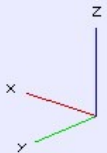


Practical Solid Modeling For 3D Printing With OpenSCAD

Ed Nisley • KE4ZNU
ed.nisley@pobox.com
softsolder.com

~
Squidwrench
September 2013



Upcoming Events

- Defining the Terms
 - Practical · Solid Modeling · 3D Printing · OpenSCAD
- Constructive Solid Geometry
 - CSG Solids · Operations · Transformations
 - OpenSCAD “Debugging” · Iterators · Conditionals
- Modeling Printable Objects
 - Geometric & Process Constraints
 - Hole Calibration & Compensation
 - Bridging · Overhang · Support Structures
- Other Fancy Stuff

Defining the Terms

Practical

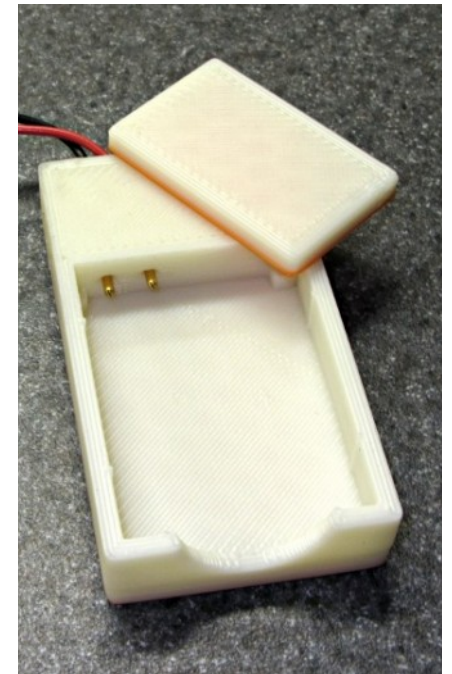
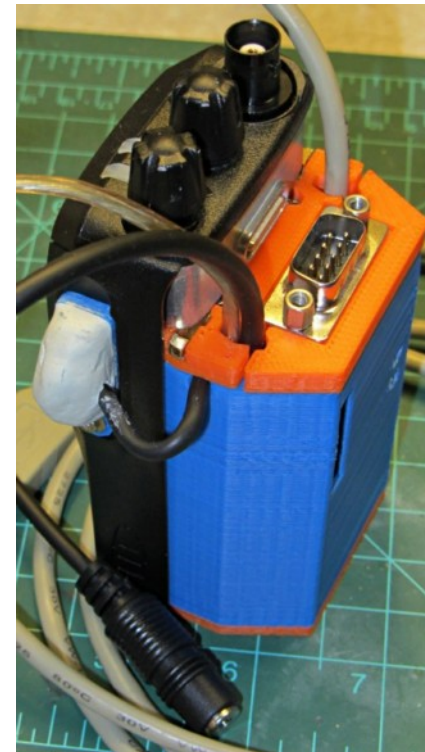
prac·ti·cal

adjective /'praktikəl/

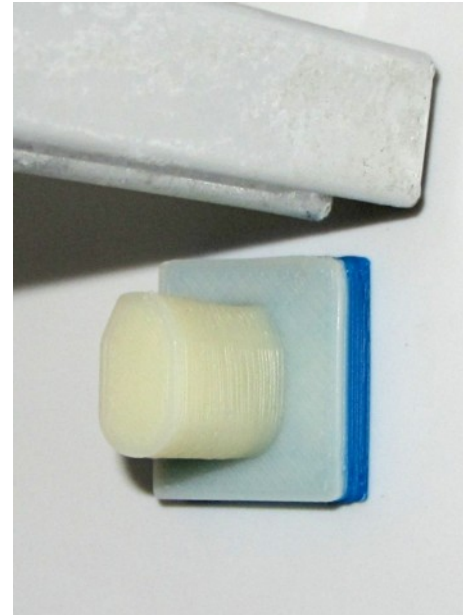
Of or concerned with
the actual doing or use of something
rather than with theory and ideas

Thus sayeth Google
define: practical

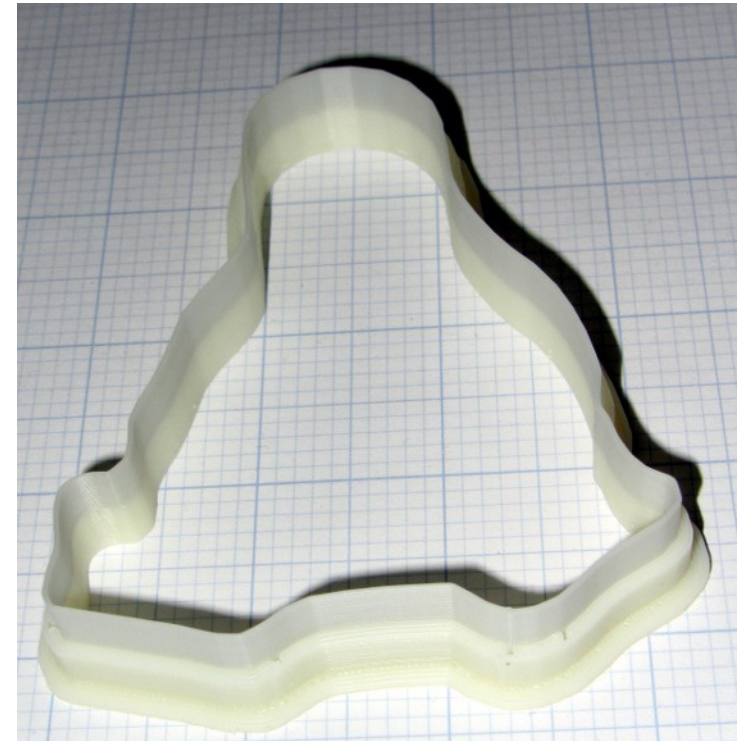
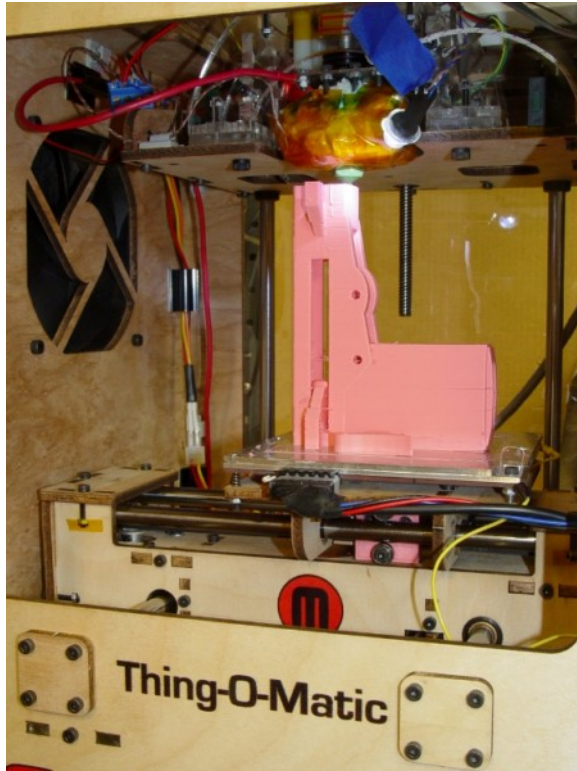
Custom Parts



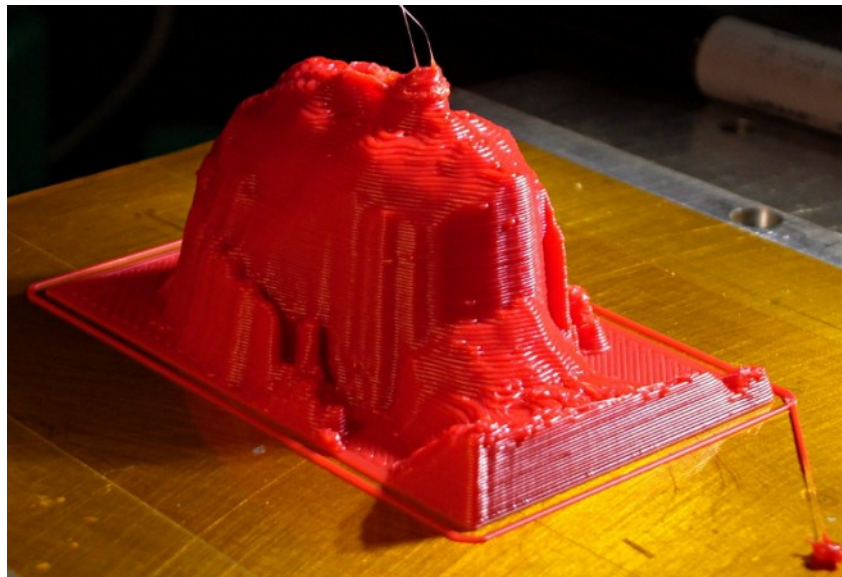
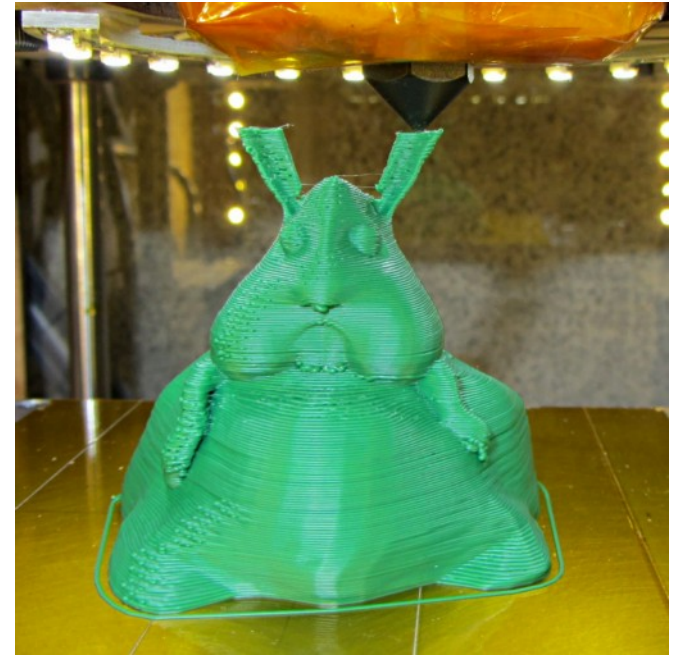
Repair Parts



Fun Stuff



Other People's (Im)practical Stuff



Project Details

Custom Parts

- Propane QD wrench
- Photodiode fixture
- Helmet mirror
- Microscope ring light
- Microscope camera
- Camera macro lens
- Amateur radio GPS
- Battery fixture

Repair Parts

- Caliper thumbwheel
- Freezer shelf bracket
- Broom handle
- Vacuum hose clamp
- Bar clamp handle

Project Details

Fun Stuff

- Nerf Pistol
- CO2 Capsule Fins
- Tux Cookie Cutter
- Concrete Blocks
- Triple Cylinder Thing
- Quilting Pin Caps

Other Peoples' Stuff

- Dr. Who Cutter/Press
- Knot
- Fat Bunbun
- Chalk people
- Companion Cube
- Stanford Bunny
- Octopus
- 3D Portrait

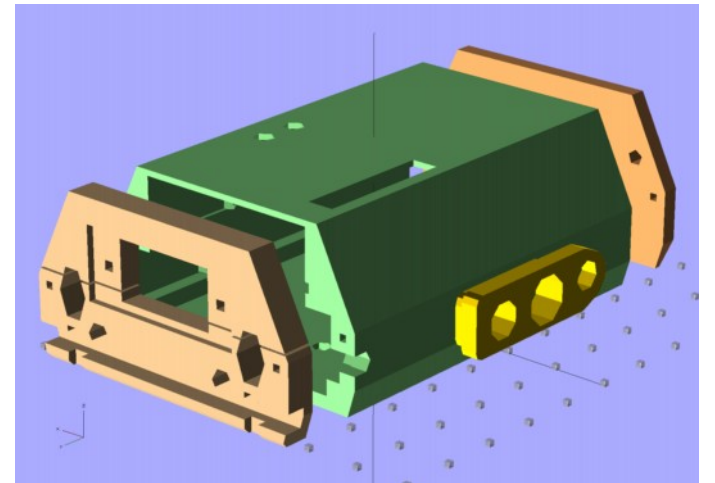
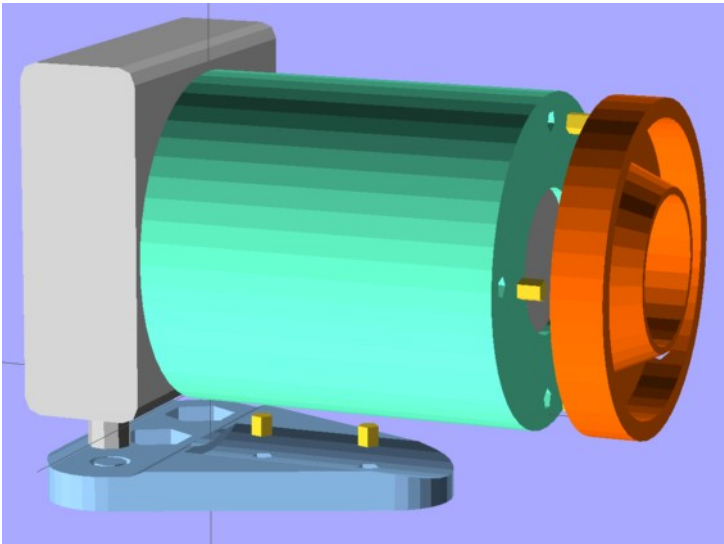
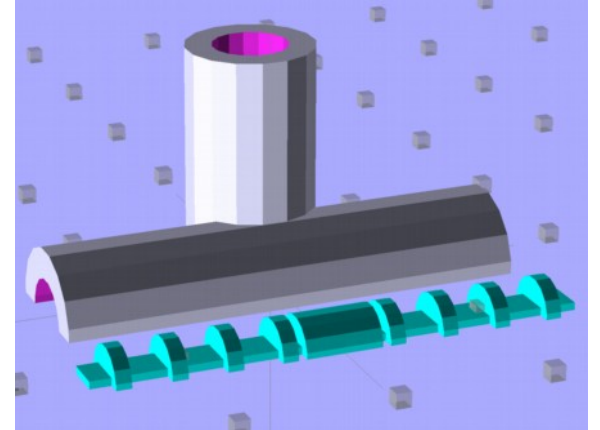
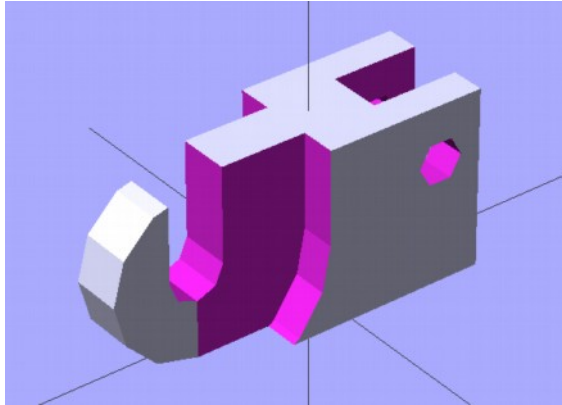
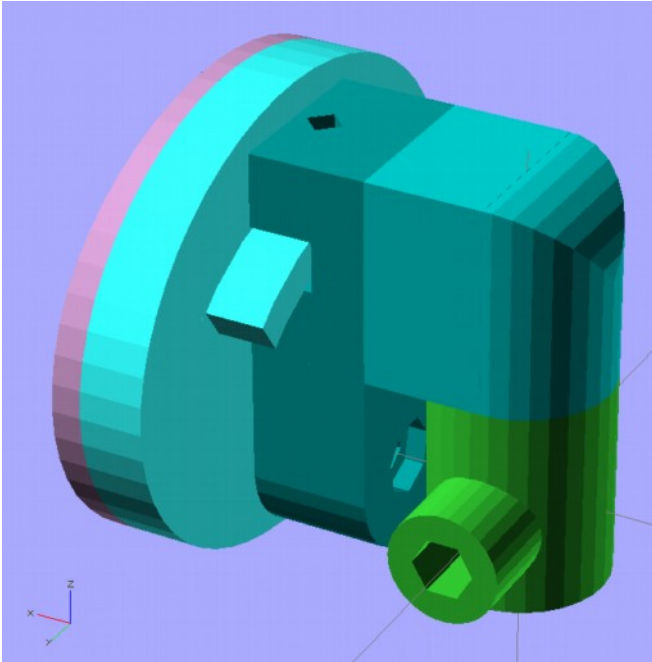
Solid Modeling

... is a consistent set of principles for mathematical and computer modeling of **three-dimensional solids**.

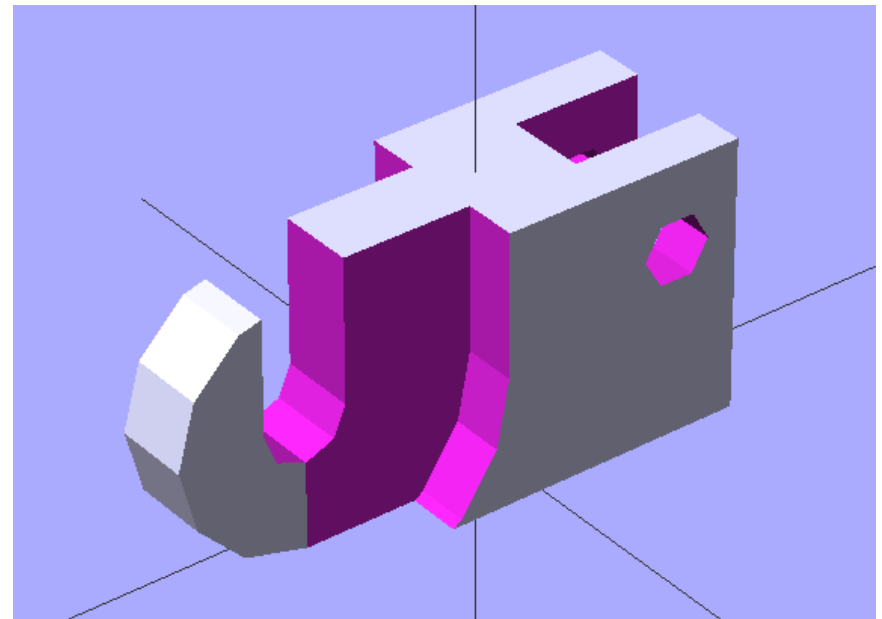
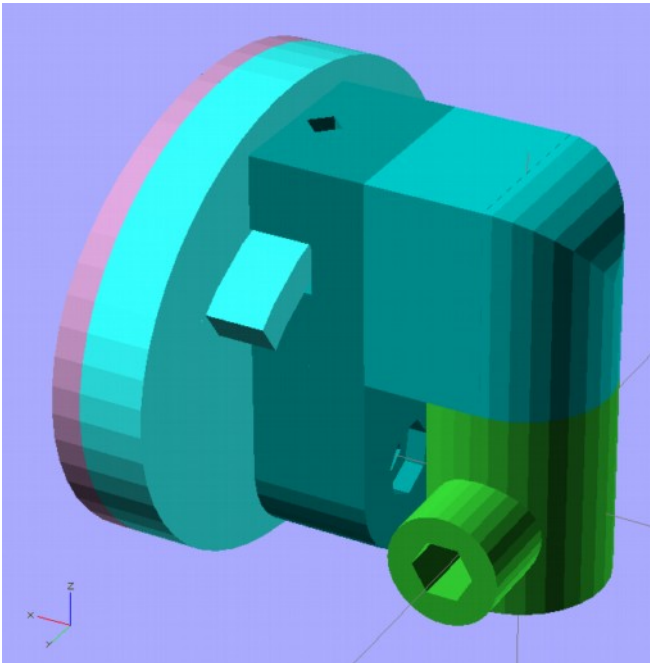
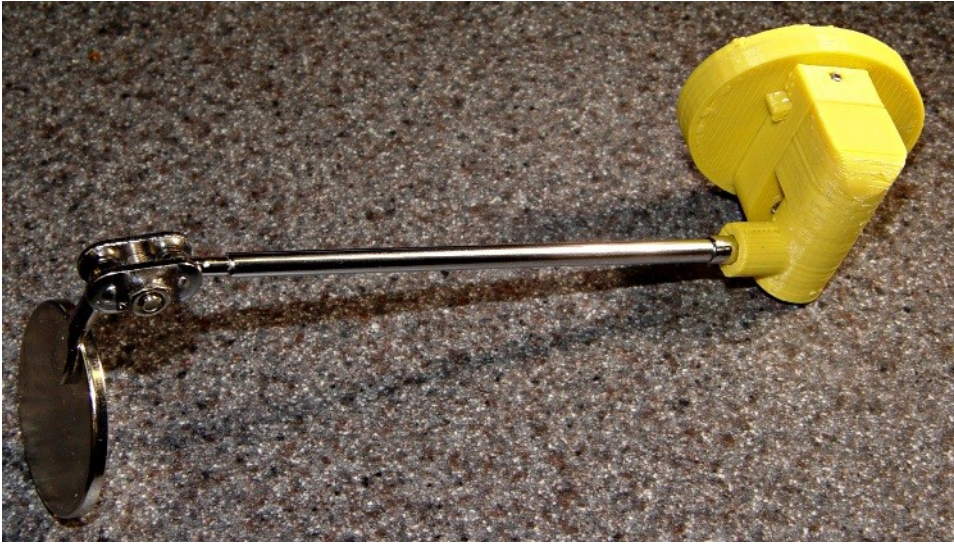
Solid modeling is distinguished from related areas of geometric modeling and computer graphics by **its emphasis on physical fidelity**.

Thus sayeth Google
define: “solid modeling”

Three Dimensional Solid Models



Emphasis on Physical Fidelity



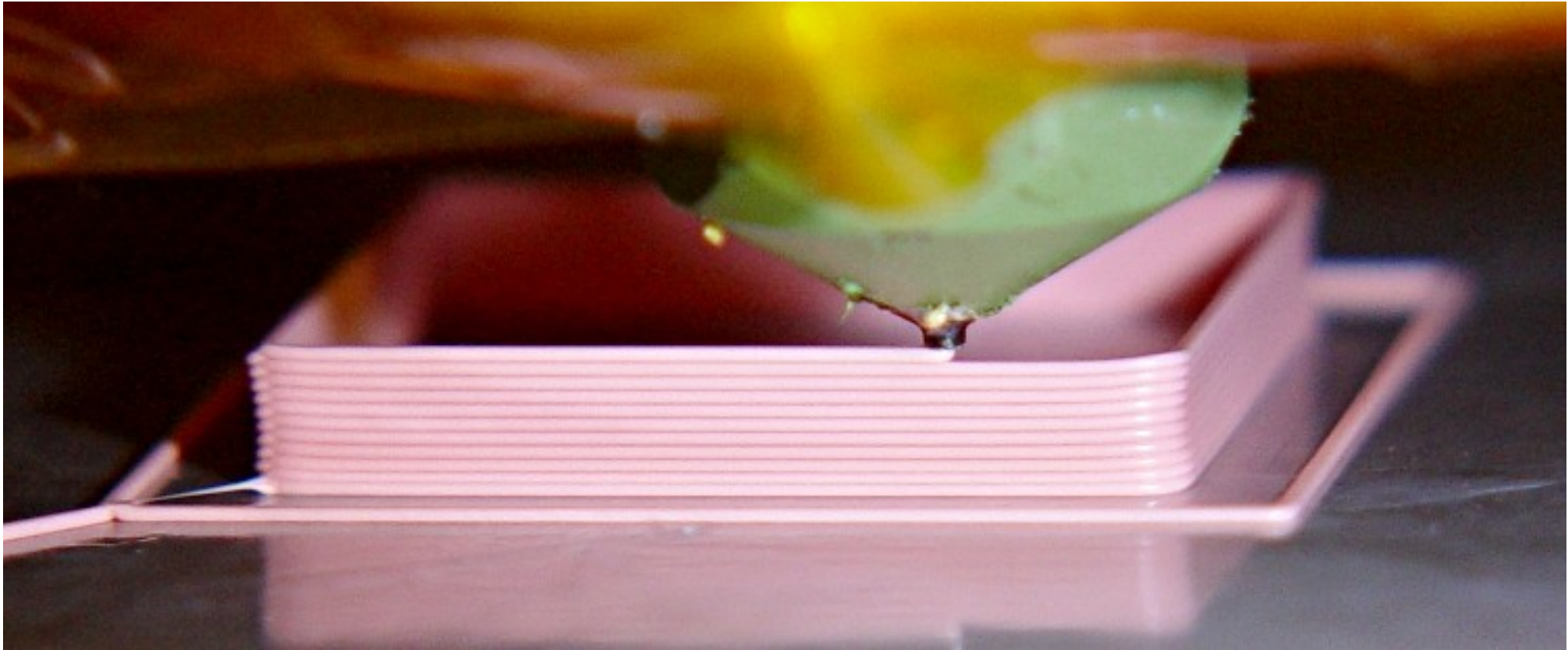
3D Printing

Additive manufacturing or 3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model.

3D printing is achieved using an **additive process**, where **successive layers** of material are laid down in different shapes.

Thus sayeth Wikipedia
http://en.wikipedia.org/wiki/3D_printing

“Fused Deposition” 3D Printing



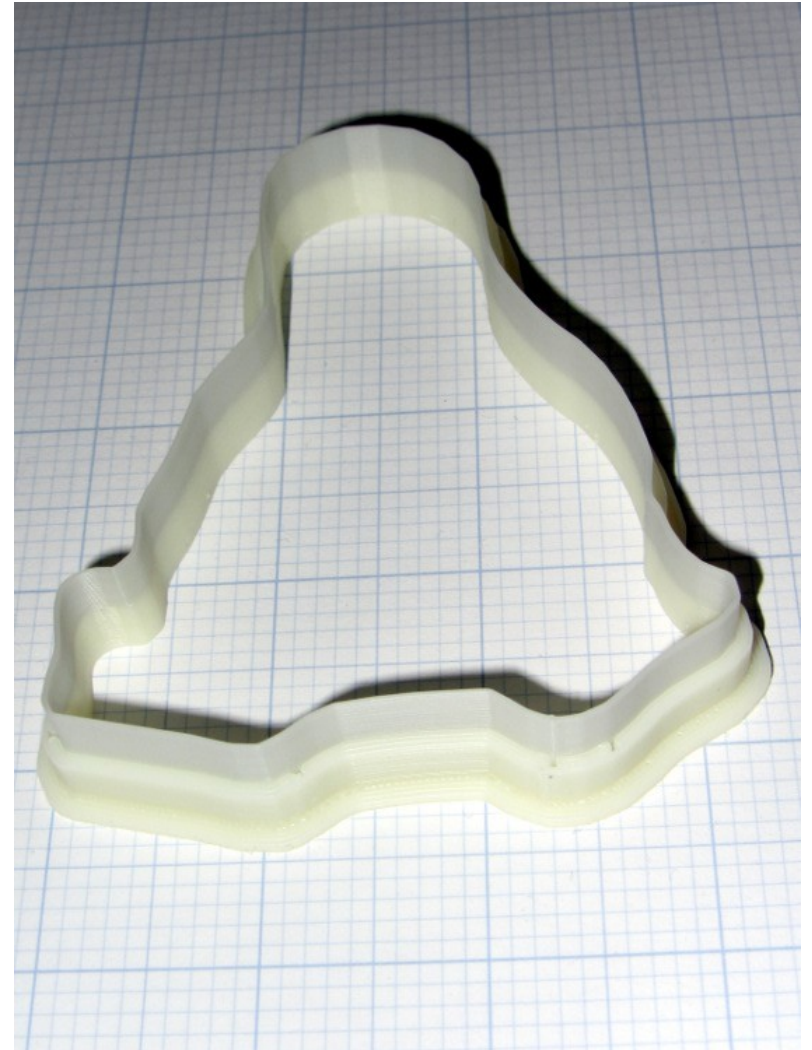
- Fused Filament Fabrication
- Glorified Glue Gun Technology ...
- Beware the trademark & IP minefield

3D Printing Up Close

Tux Cookie Cutter

~

The Movie



OpenSCAD

OpenSCAD is a software for creating **solid** 3D CAD models.

~

It is ... **a 3D-compiler** that
reads in a script file describing the object
and
renders the 3D model

Thus sayeth OpenSCAD
www.openscad.org

OpenSCAD

Thus it might be
the application you are looking for
when you are planning to
create 3D models of machine parts

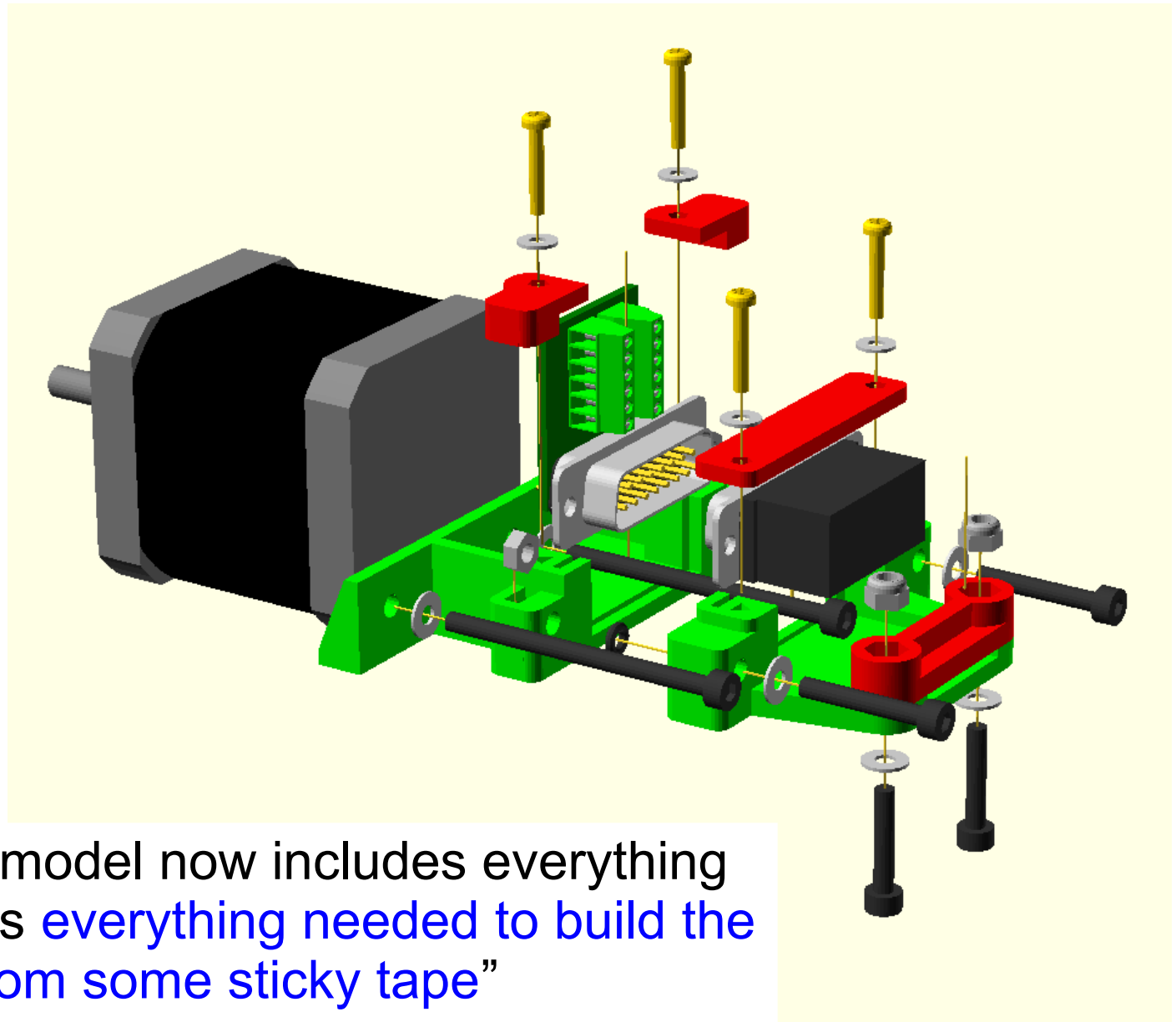
~

but pretty sure [it] is not ... for
creating computer-animated movies.

Thus sayeth OpenSCAD
www.openscad.org/about.html

OpenSCAD Machine Models

Mendel90
by nophead



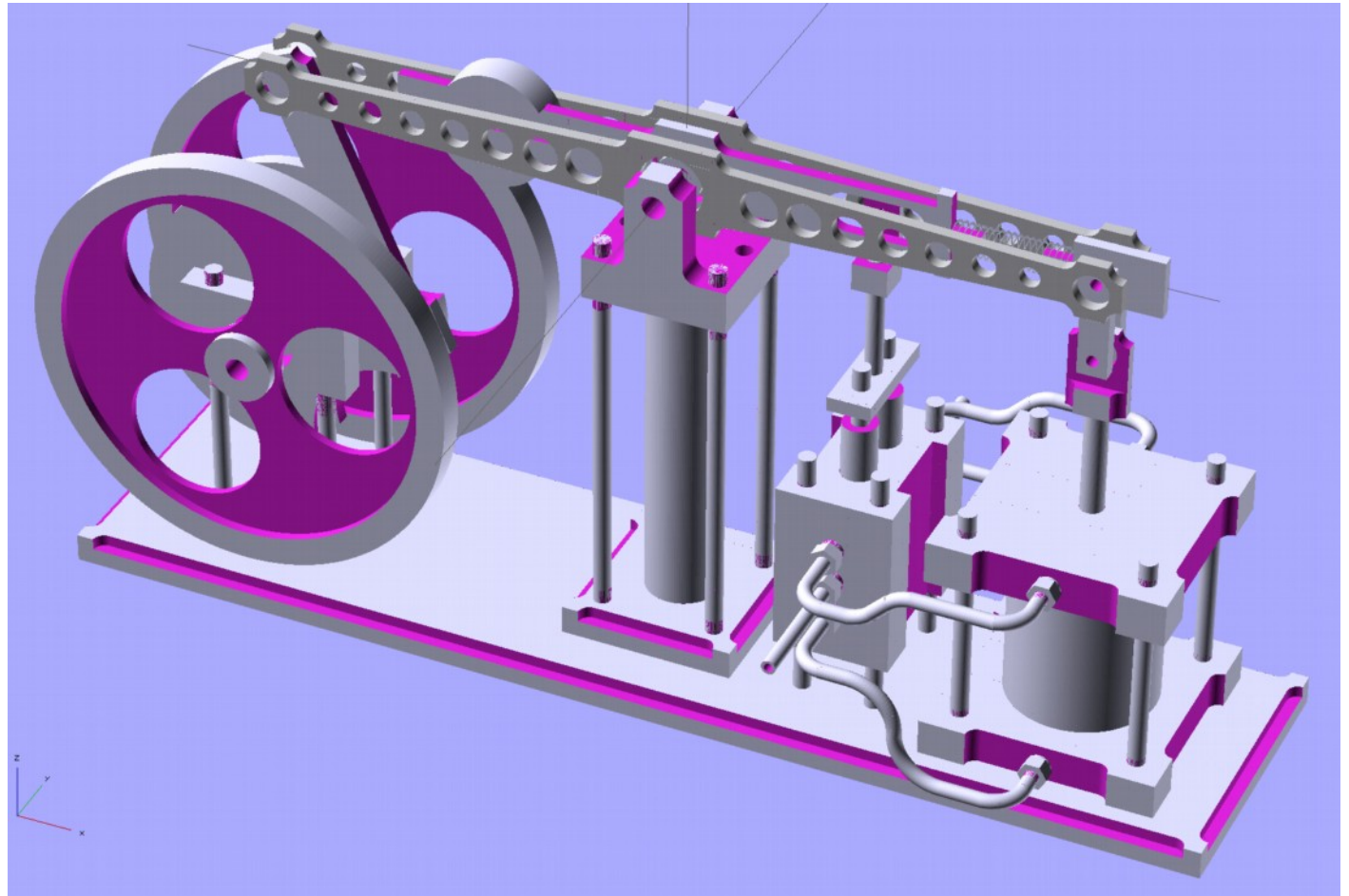
“The OpenScad model now includes everything in the kit, which is **everything needed to build the machine apart from some sticky tape**”

OpenSCAD Machine Models

Beam engine
solid model

by David
Powell

“it’s just a
mockup and
not intended
for 3d
printing”



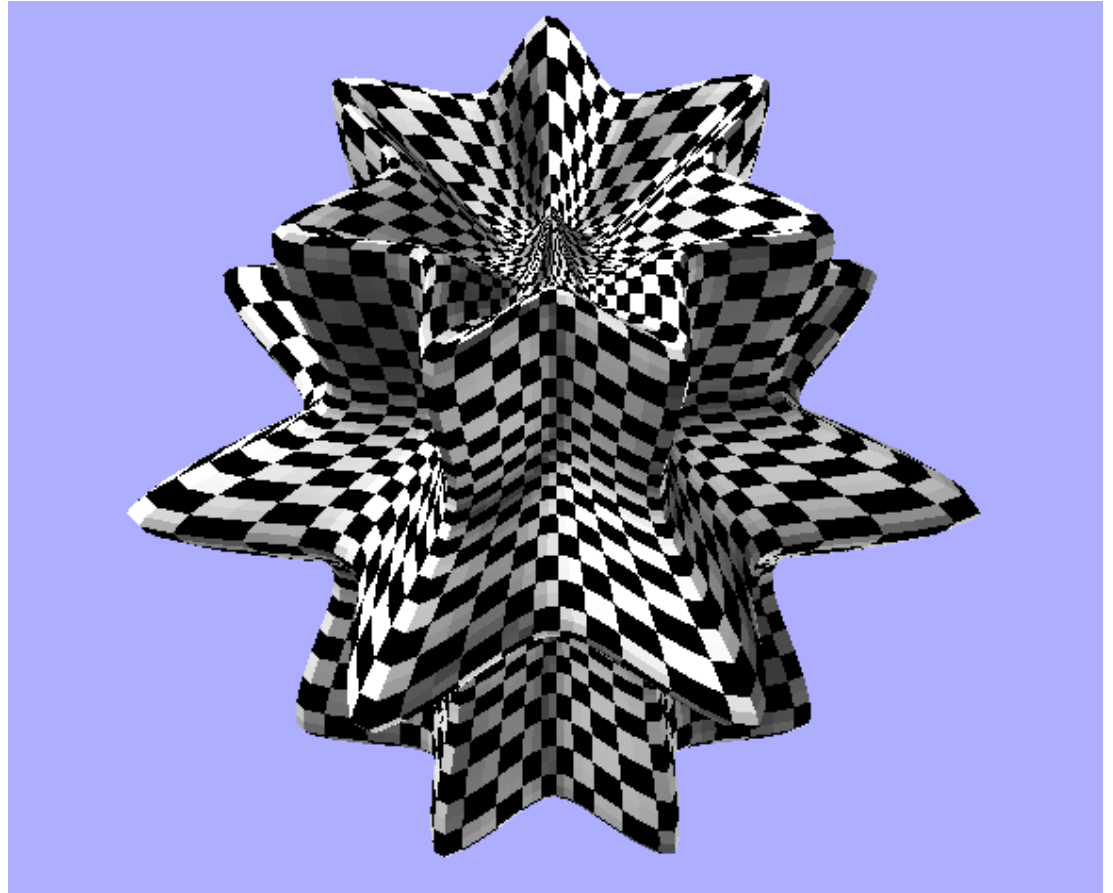
OpenSCAD (Im)Practical Models

SuperShapes

by WilliamAAdams

“You also get the procedural texture mapping checkerboard pattern, thrown in for free.”

He also does very practical stuff...



Constructive Solid Geometry

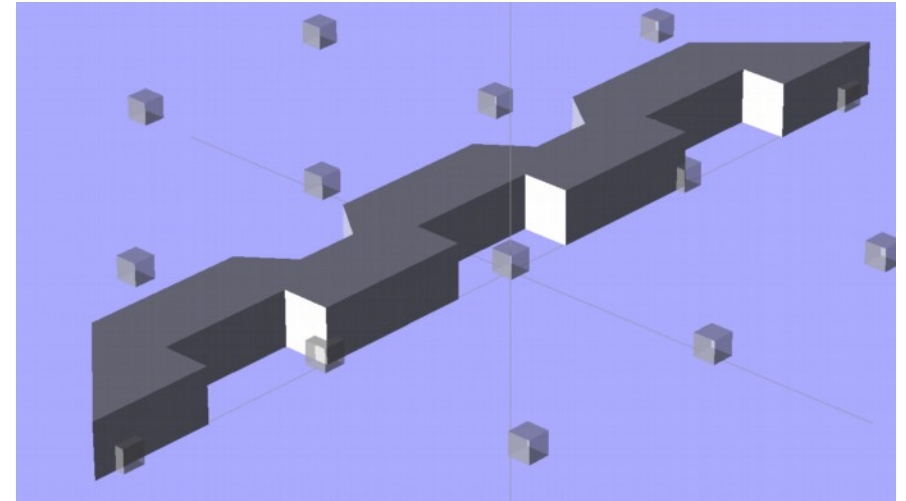
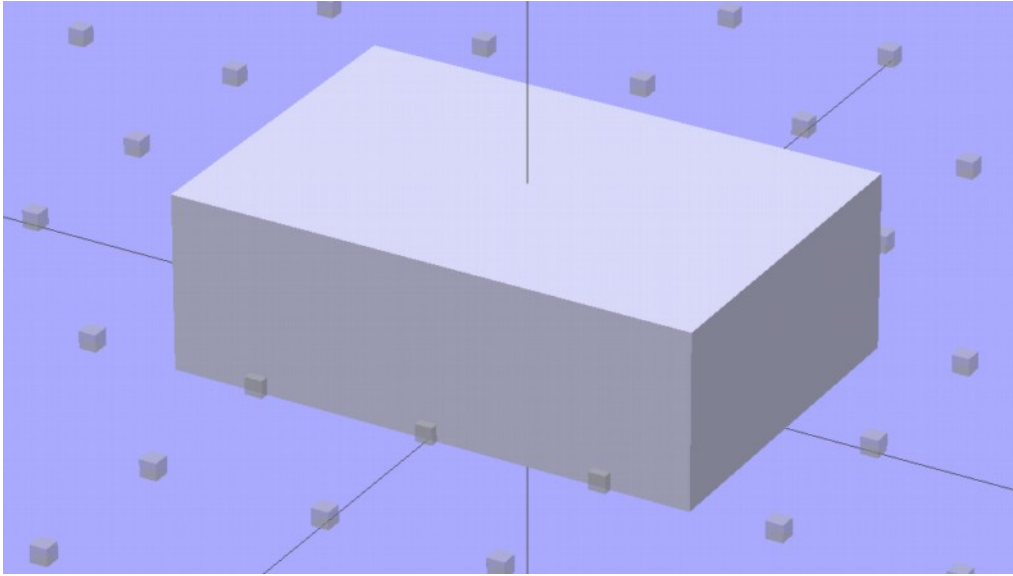
“CSG”

Constructive Solid Geometry

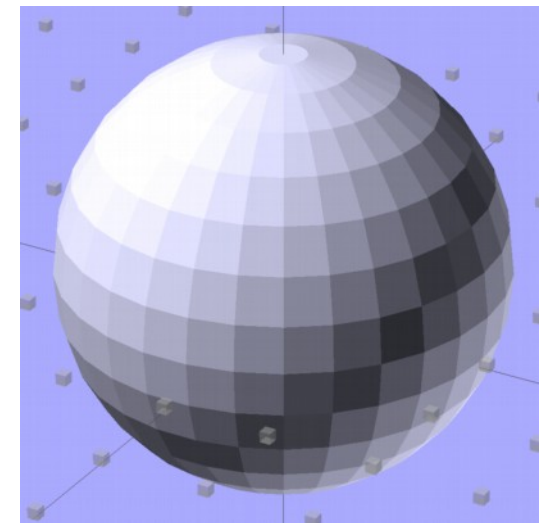
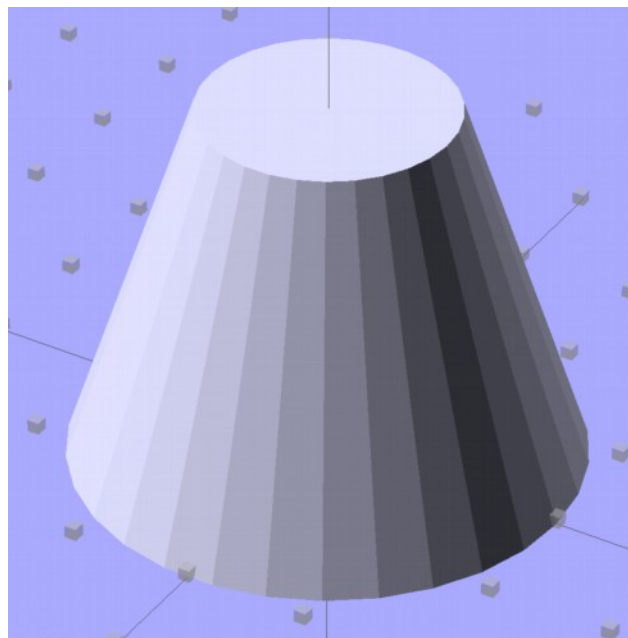
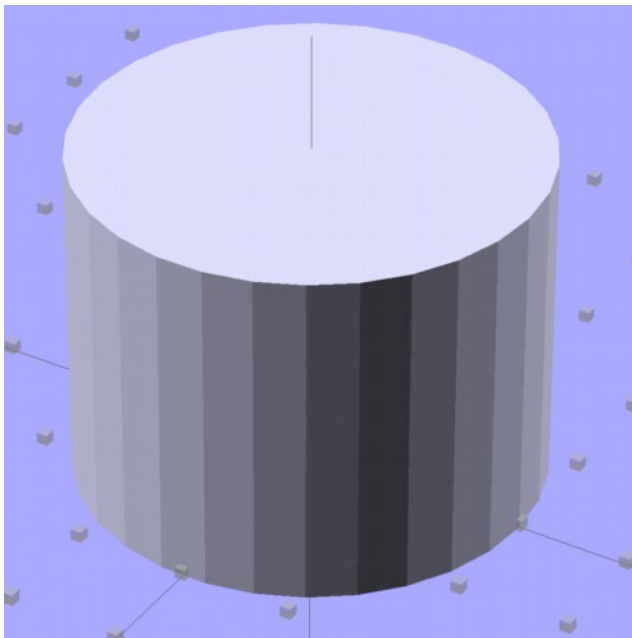
... an object is constructed from **primitives**
by means of **allowable** operations,
which are ... **Boolean operations** on sets:
union, intersection and difference.

