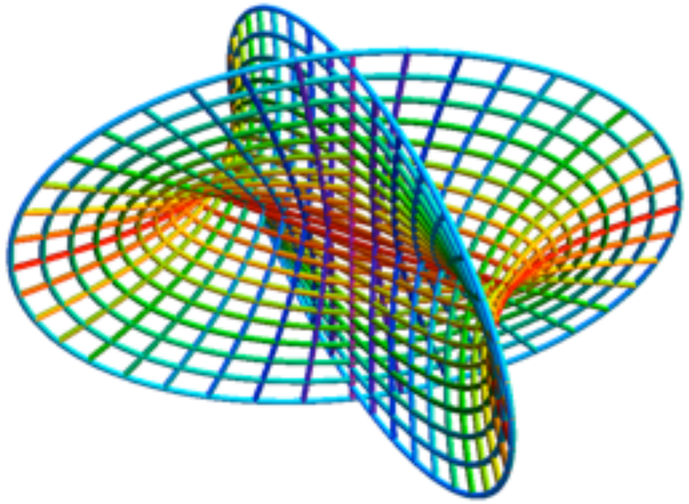
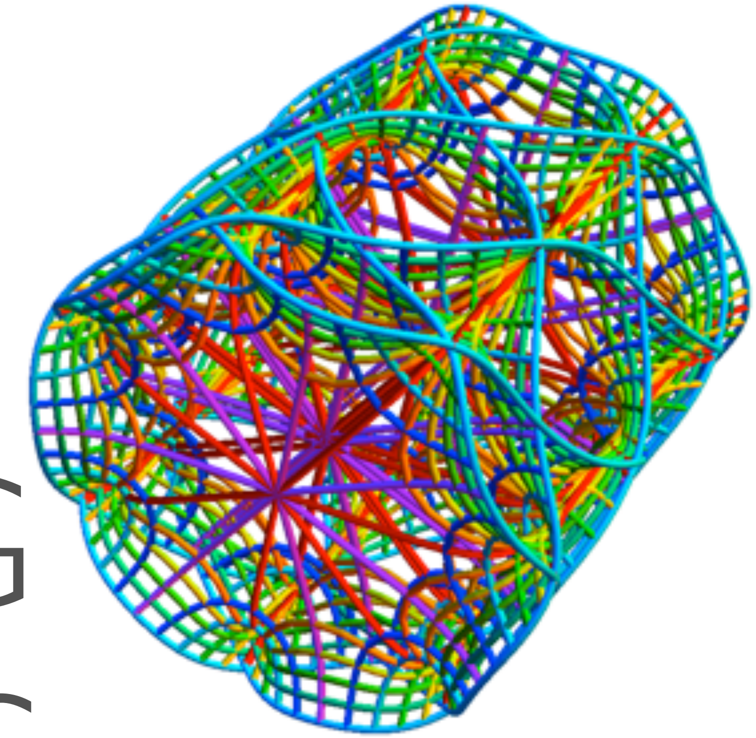
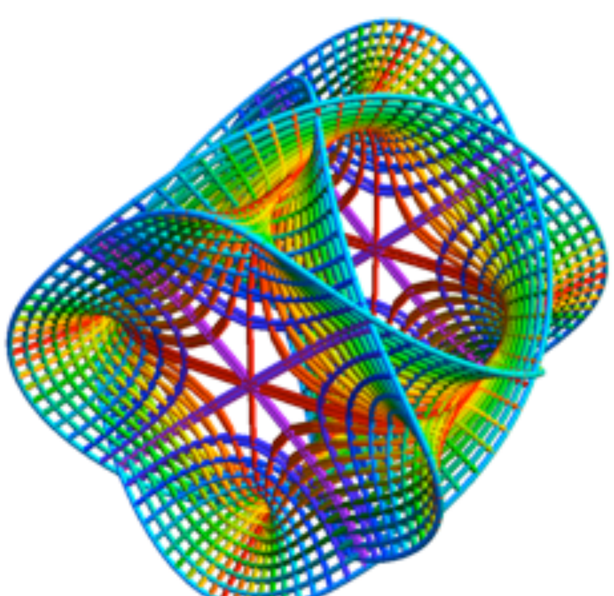


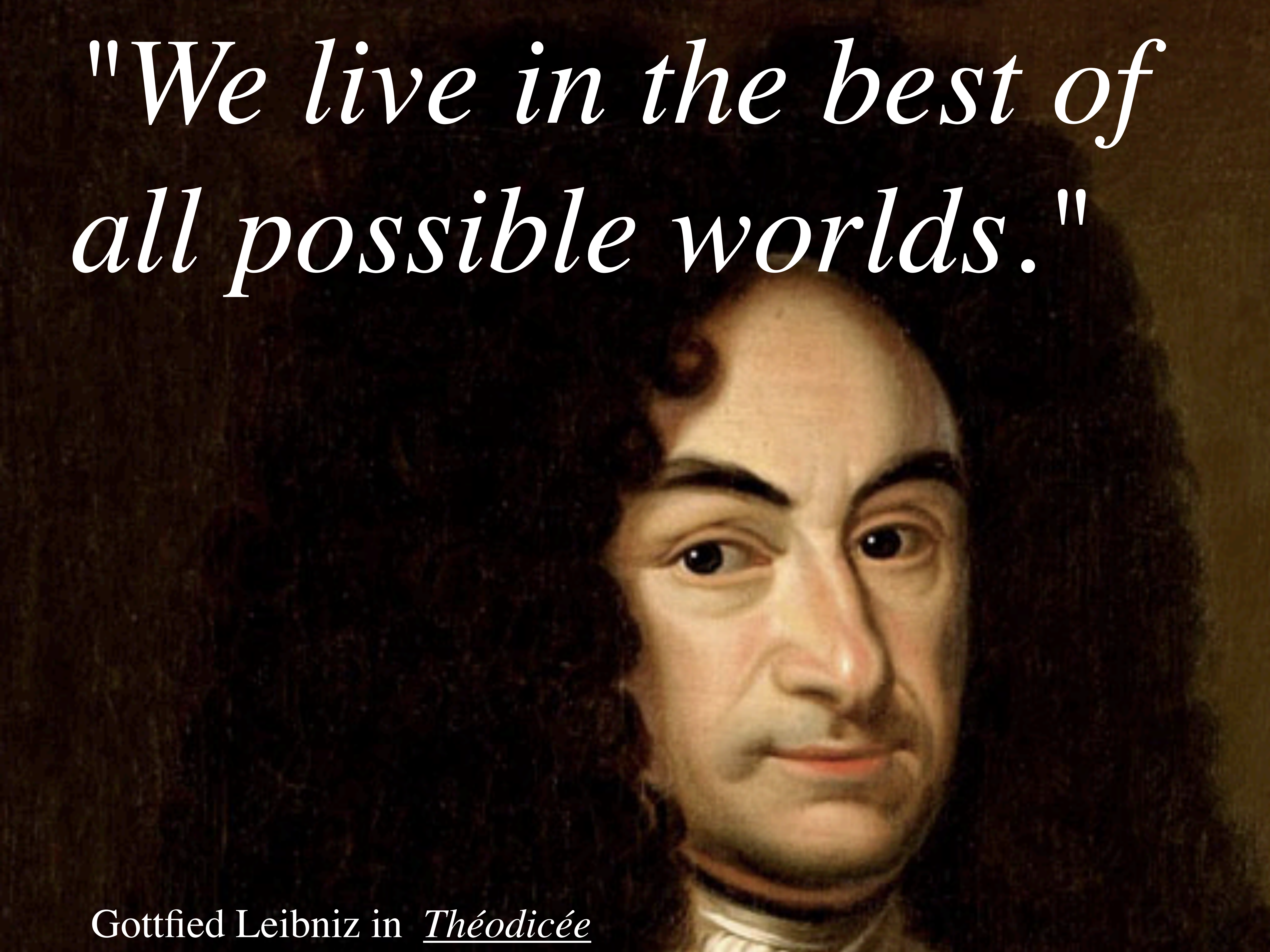


ILLUSTRATING MATHEMATICS USING 3D PRINTERS



Oliver Knill
Harvard University
Elizabeth Slavkovsky

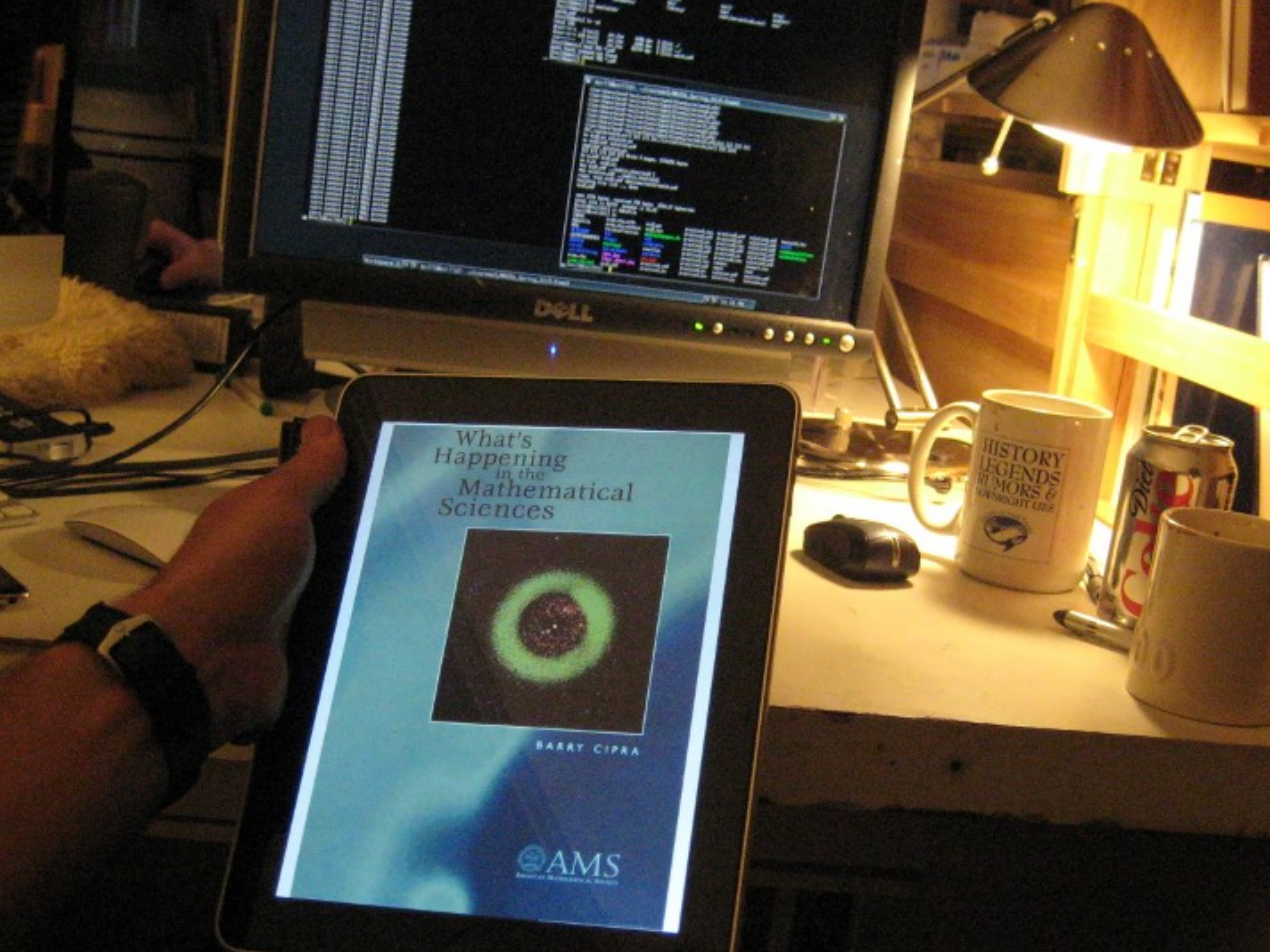
May 6, Trieste, 2013

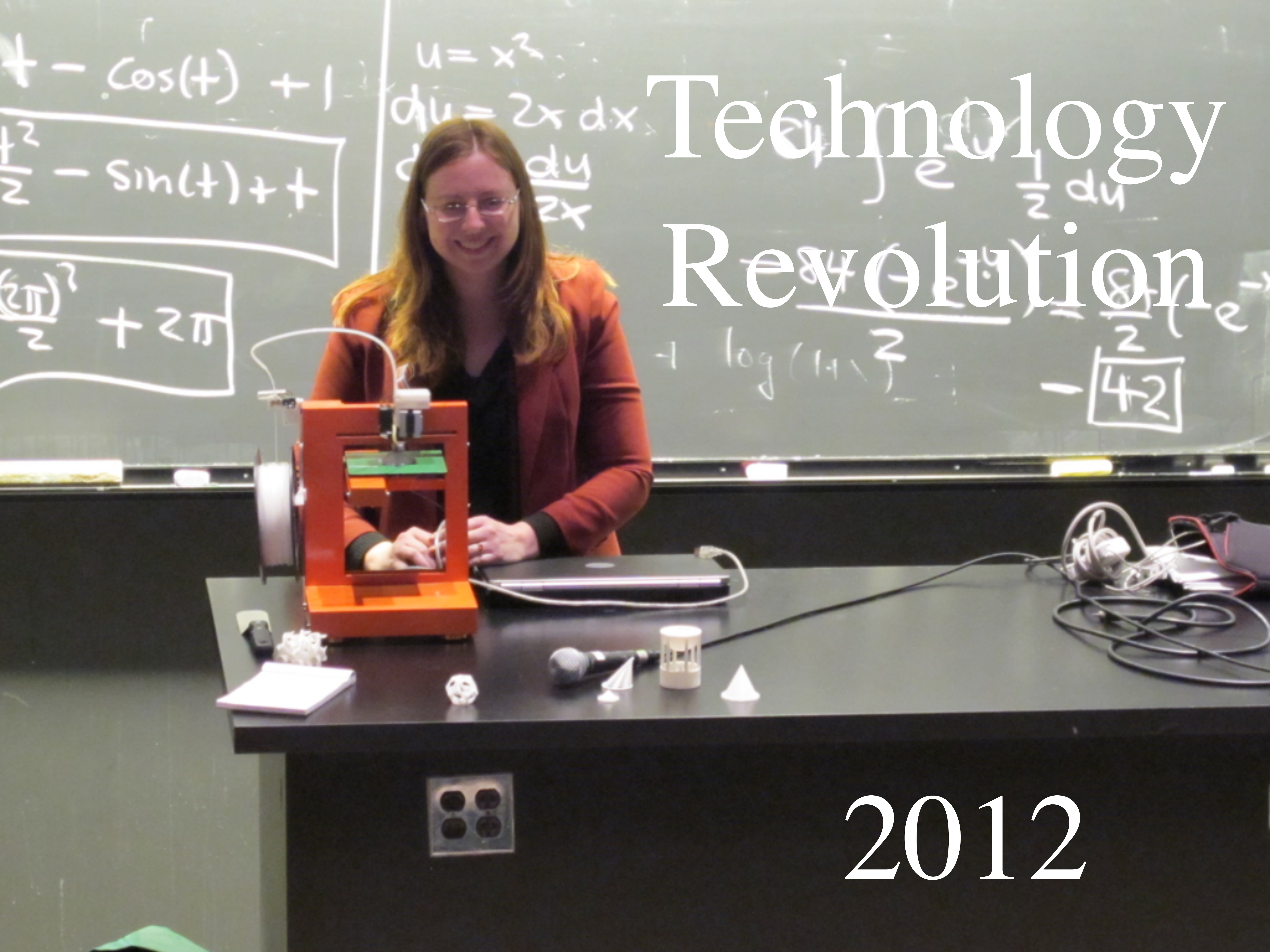

"We live in the best of all possible worlds."
Gottfied Leibniz in Théodicée

We seem to
live also in the
best of all
possible times!

Why? We experience several exciting revolutions at once.


Linear Algebra
2010
Information
Revolution


What's Happening in the Mathematical Sciences
BARRY CIPRA
AMS
DELL
HISTORY
LEGENDS
RUMORS &
Diet

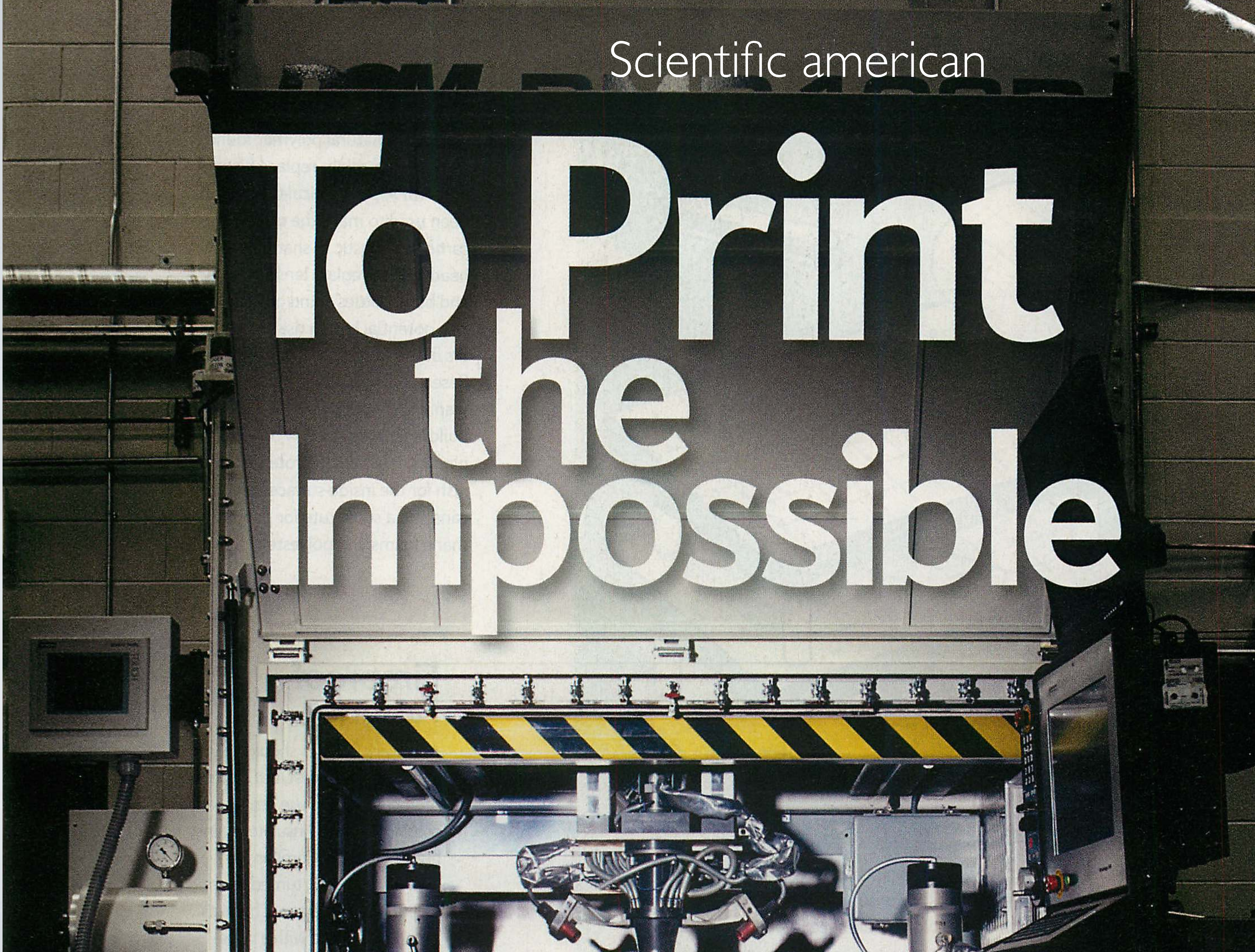

Technology
Revolution
2012

Liz has
just won a
prize for her
work!


BIOLOGY
PHYSICS
CALCULUS

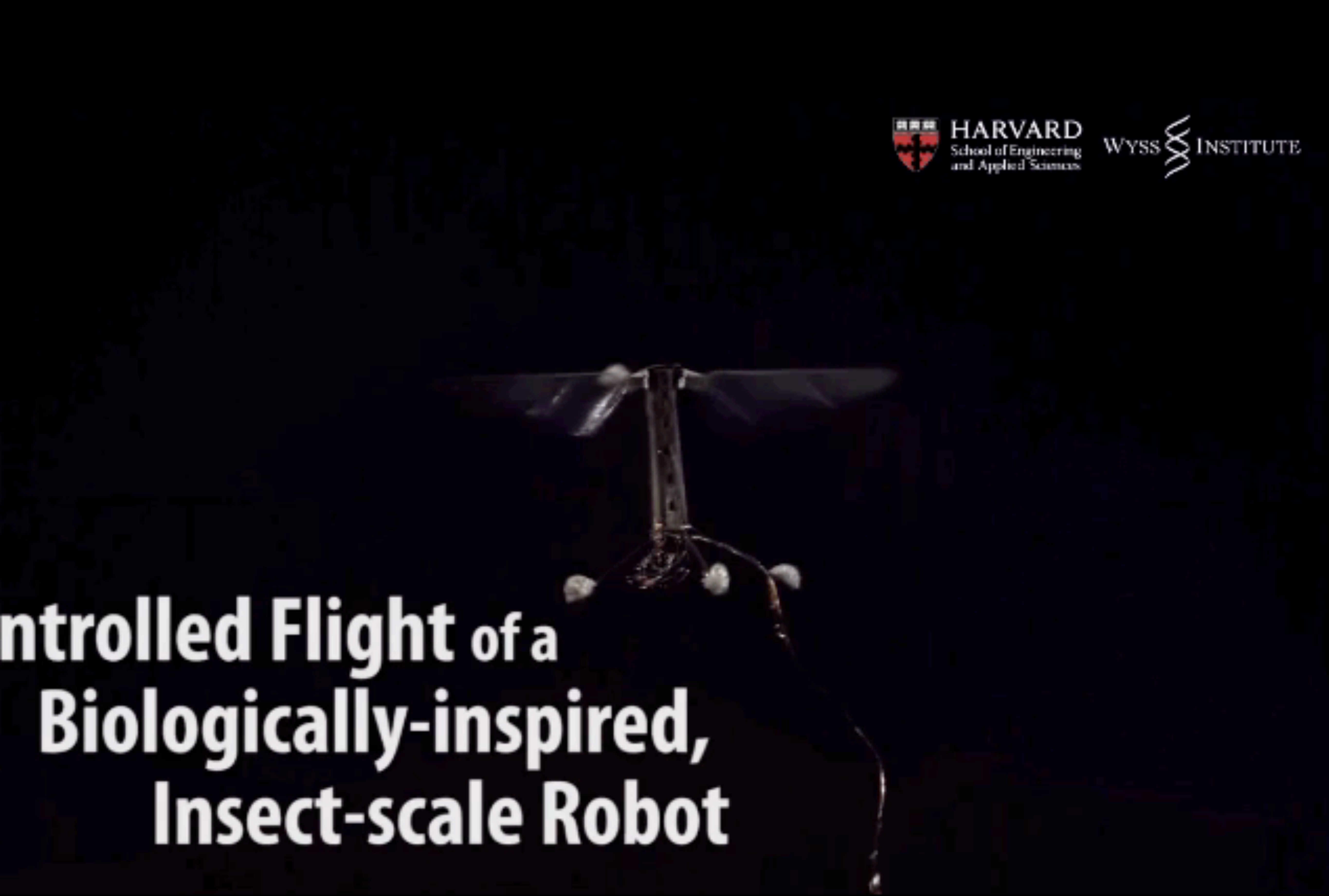
3D printing in the news. Examples from last couple of days:

To Print the Impossible

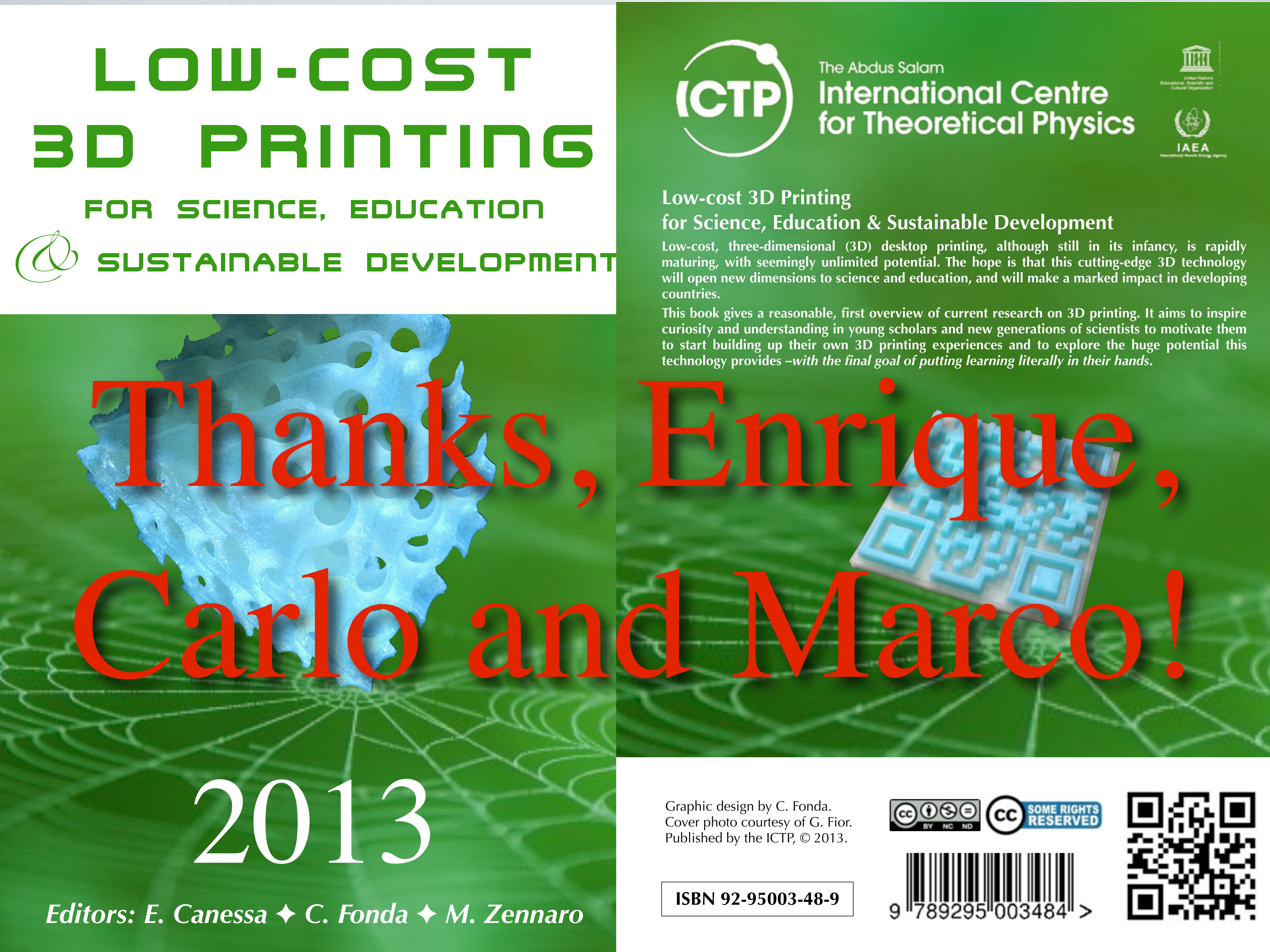



National Geographic


Revolutions
Everywhere
Harvard Bee
2013
UNITED STATES OF AMERICA
E PLURIBUS UNUM
ONE CENT

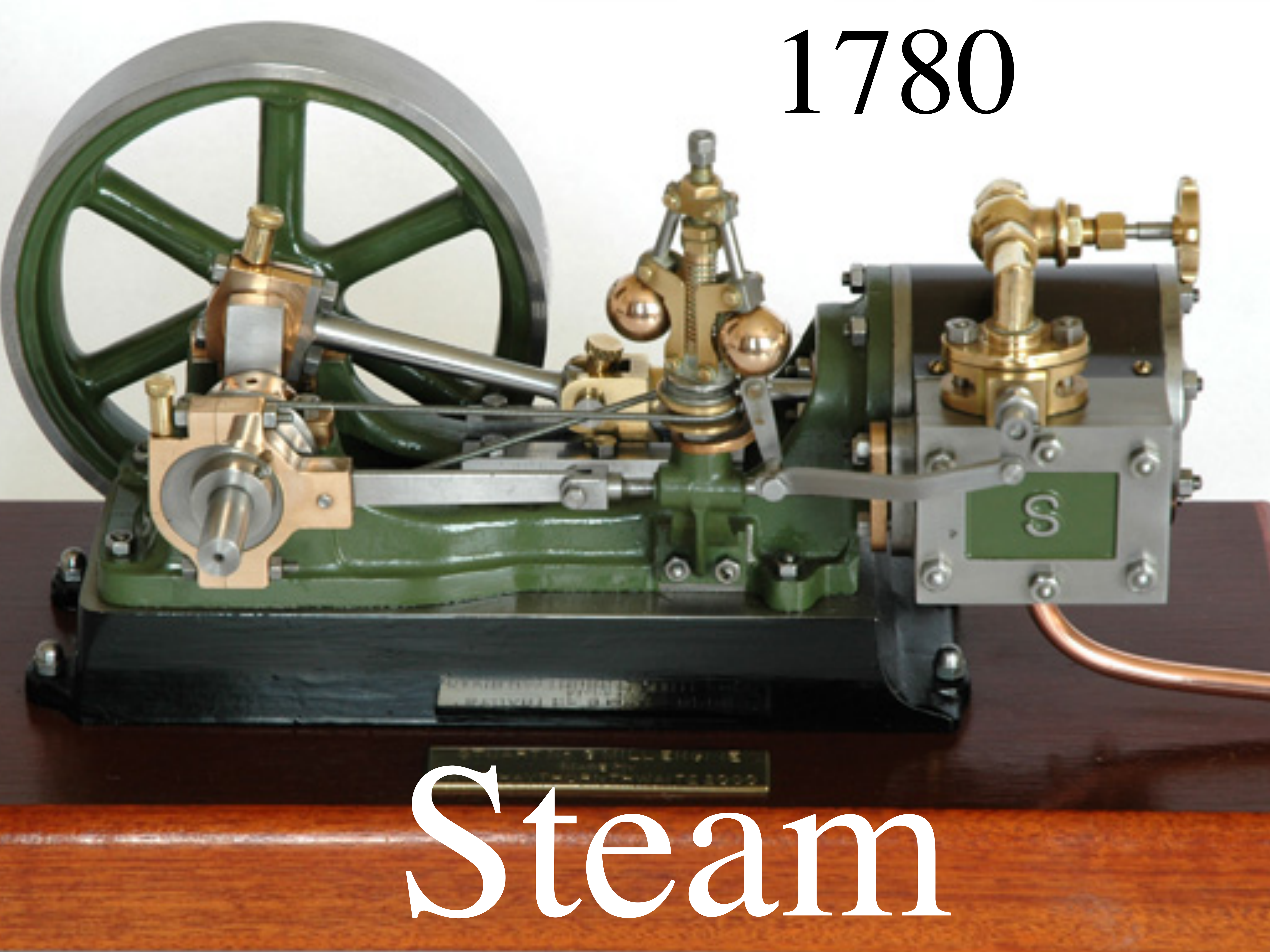

HARVARD
School of Engineering and Applied Sciences
WYSS INSTITUTE
ntrolled Flight of a
Biologically-inspired,
Insect-scale Robot

And of course:



LOW-COST
3D PRINTING
FOR SCIENCE, EDUCATION
& SUSTAINABLE DEVELOPMENT
Thanks, Enrique, Carlo and Marco!
2013
Editors: E. Canessa ✦ C. Fonda ✦ M. Zennaro
ICTP
The Abdus Salam
International Centre
for Theoretical Physics
IAEA
Low-cost 3D Printing
for Science, Education & Sustainable Development
Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly maturing, with seemingly unlimited potential. The hope is that this cutting-edge 3D technology will open new dimensions to science and education, and will make a marked impact in developing countries.
This book gives a reasonable, first overview of current research on 3D printing. It aims to inspire curiosity and understanding in young scholars and new generations of scientists to motivate them to start building up their own 3D printing experiences and to explore the huge potential this technology provides –with the final goal of putting learning literally in their hands.
Graphic design by C. Fonda.
Cover photo courtesy of G. Fior.
Published by the ICTP, © 2013.
SOME RIGHTS RESERVED
ISBN 92-95003-48-9
9 789295 003484 >

Industrial Revolutions

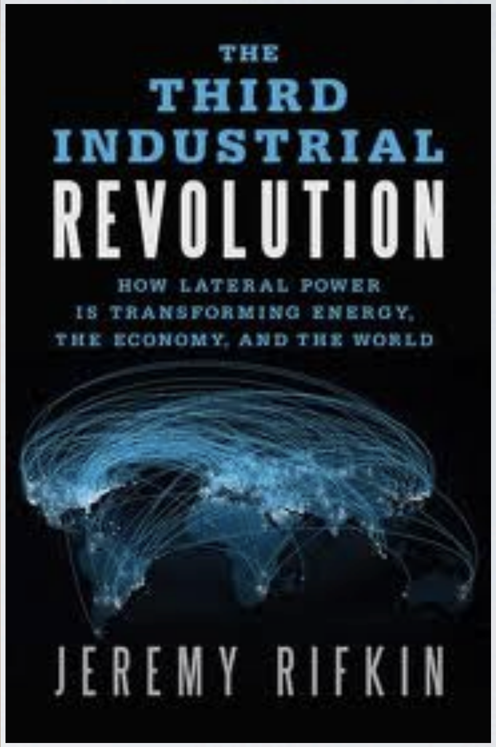

1780
Steam
S


1880
Steel


1980
Stars
Nasa: Horsehead

INDUSTRIAL REVOLUTIONS

Steam Engine, Textile	1780
Automotive, Chemistry	1850
Rapid Prototyping Personal Computing	1970



JEREMY RIFKIN

"Third Industrial Revoluion"

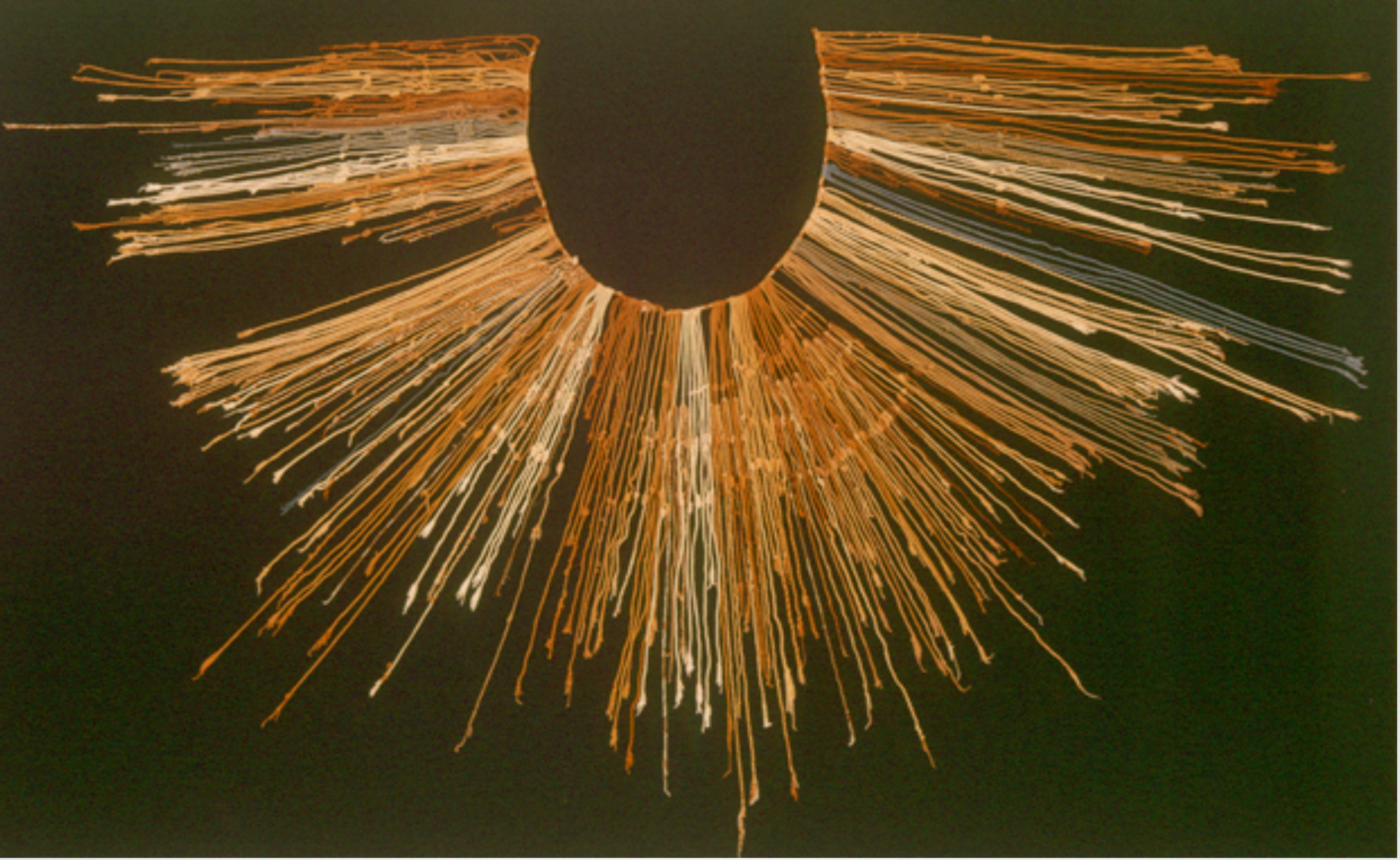
"manufacturing becomes digital, personal, and affordable"

INFORMATION REVOLUTIONS

Gutenberg Press	1439
Telegraph	1880
Personal Computer Cell Phone,Internet	1970

THIS IS A STEP OF MANY:

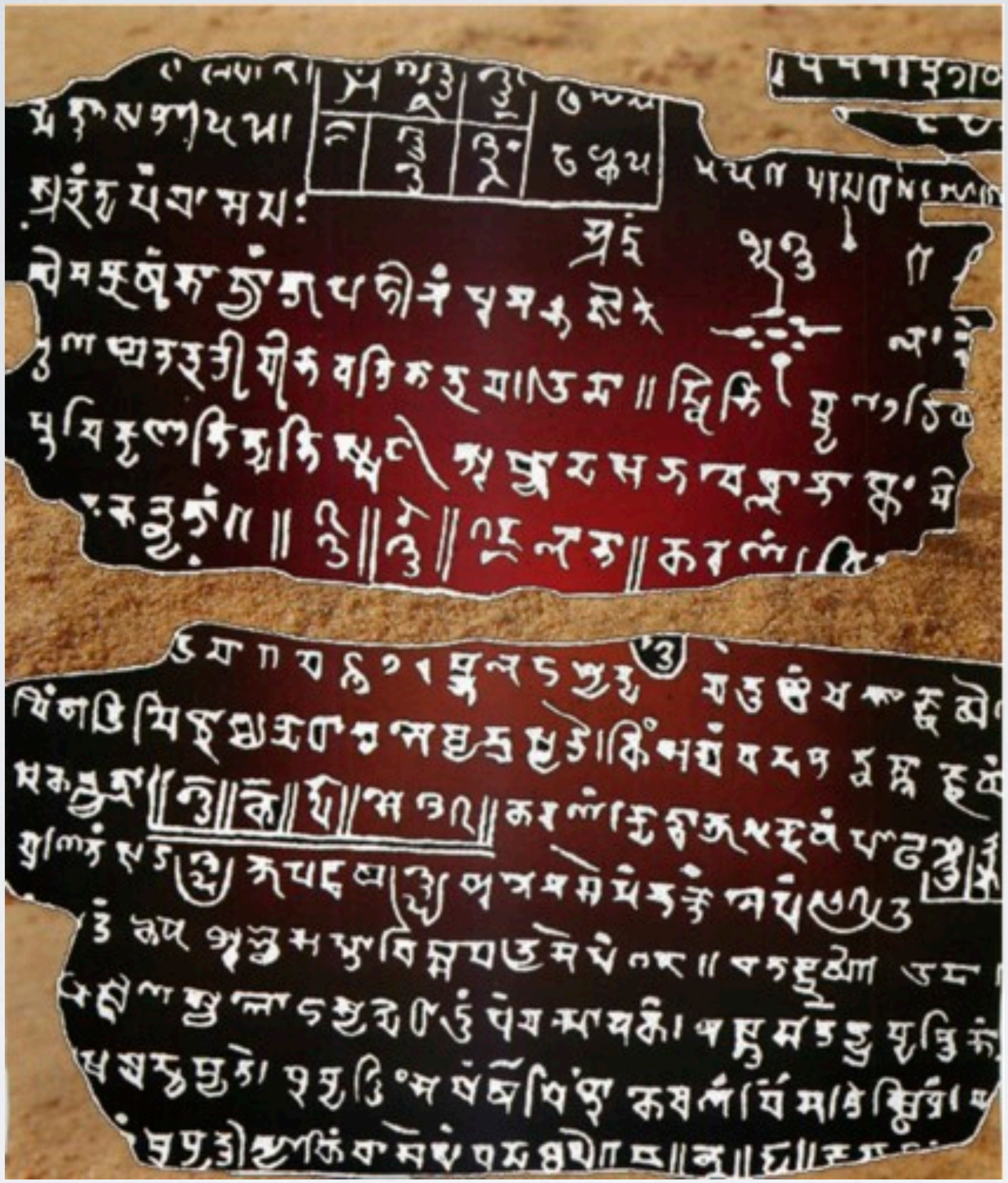
ISHANGO, 20000 YEARS AGO
AFRICA



QUIPU, 5000 YEARS AGO ANDES

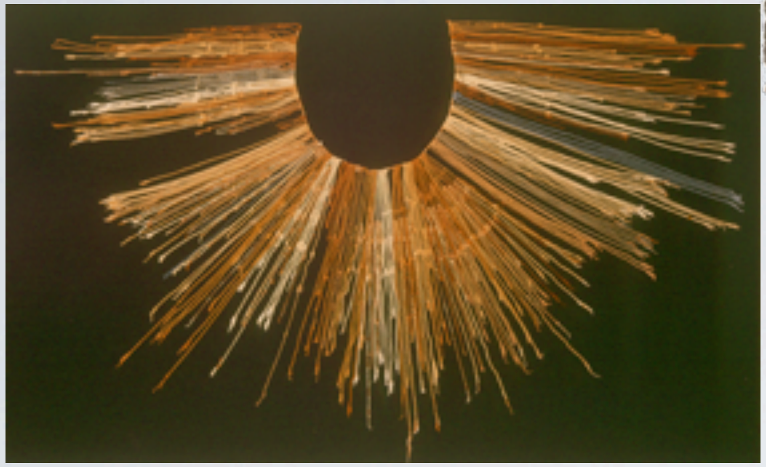
PLIMPTON 322, 4000 YEARS AGO BABILONIA

RYND, 4000 YEARS, EGYPT



BAKSHALY, 2500, INDIA

MAYAN, 2200, CENTRAL AMERICA



Rynd

1600 BC

Maya

150 AD

Quipu

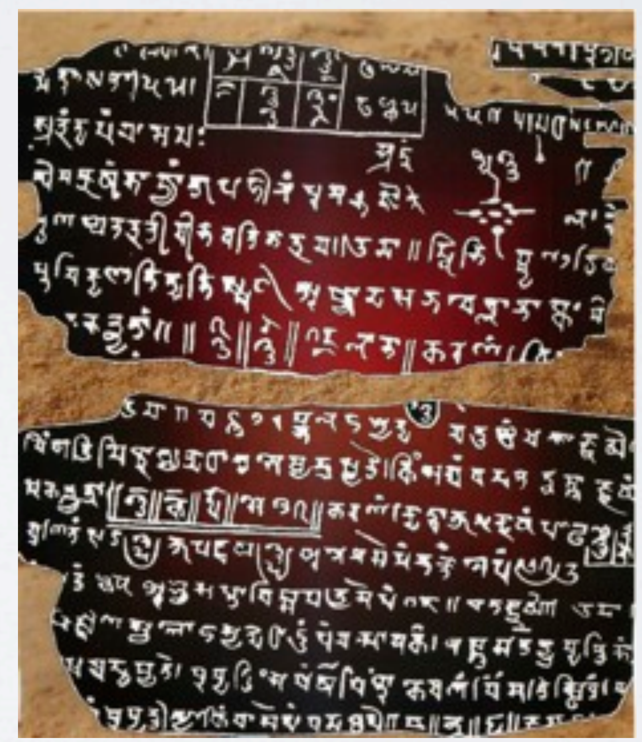
3000 BC

Ishango

80000 BC

Plympton

1800 BC



Bakshali

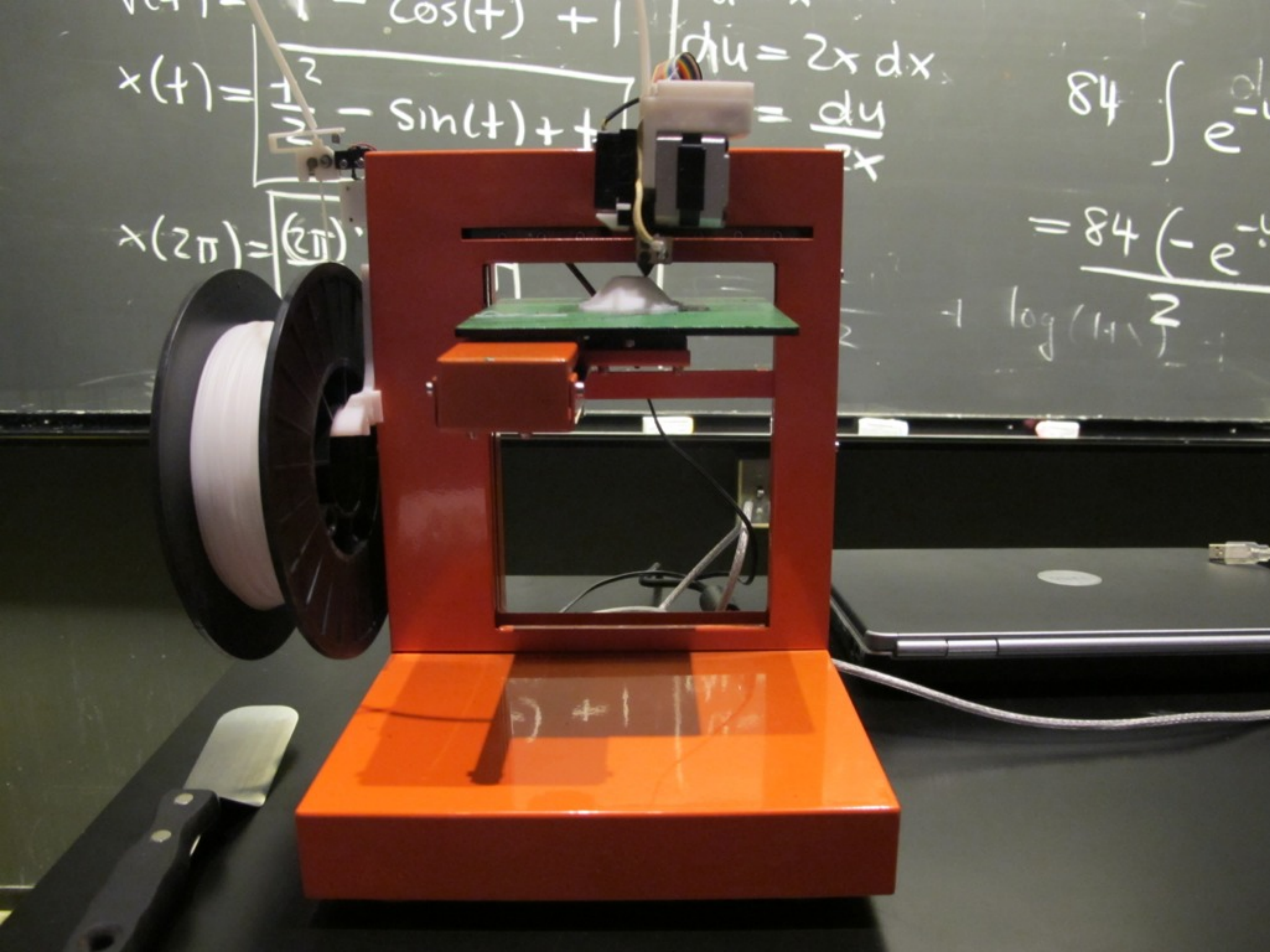
400 AD

COMMUNICATION REVOLUTIONS

Figures	6'000 years ago
Books	560 years ago
Photo	170 years ago
Film	130 years ago
3D Print	30 years ago

PRINTING, 600 YEARS

LASER PRINTER, 50 YEARS


cos(t) + 1
du = 2x dx
x(t) =
sin(t) +
x(2π) =
84
= 84
log

3D SCANNER

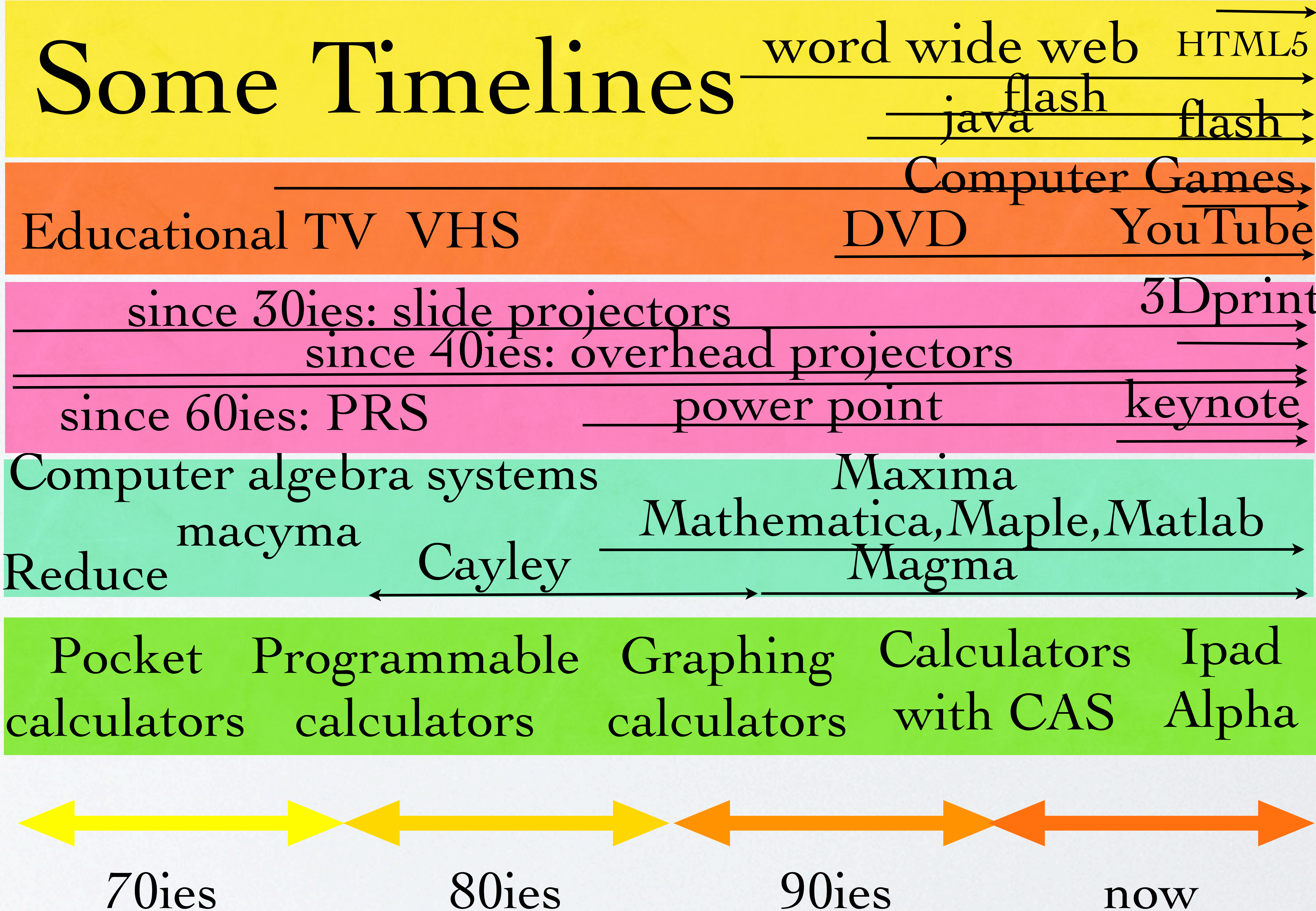
PERCEPTION REVOLUTIONS

Eye Glass	730 years ago
Microscope	420 years ago
Telescope	400 years ago
Xrays	110 years ago
MRI	60 years ago
3D Scan	25 years ago

CLASSROOM REVOLUTIONS

Abacus	1500 years ago
Blackboard	1000 years ago
Computer Algebra	50 years ago
Calculator	40 years ago
Powerpoint	30 years ago
3D printed Models	15 years ago

Some Timelines



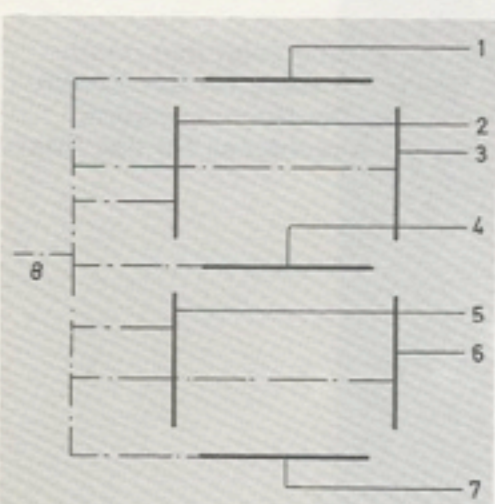
Oliver Knill

Schaltinterface für TI-59, TI-58, TI-57

Es sind schon viele gute Bauanleitungen für ein Schaltinterface in CHIP publiziert worden. Warum denn ein anderes bauen? Ich suchte eine Schaltung, die es möglich macht, mehrere Kanäle zu steuern. Dafür eignet sich die Anzeige des Rechners als Schnittstelle sehr gut.
Eine 7-Segment-Anzeige ist einfach aufgebaut. Wenn zum Beispiel Leitung 1 und 8 angesteuert werden, so leuchtet das oberste Segment. Umgekehrt: Wenn das oberste Segment leuchtet, kann bei 1 und eine Spannung abgegriffen werden.
Diese Spannung wird nun verstärkt und schaltet ein Relais. In der Anzeige können die Zahlen 0 bis 9 stehen. Betrachten wir das obere und mittlere waagerechte Segment. Es reichen die Ziffern 1, 4, 7, 8, um zwei Kanäle voll zu steuern. Bei den Modellen TI-58, TI-59 sind zehn Ziffern da. Es könnten also 20 Kanäle gesteuert werden. Das gibt aber Probleme:

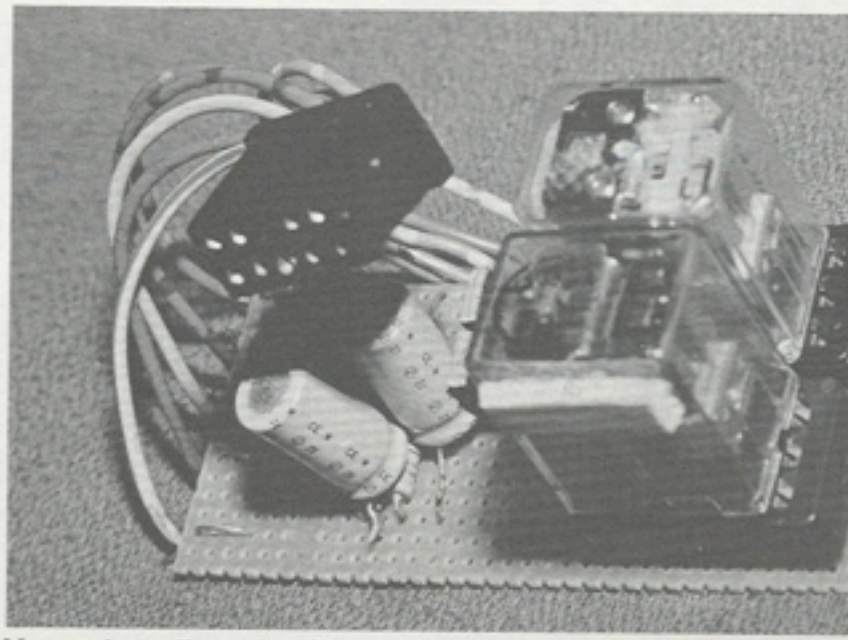
- Die Kosten für 20 Kanäle sowie der Arbeitsaufwand wären hoch.
- Es müssen 22 Leitungen vom Rechnerinnern nach draußen geführt werden.
- Im Extremfall müssen 20 Relais durchgeschaltet werden.

Ich habe mich deshalb entschlossen, zuerst nur zwei Kanäle auszubauen.

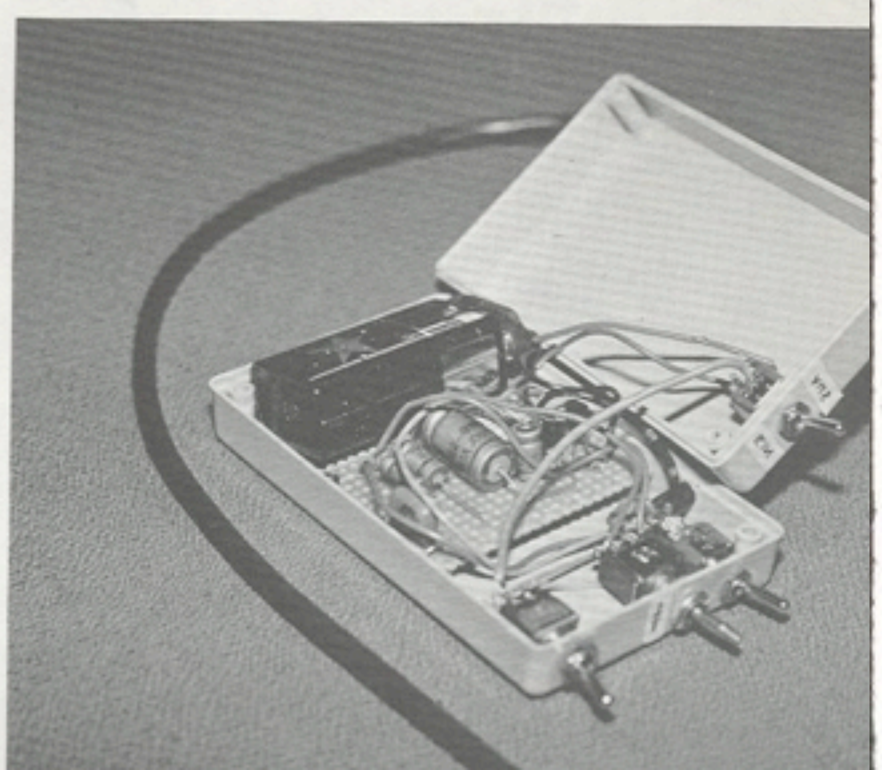


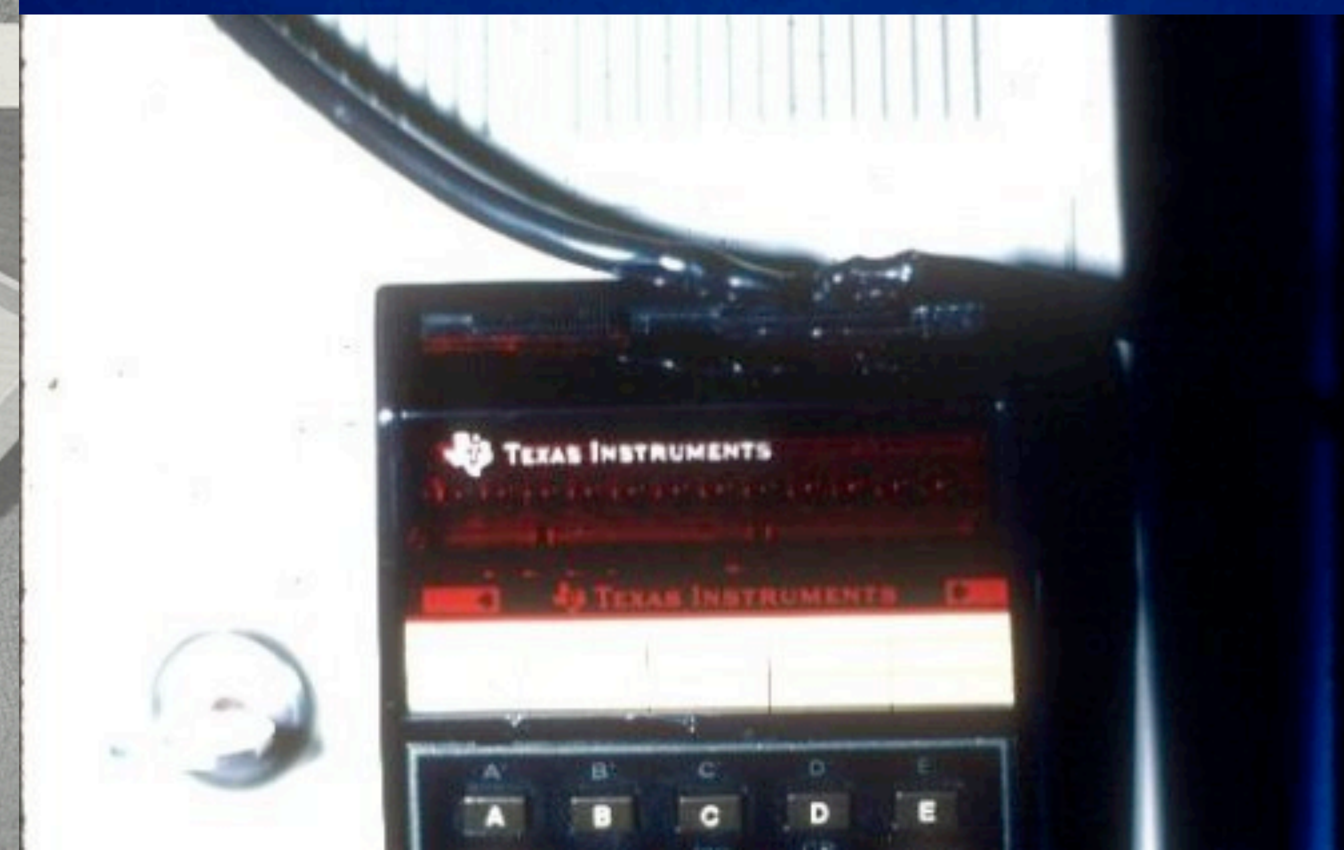
Die Schaltung

Der Schaltplan ist sehr einfach und kann auch von Computerfans aufgebaut werden, die über keine gr
erfahrung verfügen.



