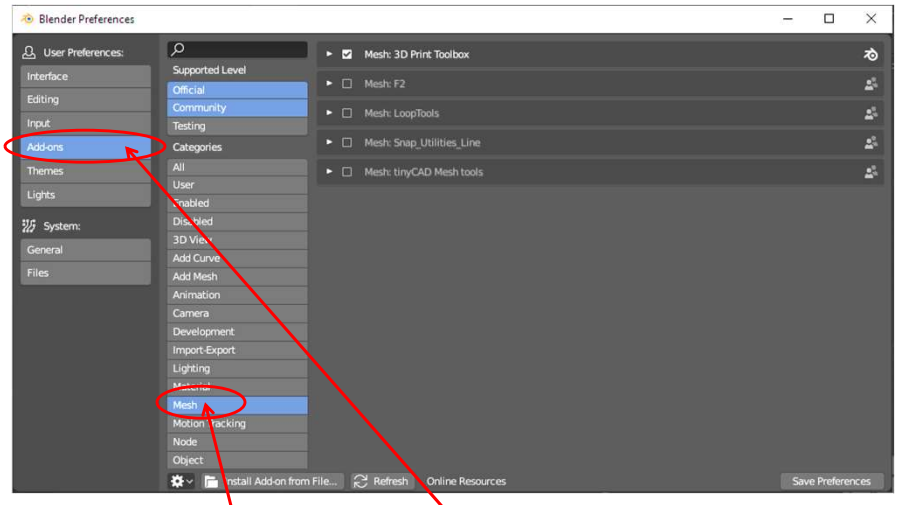

2. Click on the **Addons** tab
3. Click on **Mesh**

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Blender's 3D Printing Options aren't there by Default

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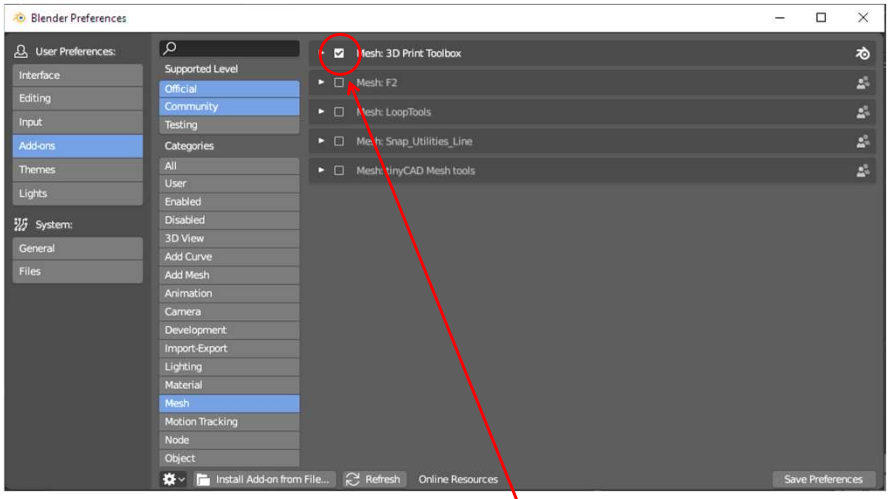

4. Click the **Mesh: 3D Print Toolbox**

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Blender Options for 3D Printing

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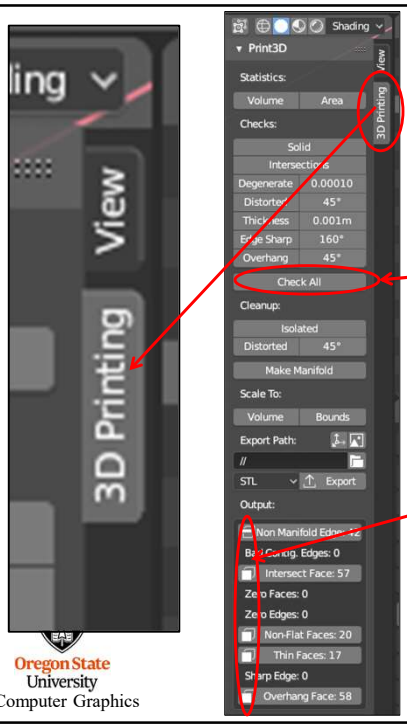

3D Printing now shows up in your Properties Region (hit the 'n' key if you're not seeing it)

Objects destined for 3D Printing must be "legal solids". Clicking on object and then on **Check All** will try to determine that

Tab over to Edit Mode. Clicking on any of these will highlight where they are on your object.