Thus sayeth Wikipedia
http://en.wikipedia.org/wiki/Constructive_solid_geometry

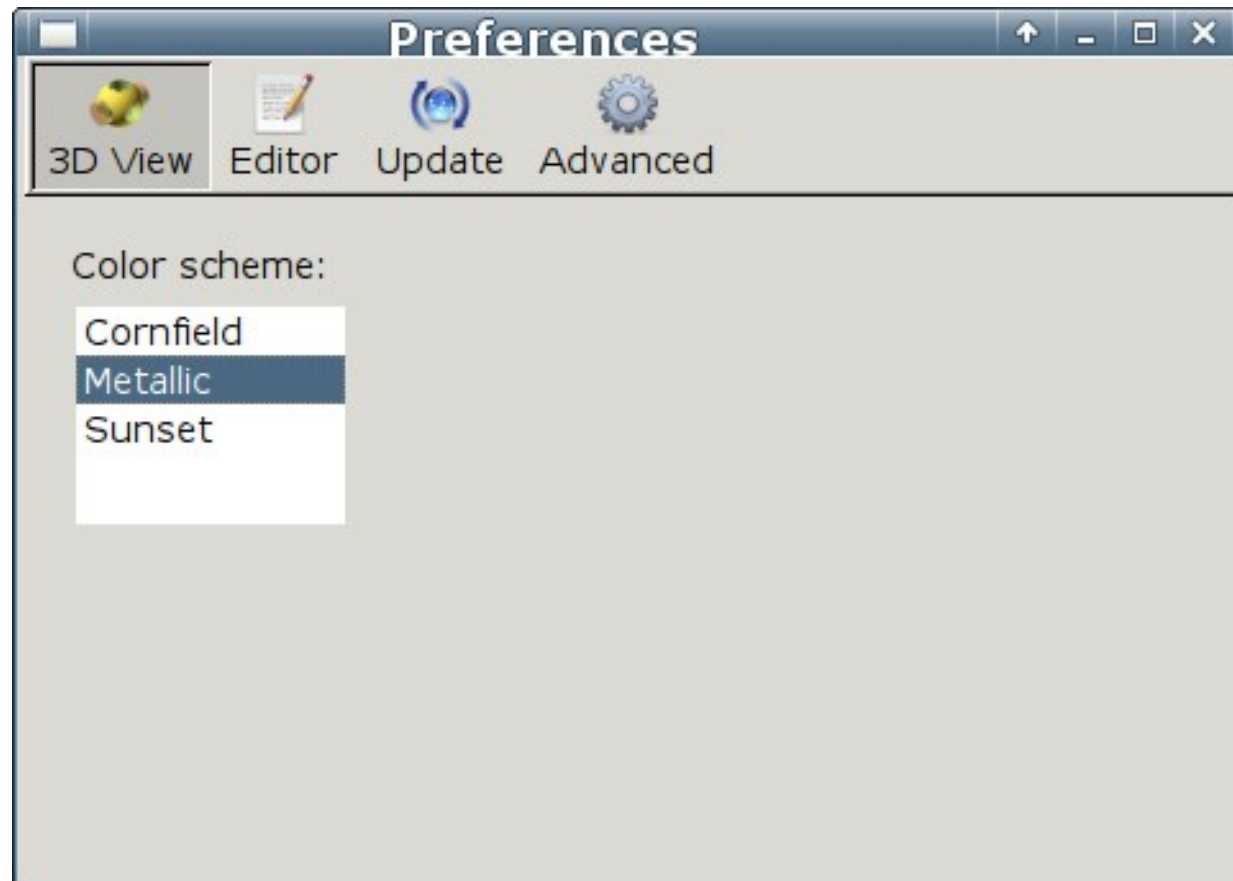
CSG Primitives



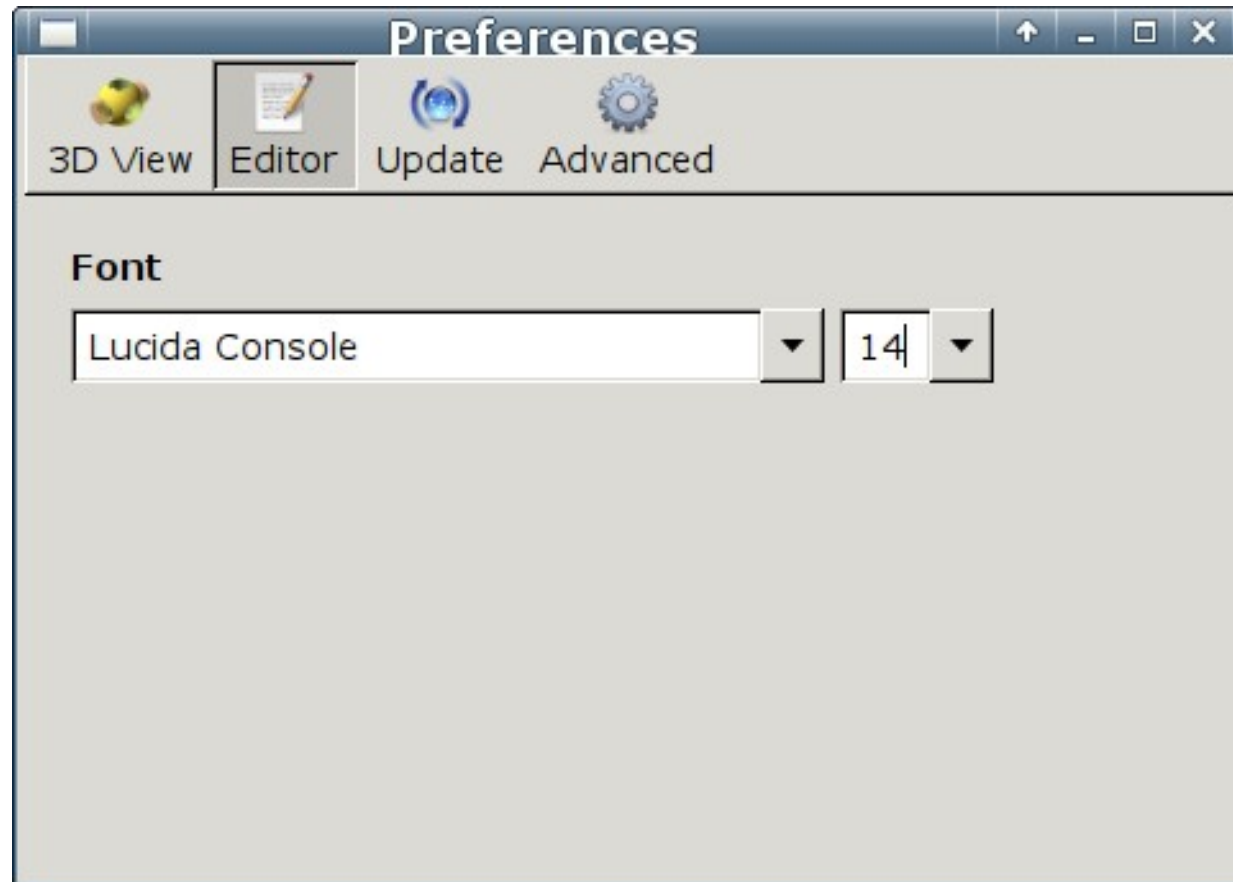
OpenSCAD: cube cylinder sphere



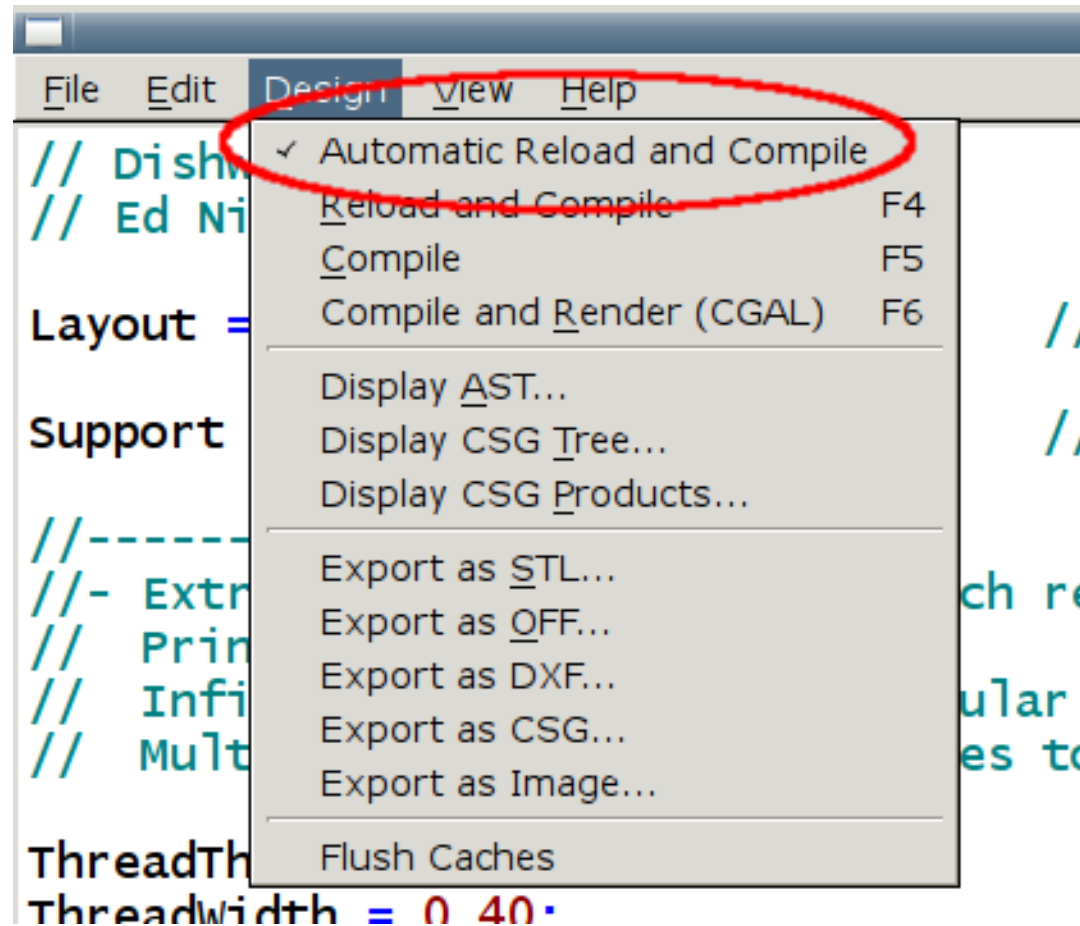
OpenSCAD Color Scheme



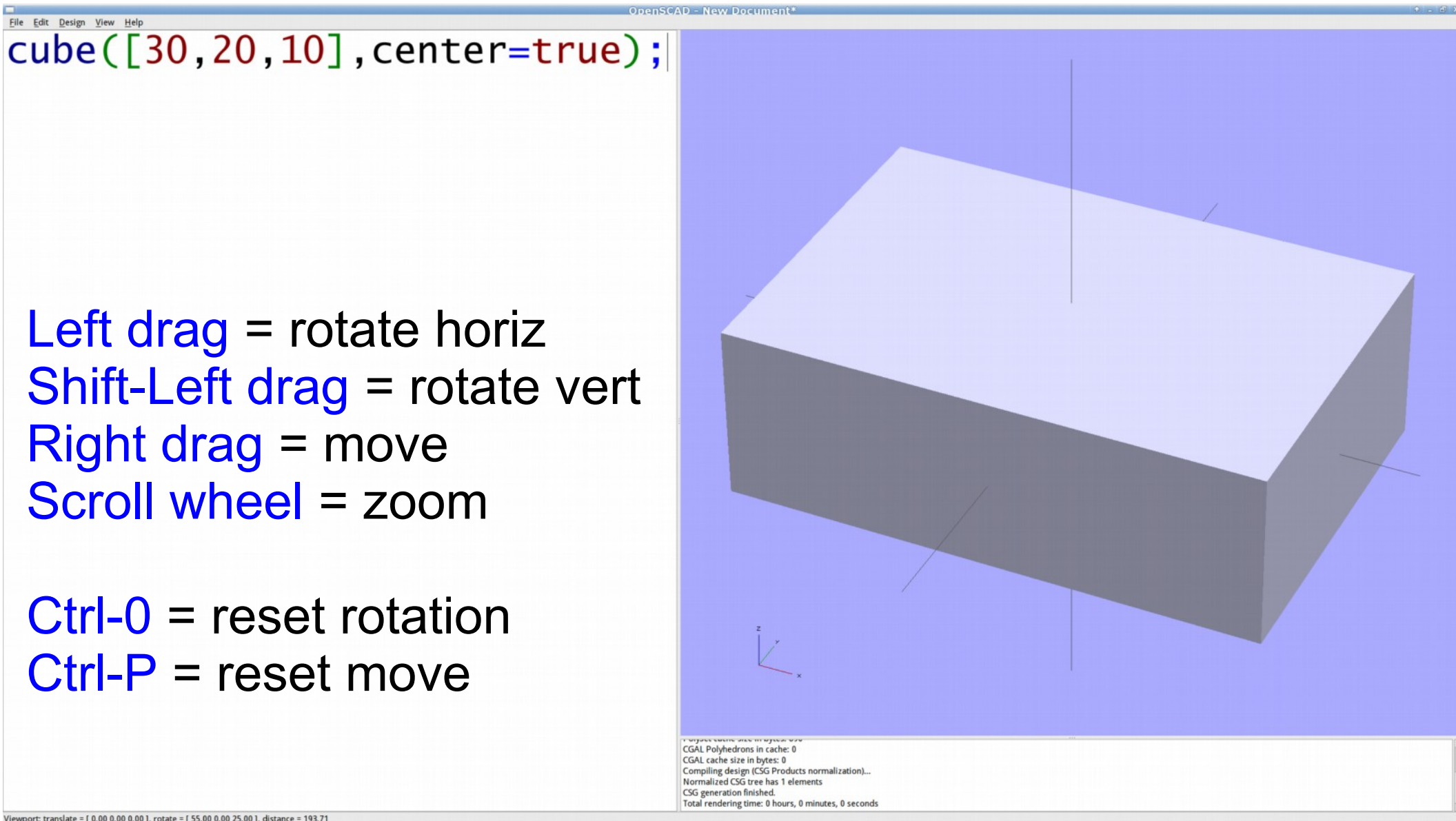
OpenSCAD Editor Preferences



OpenSCAD Design Option



CSG Primitive: Cube



CSG Primitive: Cylinder

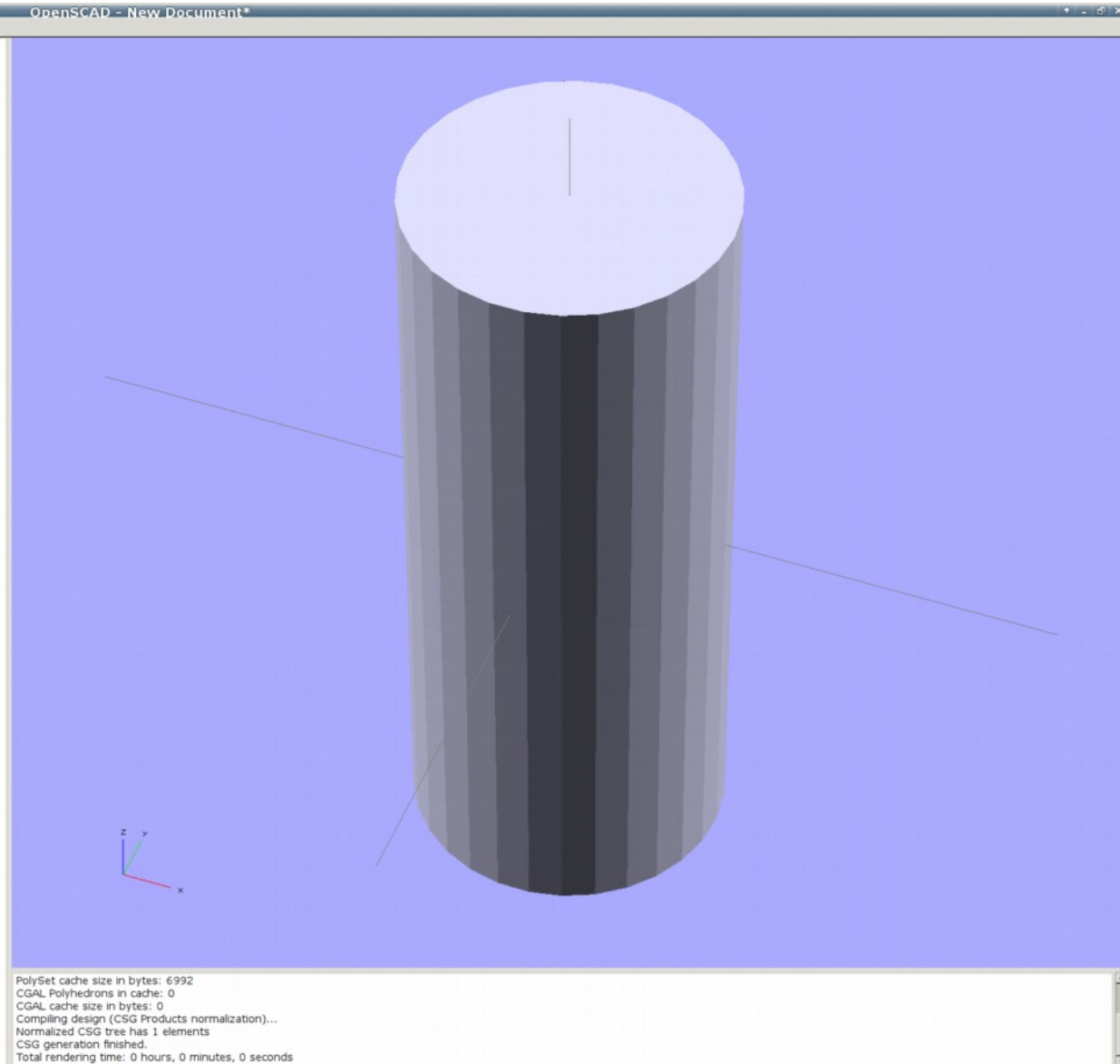
```
cylinder(r=20,h=100,  
        center=true);
```

Define number of sides:

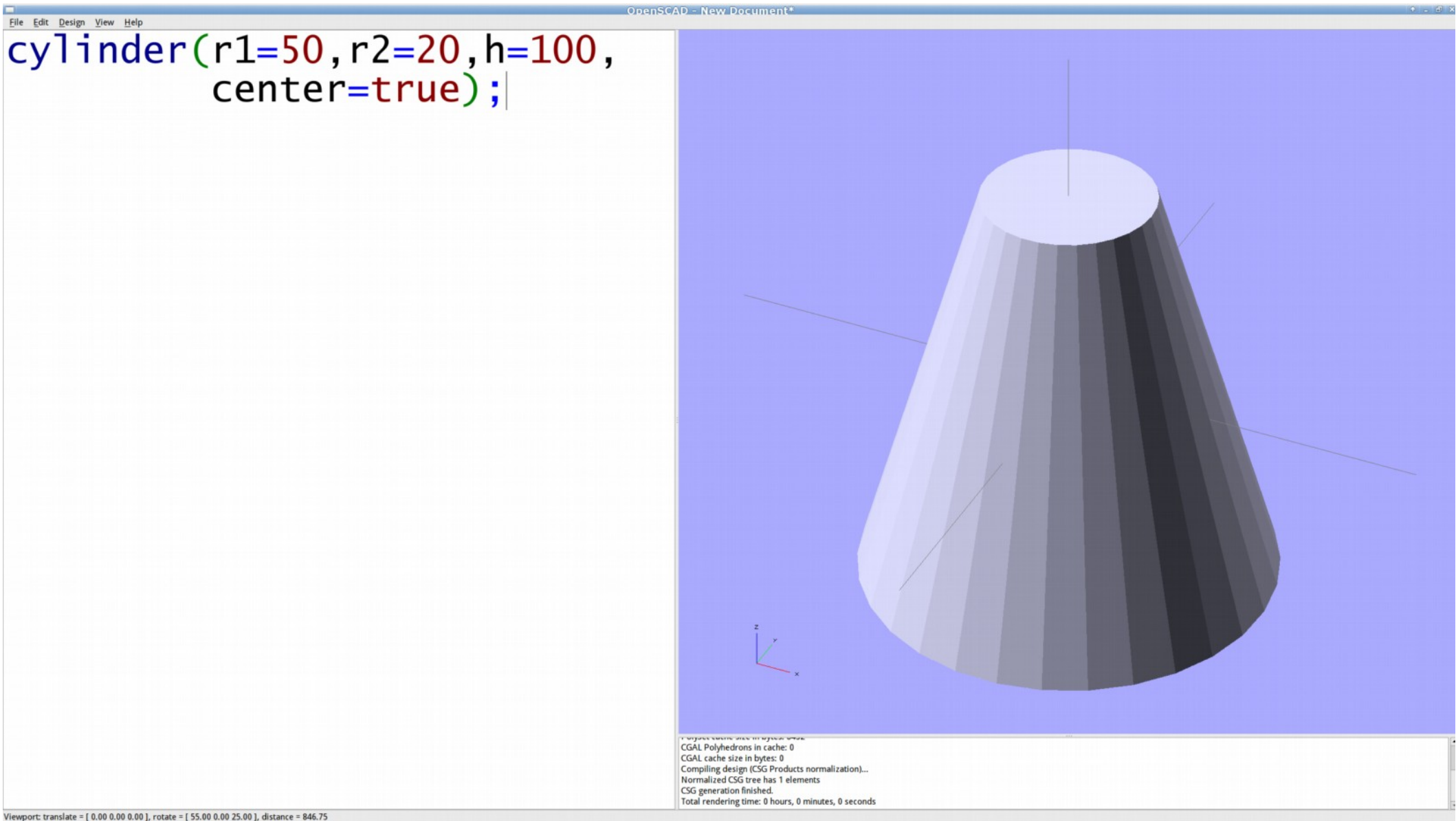
\$fn=3 → triangular

\$fn=6 → hexagonal (nuts!)

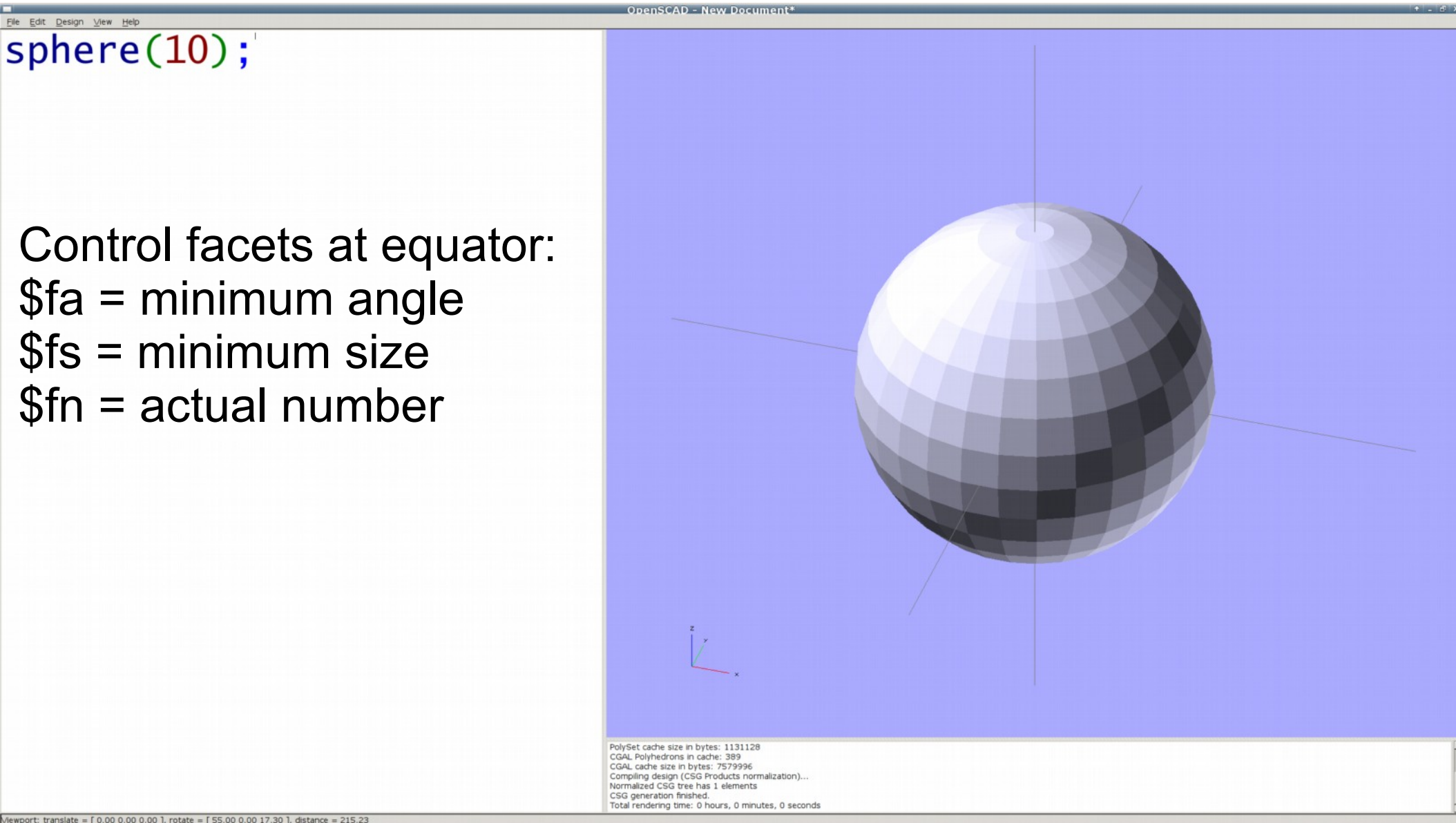
\$fn=8 → octagonal



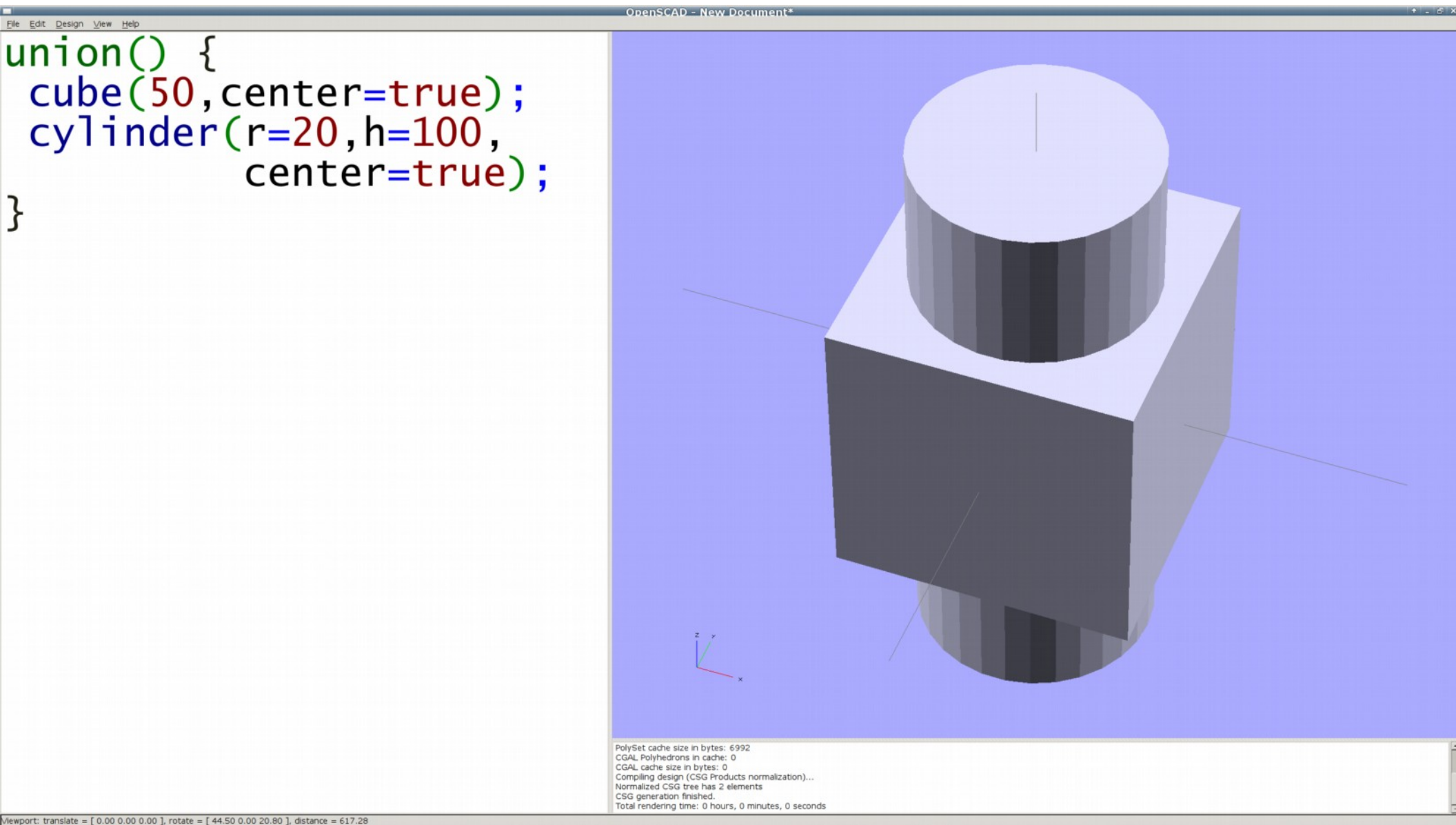
CSG Primitive: Cylinder



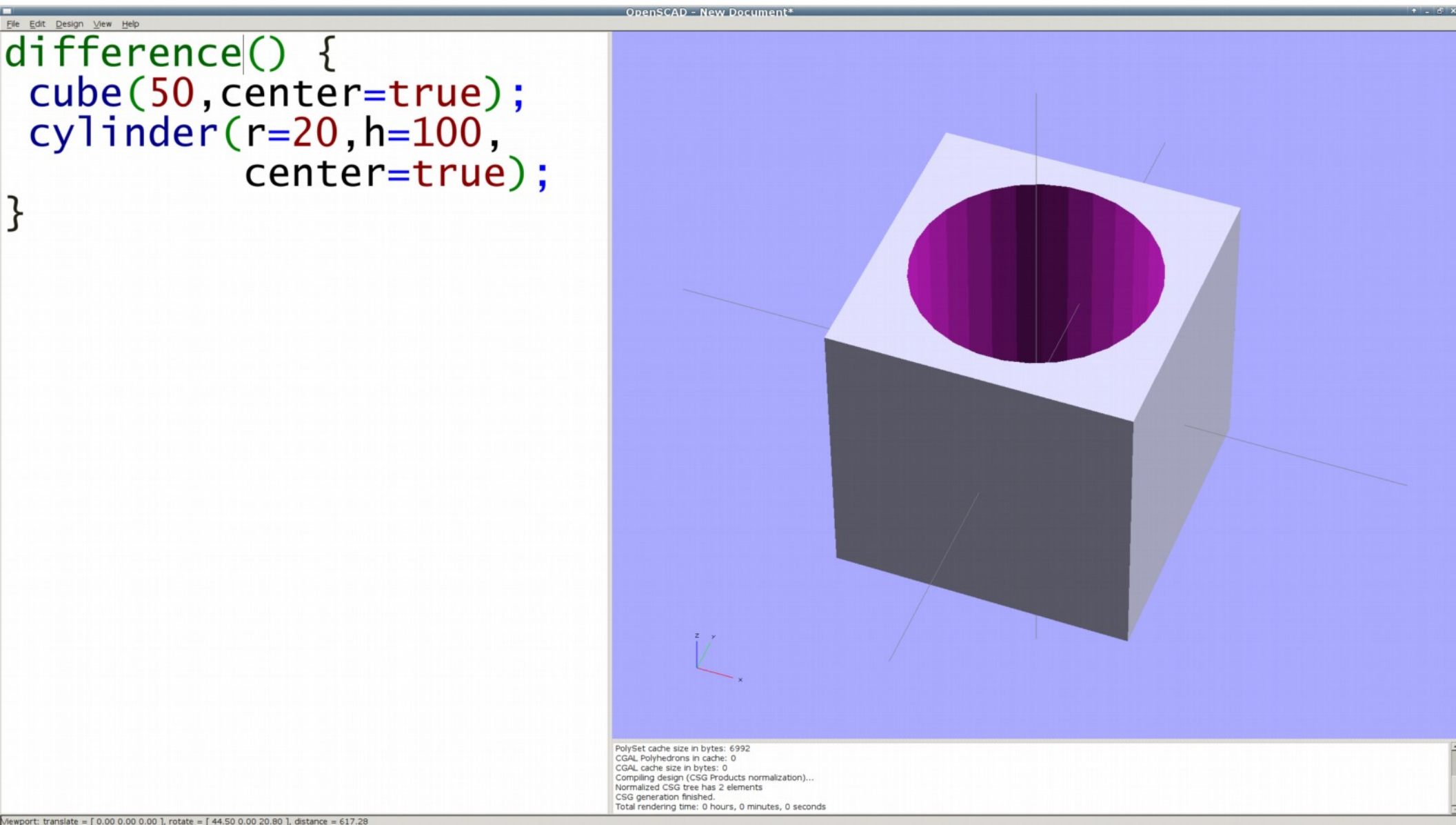
CSG Primitive: Sphere



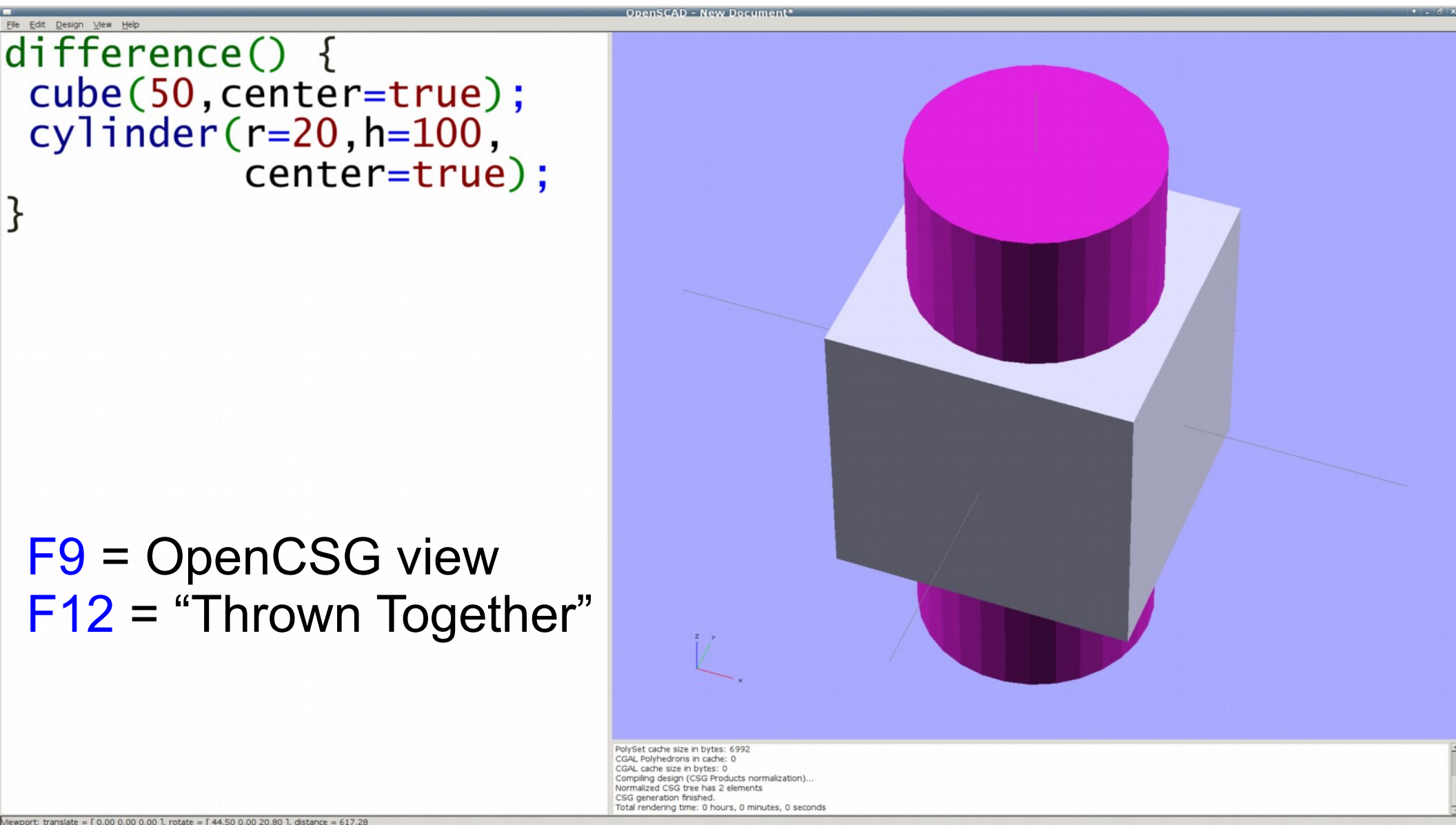
CSG Operation: Union



CSG Operation: Difference



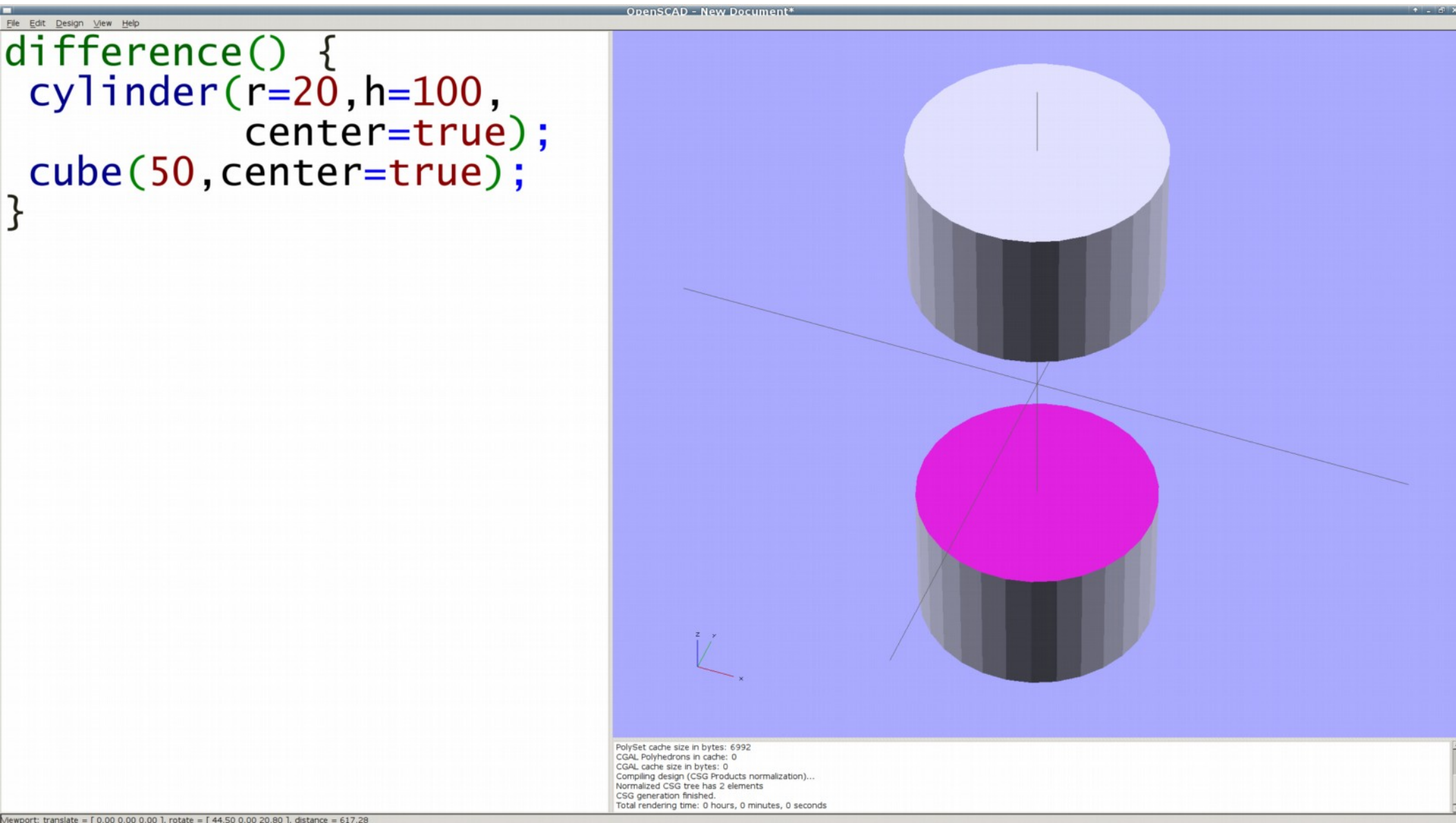
CSG Operation: Difference



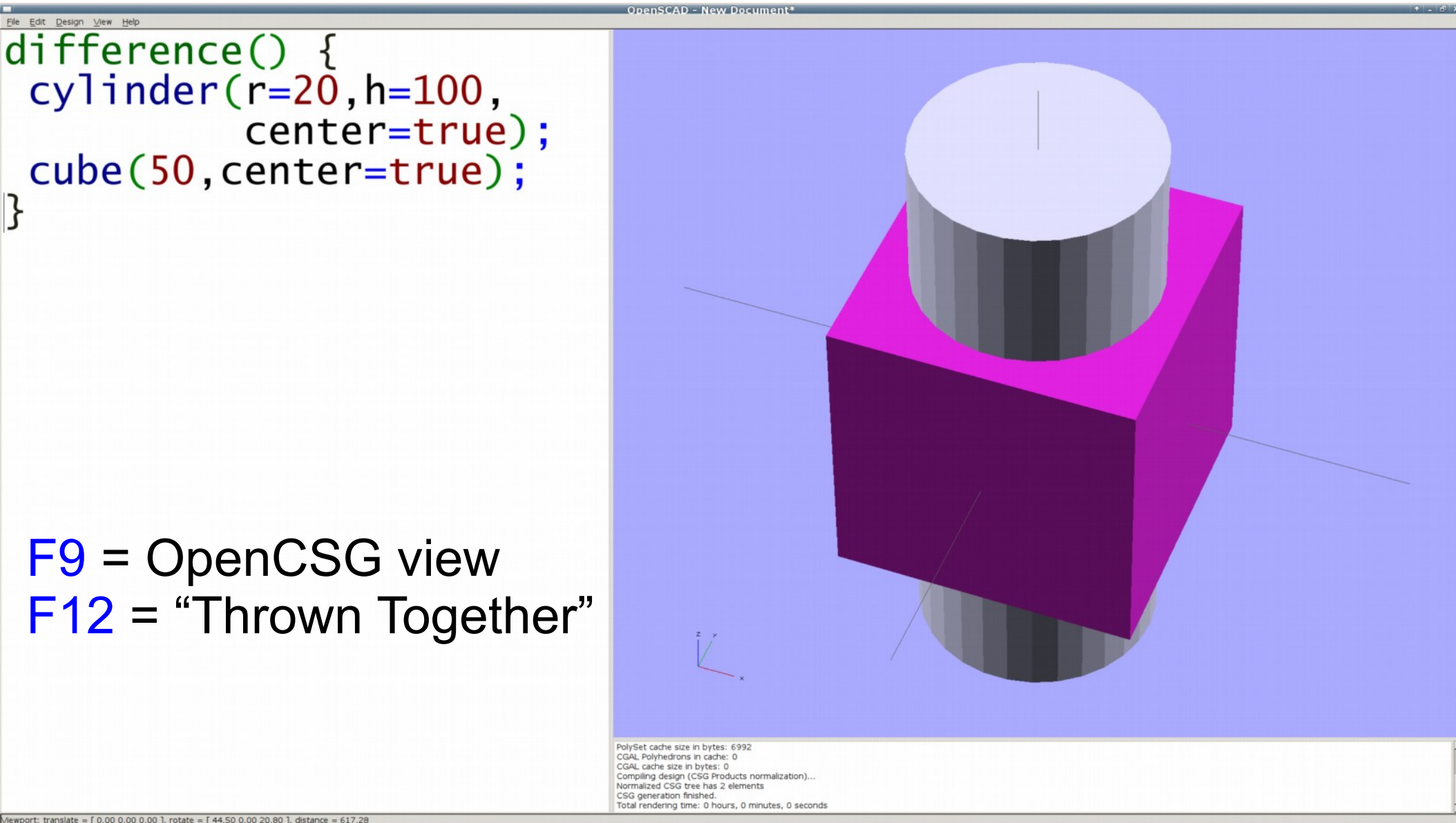
F9 = OpenCSG view

F12 = “Thrown Together”

CSG Operation: Difference



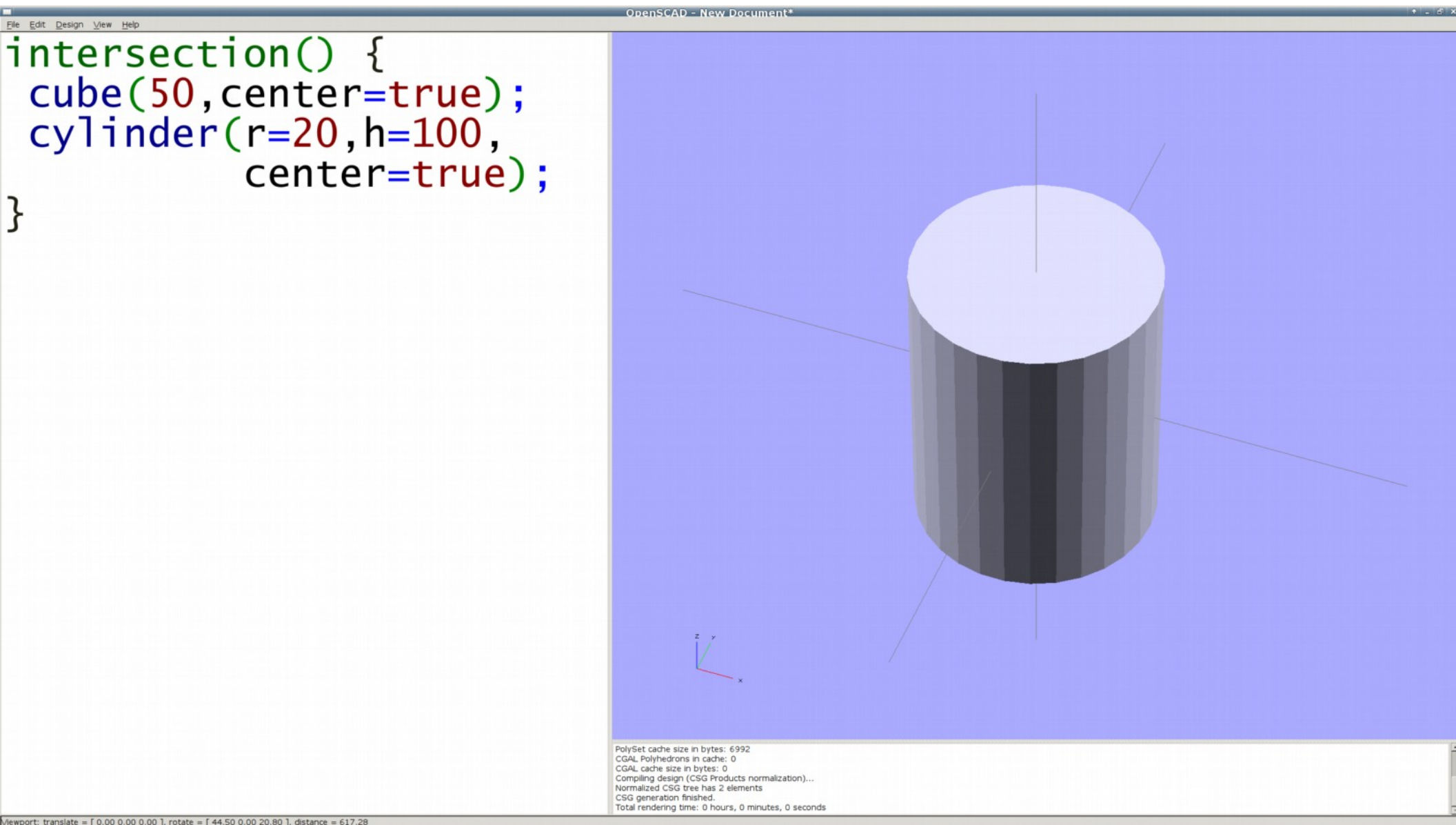
CSG Operation: Difference



F9 = OpenCSG view

F12 = “Thrown Together”

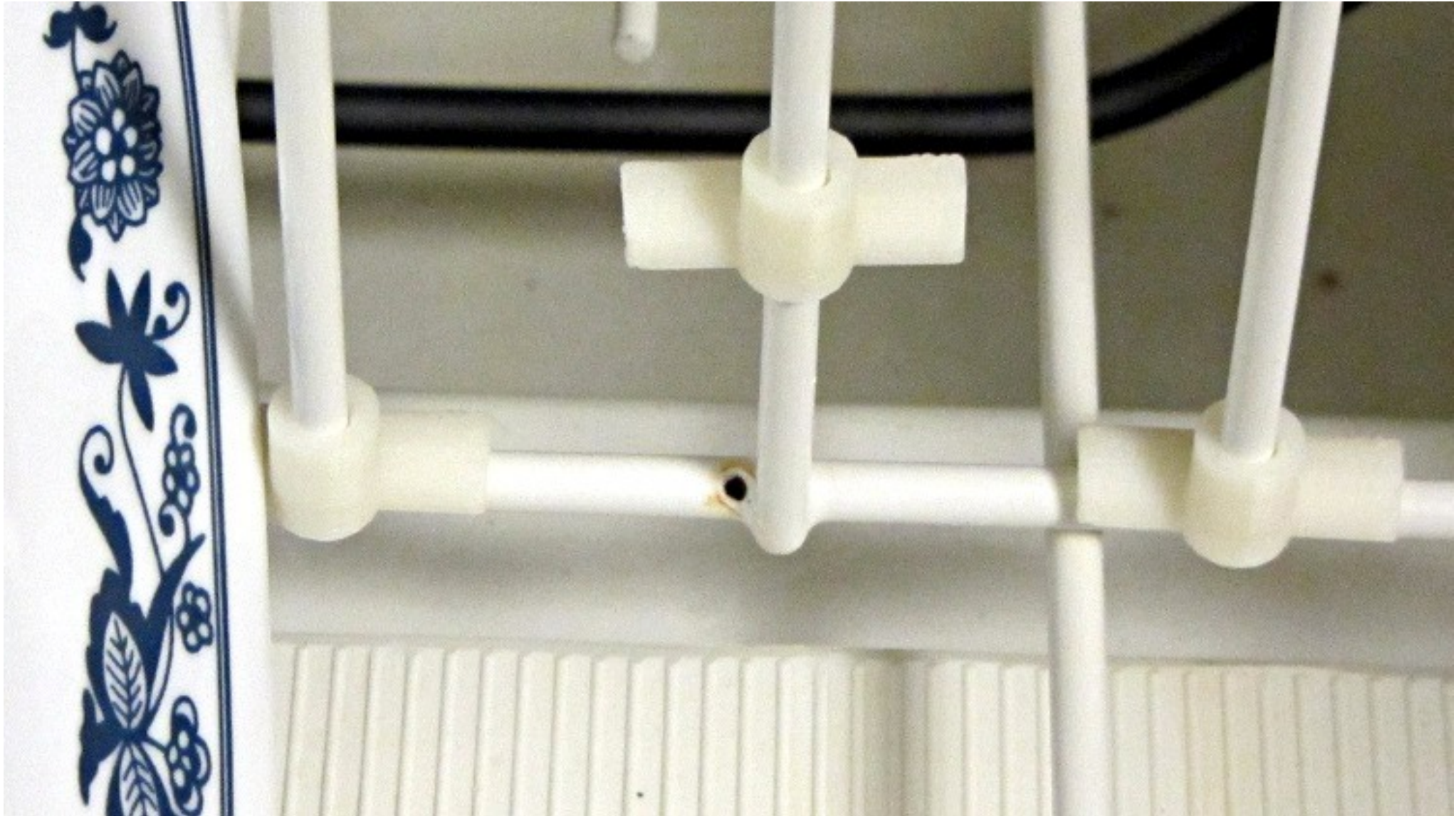
CSG Operation: Intersection



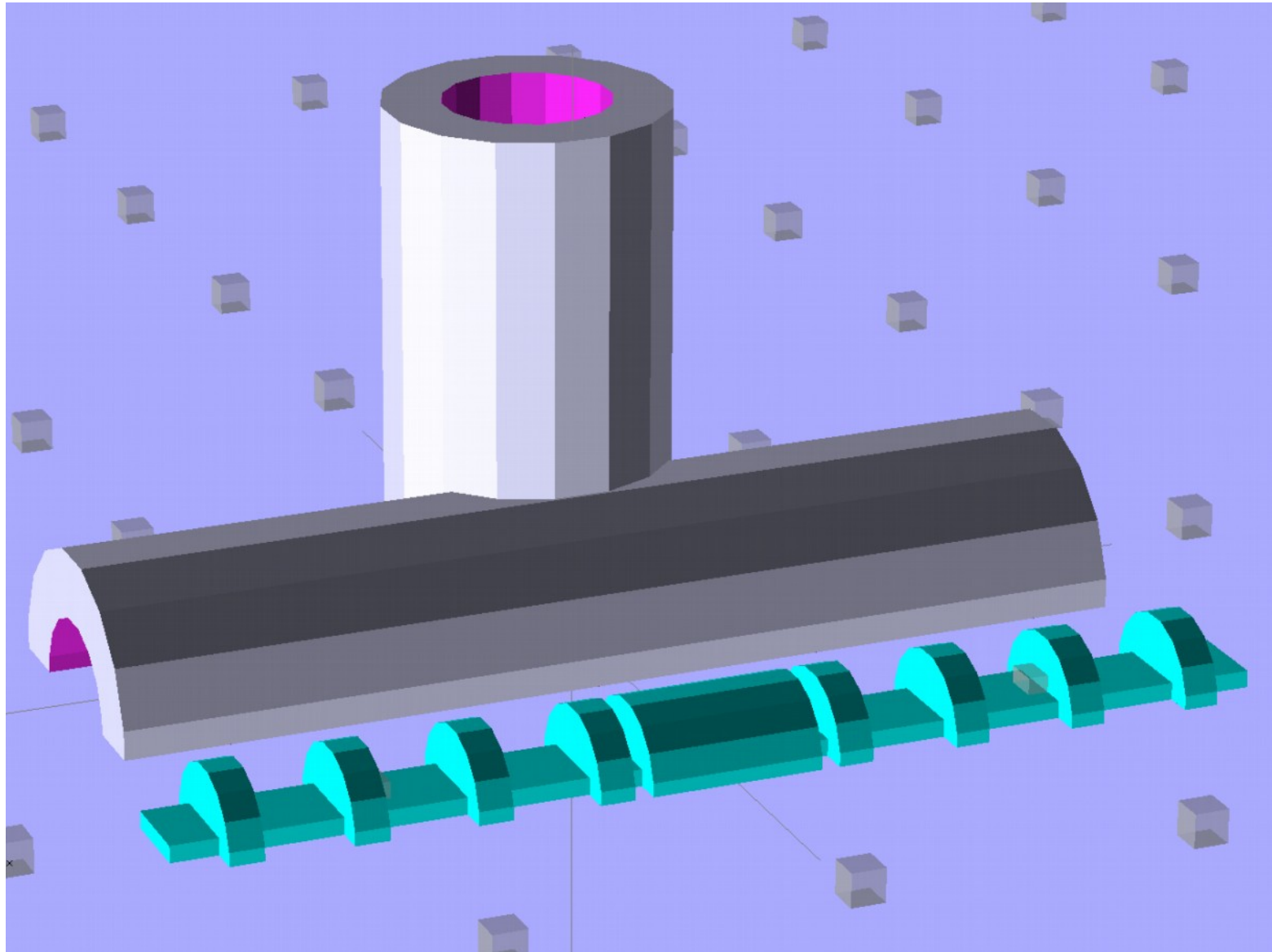
Essential Transformations

- **Translate**([x,y,z])
- **Rotate**([x,y,z])
 - Rotate(angle) around Z axis
- **Color** (“name”) or Color(“name”,alpha)
 - “name” *not* case sensitive!
- **Mirror**([x,y,z])
 - xyz = normal of mirror plane through origin
- **Scale**([x,y,z])
- **Resize**([x,y,z])