Versuchsaufbau des Schaltinterface mit zwei Relais



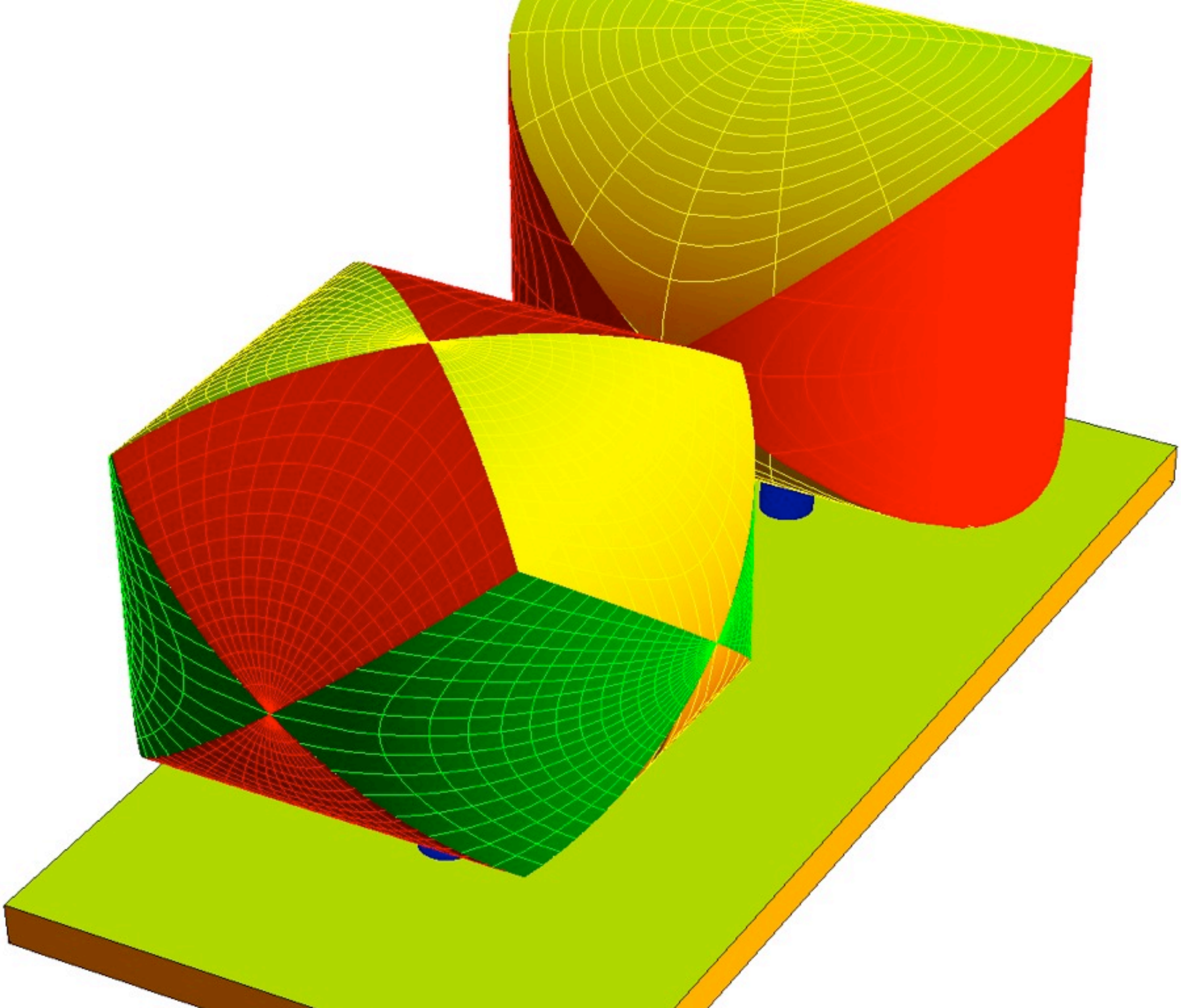


2300 YEARS

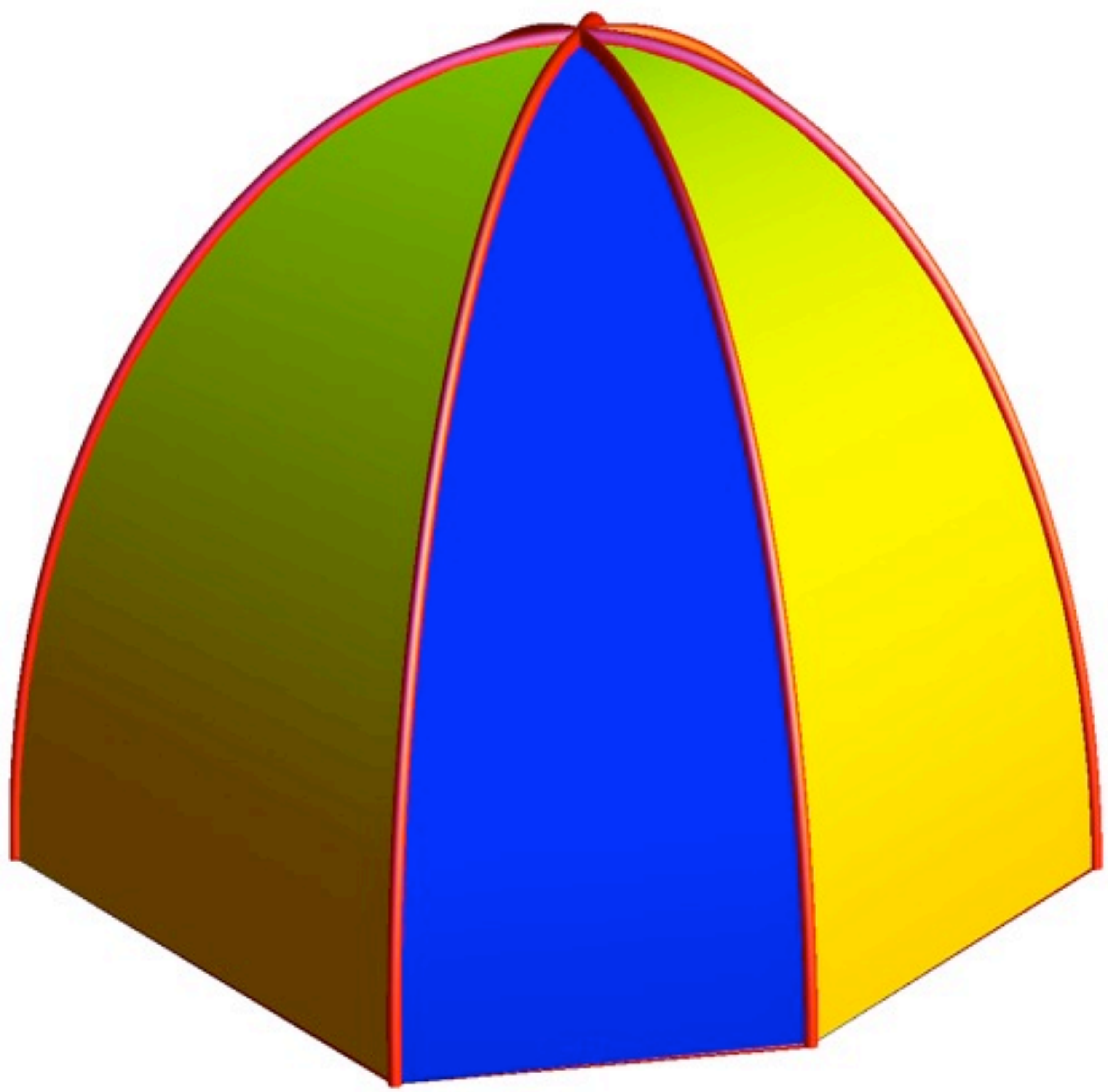
Archimedes

287-212 BC

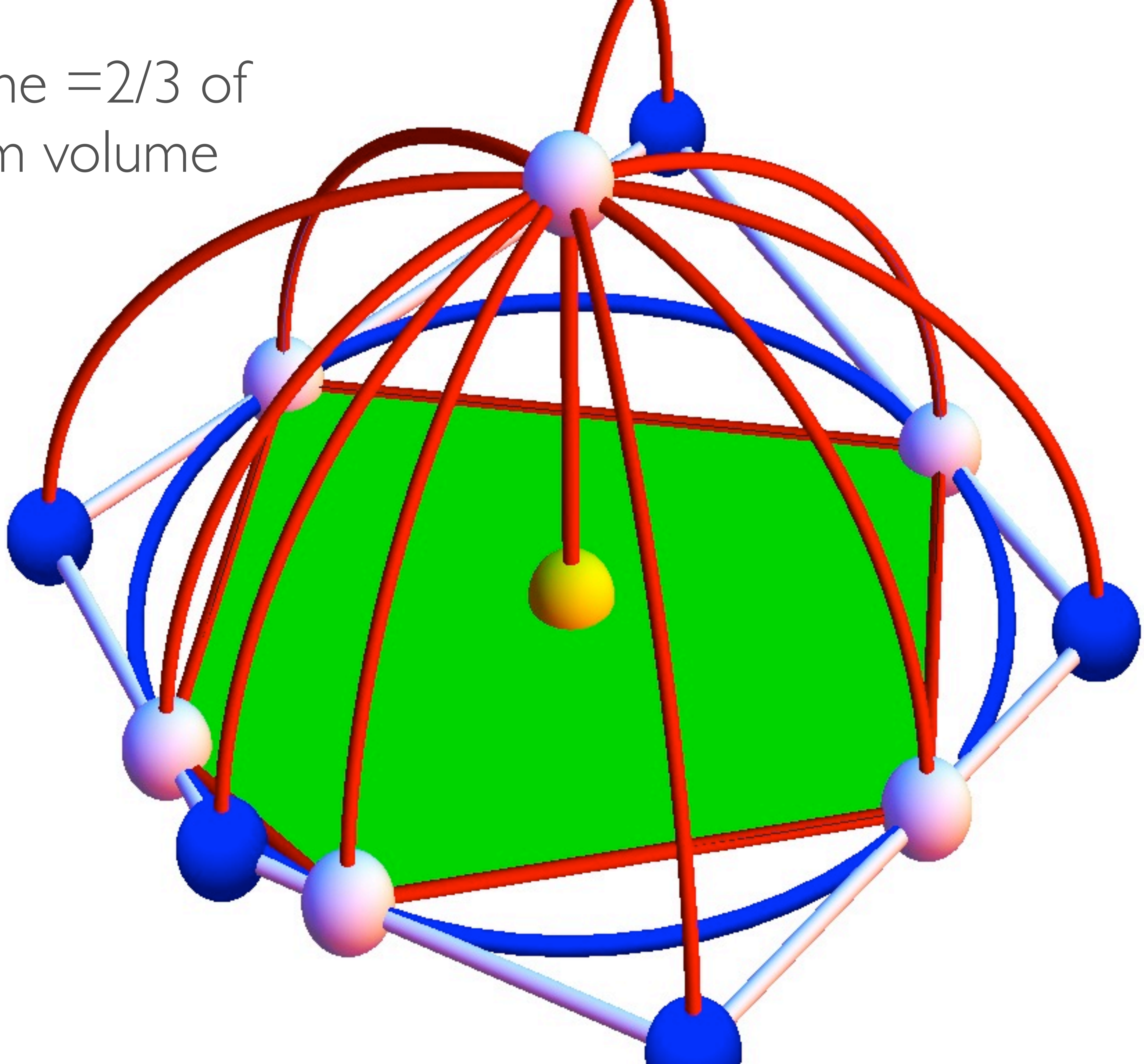

Domenico Fetti, Archimedes, 1620
287-212 BC



ARCHIMEDEAN DOME

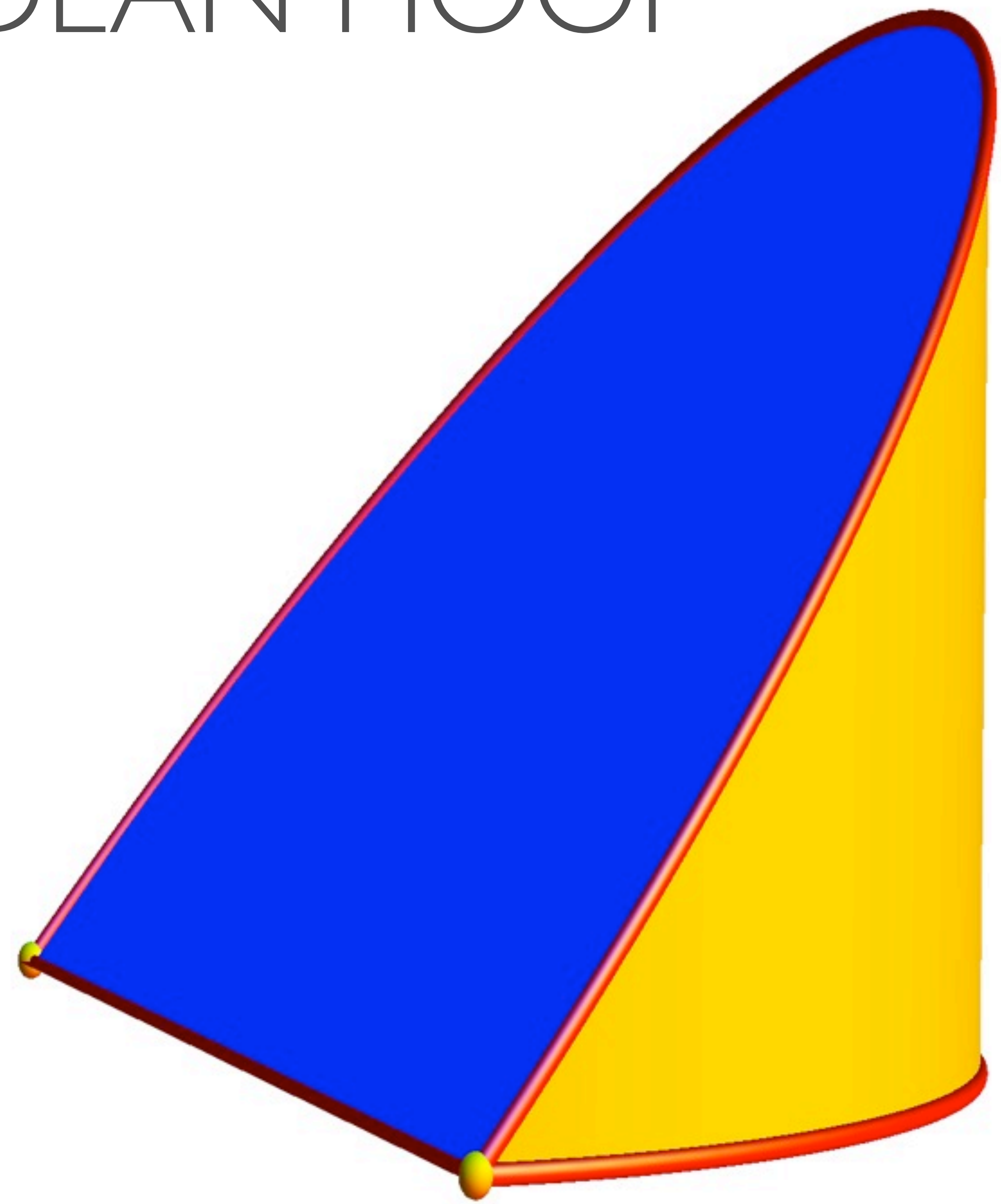


Volume =2/3 of
prism volume

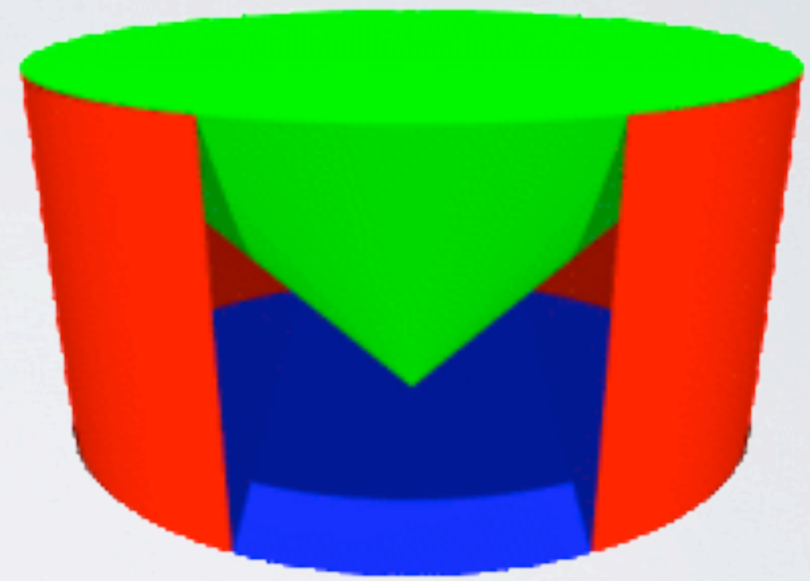


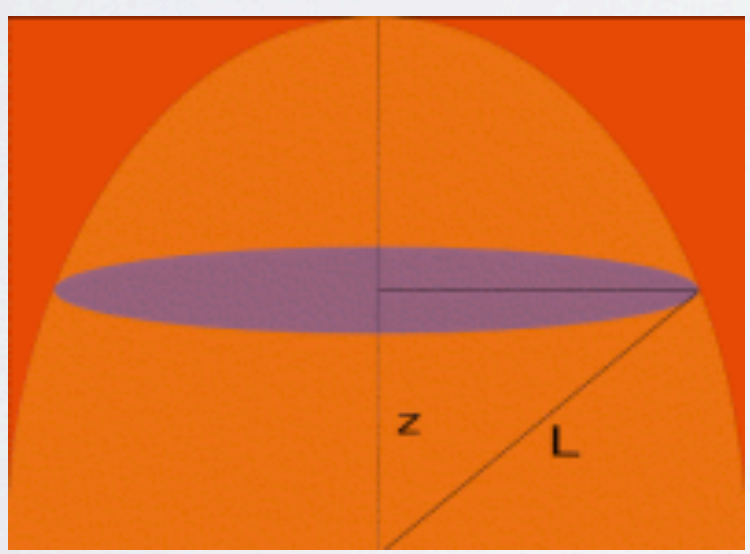
ARCHIMEDEAN HOOF

"Birth place of calculus"



CAVALIERI PRINCIPLE





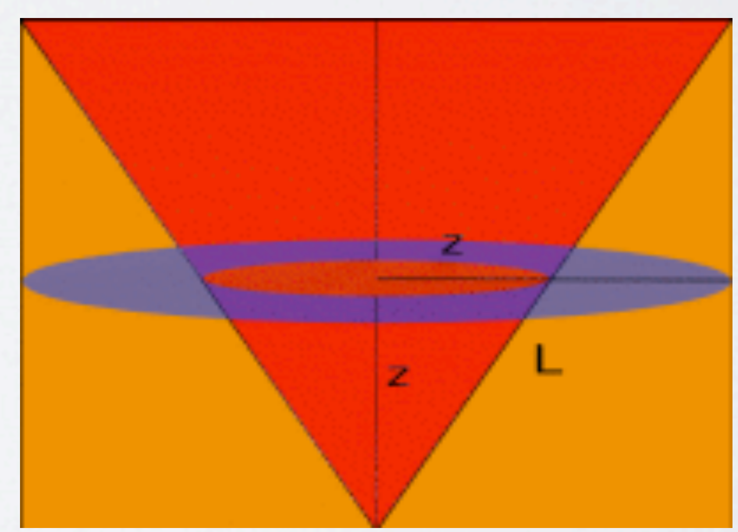


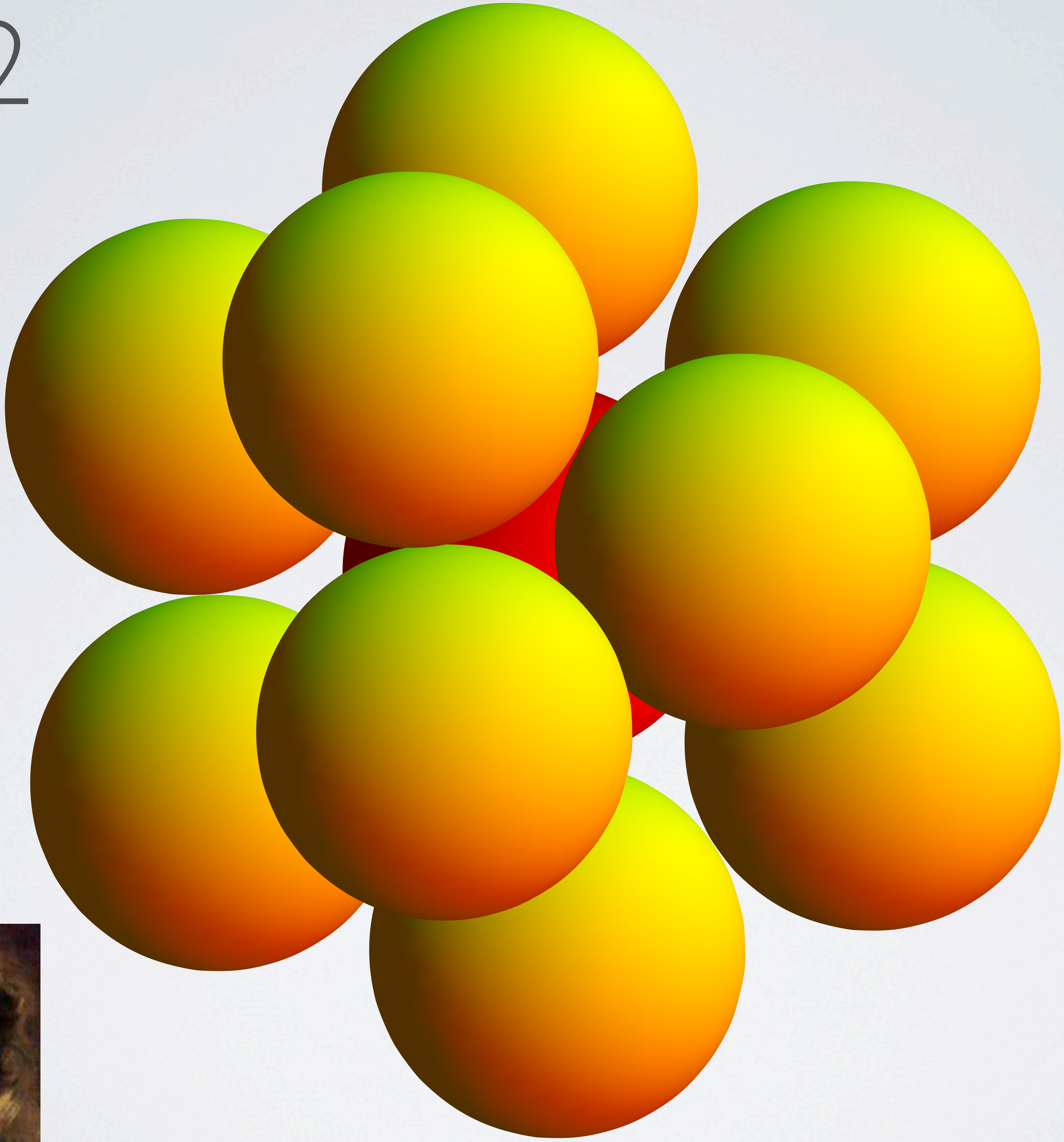

Image U.S. Geological Survey

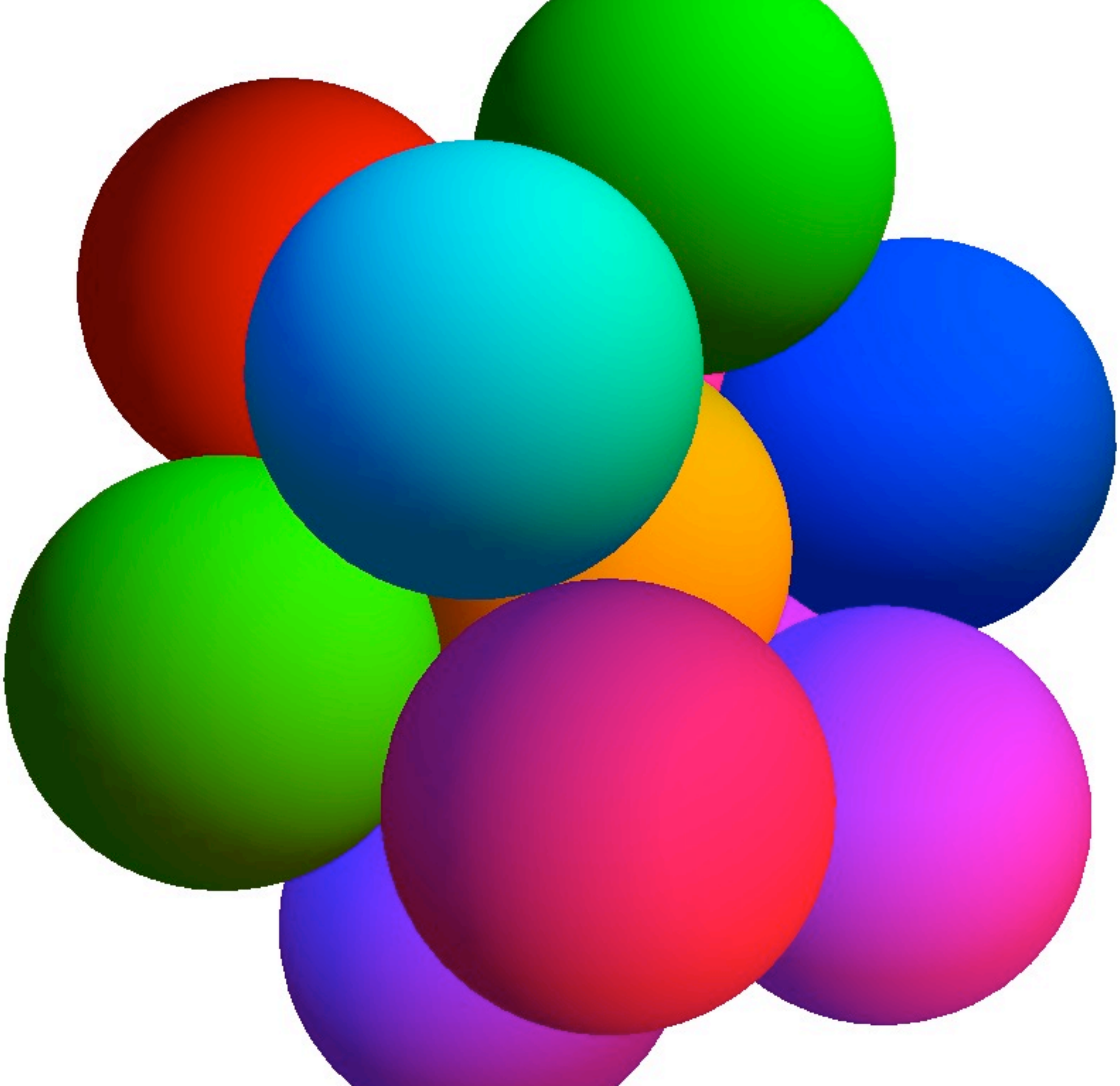
MORE ABOUT PROOFS
in Mathematics

NEWTON - GREGORY

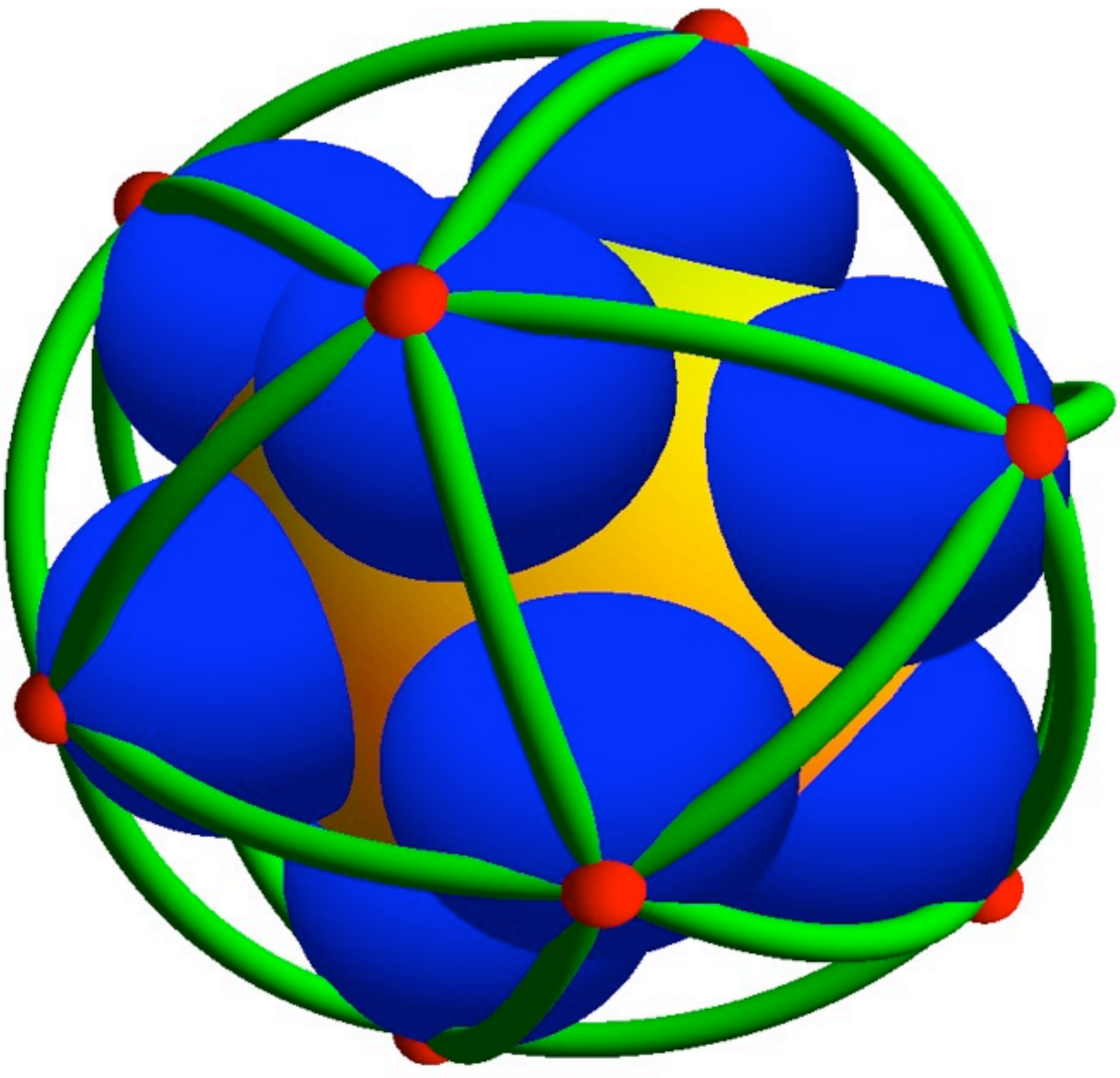
12

13

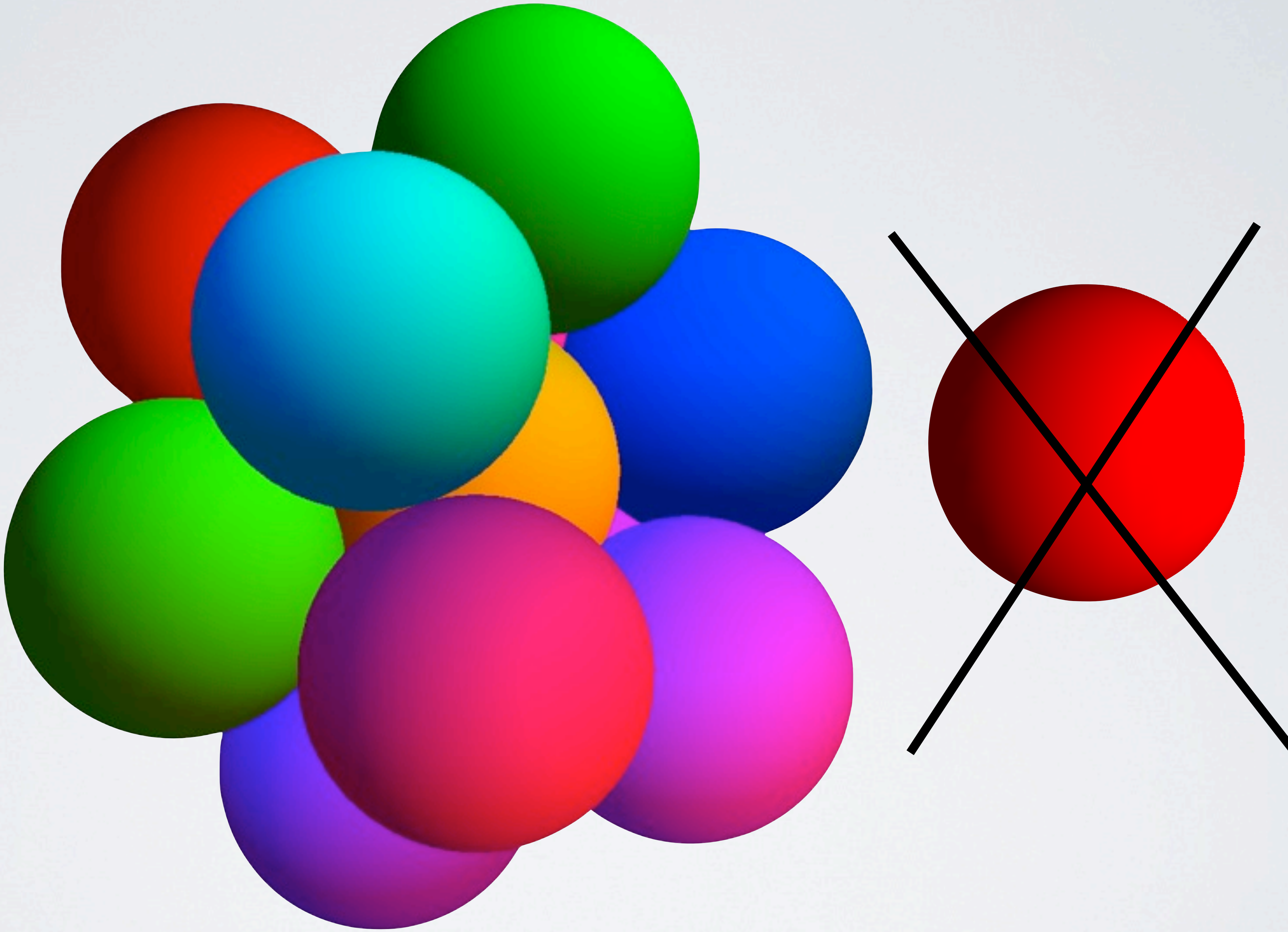




ICOSAHEDRAL ARRANGEMENT

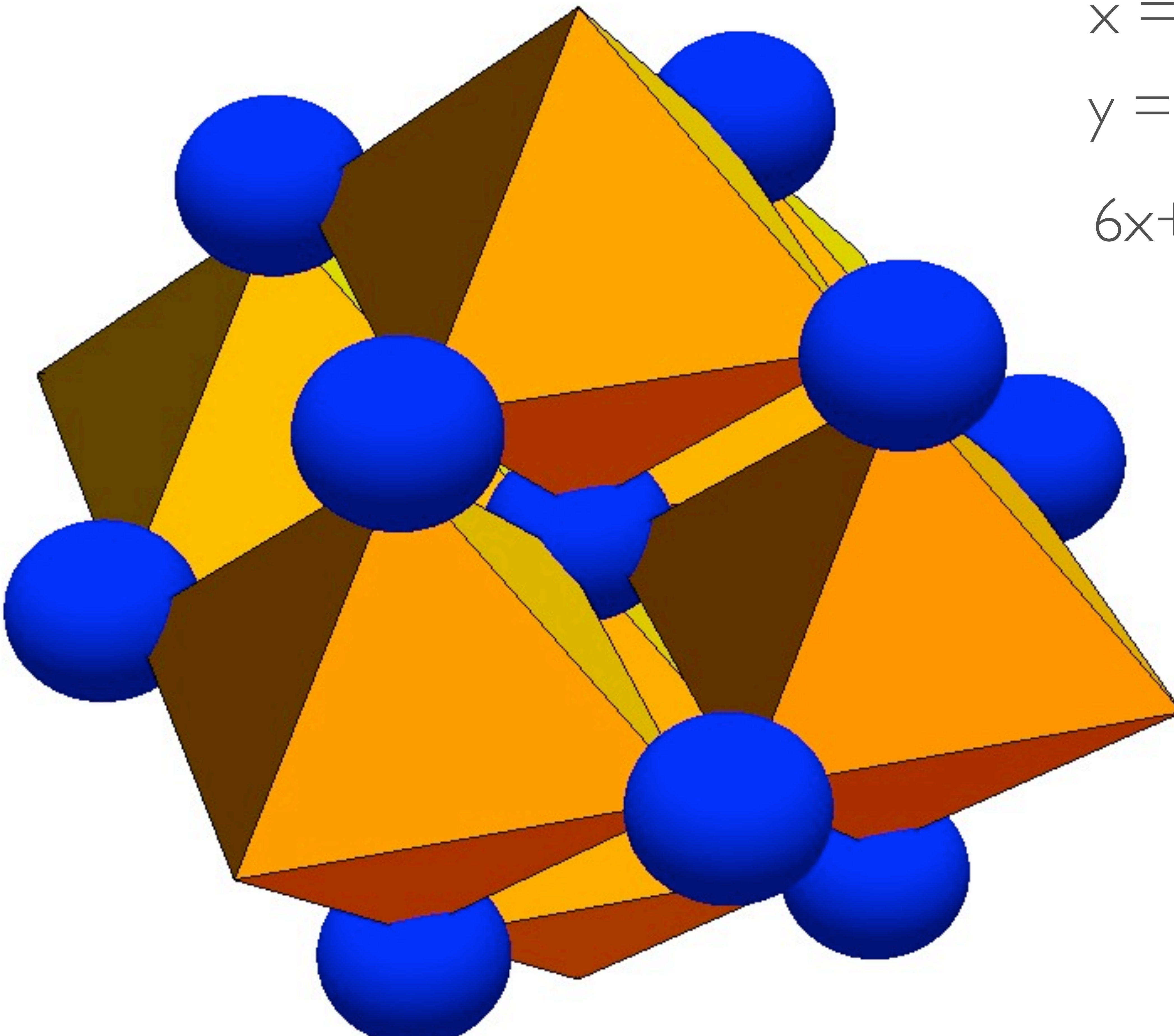


NEWTON WON



ONLY IN 1953!

OCTAHEDRON AND TETRAHEDRON



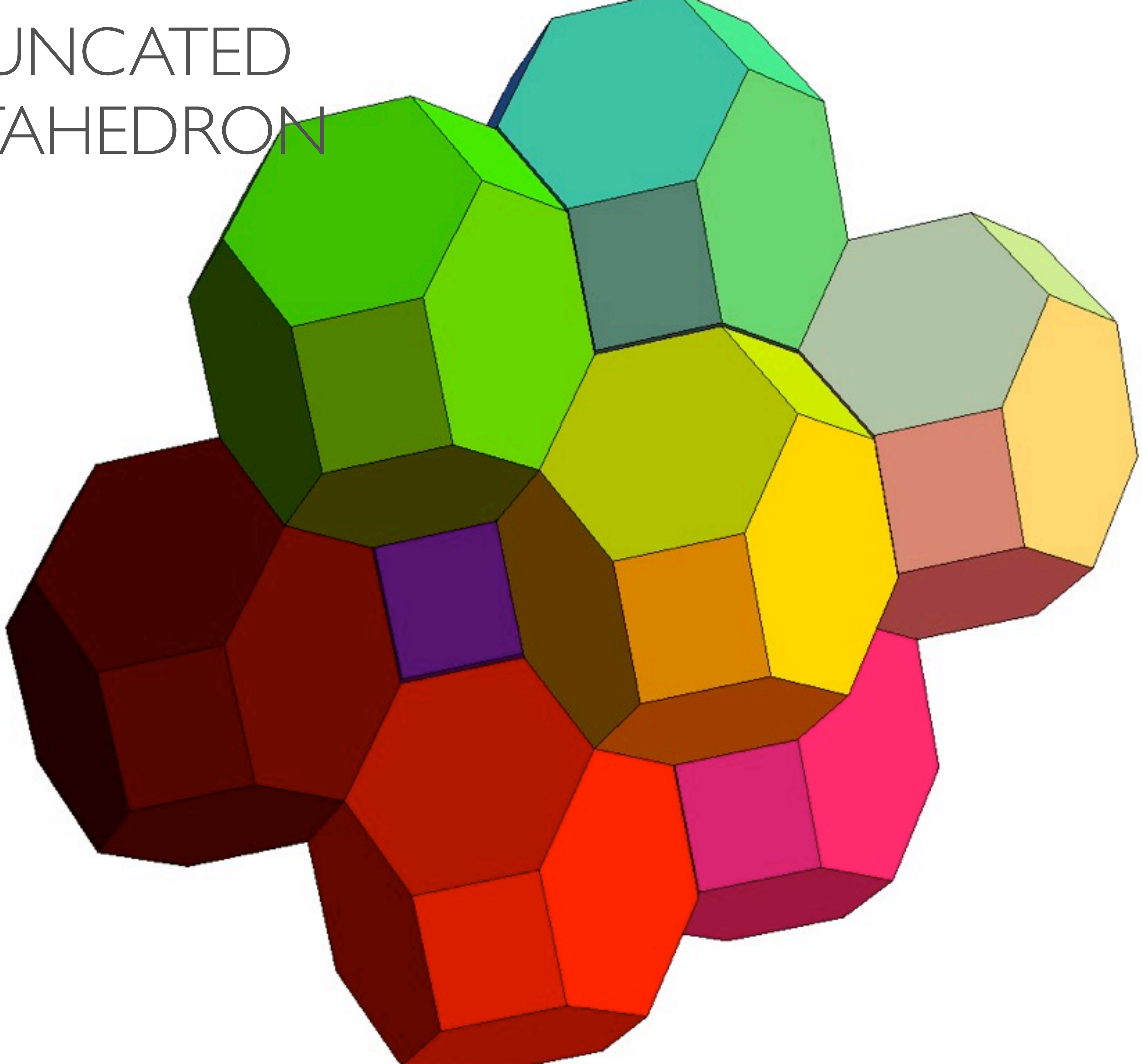
$x = Vol(O)$

$y = Vol(T)$

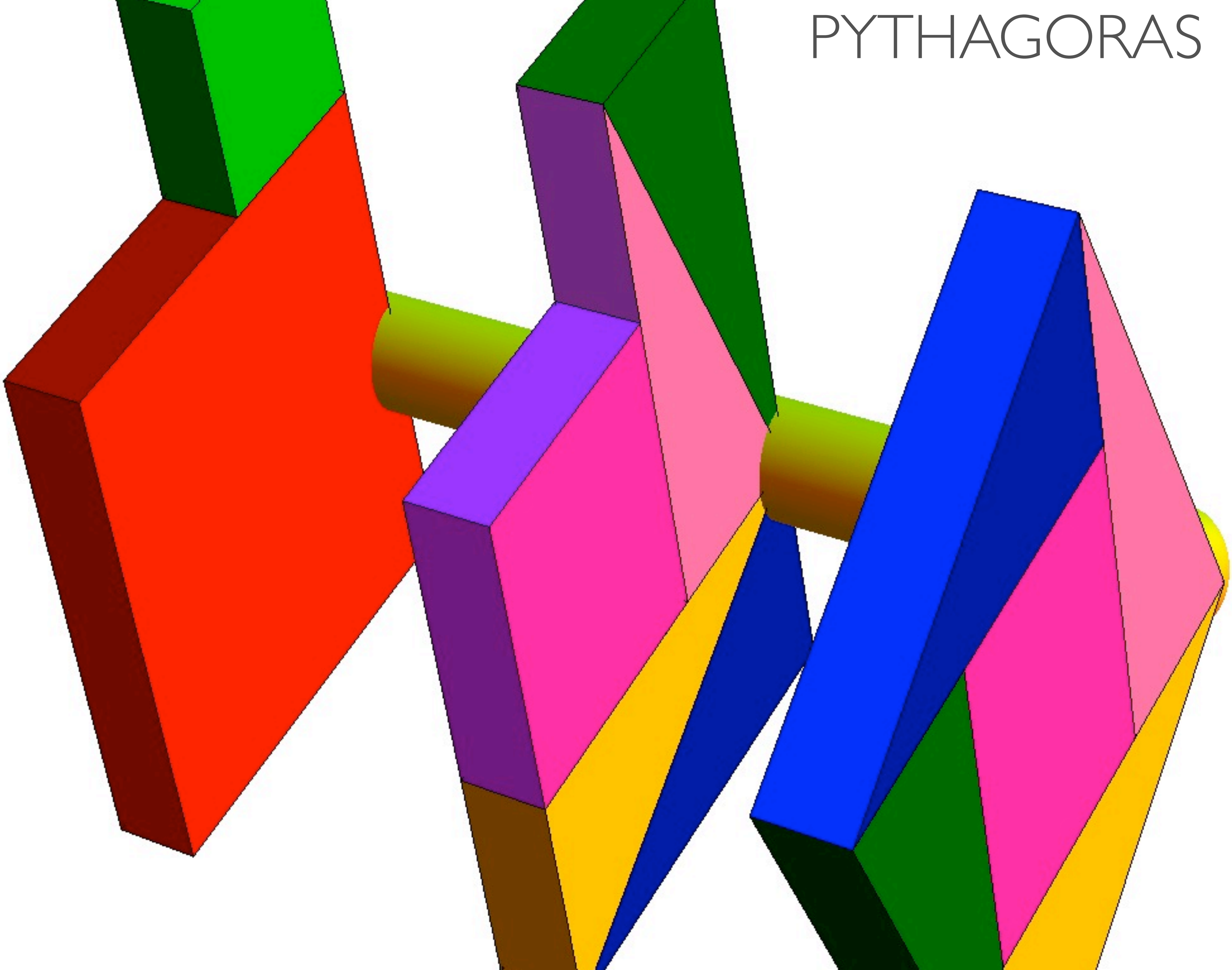
$6x+8y=8x$

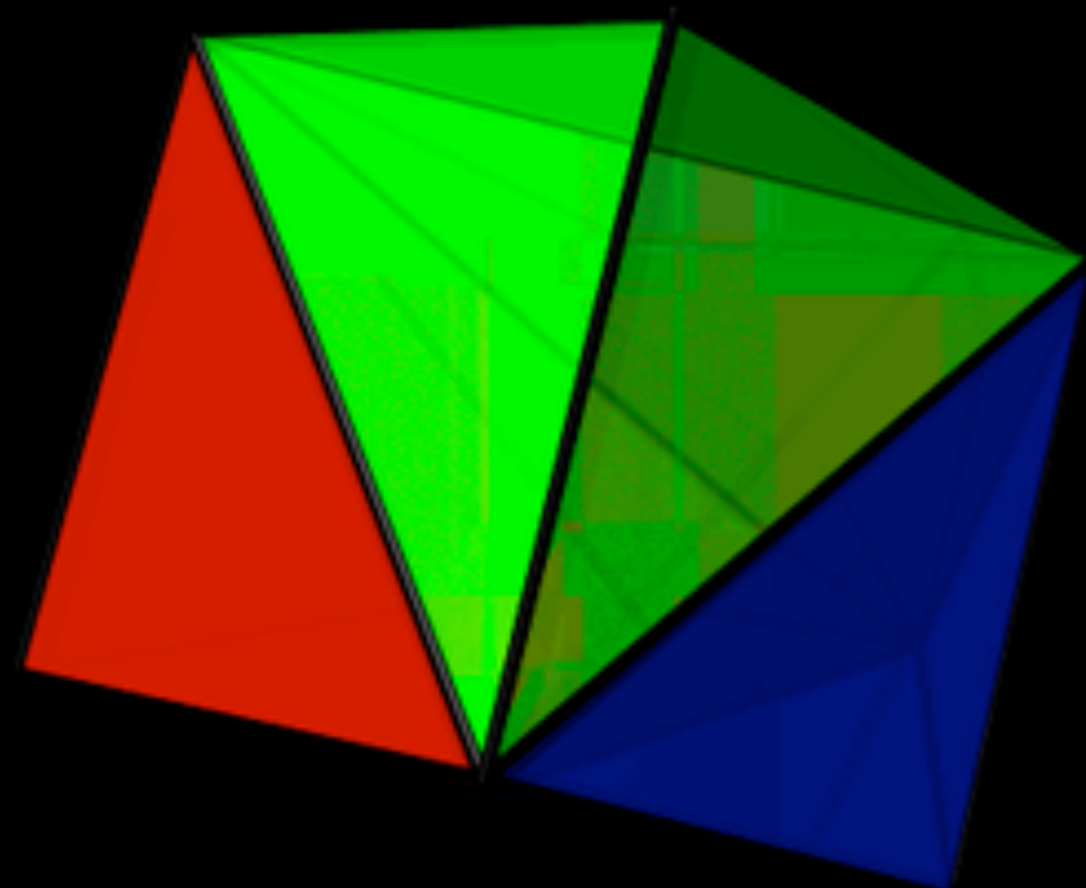
$y=x/4$

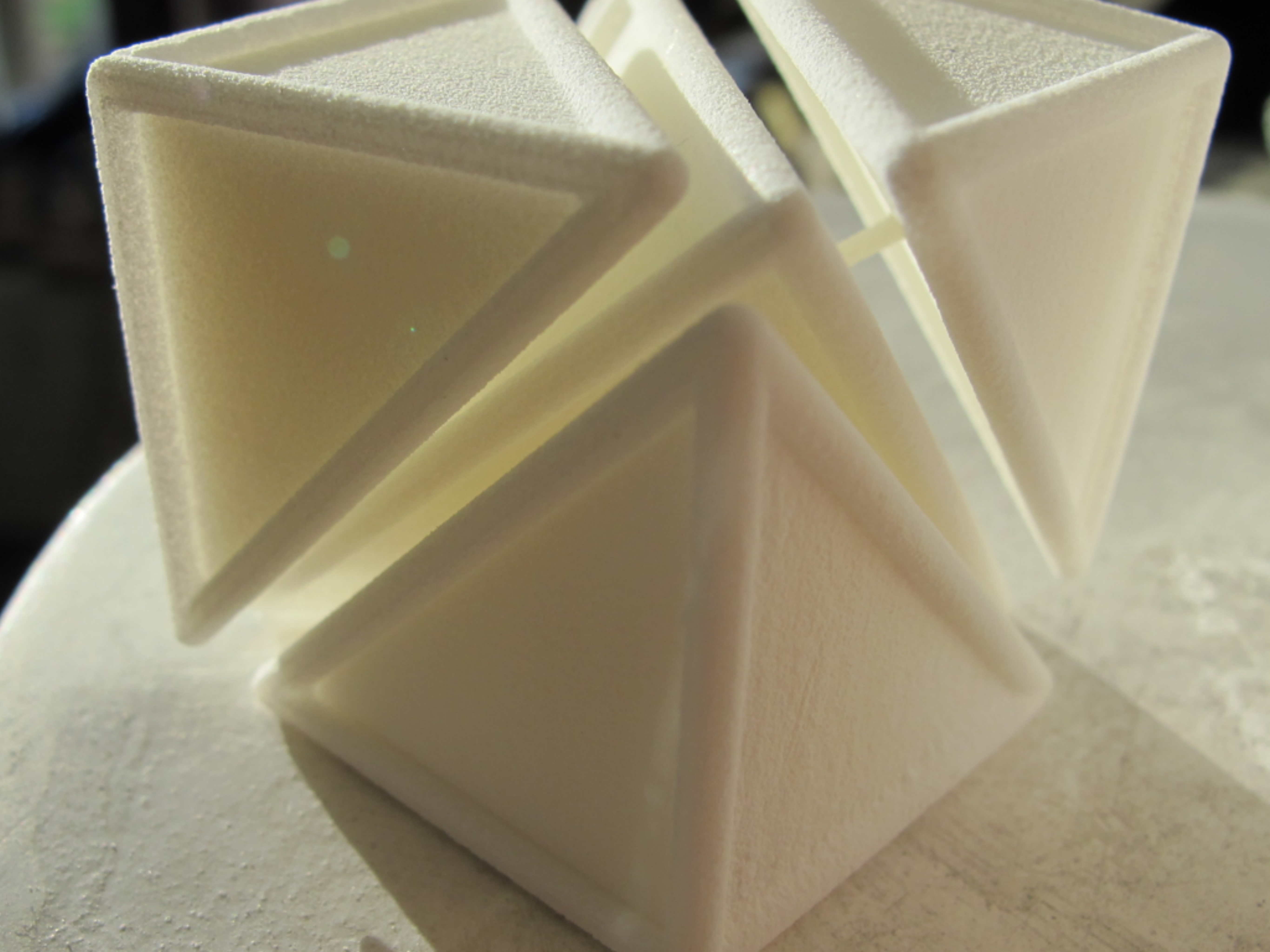
TRUNCATED OCTAHEDRON



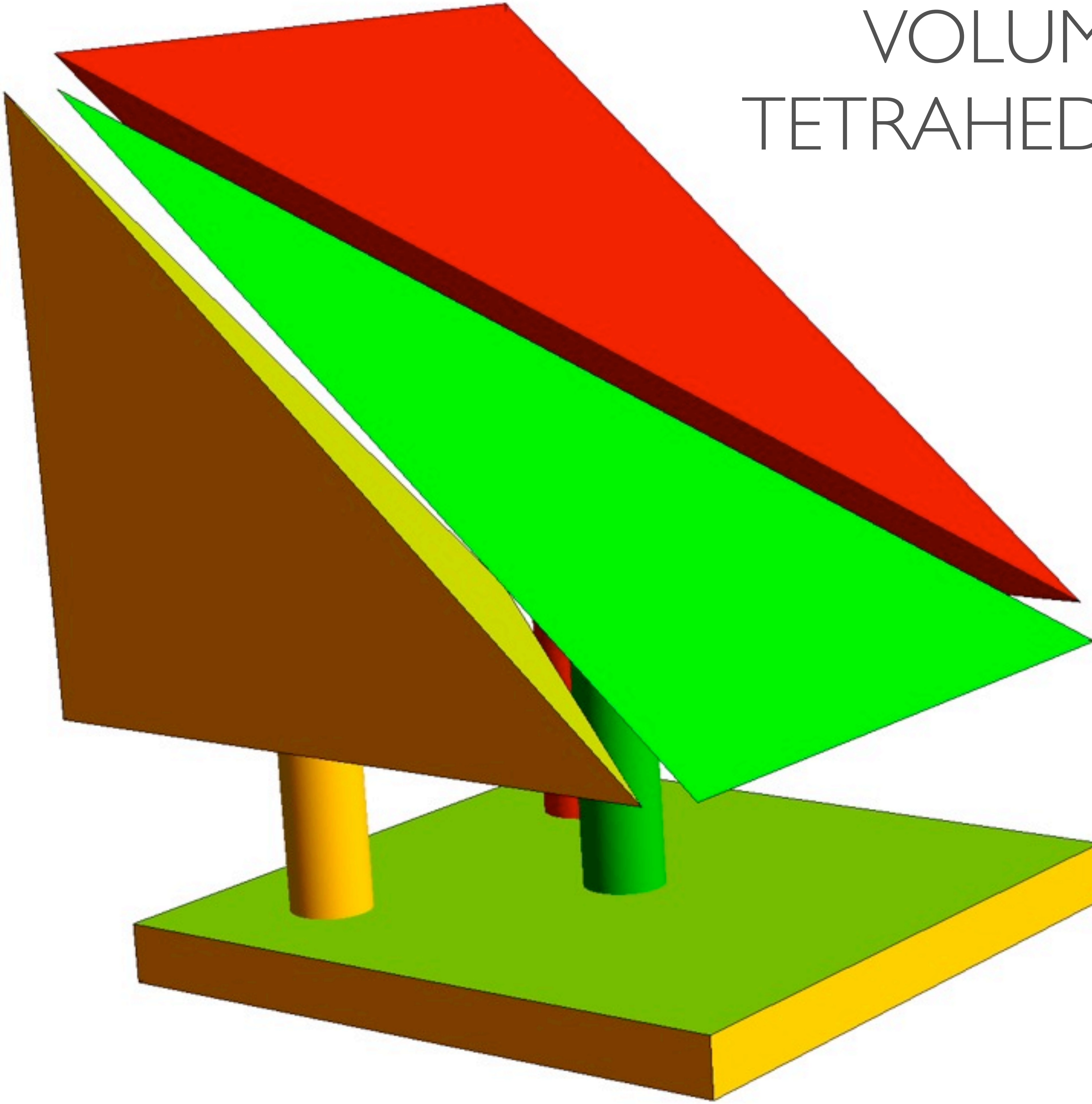
PYTHAGORAS







VOLUME TETRAHEDRON

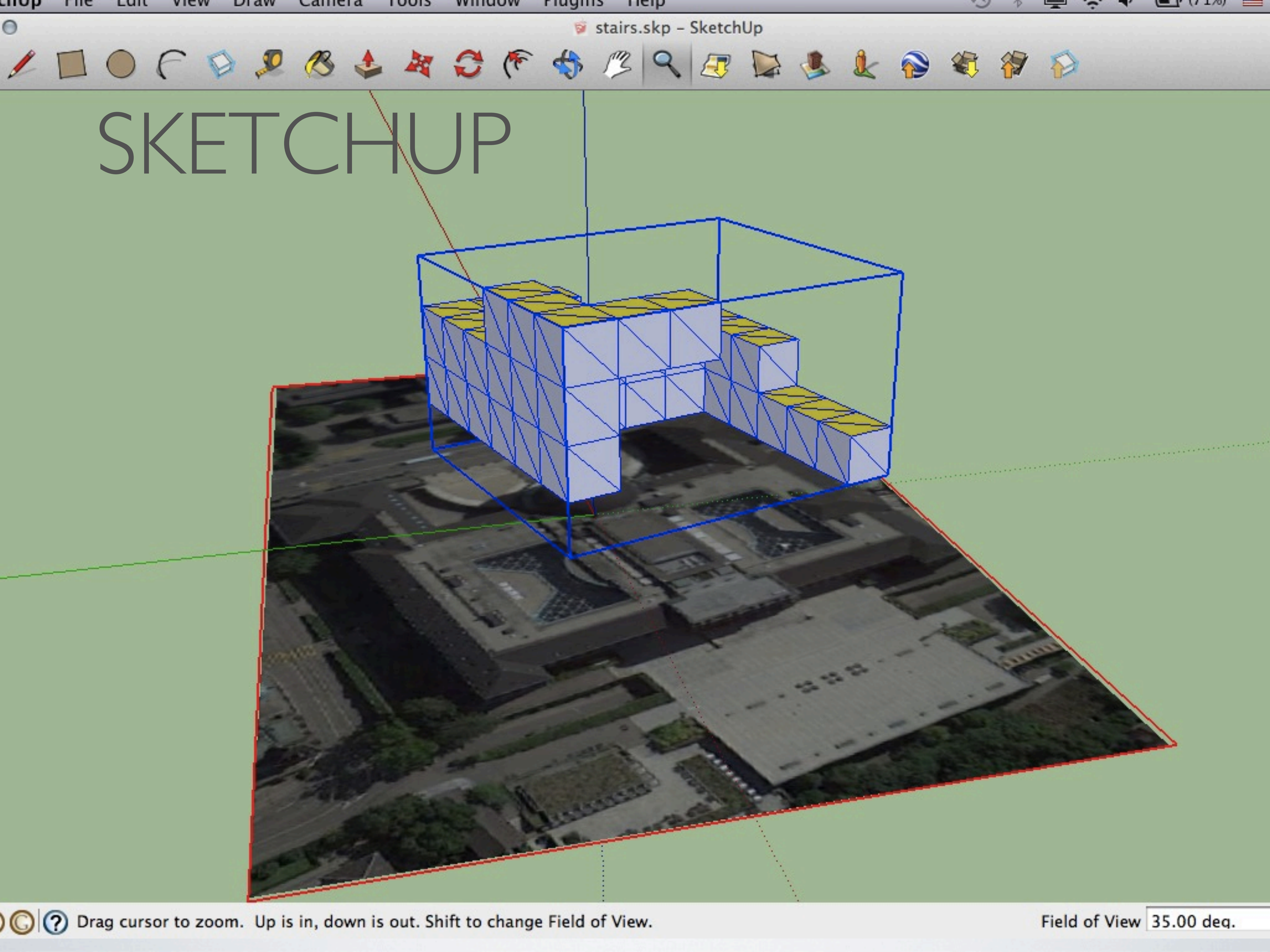


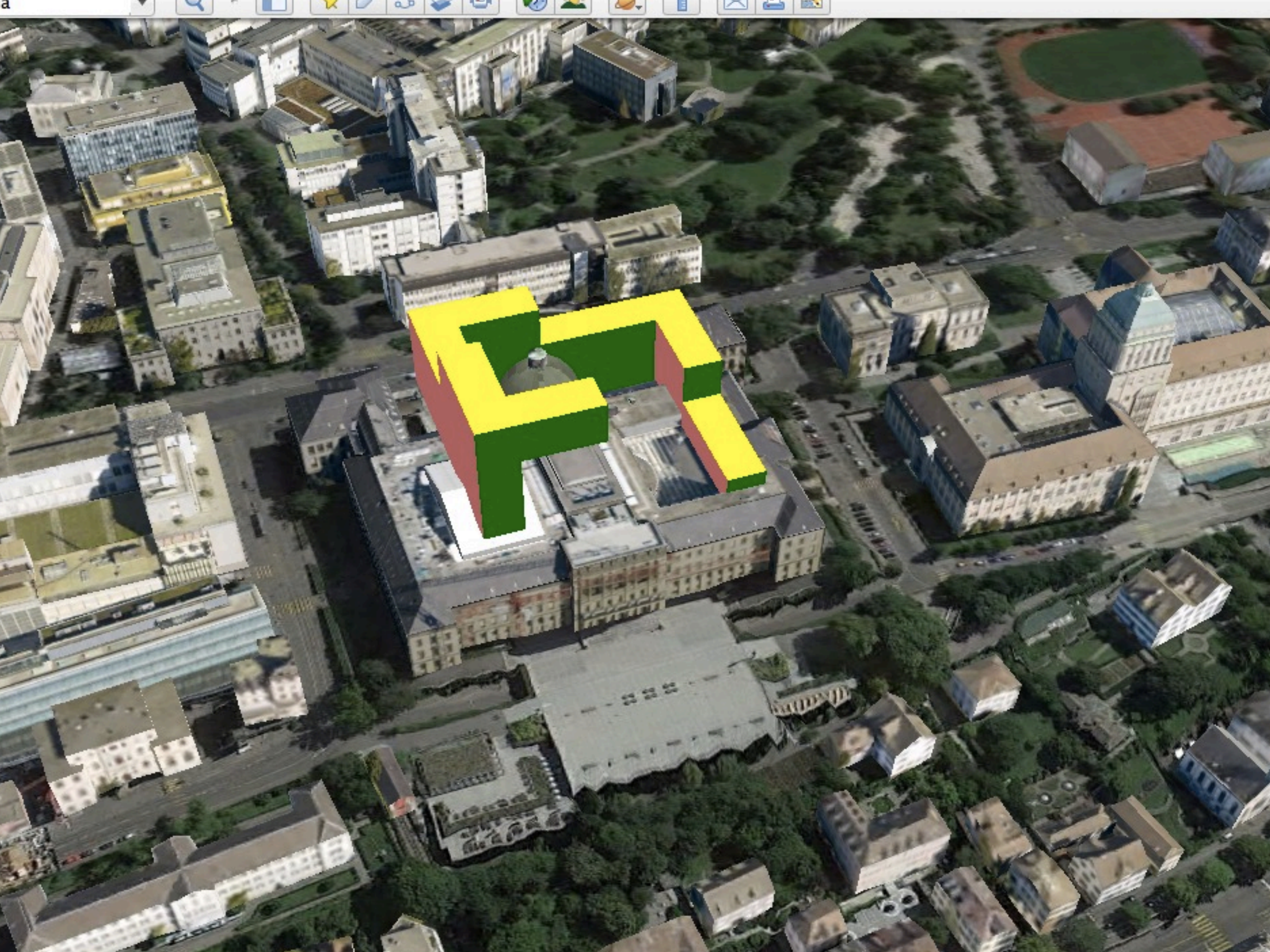
TOOLS FOR PRODUCING MATH MODELS

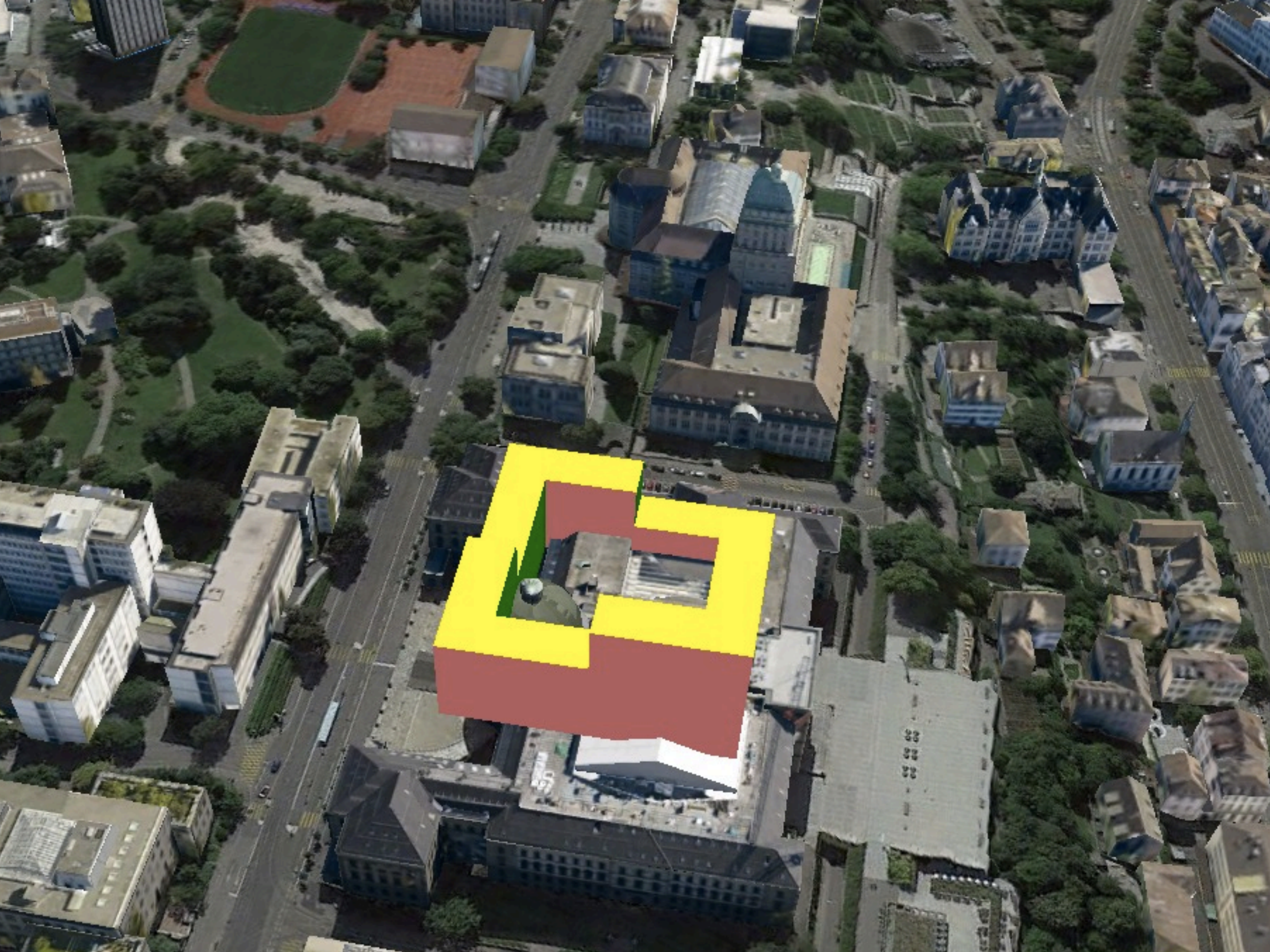
TOOLS

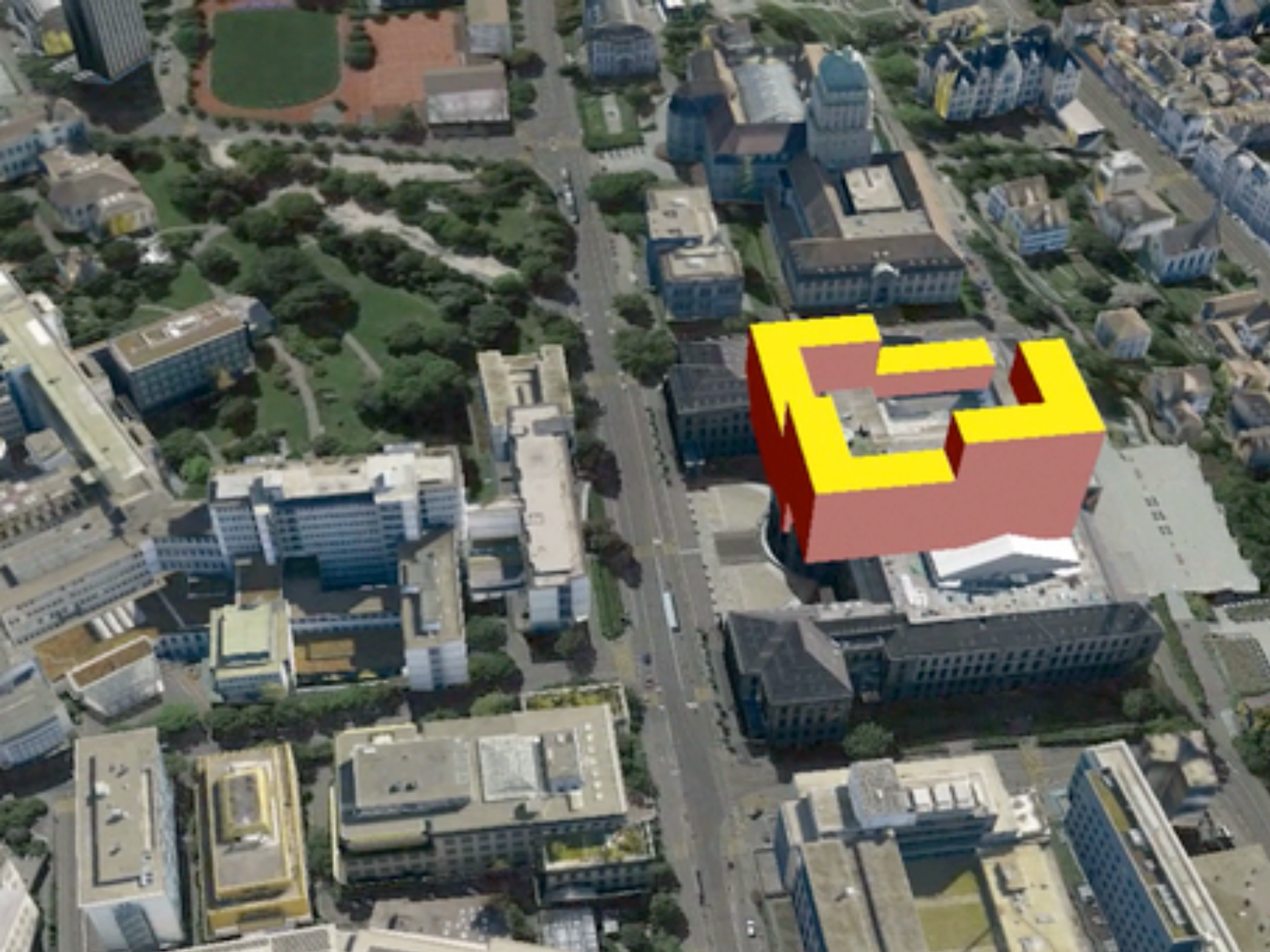
- Modelers: like Blender, Trimble Sketchup
- CAD: AutoCAD
- Generate STL directly: python, C, etc.
- Computer Algebra systems: Mathematica
- Intelligent CAD: OpenCAD

SKETCHUP


stairs.skp – SketchUp
Drag cursor to zoom. Up is in, down is out. Shift to change Field of View.
Field of View
35.00 deg.