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Blender Options for 3D Printing

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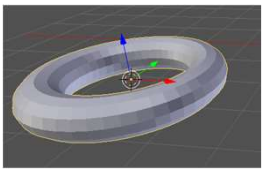

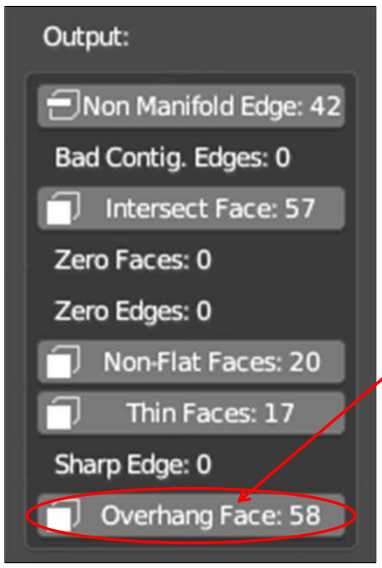

An overhang face is not necessarily a bad thing. The entire bottom of the part will consist of, by necessity, overhang faces.

However, overhang faces that are not the bottom of the part could be a problem.

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Heightmap Files are Straightforward to use with 3D Printing

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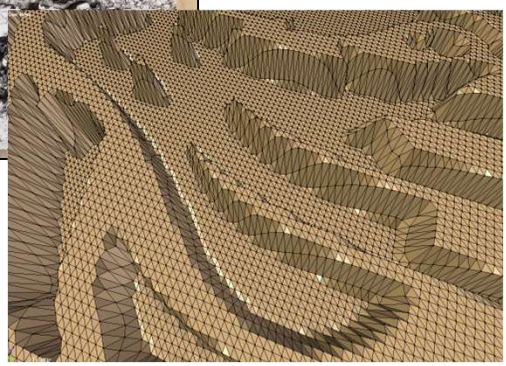

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A Very Special Heightmap 3D Printing Model (mmm…)

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A Very Special Heightmap 3D Printing Model (mmm…)

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Most Any *Data* Can be Turned into a 3D-Printable Model

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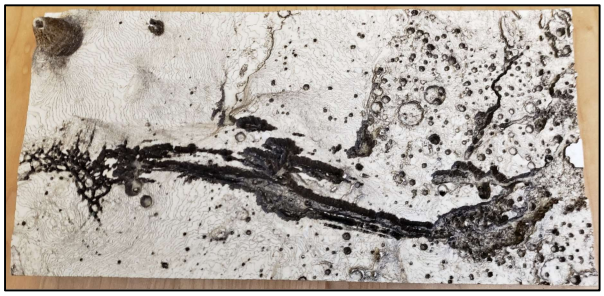
Mars



Mars

3D Ultrasound

Molecular Modeling

Ore University Computer Graphics

3D Ultrasound

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Most Any *Data* Can be Turned into a 3D-Printable Model

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Oregon

Grand Canyon

Dinosaur Egg

Earth

University Computer Graphics

MRI Scan

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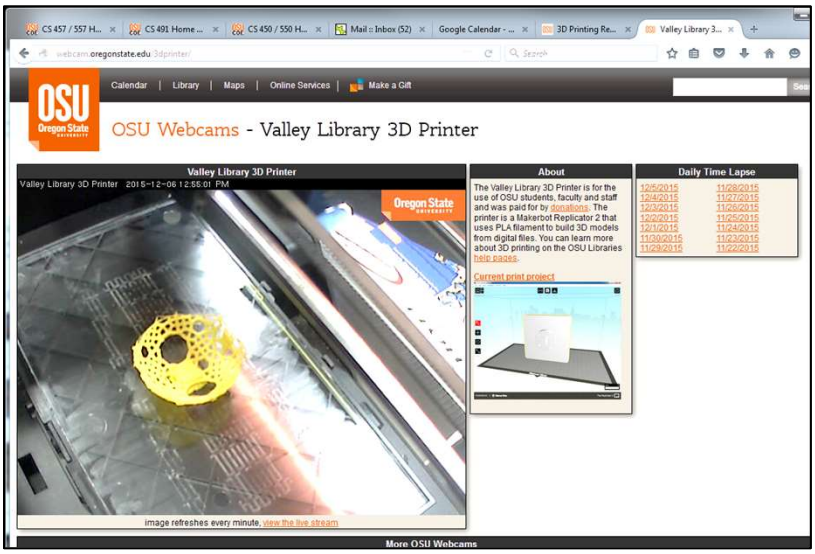
The OSU Library Has Four 3D Printers for Student Use

To watch the OSU Library's 3D Printers, go to:

http://webcam.oregonstate.edu/3dprinter/



The OSU Library Has Four 3D Printers for Student Use

To send an STL model to the OSU Library's 3D Printers, go to:

http://guides.library.oregonstate.edu/3Dprinting/3Dprintform