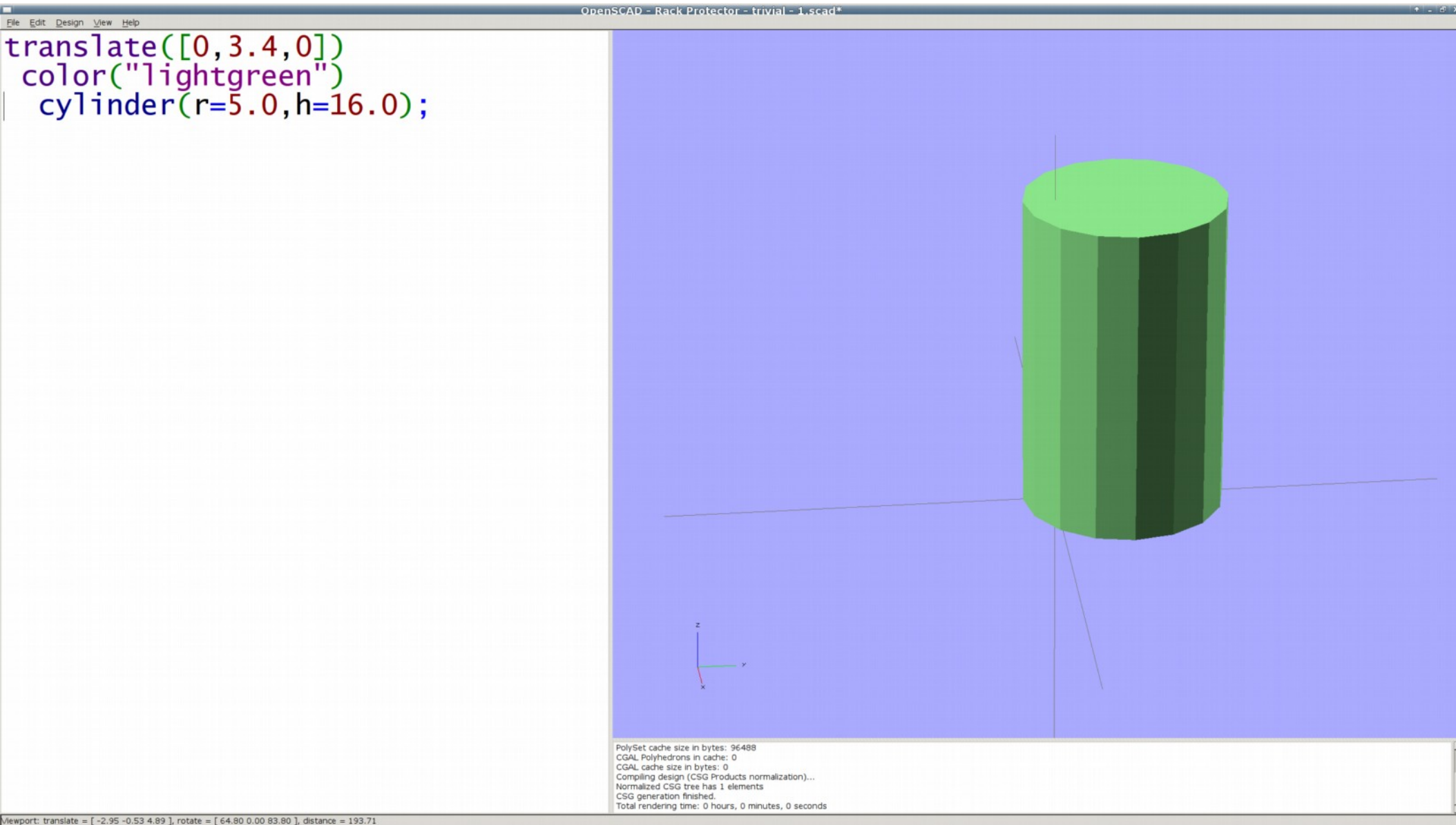
Dishwasher Rack Protector



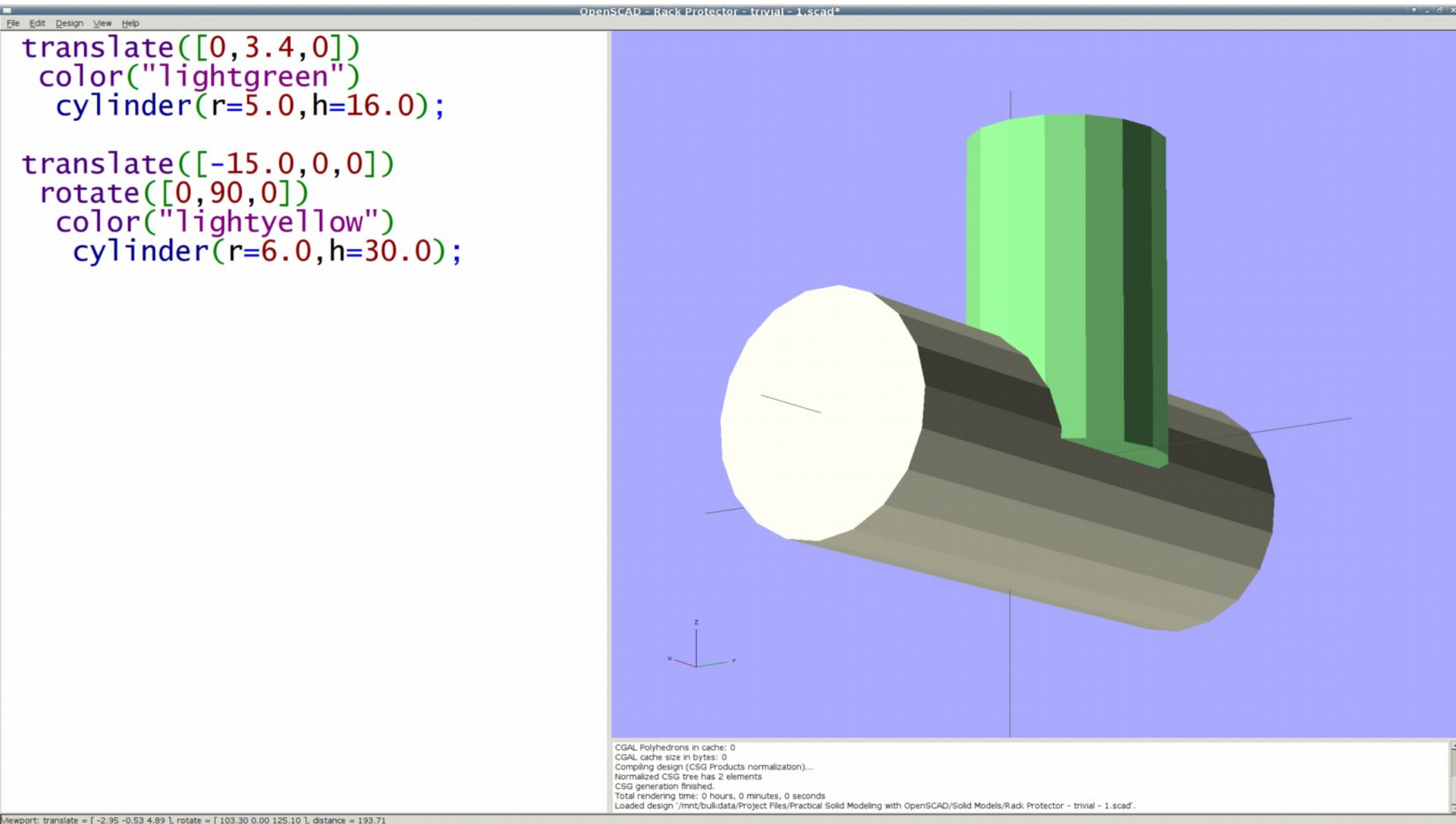
Dishwasher Rack Protector



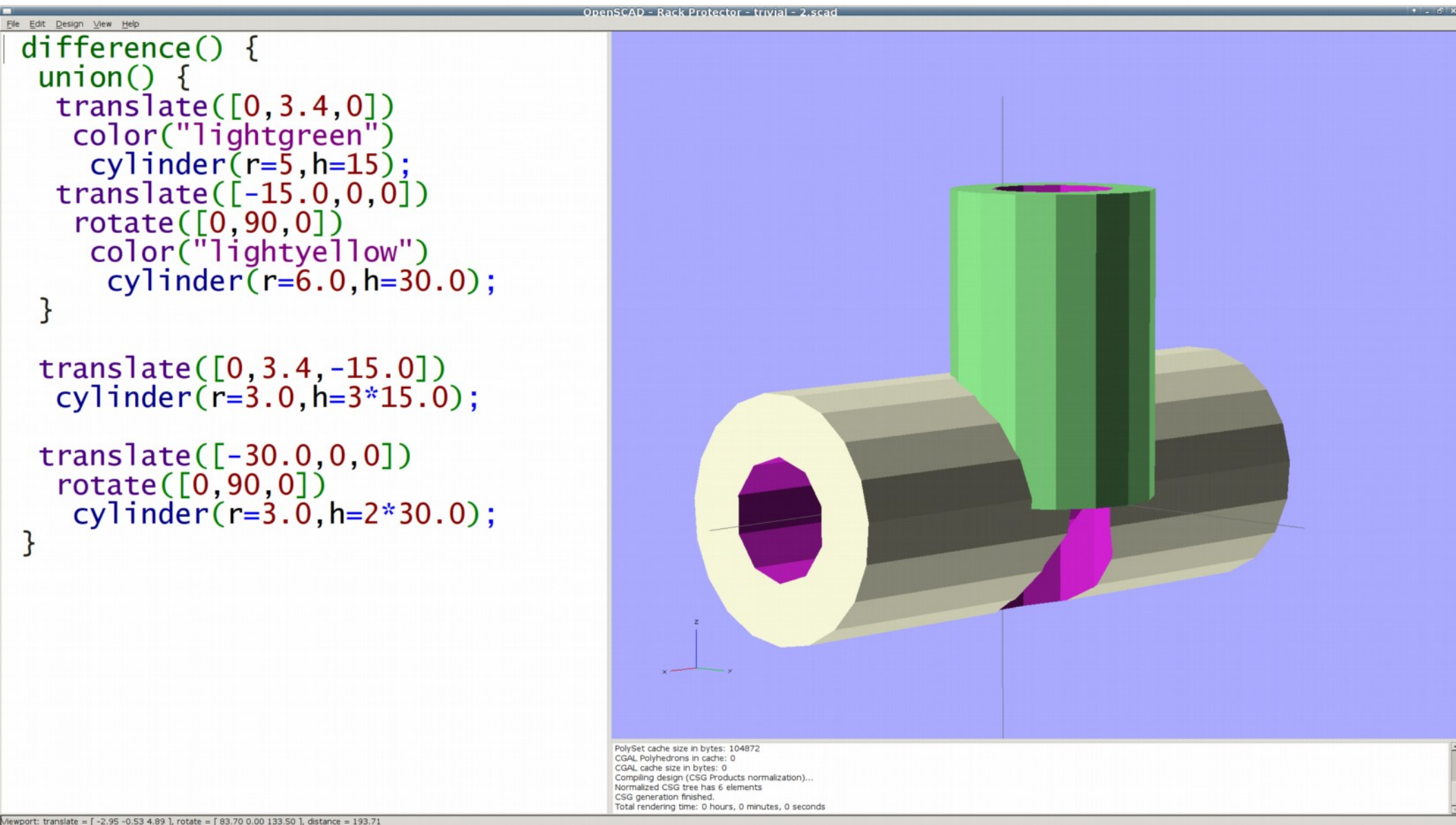
Translate([x,y,z])



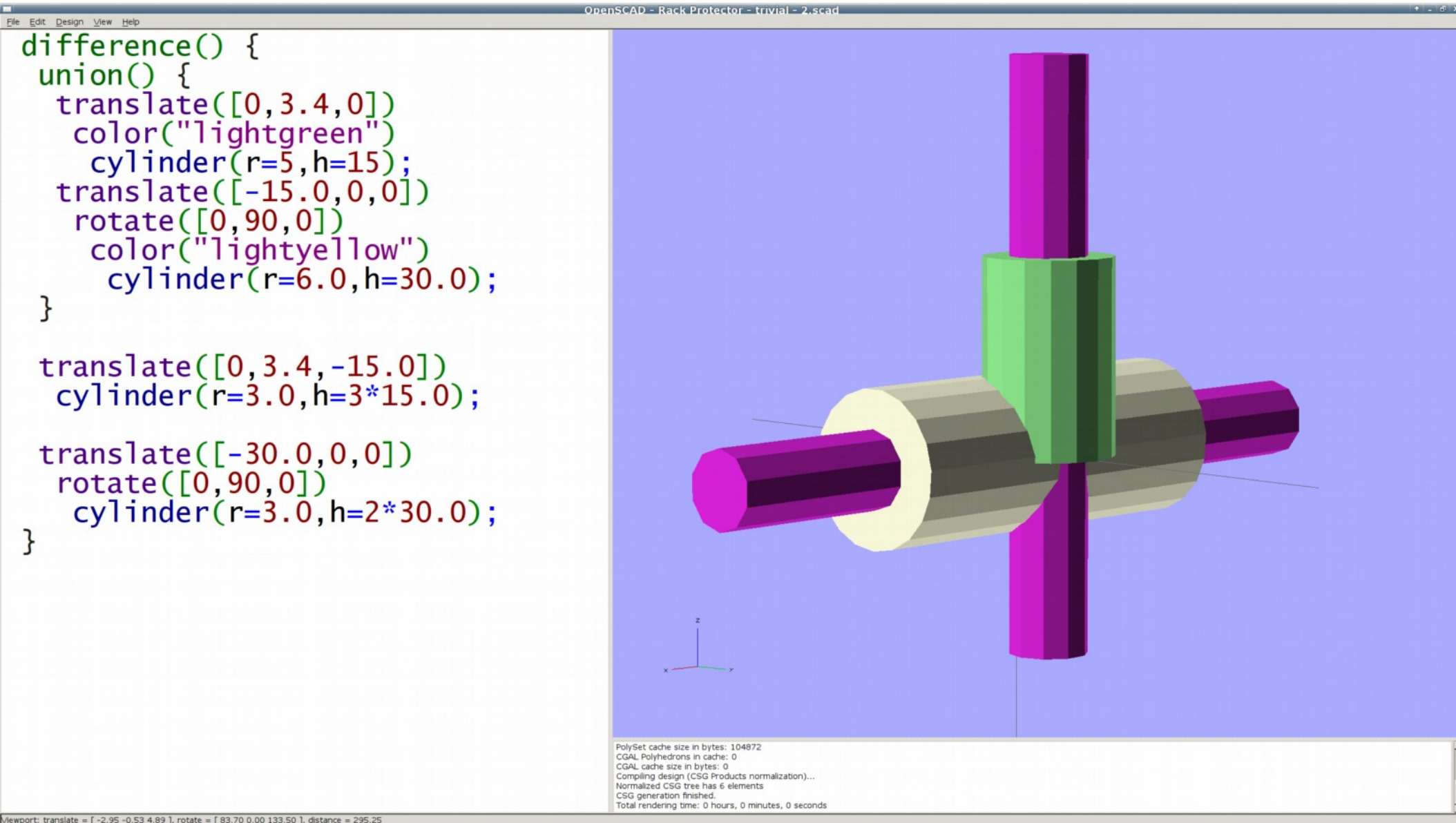
Rotate([x,y,z])



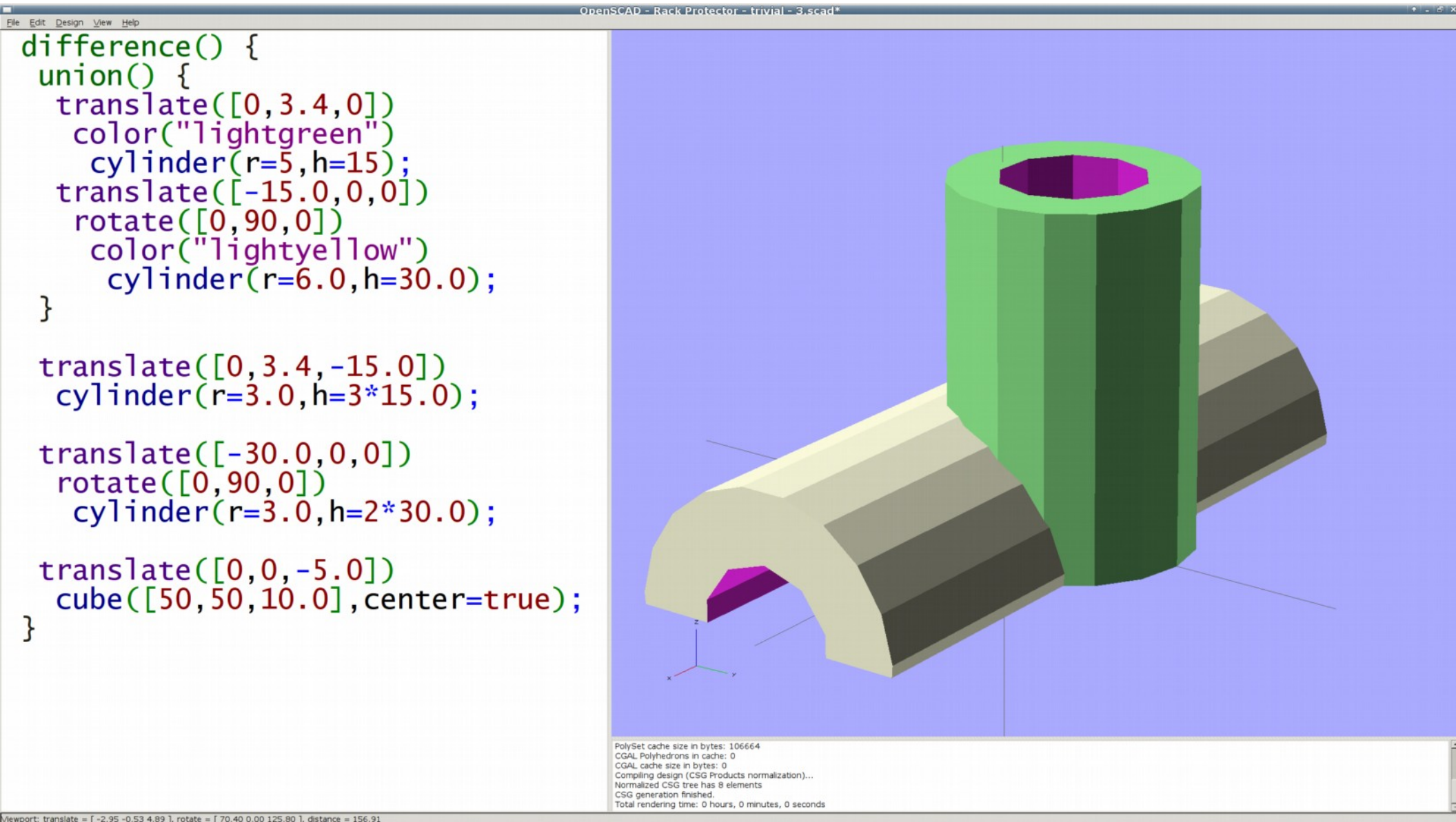
Difference: F9 View



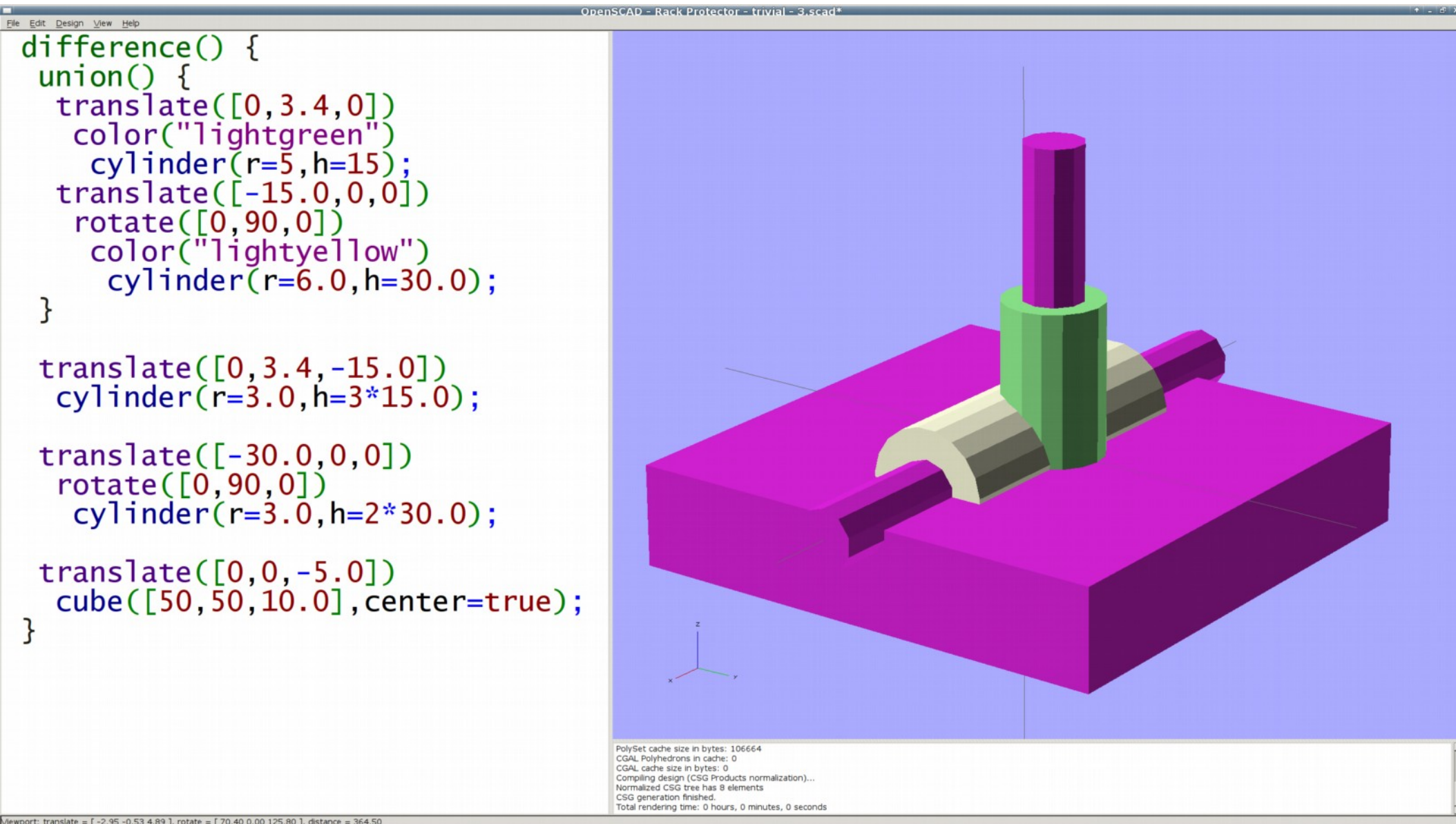
Difference: F12 View



Difference: F9 View

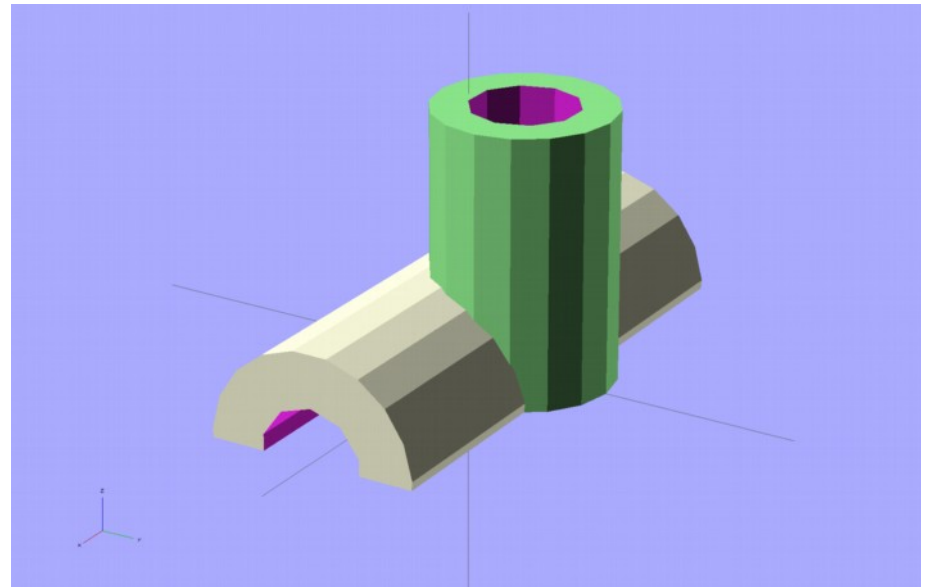


Difference: F12 View



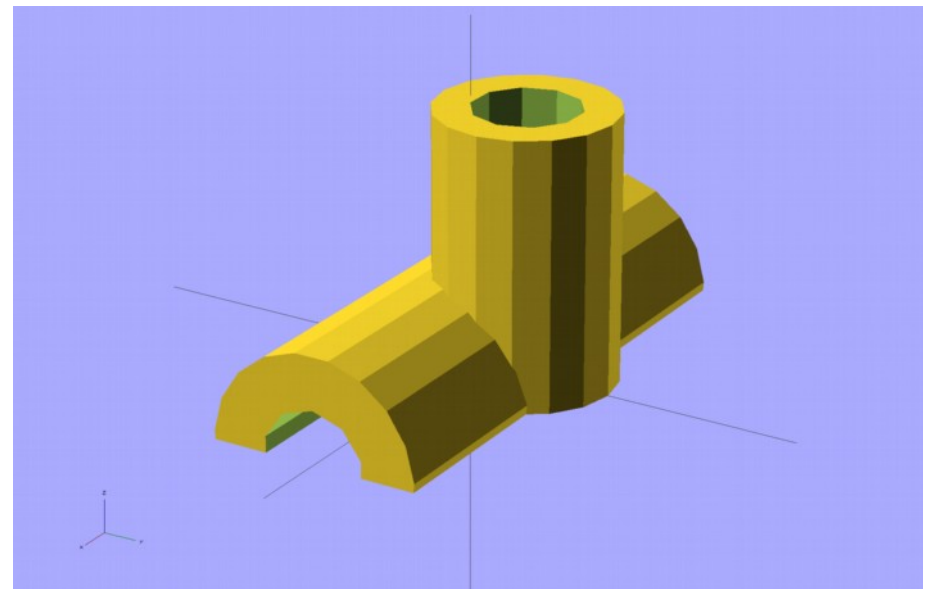
(Re)Compile: F5

- Fast preview mode
 - Simple depth buffer
 - No actual 3D model
 - Colors as expected
- **Not** exportable!



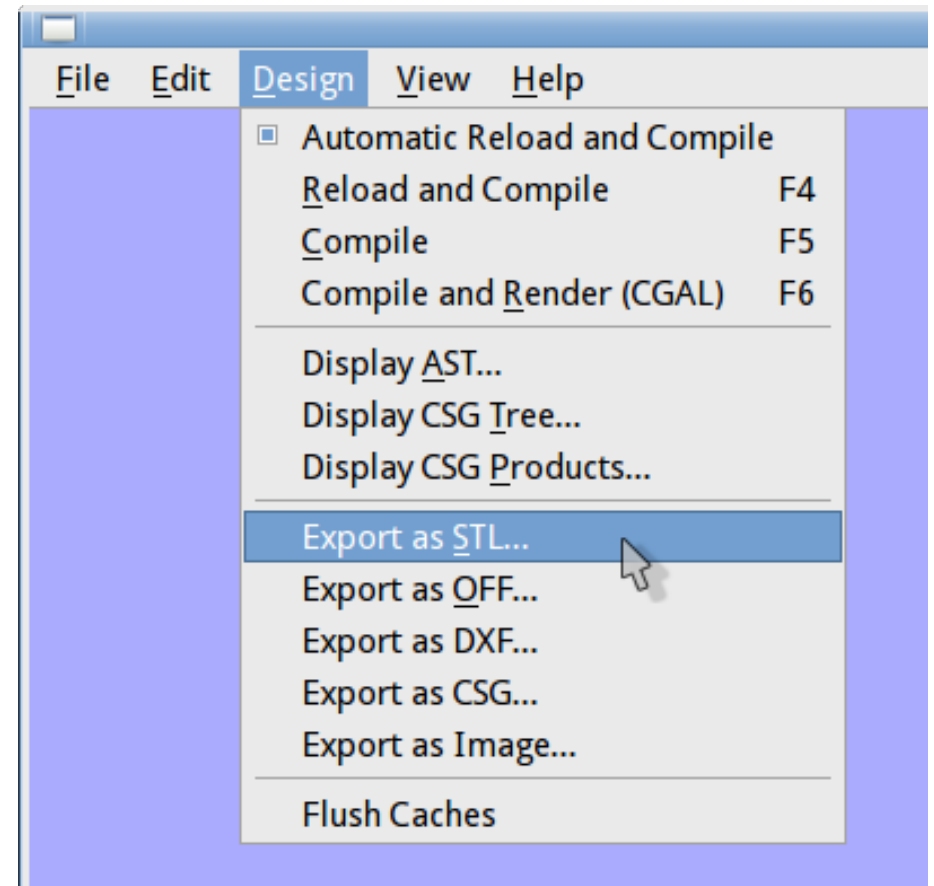
Compile & Render: F6

- Solid Model Generation
 - Full 3D rendering
 - All geometry resolved
 - Single color
- May not be manifold
 - If you screwed up
- Exportable!



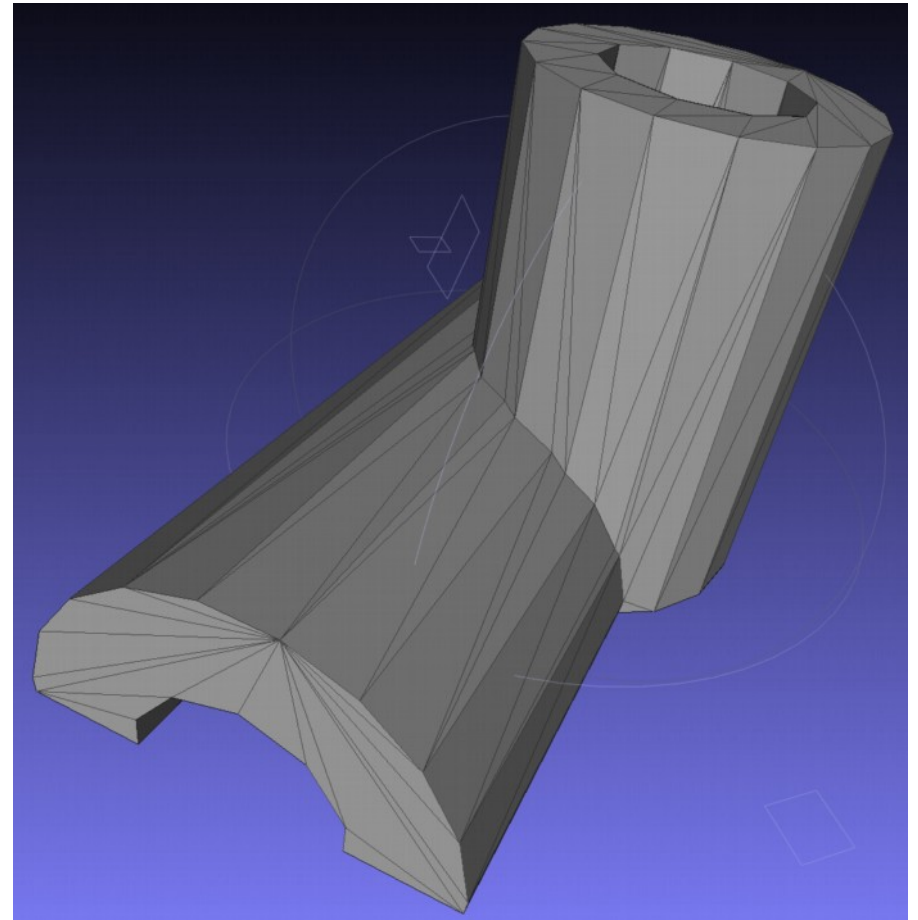
STL File Generation

- ASCII file format
 - Huge files
- That's all it takes



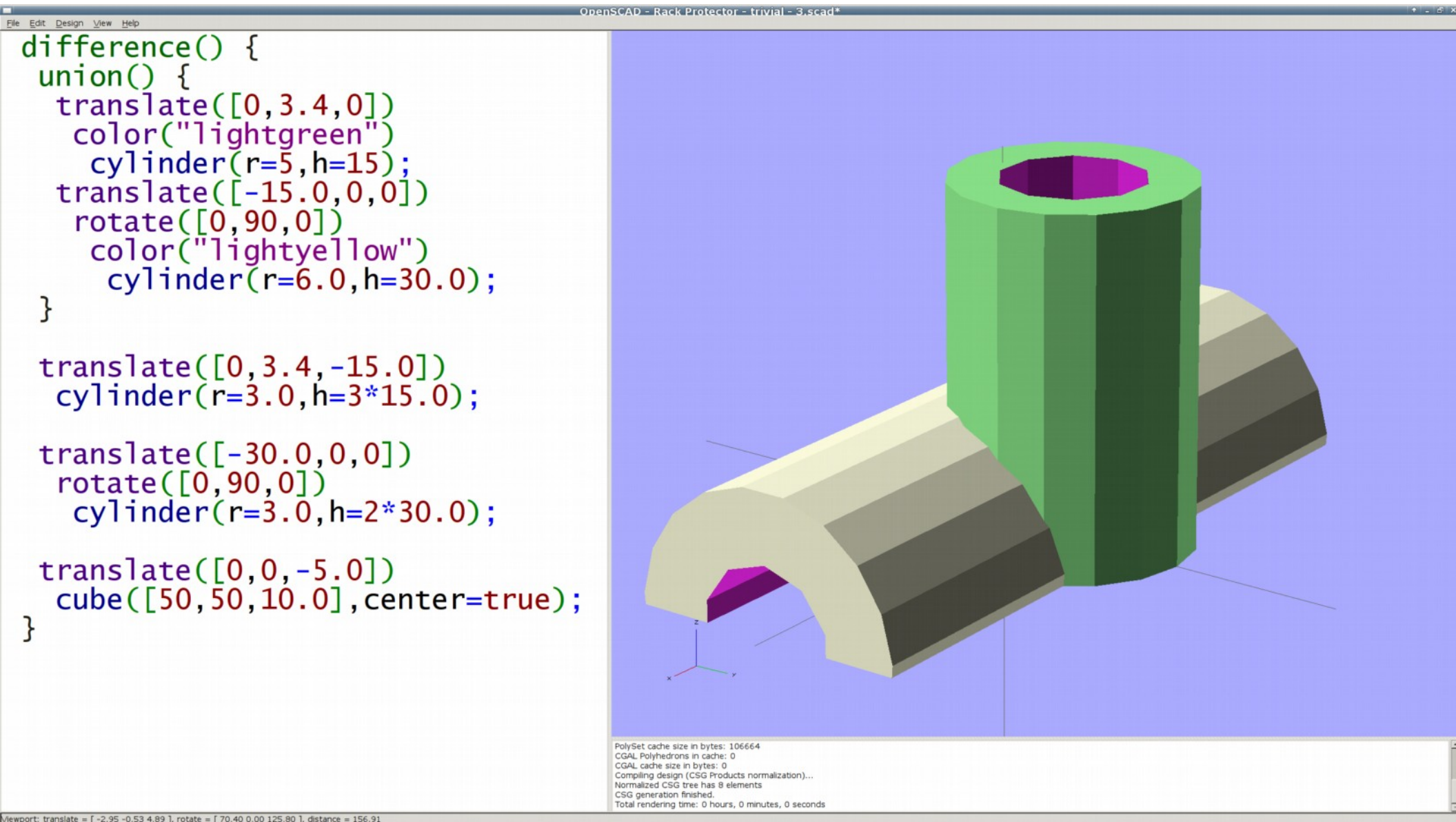
STL File Contents

- Triangle tessellation
 - No curves!
 - No “model” content
 - No smarts
- Surface normals
 - For each triangle
 - You have no control

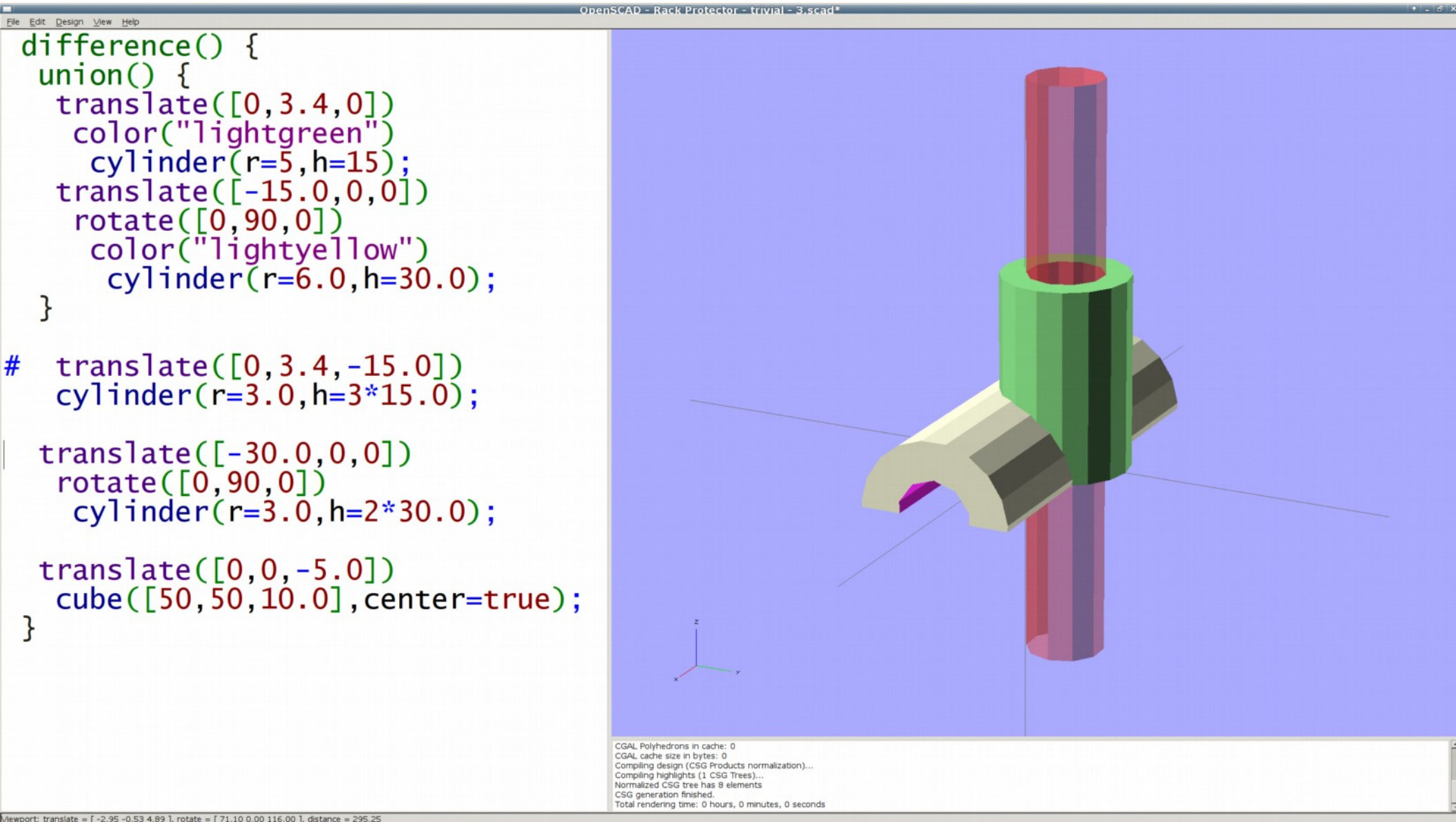


OpenSCAD CSG “Debugging”

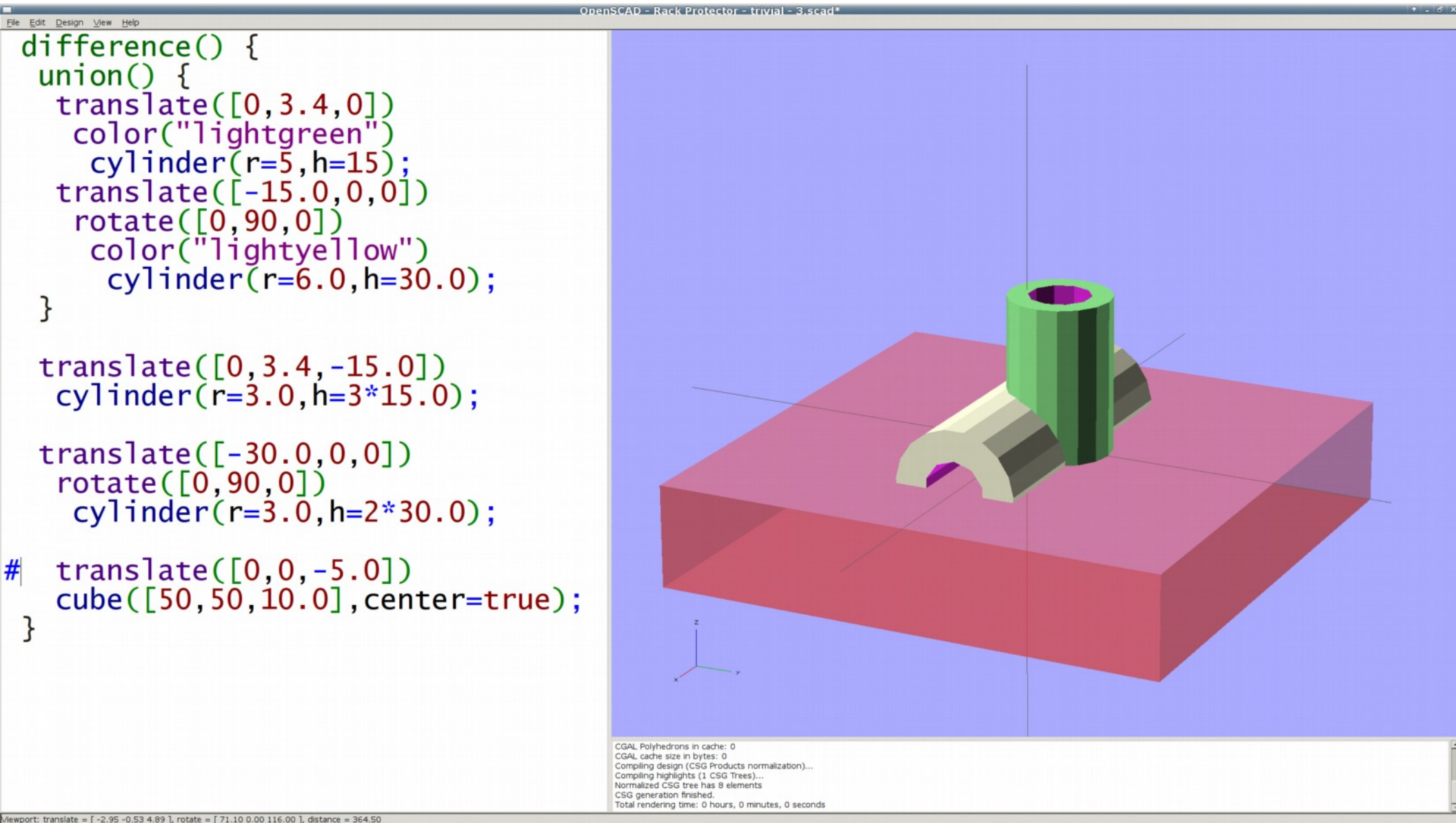
Ordinary F9 View



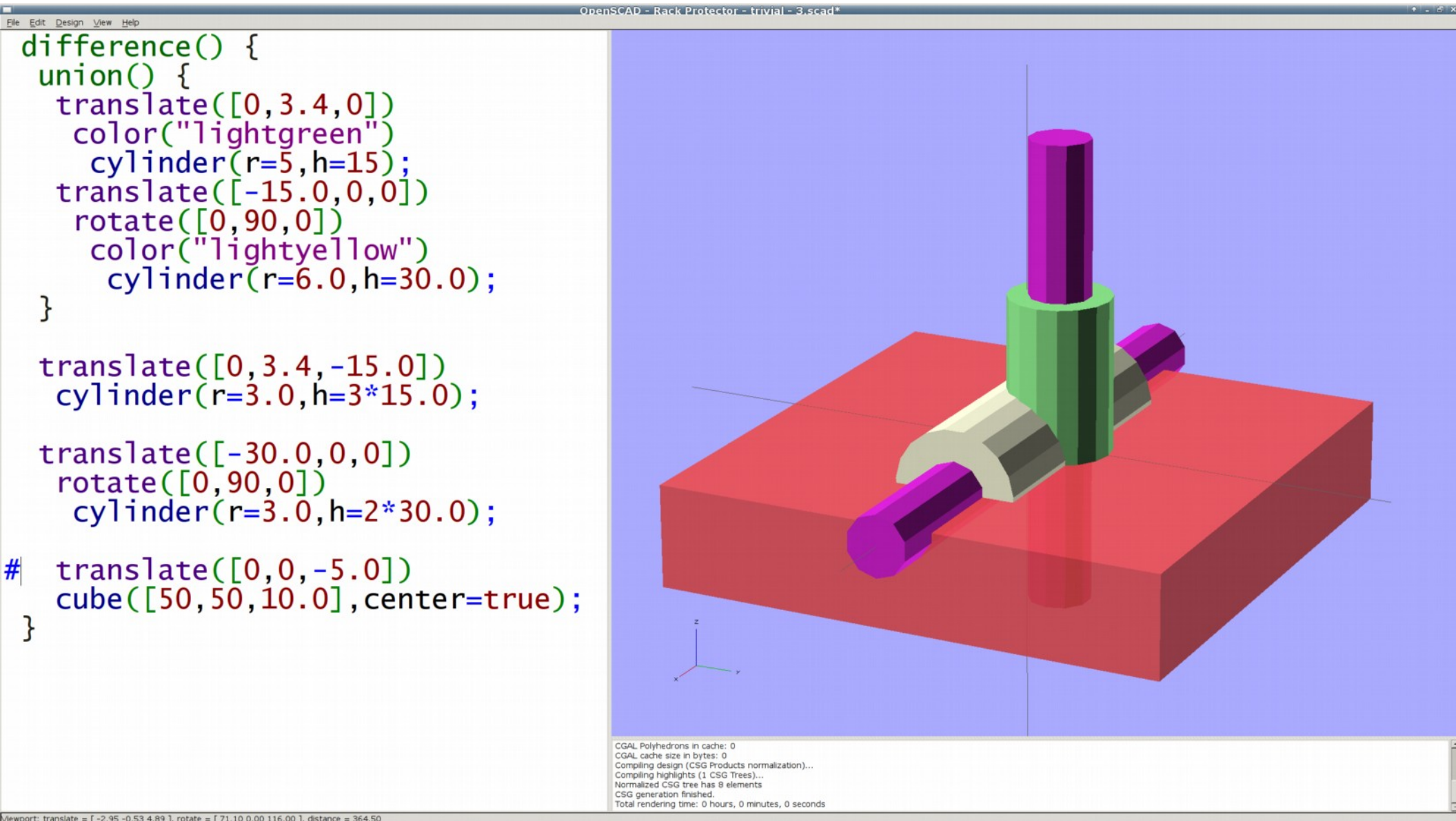
Highlighting an Object:



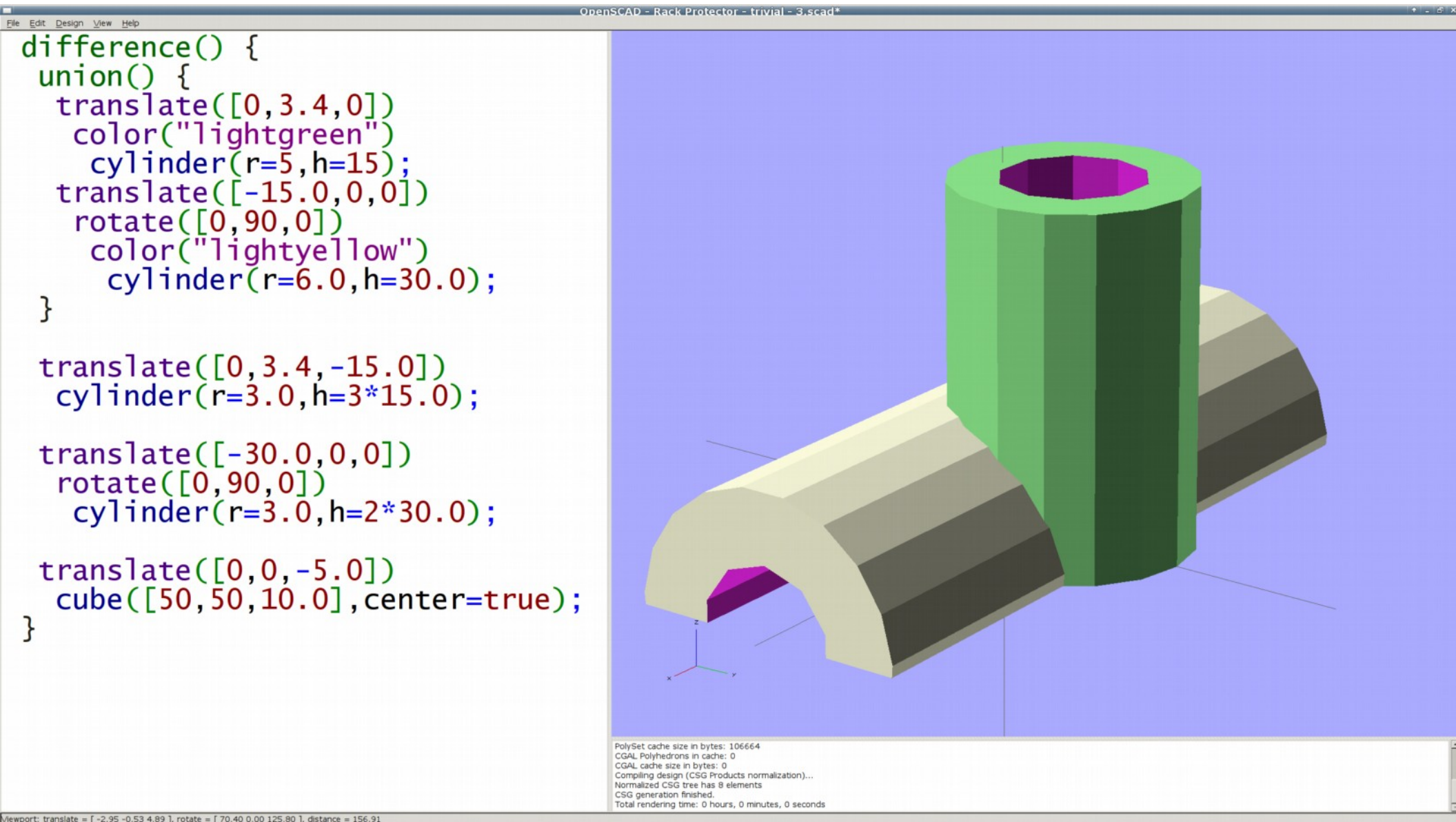
Highlighting an Object: # in F9



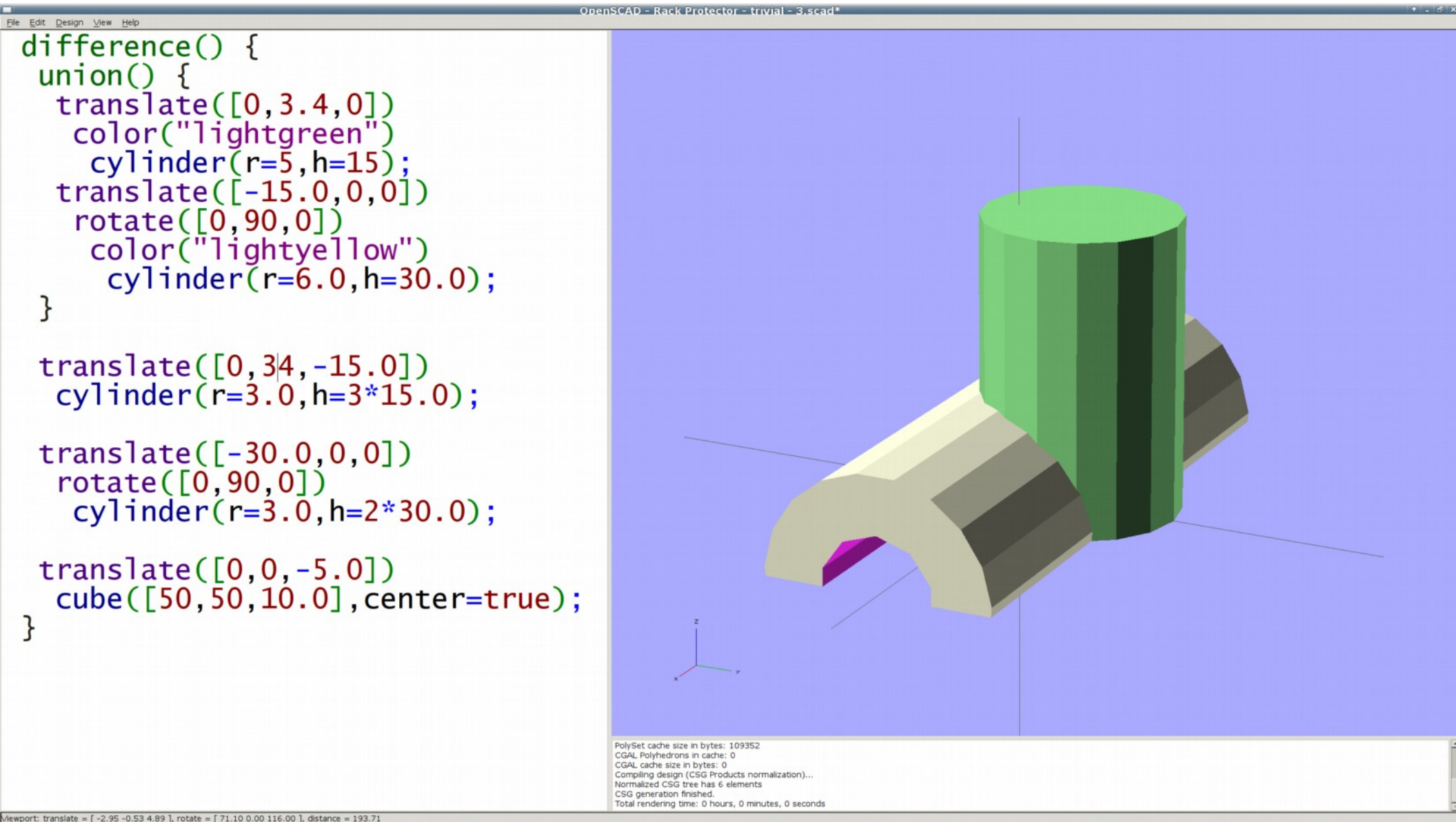
Highlighting: # in F12



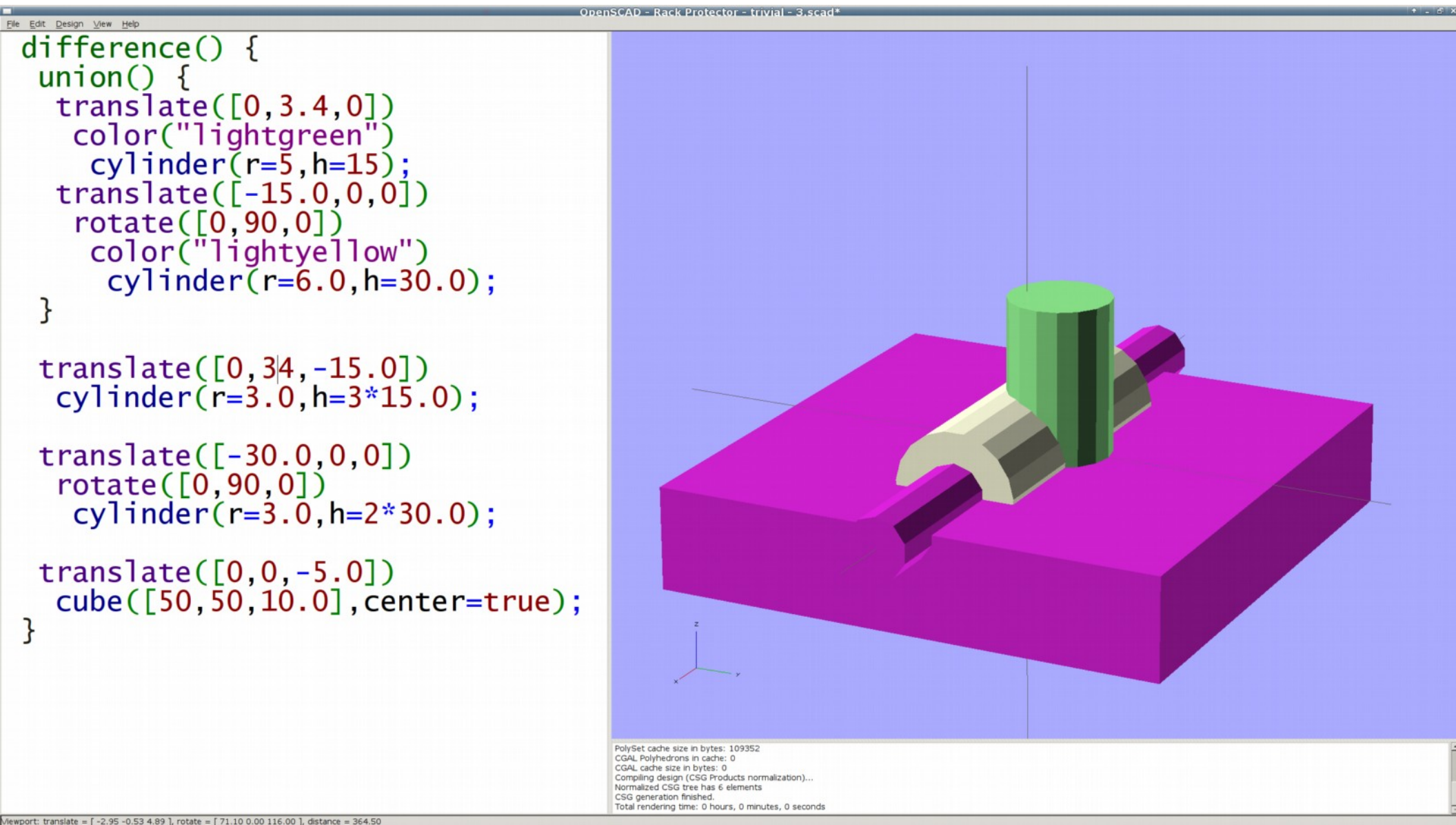
What You Expected



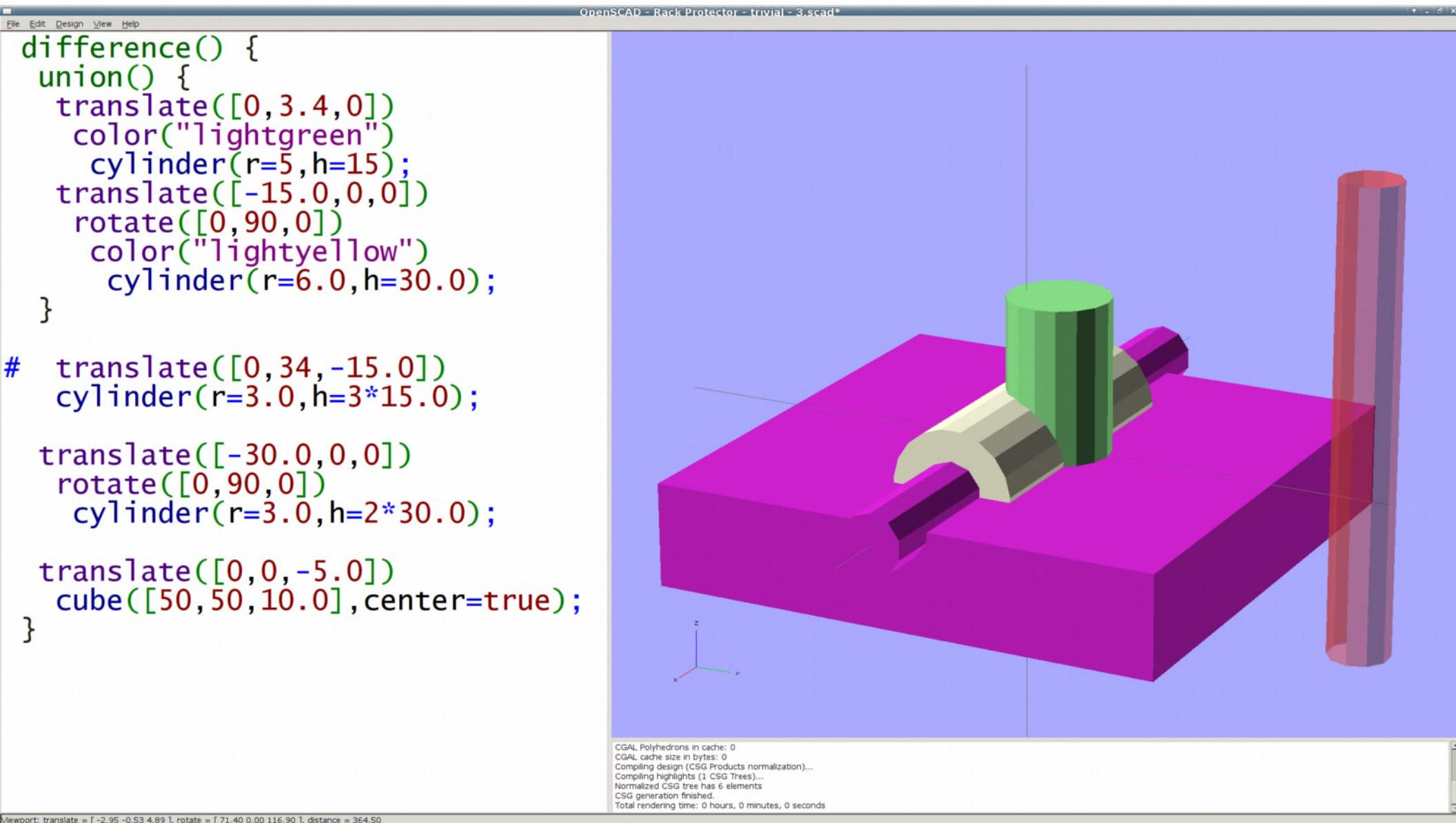
What You Got



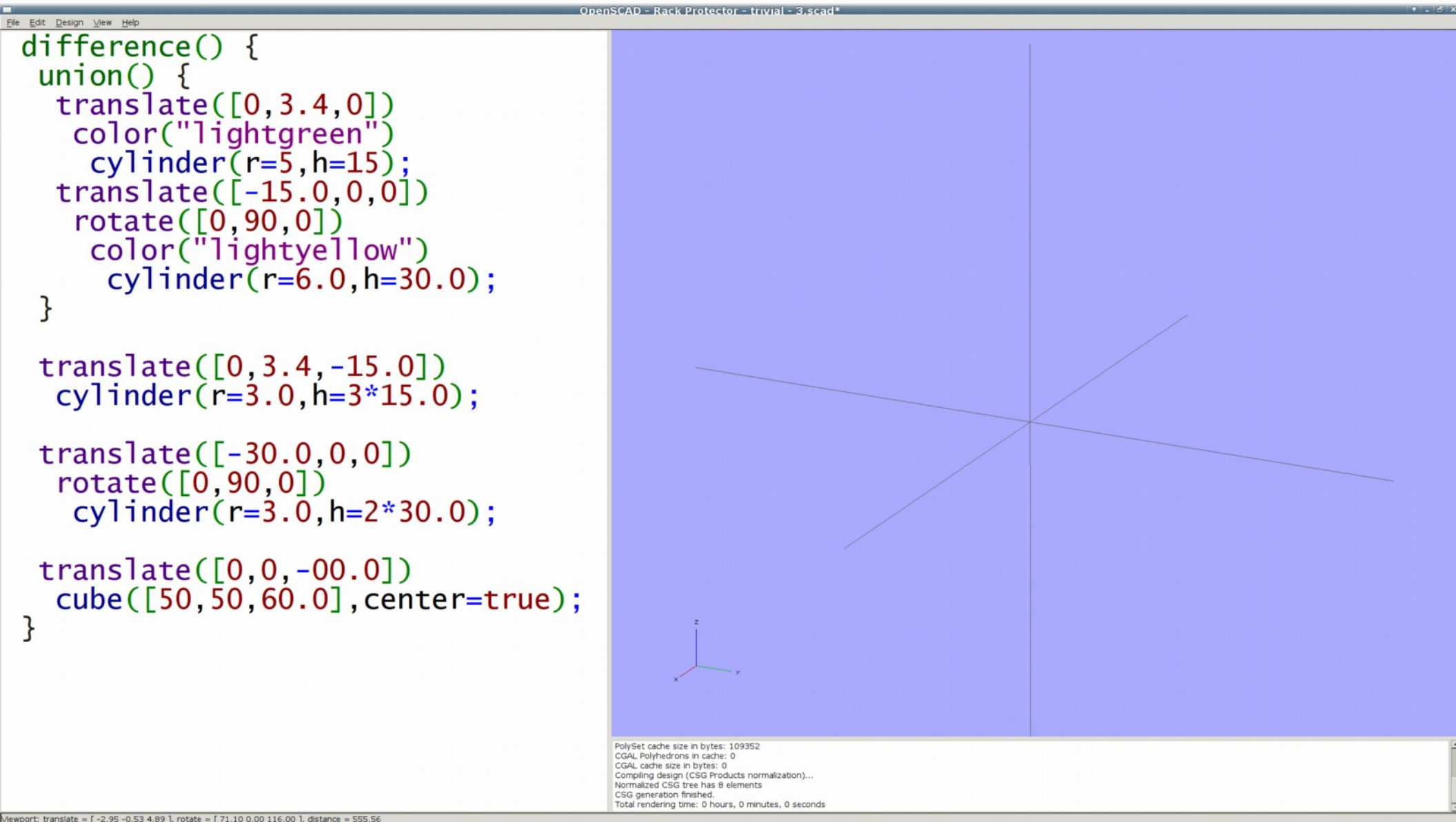
Where's the Missing Hole in F12?



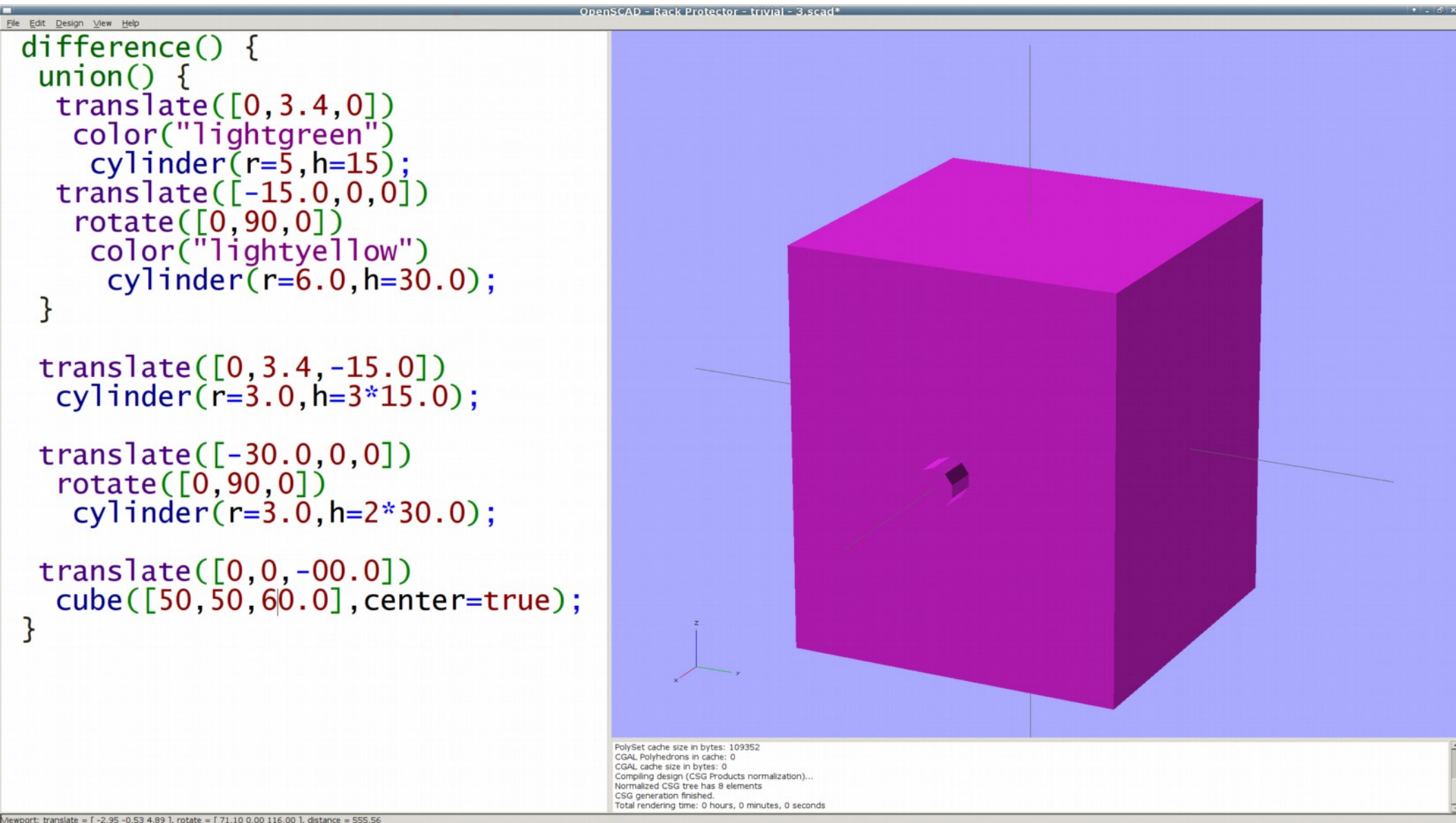
Highlighting: # in F12



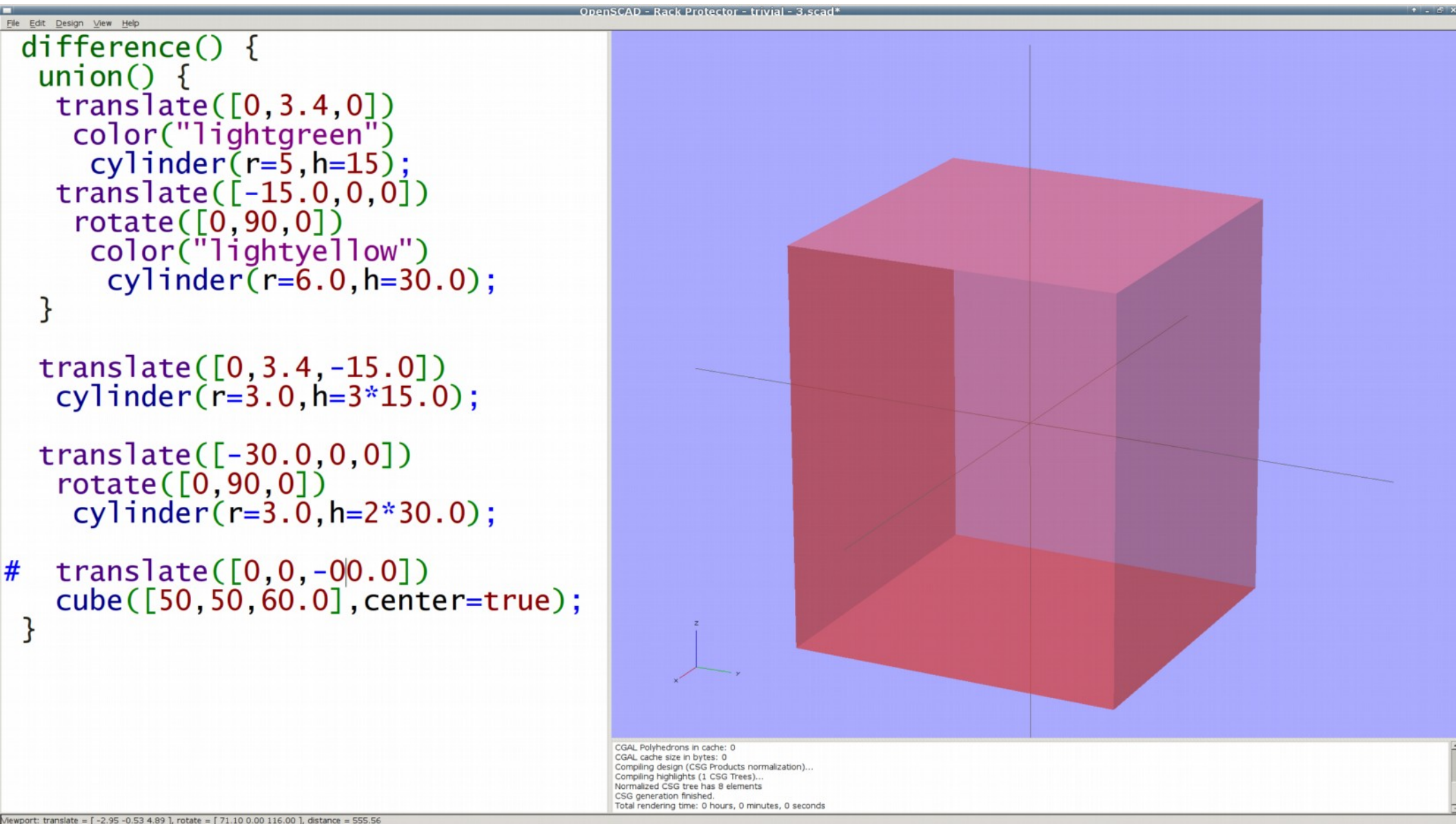
Where Did Everything Go?



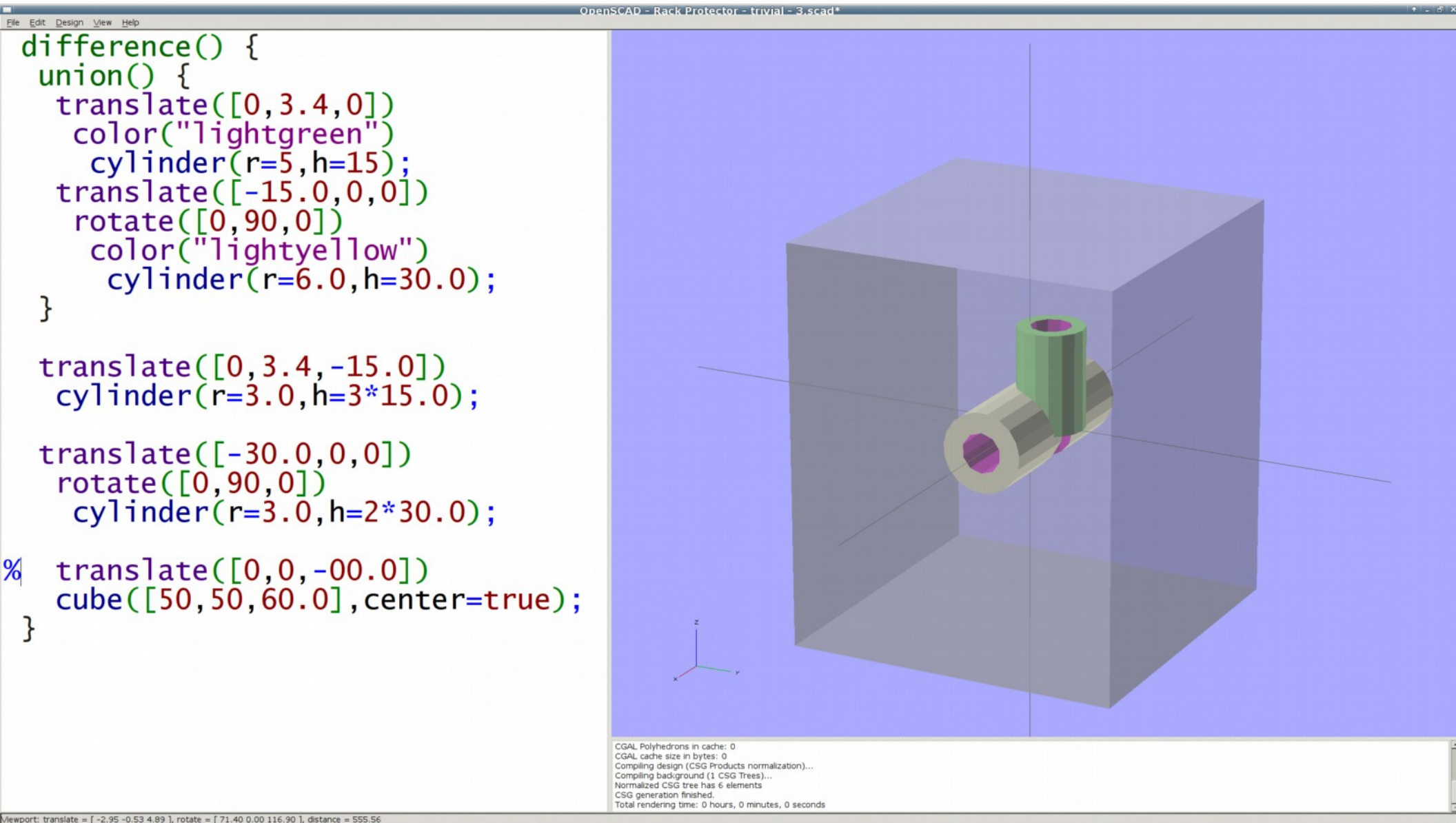
Everything in F12 View



Everything Highlighted Cube: F9



Debug Modifier: % in F9



OpenSCAD Non-Bugging

- Use an **external editor!**
 - Hide the OpenSCAD editor pane
- Add / change **one tiny little thing at a time**
 - Editor's Undo function will be your BFF
- Use what meager assistance you have
 - F12: Thrown Together view
 - **Modifier characters:** % and #
 - `echo(str("This: ",name))` shows computed values
- Keep it simple and make it obvious

OpenSCAD
Is
Not
C

OpenSCAD Is Not C

- Similar syntax, *vastly* different semantics
 - Declarative, not procedural
 - Describes geometry, not process
- Lacks many “high level” features
 - This is not a bug
- Probably a write-only language
 - Not easy to visualize the effects
 - Modules not easily re-usable due to geometry
 - Global / local variables vs. parameters

The better you are
at C / C++ / Java / whatever

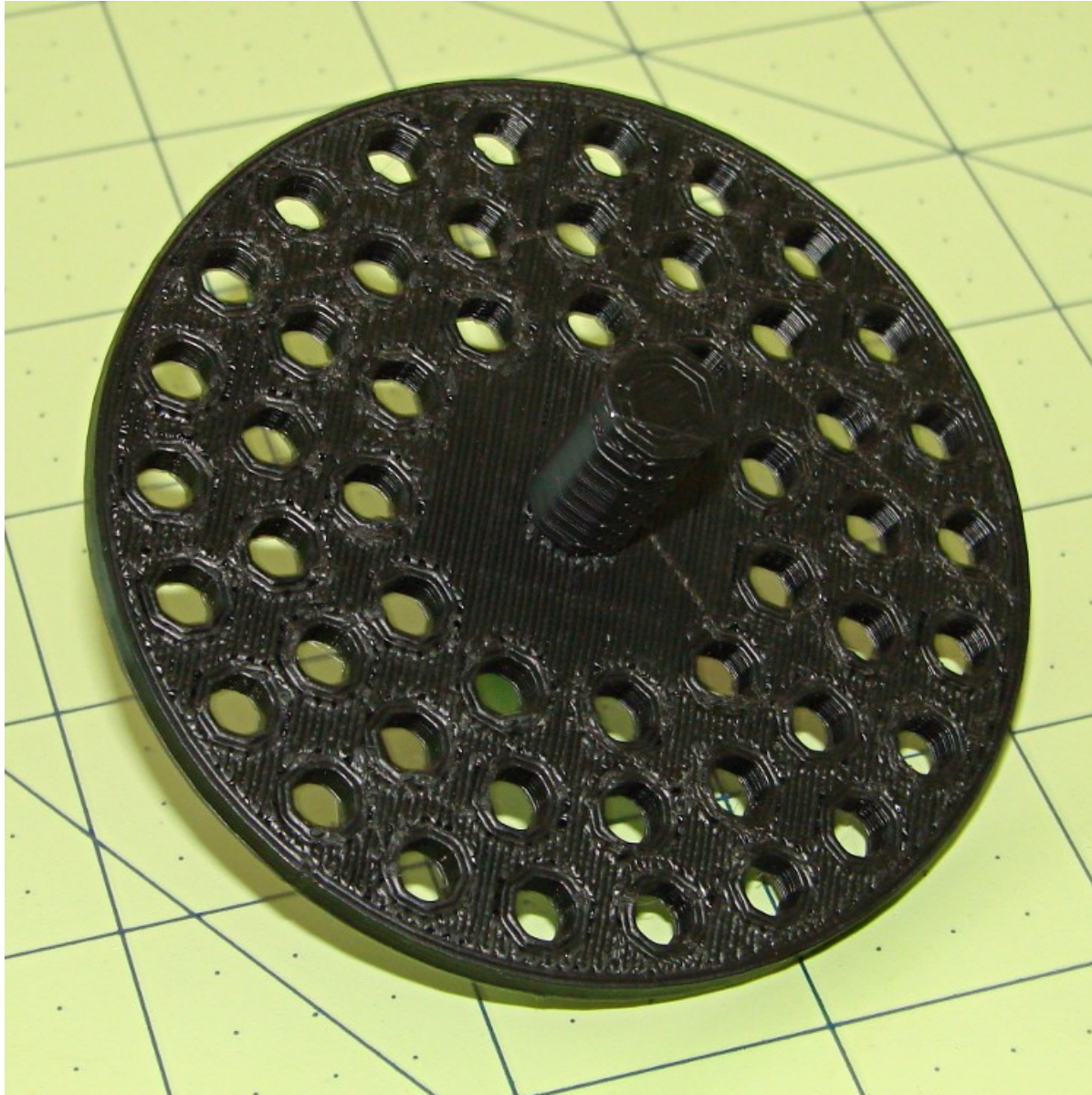
~

The more trouble you are
about to have
with OpenSCAD

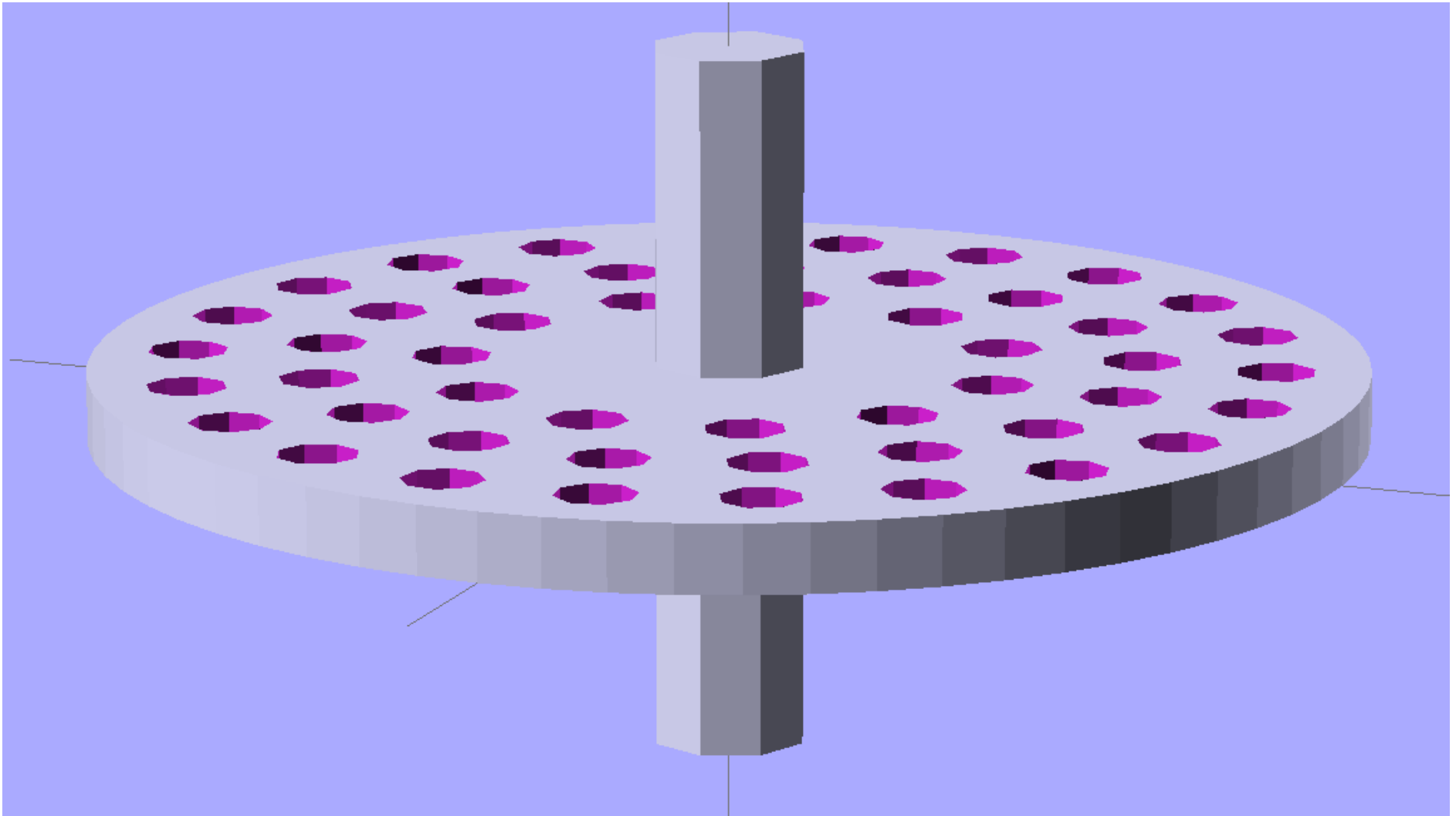
Iteration

- for (i = [start:increment:end])
 - Don't get clever with increment value
 - Use integers, compute floats in loop
- for (i = [list, of, many, values, in, a, vector])
 - Don't get clever with nested vectors = arrays
- Implicit union() of all objects within loop
 - Use intersection_for() for intersections...

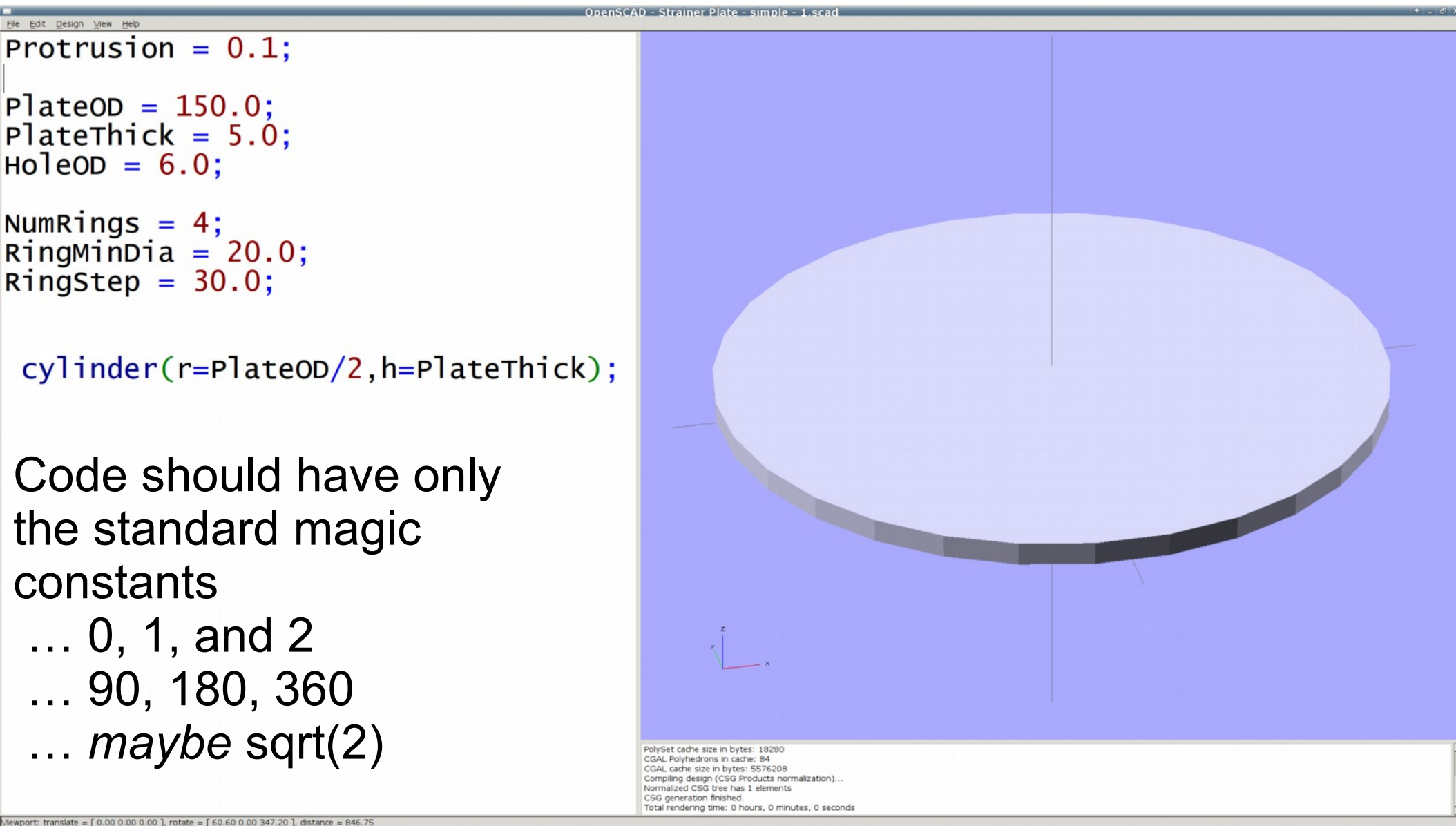
Sink Strainer



Sink Strainer



Define the Dimensions!



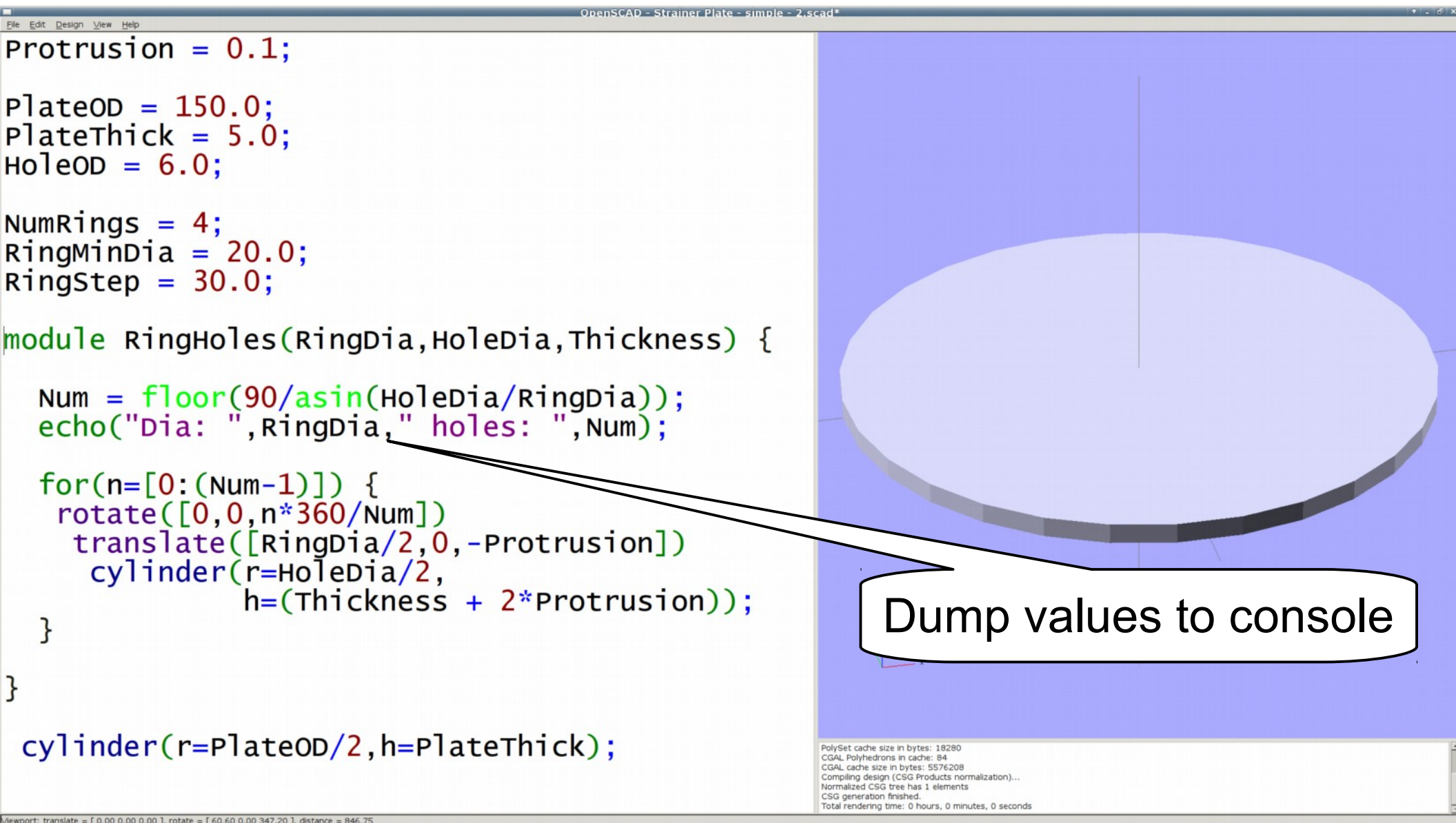
Code should have only
the standard magic
constants

... 0, 1, and 2

... 90, 180, 360

... *maybe* sqrt(2)

Create a Module



Try a Simple Case

OpenSCAD - Strainer Plate - simple - 2.scad*

```
Protrusion = 0.1;

PlateOD = 150.0;
PlateThick = 5.0;
HoleOD = 6.0;

NumRings = 4;
RingMinDia = 20.0;
RingStep = 30.0;

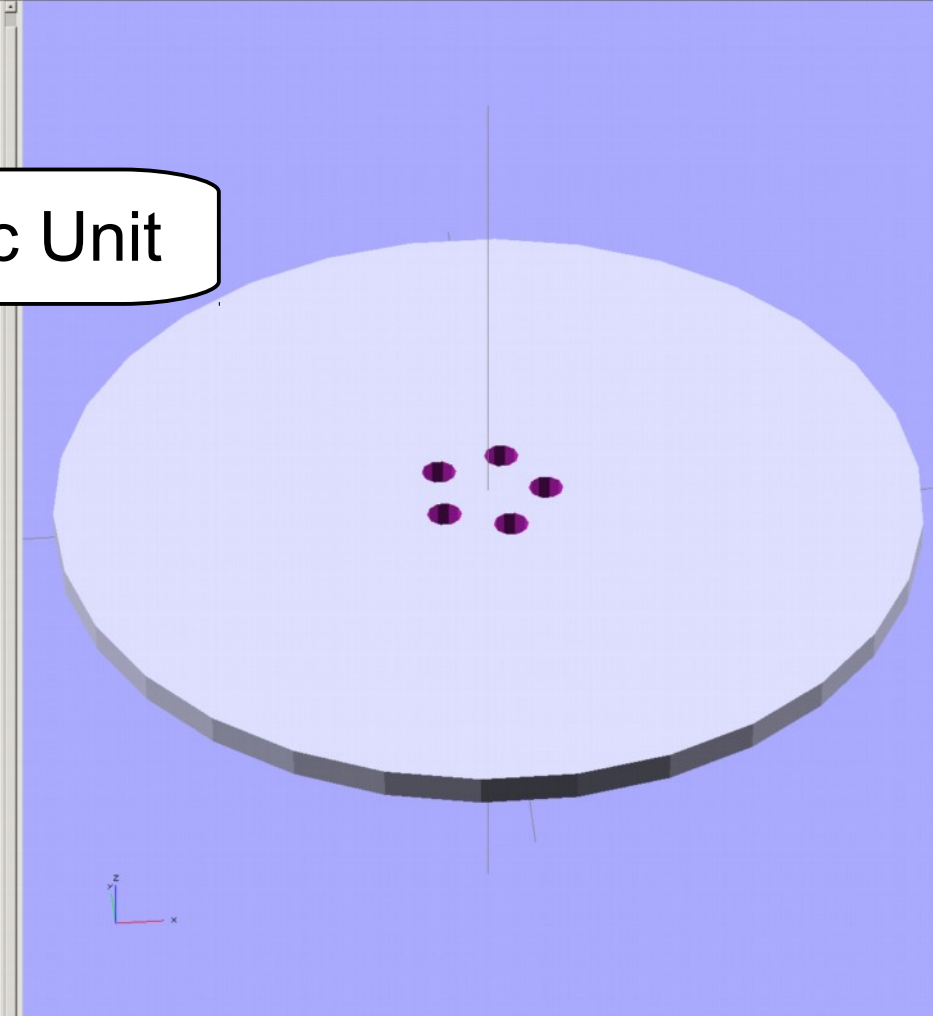
module RingHoles(RingDia,HoleDia,Thickness) {

  Num = floor(90/asin(HoleDia/RingDia));
  echo("Dia: ",RingDia," holes: ",Num);

  for(n=[0:(Num-1)]) {
    rotate([0,0,n*360/Num])
    translate([RingDia/2,0,-Protrusion])
    cylinder(r=HoleDia/2,
             h=(Thickness + 2*Protrusion));
  }
}

difference() {
  cylinder(r=PlateOD/2,h=PlateThick);
  RingHoles(RingMinDia,HoleOD,PlateThick);
}
```

Geometric Unit



PolySet cache size in bytes: 18280
CGAL Polyhedrons in cache: 84
CGAL cache size in bytes: 5576208
Compiling design (CSG Products normalization)...
Normalized CSG tree has 6 elements
CSG generation finished.
Total rendering time: 0 hours, 0 minutes, 0 seconds

Viewpoint: translate = [0.00 0.00 0.00], rotate = [51.50 0.00 354.90], distance = 846.75

Dump Values to “Console”

Module cache size: 0 modules

Compiling design (CSG Tree generation)...