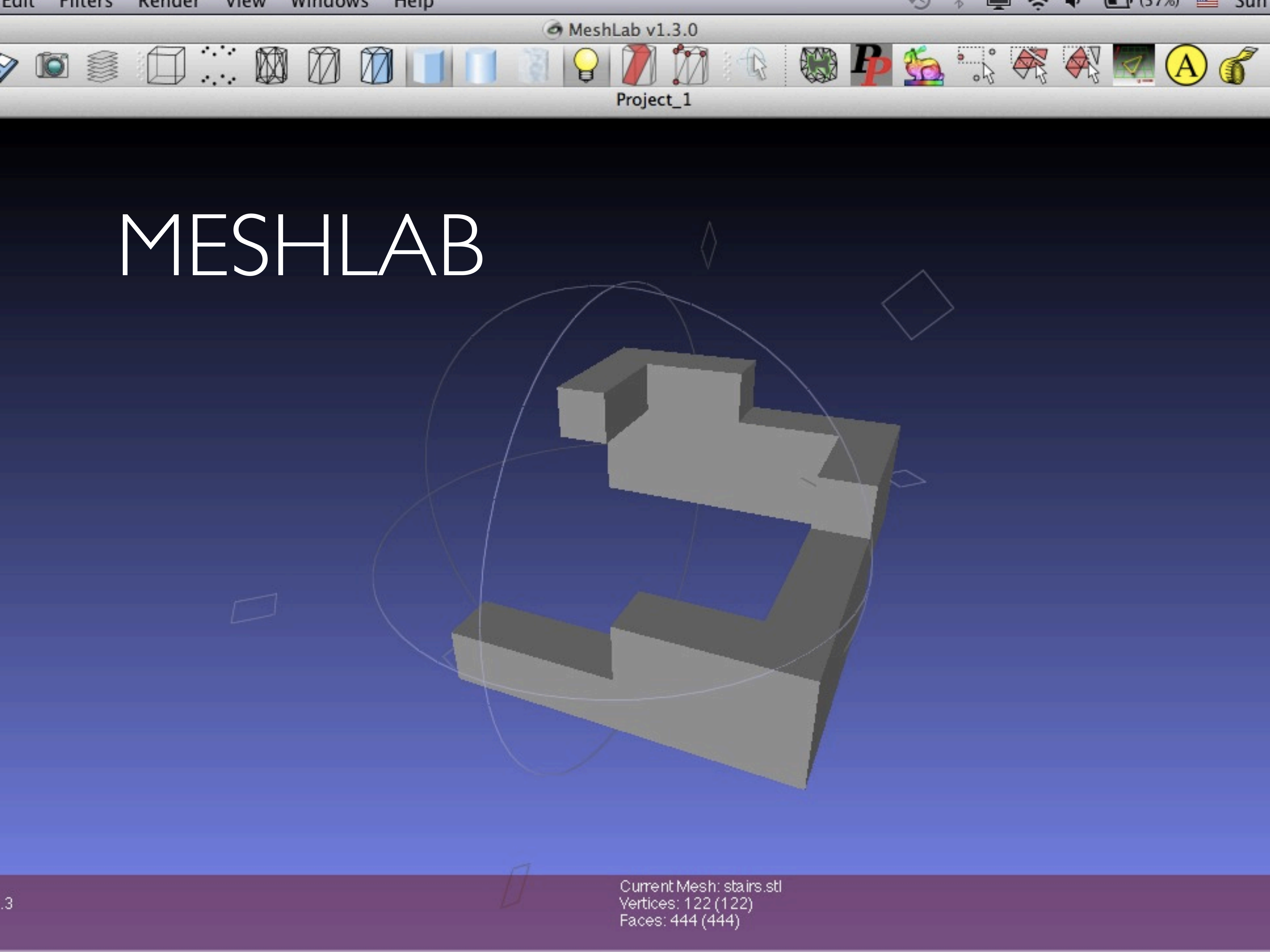




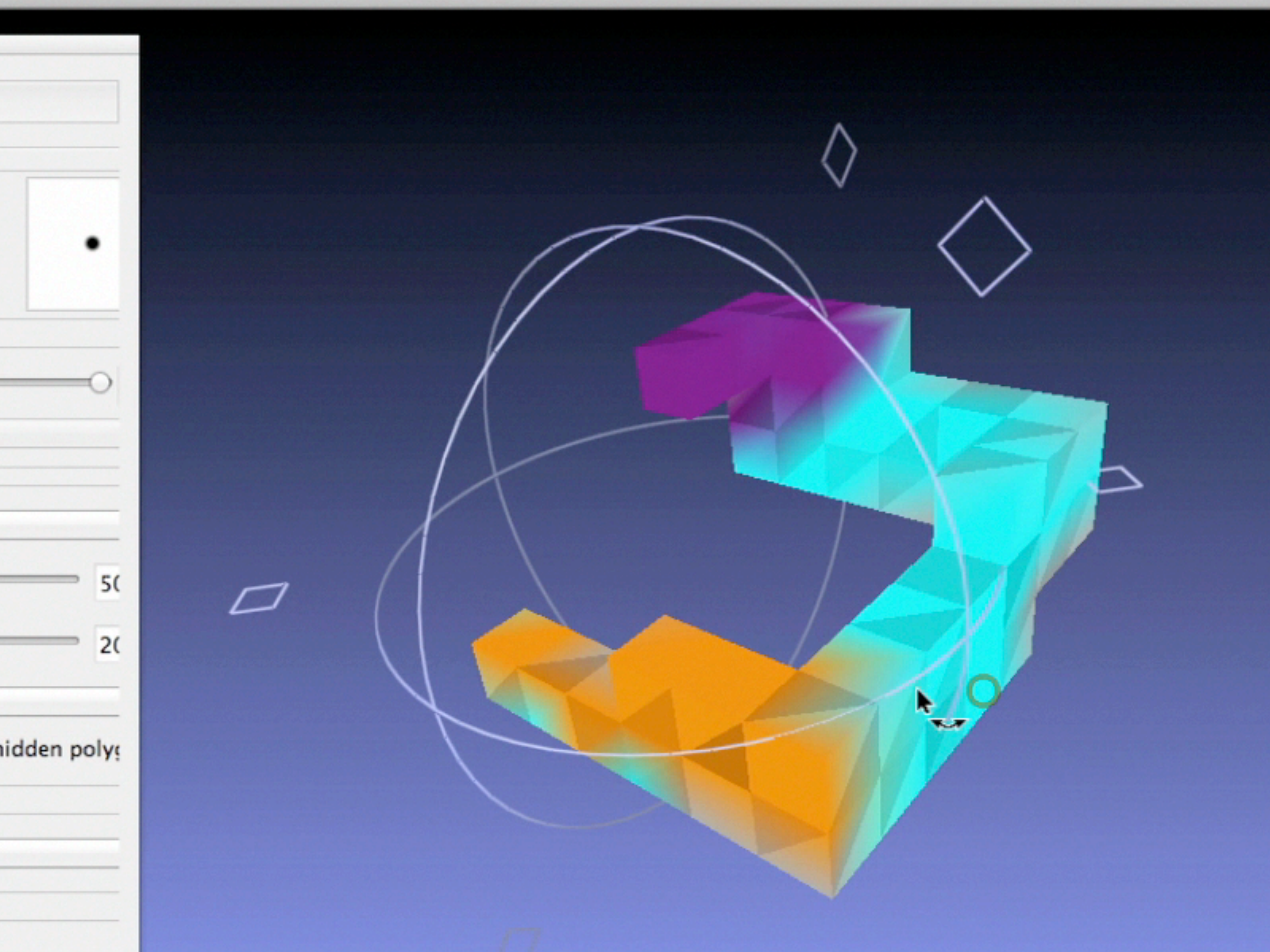


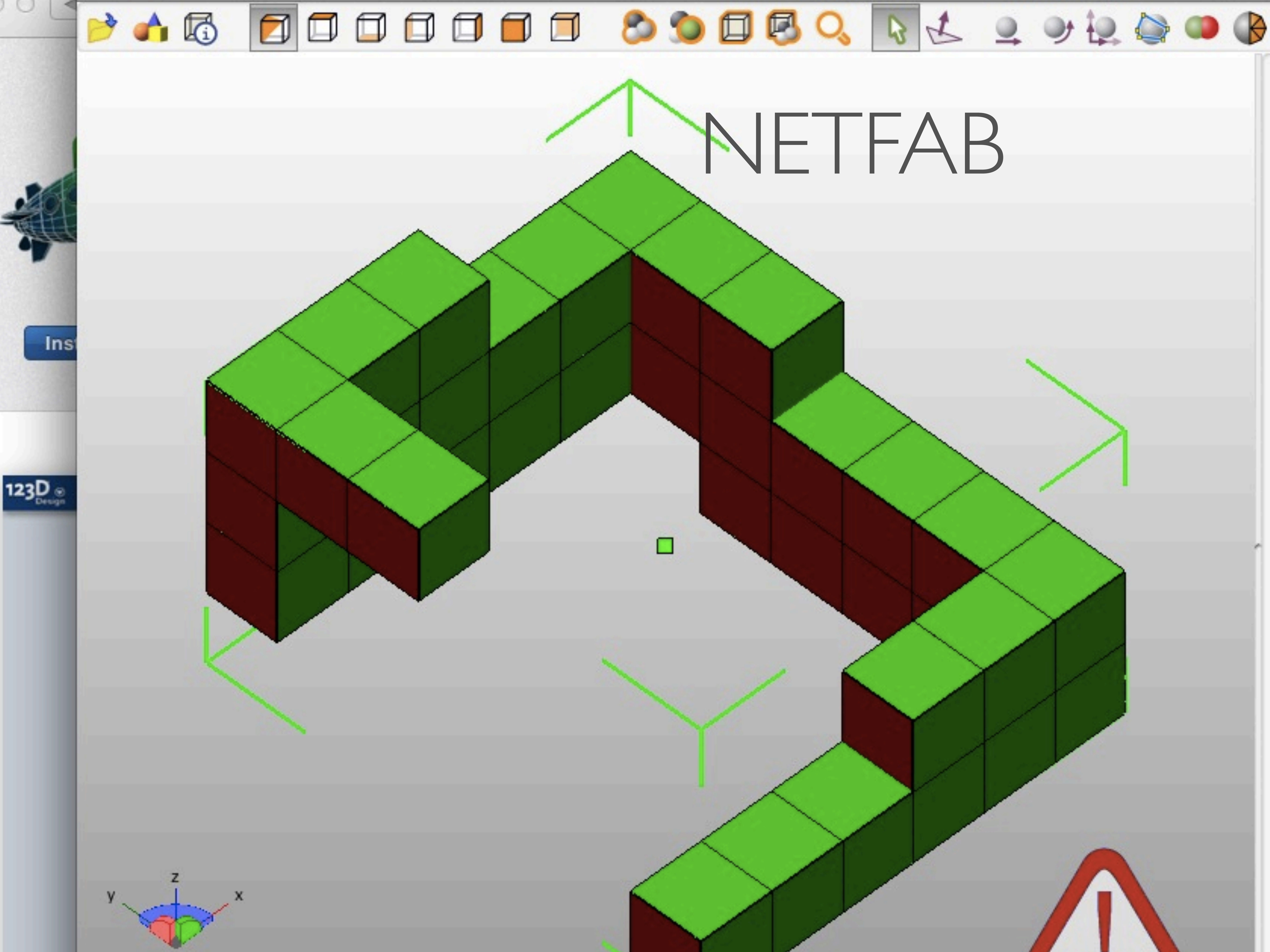

123 DESIGN

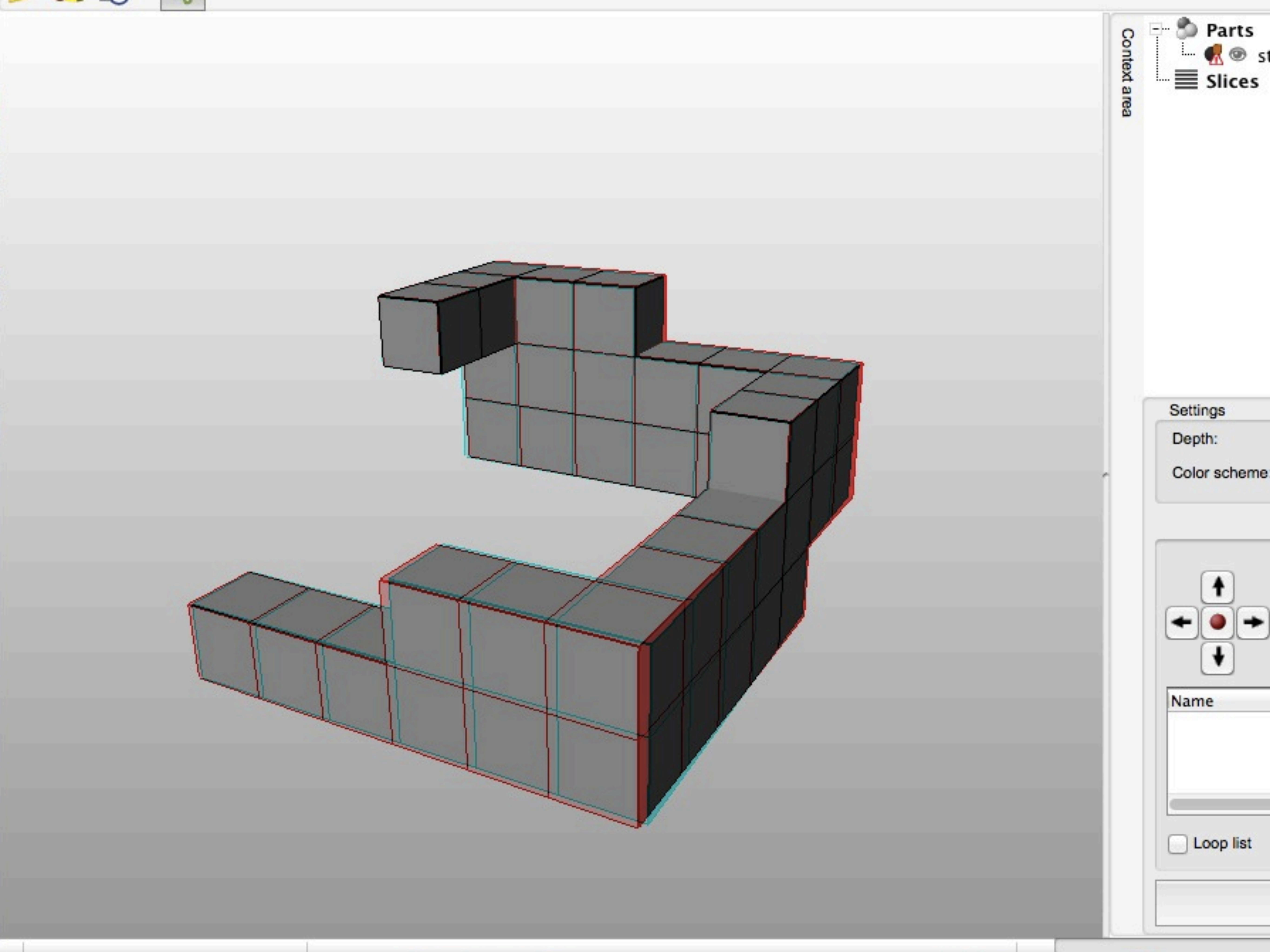
MESHLAB



Filters
Render
View
Windows
Help
MeshLab v1.3.0
Project_1
Current Mesh: stairs.stl
Vertices: 122 (122)
Faces: 444 (444)

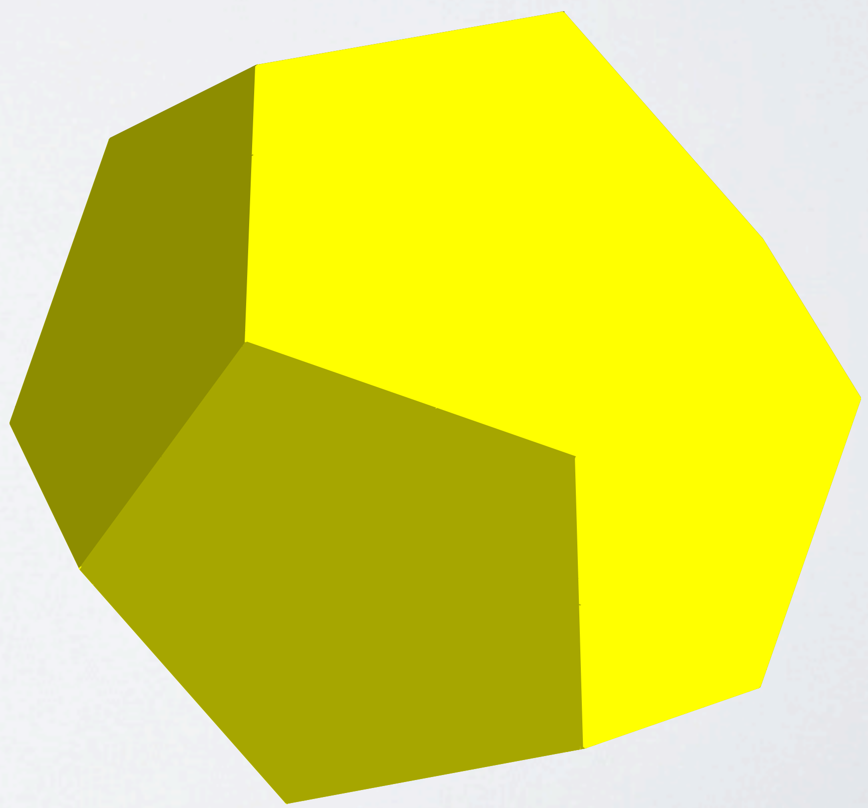



NETFAB
Ins
123D
Design
z
y
x

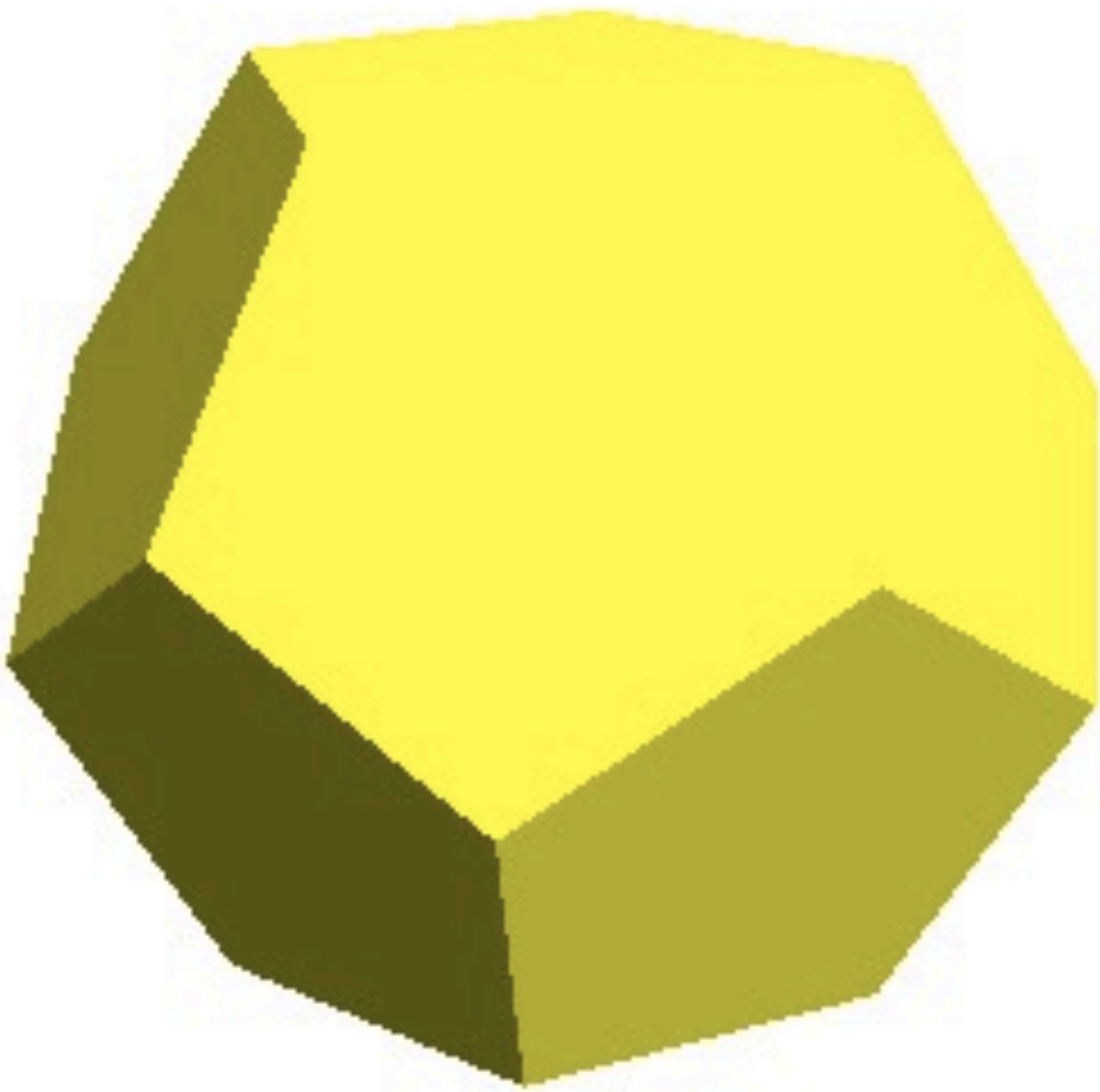

Context area
Parts
Slices
Settings
Depth:
Color scheme
Name
Loop list

MATHEMATICA

```
S = Graphics3D[{Yellow, PolyhedronData["Dodecahedron"][[1]]}];
Export["dodecahedron.3ds", S, "3DS"];
Import["dodecahedron.3ds"]
```



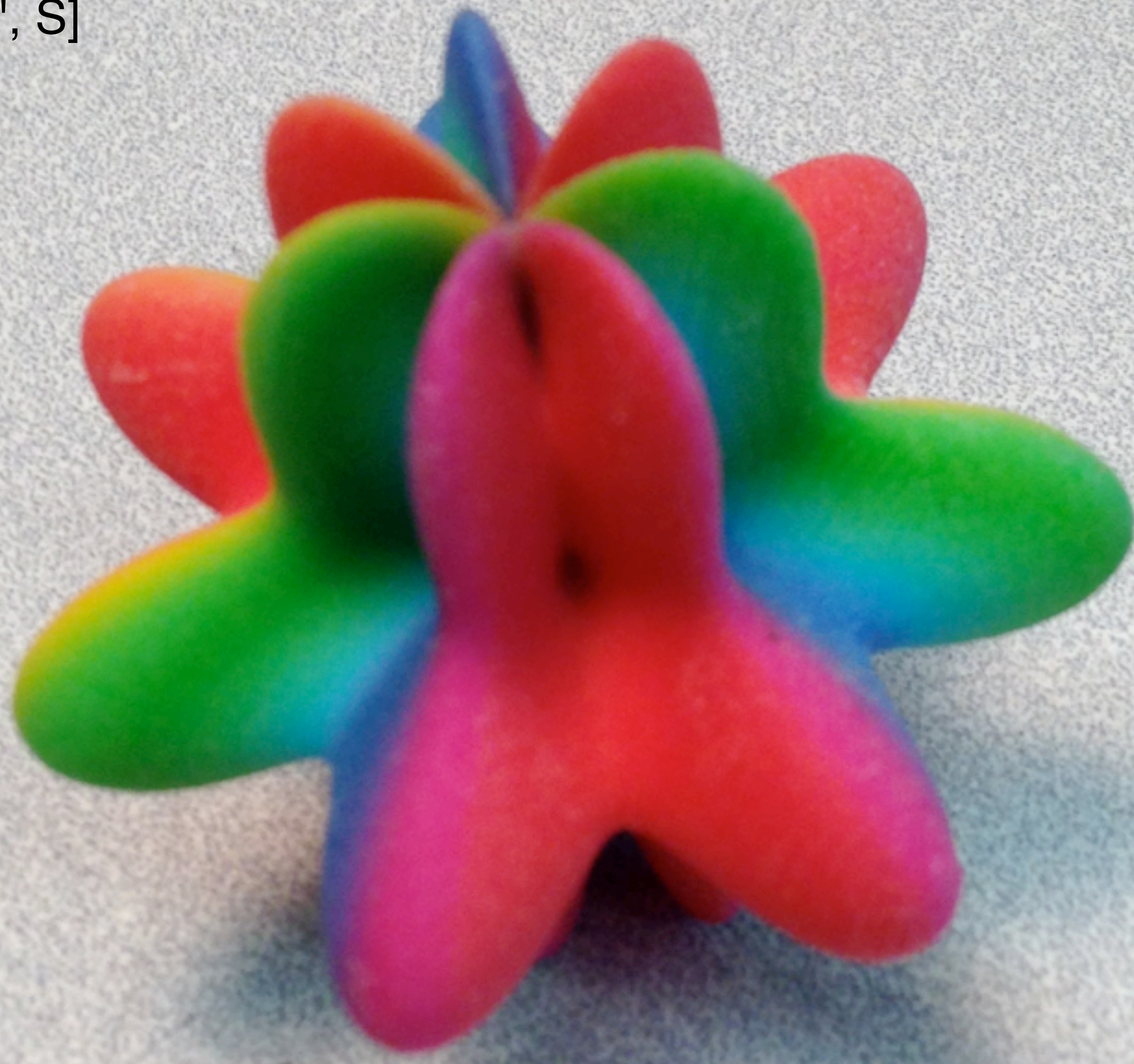
```
S = Graphics3D[{Yellow, PolyhedronData["Dodecahedron"][[1]]}];
Export["dodecahedron.3ds", S, "3DS"];
Import["dodecahedron.3ds"]
```



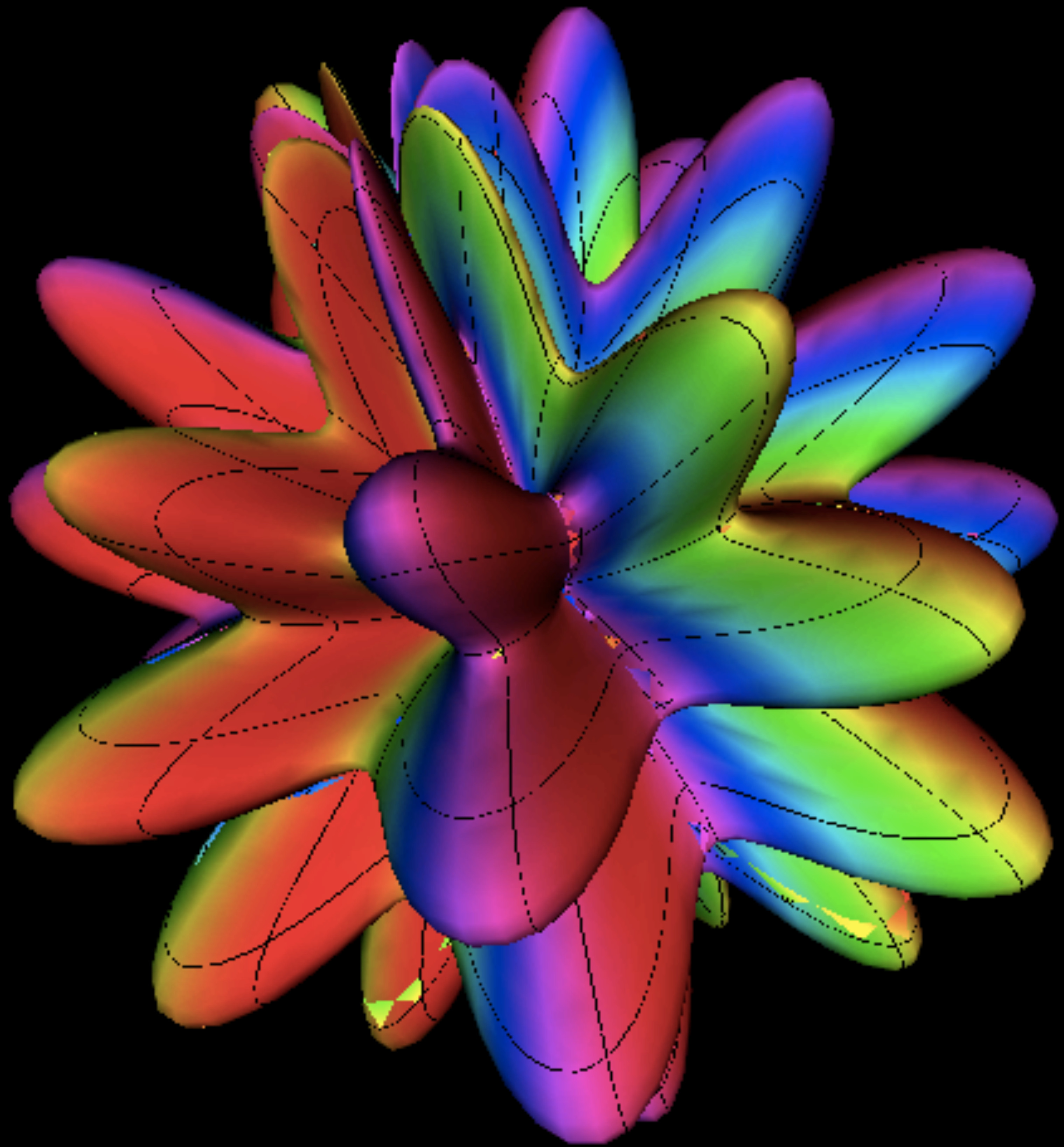
S = Graphics3D[{Yellow, PolyhedronData["Dodecahedron"][[1]]}]; Export["dodecahedron.3ds", S, "3DS"]; Import["dodecahedron.3ds"]

axes | background | viewpoint | add bounding box | more...

```
S = ParametricPlot3D[
   5 (3 + Sin[11 s] - Sin[7 t]) {Cos[t] Sin[s], Sin[t] Sin[s], Cos[s]}, {t, 0,2 Pi}, {s, 0, Pi},
   ColorFunction -> Function[{x, y, z, u, v}, Hue[(Sin[11 u])^2]]];
Export["sphere.x3d", S]
```



Free WRL



AND JUST LEARNED FROM THE BOOK

COMBINE TOOLS

3D Modeling with OpenSCAD - *Part 1*

Sebastian Büttrich

pITLab, IT University of Copenhagen, Denmark

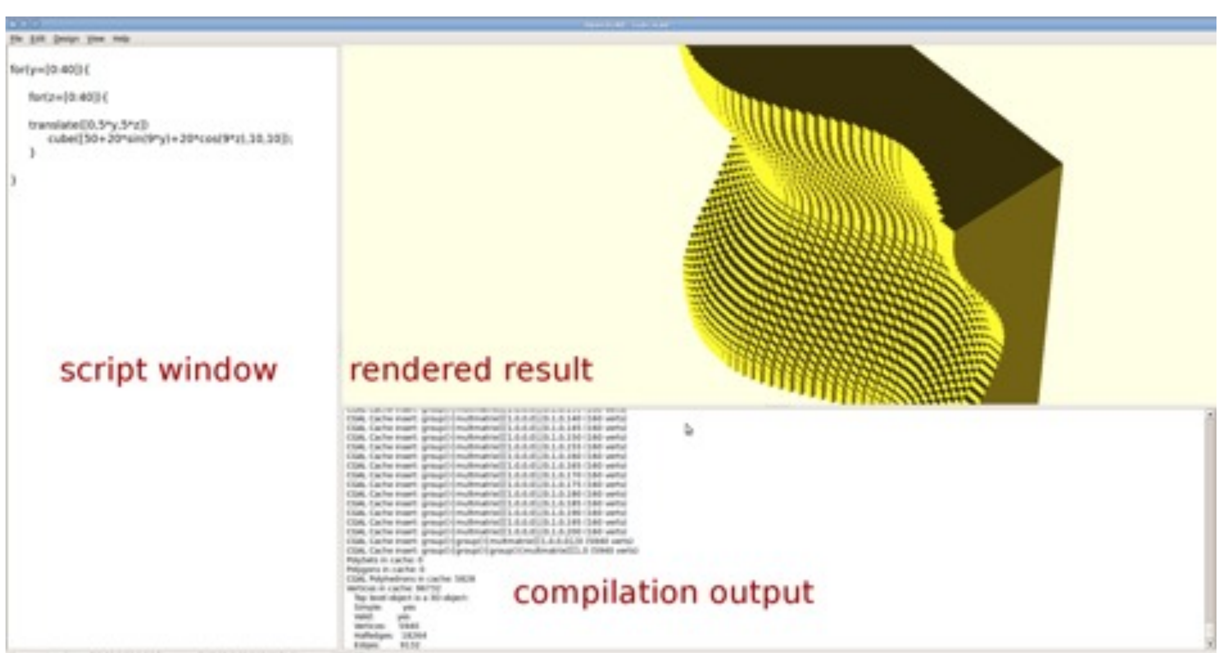
sebastian@itu.dk

On the way from idea to finished 3D print, there are a number of different steps to perform. Starting with the design of a CAD file or the capture of an existing object, followed by the conversion to an STL file, possibly some post-processing/repair work, and finally to the conversion to a printer-executable gcode file.

Your first steps in 3D printing might be based on 3D designs found on the internet, but when you are getting serious, you will want to design your own, or improve existing designs, rather than just replicating the work of others. We will focus on the design step here –*i.e.*, the production of 3D models and export of STL files.

There are many software tools available, and the following two URLs are good starting points for learning about them:

- http://www.reprap.org/wiki/Useful_Software_Packages
- https://en.wikipedia.org/wiki/Comparison_of_3D_computer_graphics_software



Designing in OpenSCAD

3D Modeling with OpenSCAD - *Part 2*

Marius Kintel

OpenSCAD developer, Austria

marius@kintel.net

Some words from the author

OpenSCAD grew out of the RepRap community, more exactly out of the 3D printin activities at the Metalab (http://metalab.at), a hackerspace in Vienna, Austria.

The idea of OpenSCAD was born because we lacked a free software design tool fo rapidly and iteratively creating mechanical parts. The existing tools at the time were too time consuming to use and changing details often required full remodeling. Commercial CAD tools which solve these problems do exist. However, apart from them being prohibitivel expensive, they weren't Open Source and we felt that the world needed a better Open Source design tool.The basic idea of OpenSCAD was to allow people to describe their 3D models beginning with basic building blocks, and iteratively build from there. Additionall we wanted it to be possible to parametrically describe shapes and positions in order t facilitate customizations and adaptations without having to go through time consuming and boring remodeling tasks.

Early on, we realized that OpenSCAD would have severe limitations in terms of creatin geometric shapes, so we decided to enable users to model more complex building blocks in their software of choice. OpenSCAD can then and import these files for further modeling while you at any time can go back and change the basic geometry without having to redo th work already done in OpenSCAD. Keeping source code as the user interface also has an important emergent property in that people are enticed to share their designs, as well as thei design intentions. This also makes it possible to change, reuse, or in other ways build on th existing ideas and designs of other people.

Parametric designs

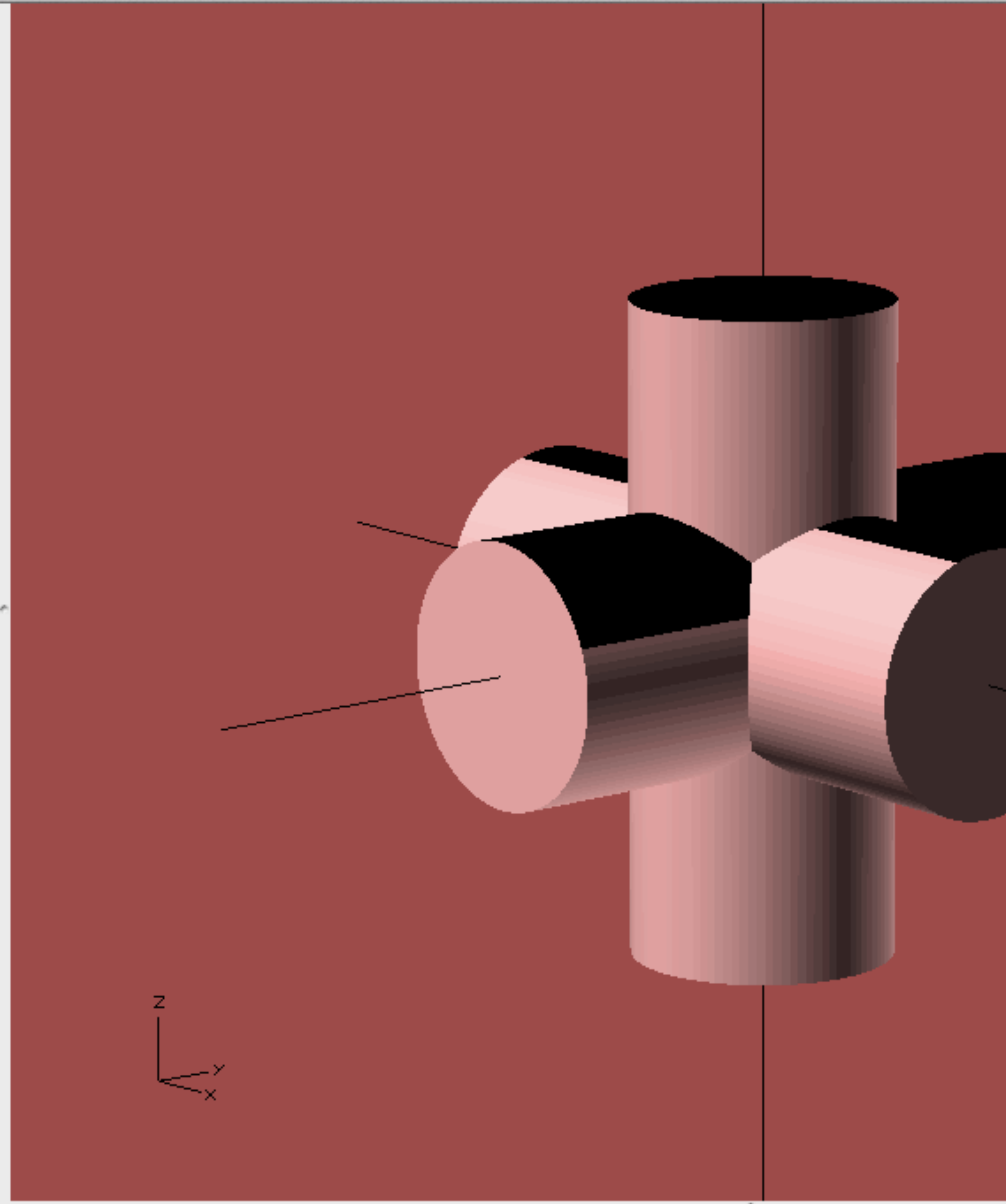
One of the primary strengths of OpenSCAD is that it supports parametric designs Parametric in this context means that you can create logical building blocks, which take certain parameters and in return create a 3D component satisfying those parameters Examples of parameters can be *Object sizes*, *Nut and bolt holes*, *Object descriptors* (e.g. *number of teeth in a gear*) or *Design elements* (text to emboss onto a design).

An example motivated by the book

OpenSCAD – New Document

```
module cyl(a){
 rotate(90,a)
 cylinder(r=10,h=50,
 center=true,
 $fn=100);
}


intersection() {
cyl([0,0,0]);
cyl([1,0,0]);
cyl([0,1,0]);
 }
```



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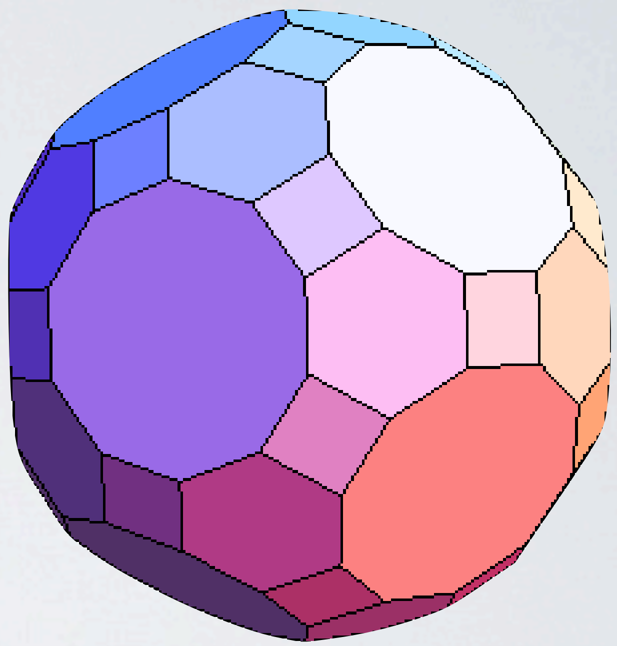
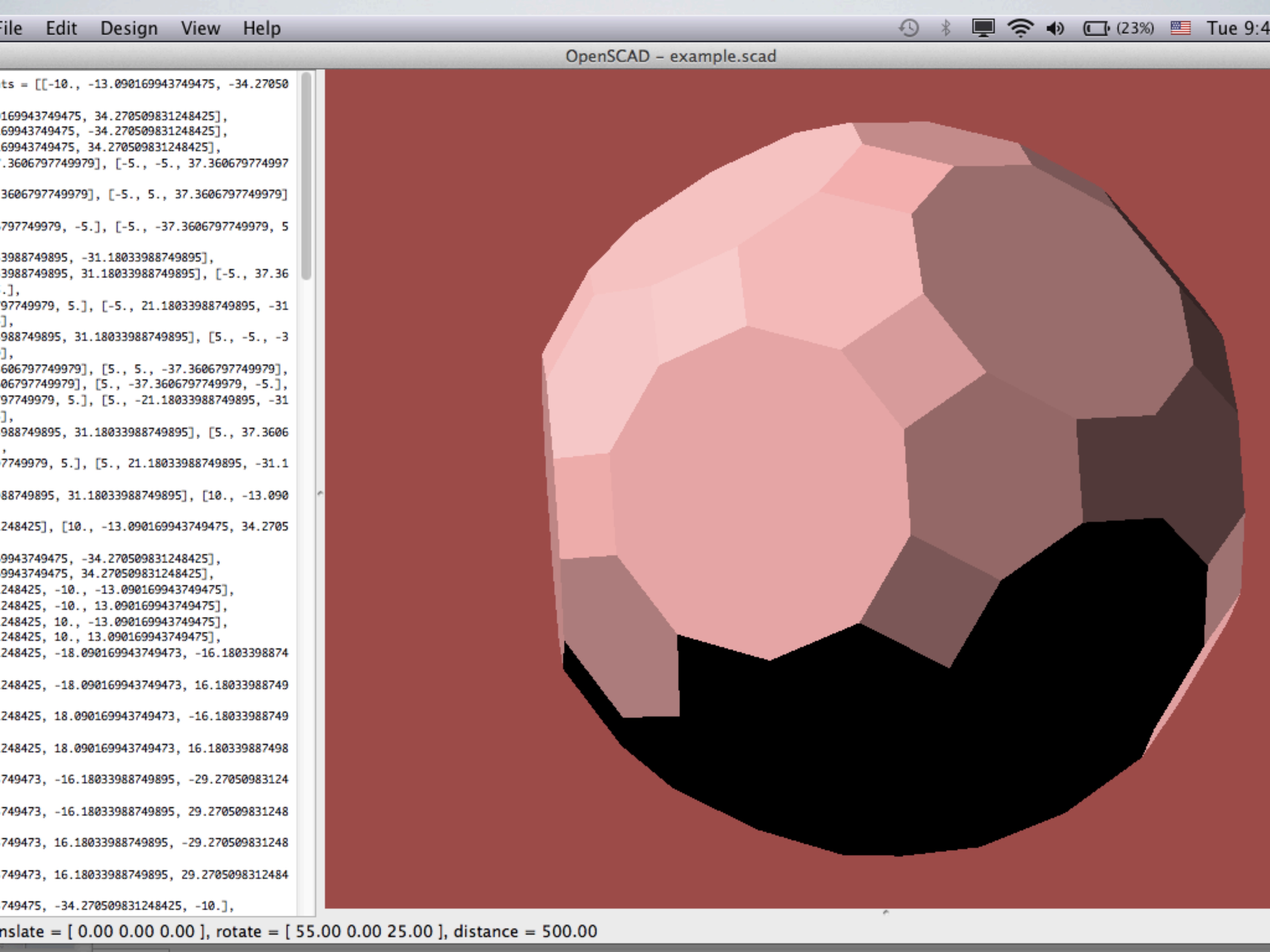
```
A=PolyhedronData["GreatRhombicosidodecahedron","Faces"];
points=10*A[[1]];  triangles = A[[2,1]]-1;
WriteString["example.scad","polyhedron("];
WriteString["example.scad","points = "];
Write["example.scad",N[points]];
WriteString["example.scad",","];
WriteString["example.scad","triangles = "];
Write["example.scad",triangles];
WriteString["example.scad",");"]
Run["cat example.scad |tr \"{\" \"[\"|tr \"}\" \"]\" >tmp; mv tmp
example.scad"];
```




File Edit Design View Help
(23%) Tue 9:4
OpenSCAD – example.scad
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749473, 16.18033988749895, -29.270509831248
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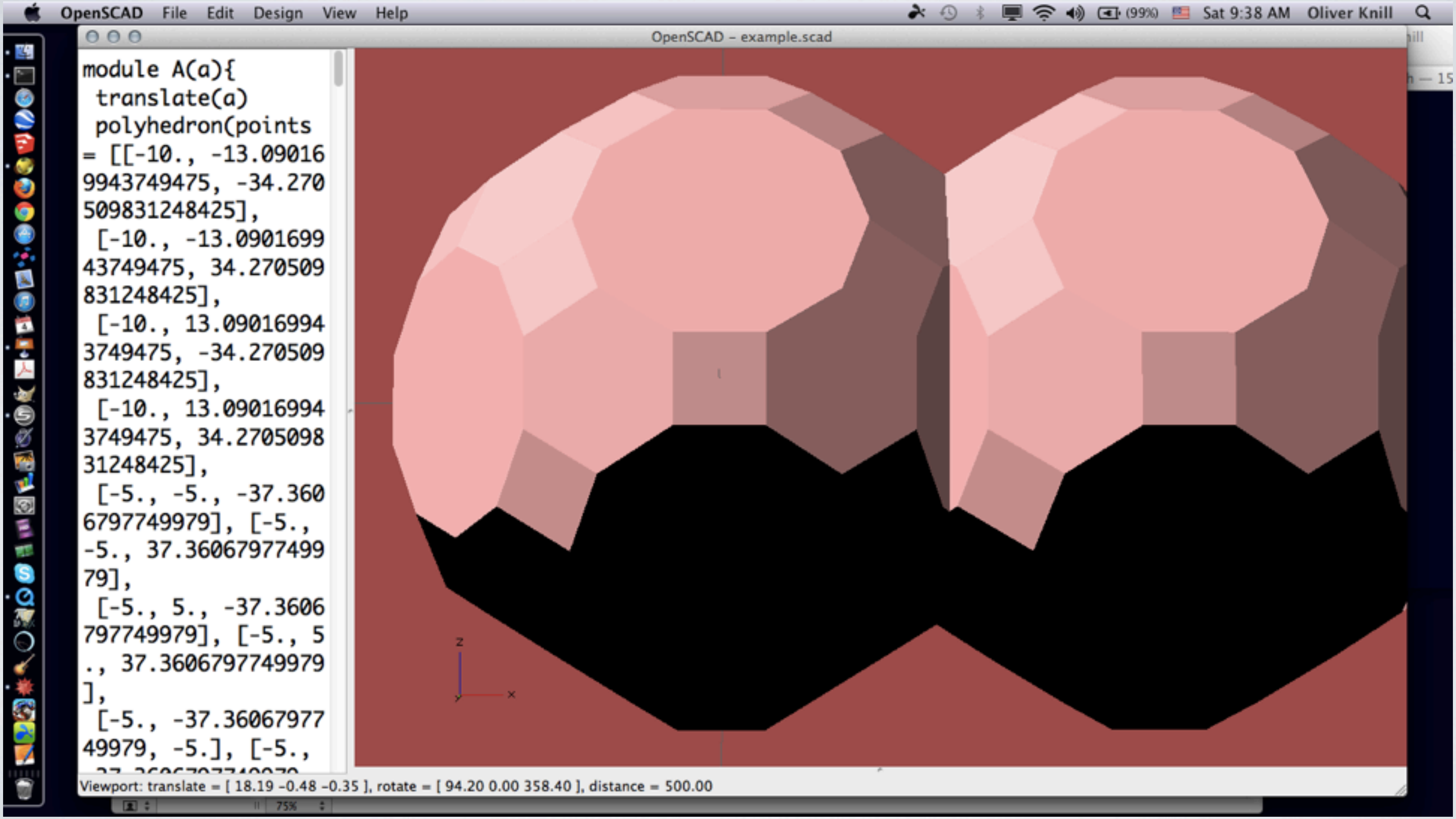
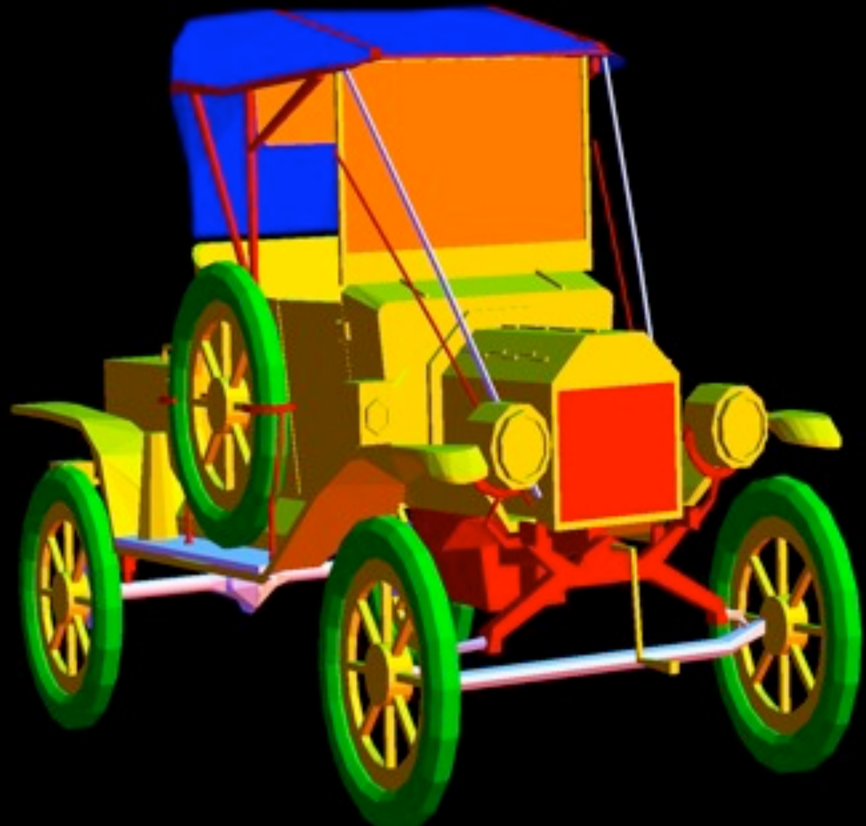
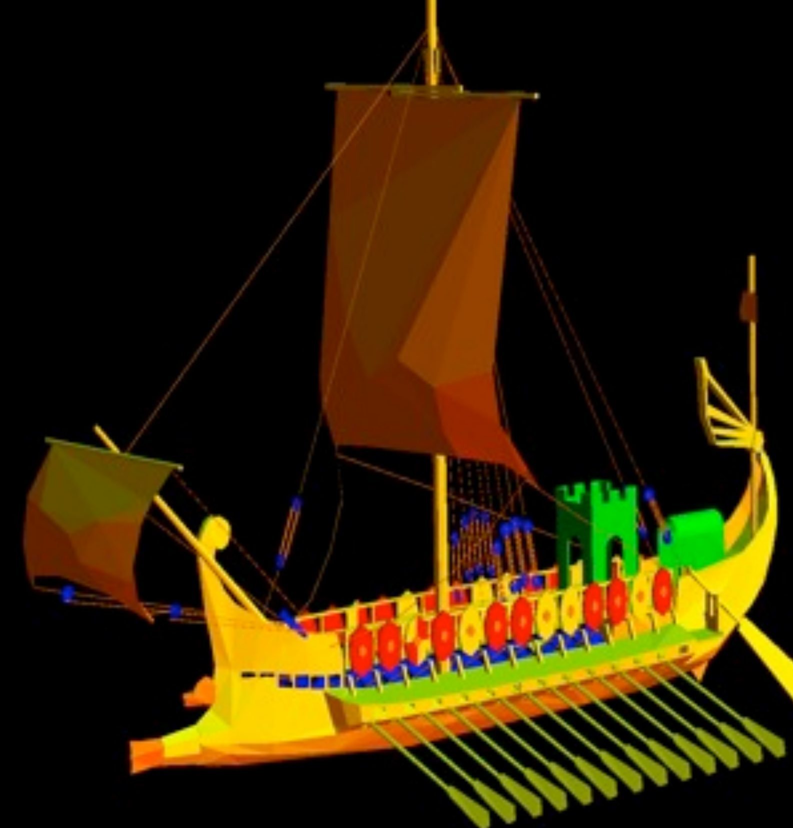
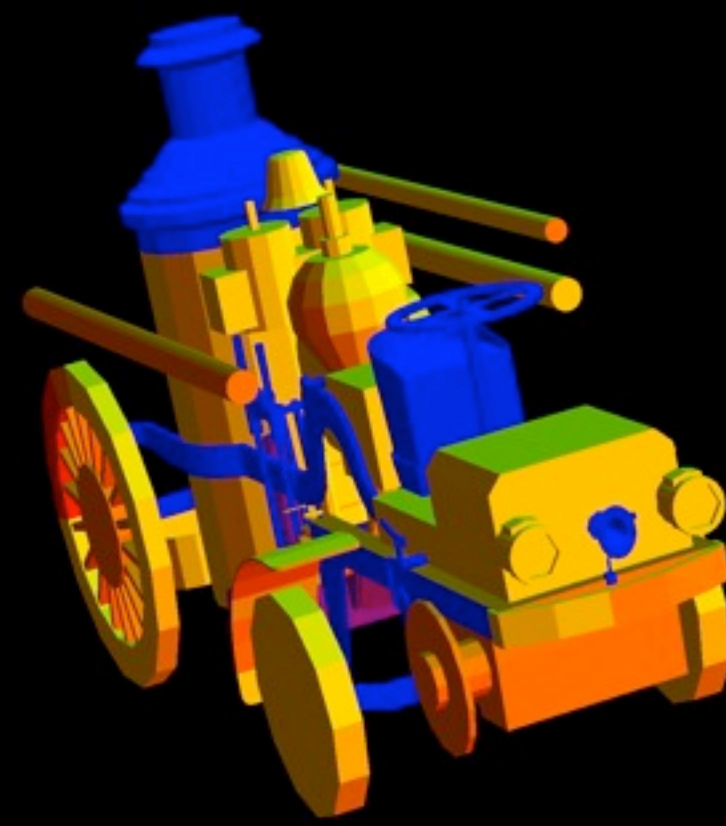
BOOLEAN OPERATIONS

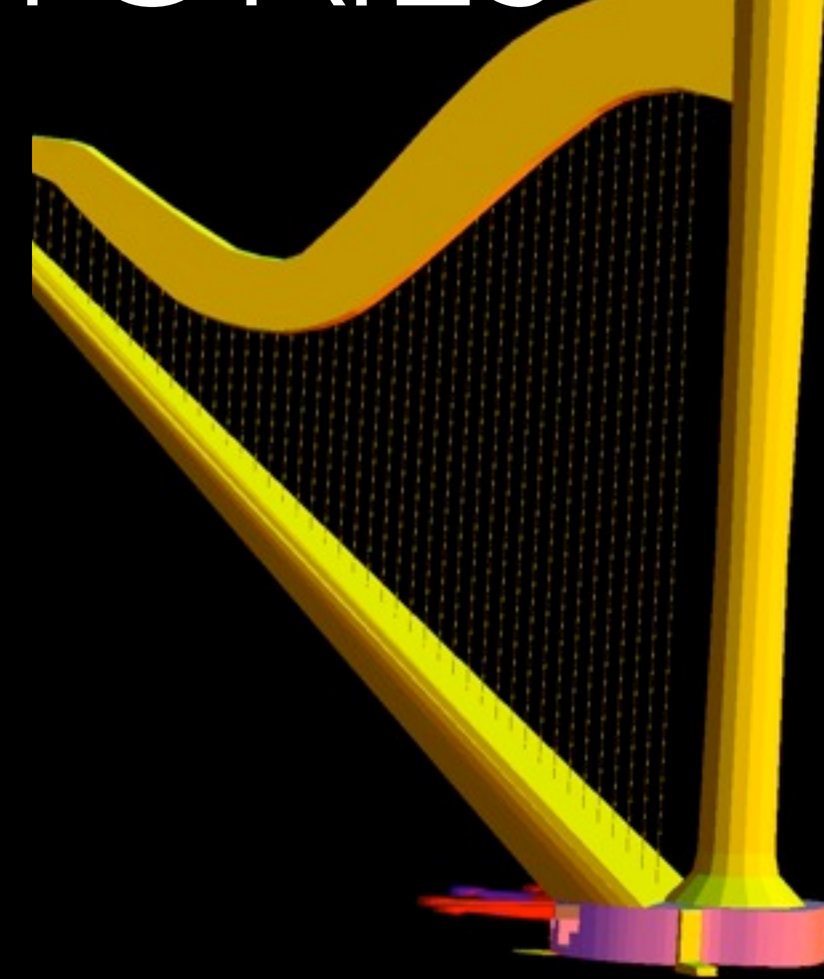




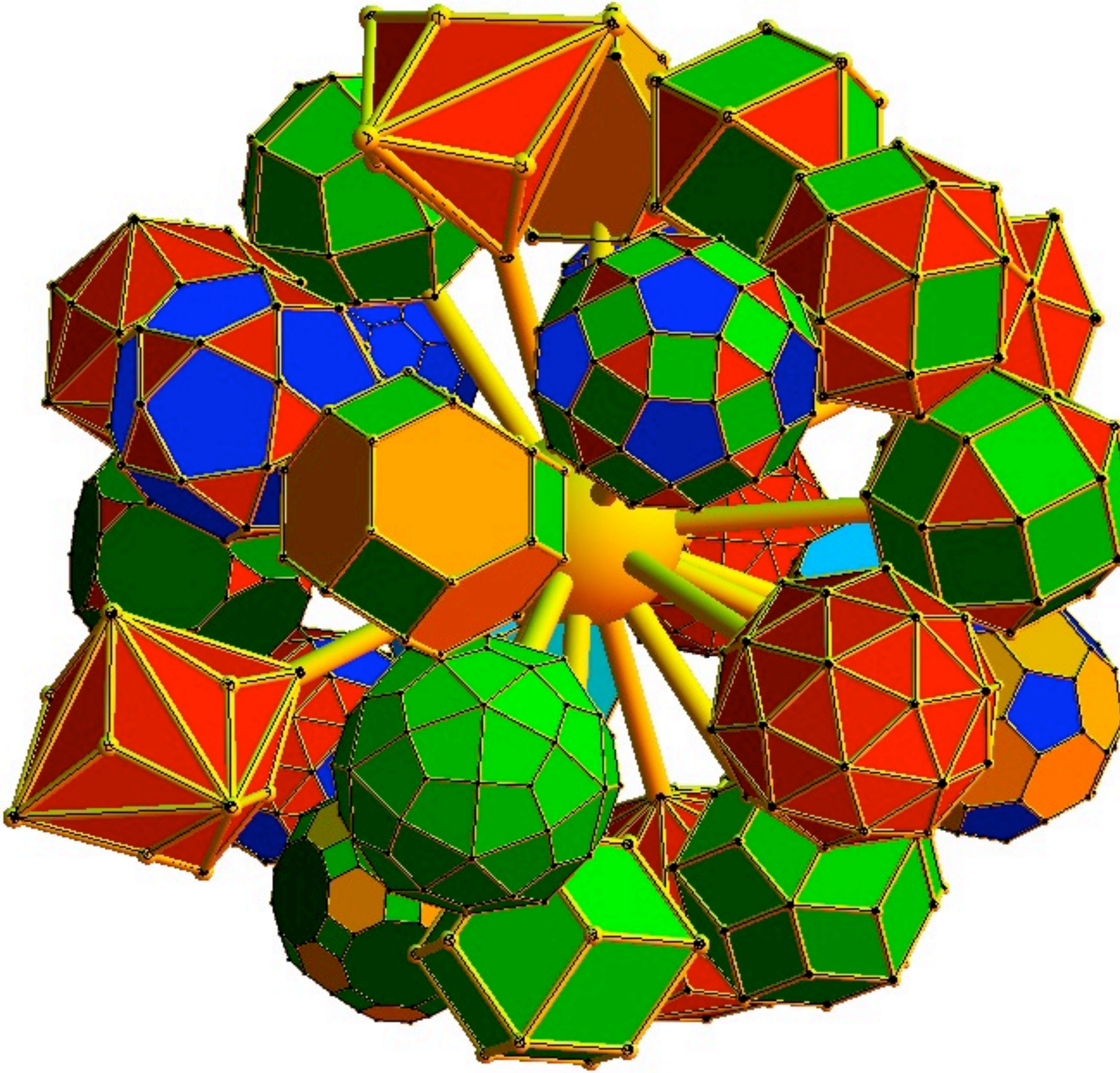


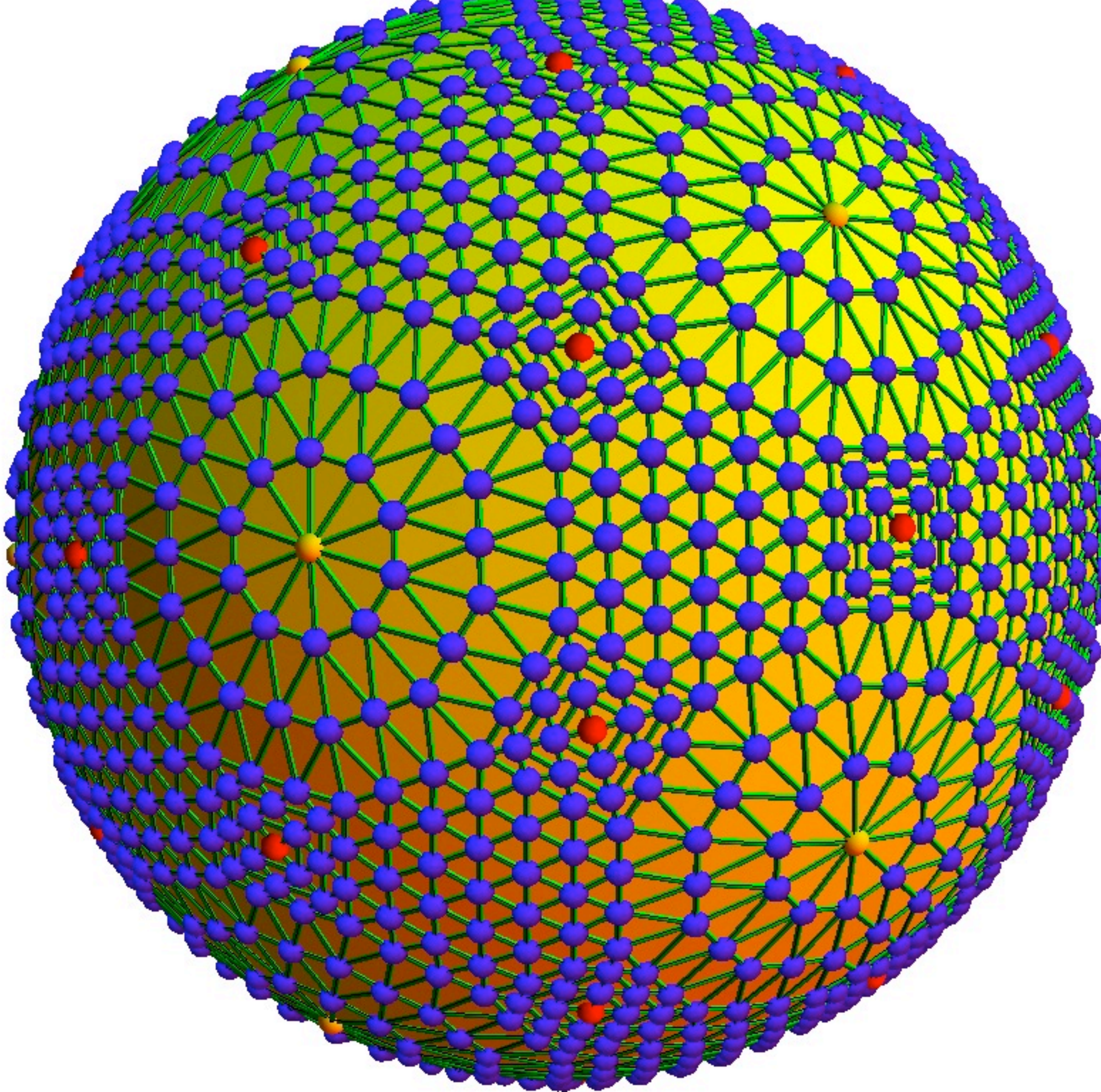
EXISTING 3D REPOSITORIES

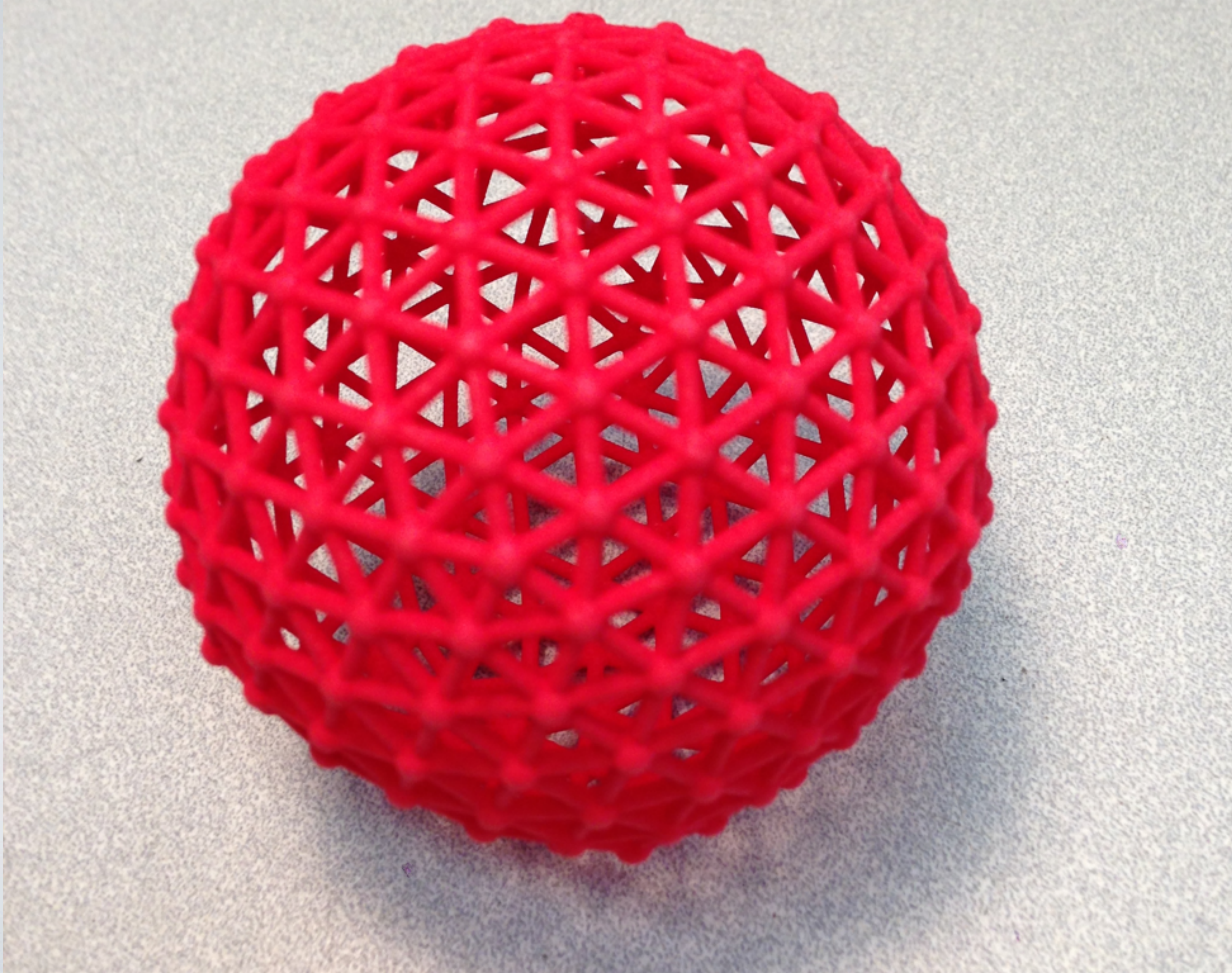


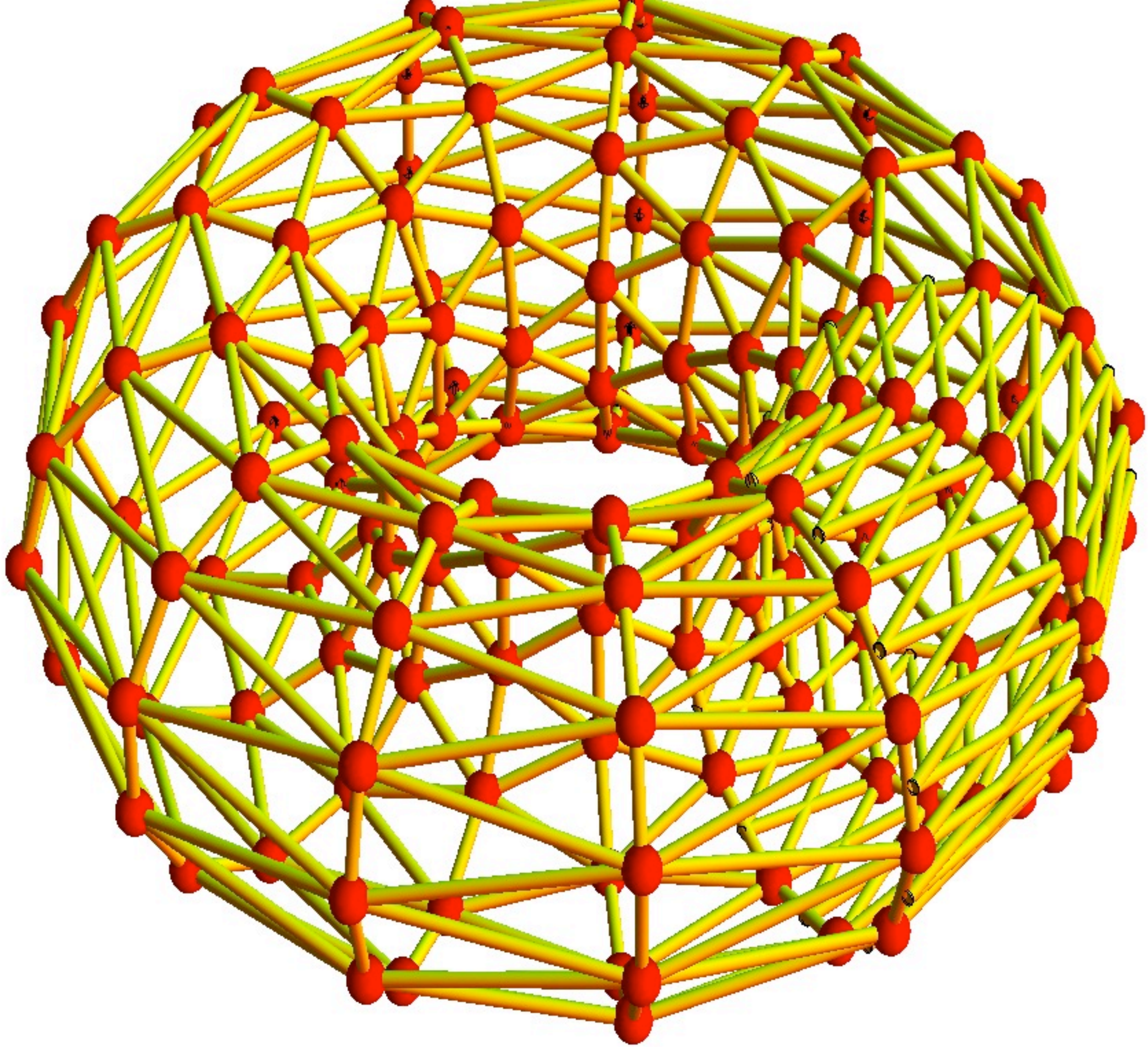


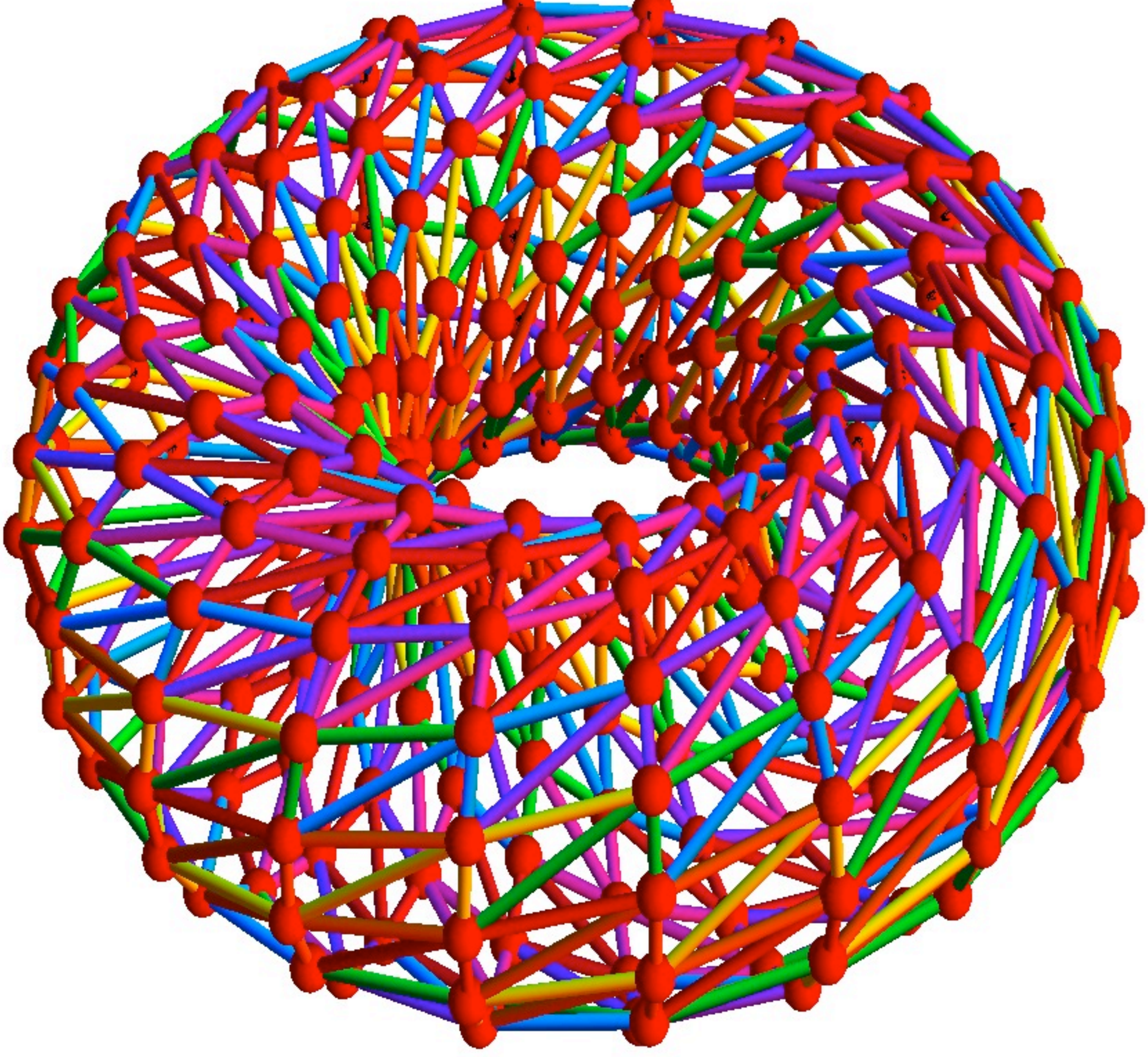
ILLUSTRATING MATHEMATICS

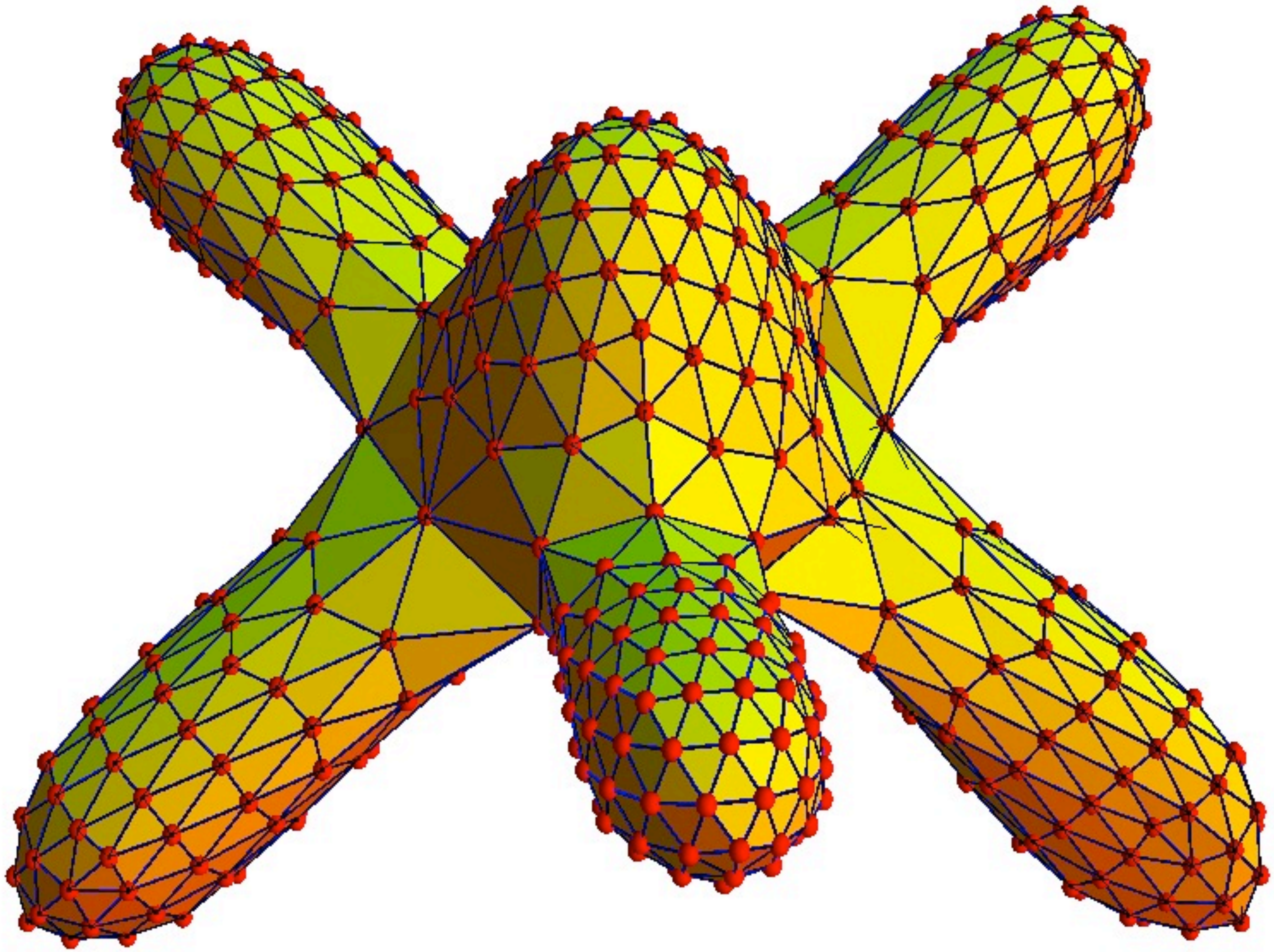












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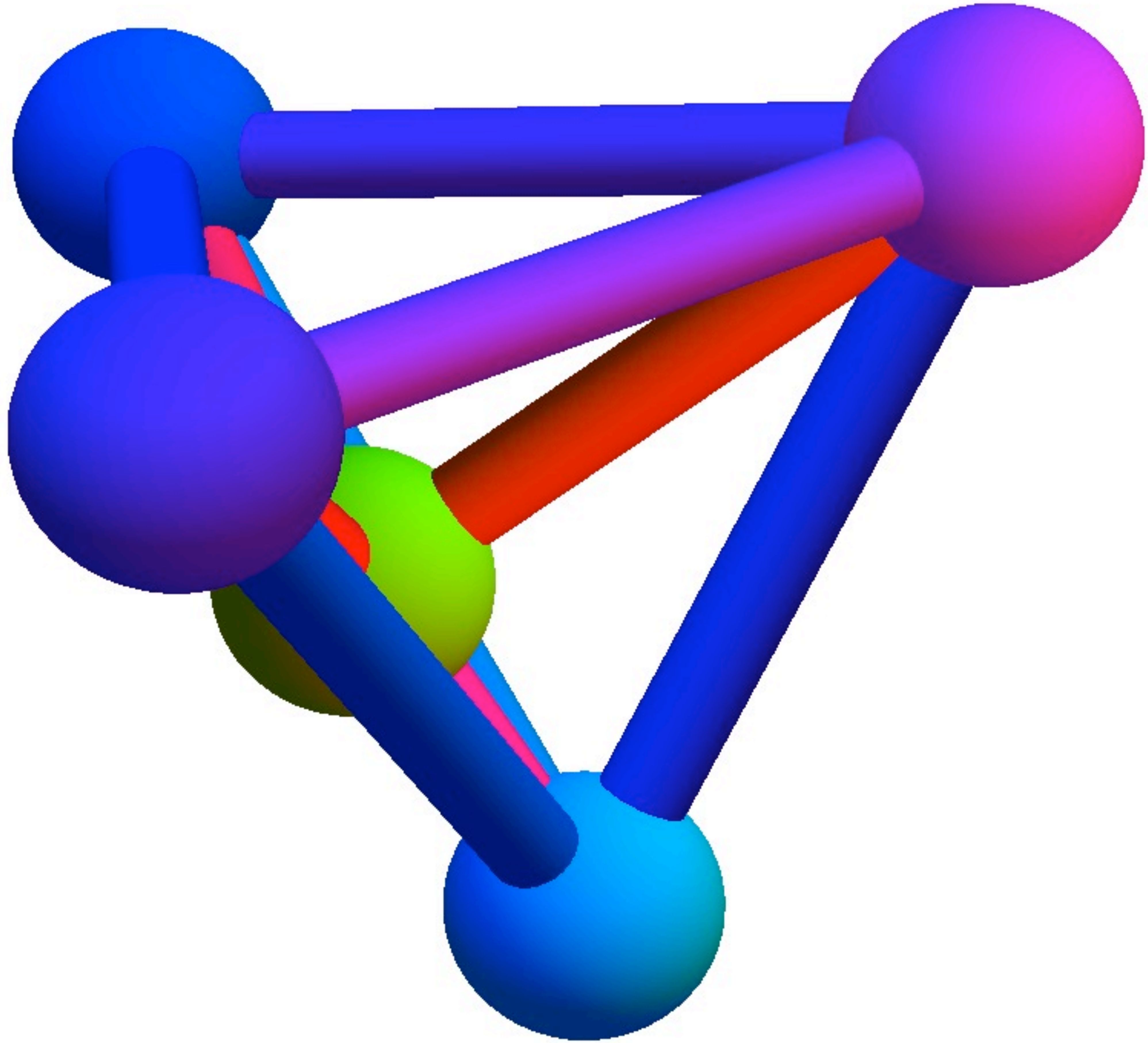

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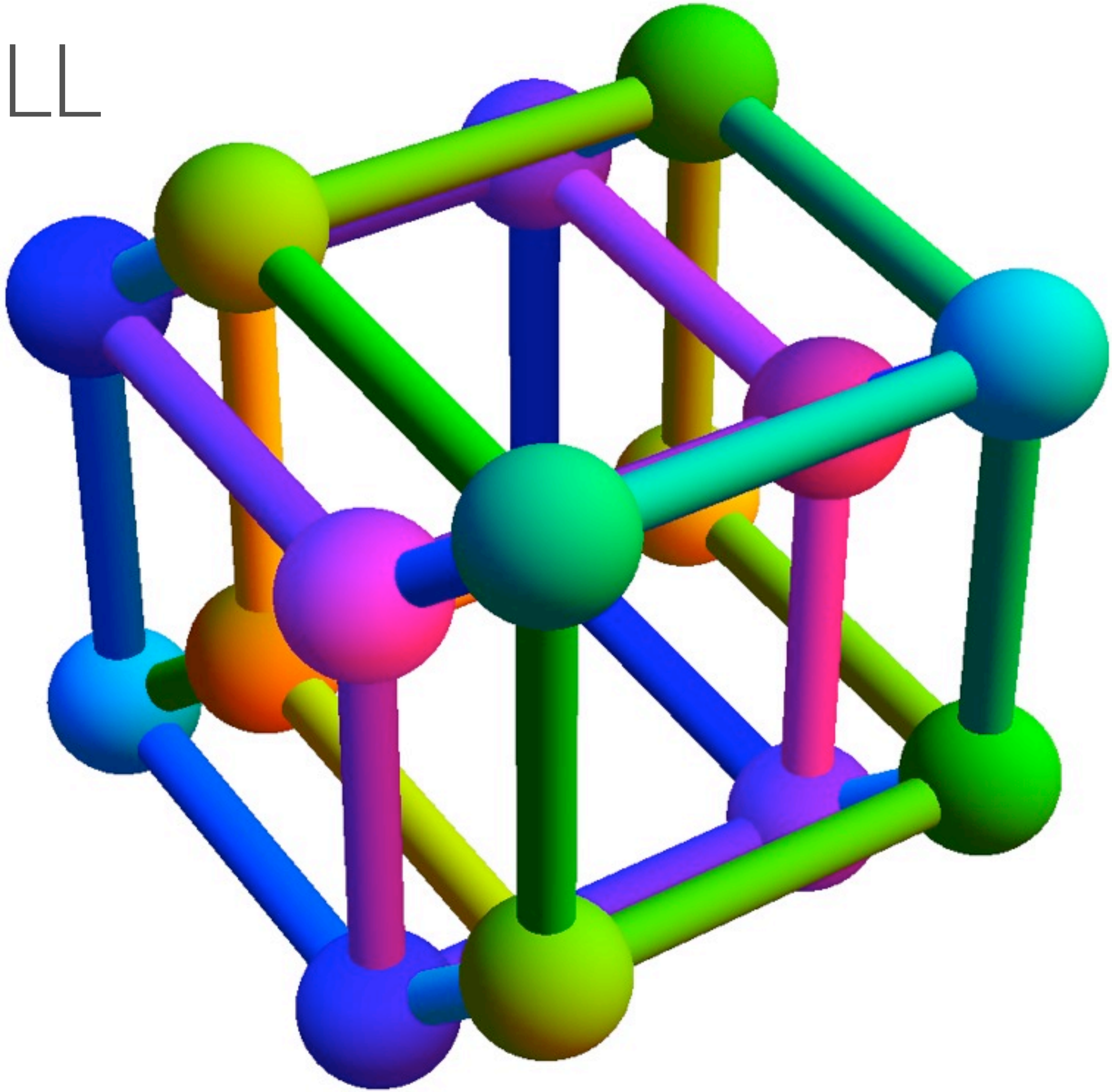

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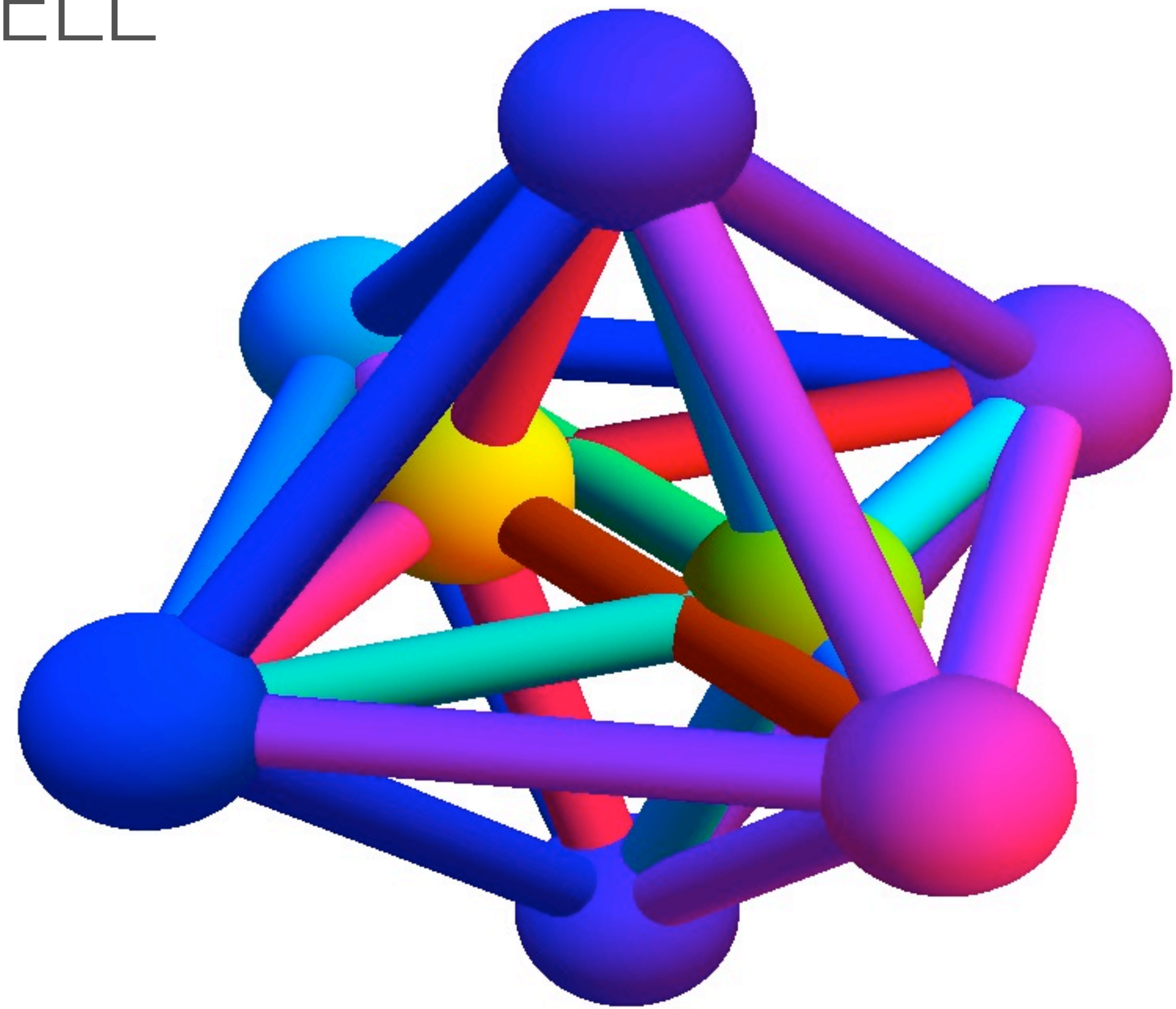

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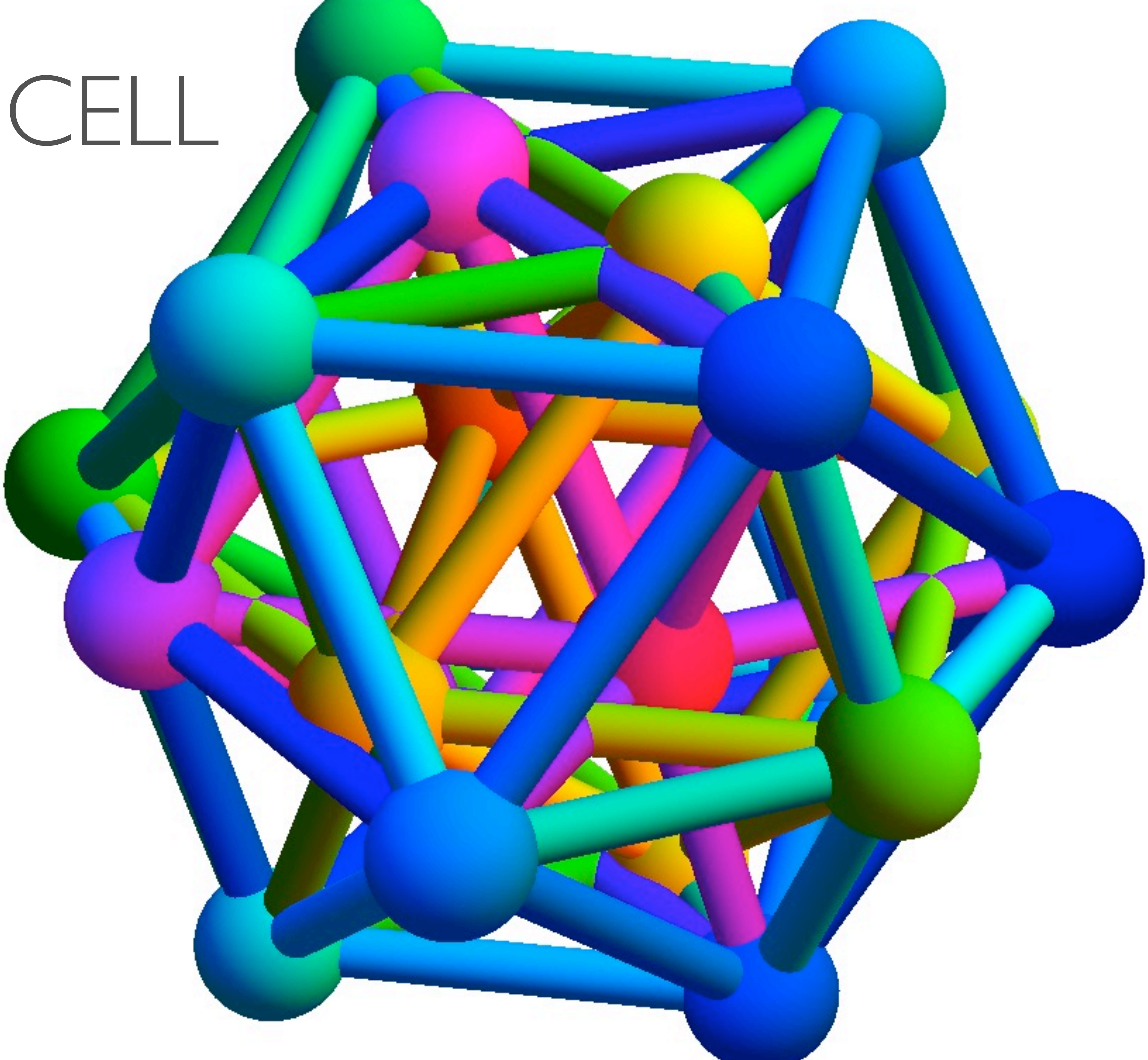

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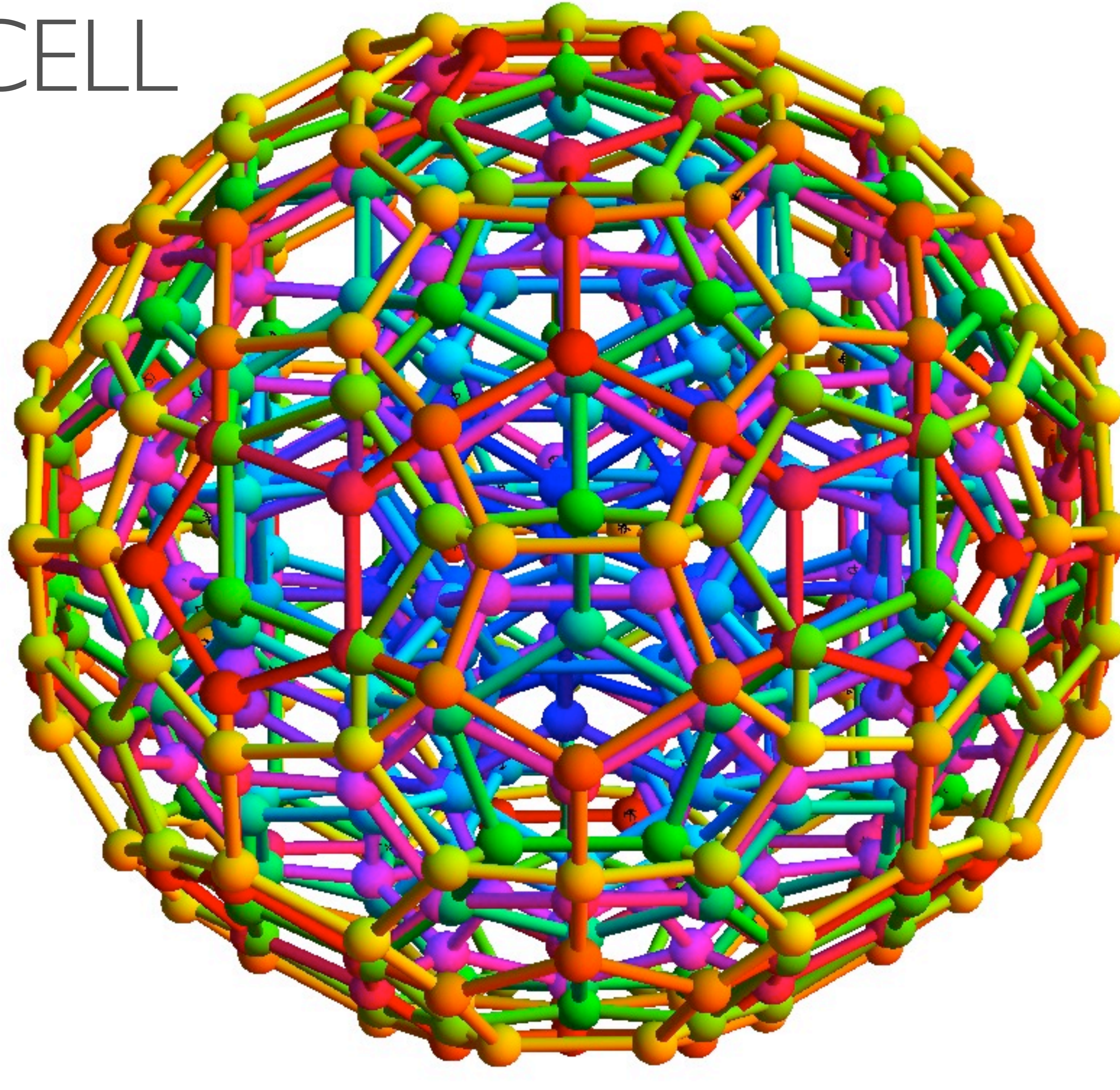

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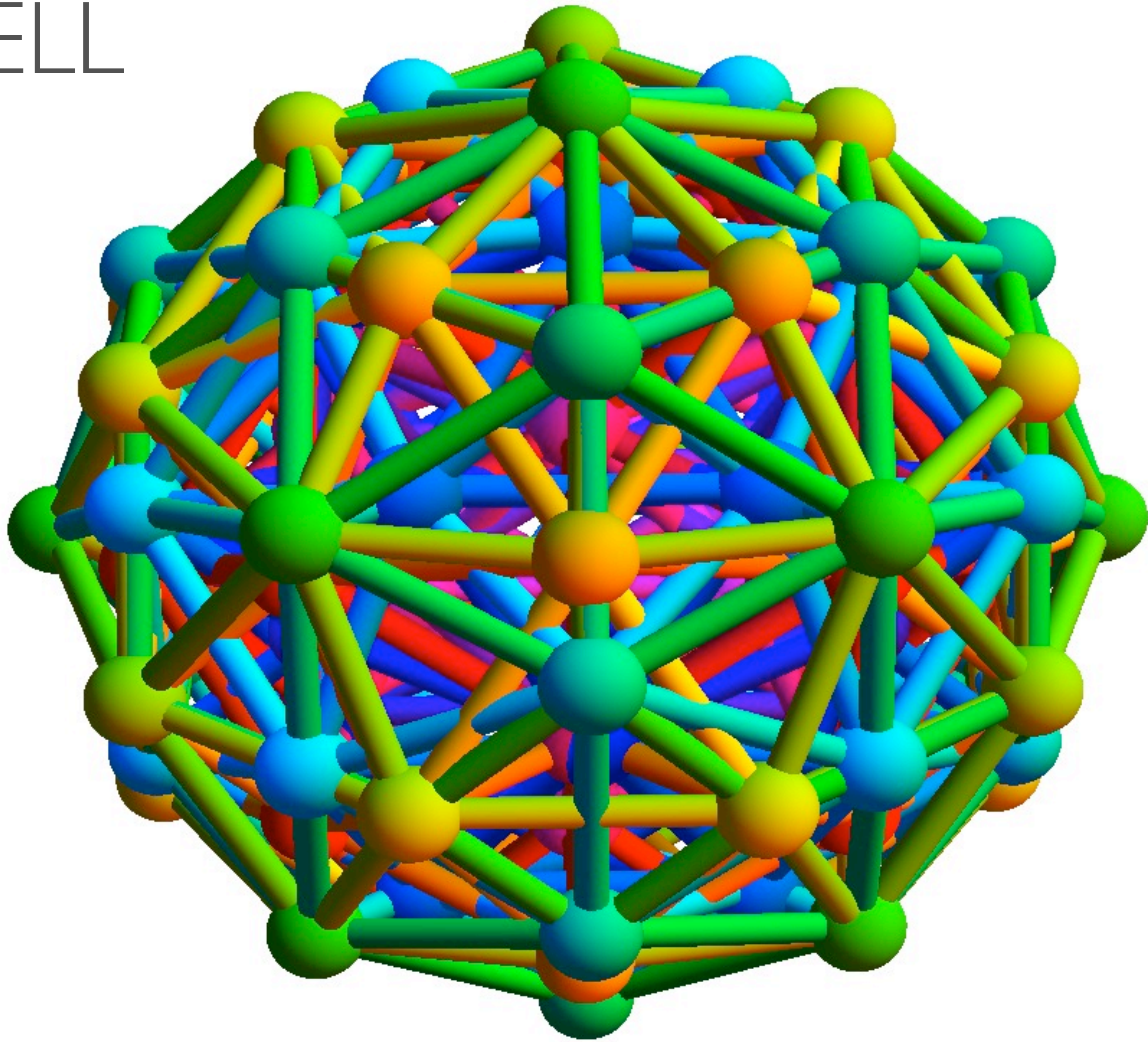
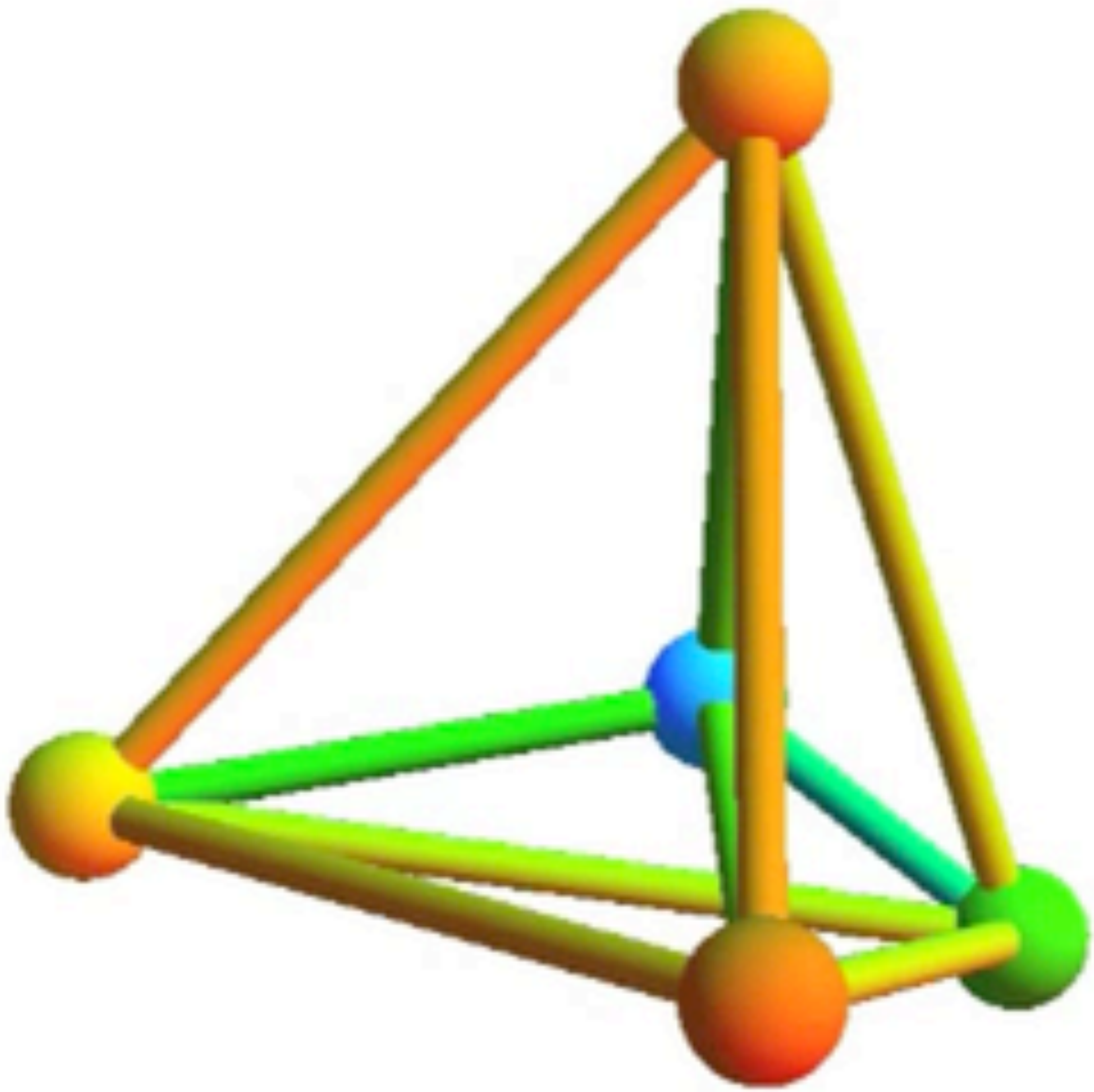
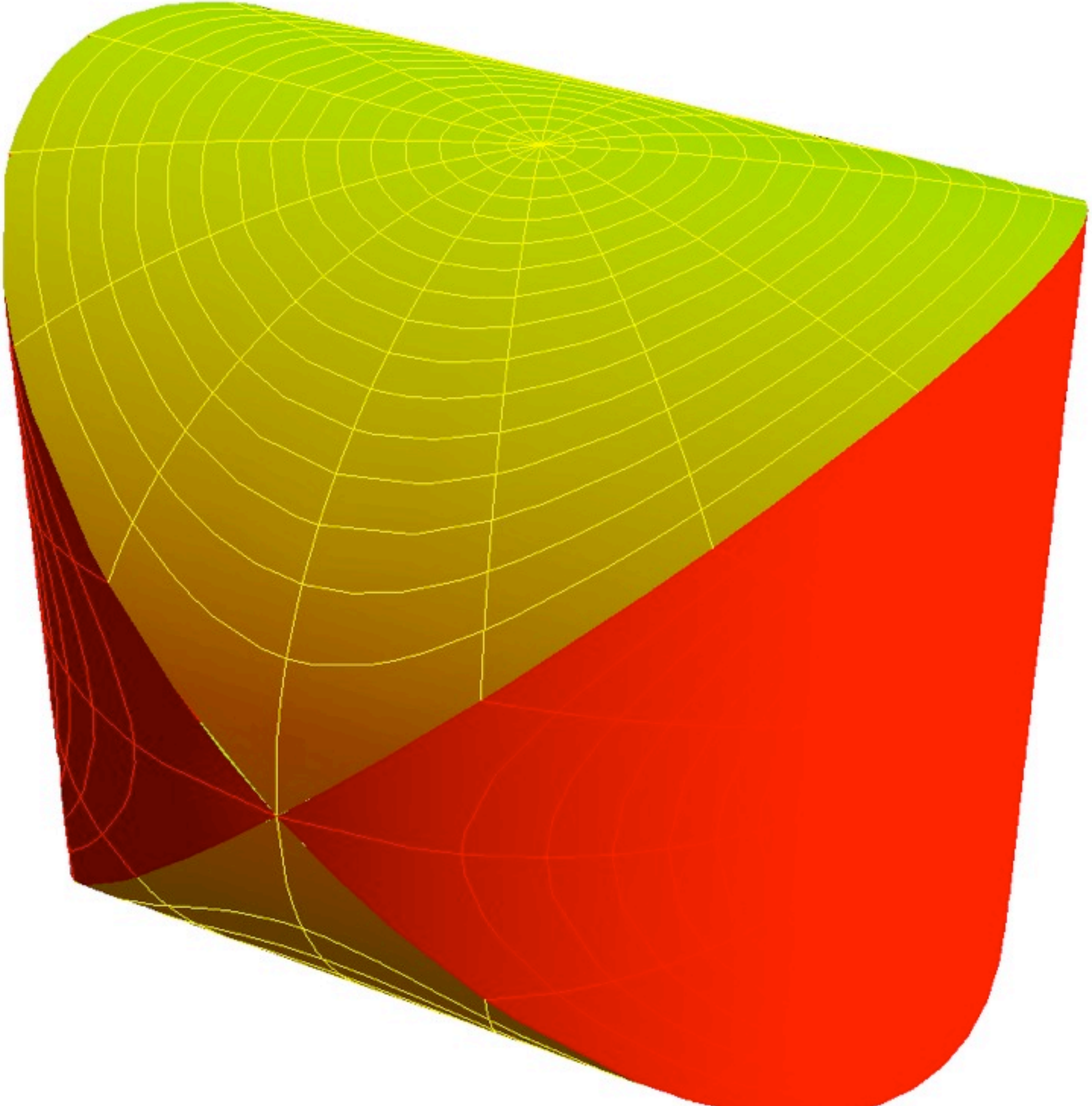
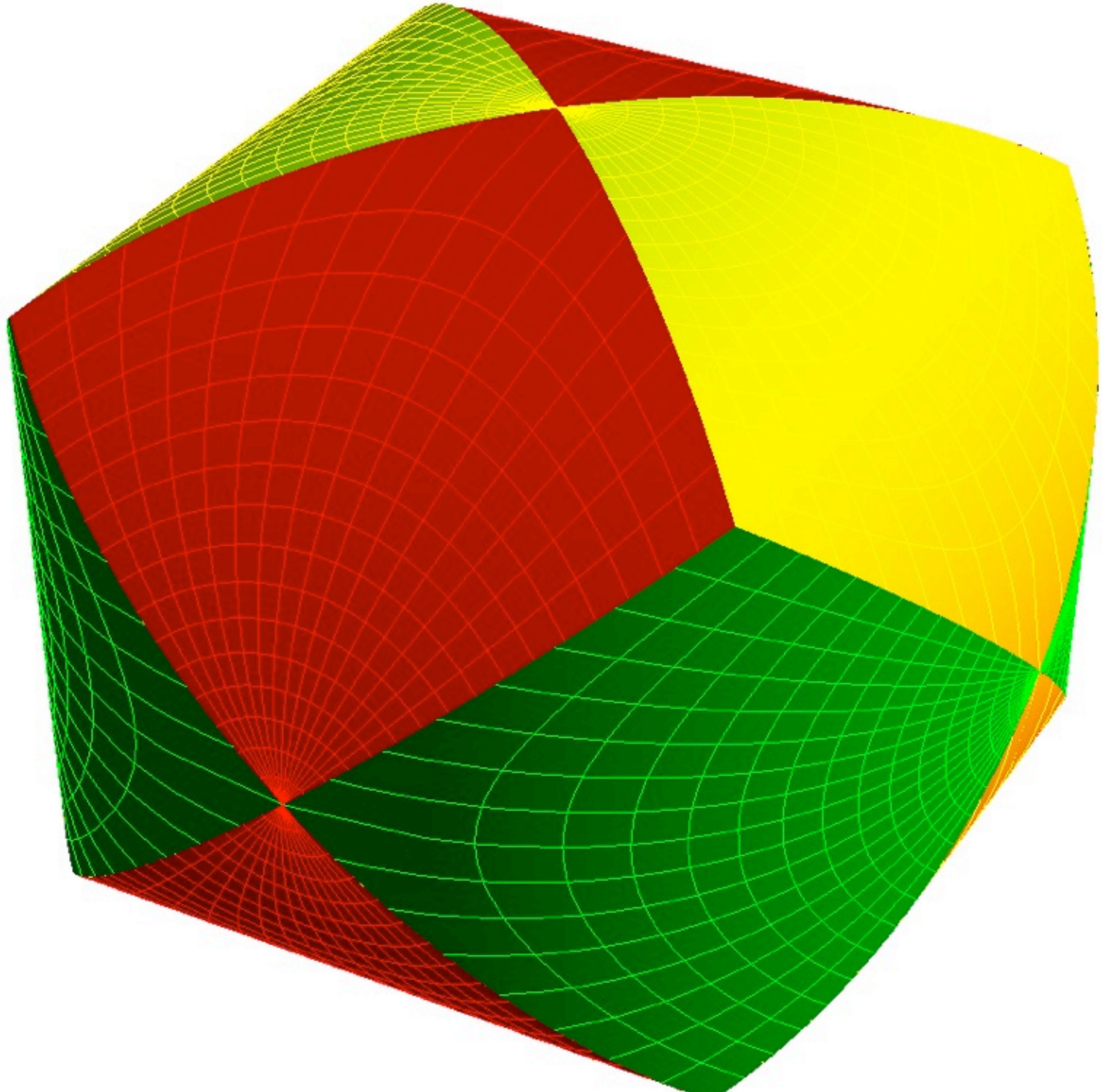




2D Infinitely Polygons
3D Five Platonic solids
4D Six Platonic solids
5D Three





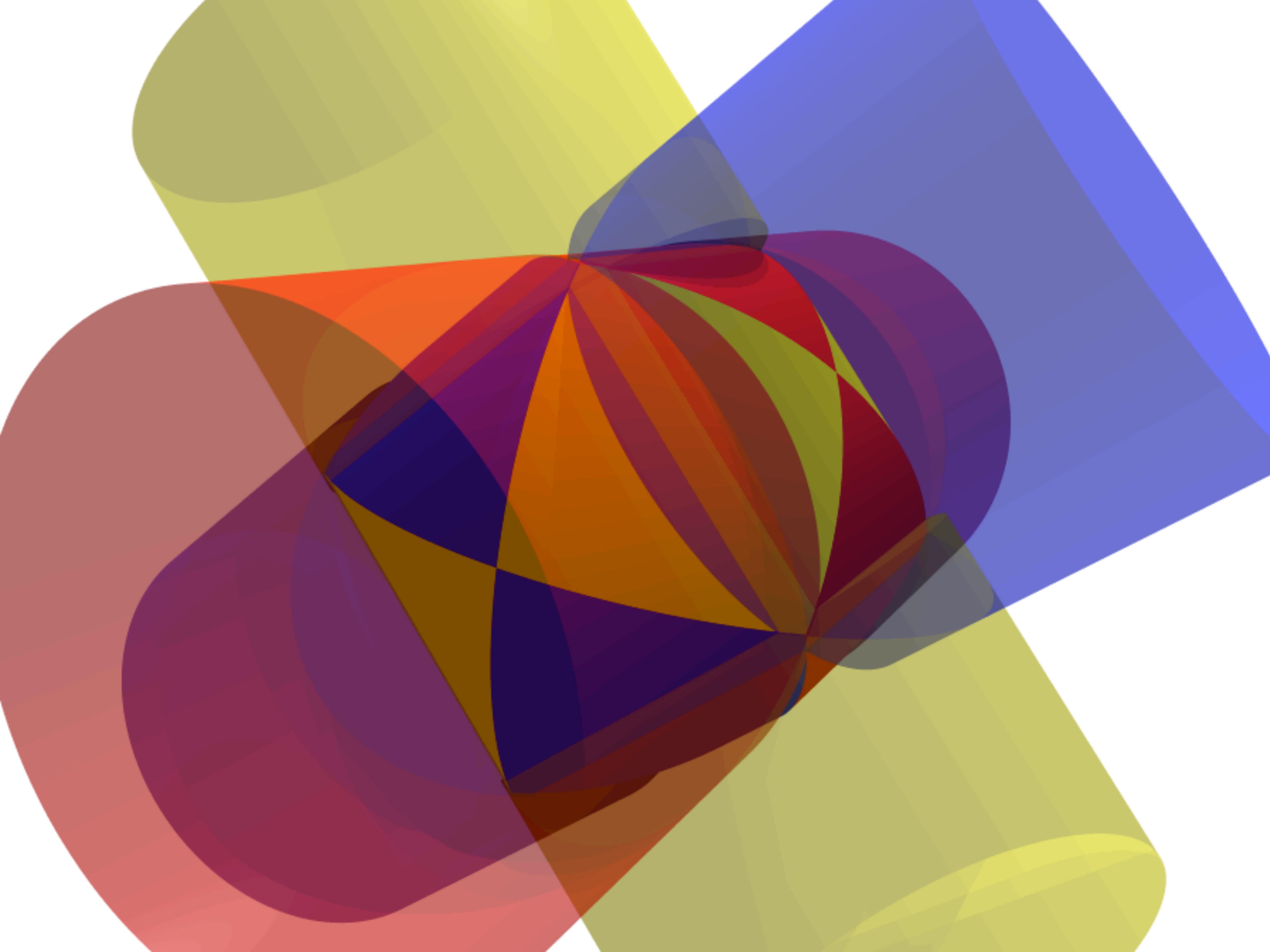
POVRAY

```
camera{up y right x location <1,3,-2> look_at <0,0,0>}
light_source { <0,300,-100> color rgb <1,1,1> }
background { rgb<1,1,1> }

#macro r(c) pigment{rgb c} finish {phong 1 ambient 0.5} #end

intersection {
  cylinder{<-1,0,0>,<1,0,0>, 1 texture {r(<1,0,0>)}}
  cylinder{< 0,-1,0>,<0,1,0>,1 texture {r(<1,1,0>)}}
  cylinder{<0,0,-1>,<0,0,1>, 1 texture {r(<0,0,1>)}}
}
```

POVRAY



OpenSCAD – New Document

```
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 cylinder(r=10,h=50,
 center=true,
 $fn=100);
}

intersection() {
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cyl([1,0,0]);
cyl([0,1,0]);
 }
```