ECHO: "Dia: ", 20, " holes: ", 5

Compiling design (CSG Products generation)...

PolySetCache hit:

cylinder(\$fn=0,\$fa=12,\$fs=2,h=5,r1=75,r2

PolySetCache hit:

cylinder(\$fn=0,\$fa=12,\$fs=2,h=5.2,r1=3,r

... snippage ...

Iterate Over All Rings

```
OpenSCAD - Strainer Plate - simple - 2.scad*
File Edit Design View Help
PlateThick = 5.0;
HoleOD = 6.0;

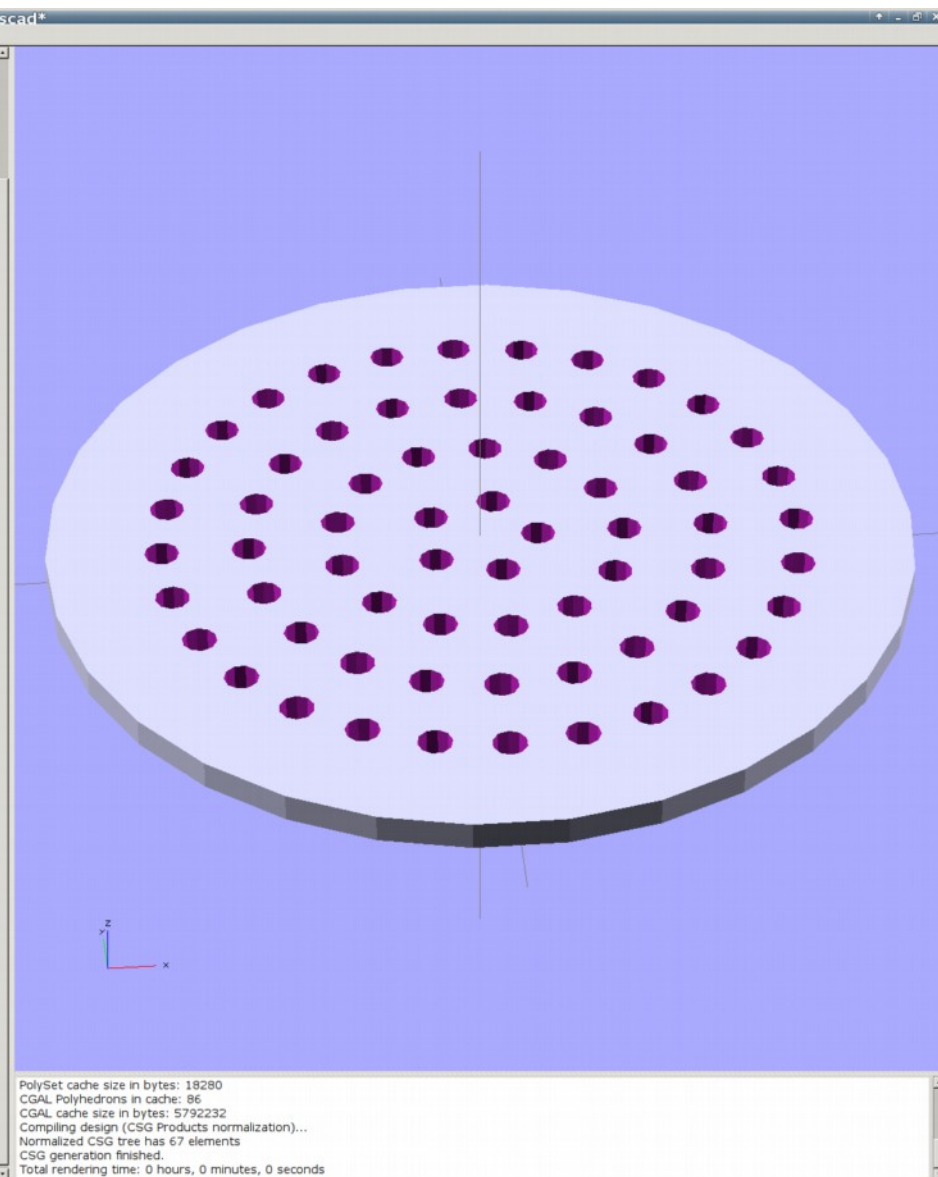
NumRings = 4;
RingMinDia = 20.0;
RingStep = 30.0;

module RingHoles(RingDia,HoleDia,Thickness) {

  Num = floor(90/asin(HoleDia/RingDia));
  echo("Dia: ",RingDia," holes: ",Num);

  for(n=[0:(Num-1)]) {
    rotate([0,0,n*360/Num])
    translate([RingDia/2,0,-Protrusion])
    cylinder(r=HoleDia/2,
            h=(Thickness + 2*Protrusion));
  }
}

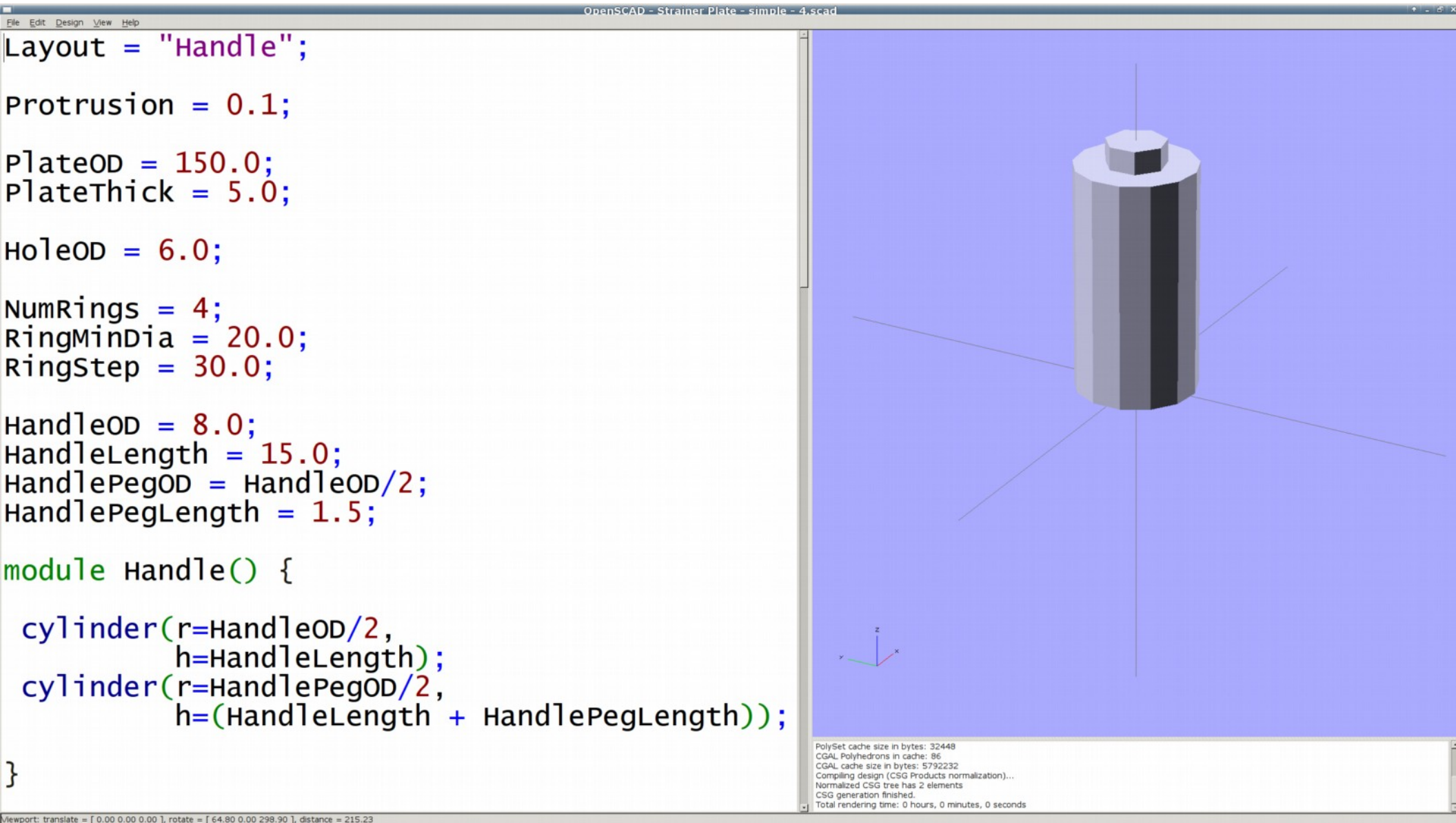
difference() {
  cylinder(r=PlateOD/2,h=PlateThick);
  for (RingID = [0:NumRings-1]) {
    RingHoles((RingMinDia + RingID*RingStep),
            HoleOD,PlateThick);
  }
}
```



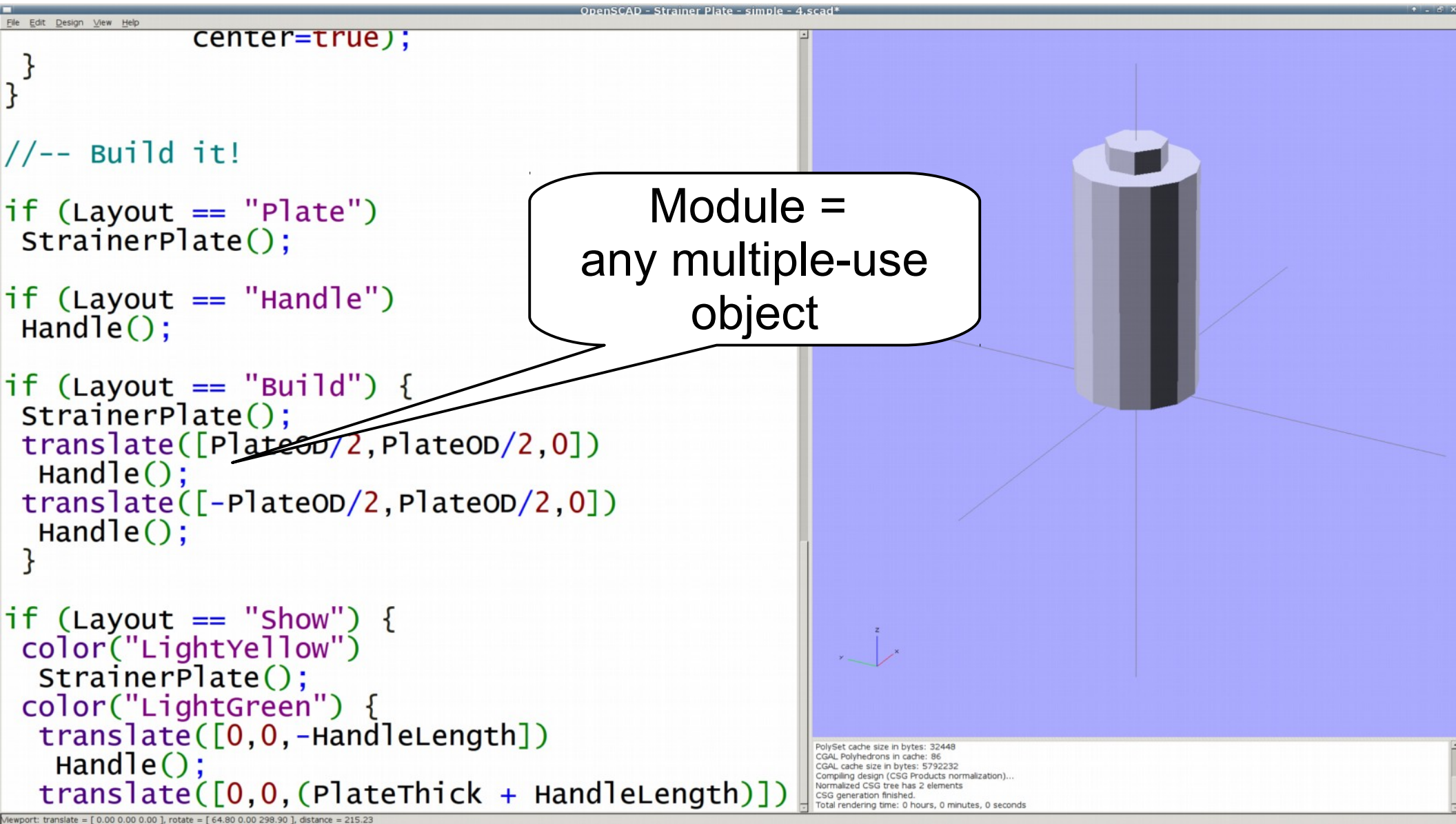
Conditionals

- if (this operator that)
 - As in C: double-equal == equality operator
 - Use to select objects, not values
- if (this == “string value”)
 - Case matters
- value = (this operator that) ? if_true : if_false
 - Use to select values, not objects
 - Remember: There Are No Variables!

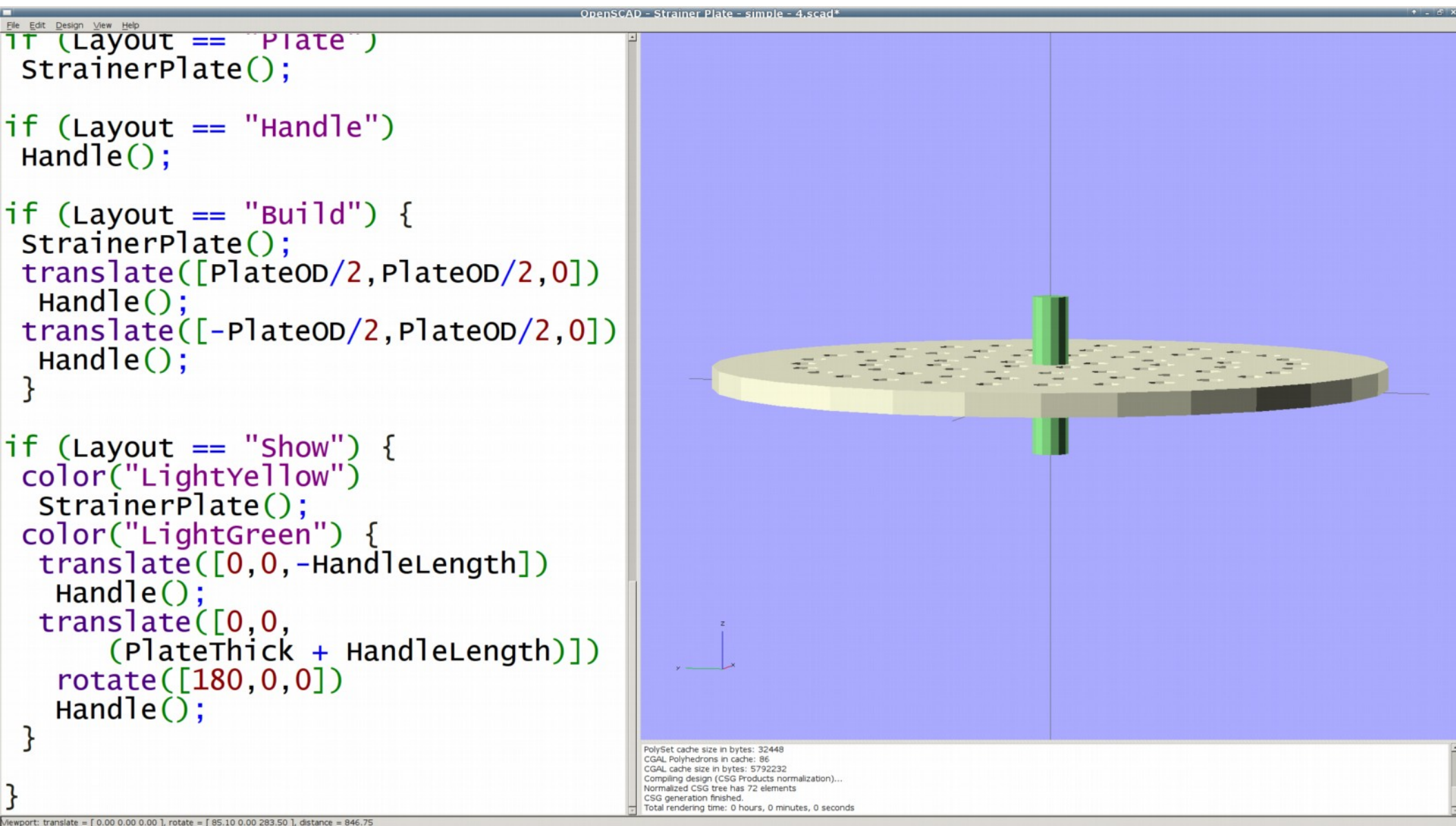
Construct a Handle



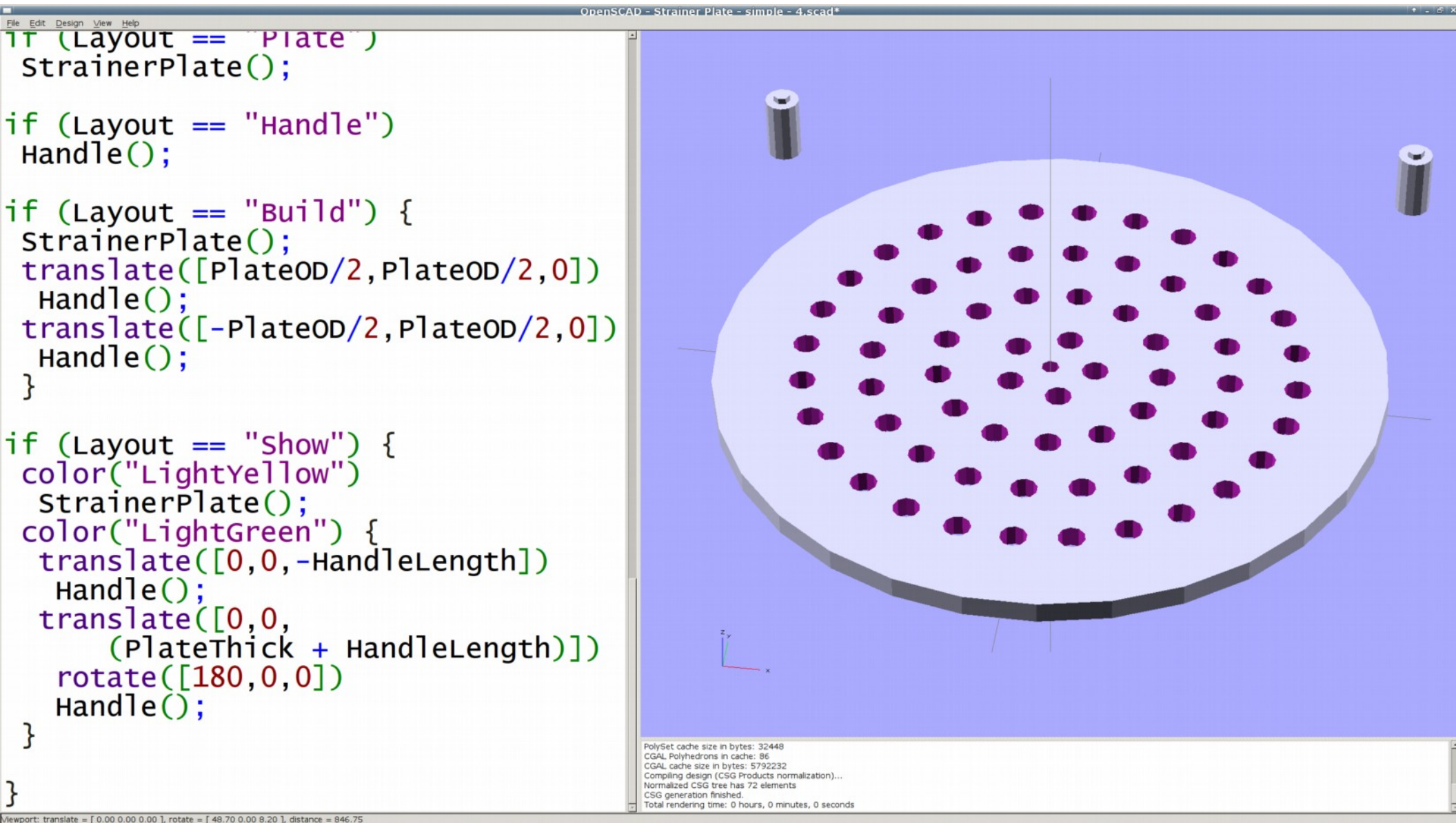
Conditional Object Instances



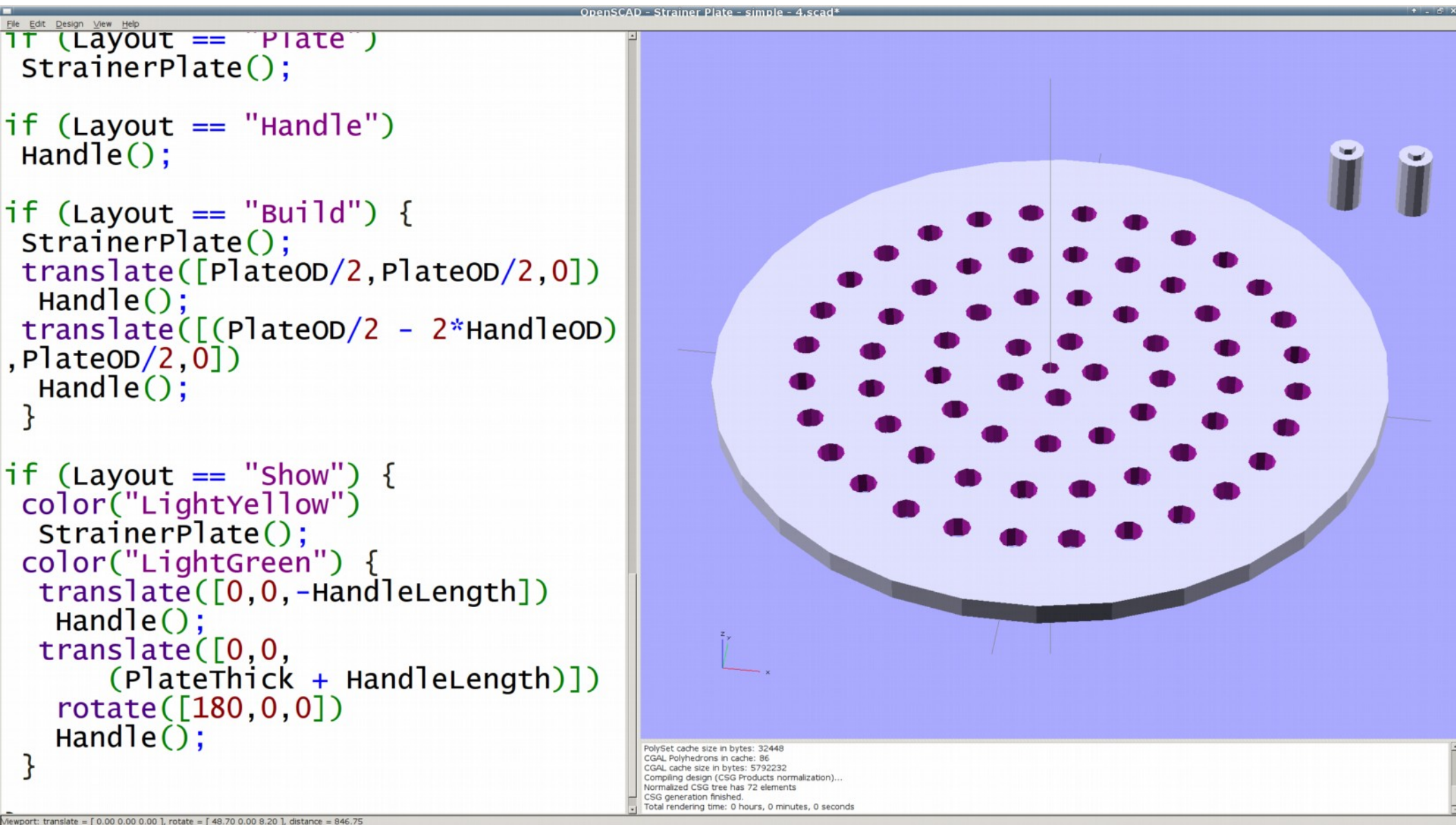
Layout = Show



Layout = Build



Optimize Build Platform Layout



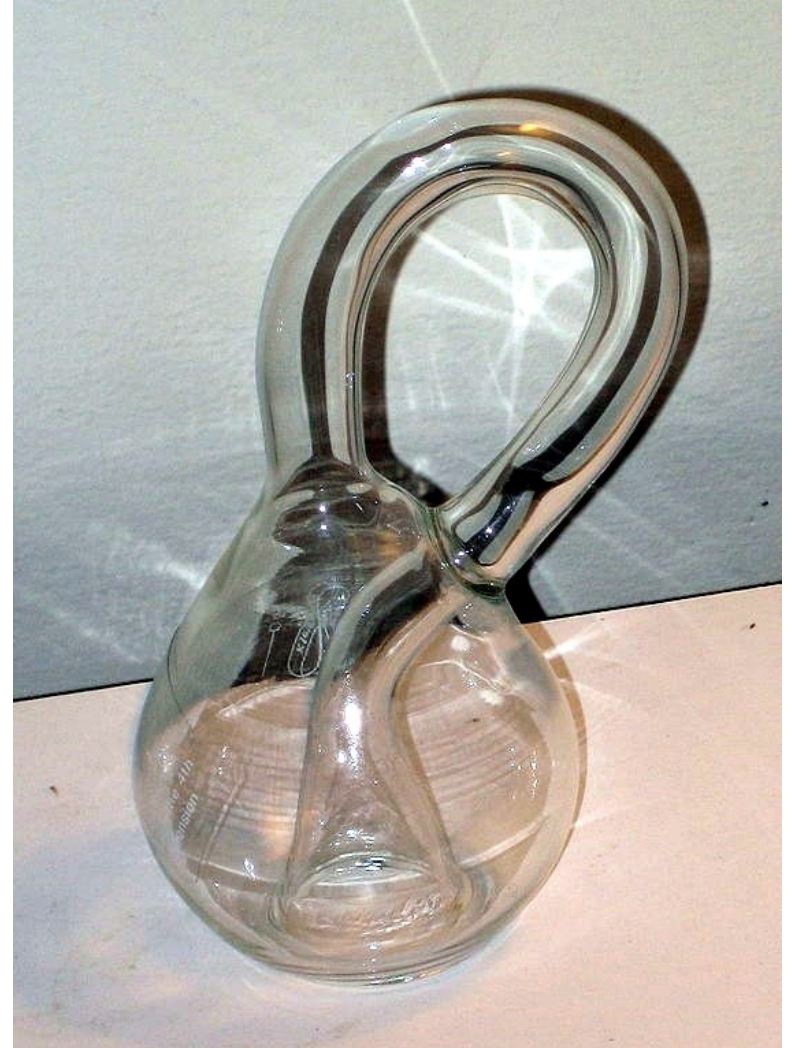
My “Best Practices”

- OpenSCAD is not a programming language
- Don't. Be. Clever.
 - If you must be clever, preprocess in Python, et. al.
- There Are No Variables
 - Only defined constants with global scope
 - Get over it
- Have a conditional layout for every module
 - Think of it as a unit test harness
- Proceed in tiny steps

Modeling Printable Objects

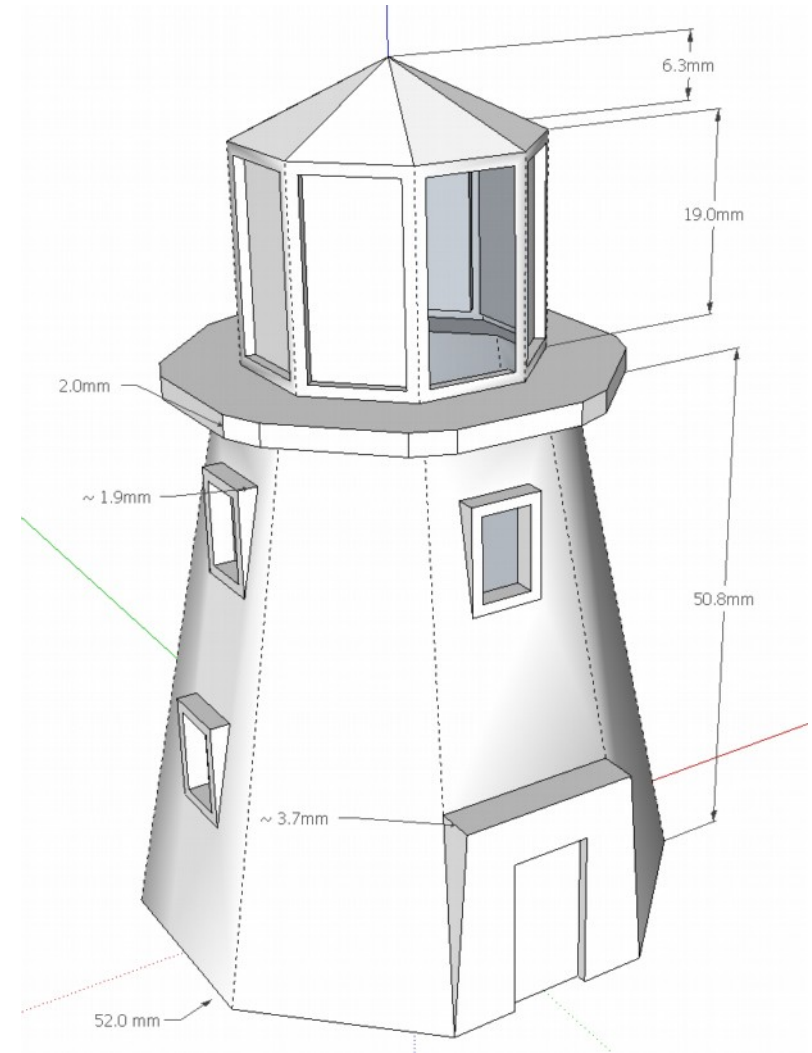
Geometric Requirements

- Closed surface
 - “Watertight” objects
- Consistent Normals
 - All aimed outward
- 2-Manifold
 - Exactly 2 faces / edge
 - No coincident faces

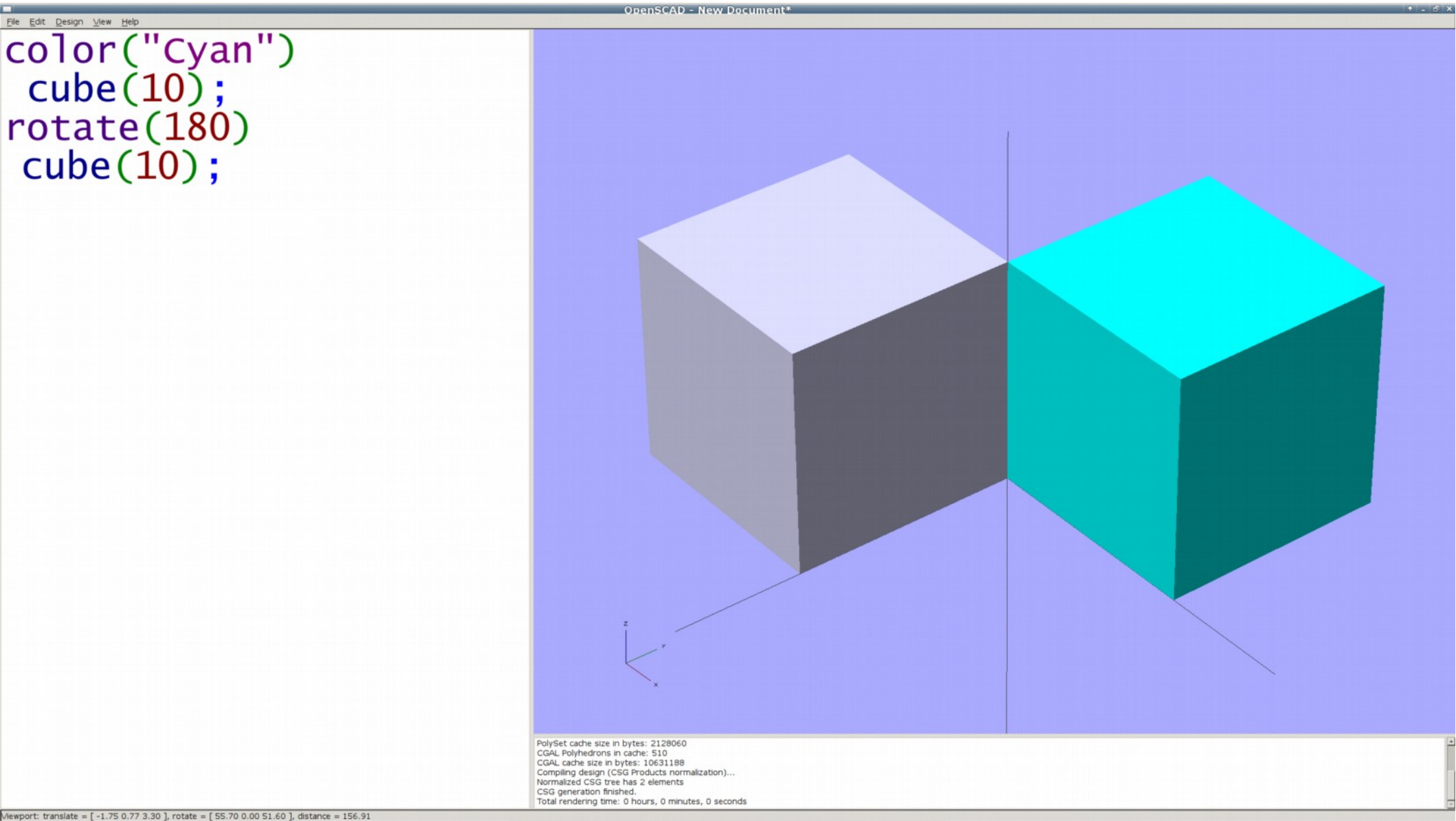


What's Wrong With This Picture?

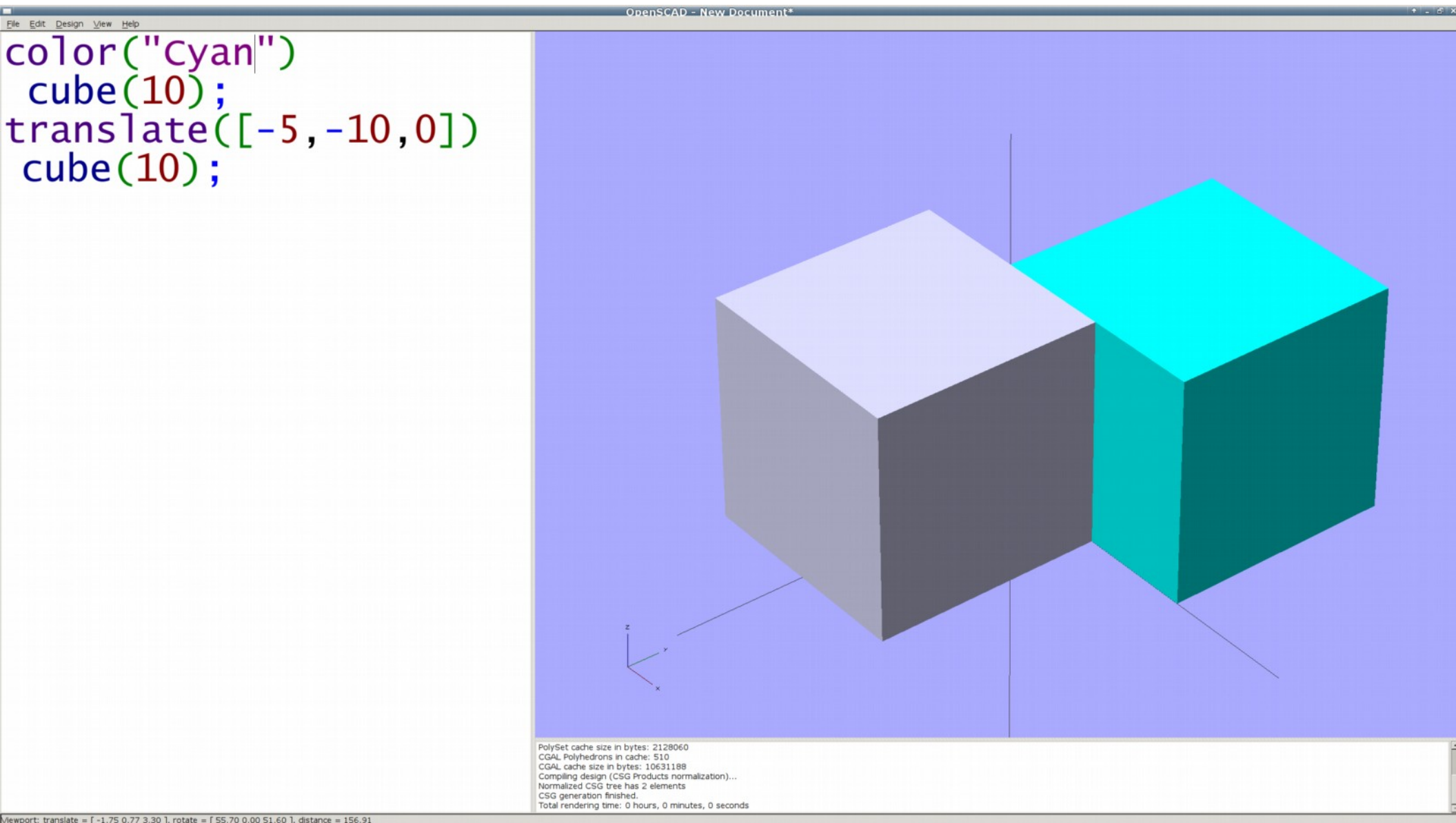
- Not a closed surface
 - Not “watertight”
- Inconsistent normals
- Easy to see?
 - Maybe in *this* model...
 - Book version is OK
- CSG = 3D volumes
- Mesh = 2D surfaces



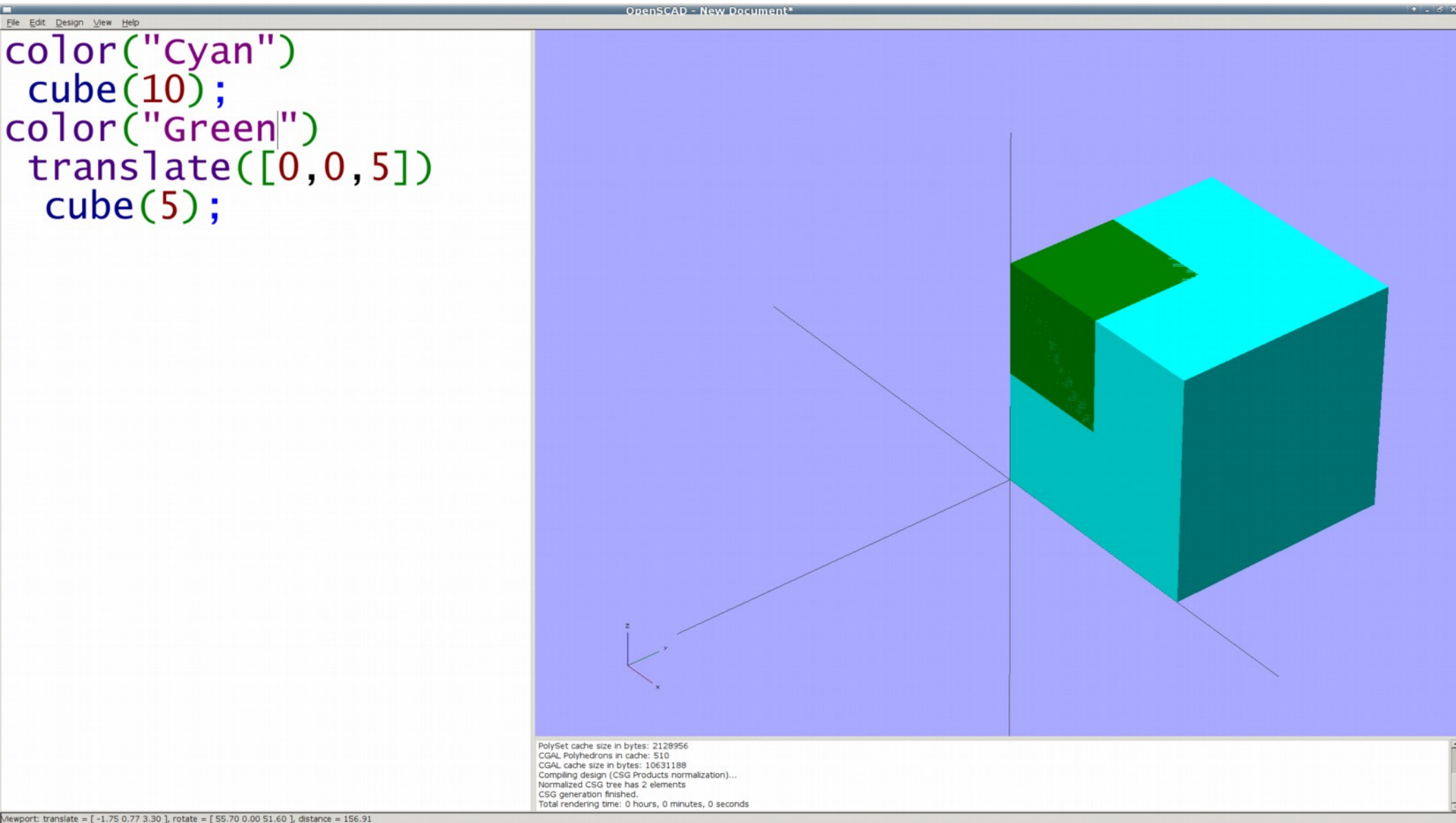
Not 2-Manifold: 4 Sides/Edge



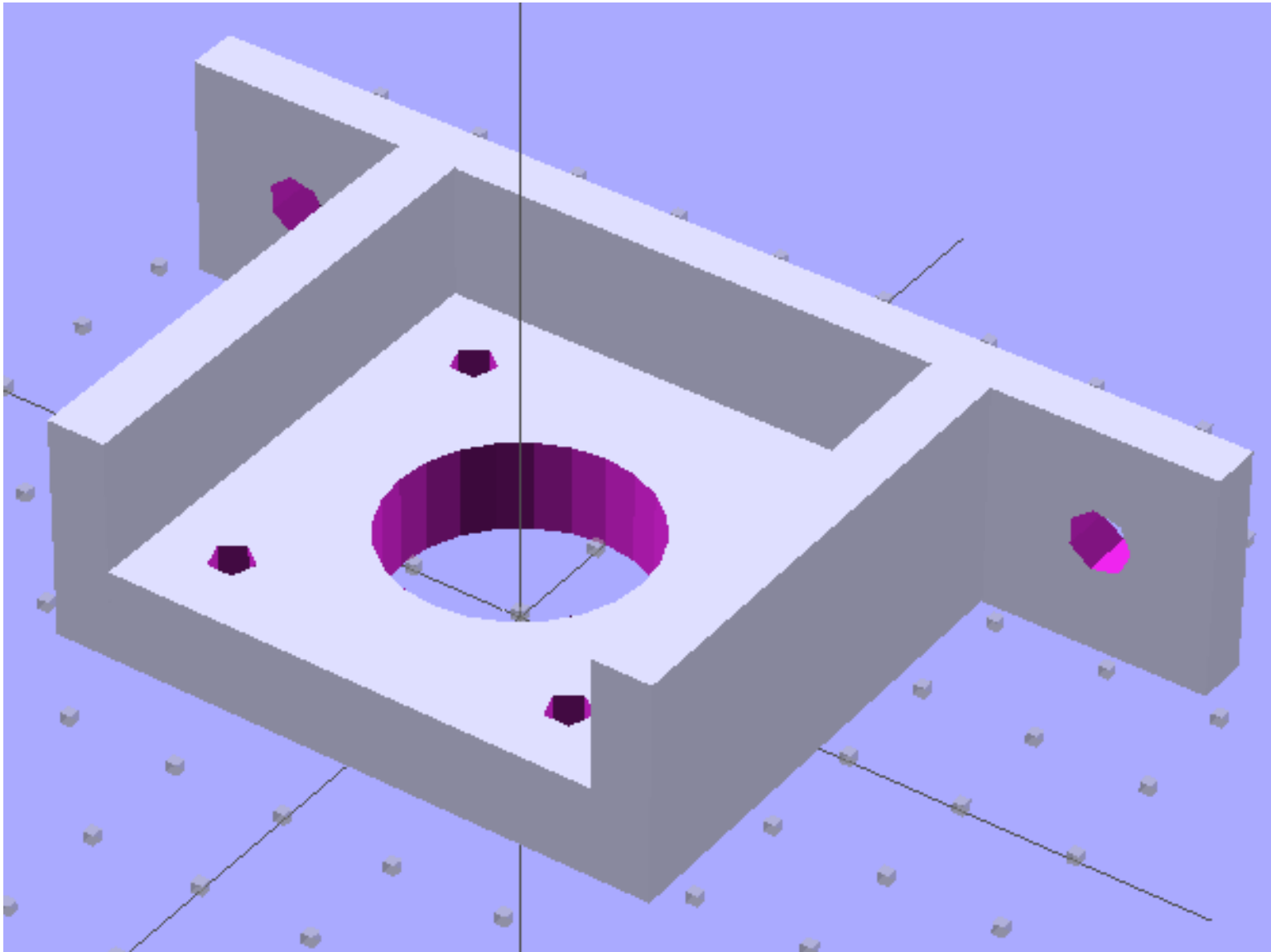
Not 2-Manifold: Coincident Faces



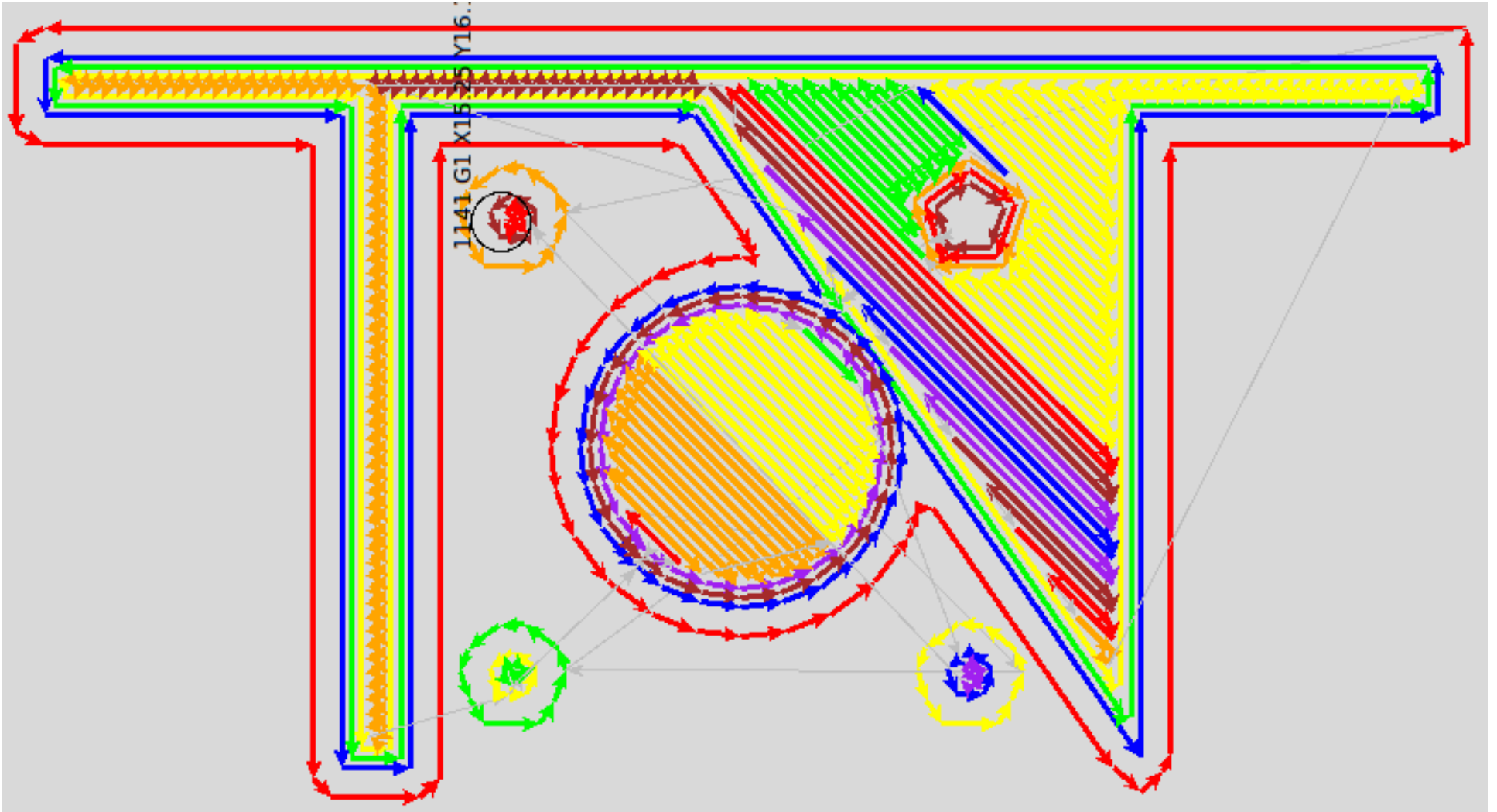
Not 2-Manifold: Coincident Faces



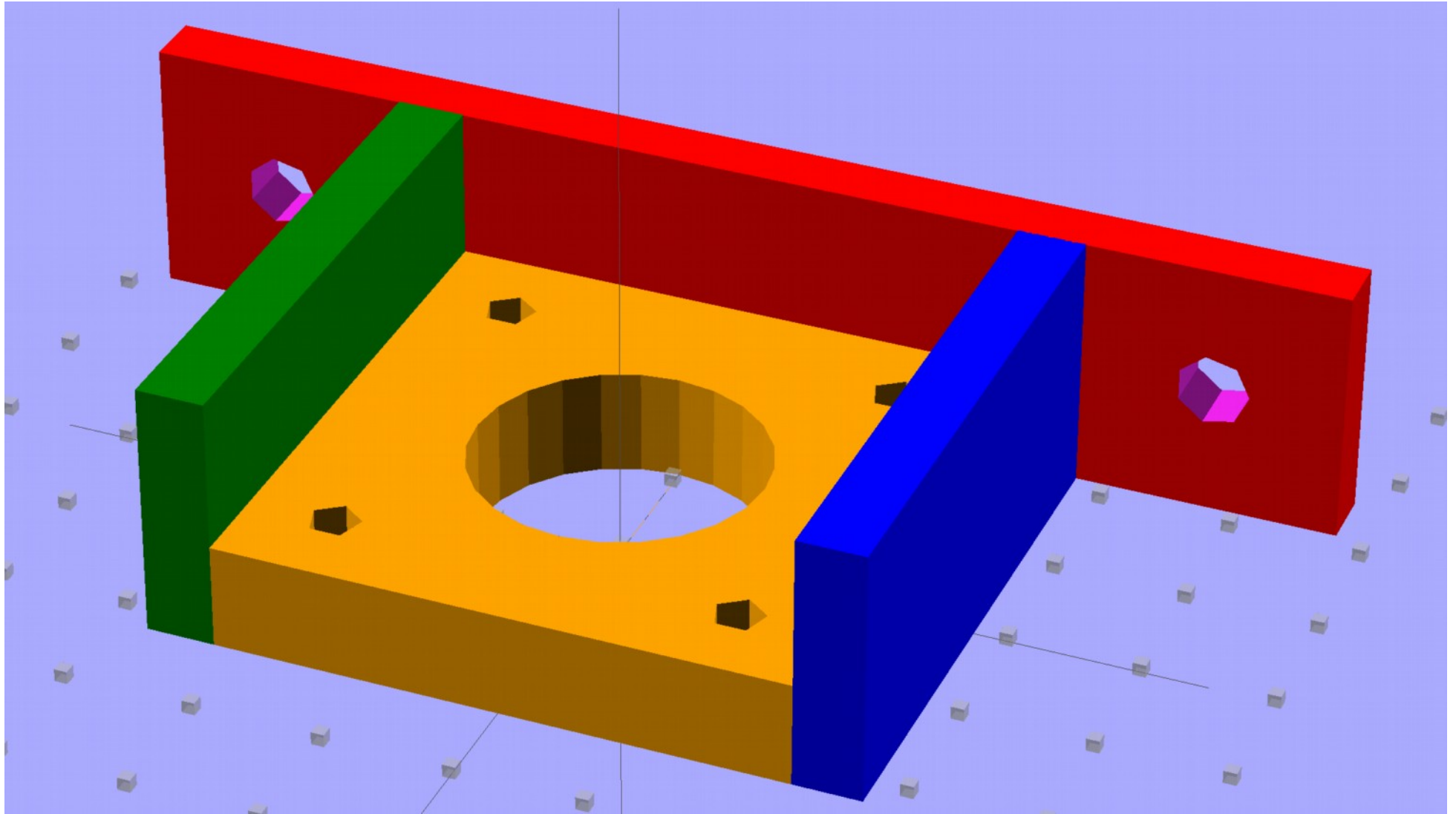
What's Wrong With This Picture?