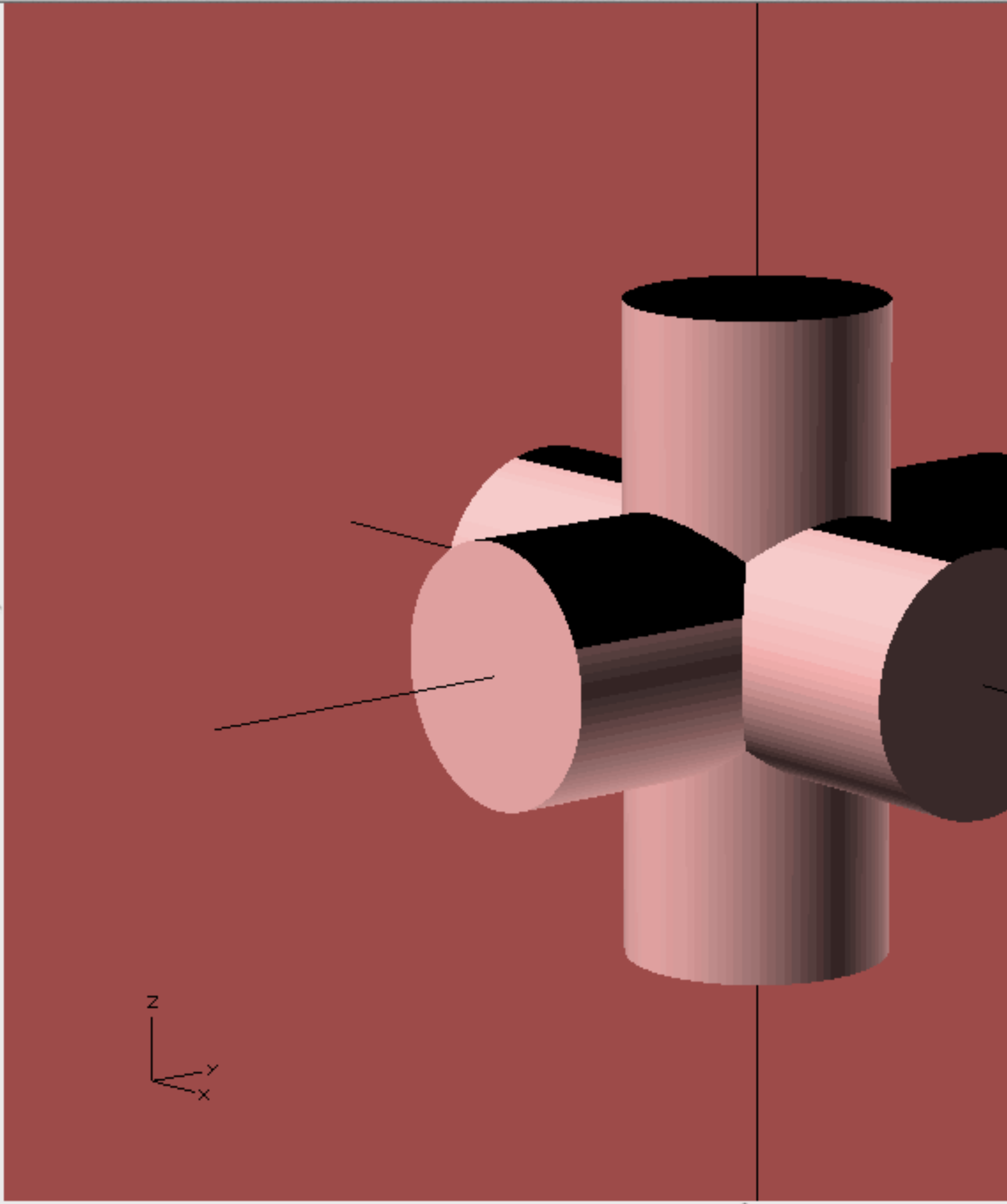

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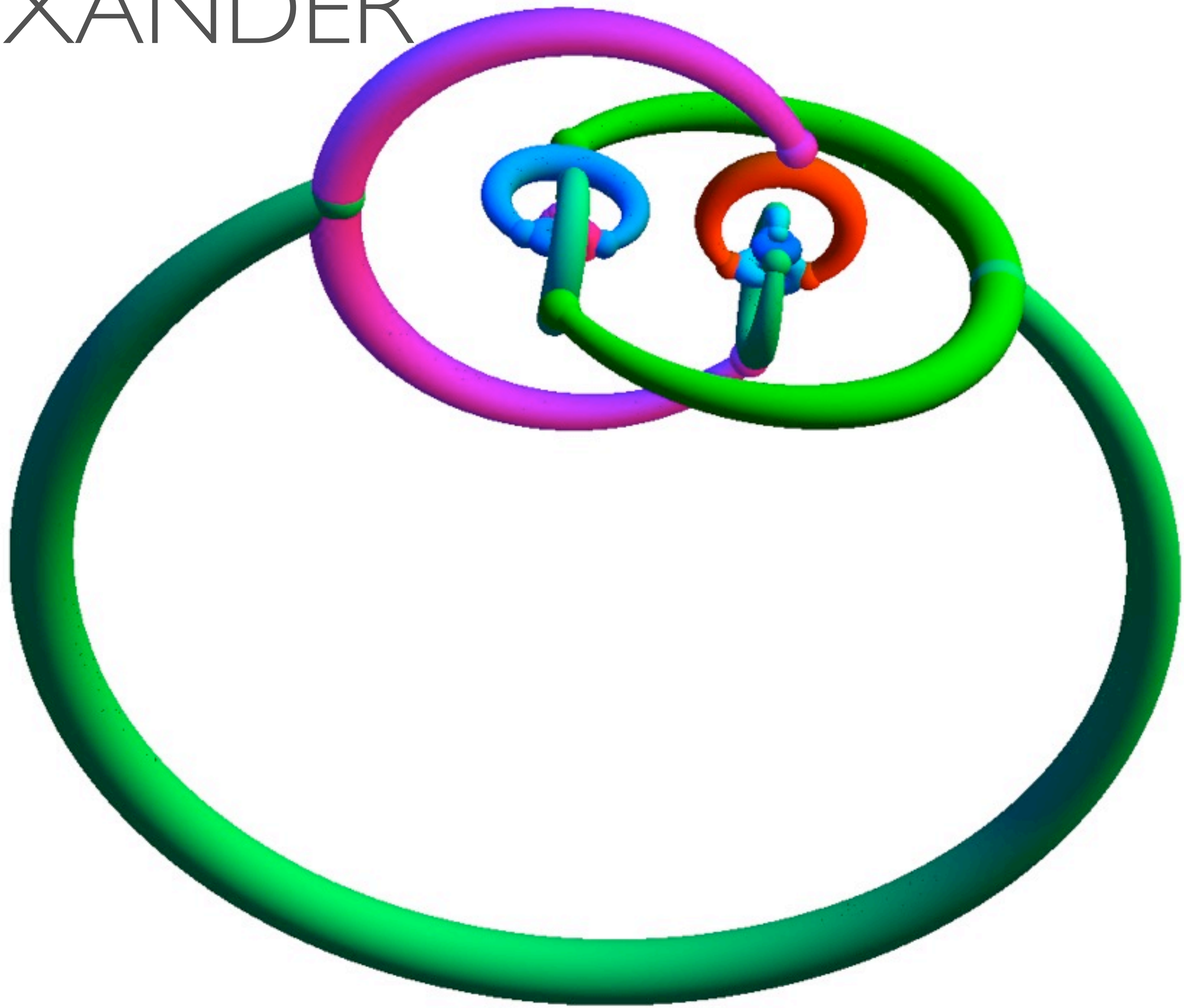
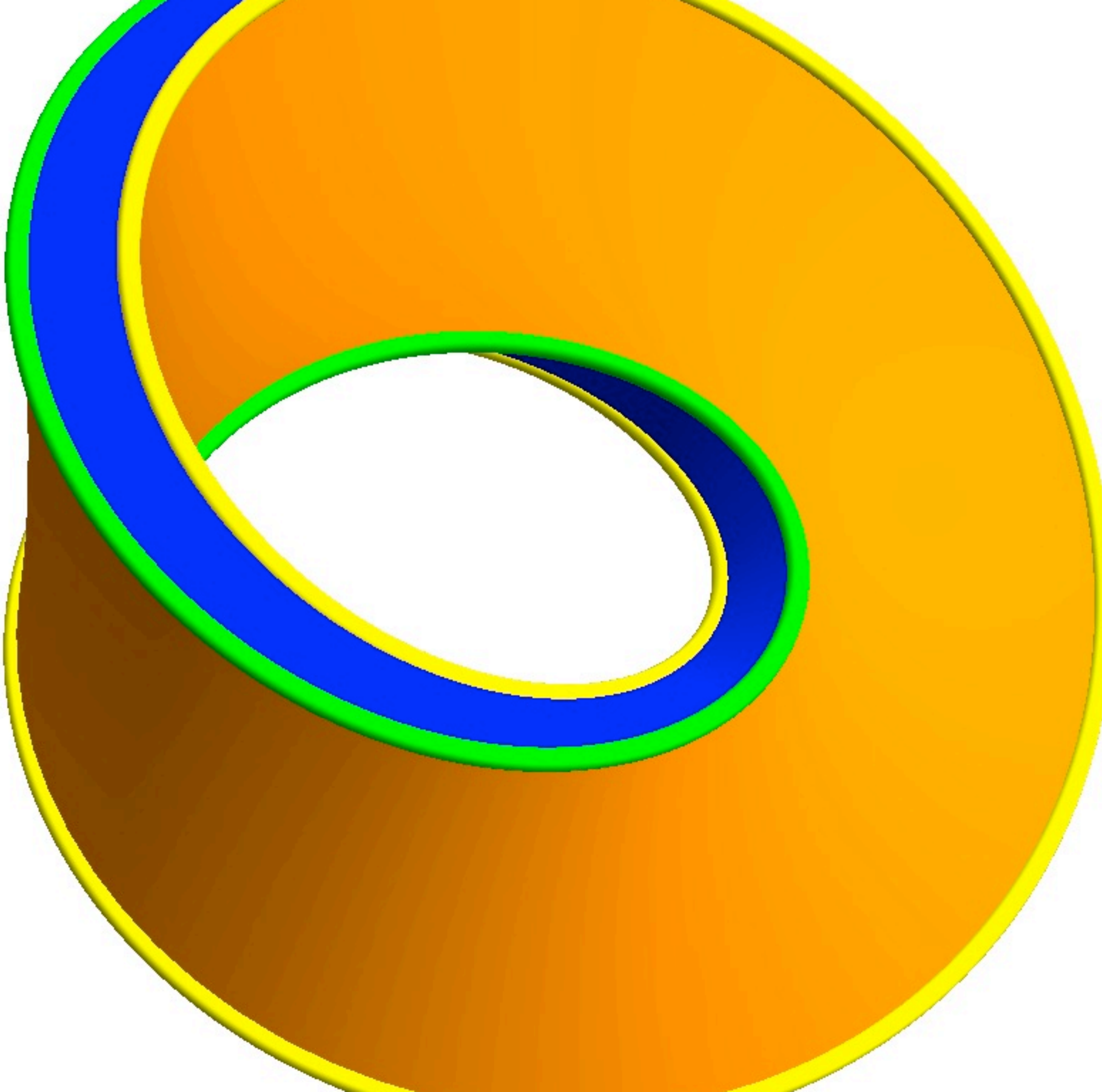
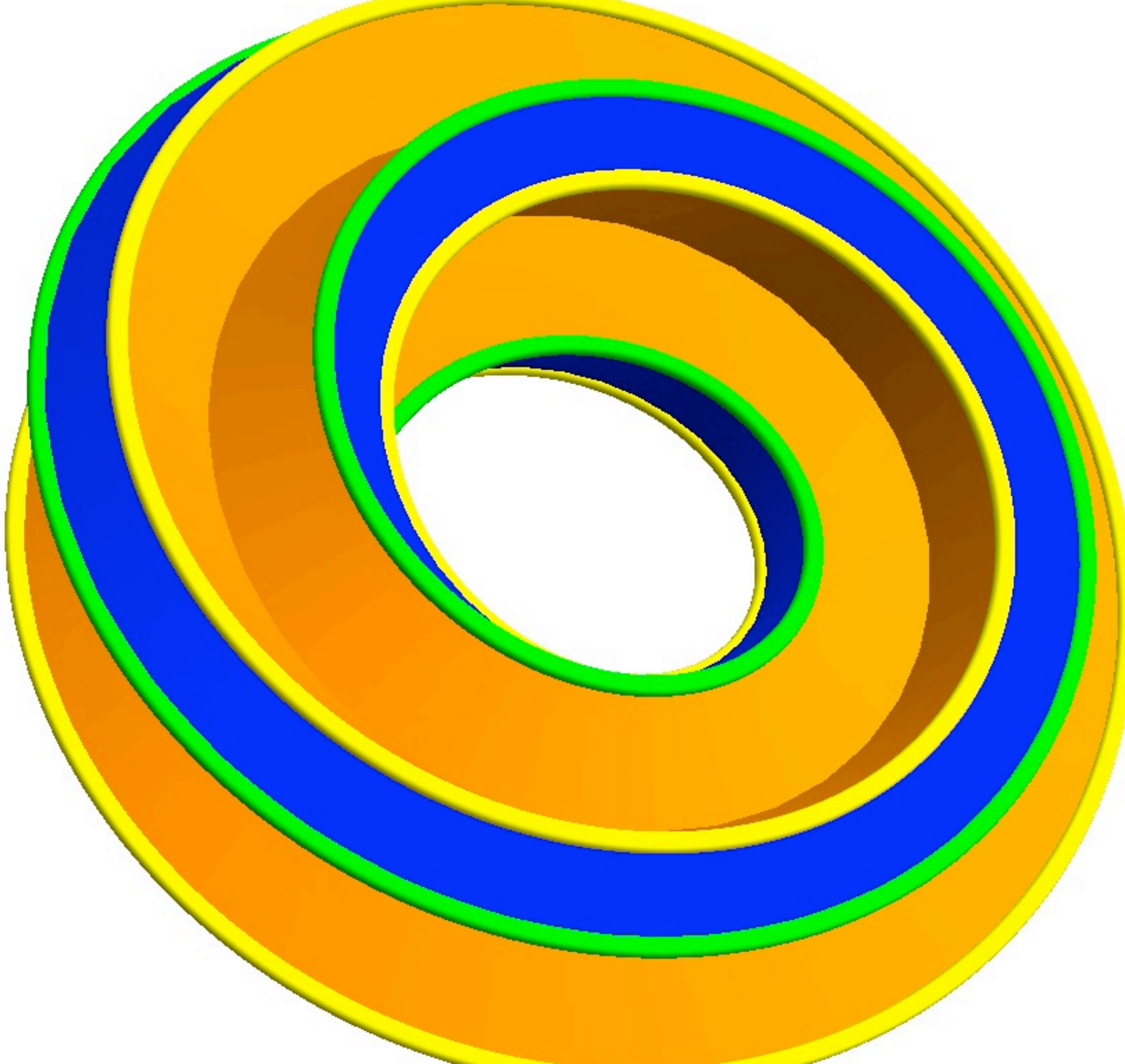
ALEXANDER

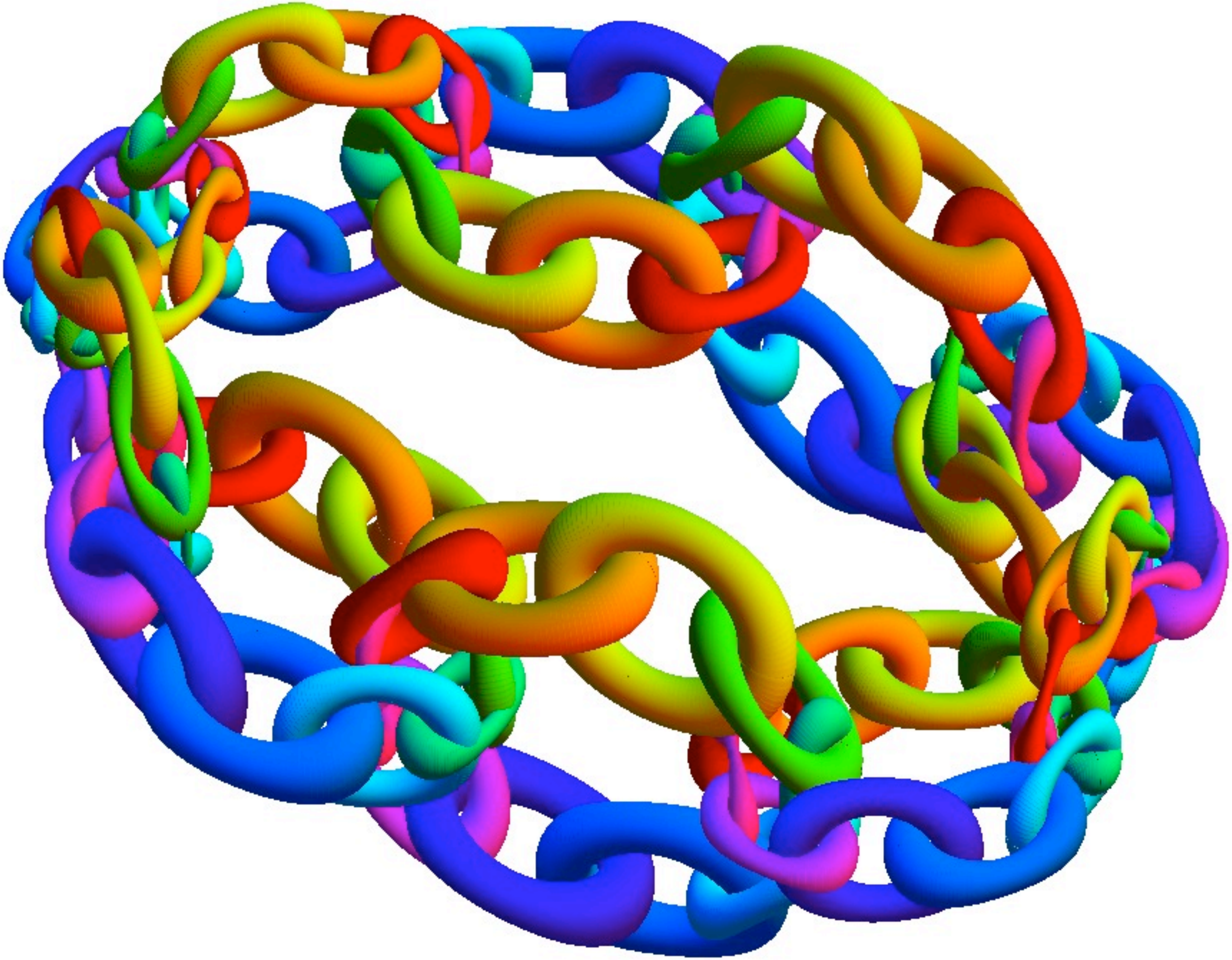


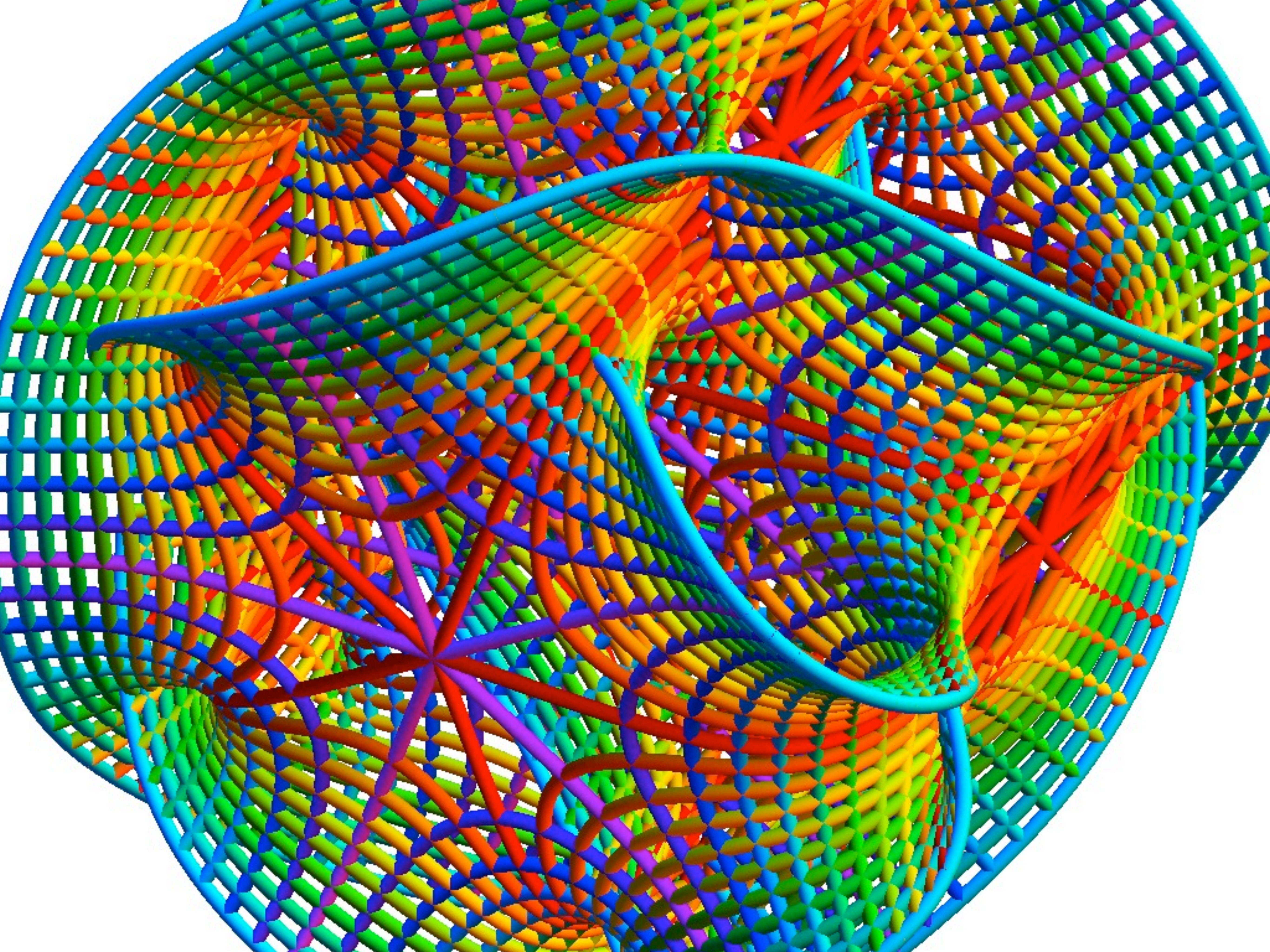
KNOTS

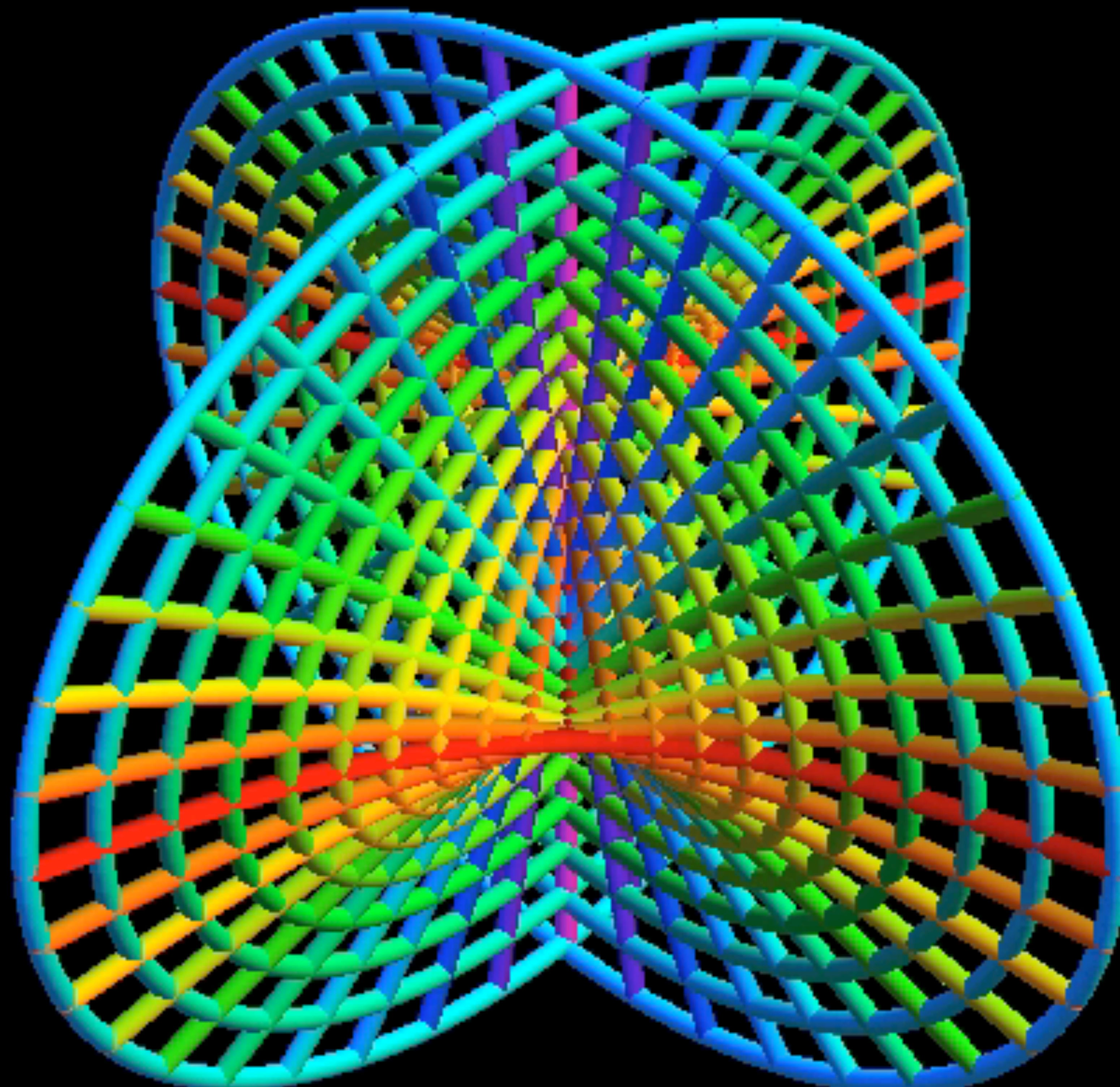


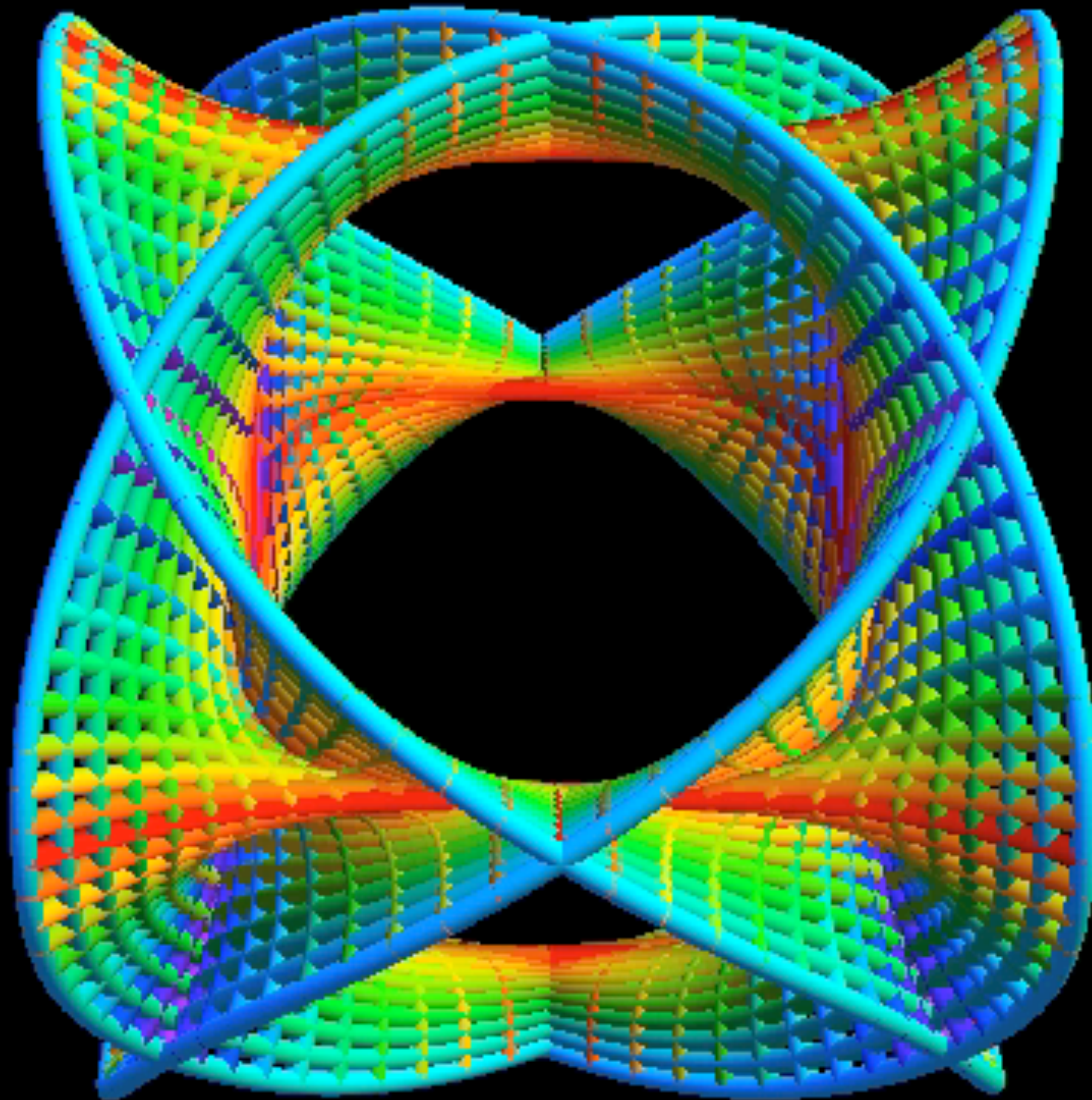


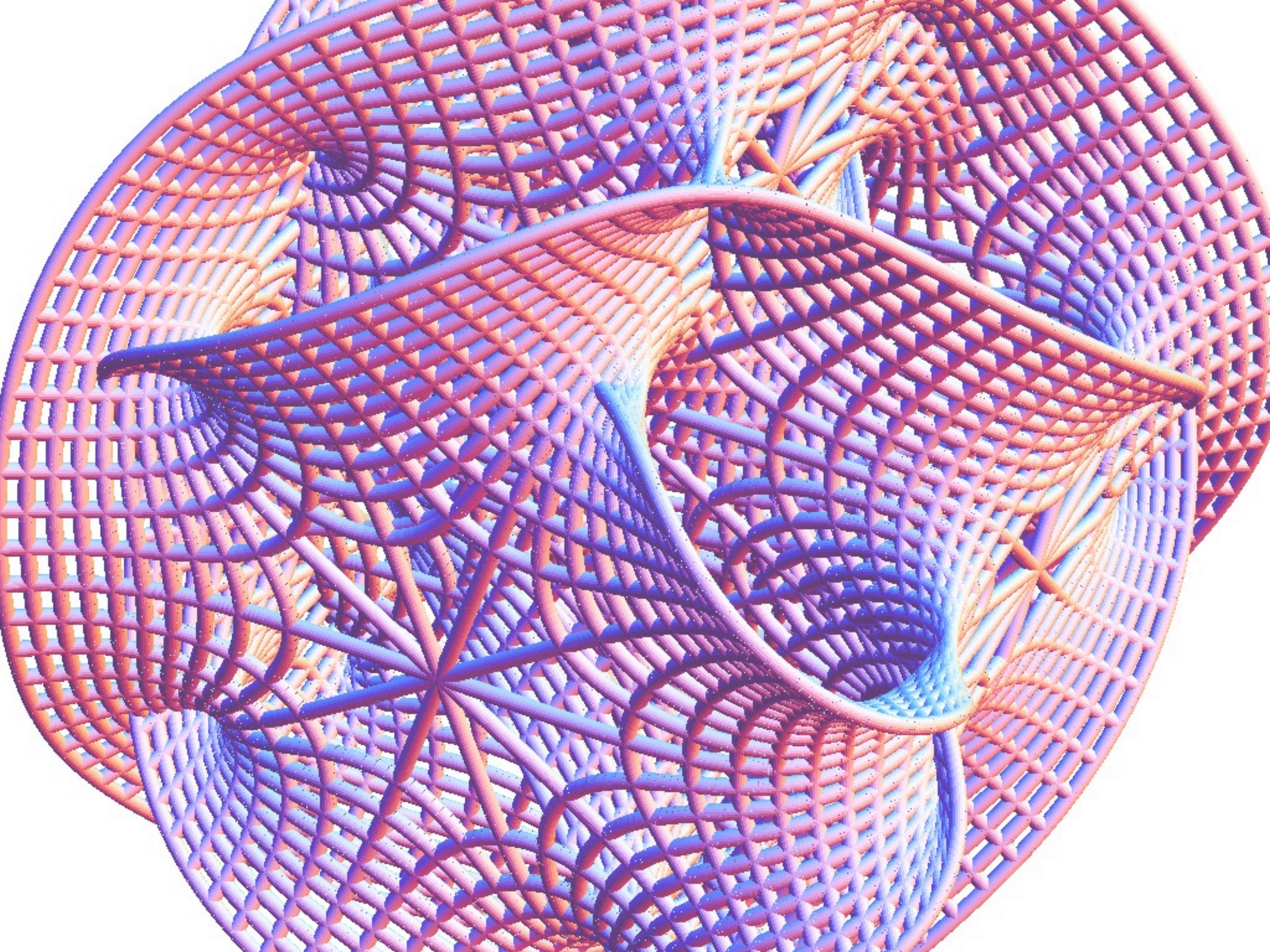
ANTOINE

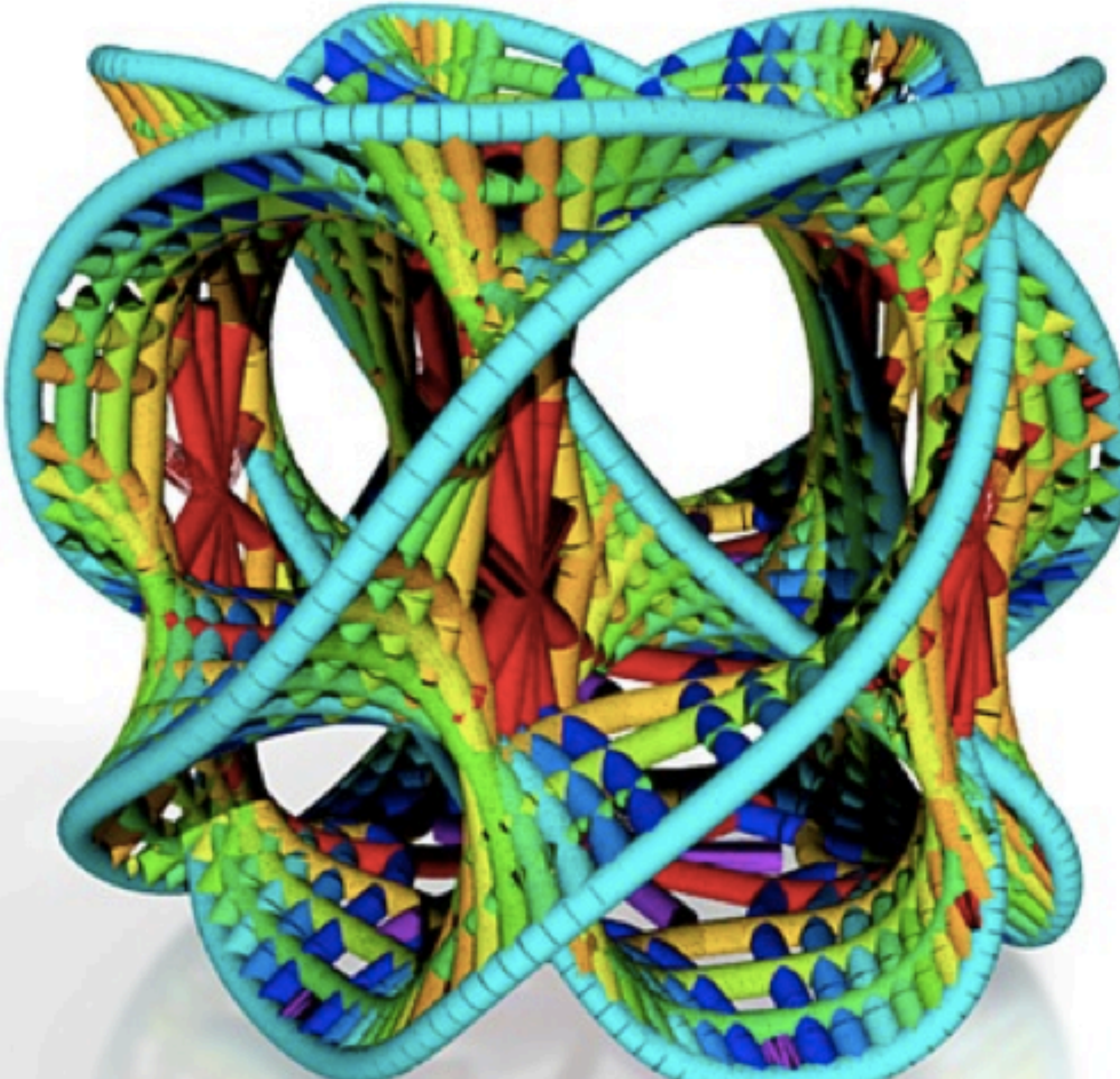












SHAPEWAYS

Calabiyau5

Edit Model

White Strong & Flexible $35.22

$35.22 Add to Cart

Calabiyau5

Edit Model

White Strong & Flexible $35.22

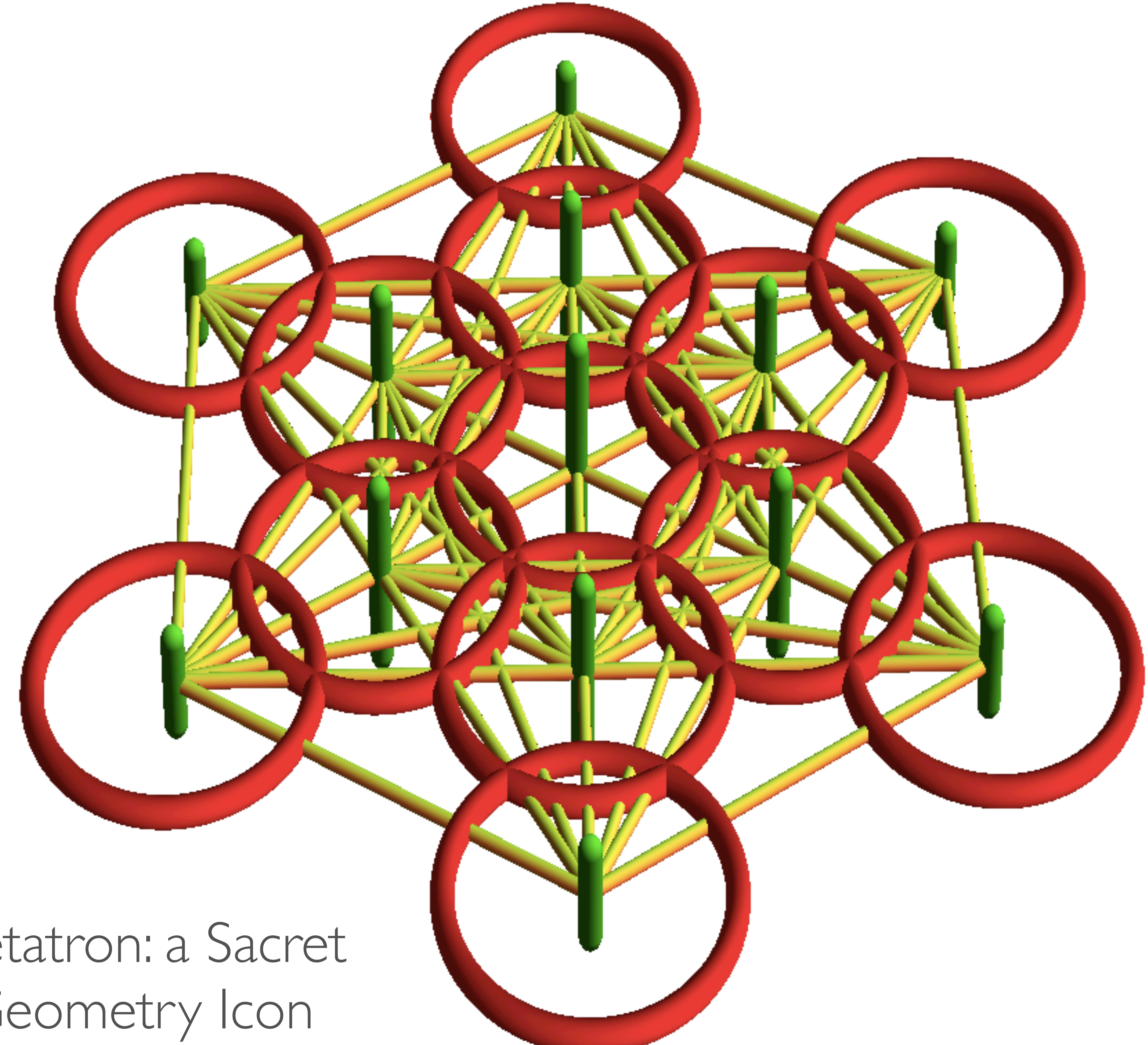
$35.22 Add to Cart

Calabiyau5a

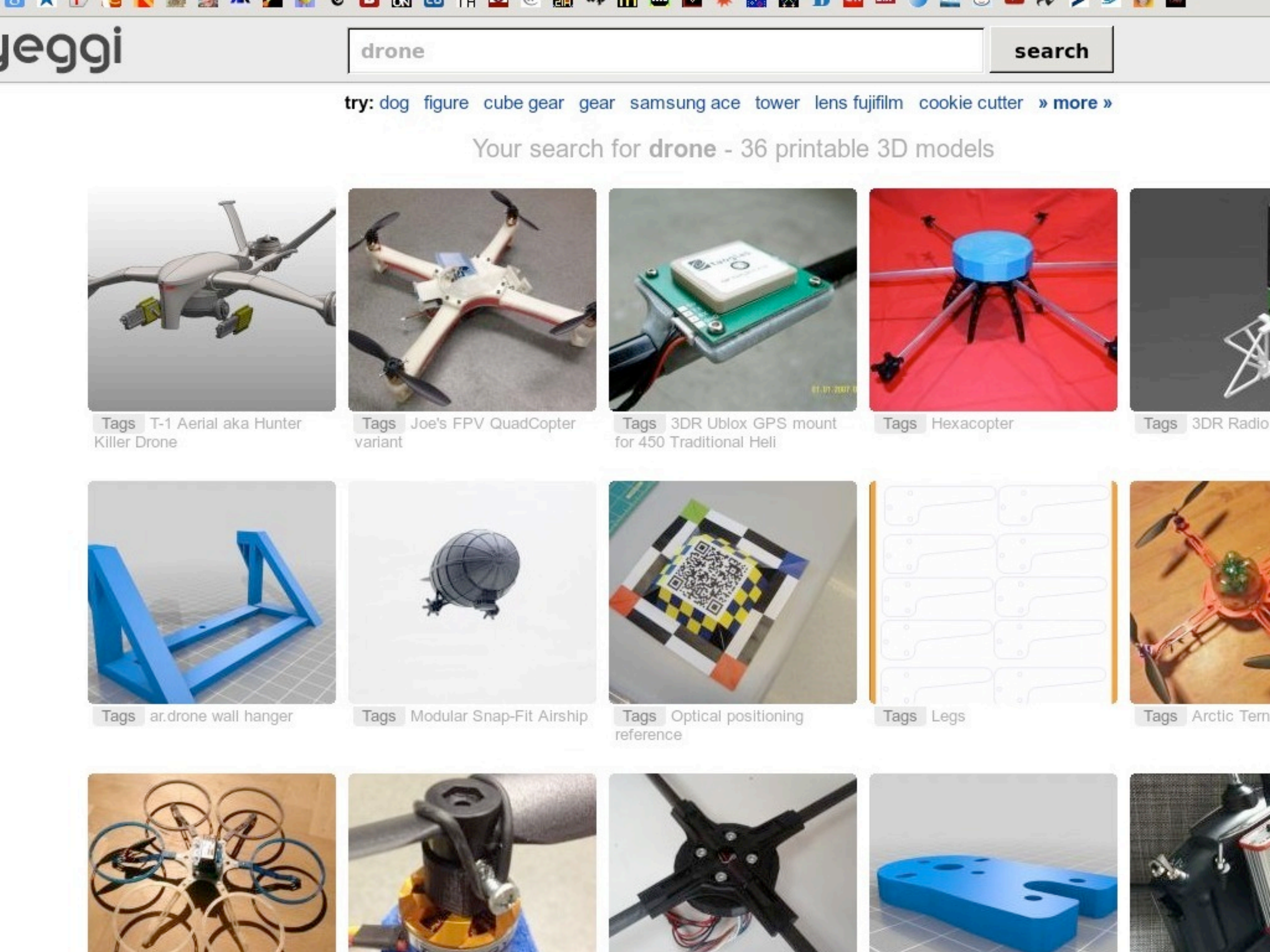
Edit Model

White Strong & Flexible $148.42

$148.42 Add to Cart



Metatron: a Sacret
Geometry Icon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Your search for drone - 36 printable 3D models
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Tags 3DR Radio
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Tags Modular Snap-Fit Airship
Tags Optical positioning reference
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Tags Arctic Tern

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36 Pencil Bowl DIY...
Michiel Corn... 35.00 €

Brass Bracelet Con...
Maaike van d... 150.32 €

Diamonds are forev...
Eragatory 120.00 €

MEN NR.02 by DAMN ...
DAMN 103.30 €

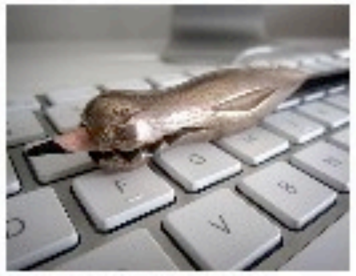
Decision Spintop
Michael Muel... 46.21 €

Merry Bird ornamen...
Michiel Corn... 28.22 €

Klein Bottle - Mat...
Dizingof 30.00 €

Basalt 114 Double ...
Kevin Wei 72.00 €

Asia Dionysos
monomer 79.99 €



Dragonbite grip (s...
Vangelis and... 42.83 €

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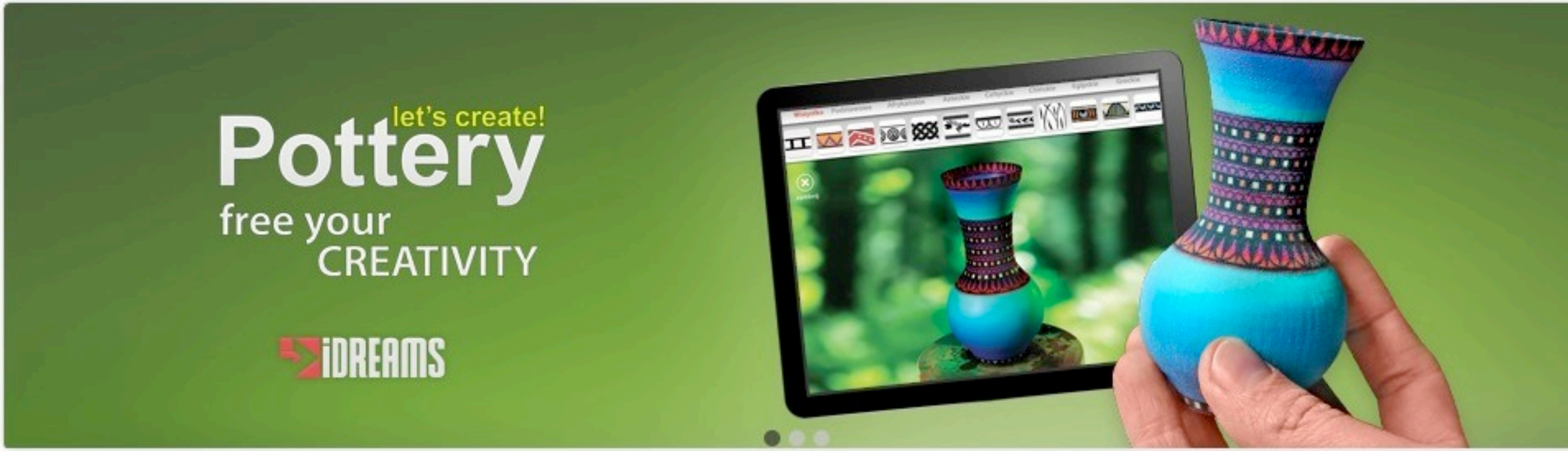

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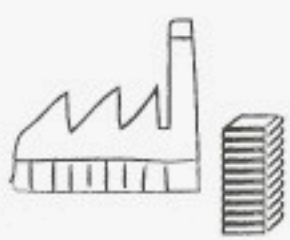

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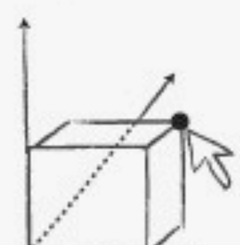

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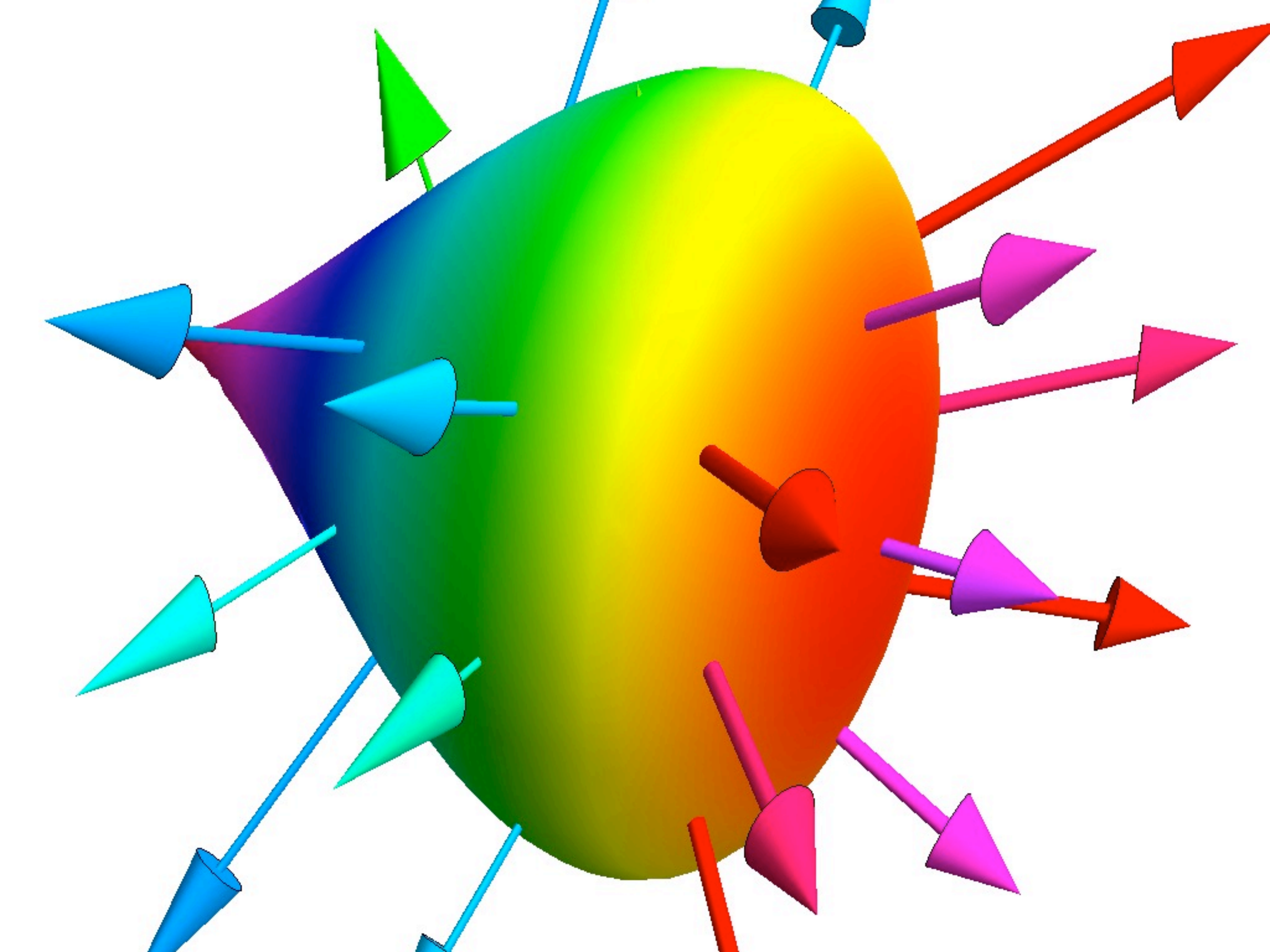

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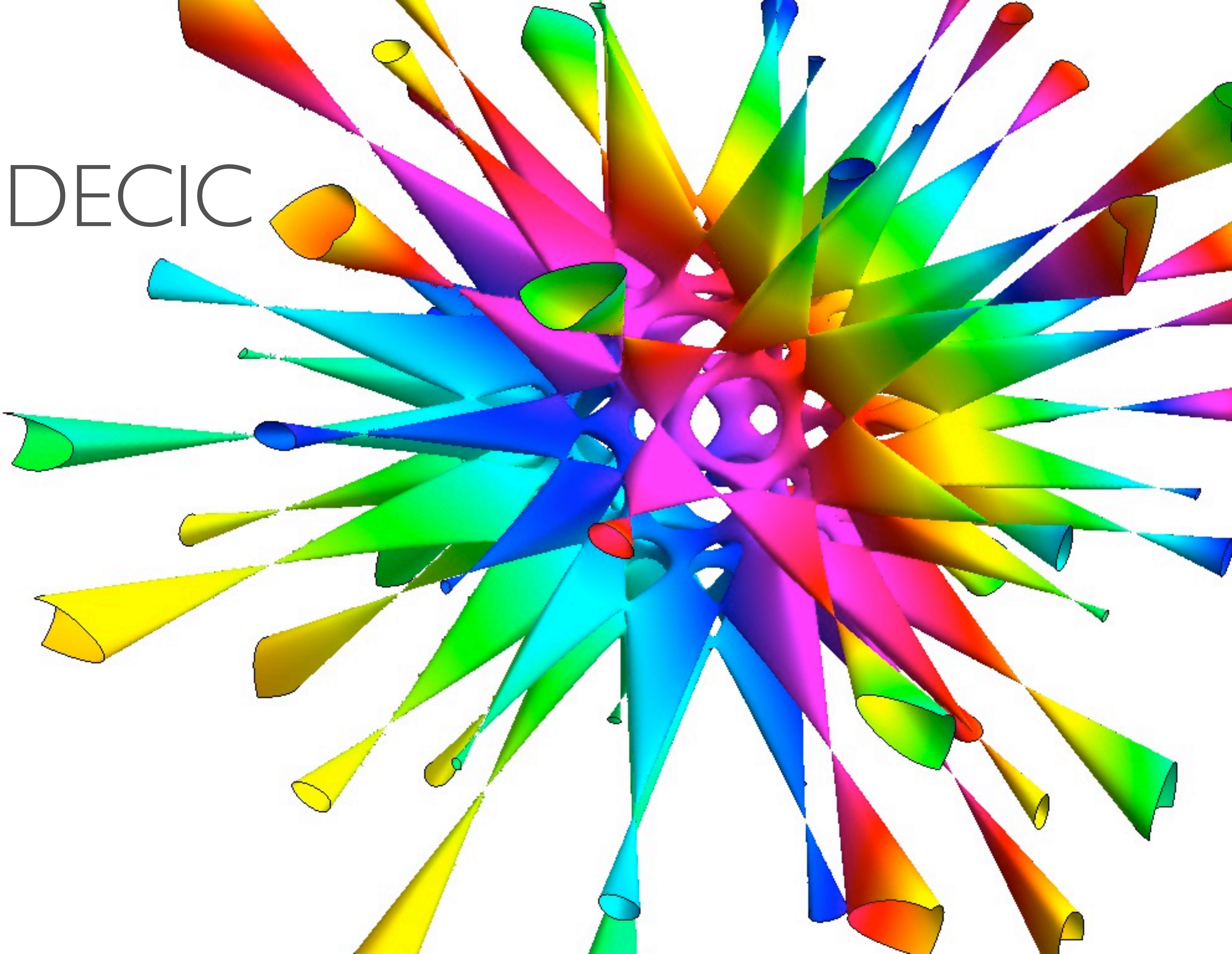
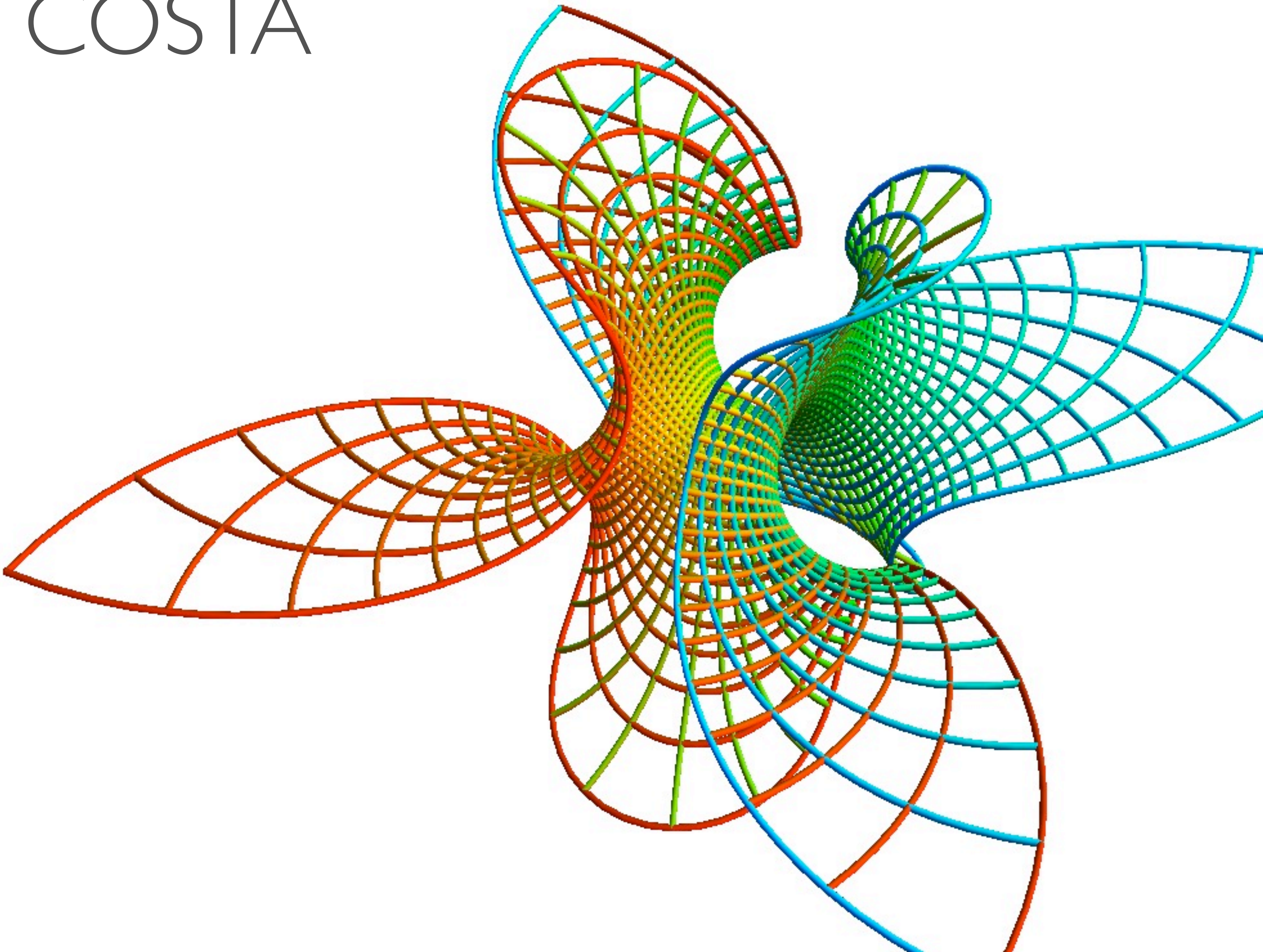
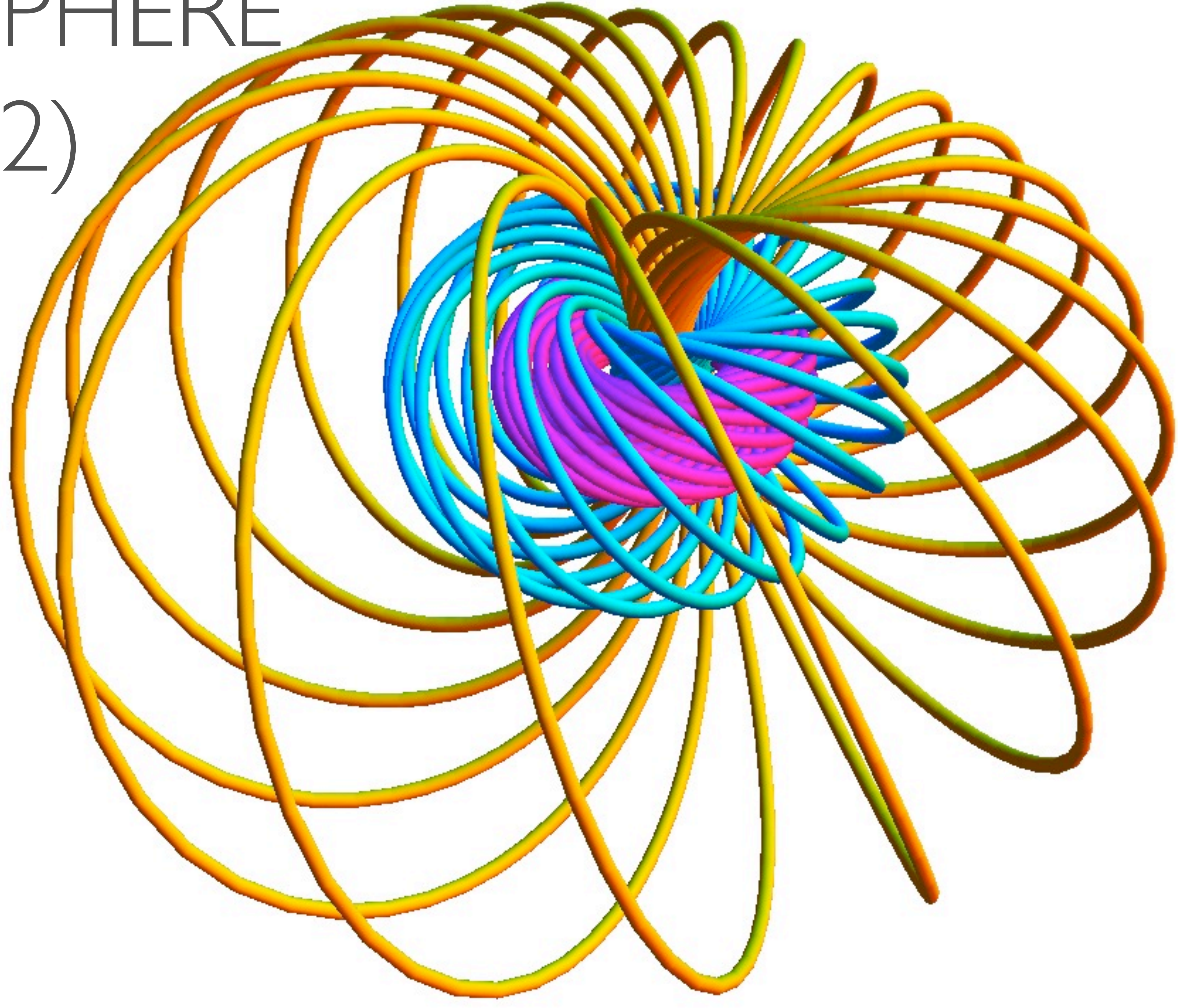
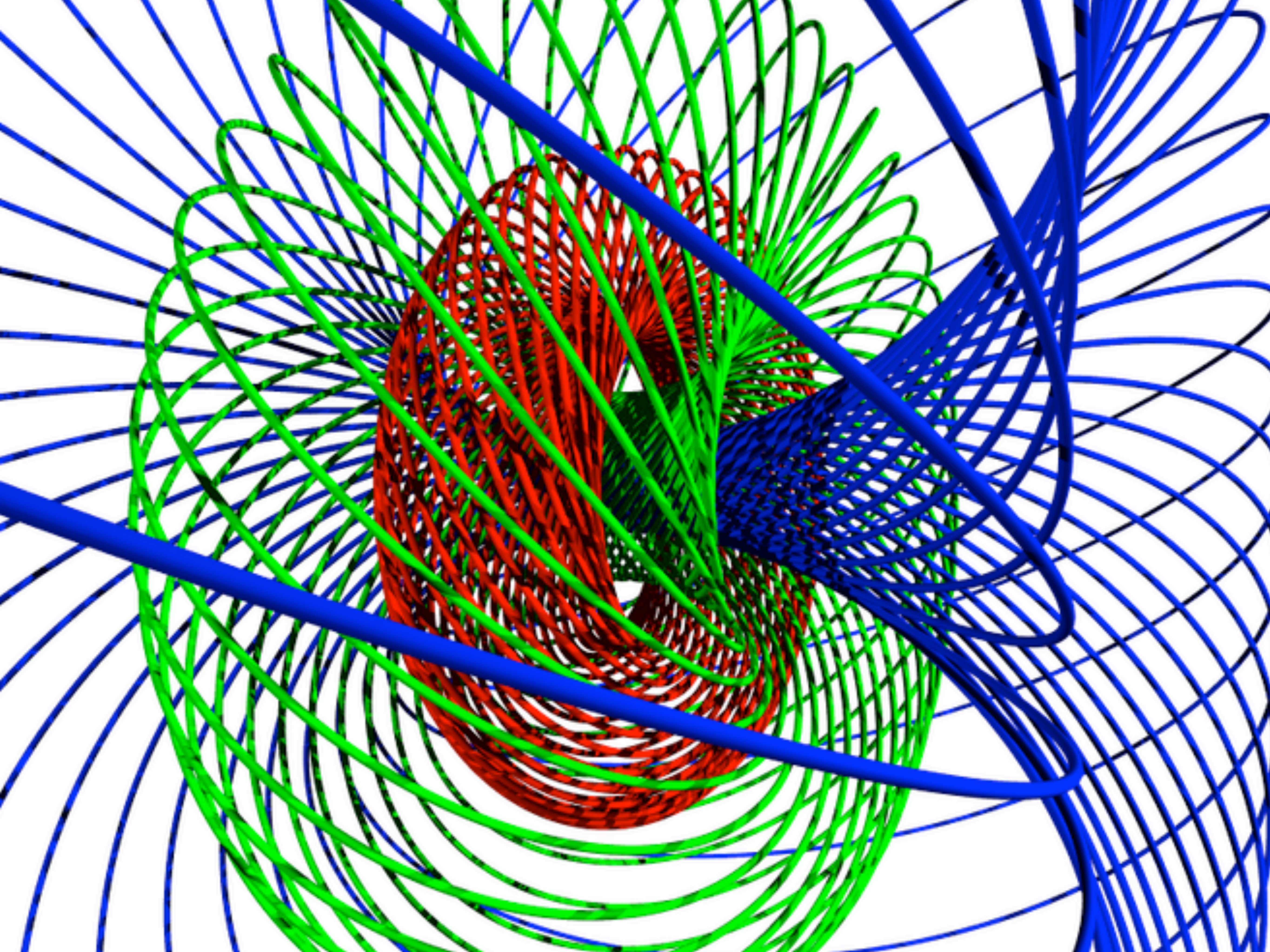


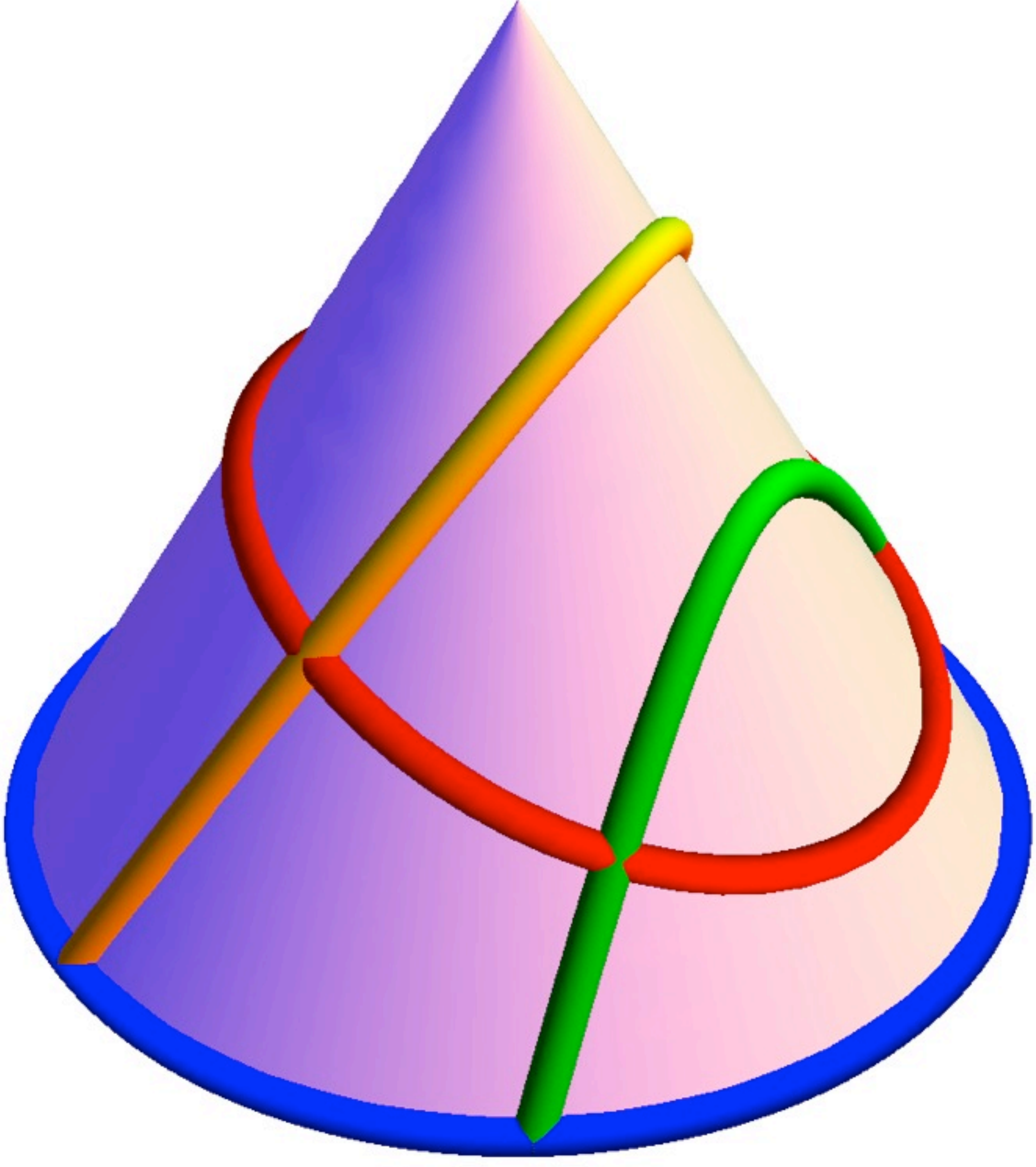
COSTA



3D SPHERE =SU(2)





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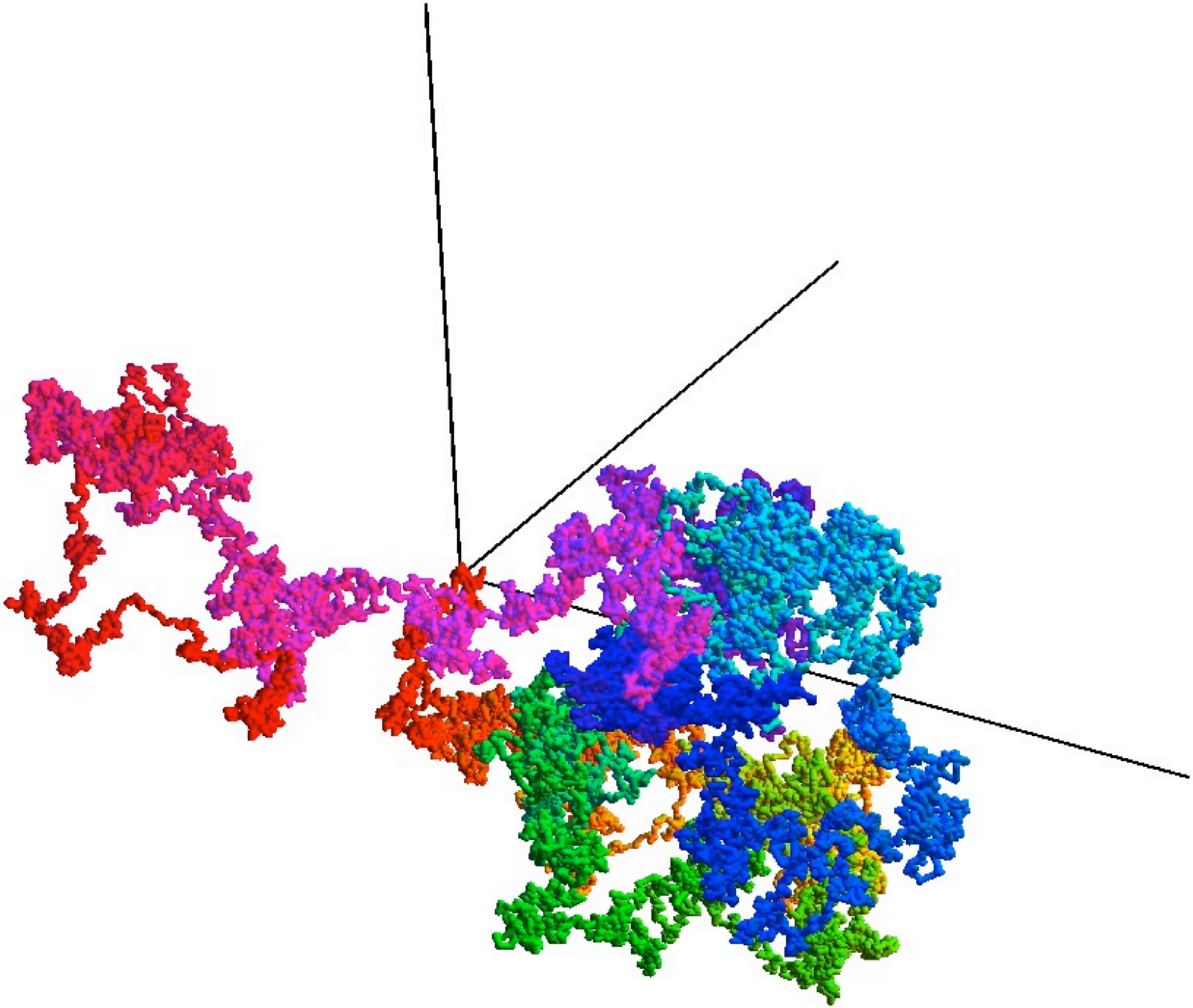
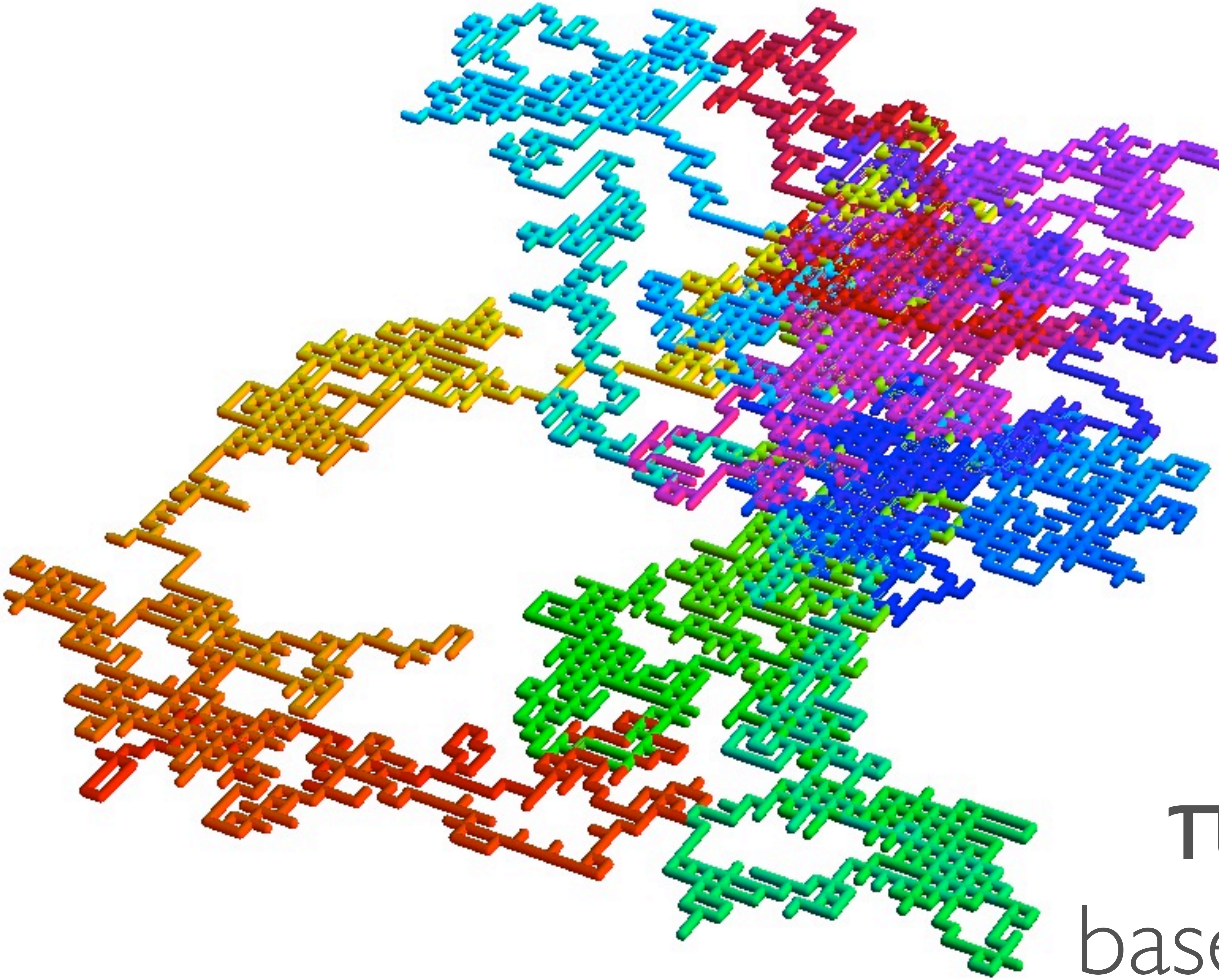
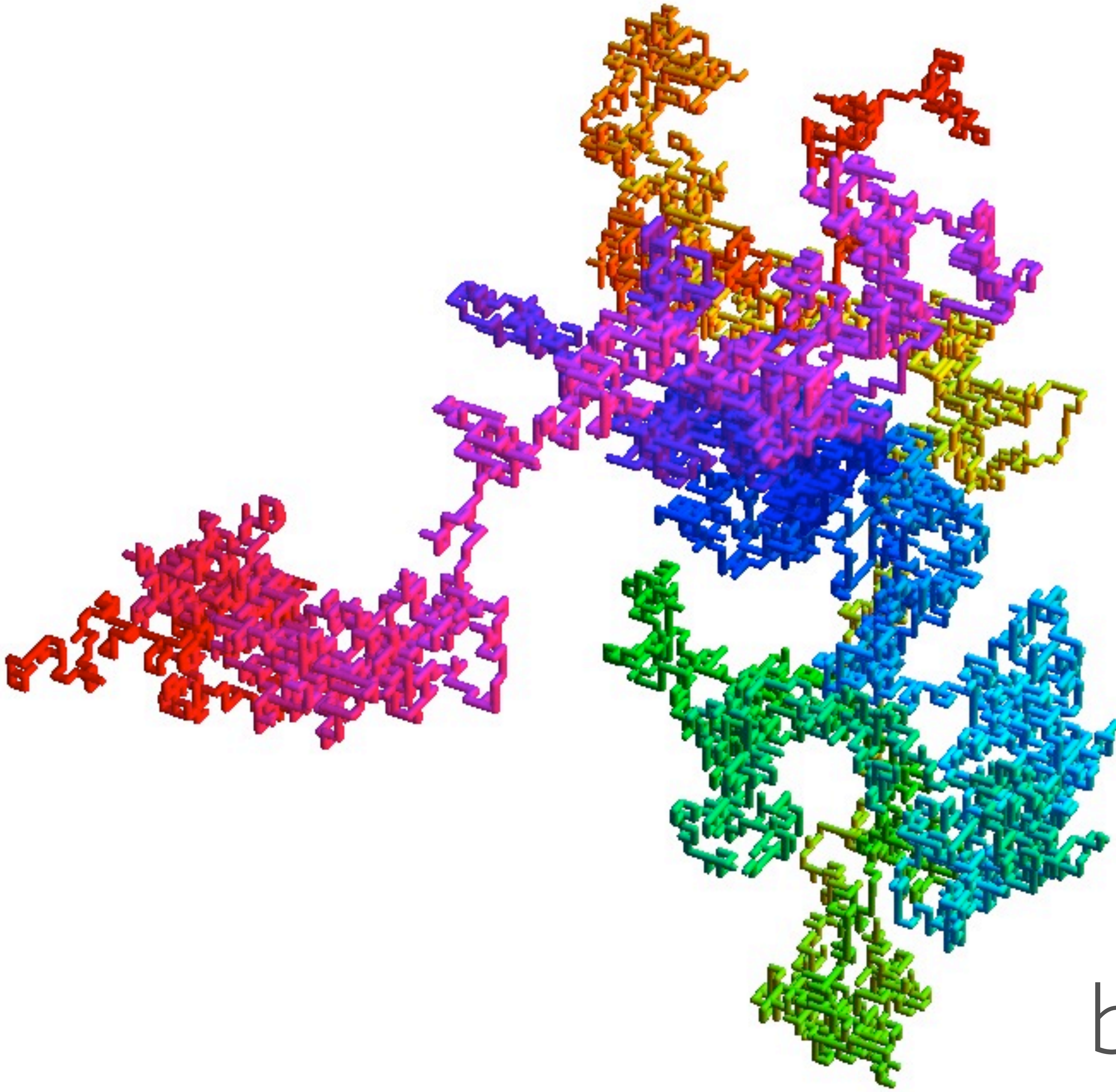
RACHEL WEISZ 'ÁGORA' MAX MINGHELLA OSCAR ISAAC ASHRAF BARHOM RUPERT EVANS HOMAYOUN ERSHADI MICHAEL LONSDALE SAMMY SAMIR

Agora

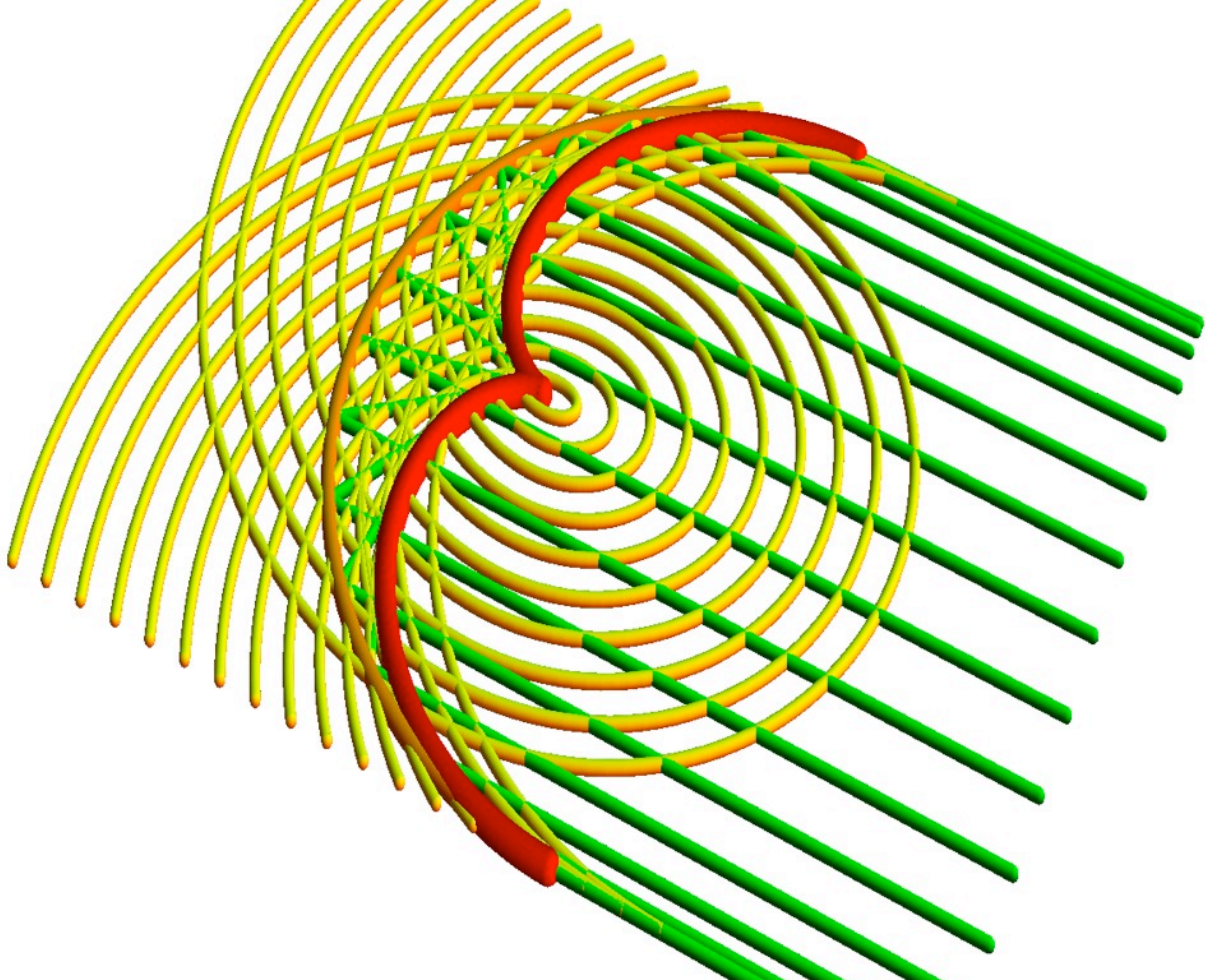


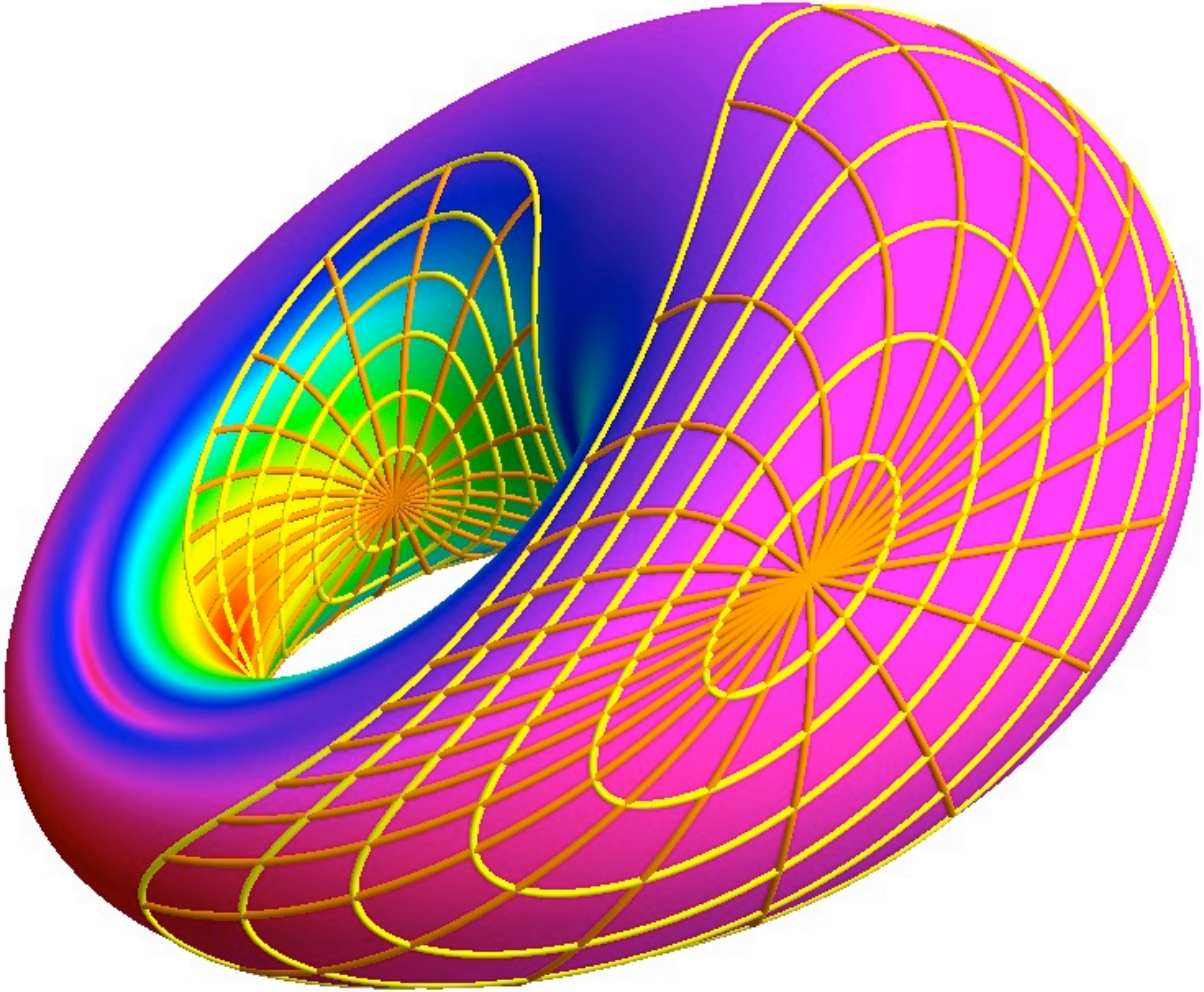


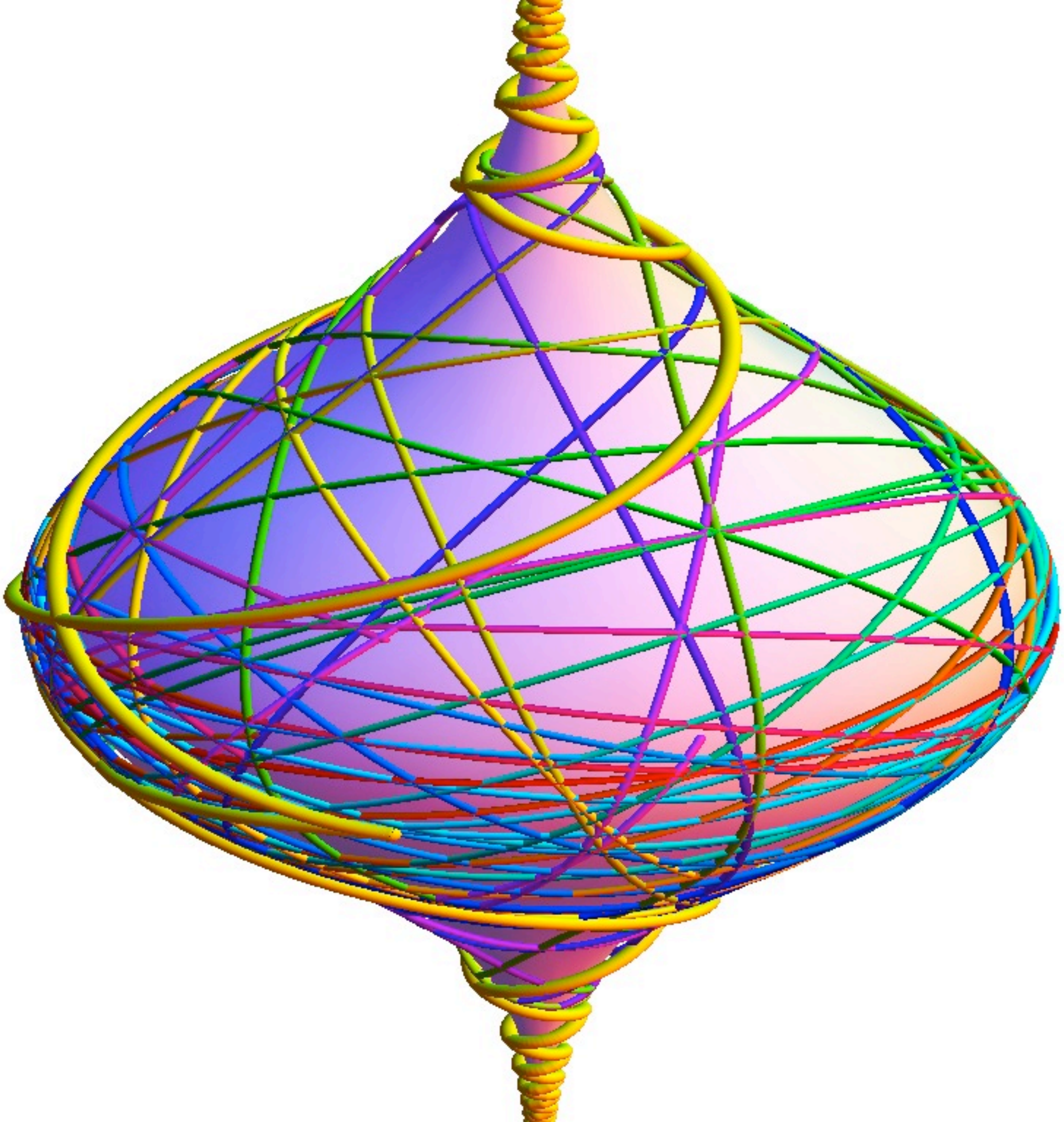
π
base 4

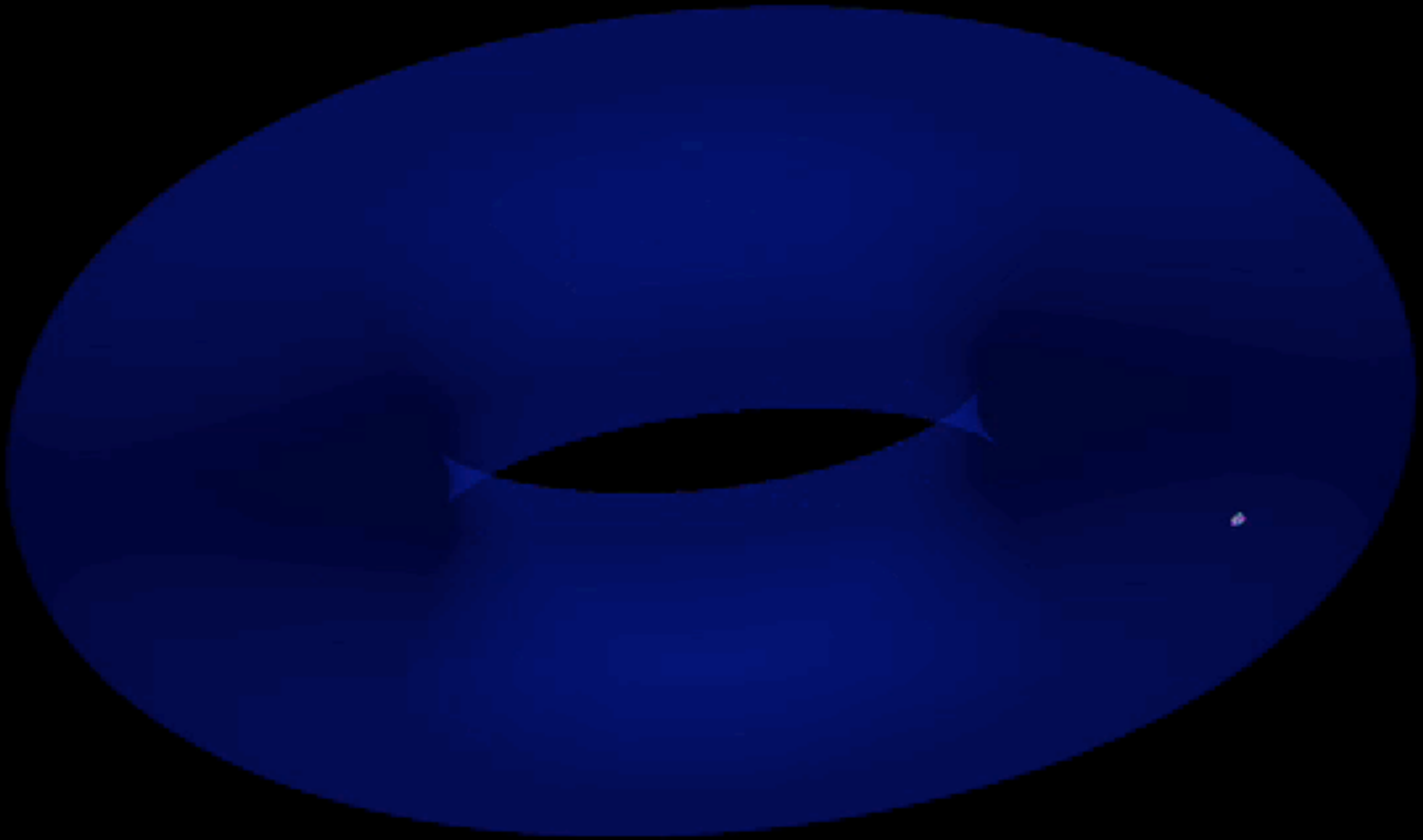


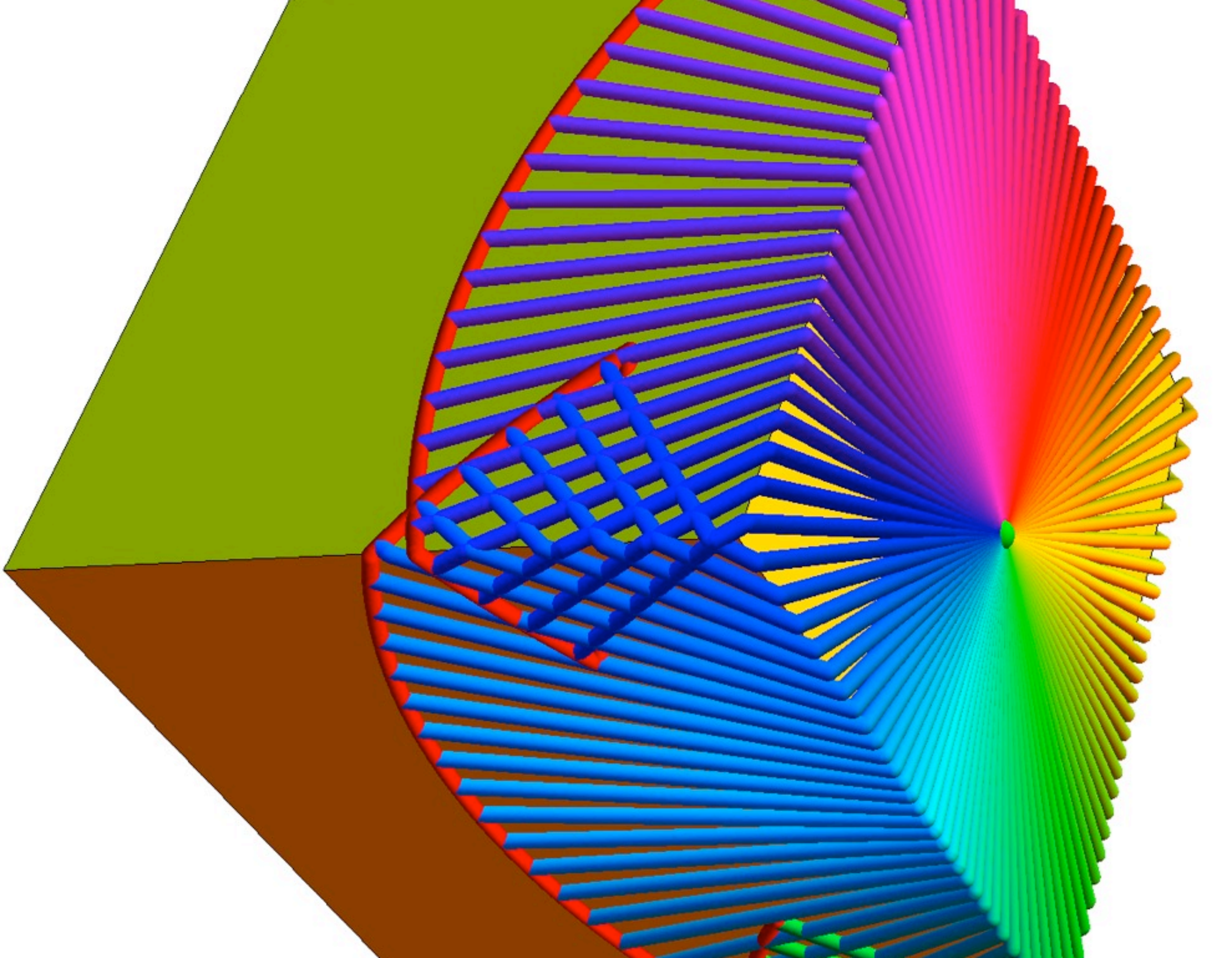
π
base 6

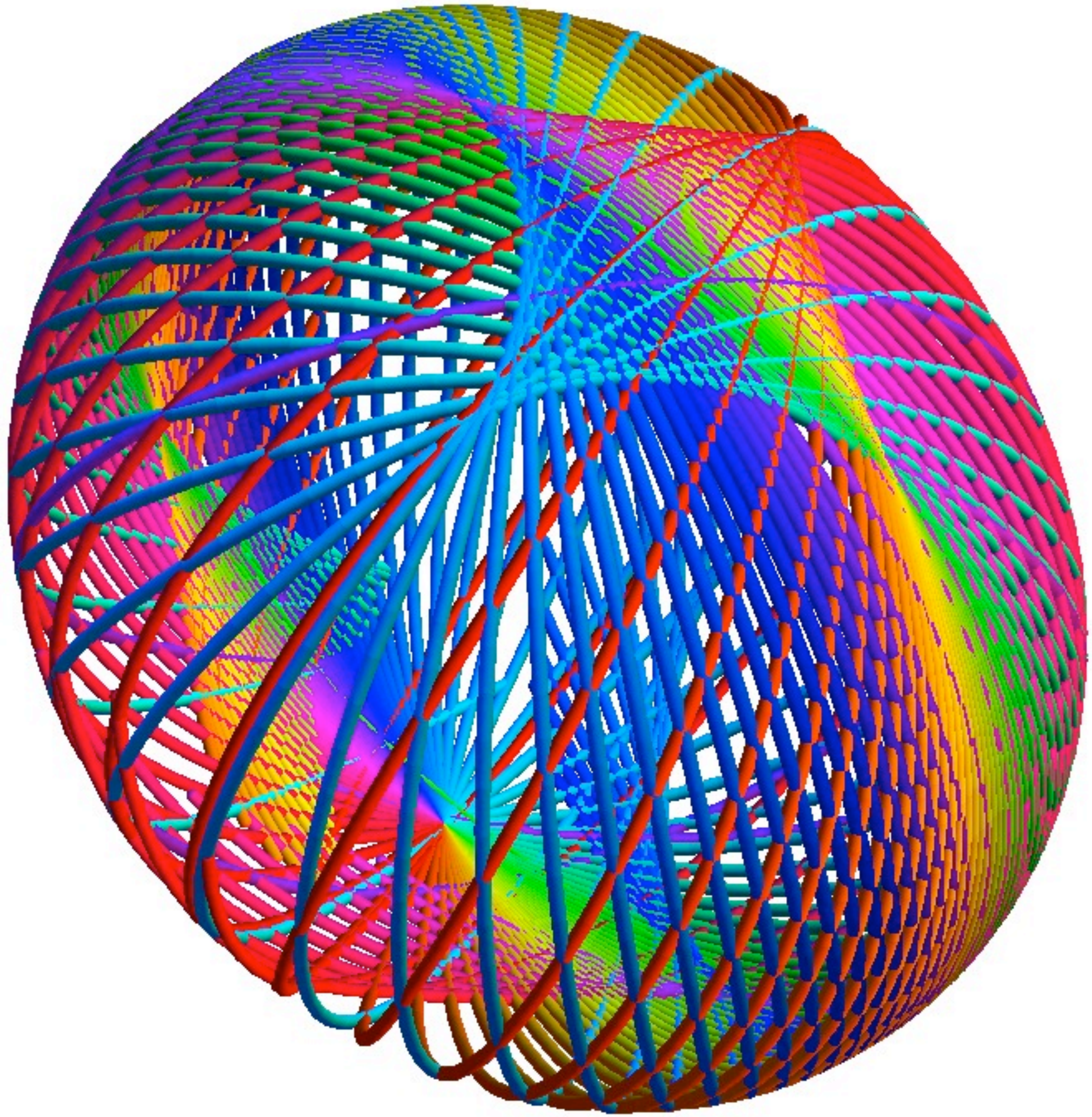




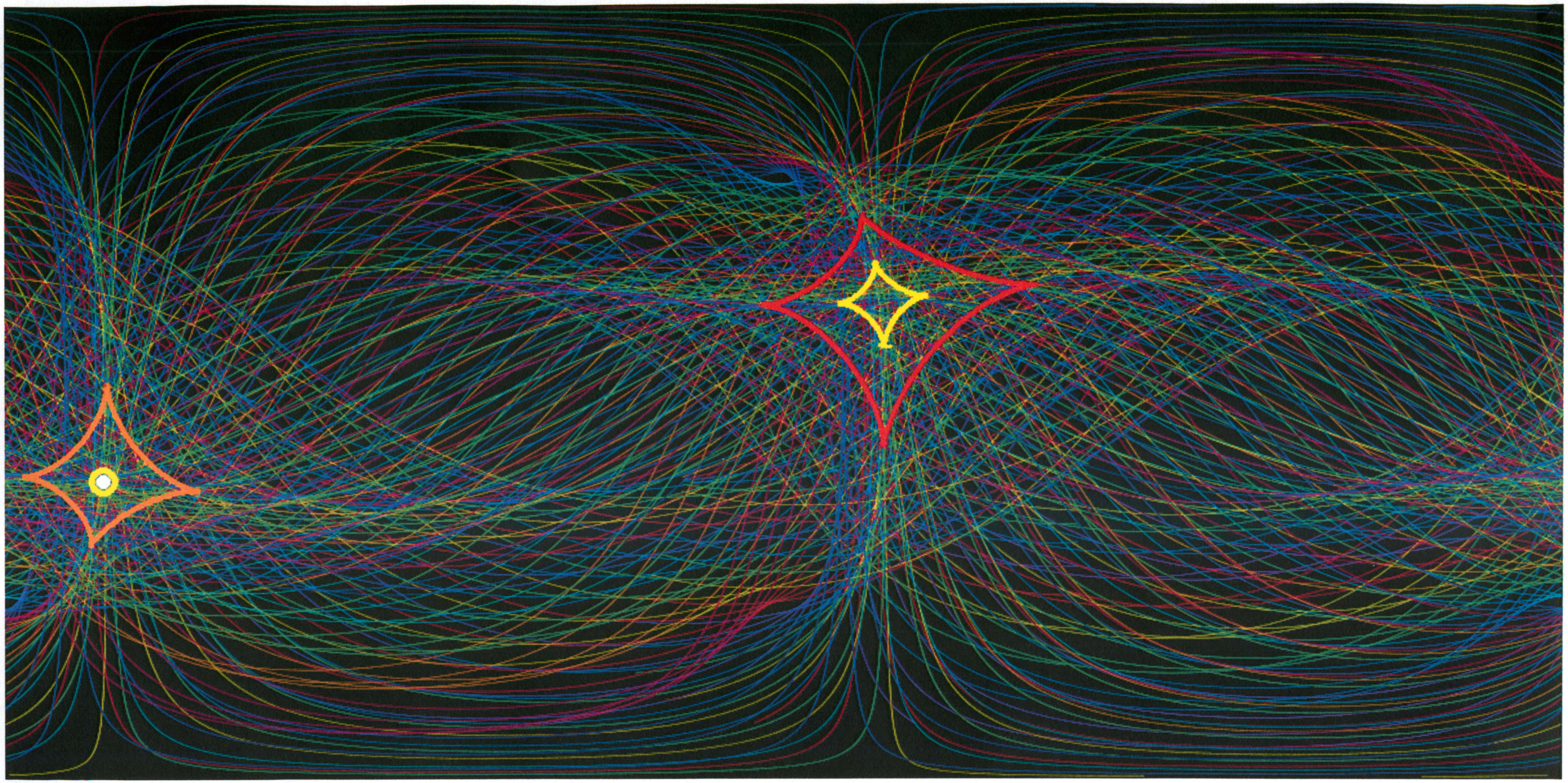








Jacobi last geometric statement



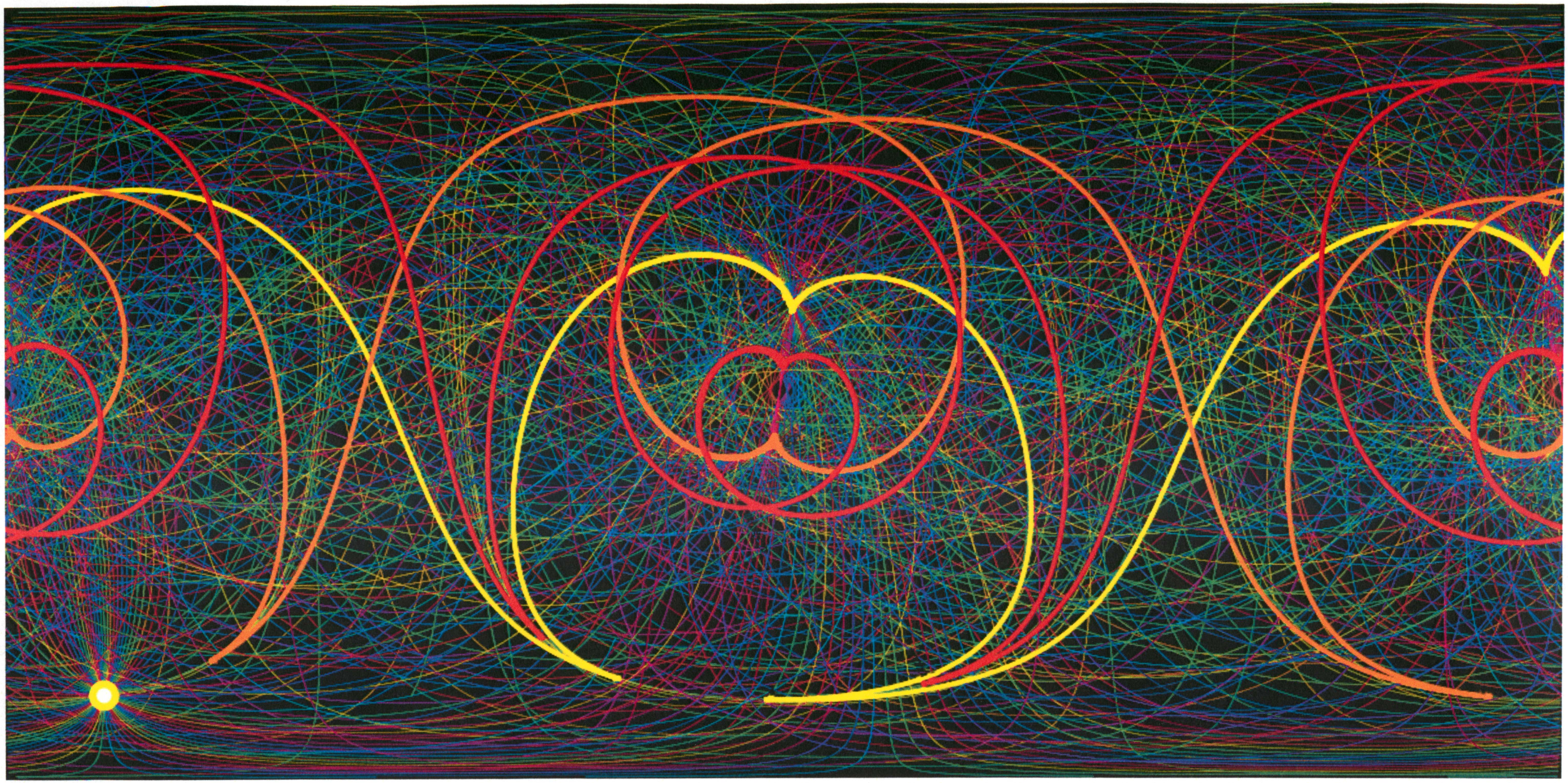
The non-rotationally symmetric ellipsoid

$$x^2/1.12 + y^2/1.062 + z^2 = 1$$

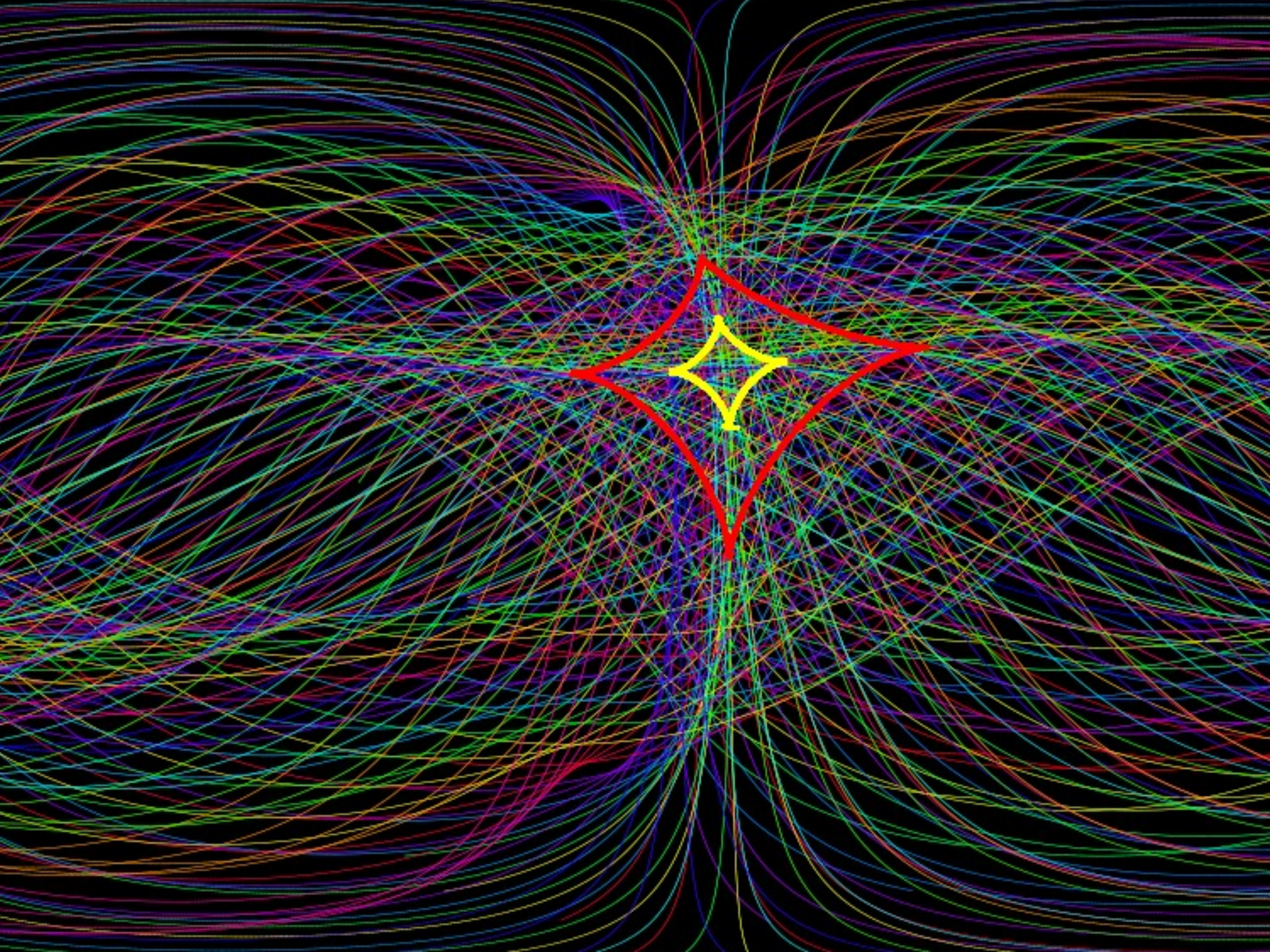
has caustics close to the antipode in the sphere case. We see again the primary, secondary and ternary caustic. 4000 geodesics

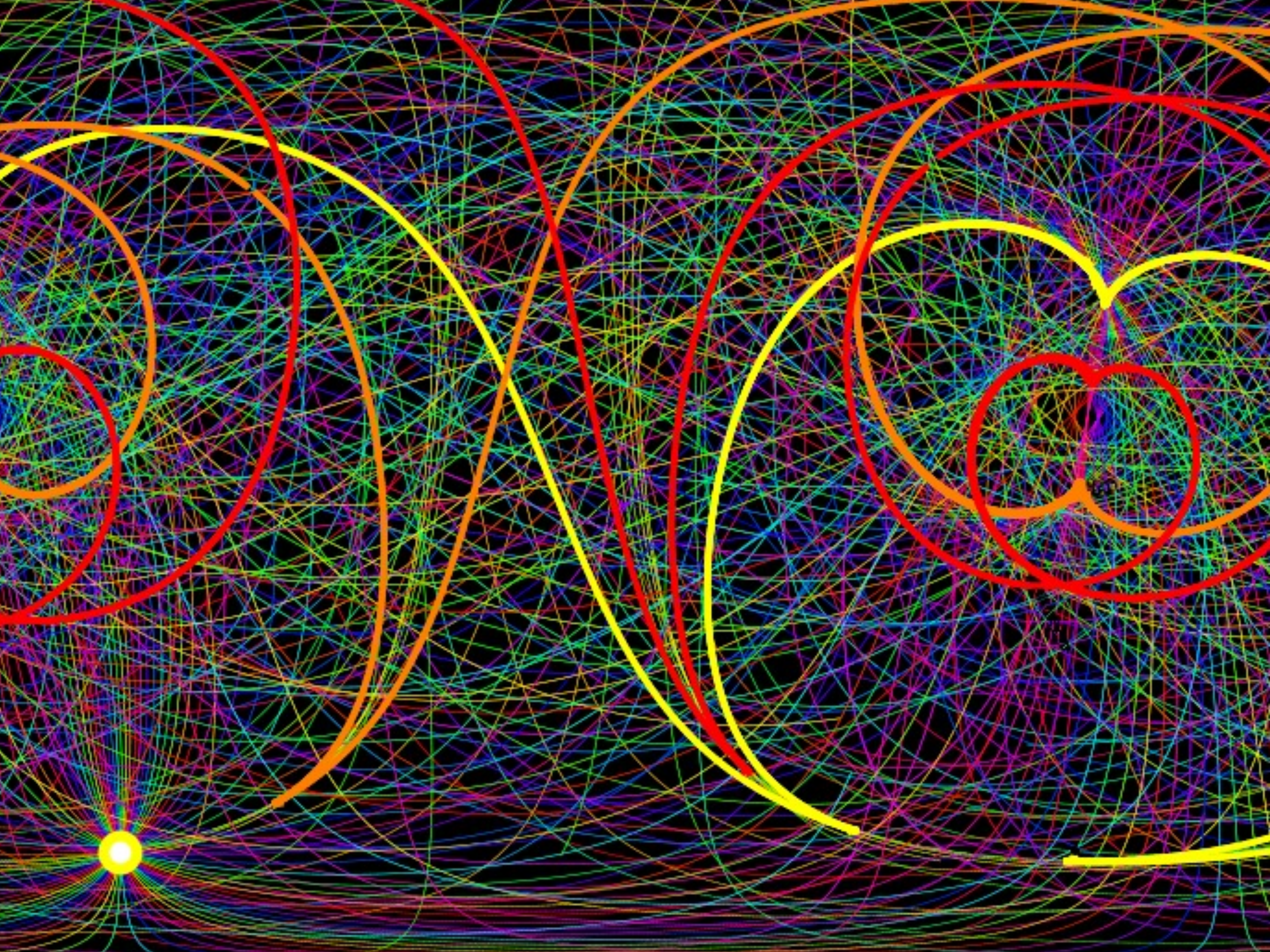
Michael Teodorescu

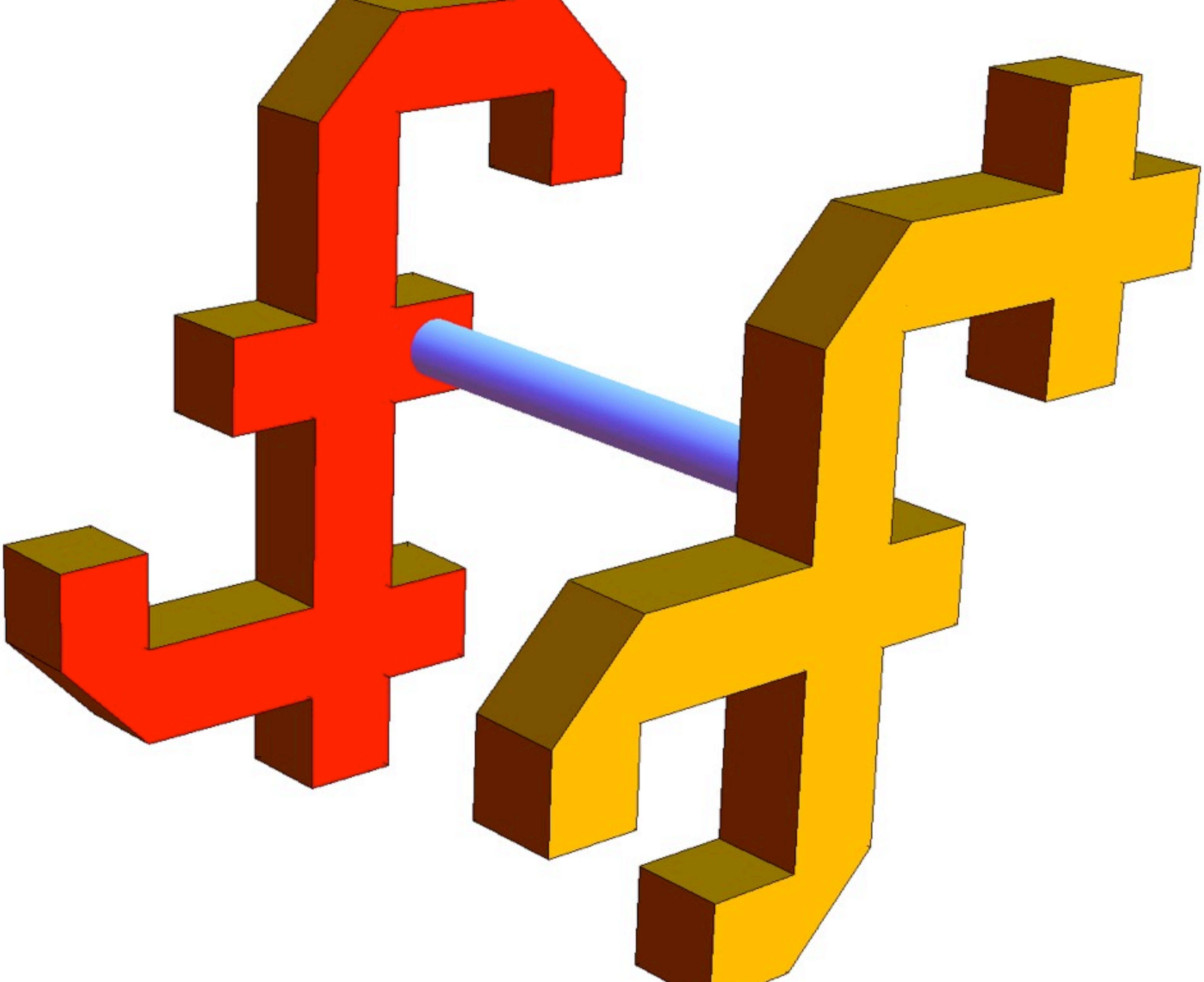
Jacobi last geometric statement

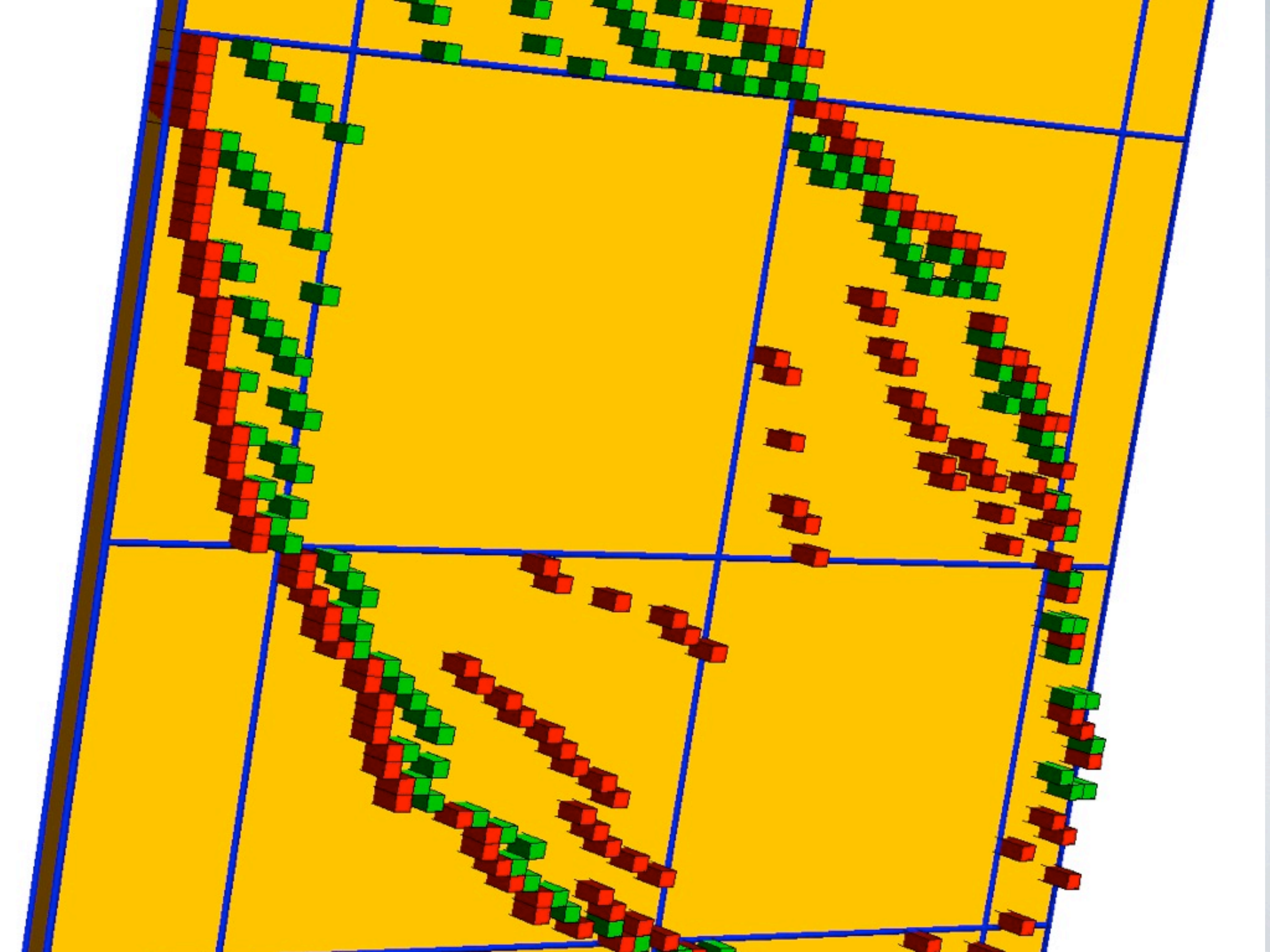


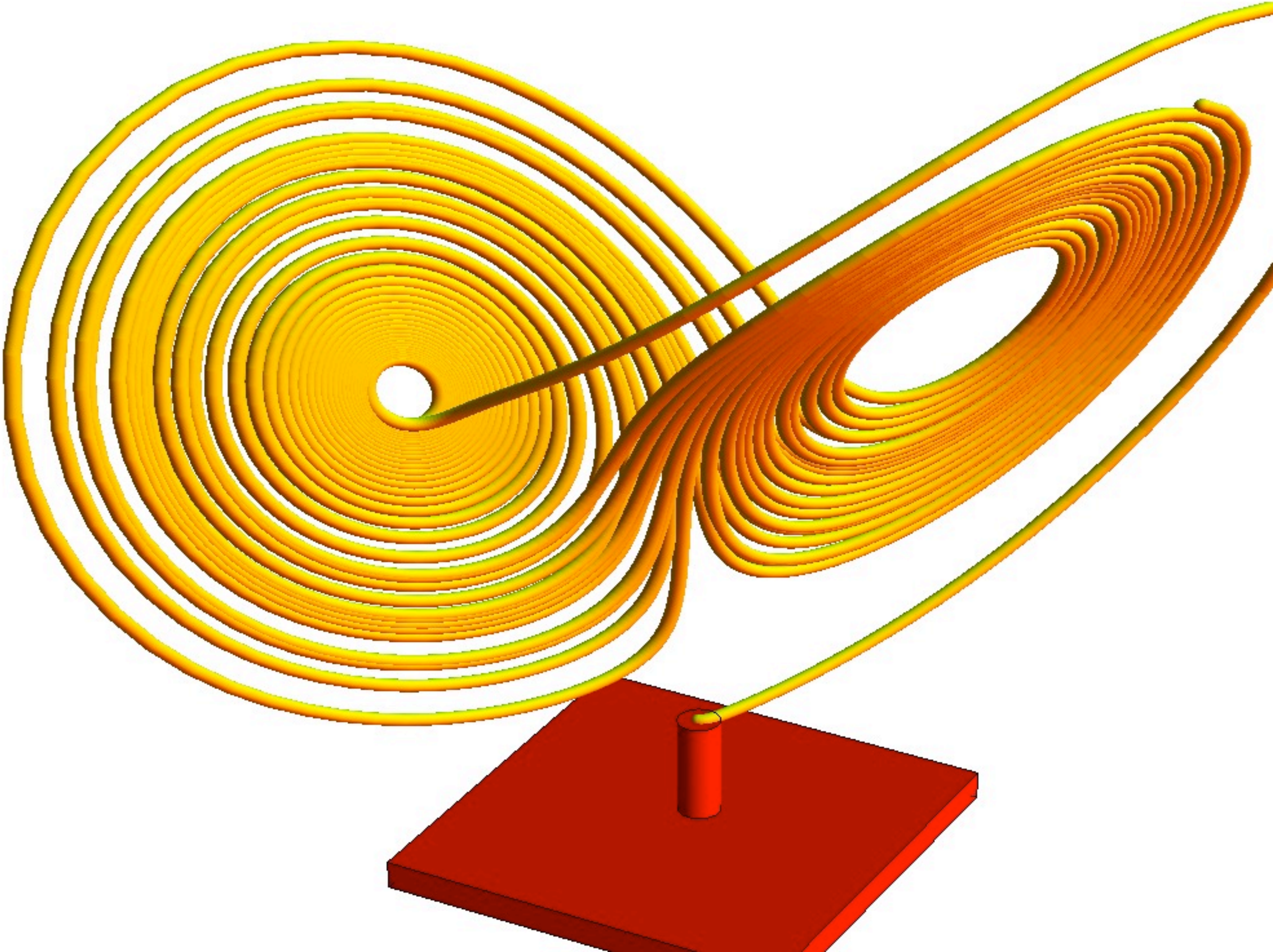
The exponential map on a spheroid $x^2/4+y^2+z^2=1$. The primary caustic (the first root of the Jacobi field f starting at the initial point) is drawn in yellow, the secondary caustic (the second root of f(g(t)) orange, the ternary red. One clearly sees the 4 cusps as the still unproven Jacobi's last geometric statement claims. 100 geodesics of the 6000 computed geodesics have been drawn. The picture was computed by solving the geodesic equations g''k = -G(i,j,k) g'i g'j (where G is the connection using Einstein notation) in conjunction with the Gauss-Jacobi equation f'= - K(g(t)) f (where K is the curvature of the surface) numerically with Mathematica. Since special needs are required (identifications of the map, assuring that we stay on the energy surface, checking whether the Jacobi field f reaches zero), the differential equations were "hand" integrated using Runge-Kutta and not using built-in DSolve routines. 6000 geodesics g(t) were computed on the ellipsoid and drawn in the spherical coordinate plane with (theta,phi) coordinate