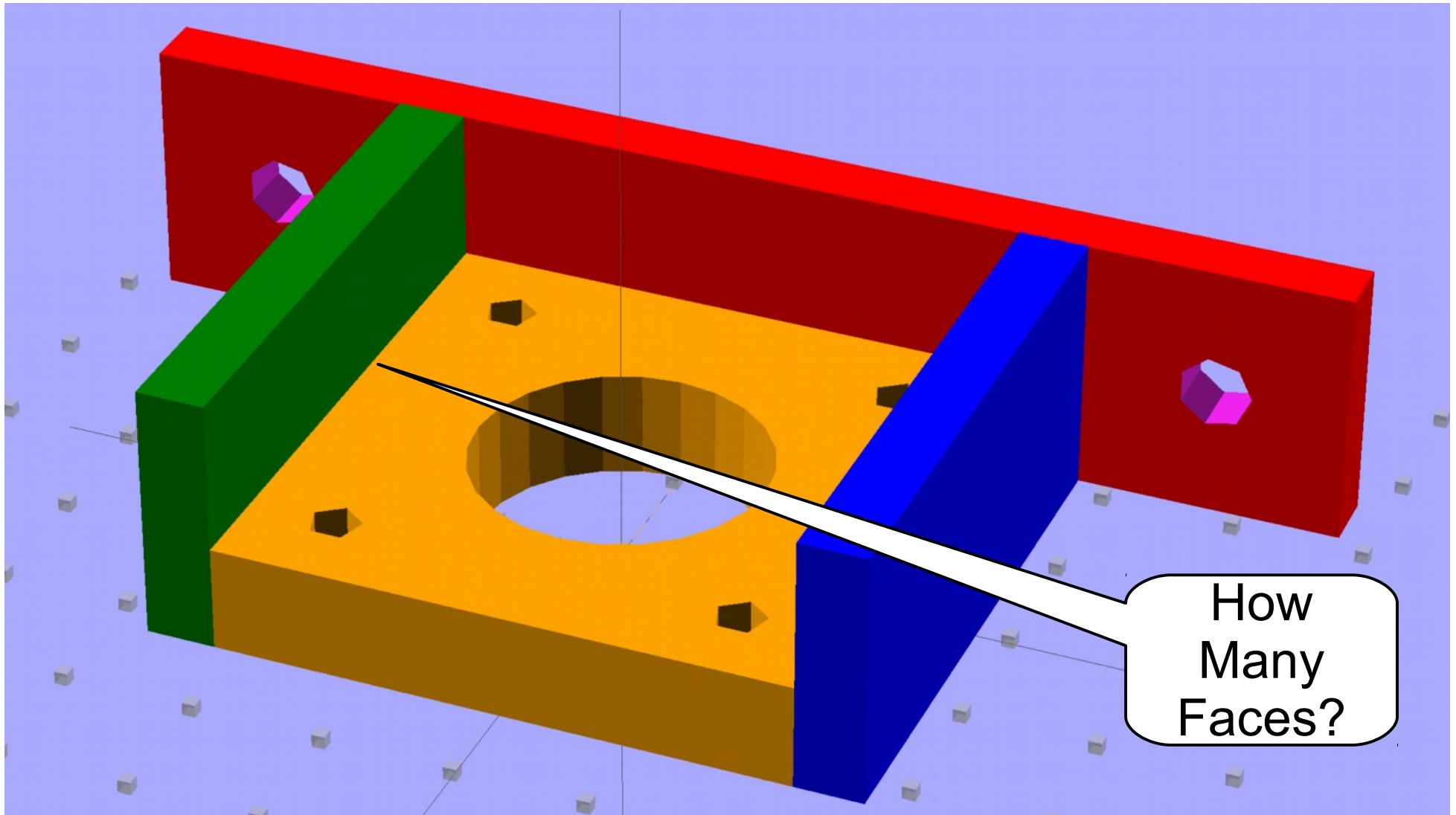
Solid Model → G-Code



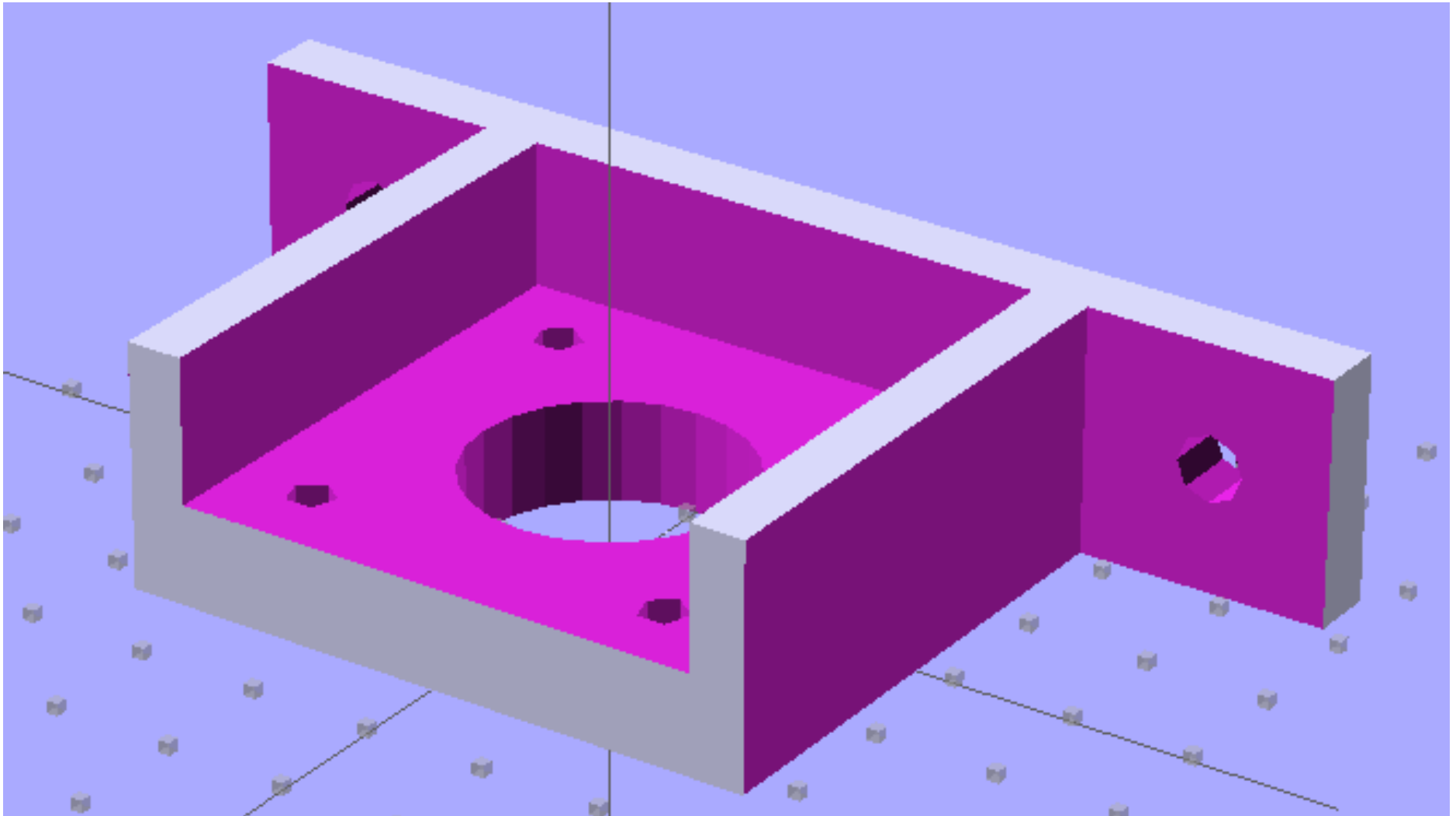
What's Wrong With **This** Picture?



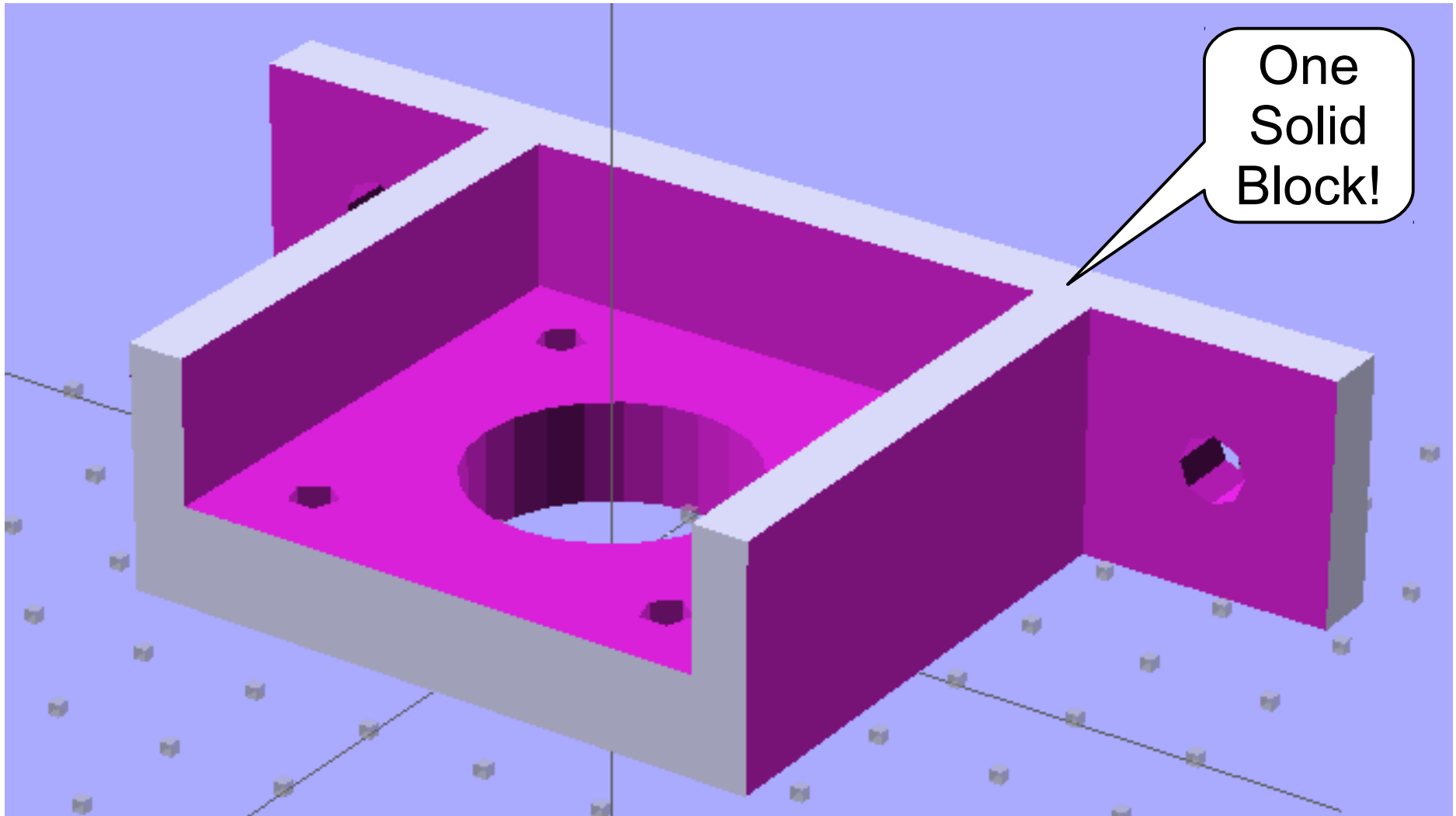
What's Wrong With **This** Picture?



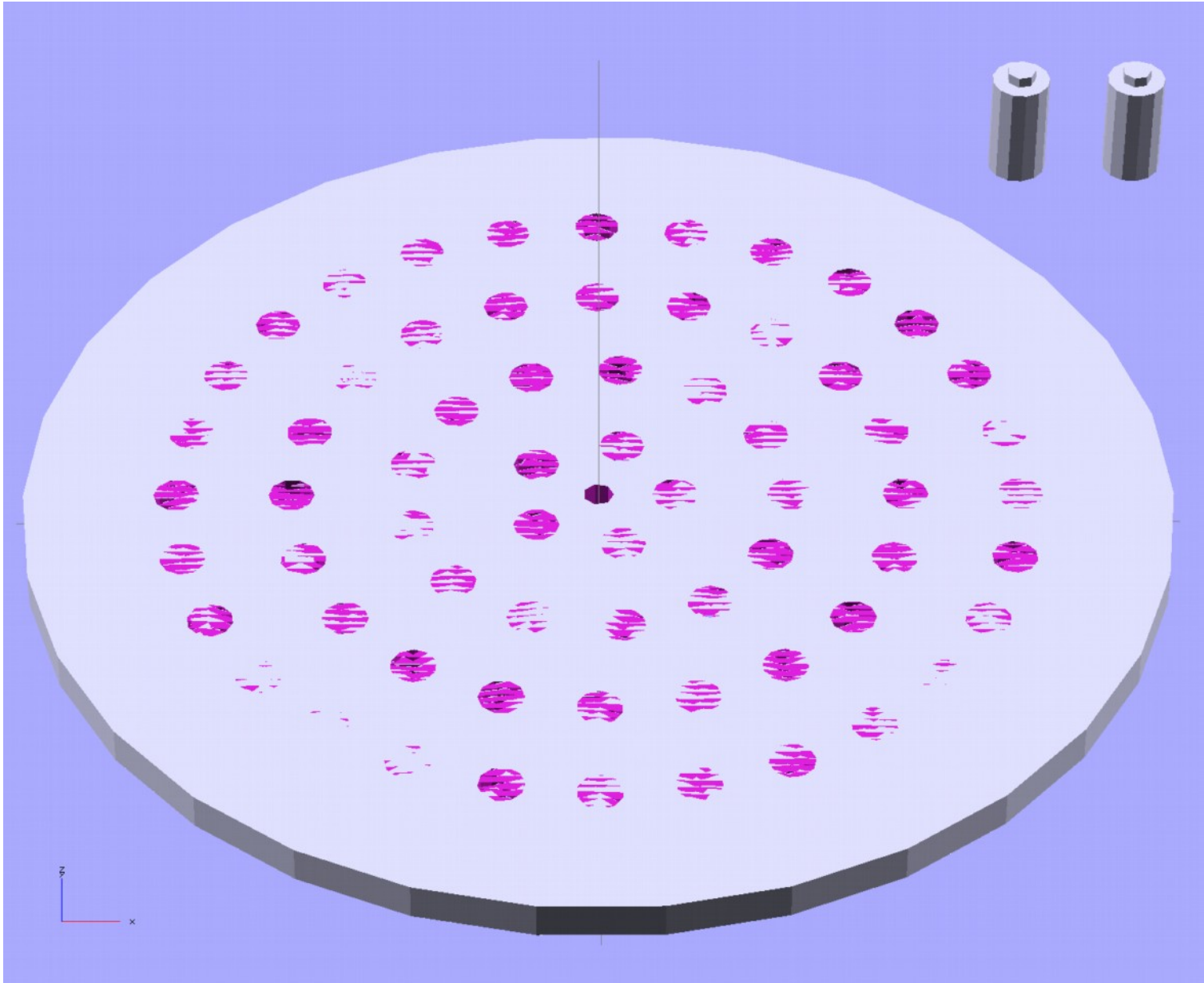
What's *Right* With **This** Picture?



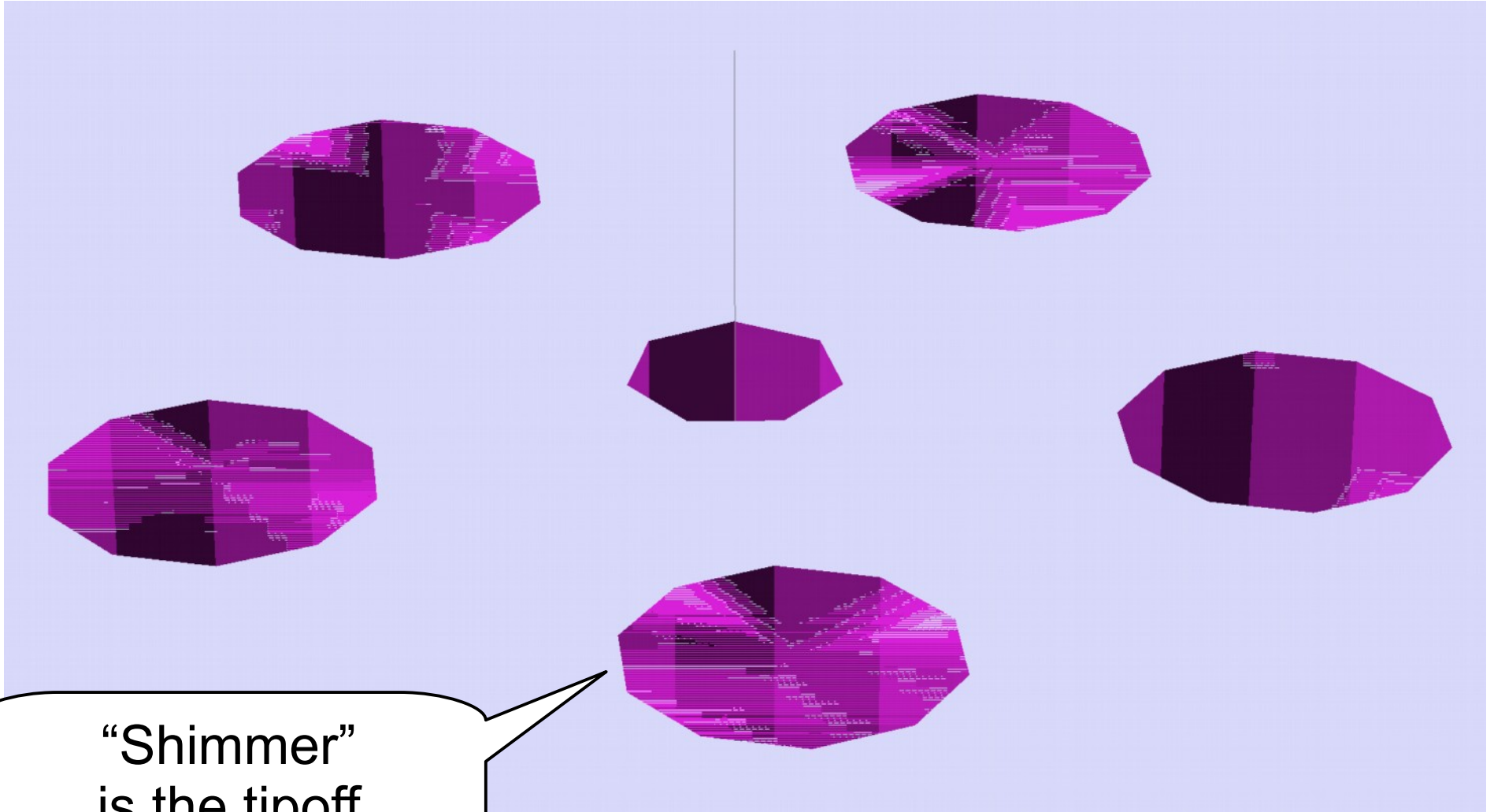
What's *Right* With **This** Picture?



What's Wrong With This Picture?

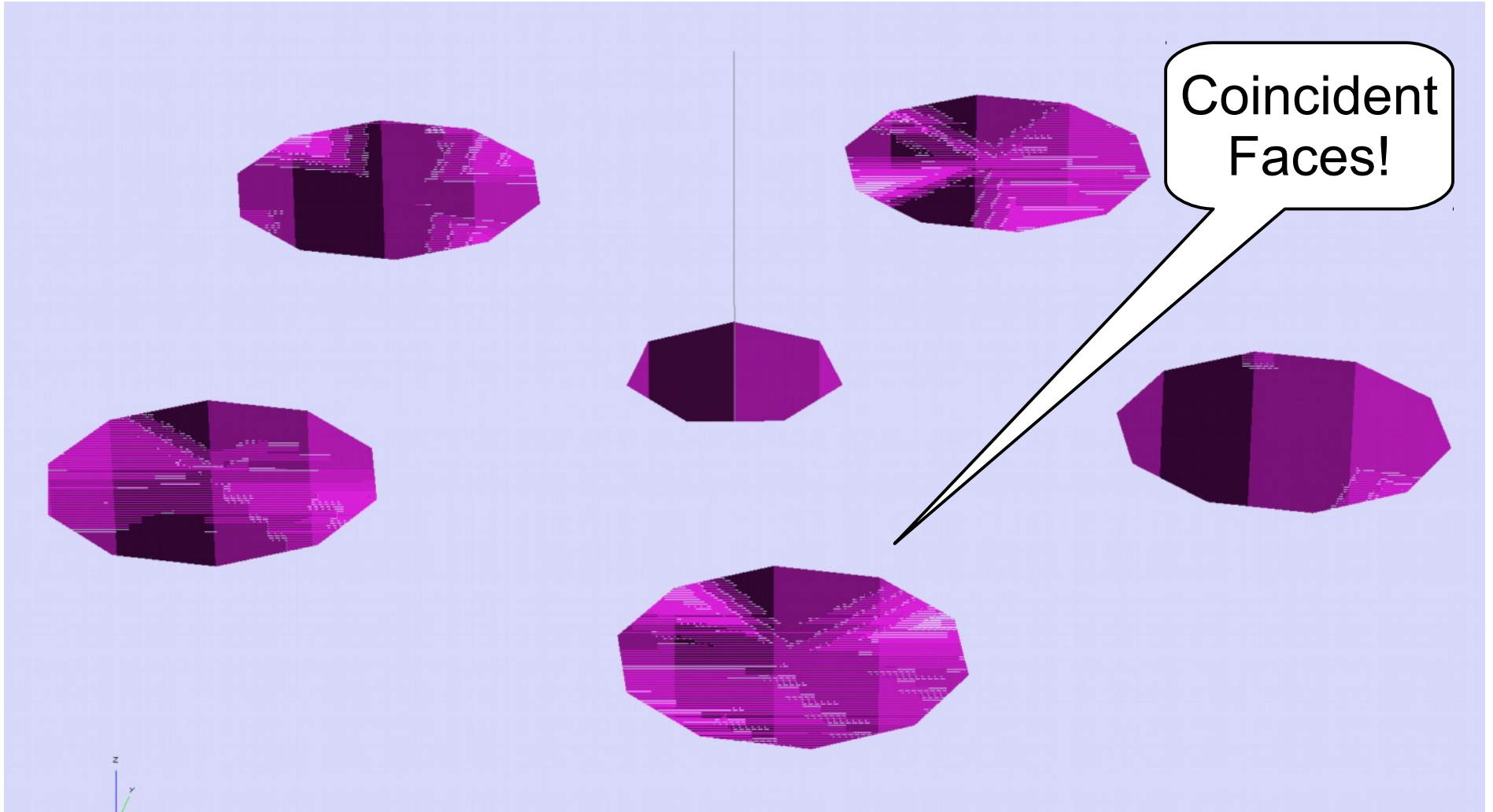


What's Wrong With This Picture?

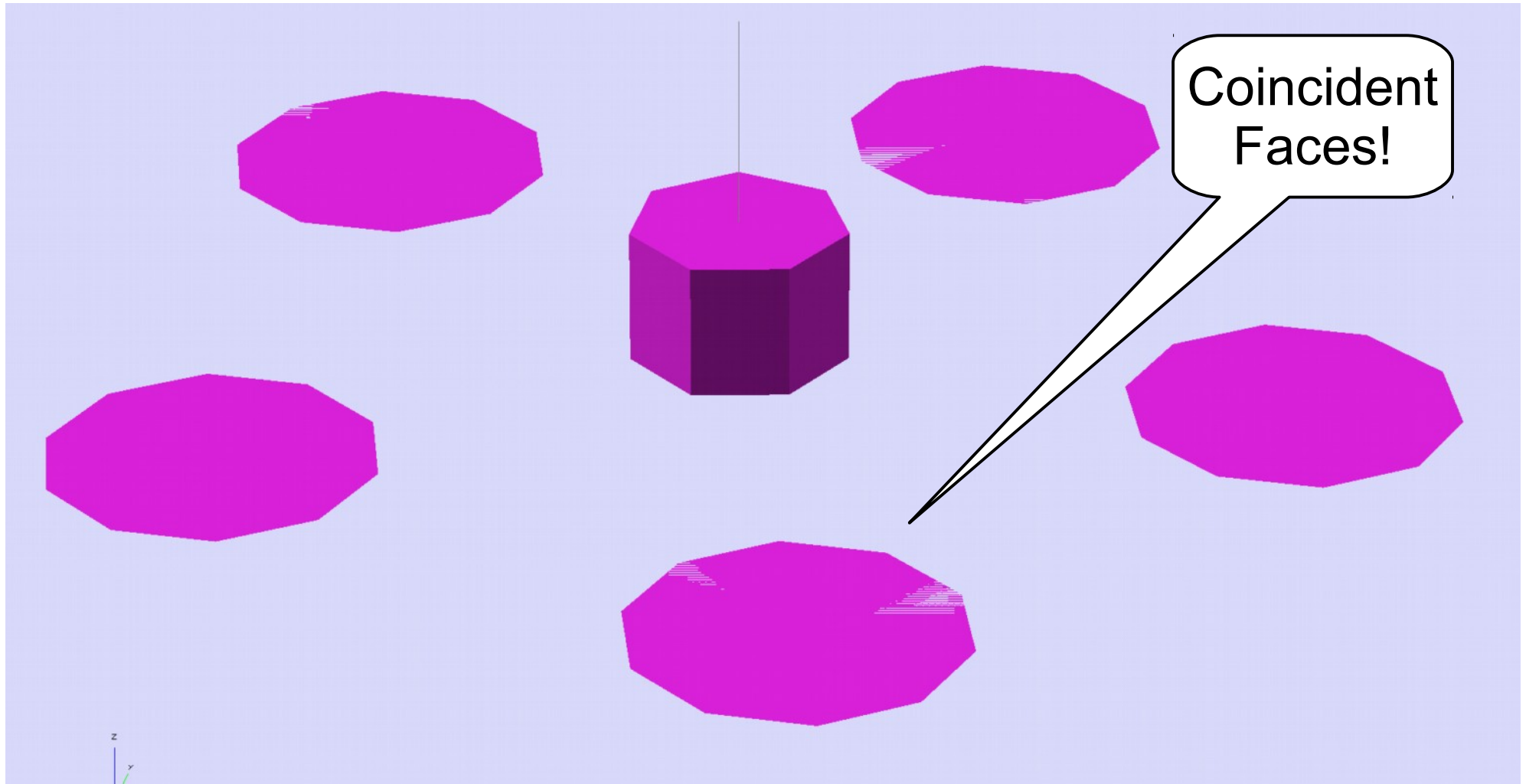


"Shimmer"
is the tipoff

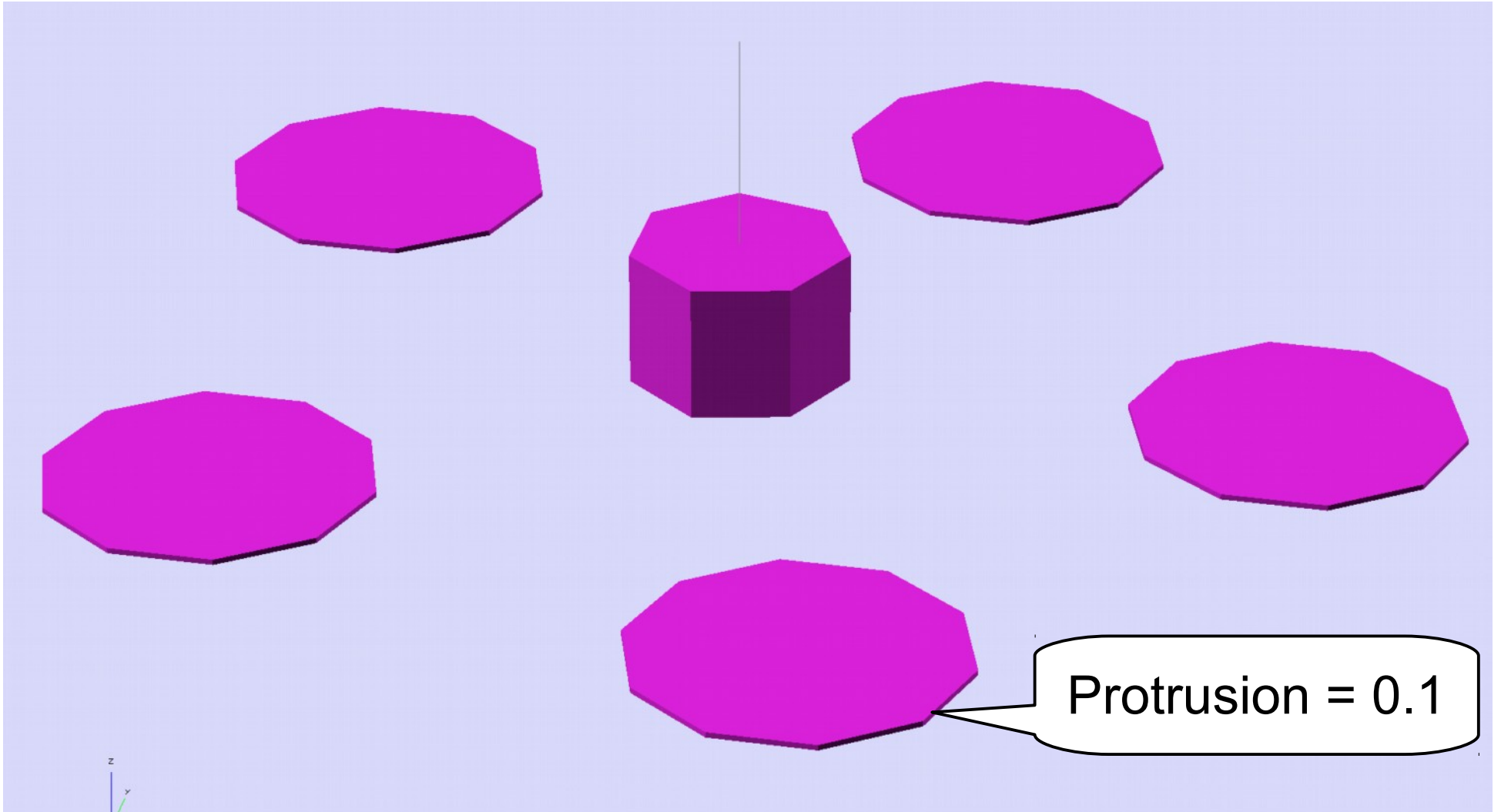
What's Wrong With This Picture?



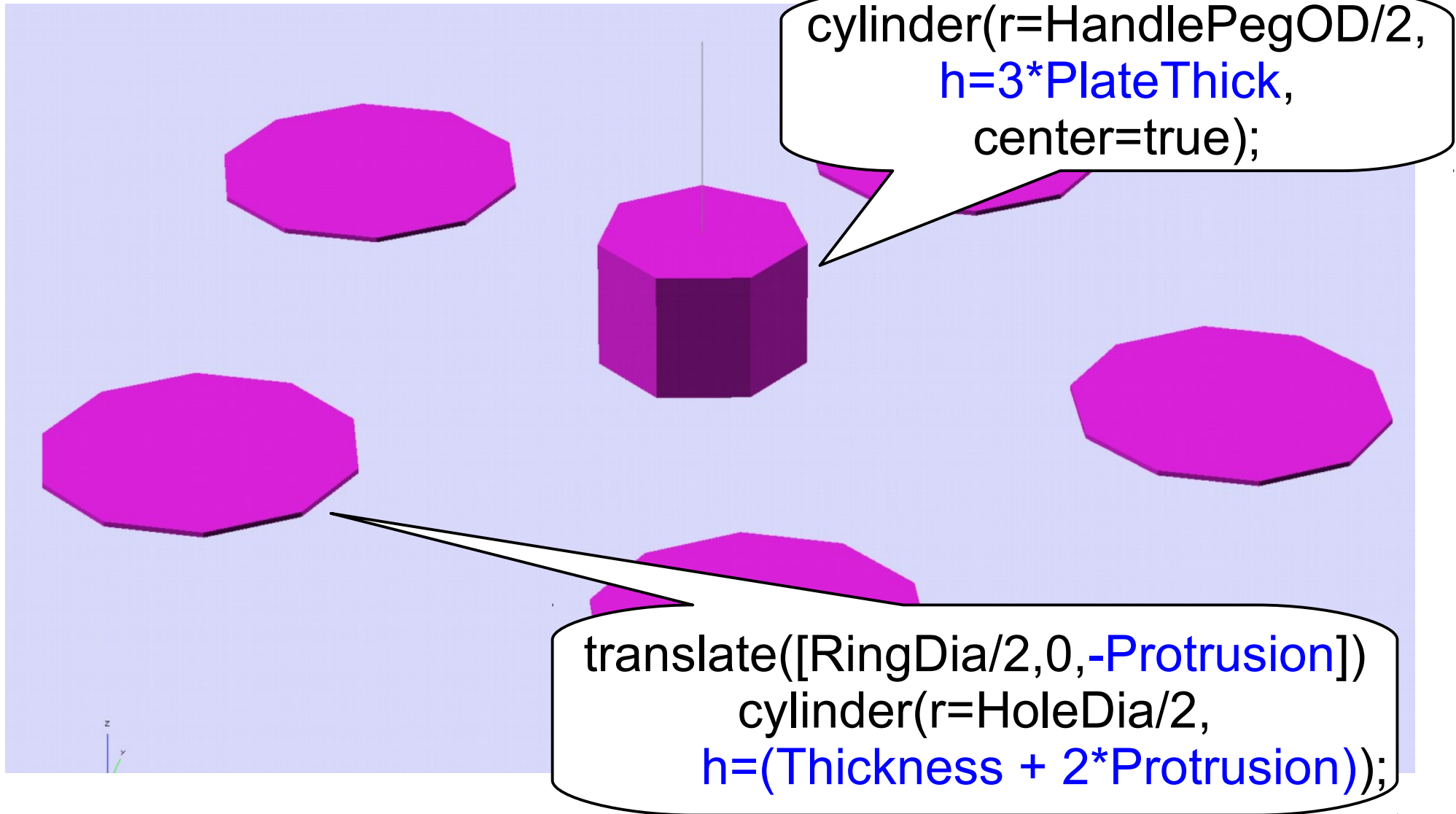
F12 View



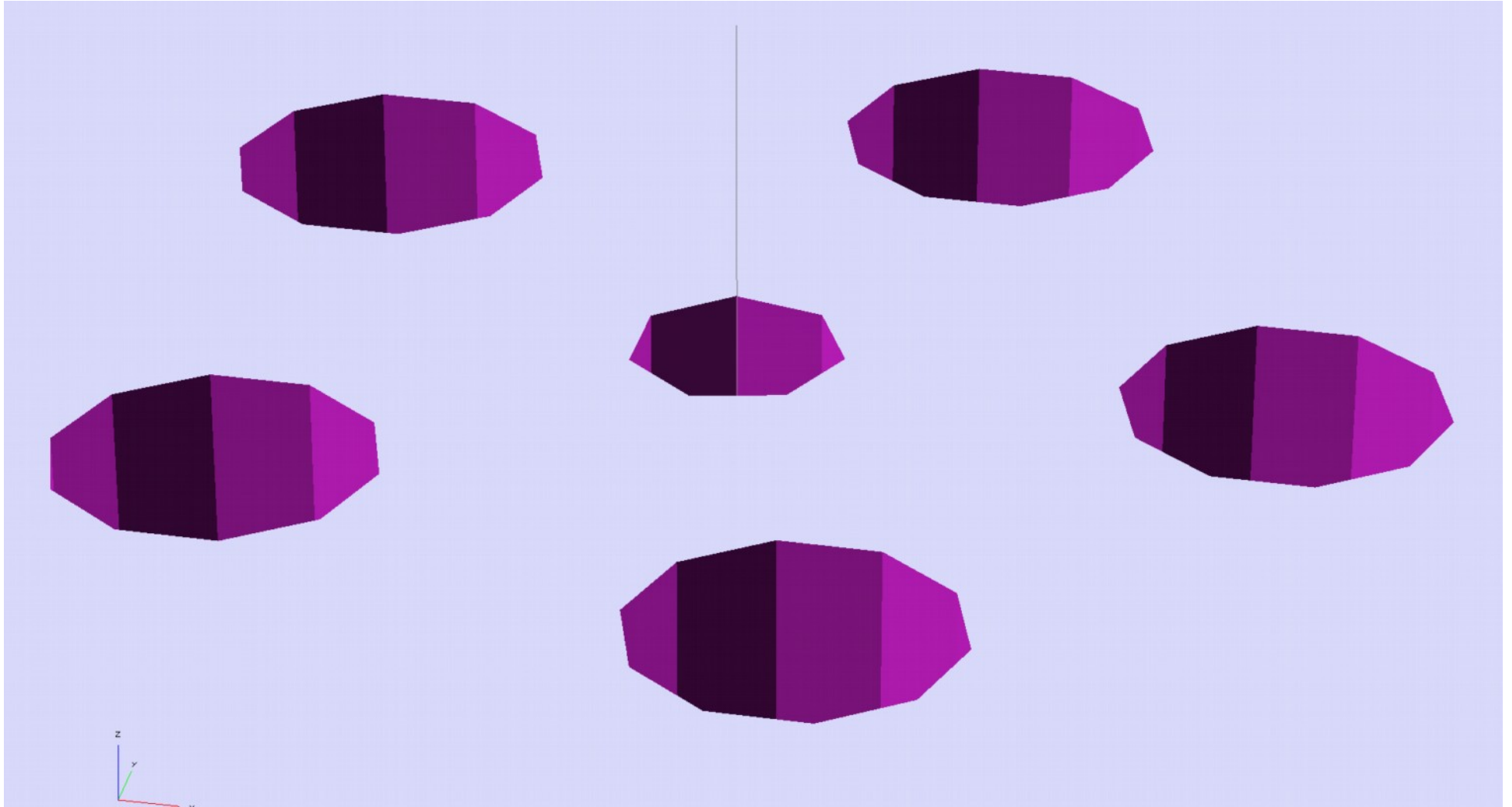
What's Right With This Picture?



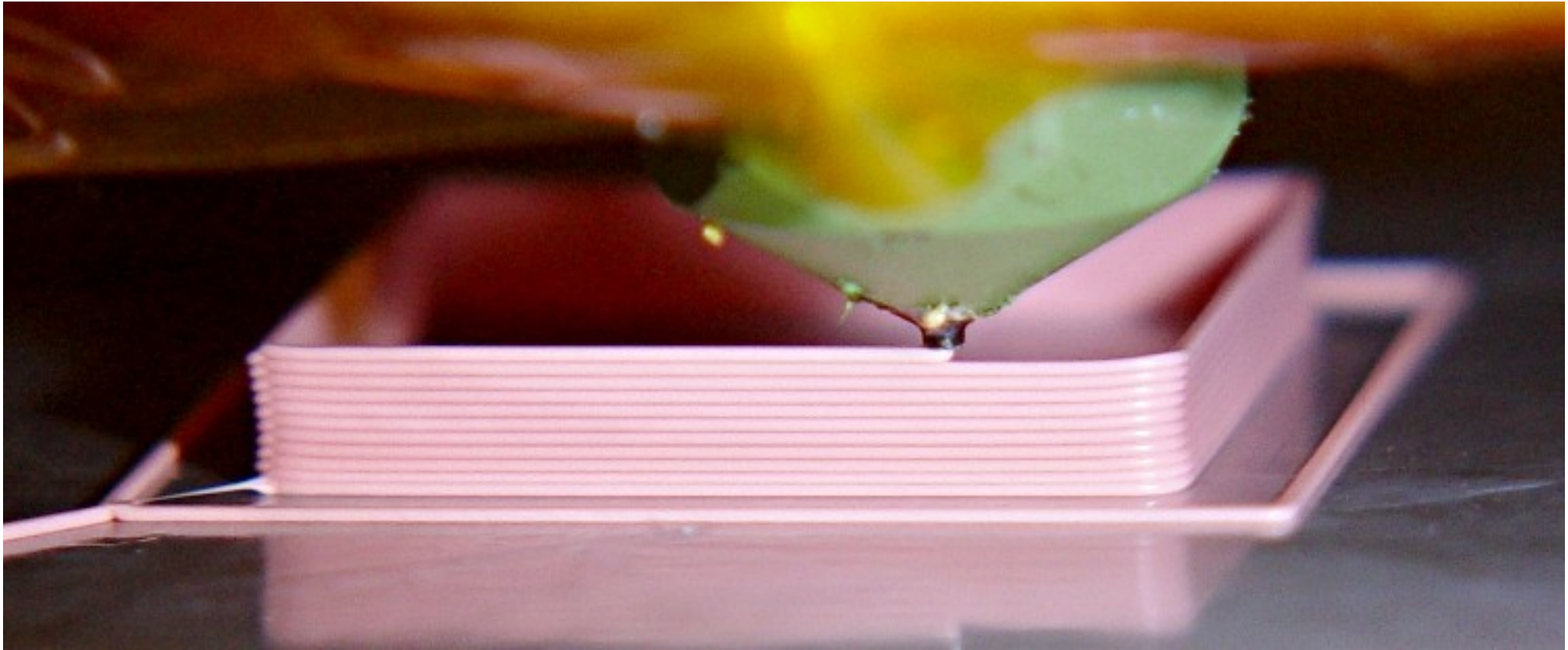
What Does It Take To Be Right?



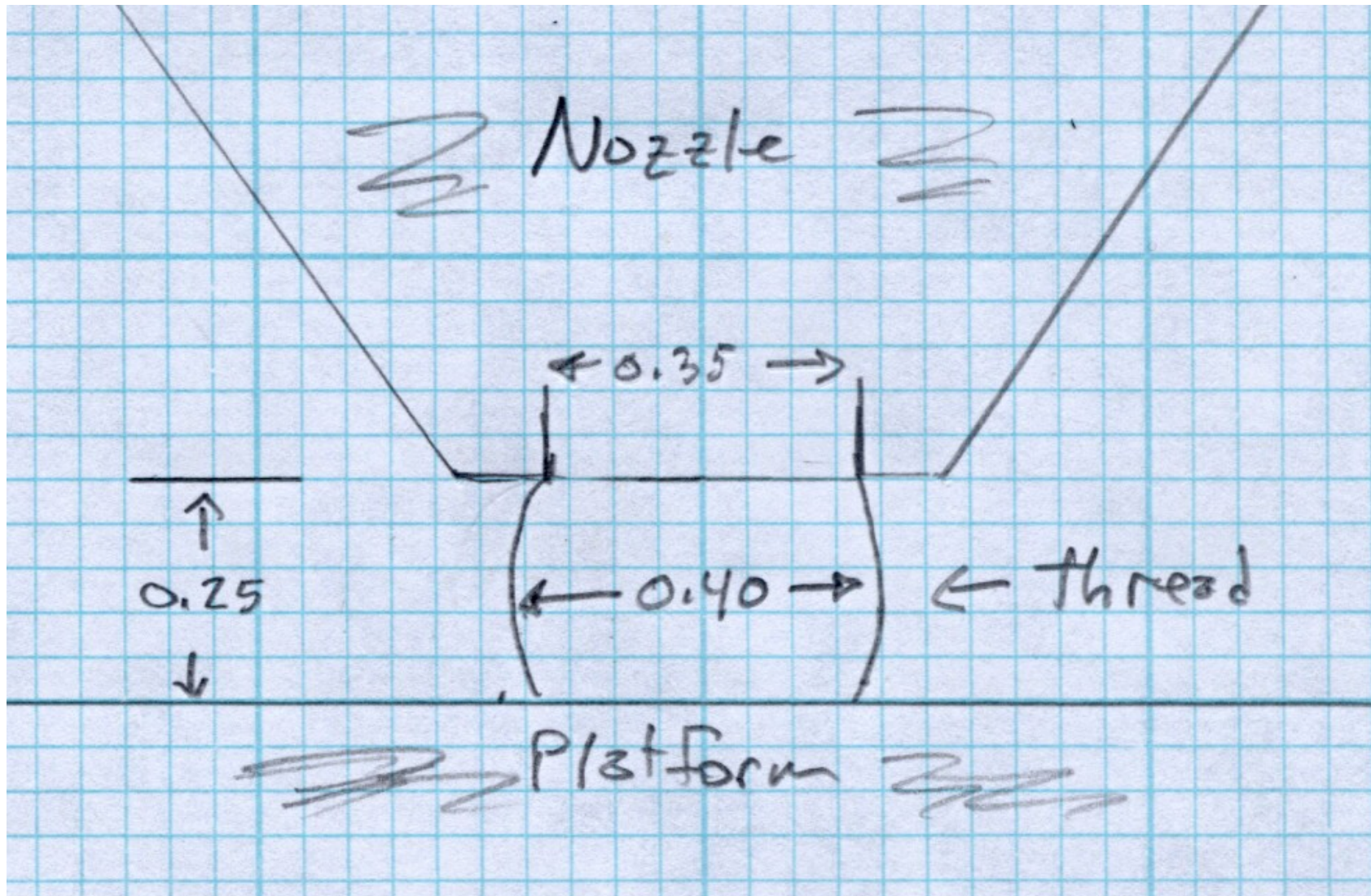
What's Right With This Picture?