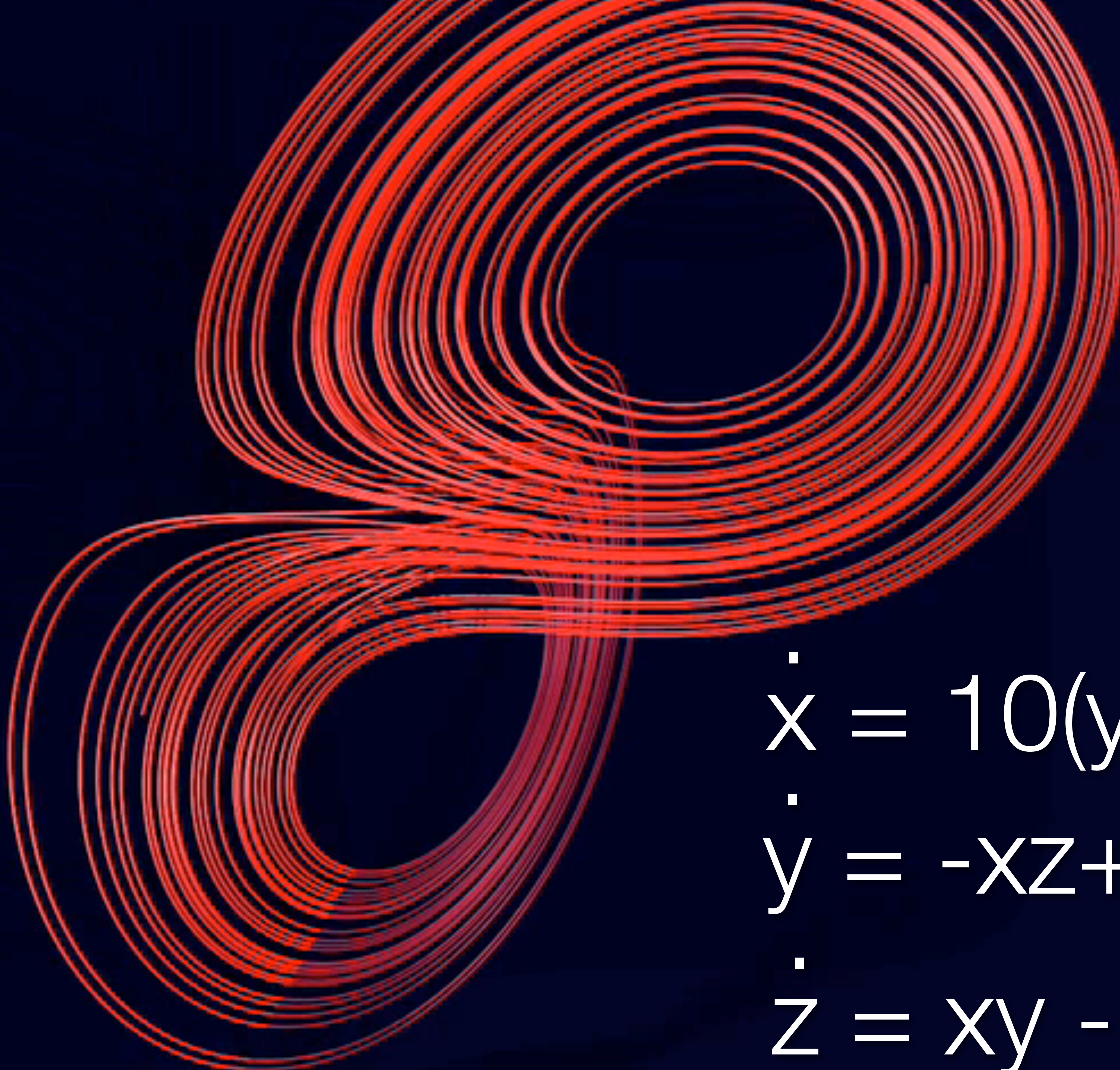








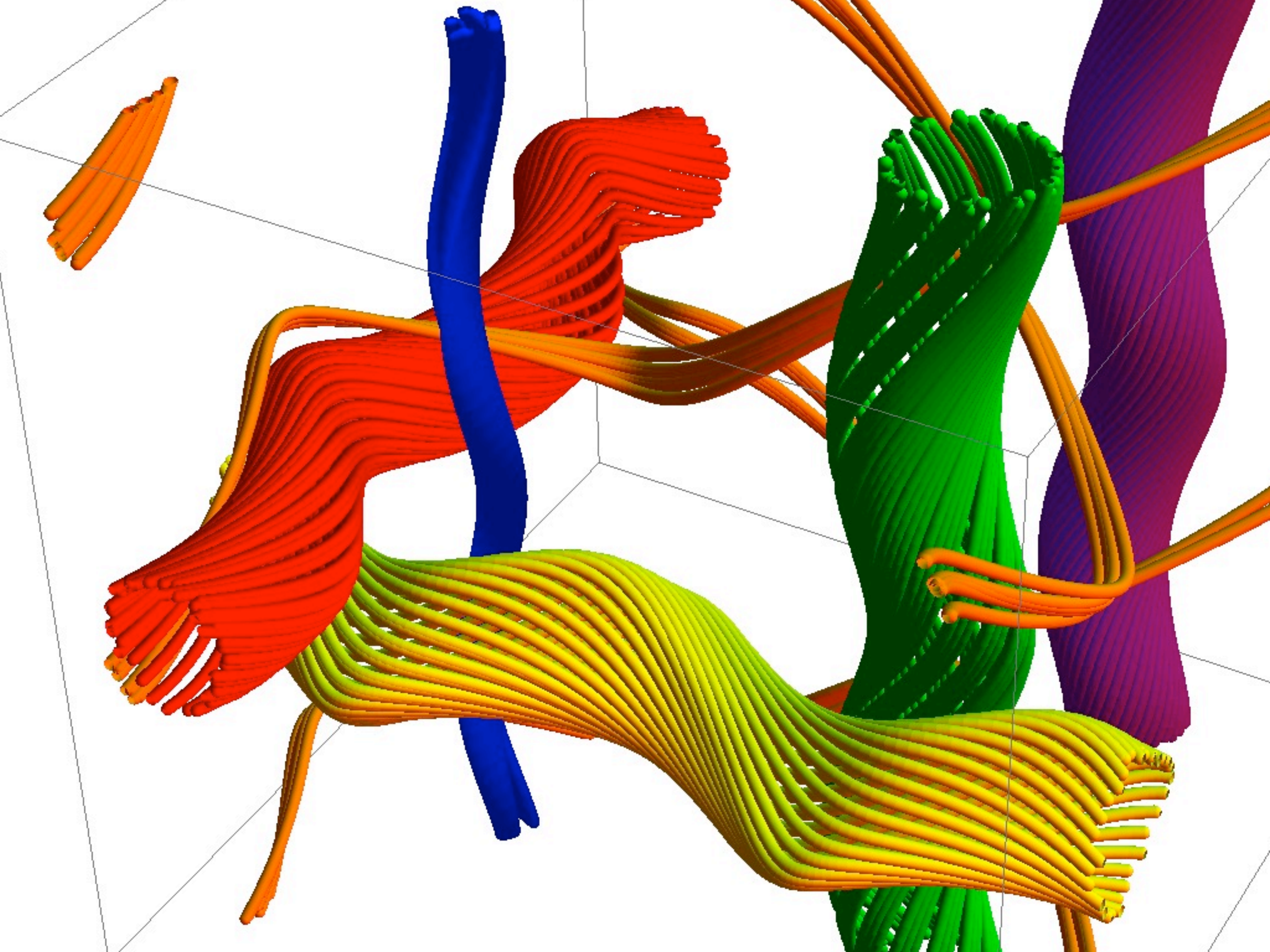


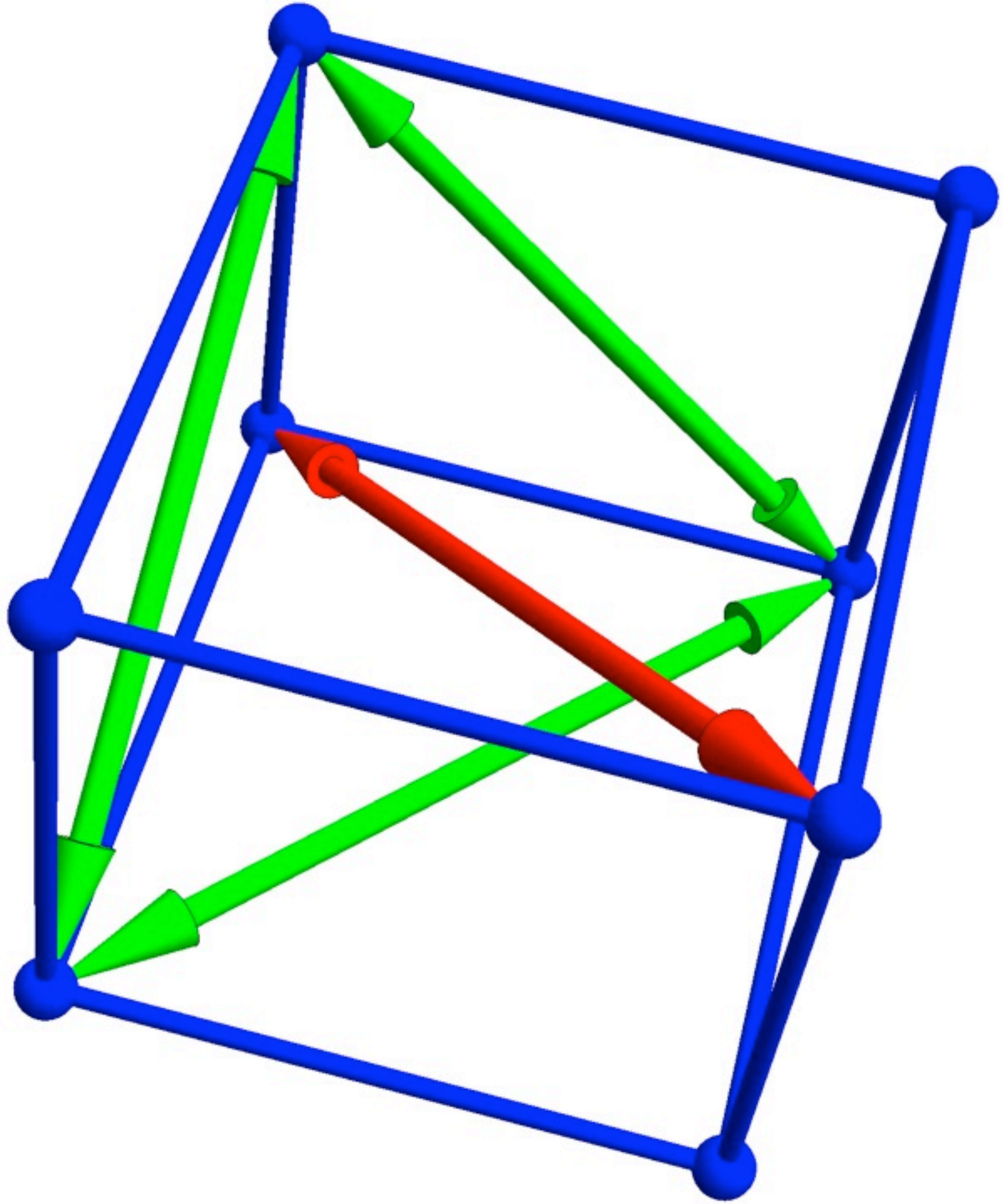


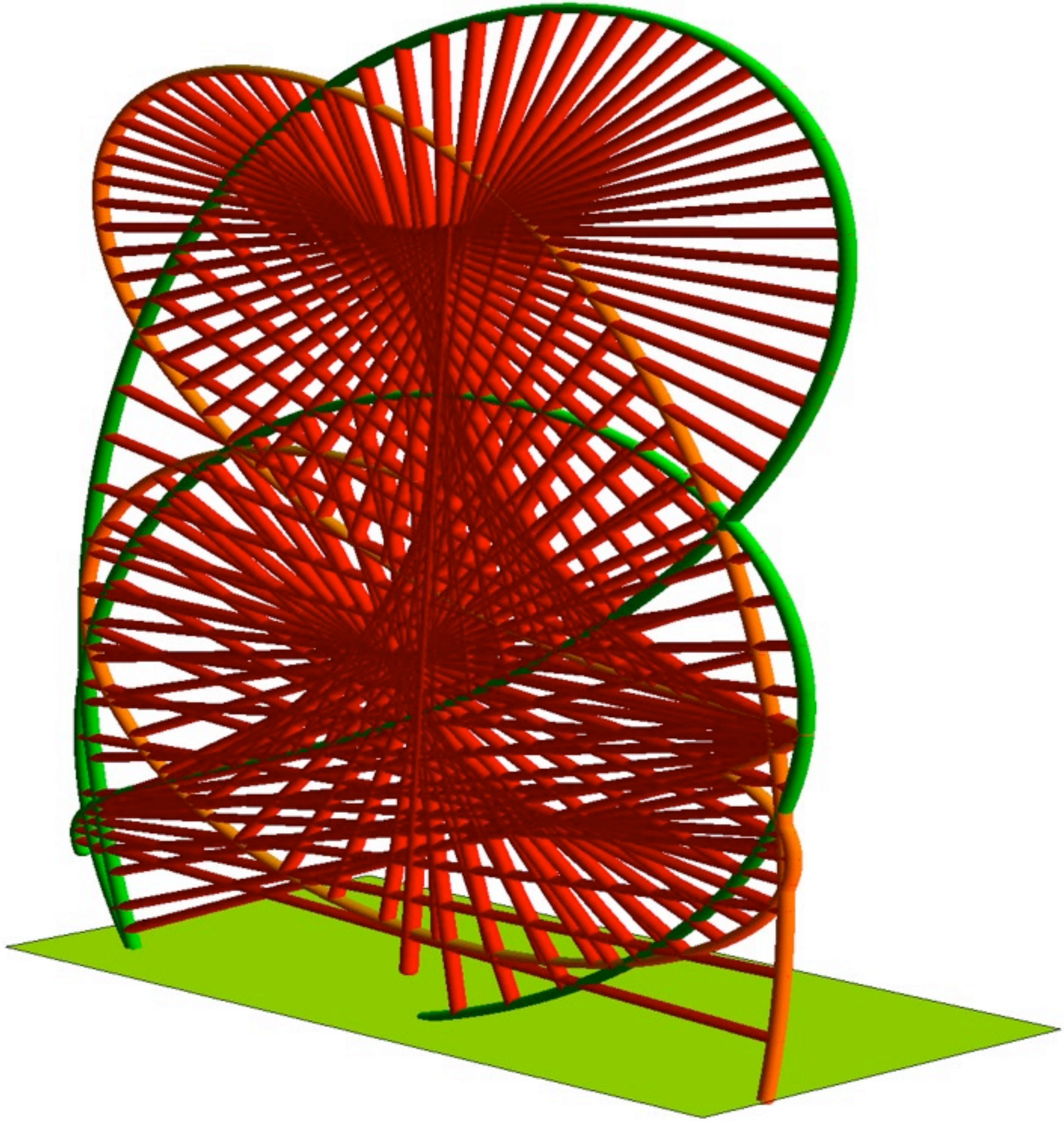
$$\dot{x} = 10(y-x)$$

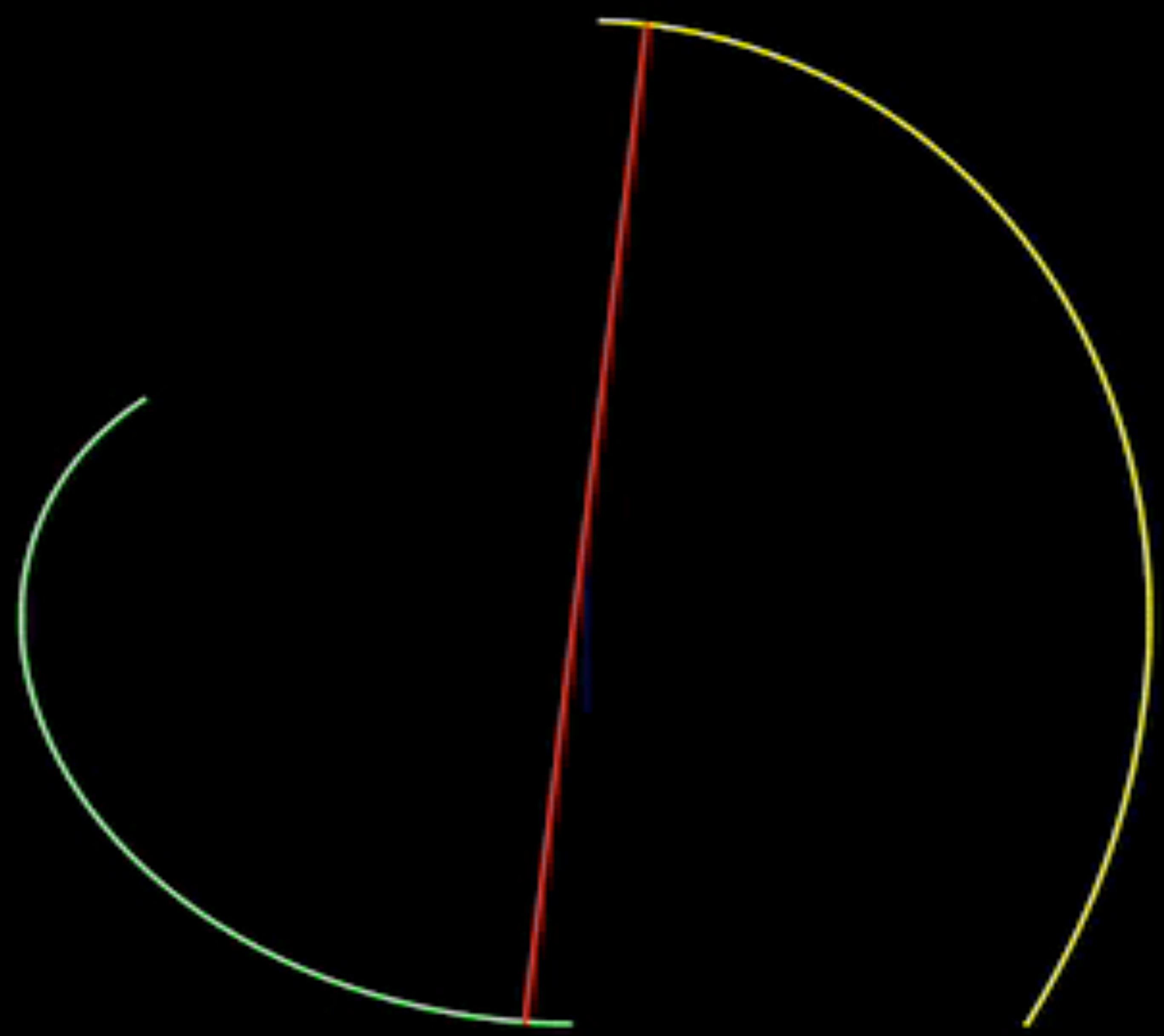
$$\dot{y} = -xz+28x-y$$

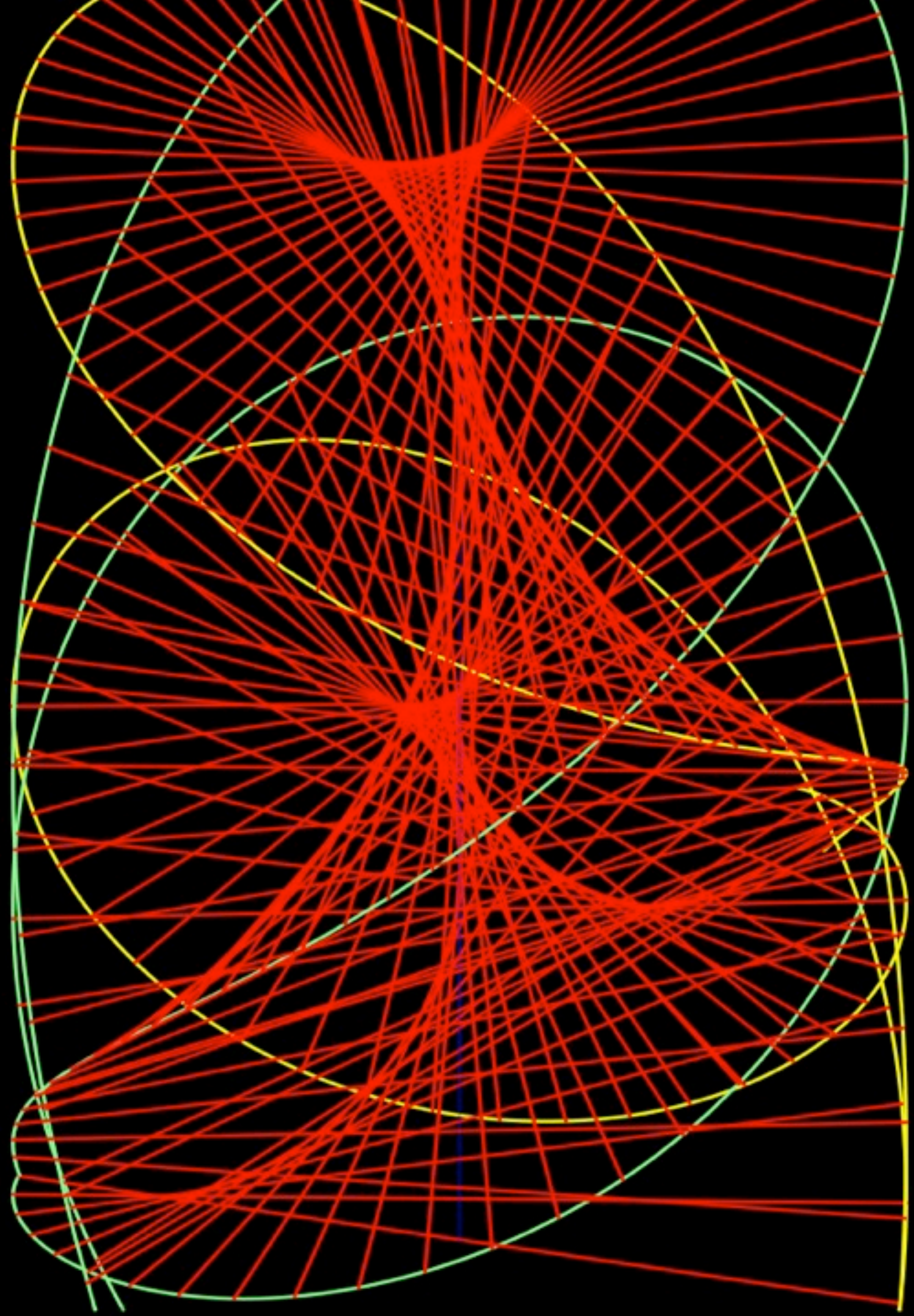
$$\dot{z} = xy - z\frac{8}{3}$$

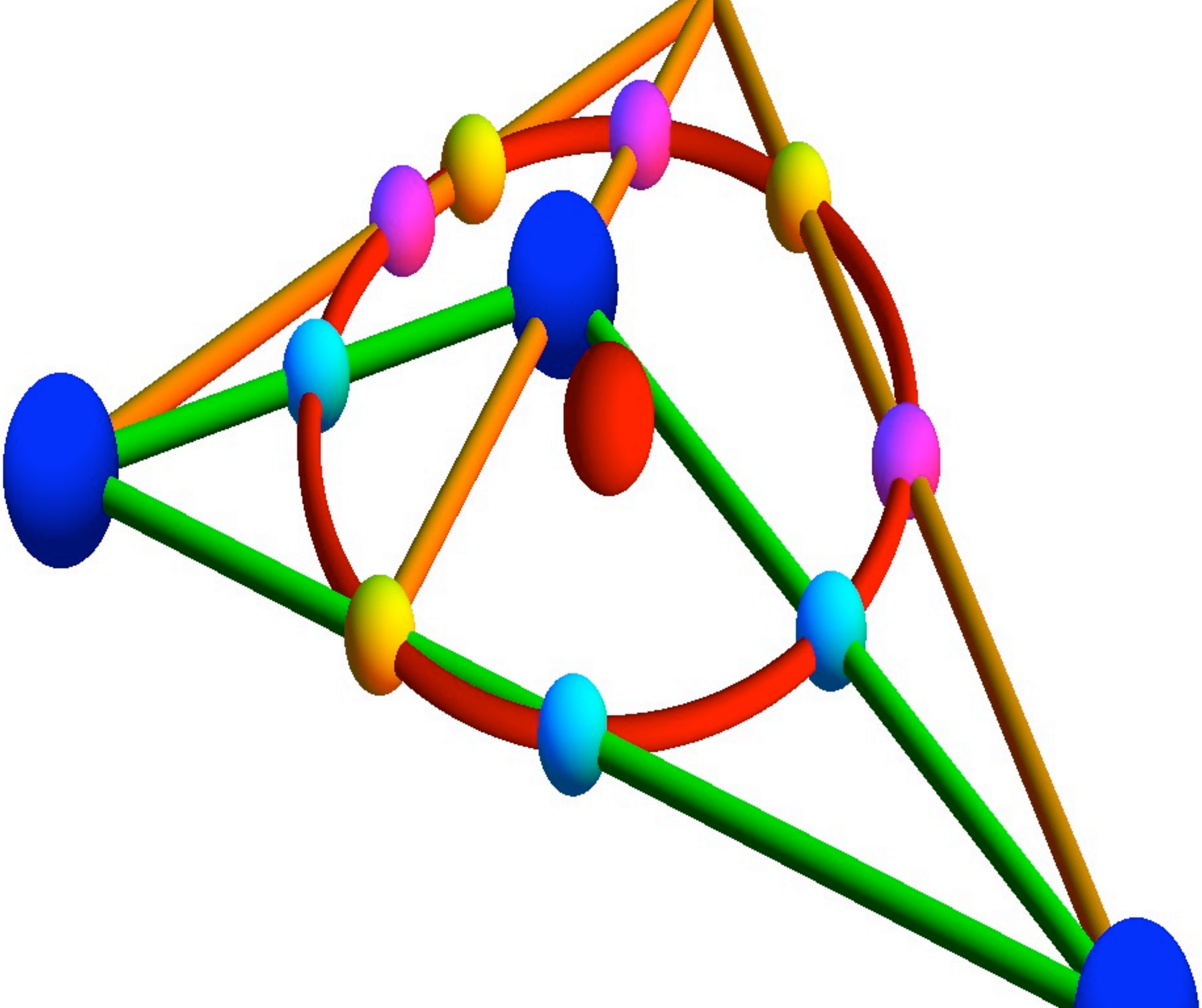


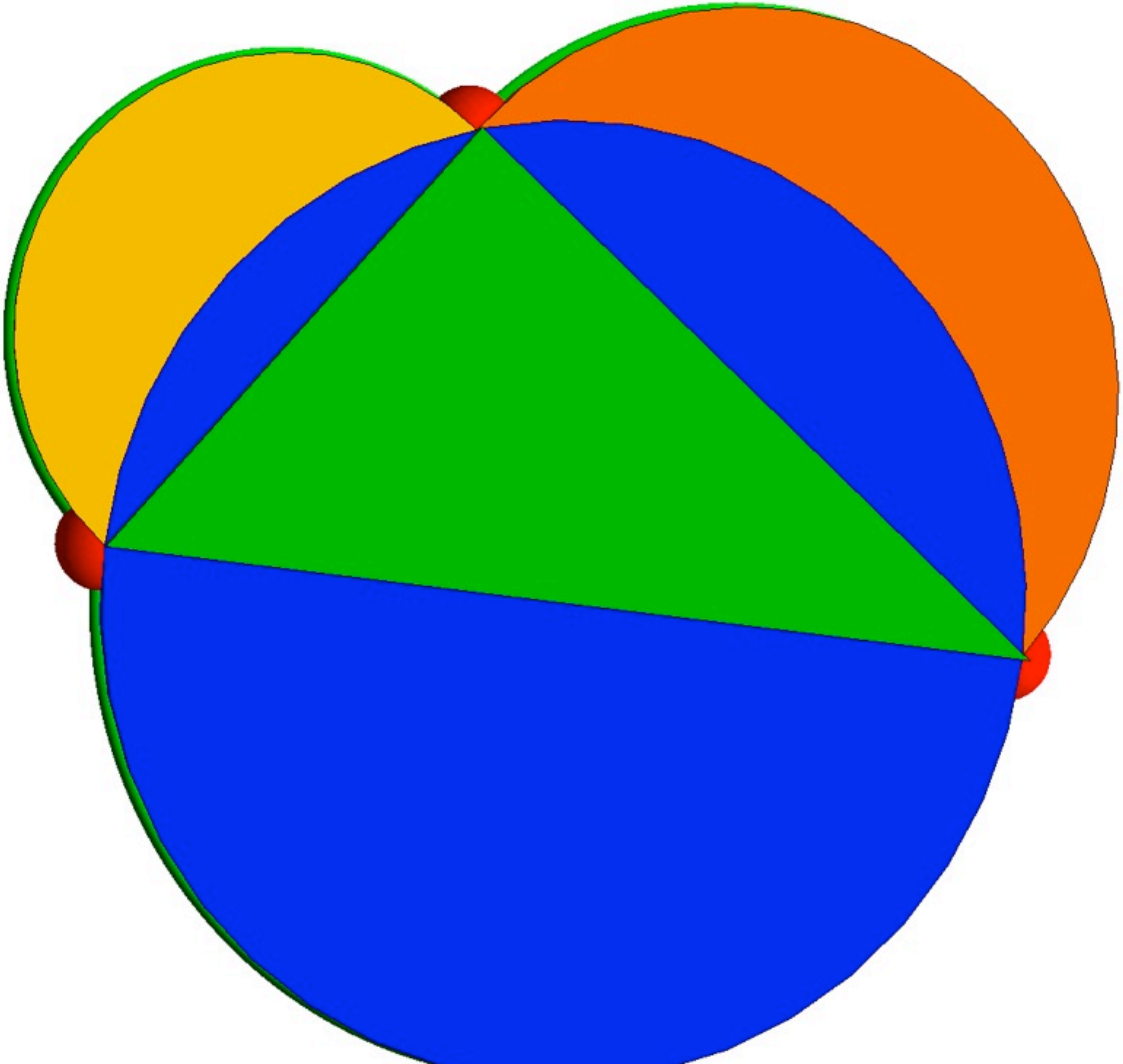


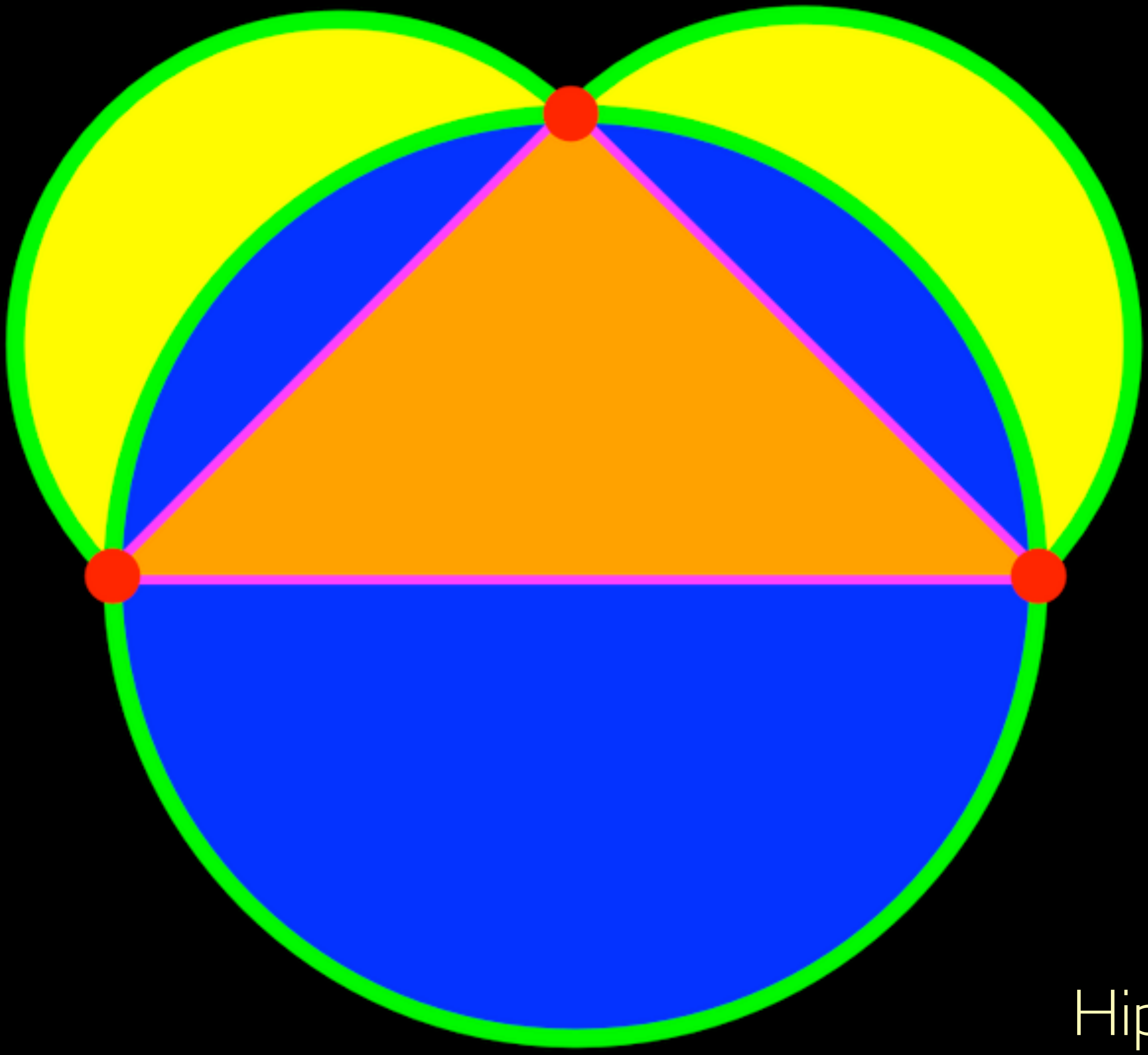




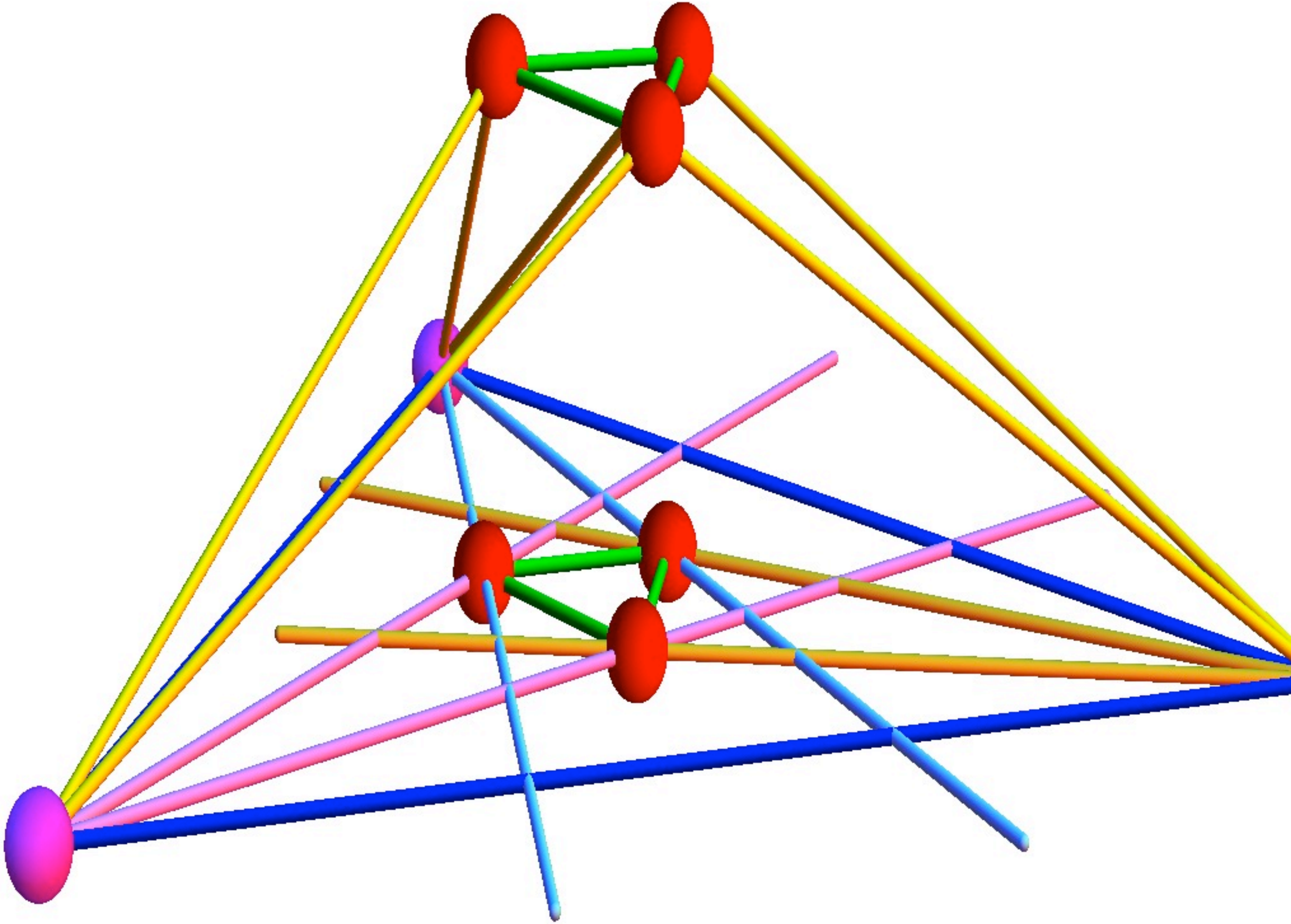


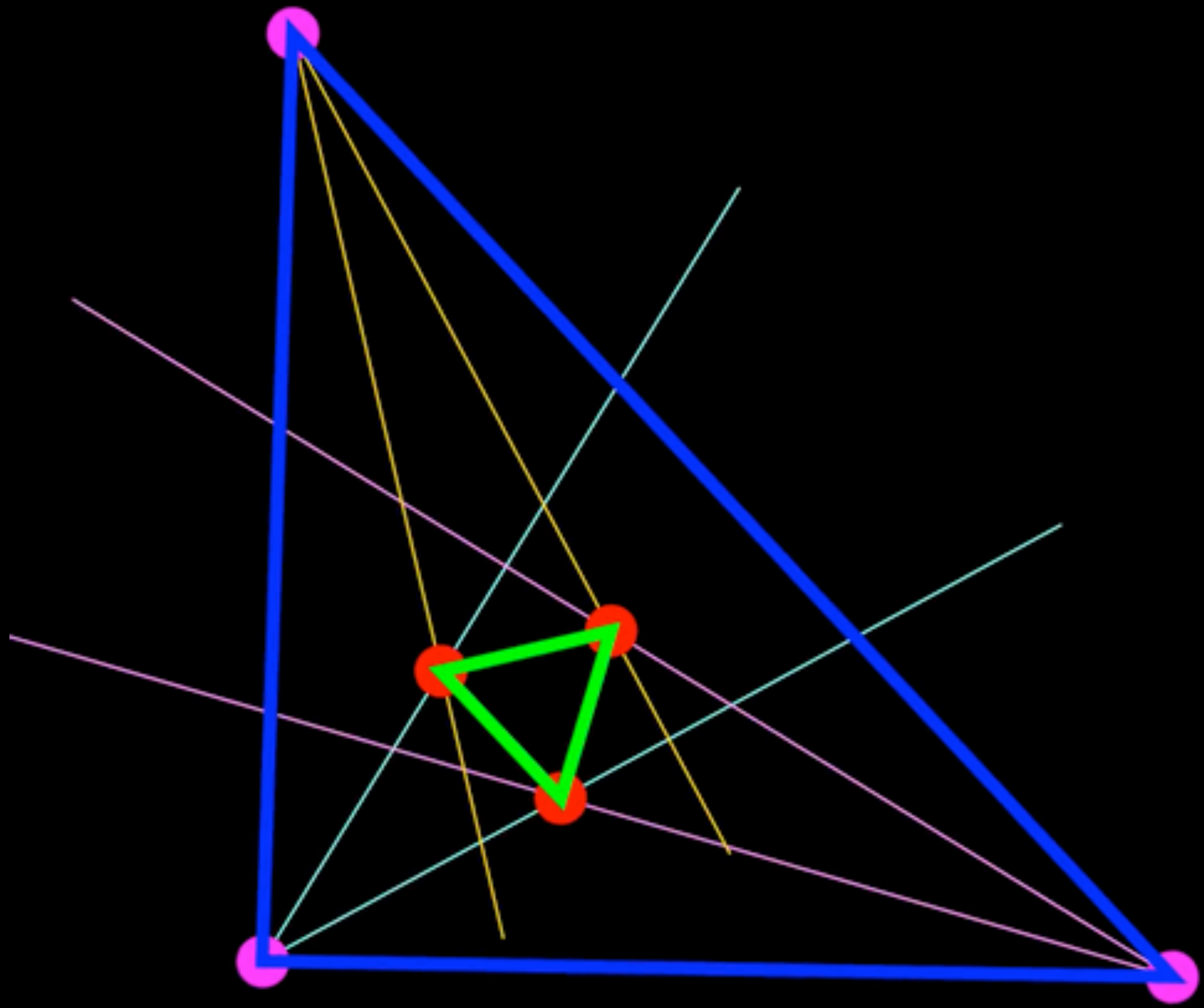


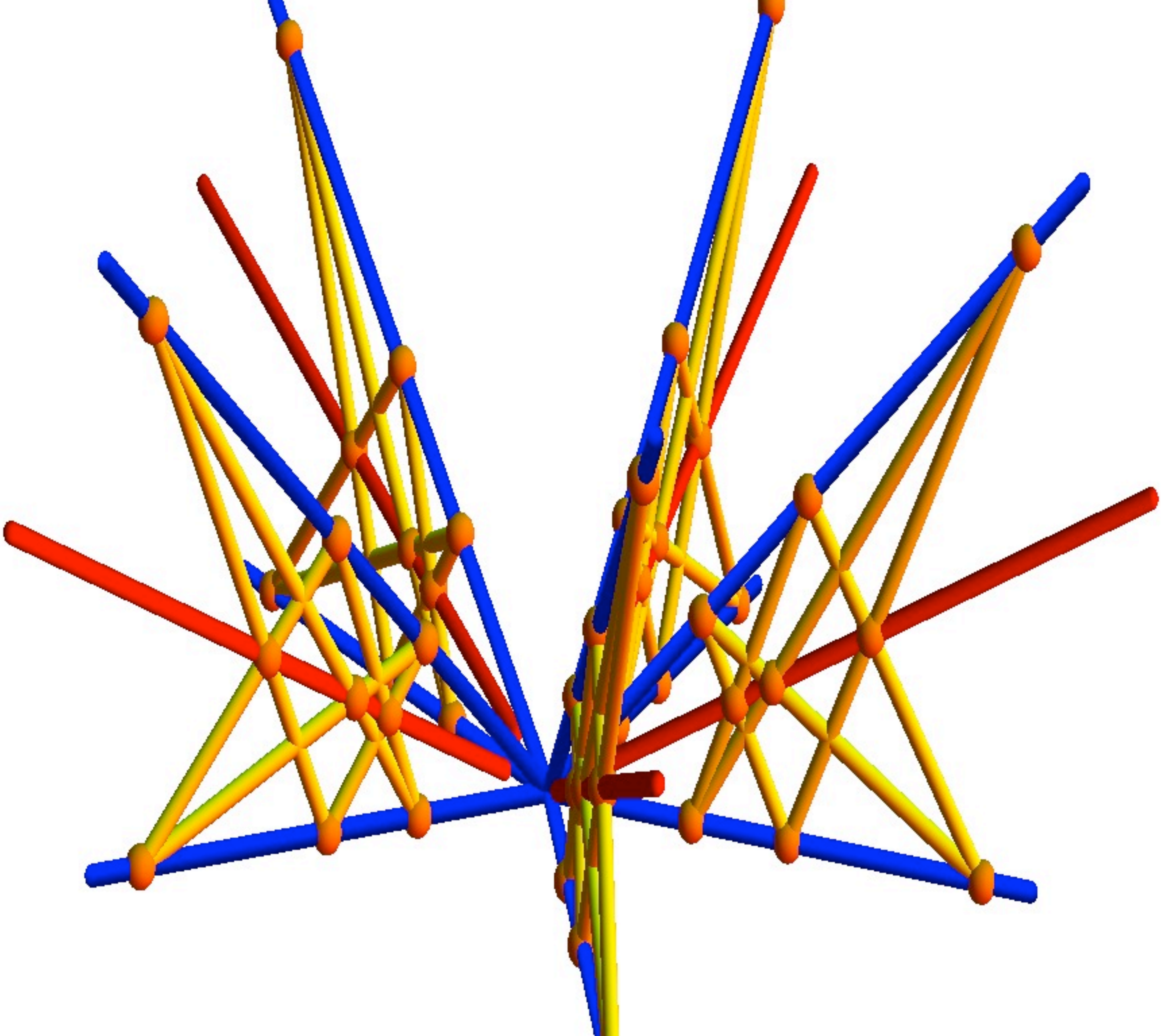


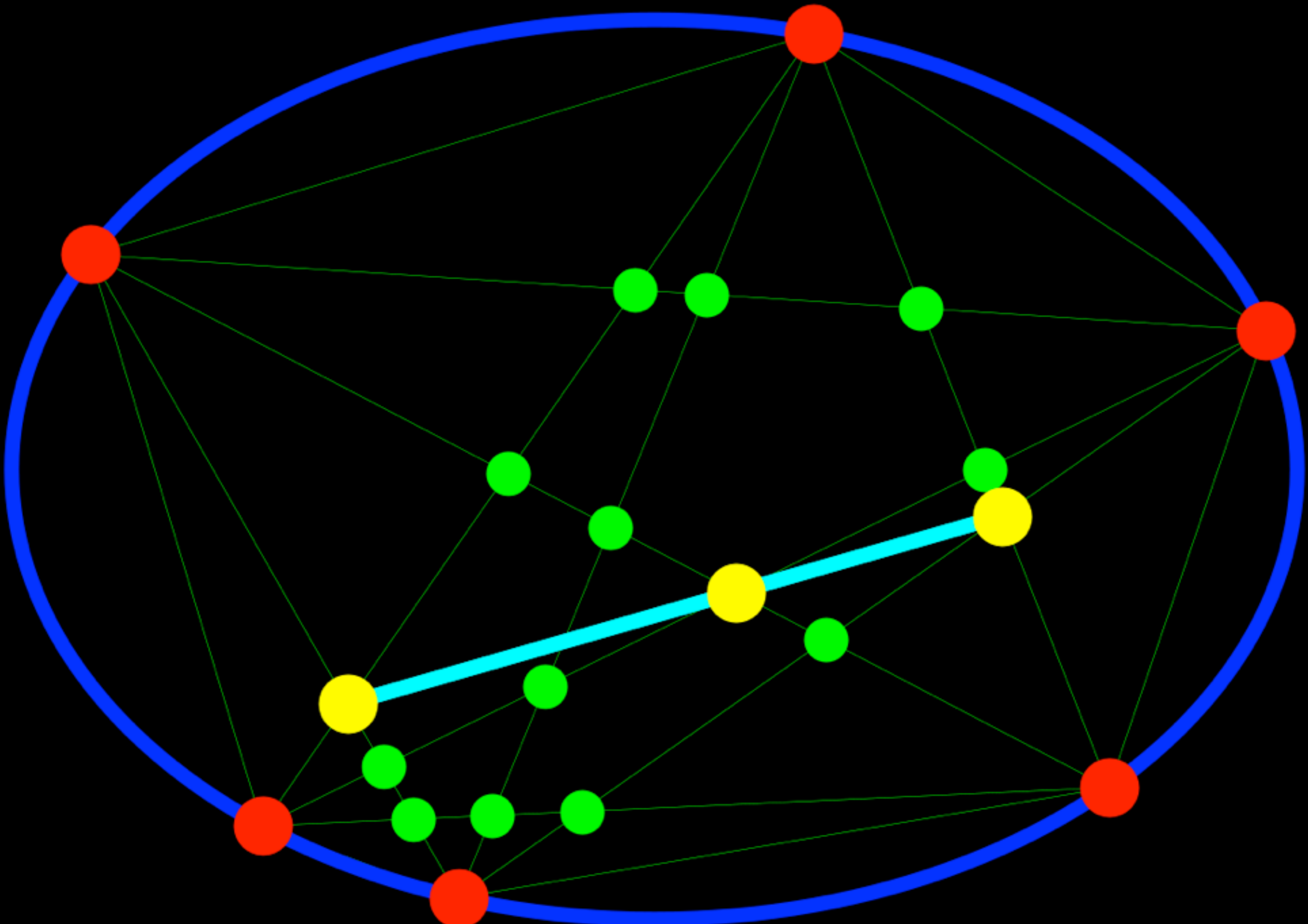


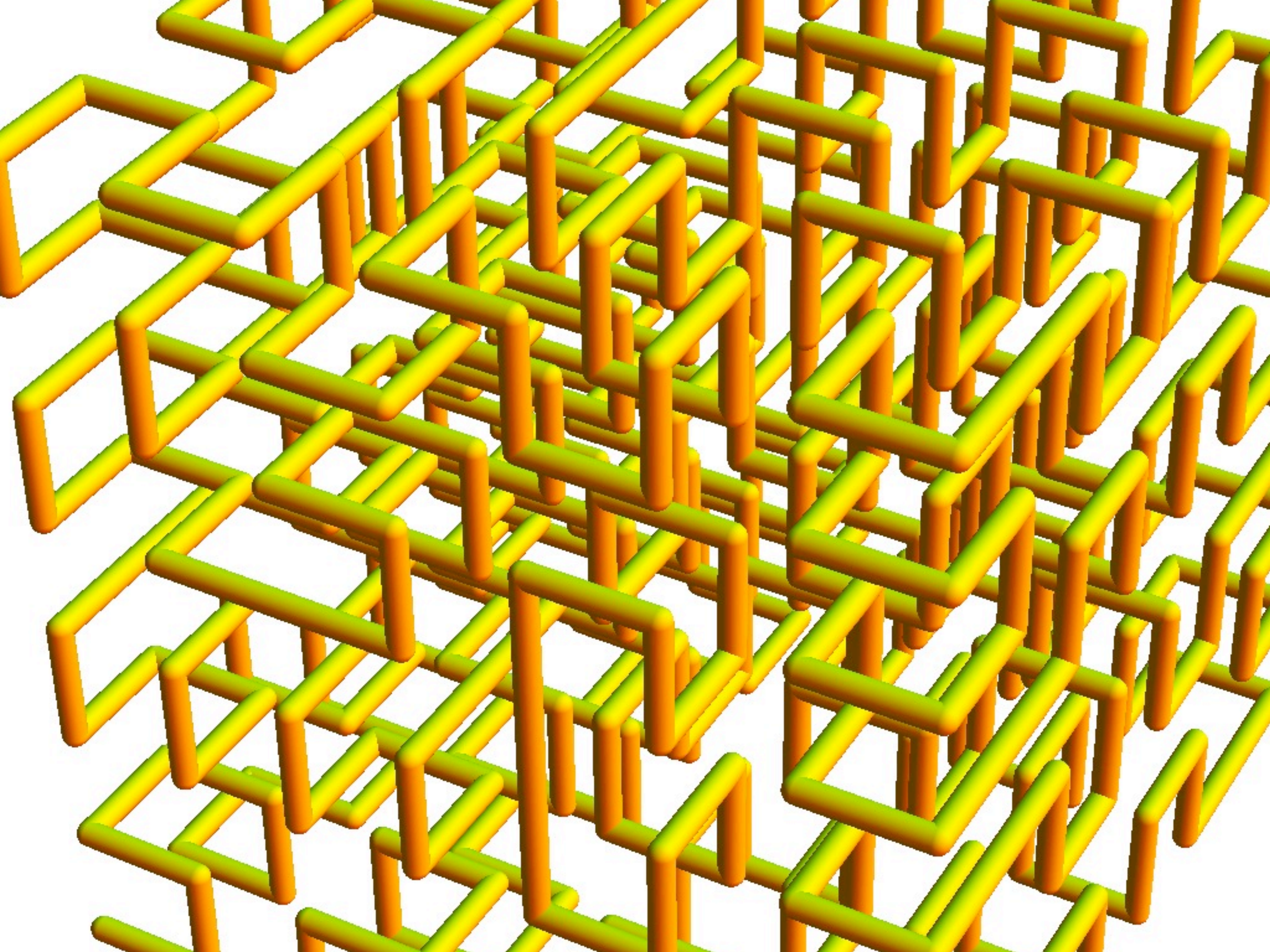
Hipocrates

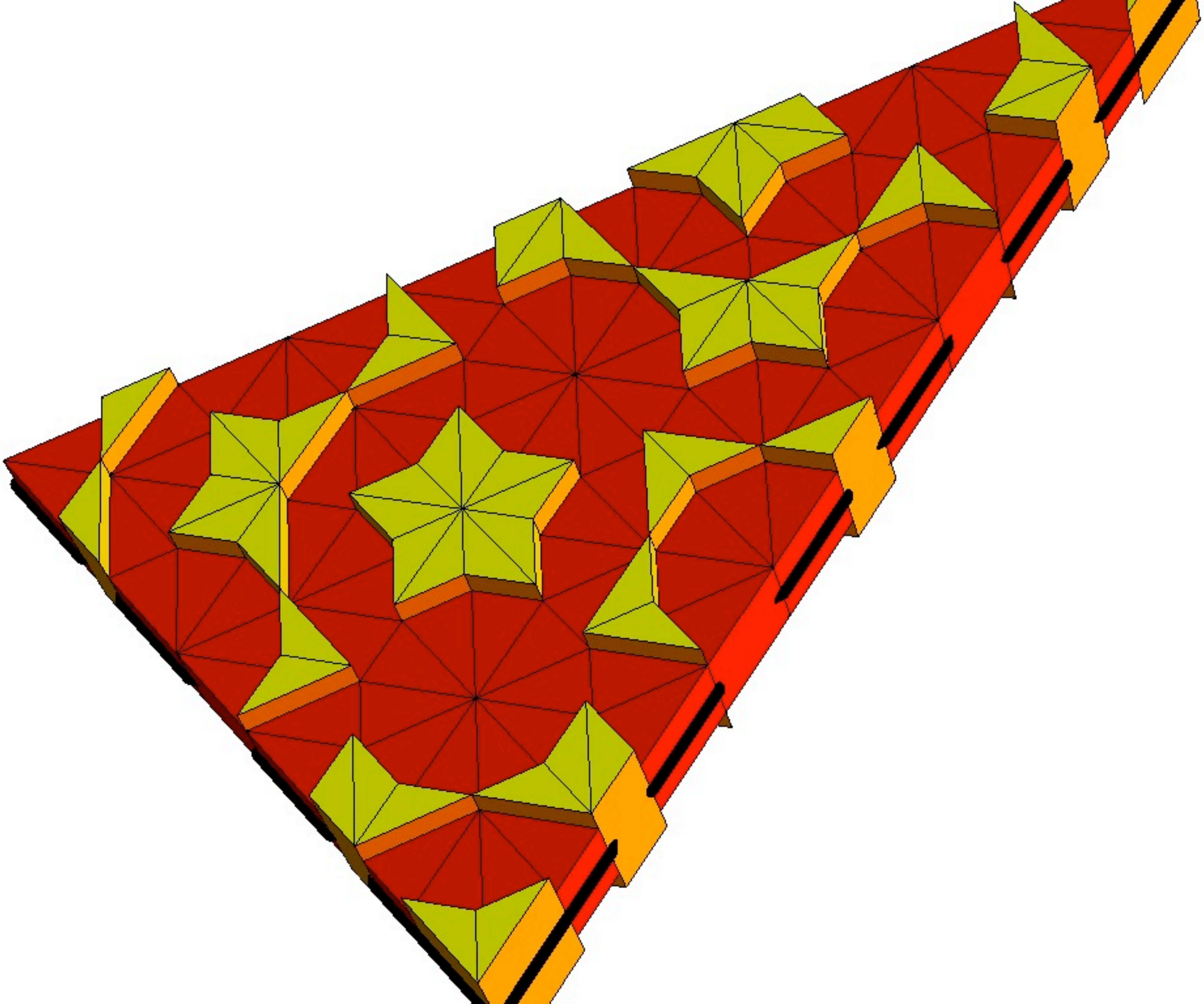


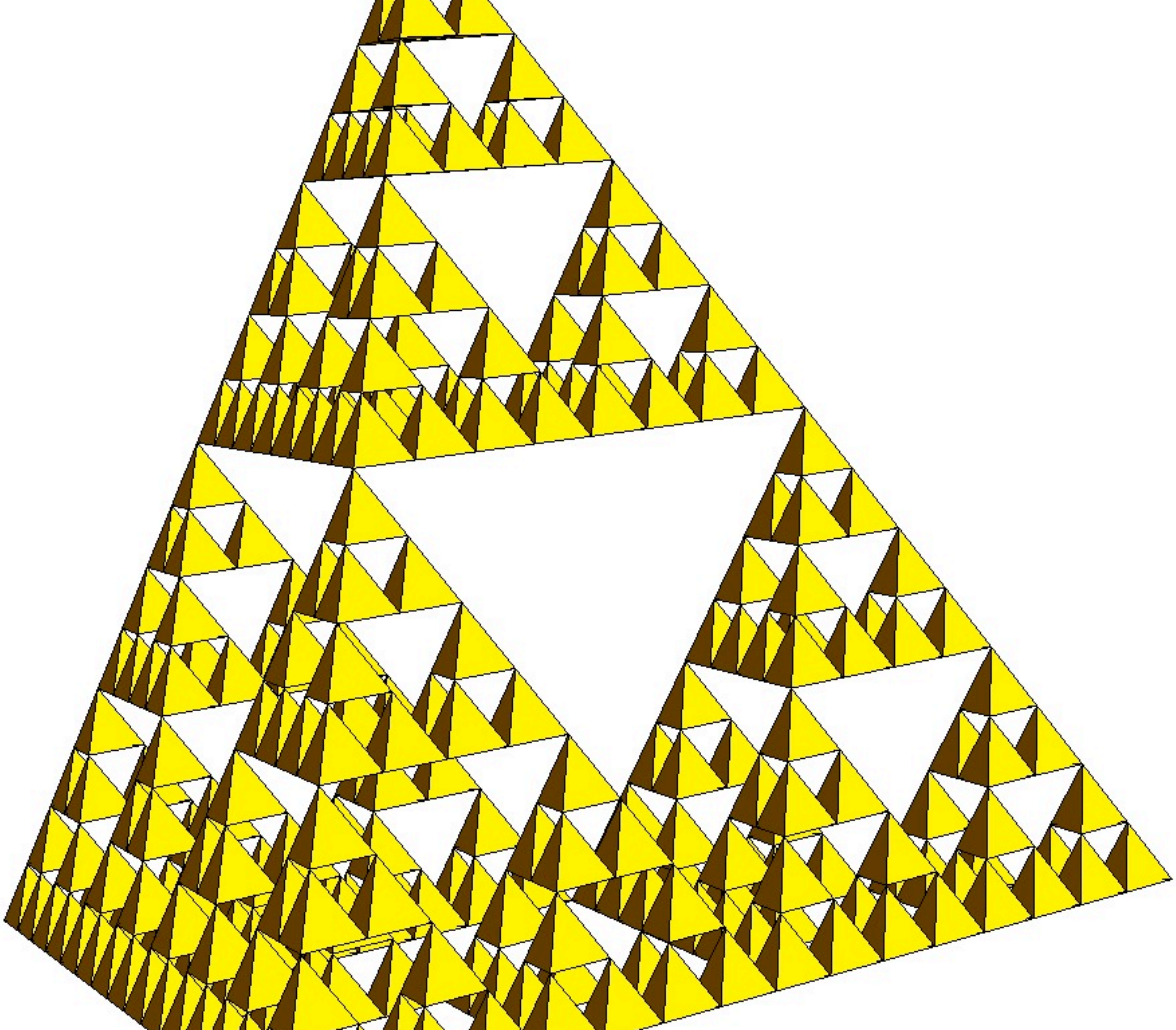


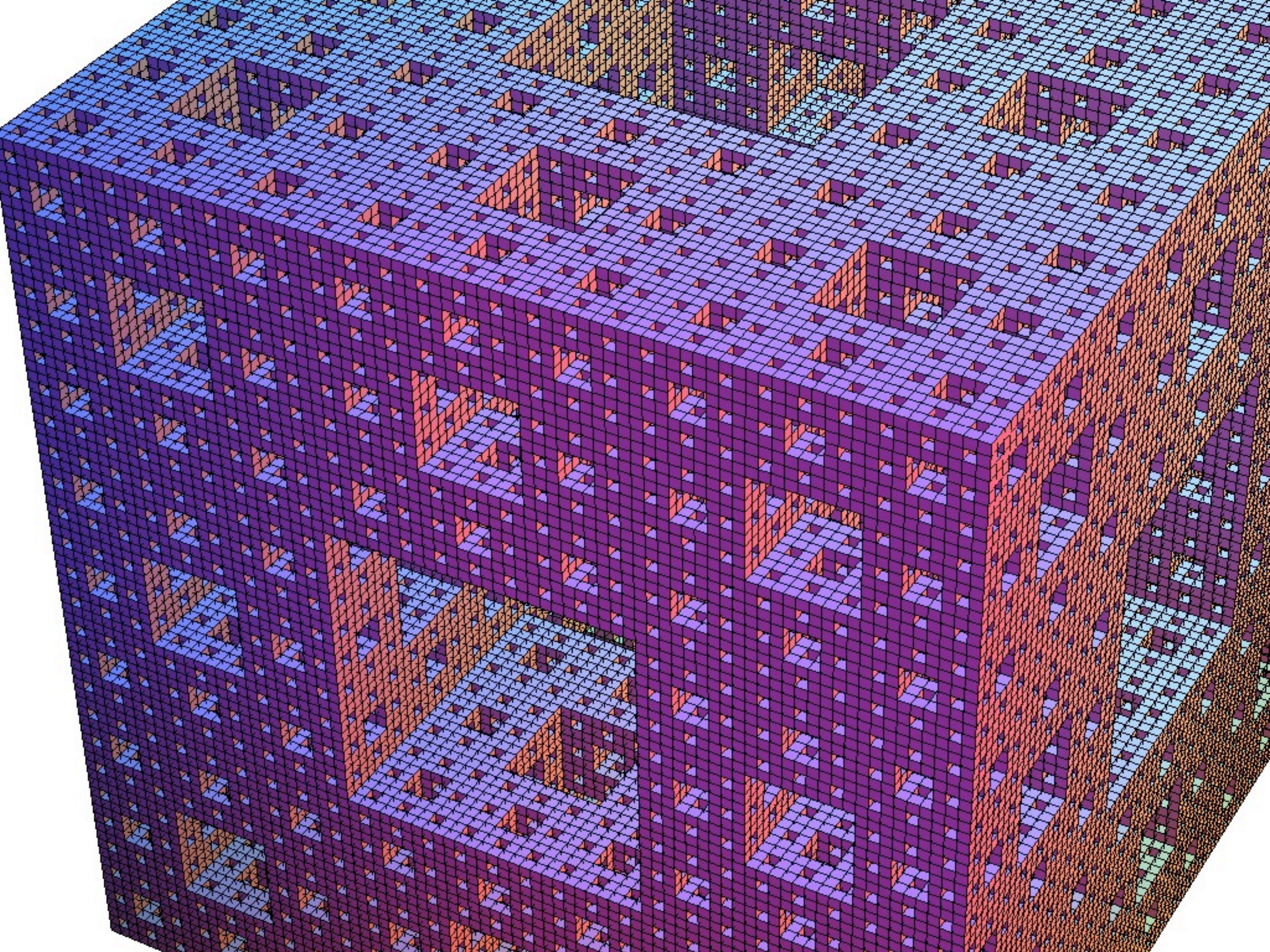


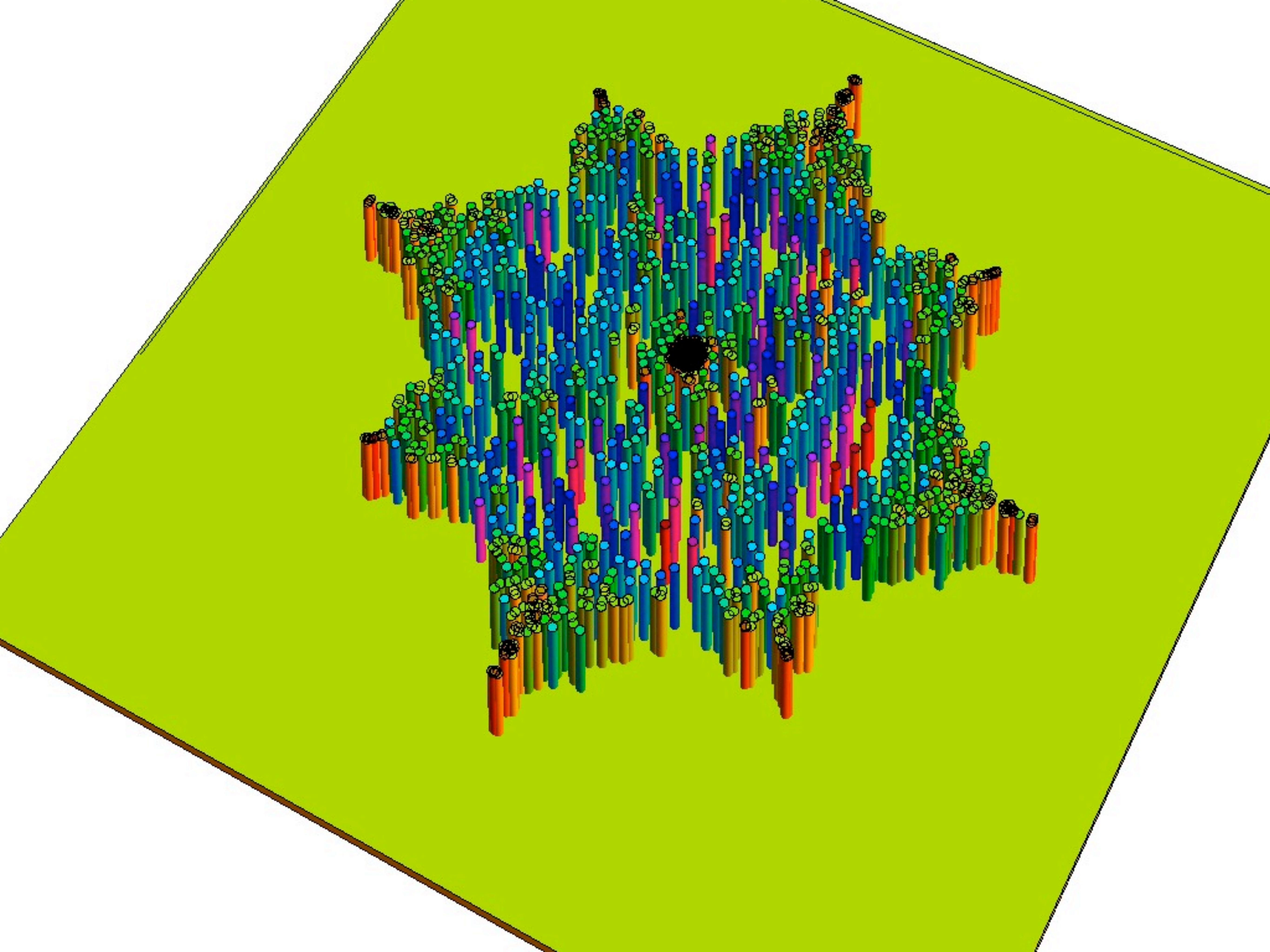