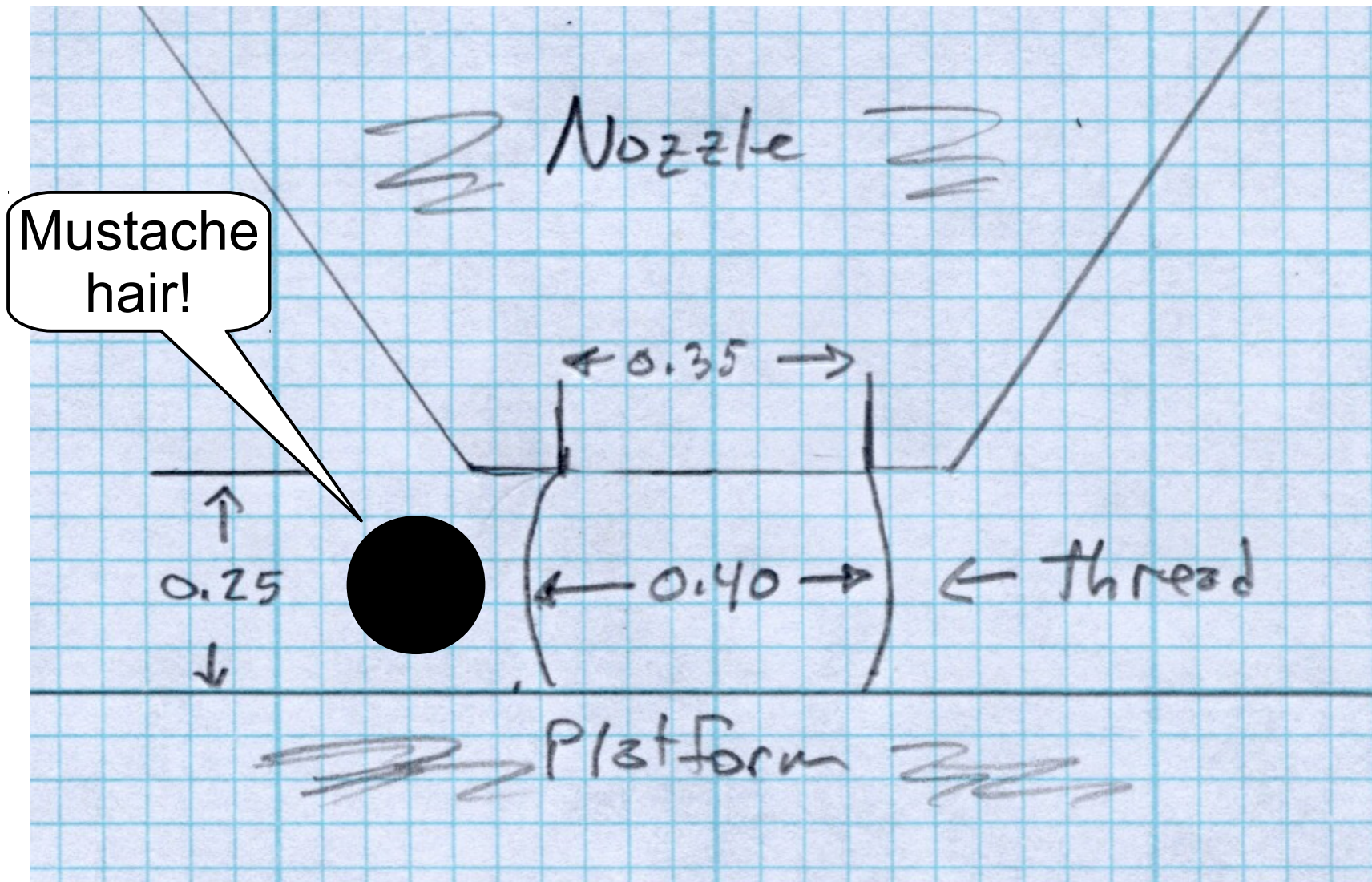
Process Limitations



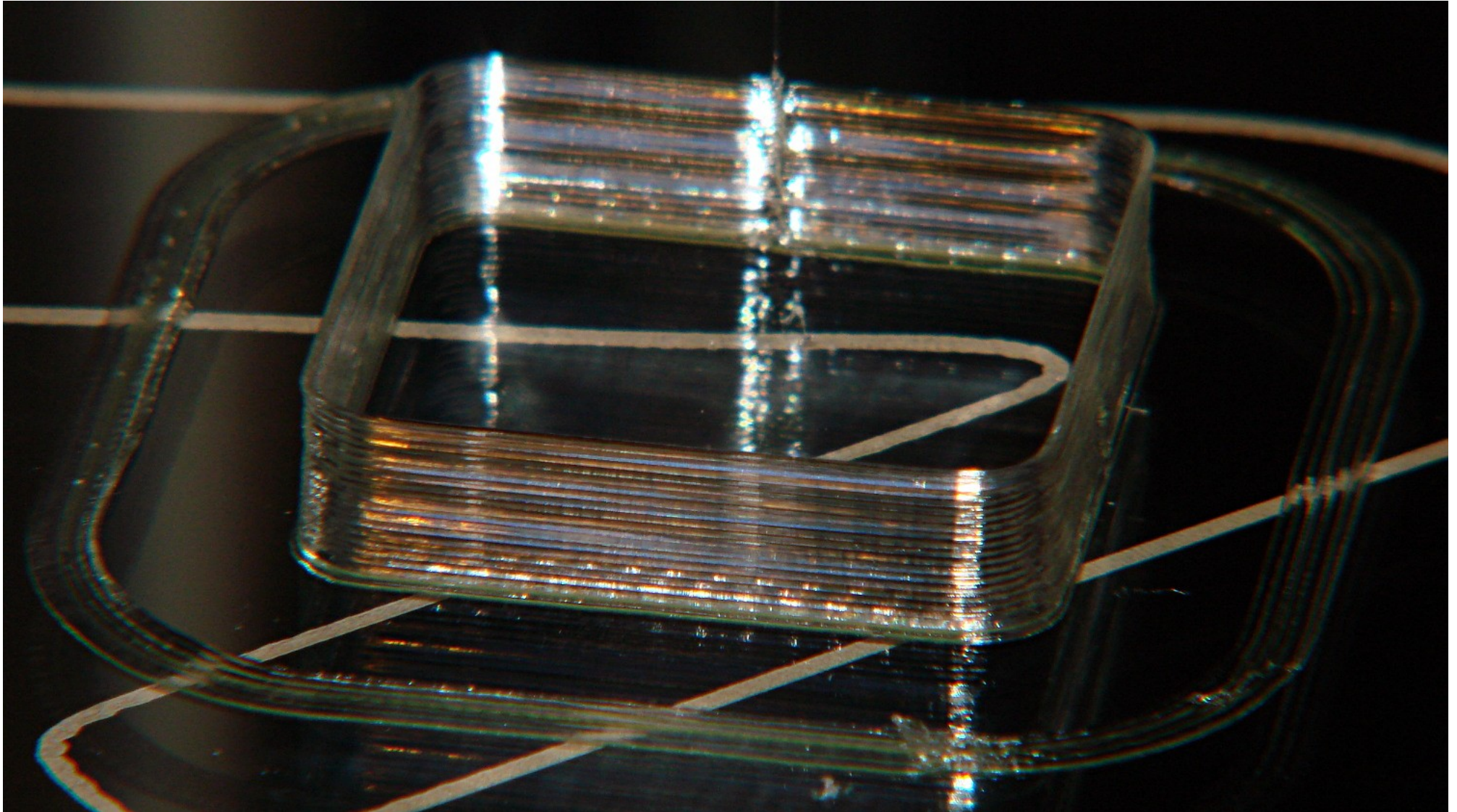
Fundamental Sizes



Fundamental Sizes



Extruder Calibration



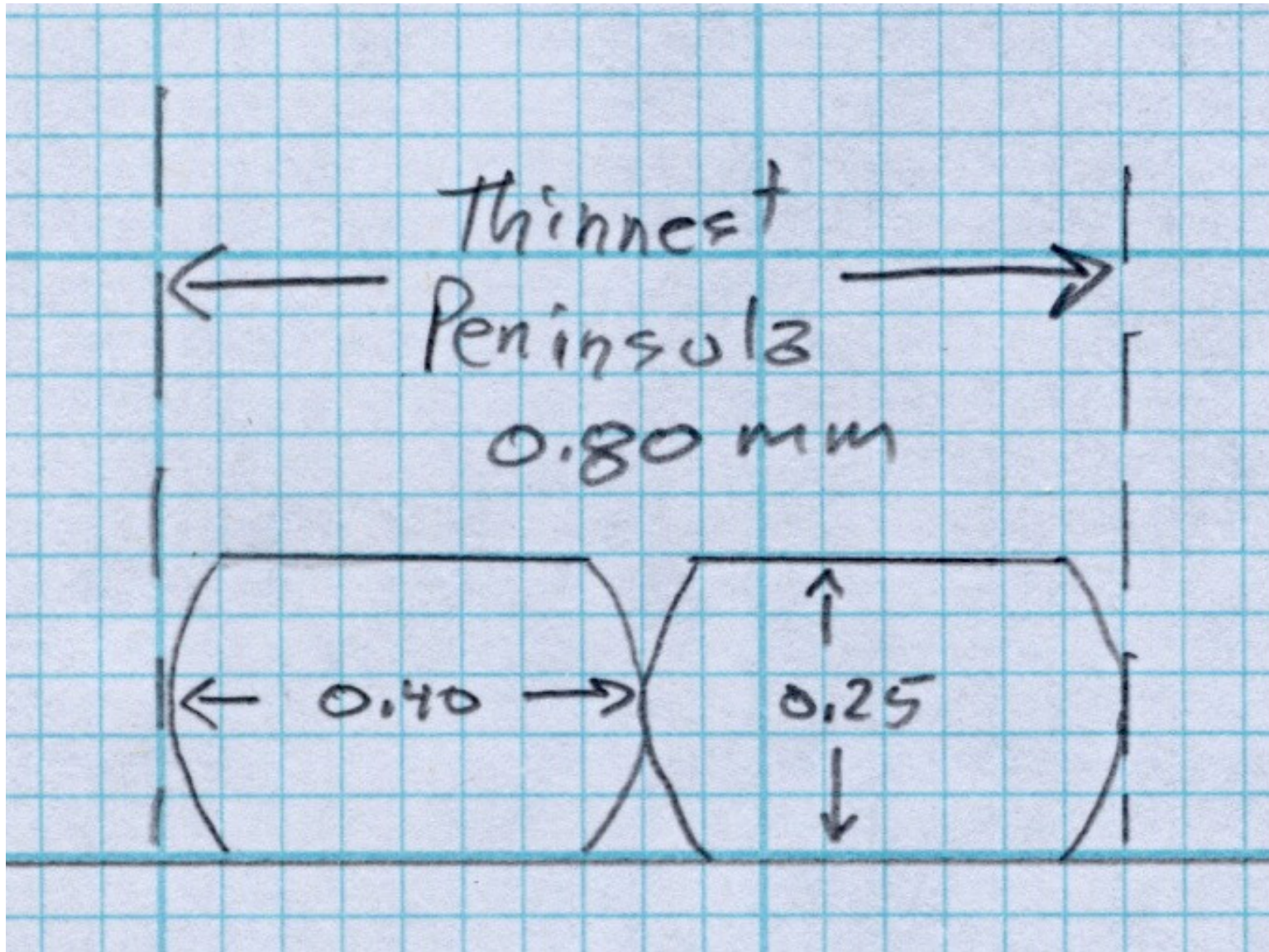
<http://softsolder.com/2013/04/16/makergear-m2-fundamental-test-object/>

Extruder Calibration

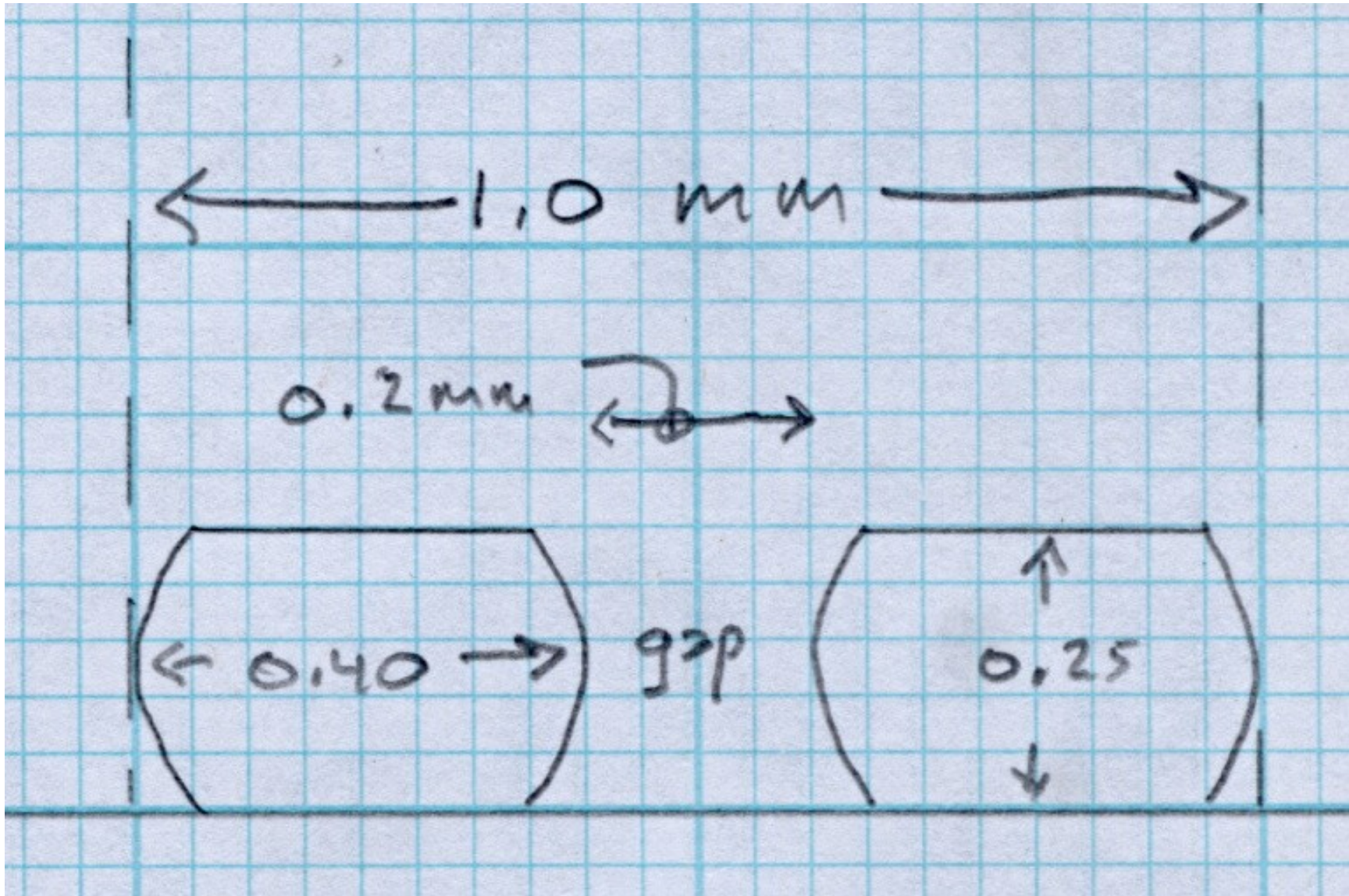


<http://softsolder.com/2013/04/16/makergear-m2-fundamental-test-object/>

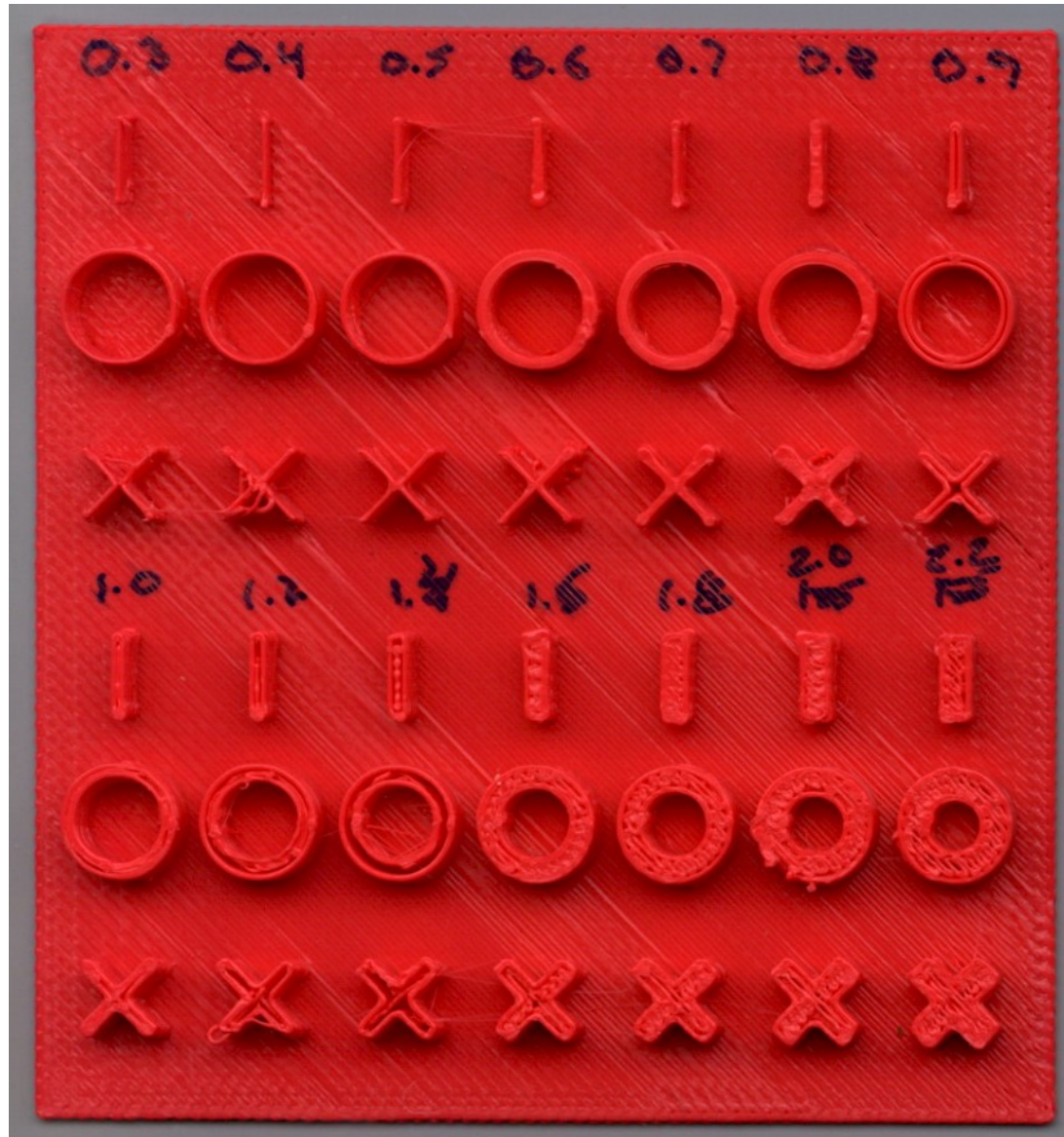
Smallest Possible Feature



Unavoidable Gap!



Wall Width Test Piece



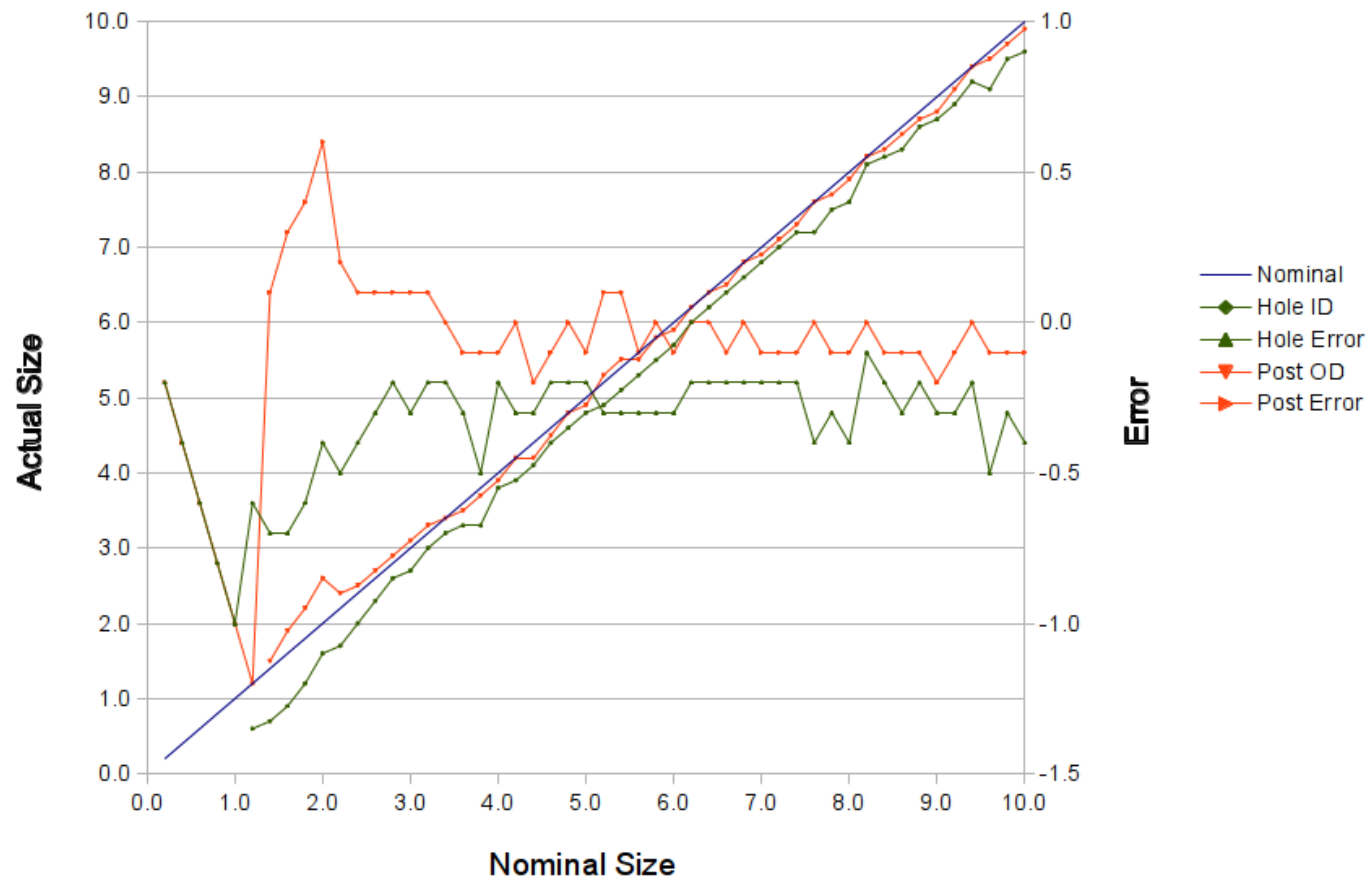
Hole & Pillar Tests



Hole & Pillar Calibration

M2 Initial Hole and Post Calibration

Infill 100 mm/s - Outer Perim 30 mm/s



Hole Size Compensation

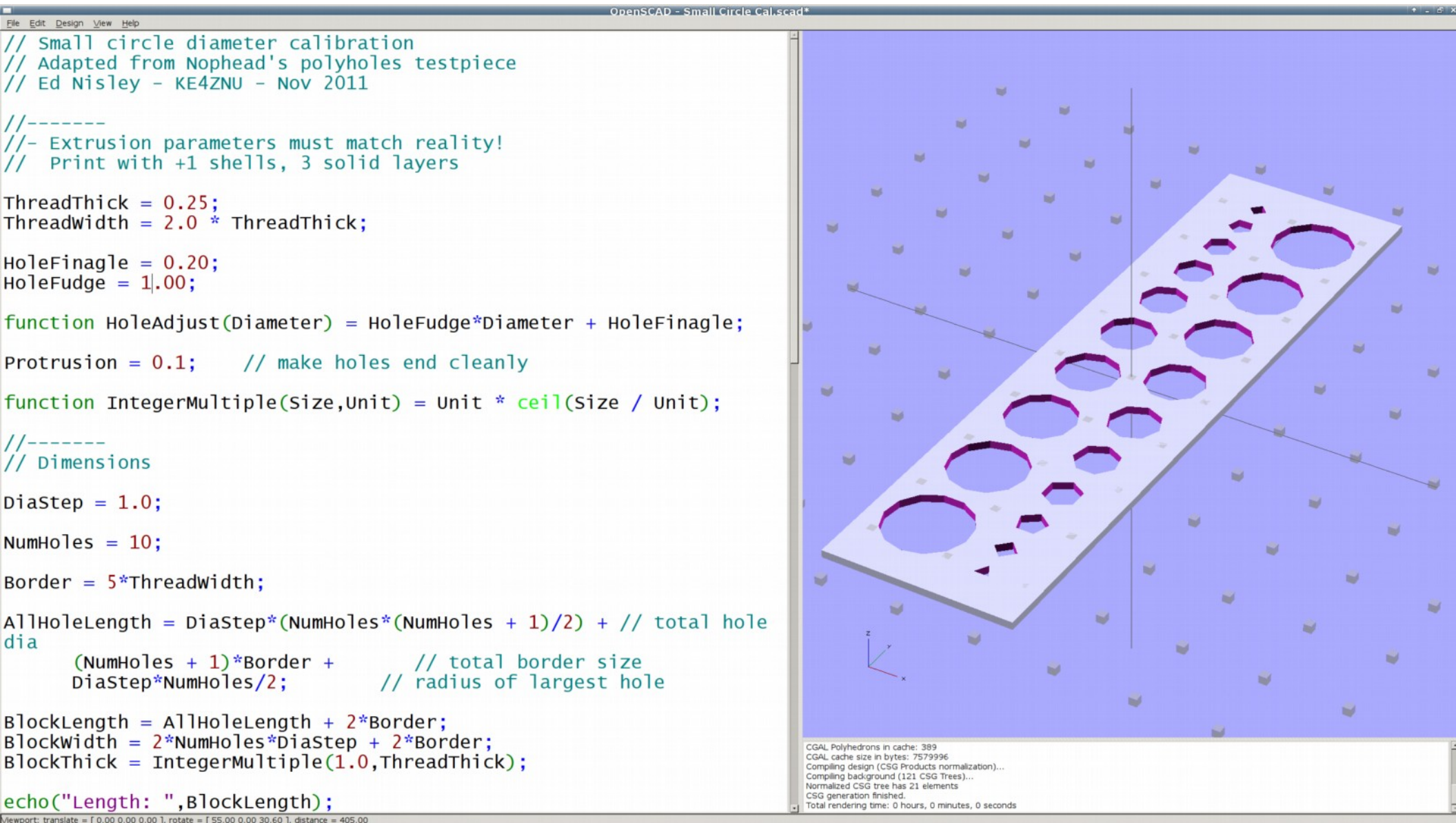
```
Holewindage = 0.2;
```

```
module PolyCyl(Dia,Height,ForceSides=0) {  
    Sides = (ForceSides != 0) ?  
            ForceSides : (ceil(Dia) + 2);  
    FixDia = Dia / cos(180/Sides);  
    cylinder(r=(FixDia + Holewindage)/2,  
            h=Height,$fn=Sides);  
}
```

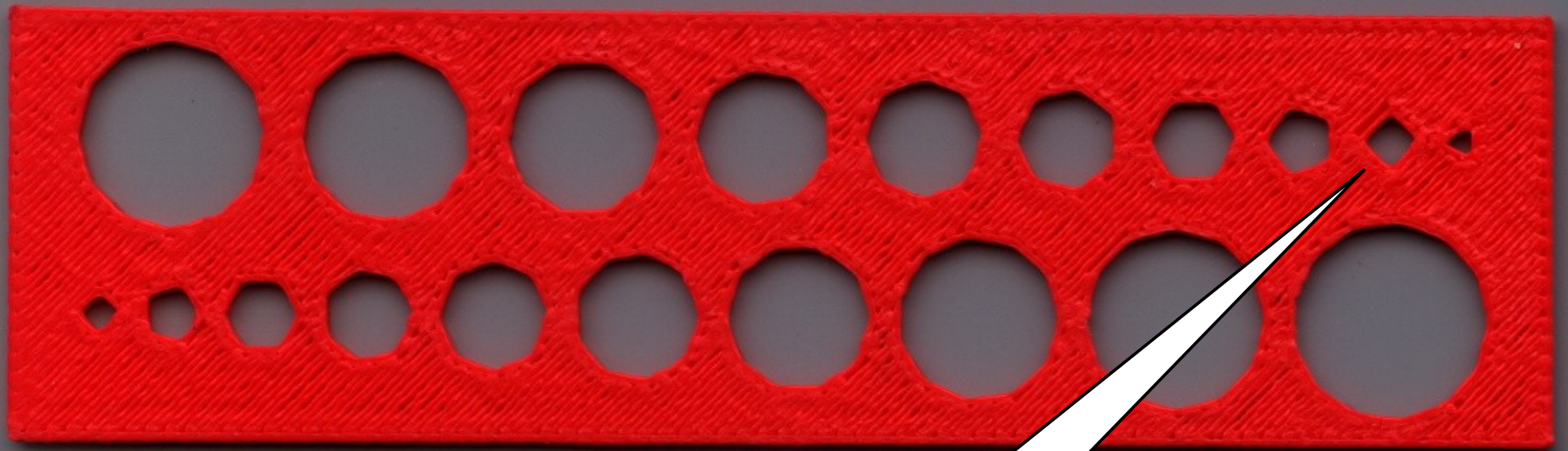
Based on Nophead's Polygonal Holes

<http://hydraraptor.blogspot.com/2011/02/polyholes.html>

Hole Size Test Piece

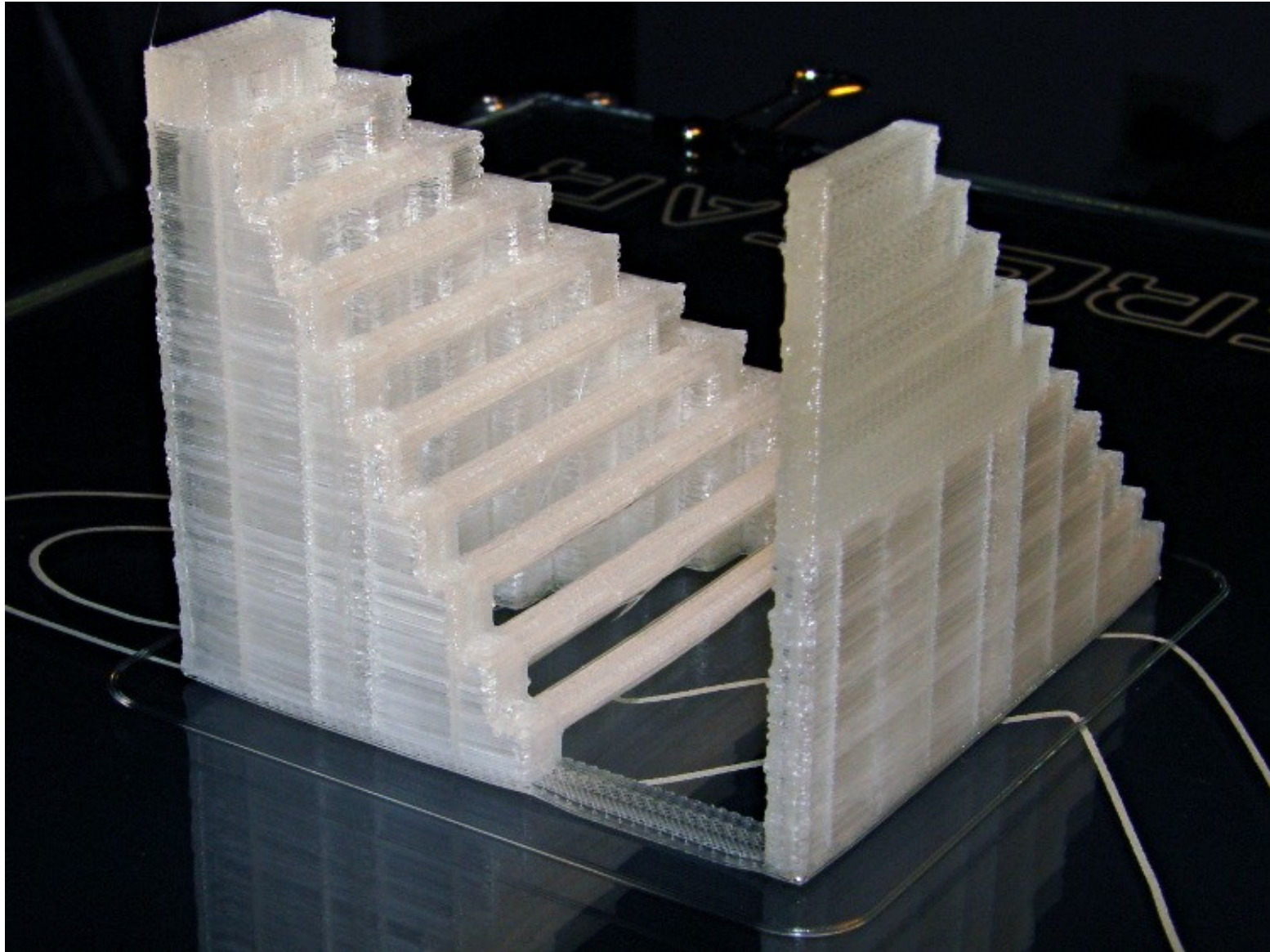


Hole Size Test Piece

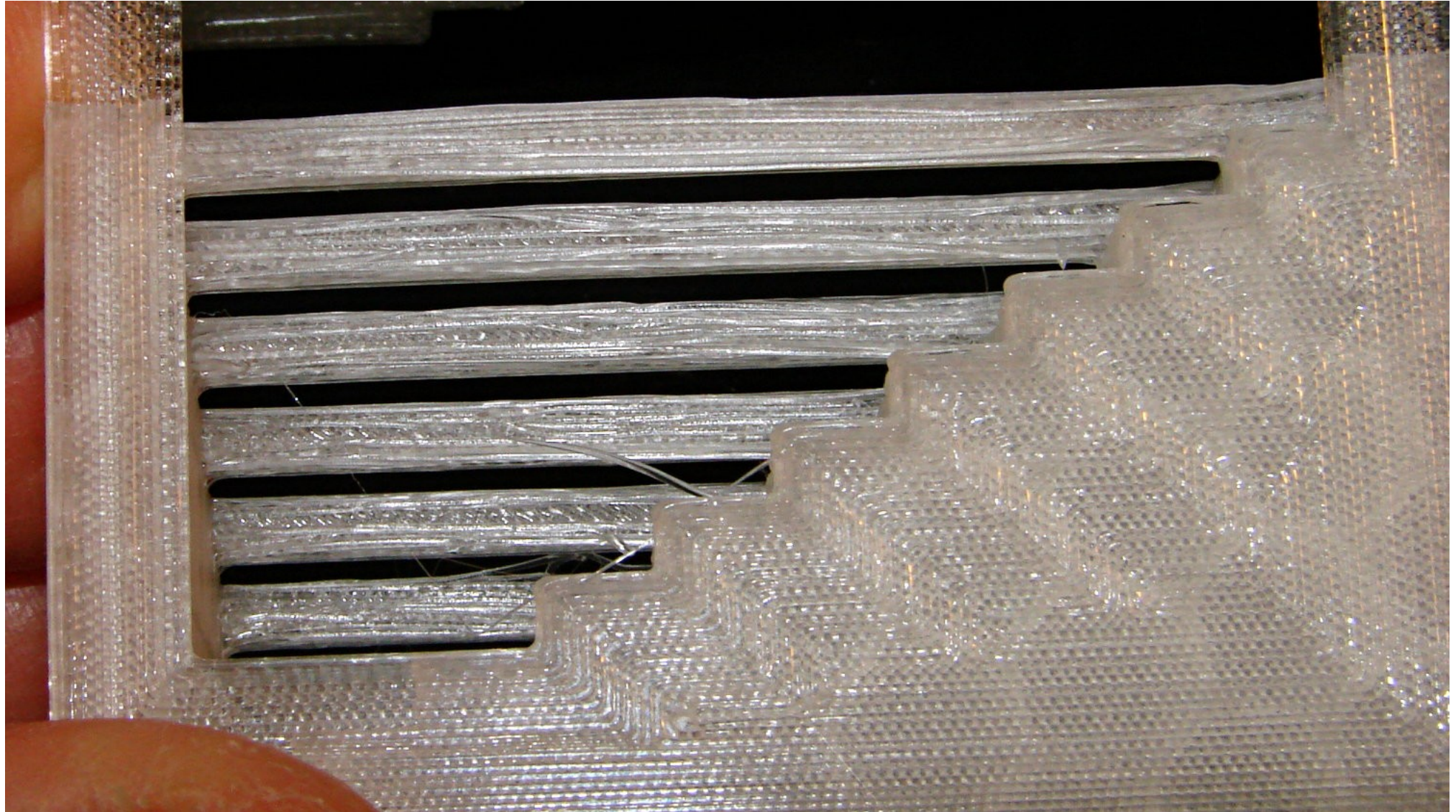


Circumscribes
original diameter

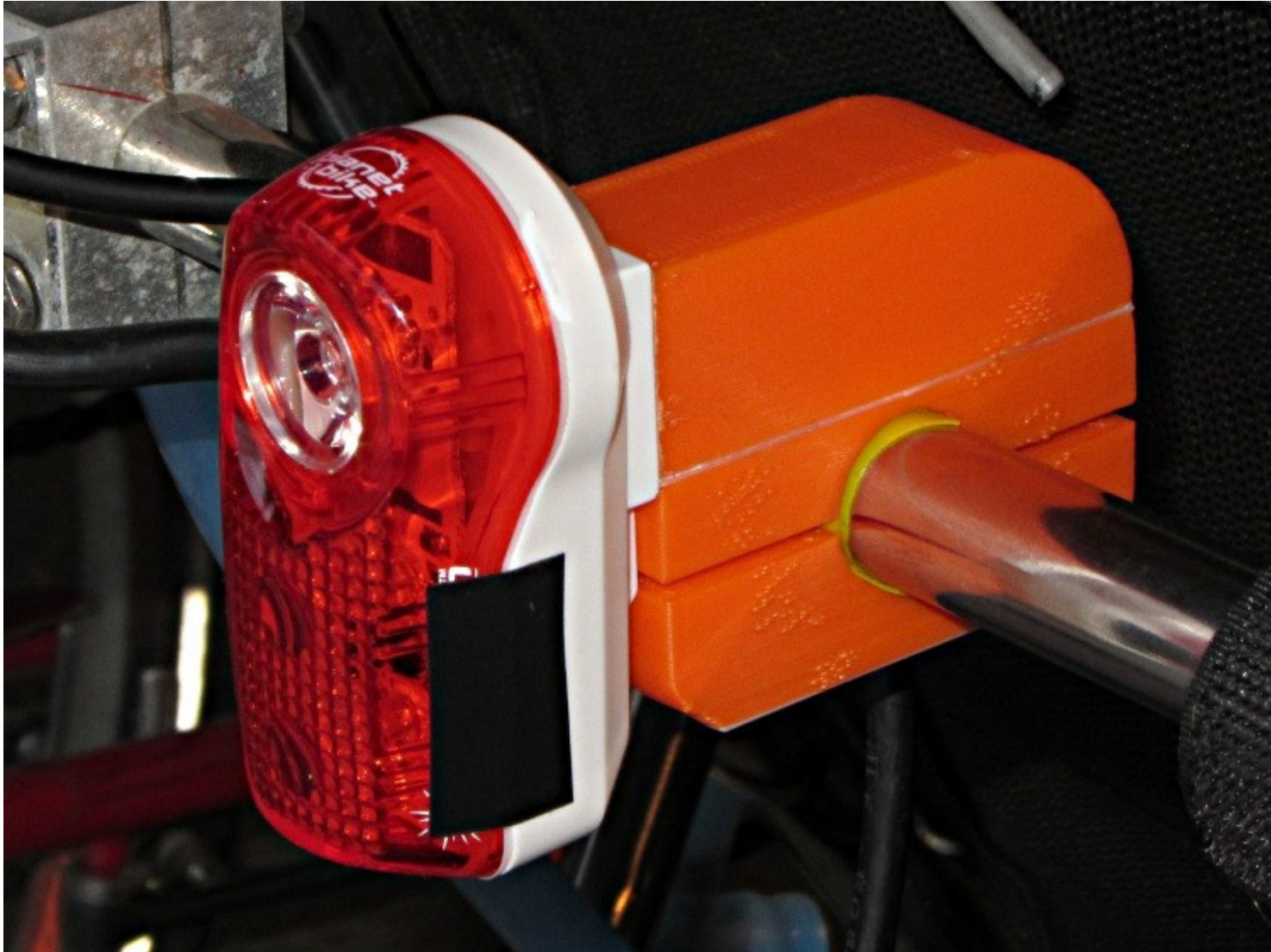
Bridge Test Piece



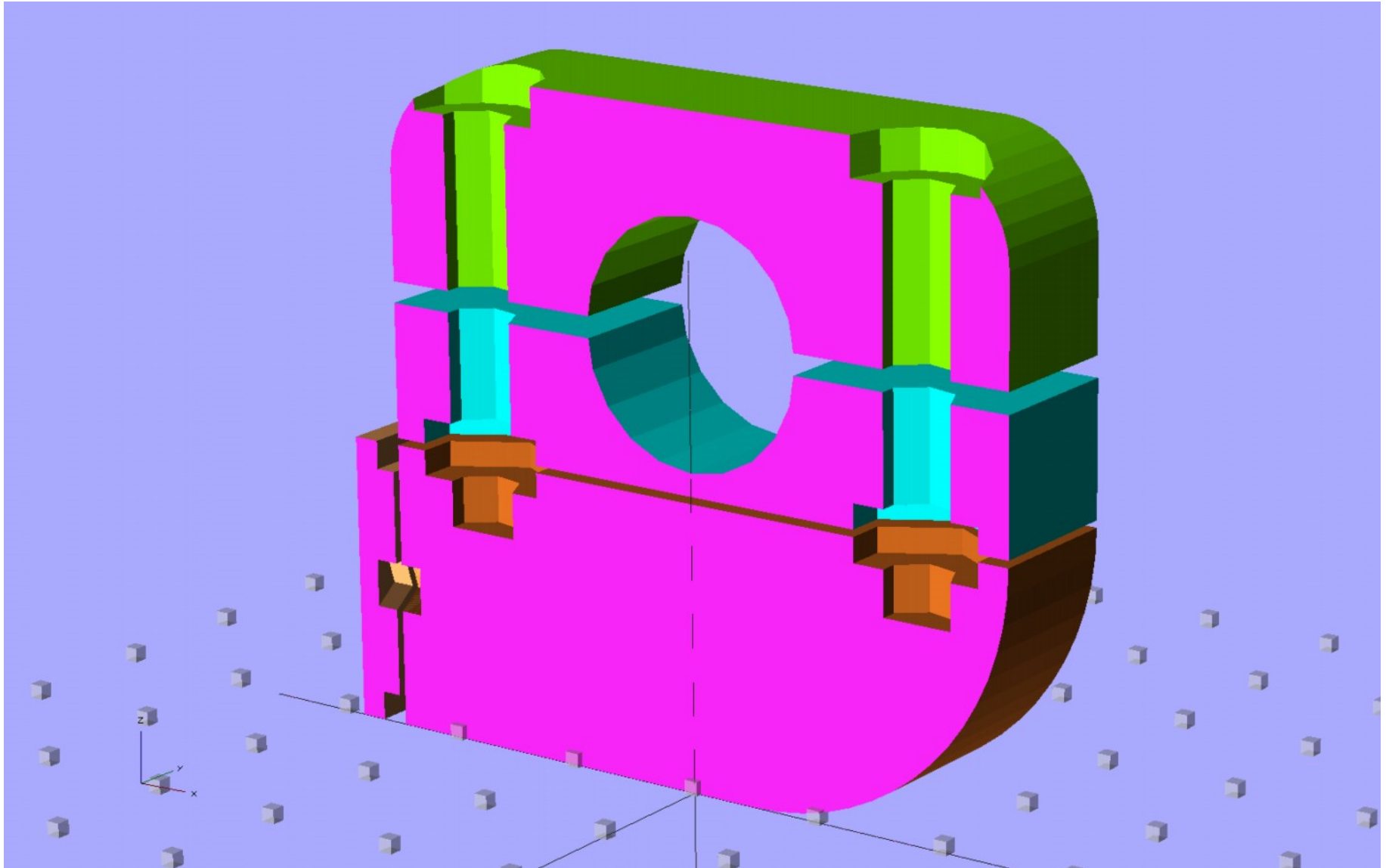
Bridge Test



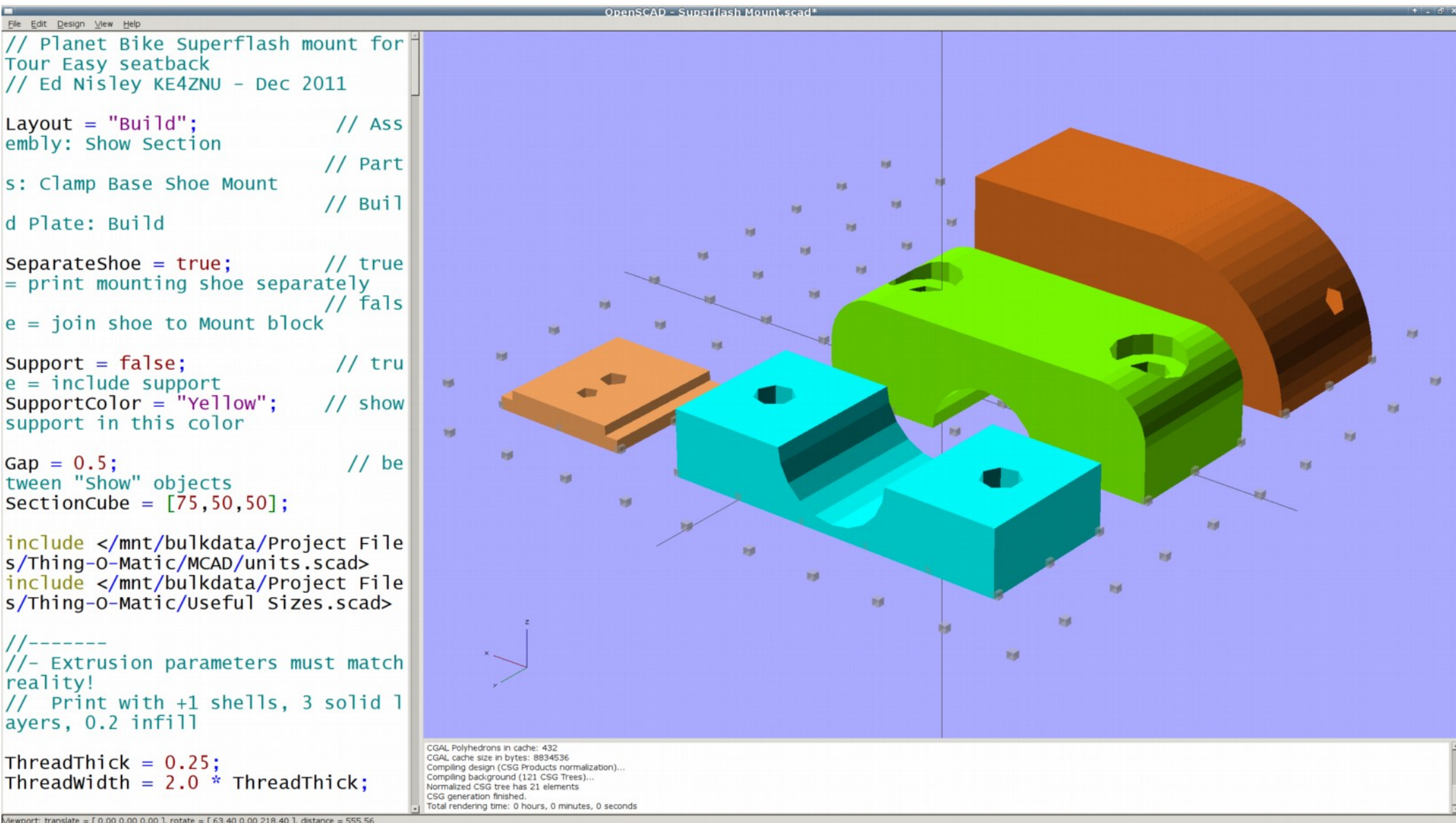
Overhang



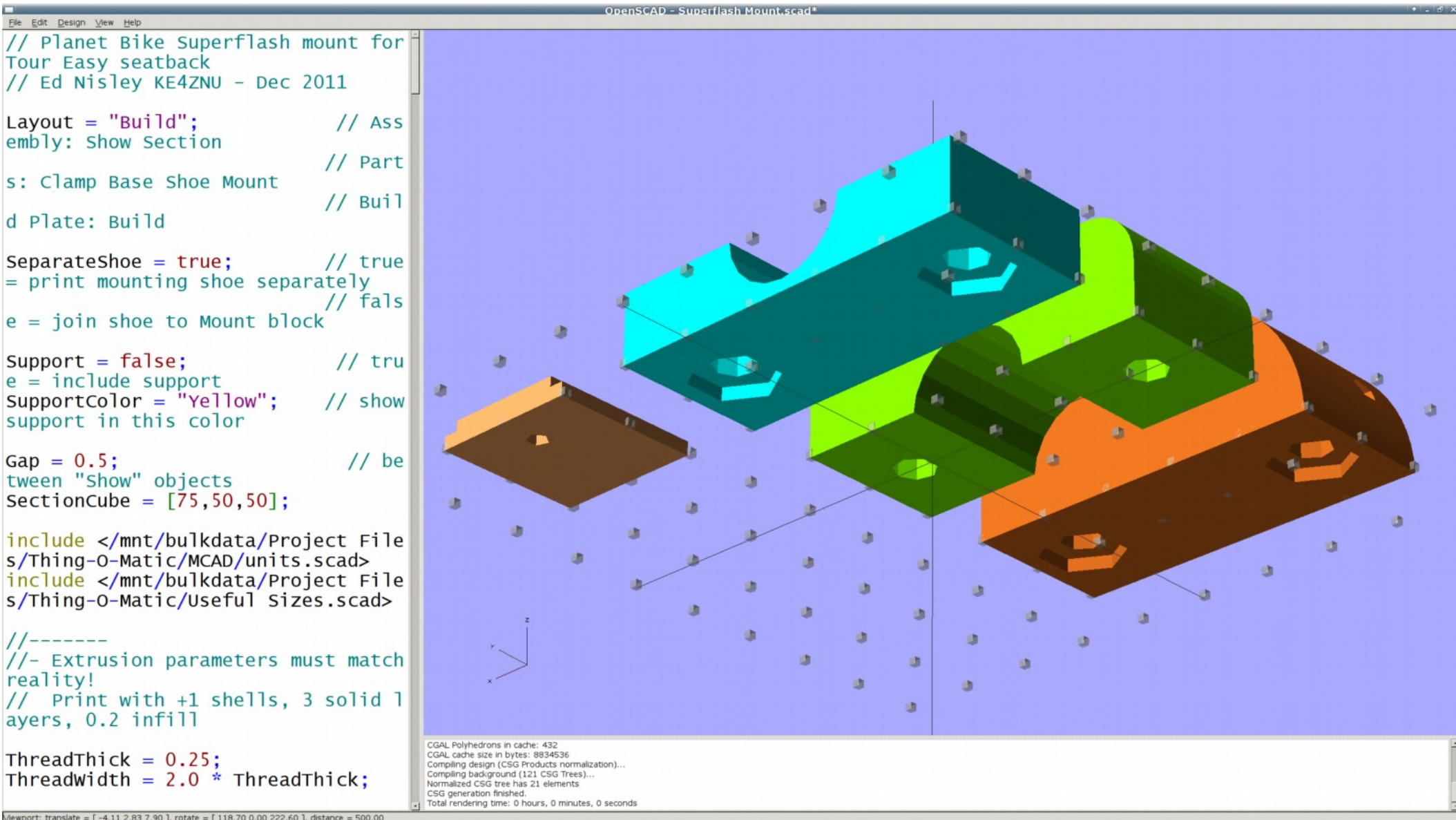
Overhang vs. Bridging



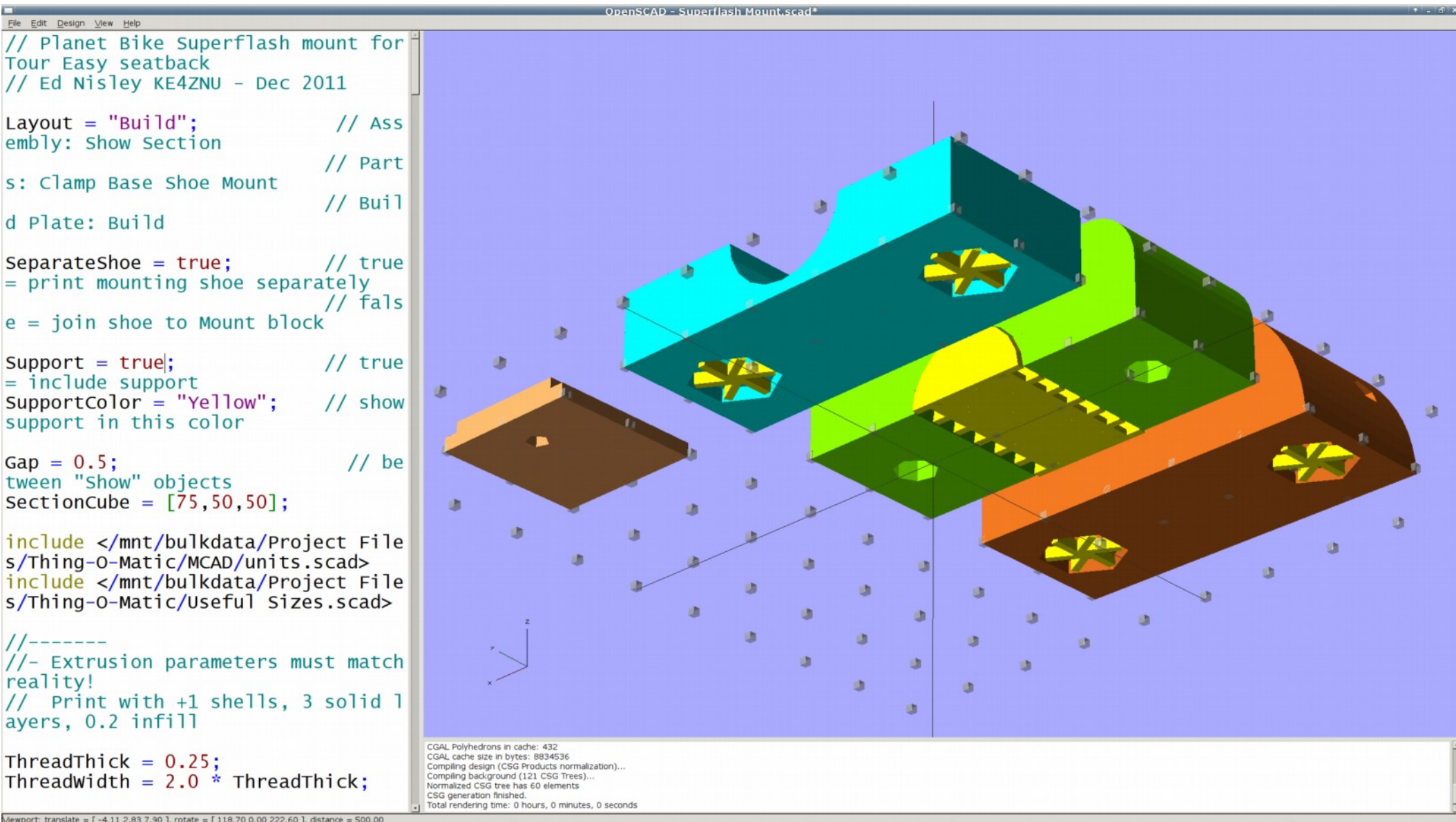
Overhang and Bridging



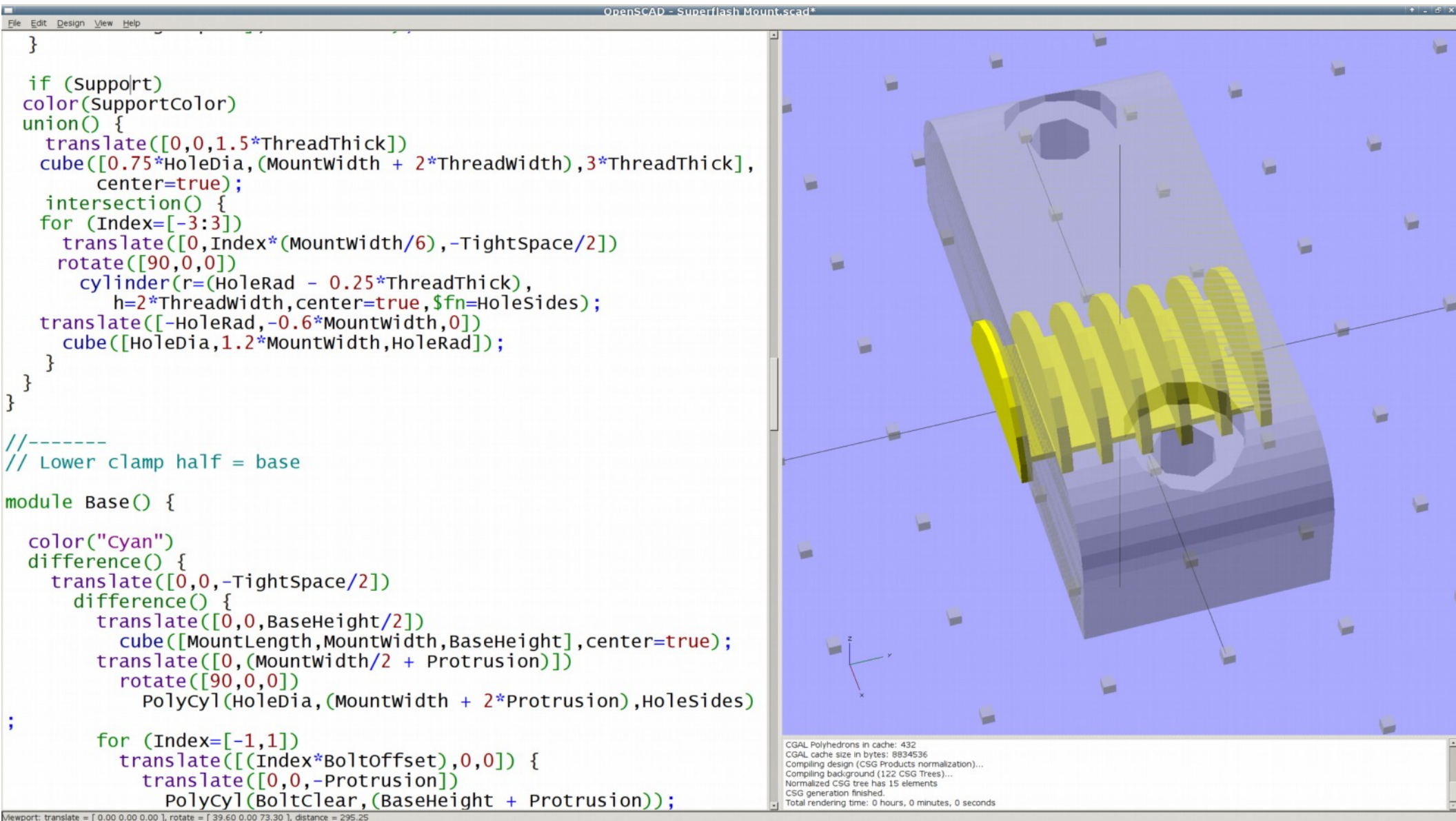
Overhang and Bridging



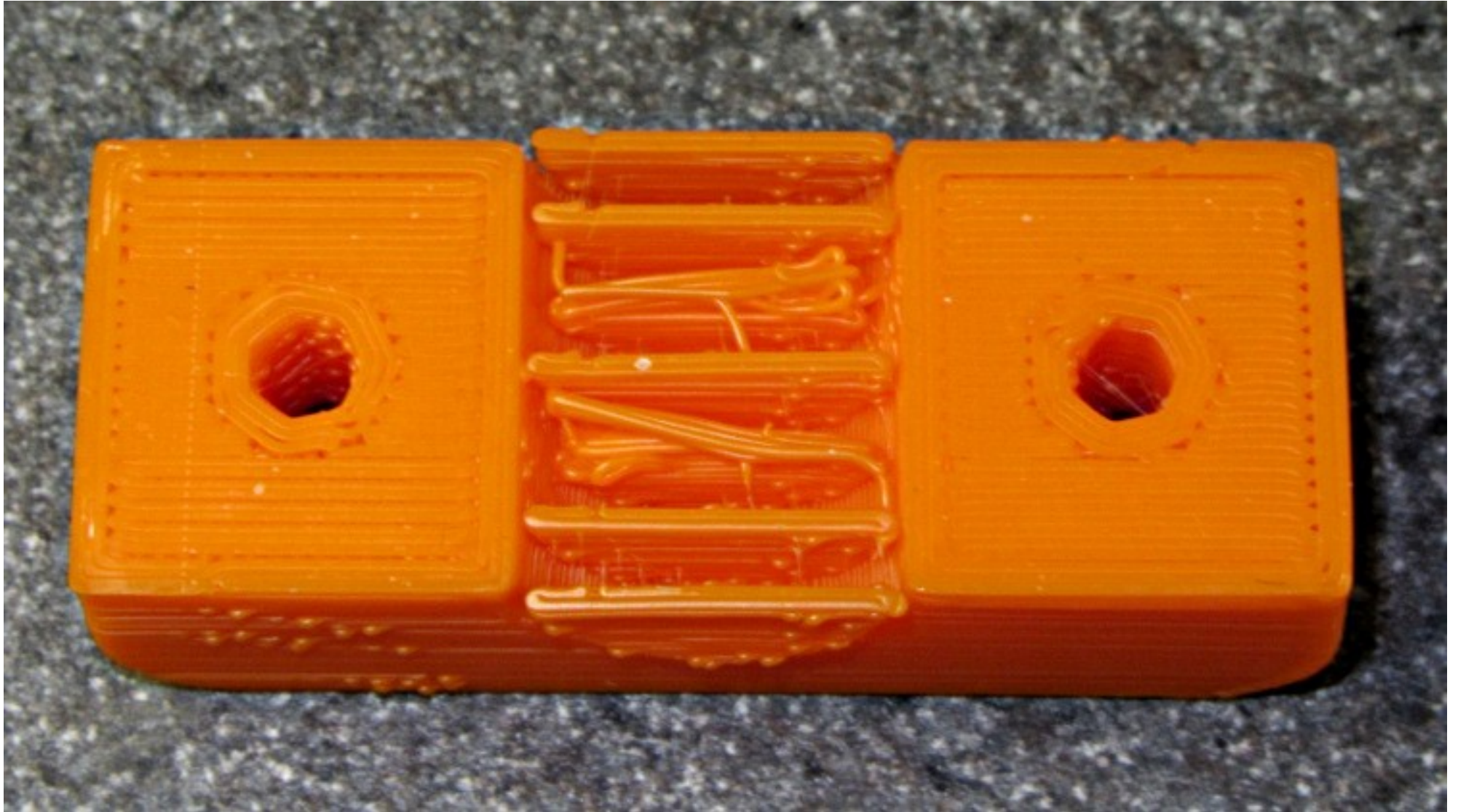
Support Structures!



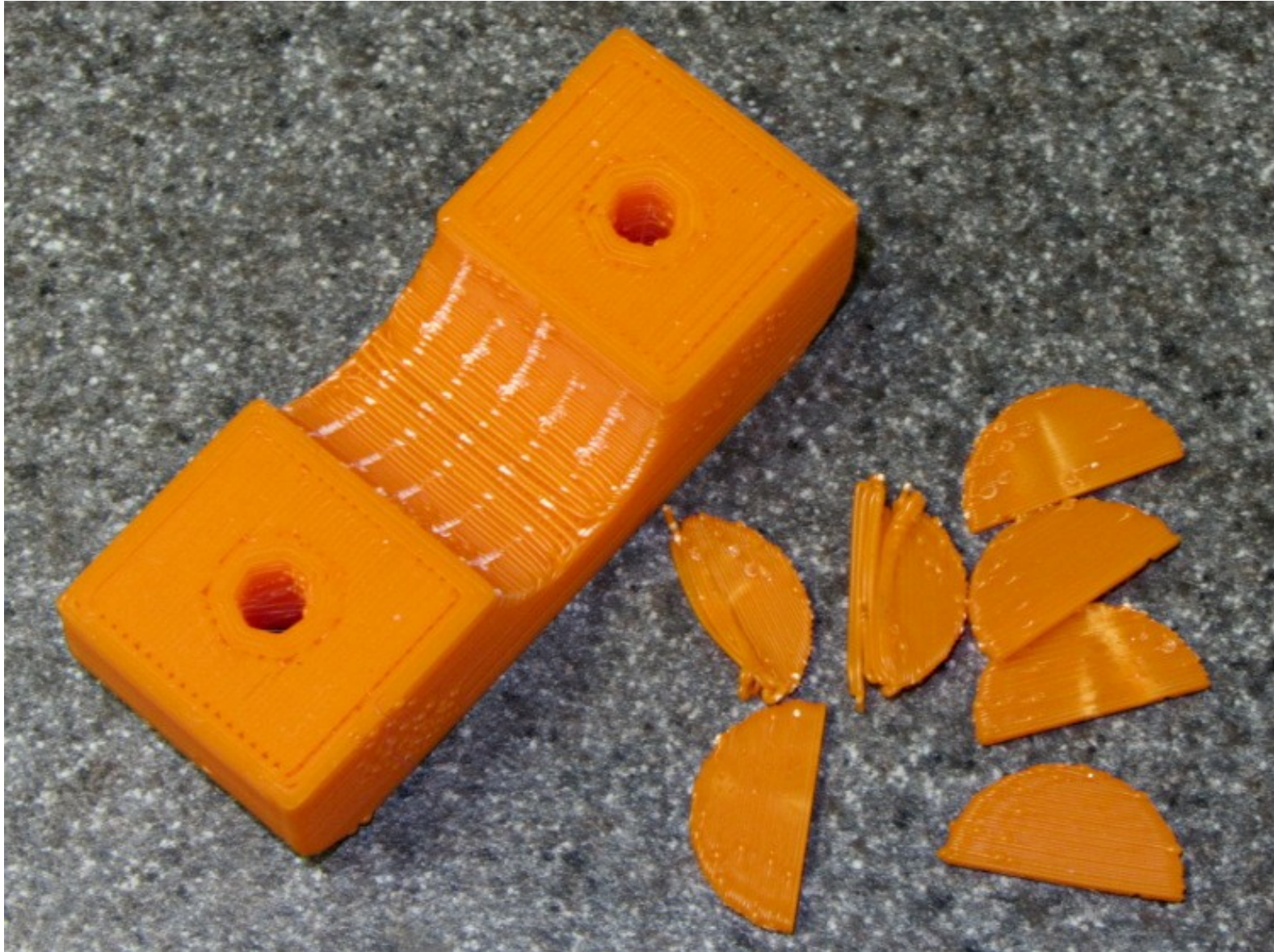
Bridge (?) Support Structure



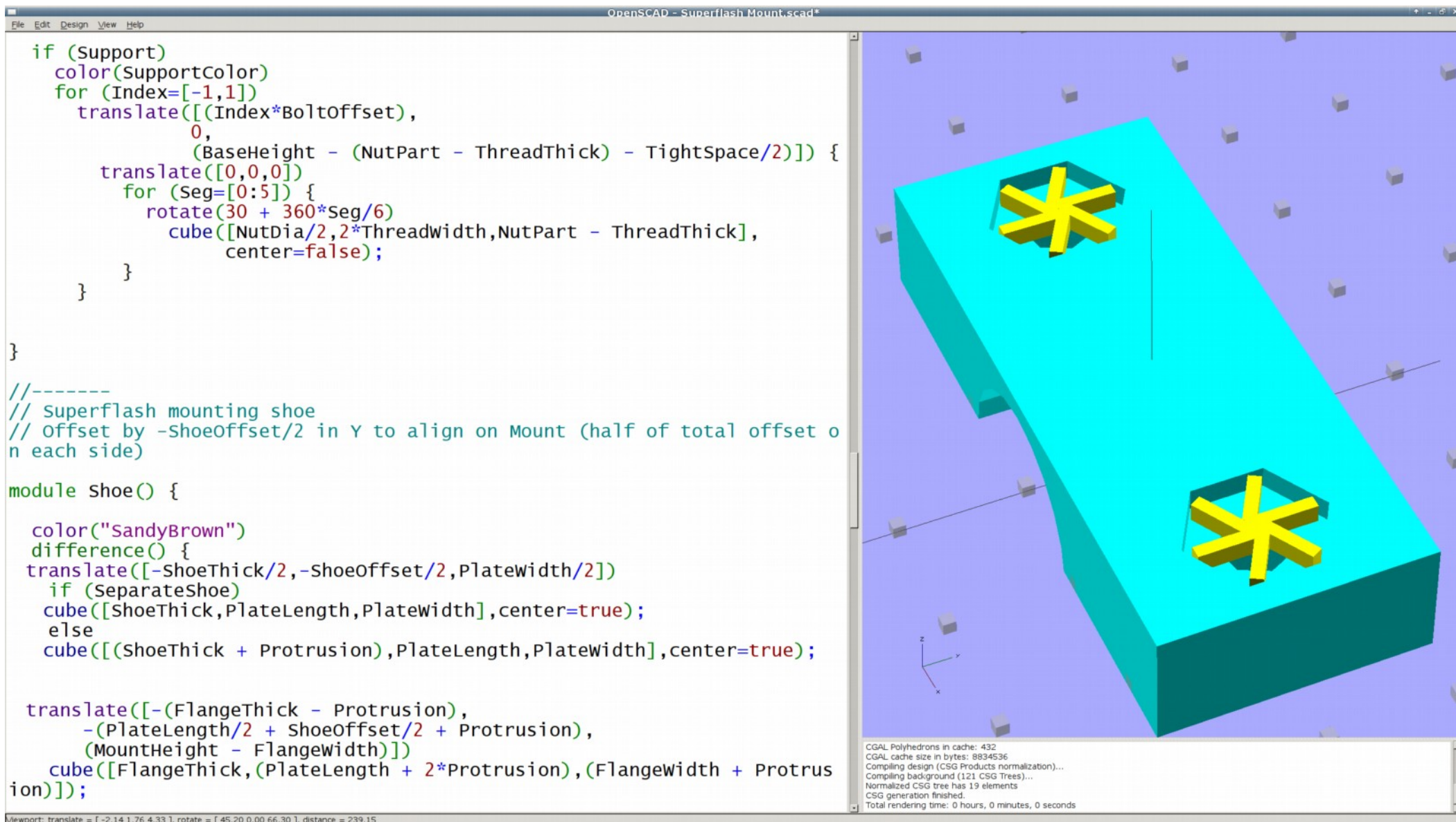
Support Structure: Oops



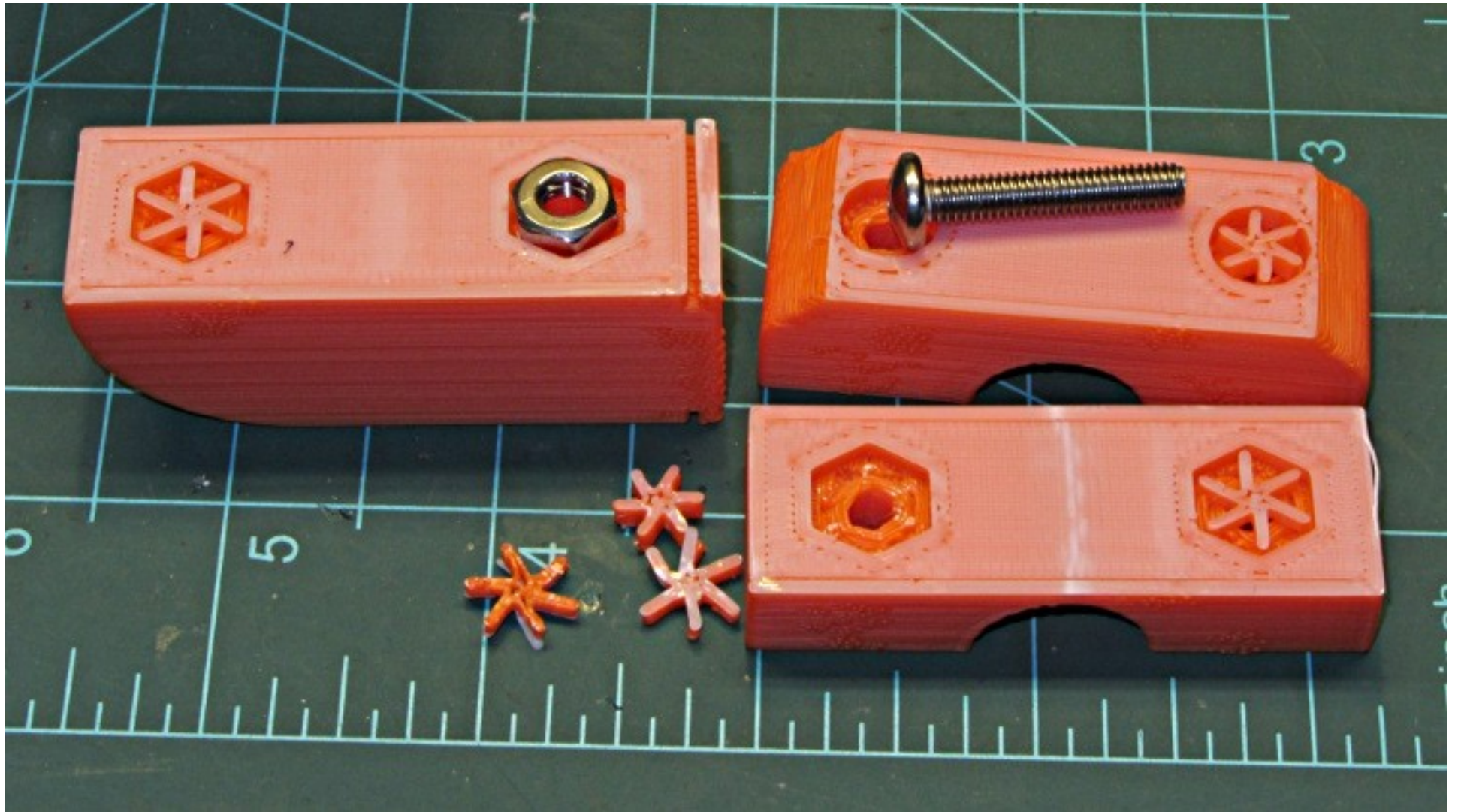
Support Structure



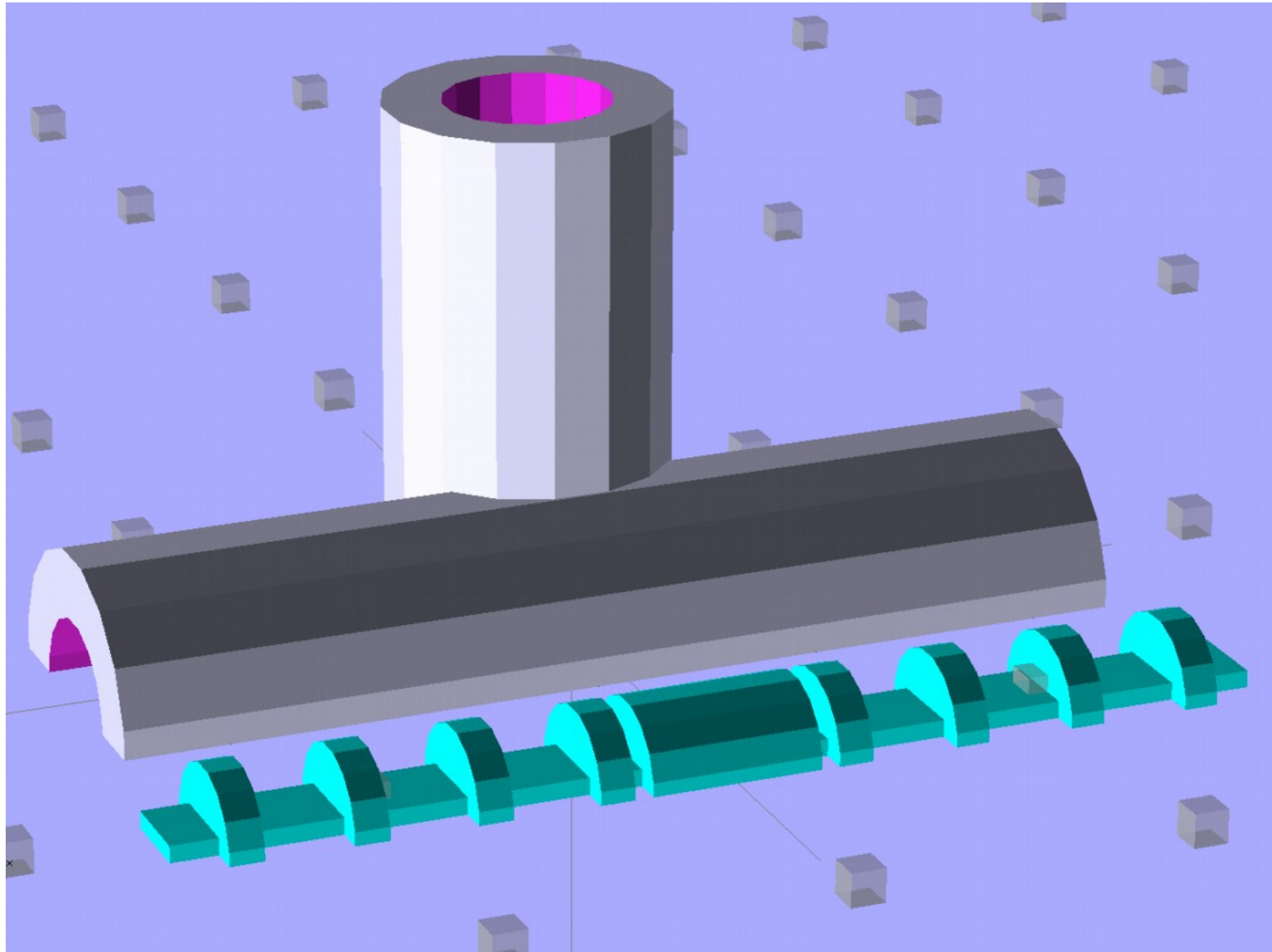
Overhang Support Structure



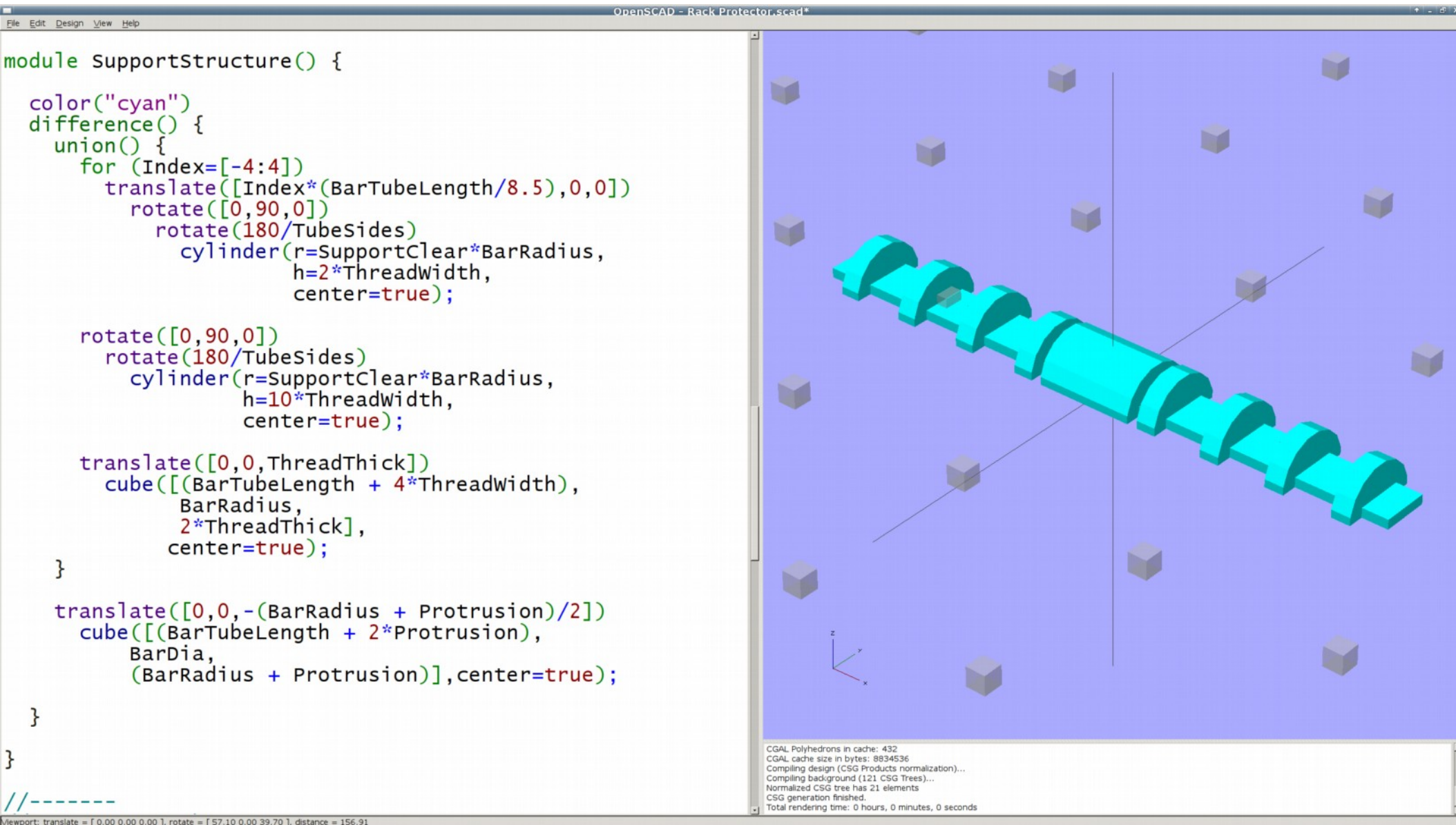
Support Structures!



Bridge (?) Support Structure



Support Structure



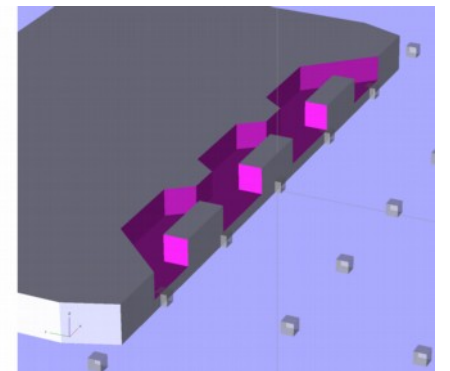
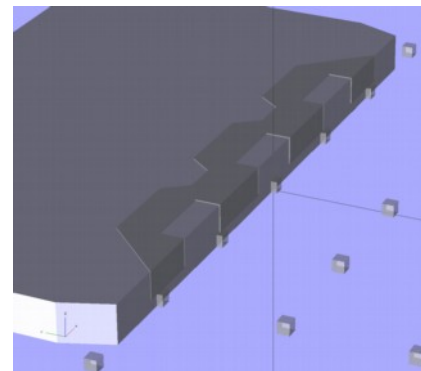
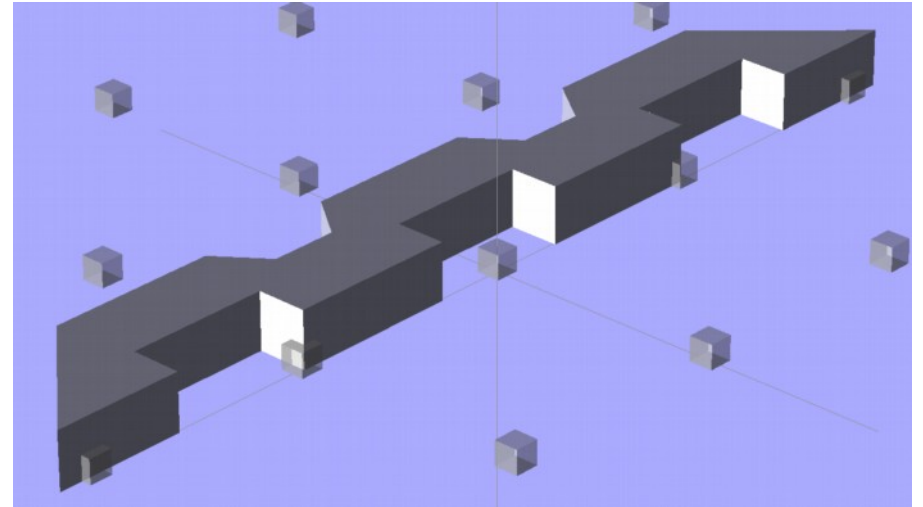
Removing Support Structures



Other Fancy Stuff

Polygons and Polyhedrons

- `polygon(...)`
 - List of points
 - `linear_extrude(...)`
- `polyhedron(...)`
 - List of points
 - List of *triangles*
- Calculate the points!
 - Internal precision
 - Direct measurement?

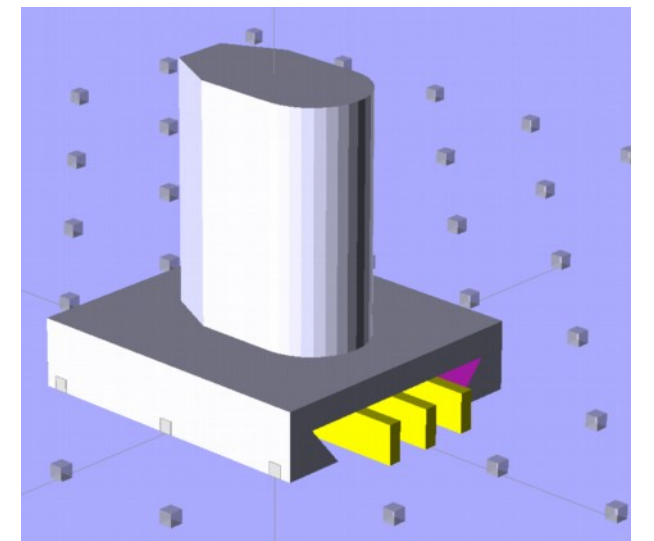
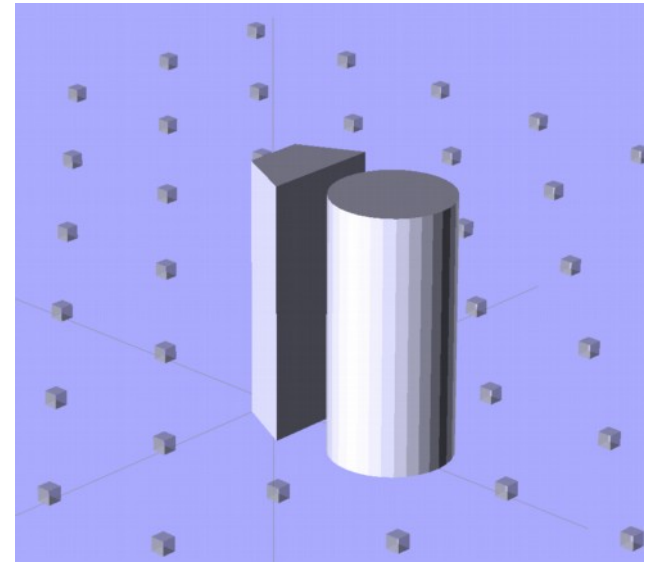


DXF Import & Export

- `import_dxf()` and `projection()`
- In theory, you can import complex diagrams
- In practice, it's *very* fussy about content
- Good luck...

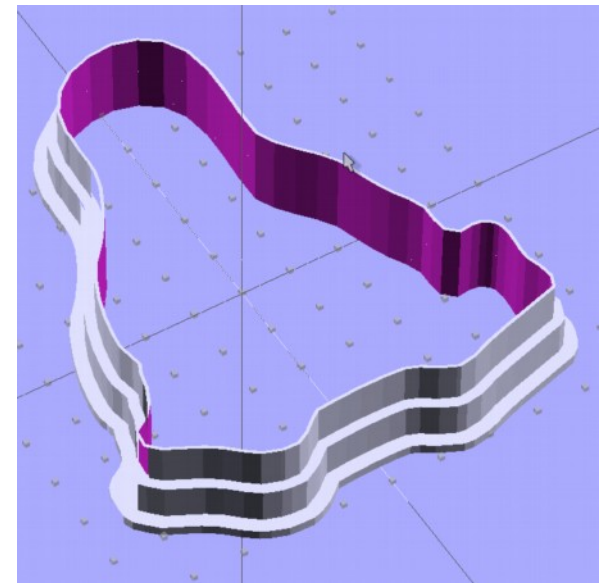
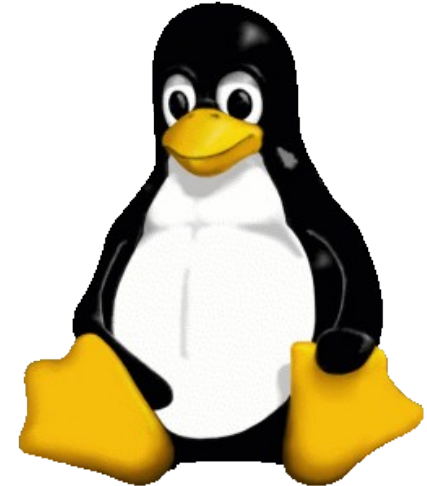
Hull

- `hull(...)`
 - 2D figures in XY
 - `polygon()`
 - `Circle()`, `square()`
 - `linear_extrude(...)`



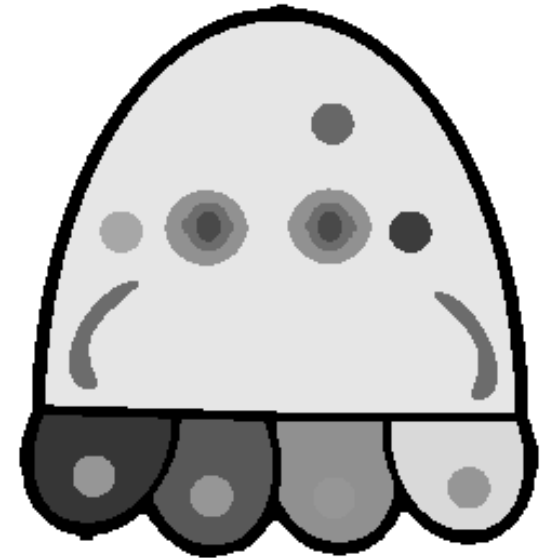
Outlines From Drawings

- Perimeter → Shape
 - Start from EPS
 - Limited resolution
 - Maintain chirality
- A simple matter of software
 - **Imagemagick** FTW!
 - **minkowski()** sum



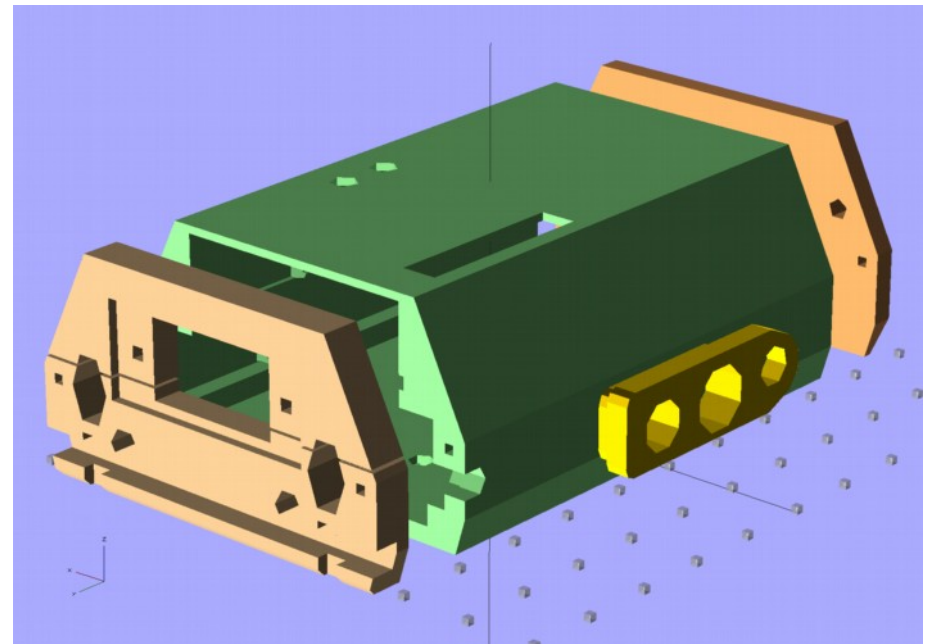
Surface Height Maps

- `surface(file=...)`
 - Very specific file format
- 8 bit grayscale $\rightarrow$ Z height
 - Yes, 256 Shades of Grey...
- A simple matter of software
 - `Imagemagick` FTW!
 - Bash scripting
 - XY resolution limit



Finally ...

- Start simple
 - Keep it simple
- Math is your friend
 - Measurements!
 - Calculate *everything*
- Slice & Verify G-Code
 - That's another talk...
 - *Always* verify before printing
- Build Stuff You Need!



More Info

reprap.org
www.openscad.org

My *Along the G-Code Way* column
In [Digital Machinist](#) magazine

And, of course...
softsolder.com

Copyright-ish Stuff

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[whatever that is]

The rest is my own work



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or send a letter to

Creative Commons, 543 Howard Street, 5th Floor
San Francisco, California, 94105, USA.



Ed Nisley

Say “NISS-lee”, although we're on the half-essed branch of the tree

Engineer (ex PE), Hardware Hacker, Programmer, Author

The Embedded PC's ISA Bus: Firmware, Gadgets, Practical Tricks

Circuit Cellar www.circuitcellar.com

Firmware Furnace (1988-1996) - Nasty, grubby hardware bashing

Above the Ground Plane (2001 ...) - Analog and RF stuff

Digital Machinist www.homeshopmachinist.net

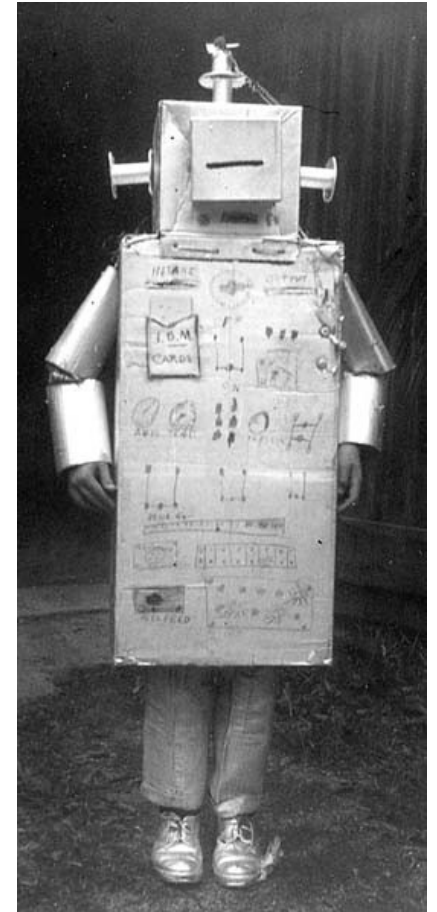
Along the G-Code Way (2008 ...) - G-Code, math, 3D printing

Dr. Dobb's Journal www.ddj.com

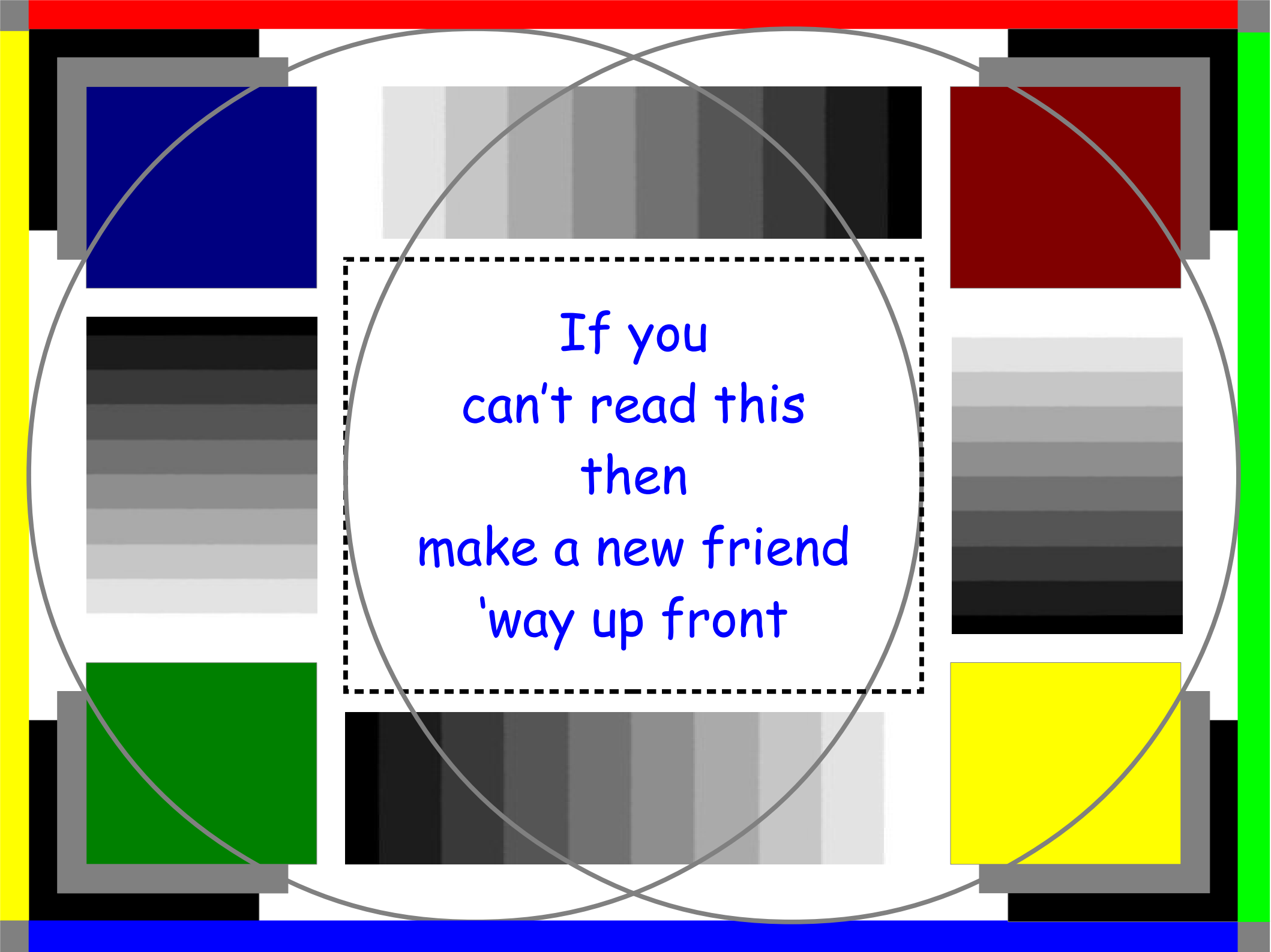
Embedded Space (2001-2006) - All things embedded

Nisley's Notebook (2006-2007) - Hardware & software collisions

My Blog: The Smell of Molten Projects in the Morning
softsolder.com



September 1962



If you
can't read this
then
make a new friend
'way up front