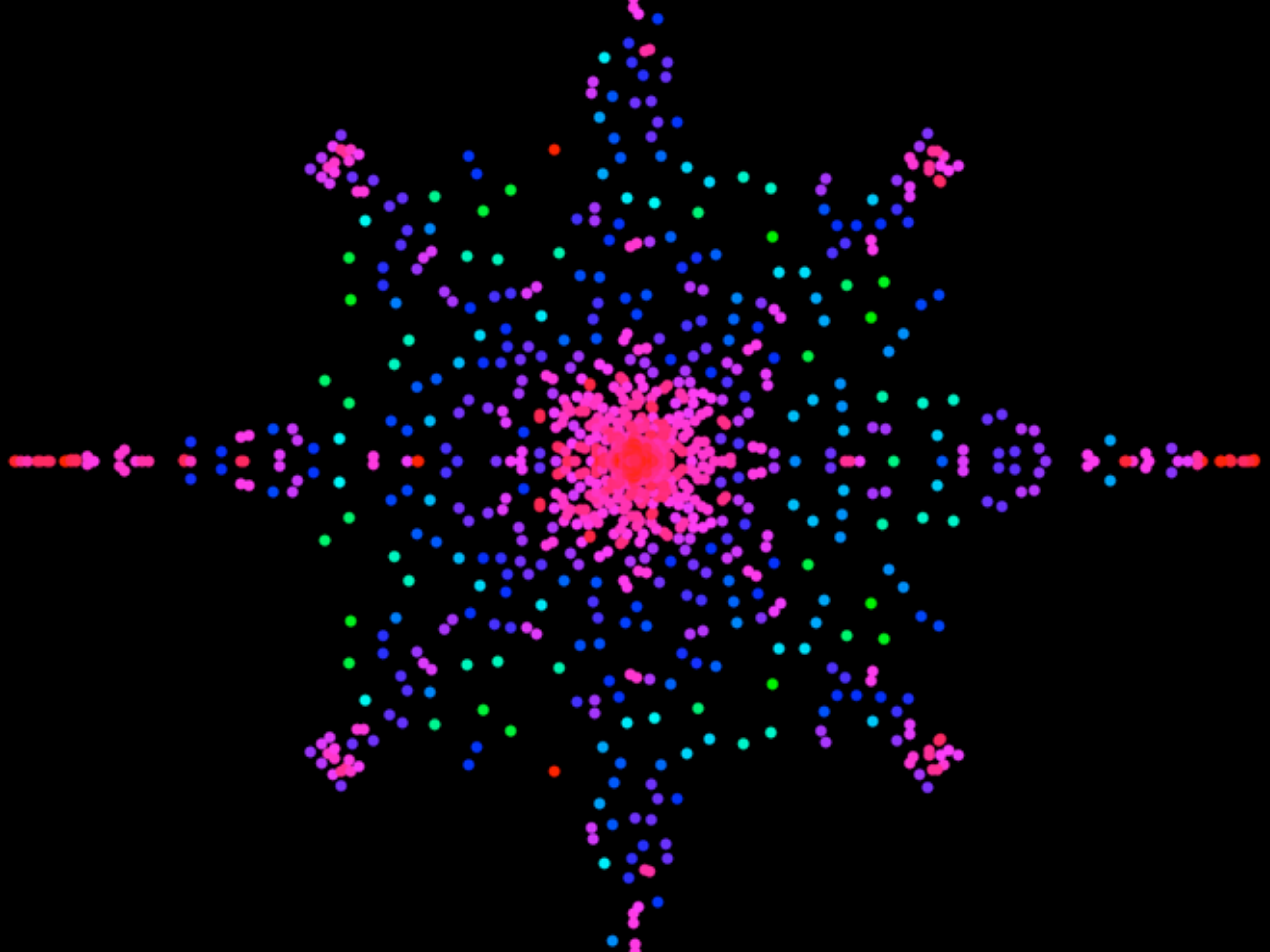


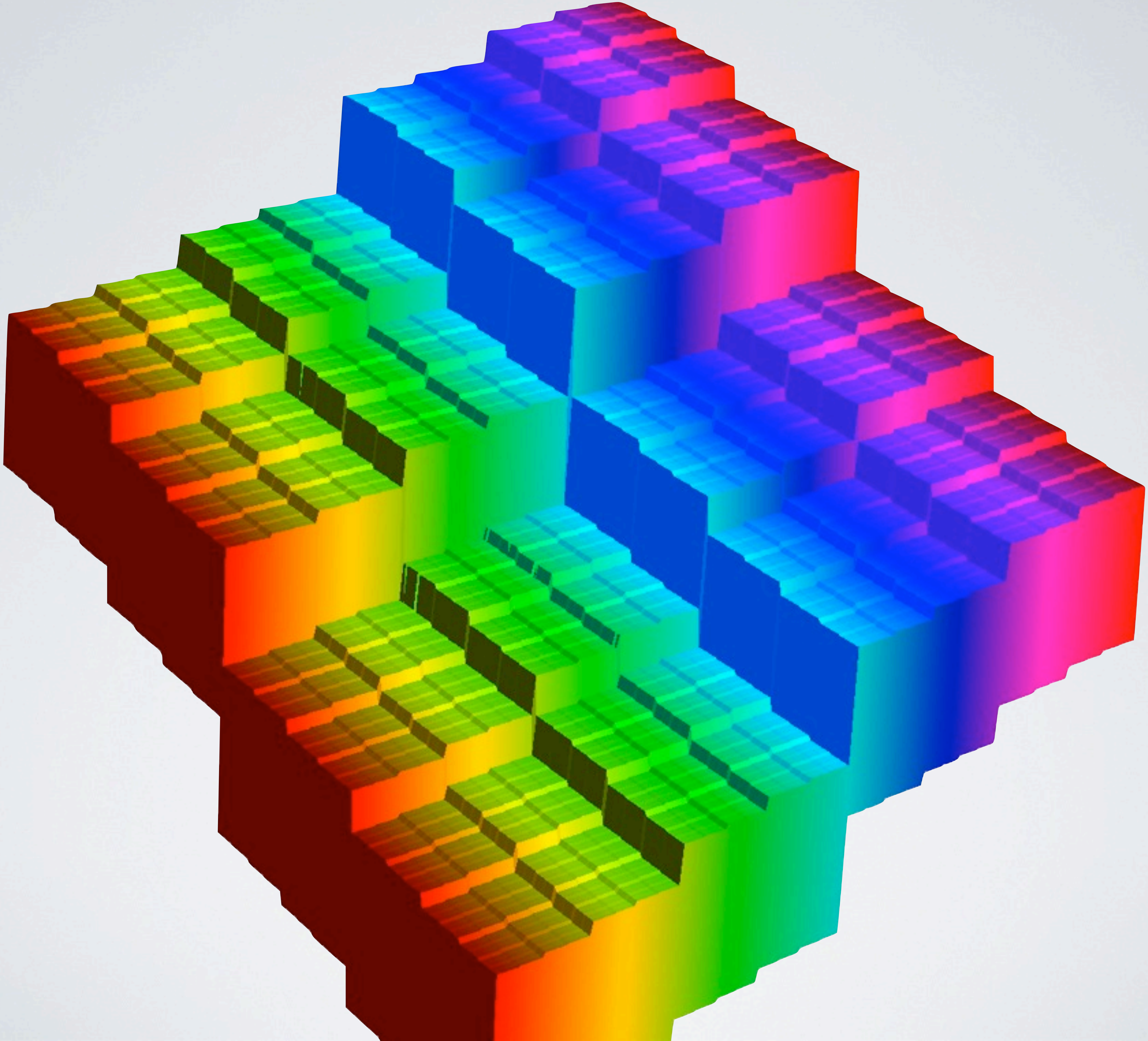


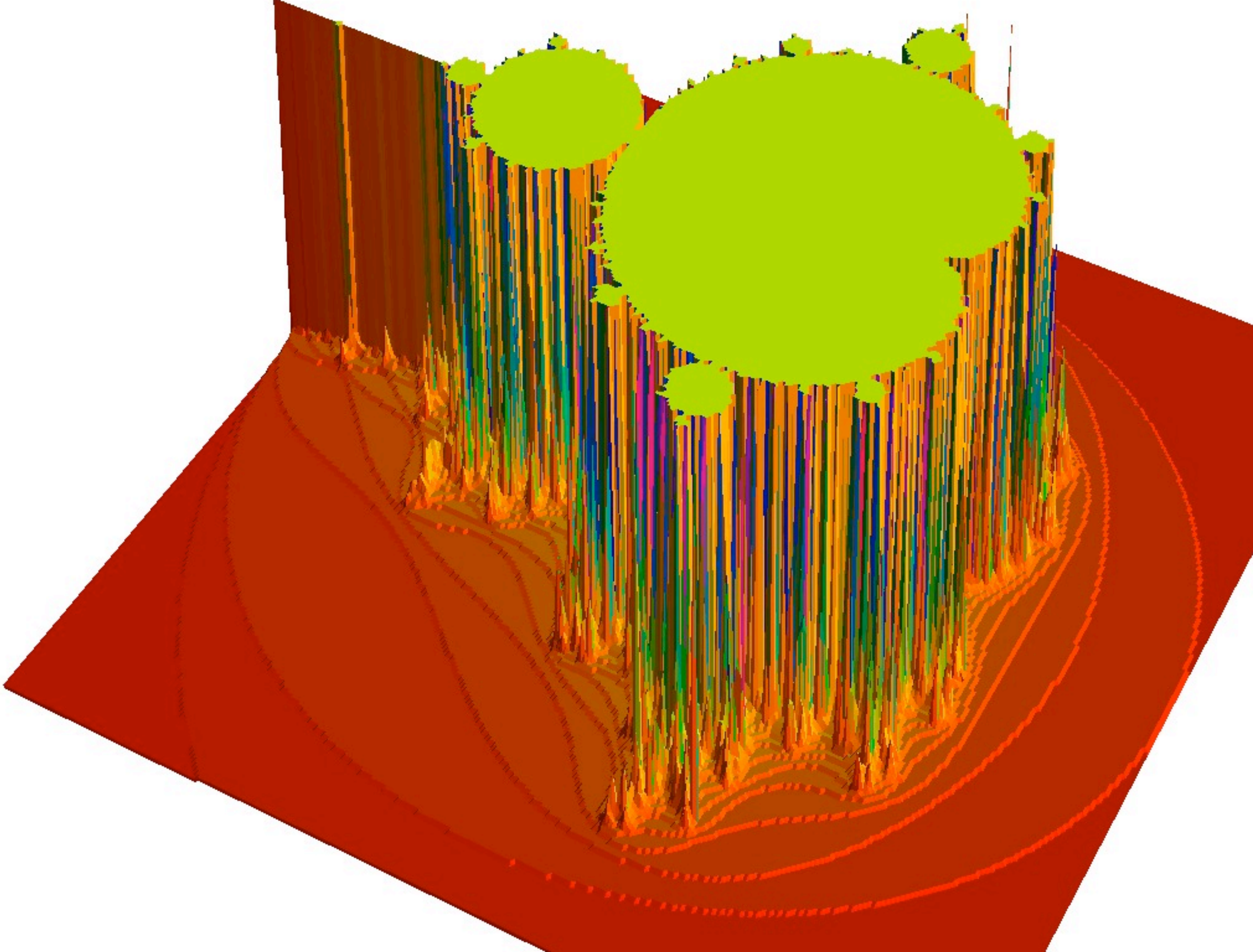


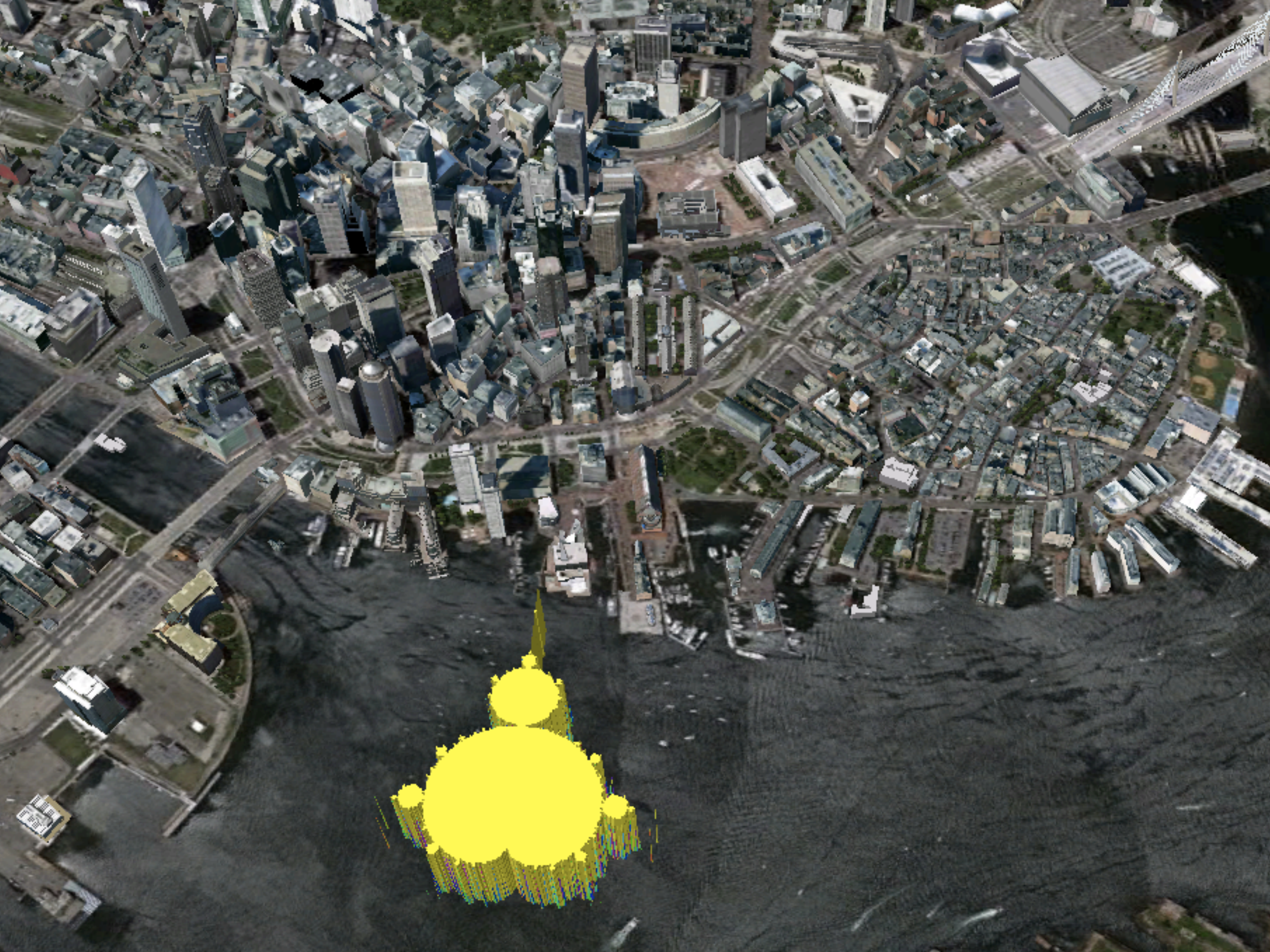


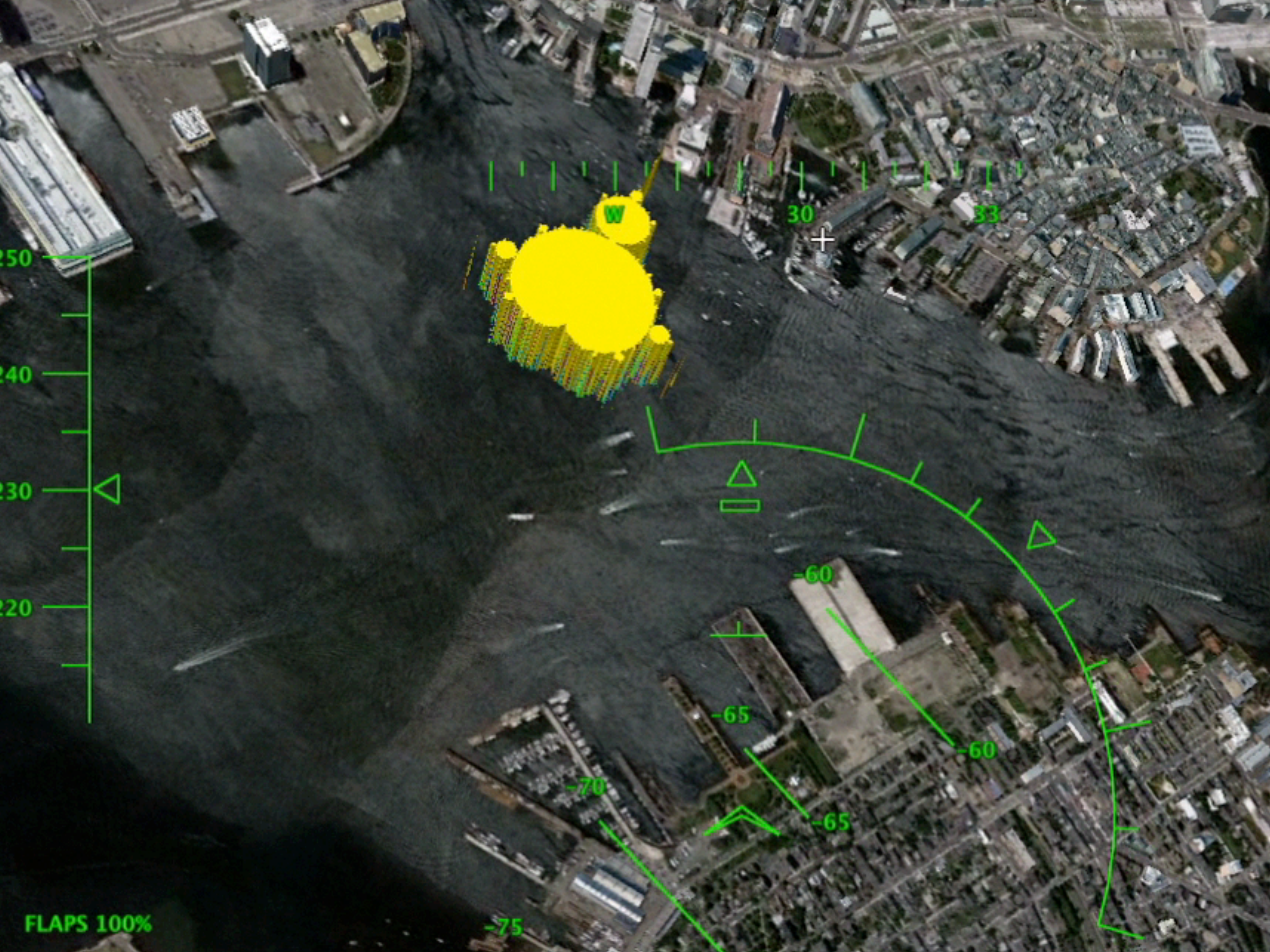












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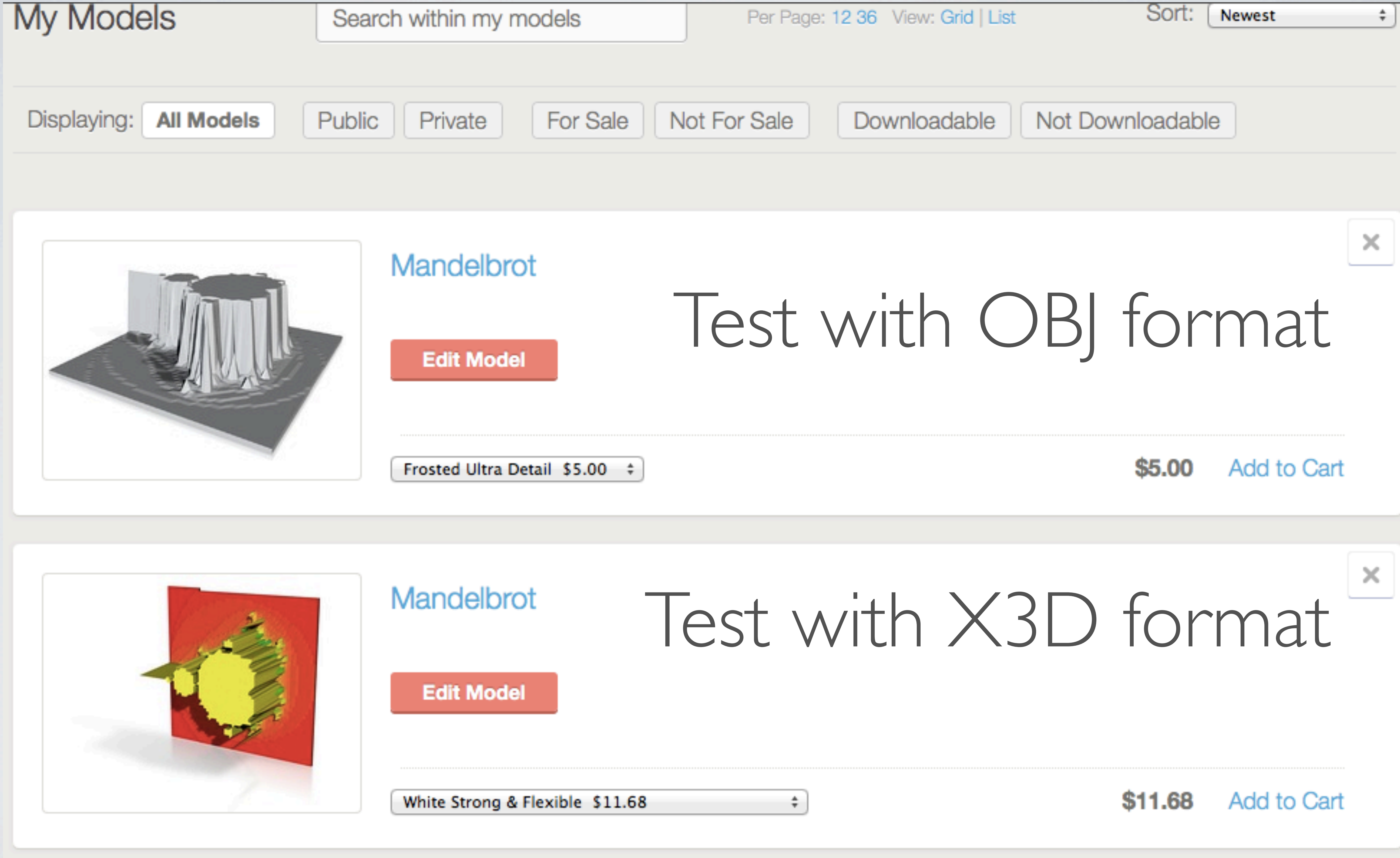
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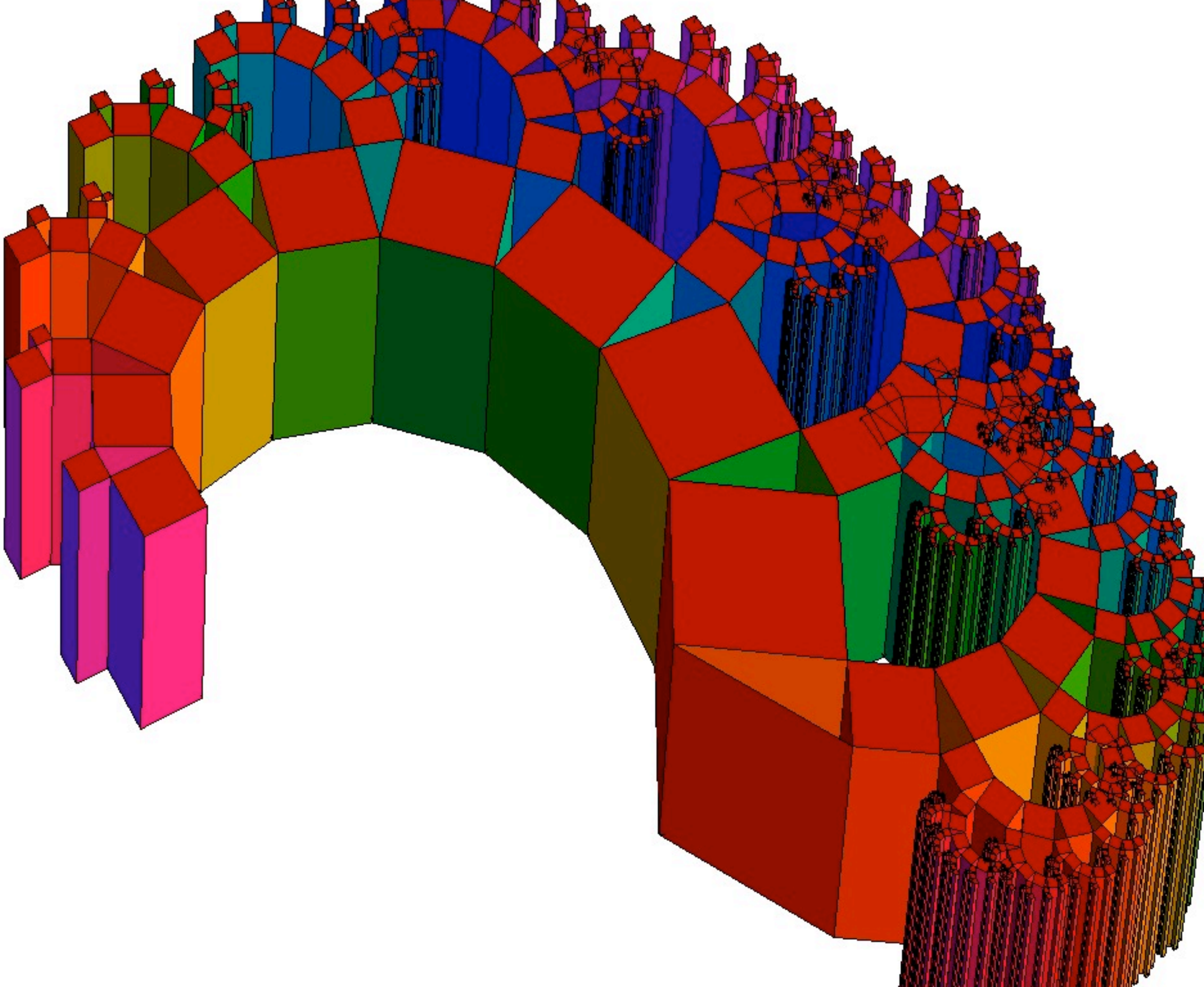

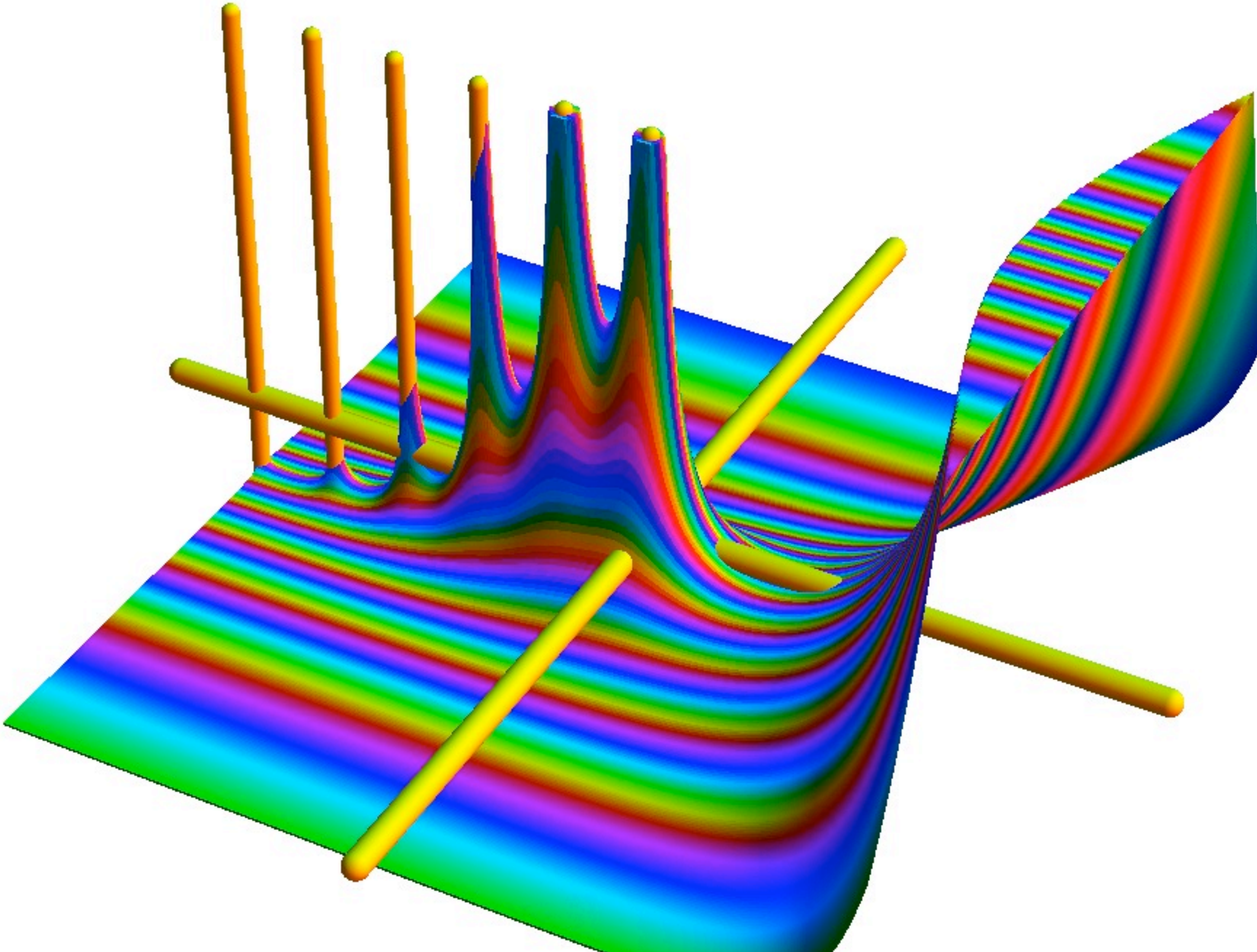

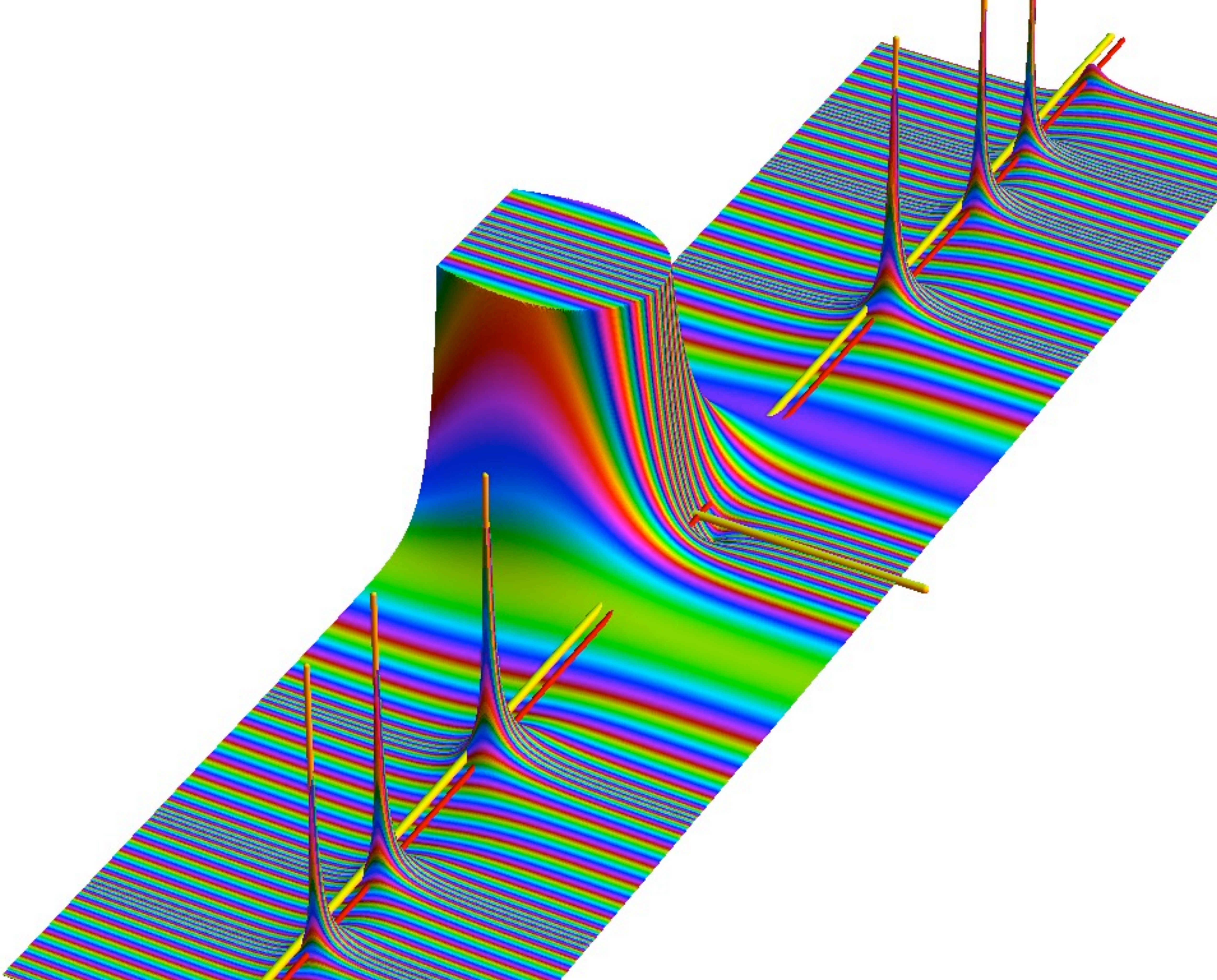

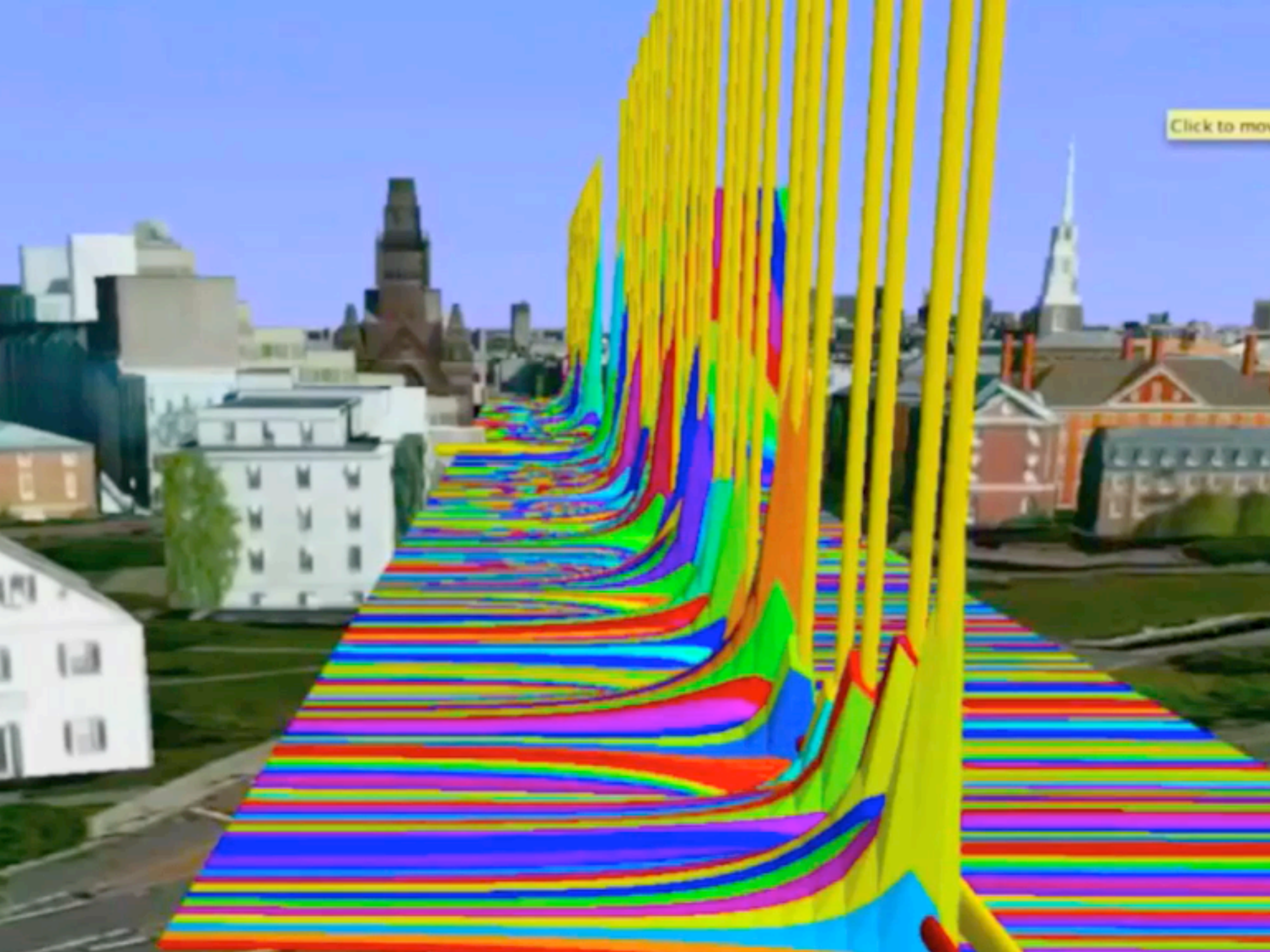
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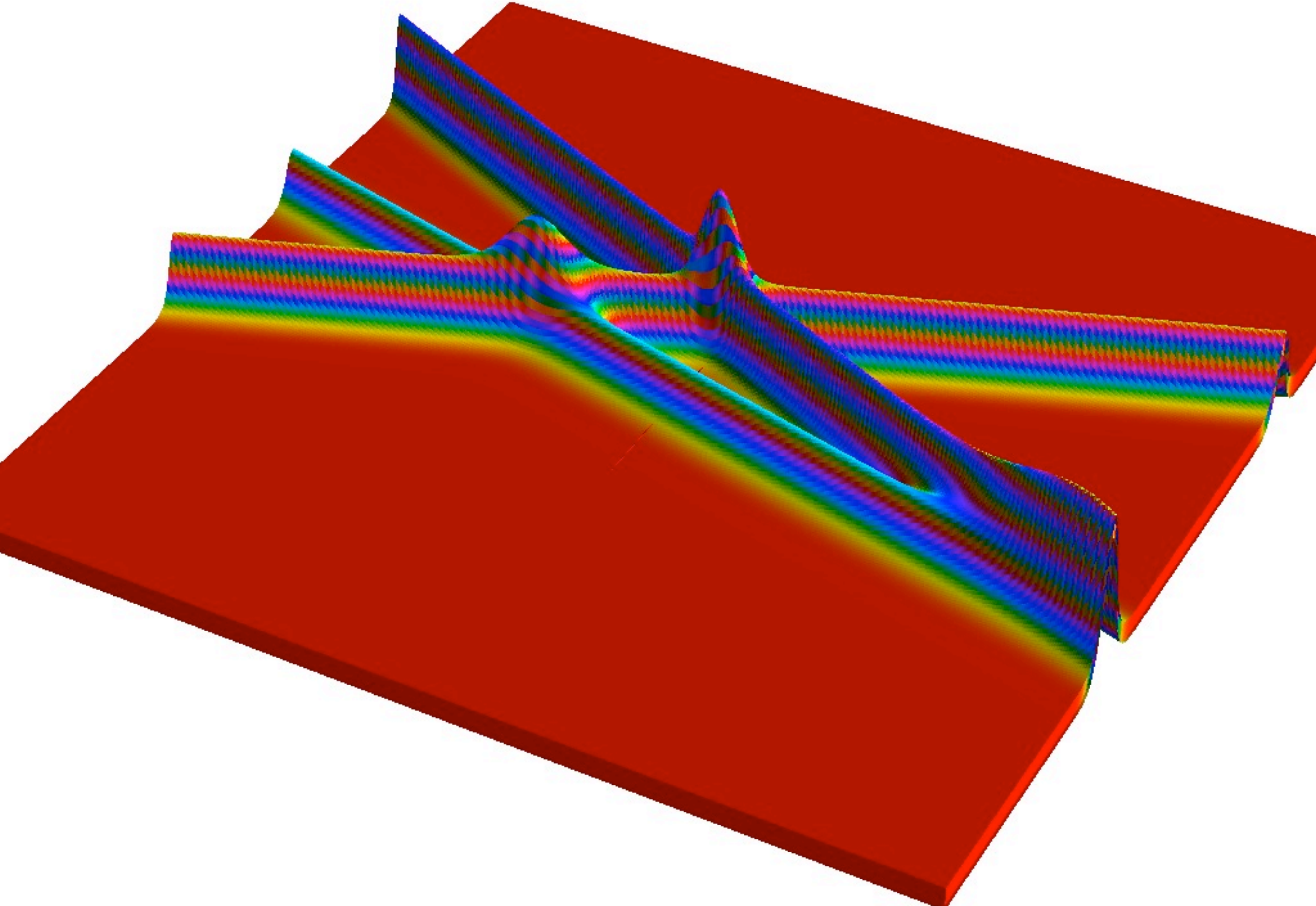

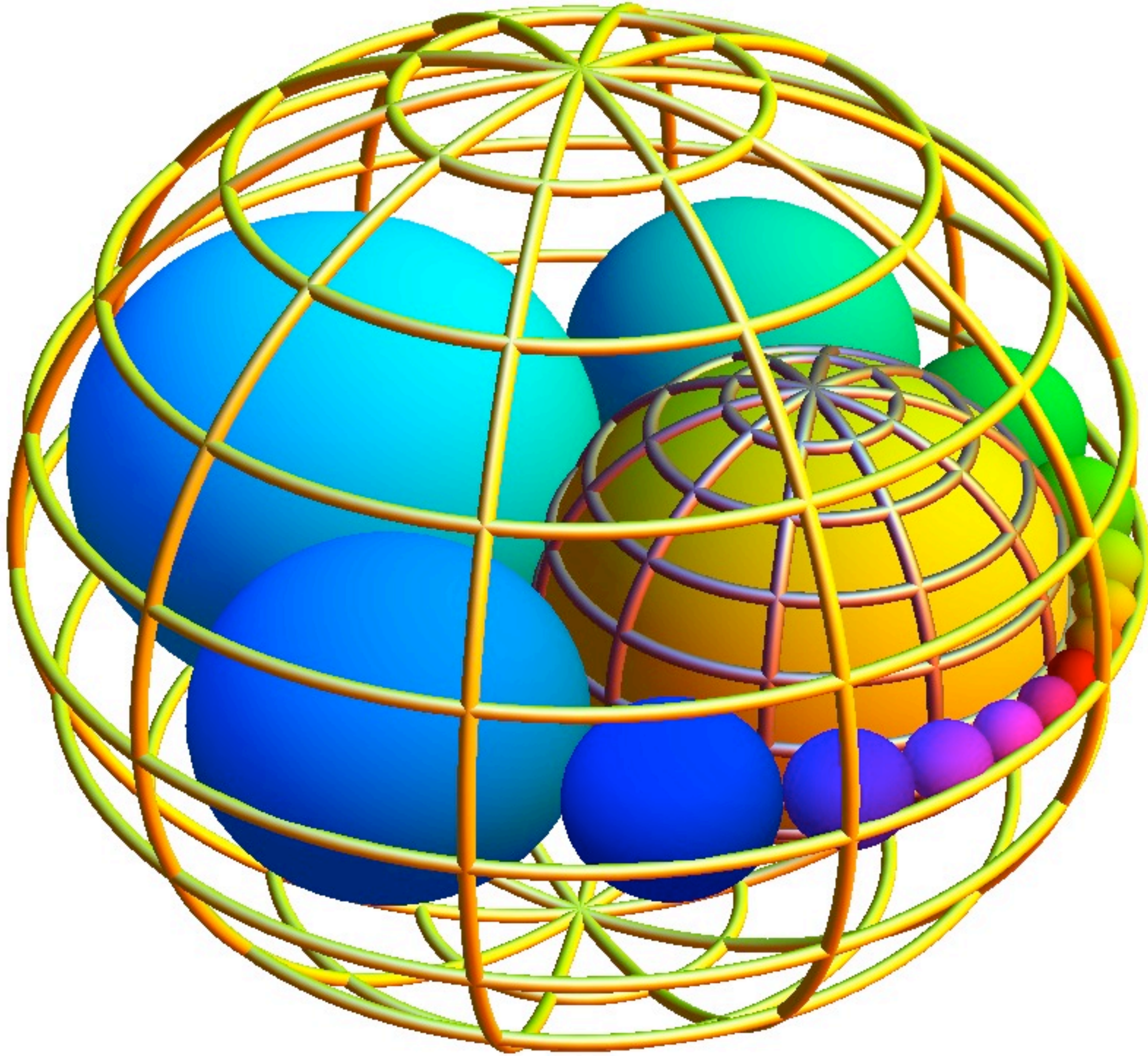

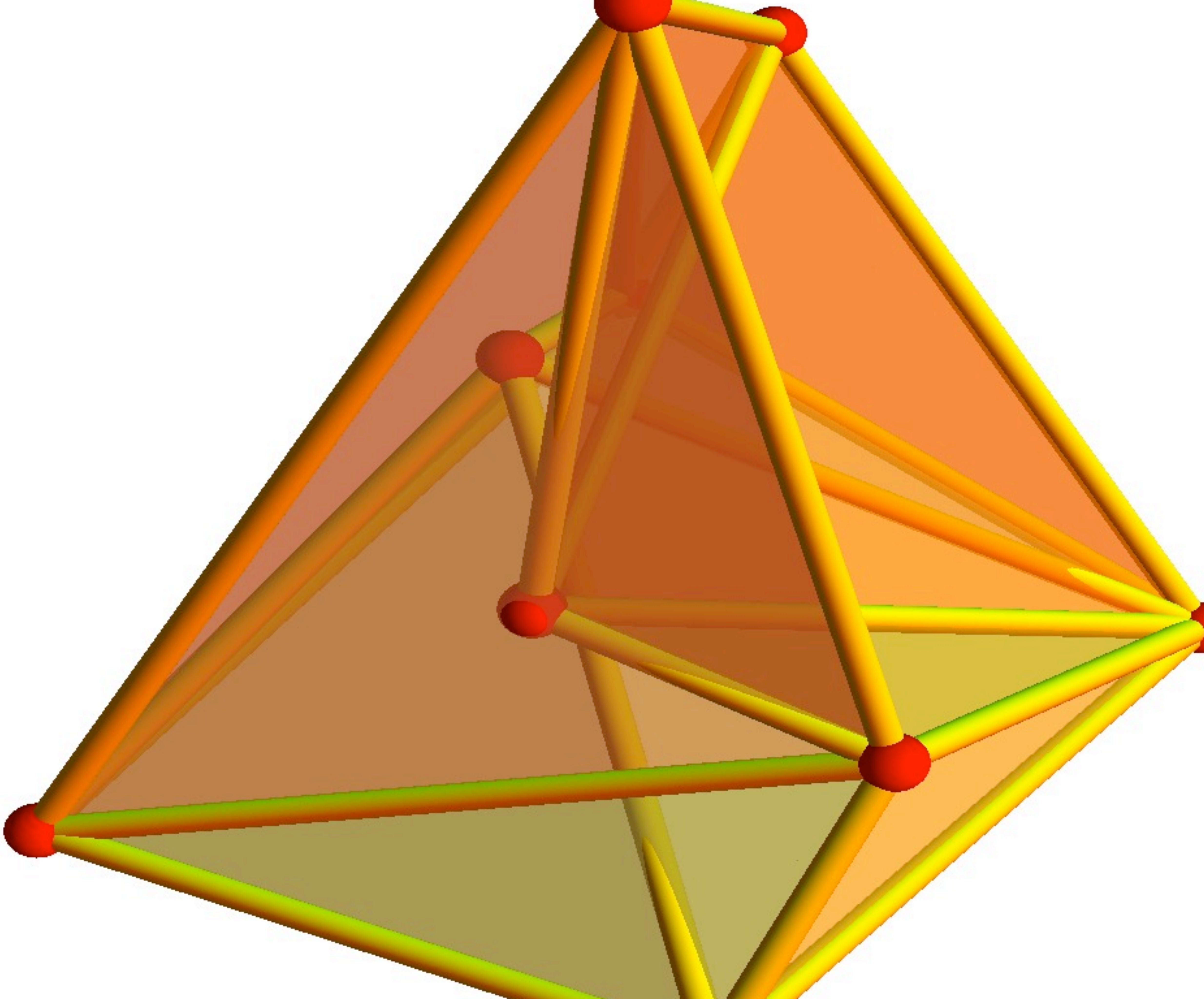

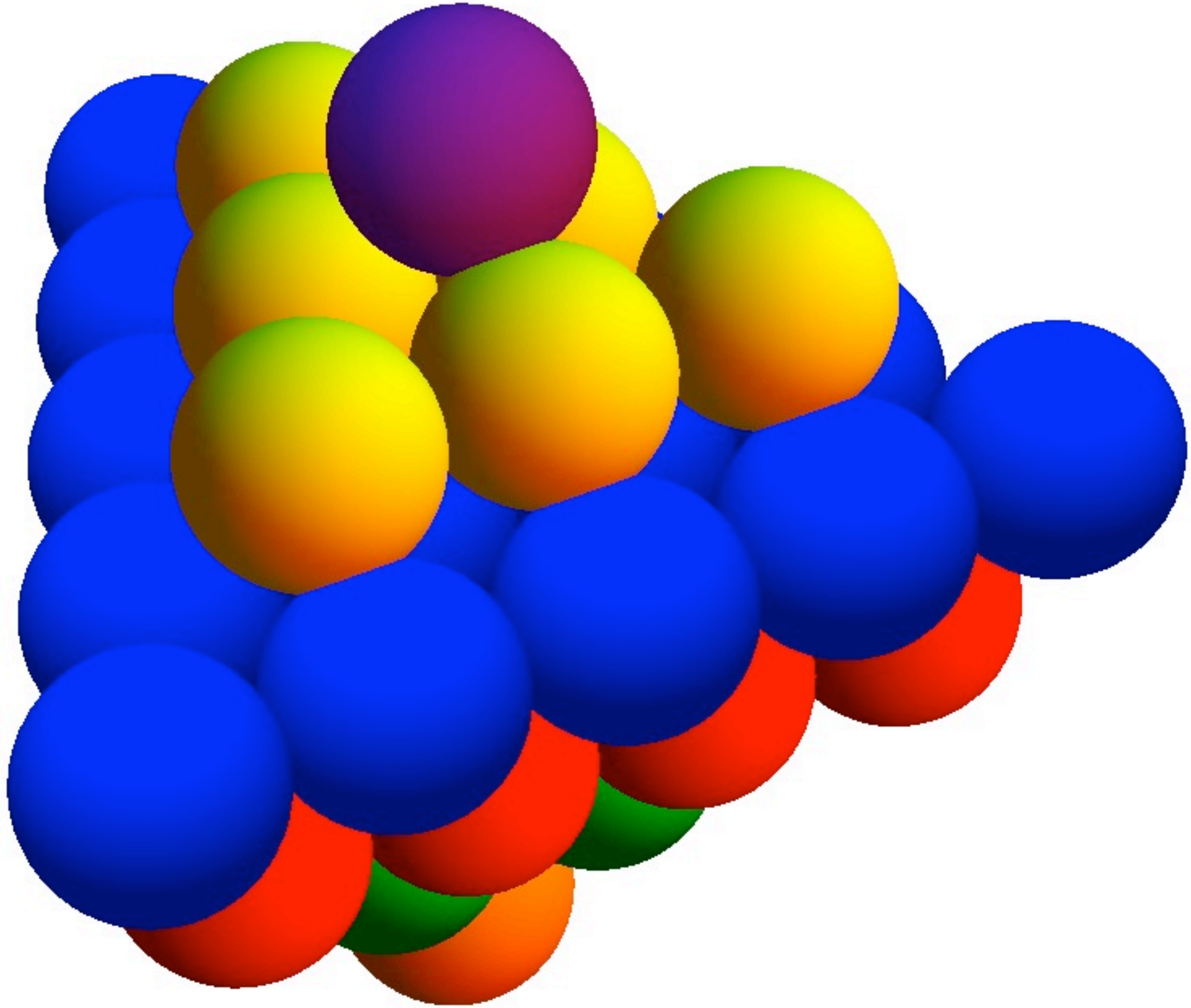

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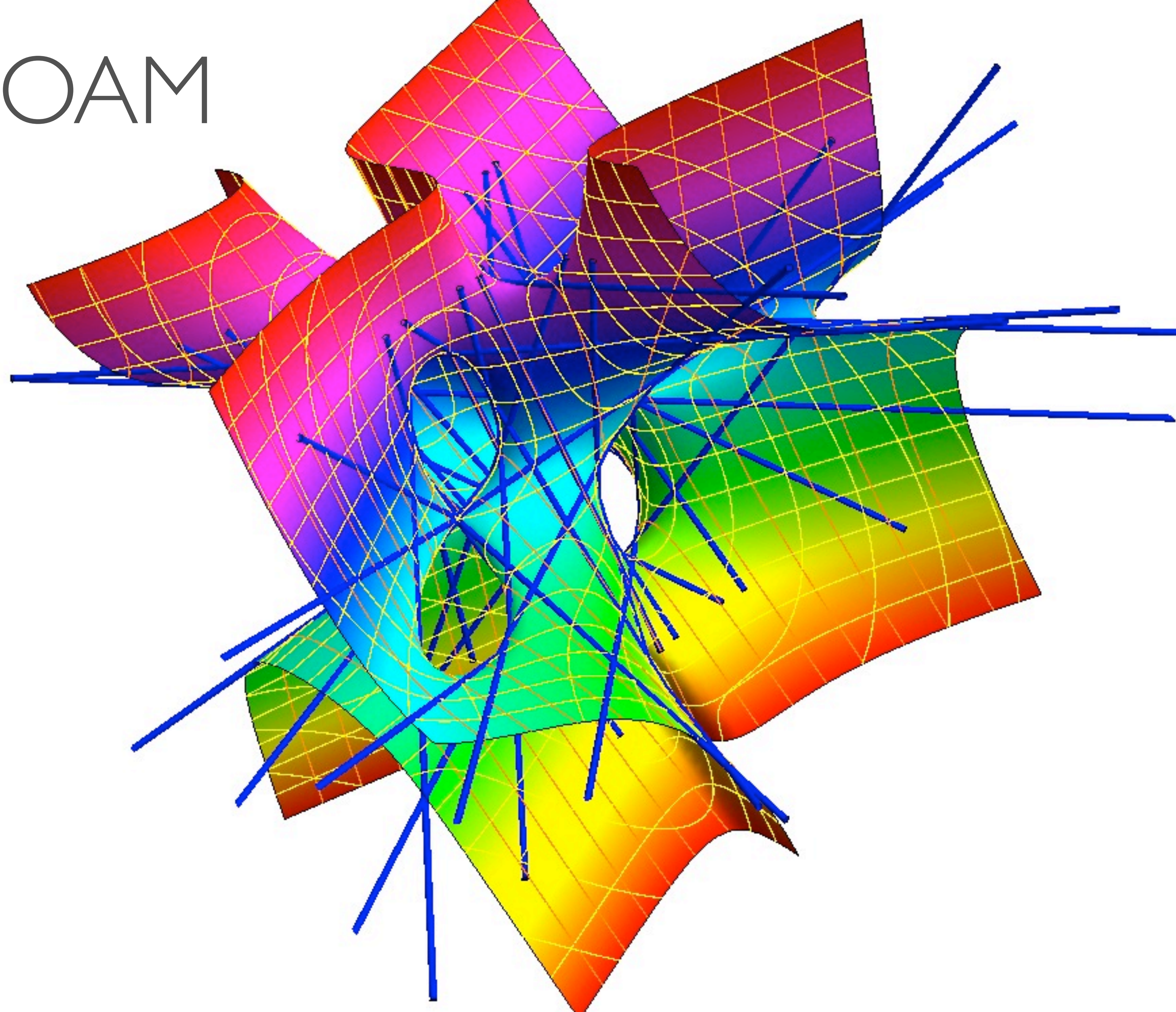

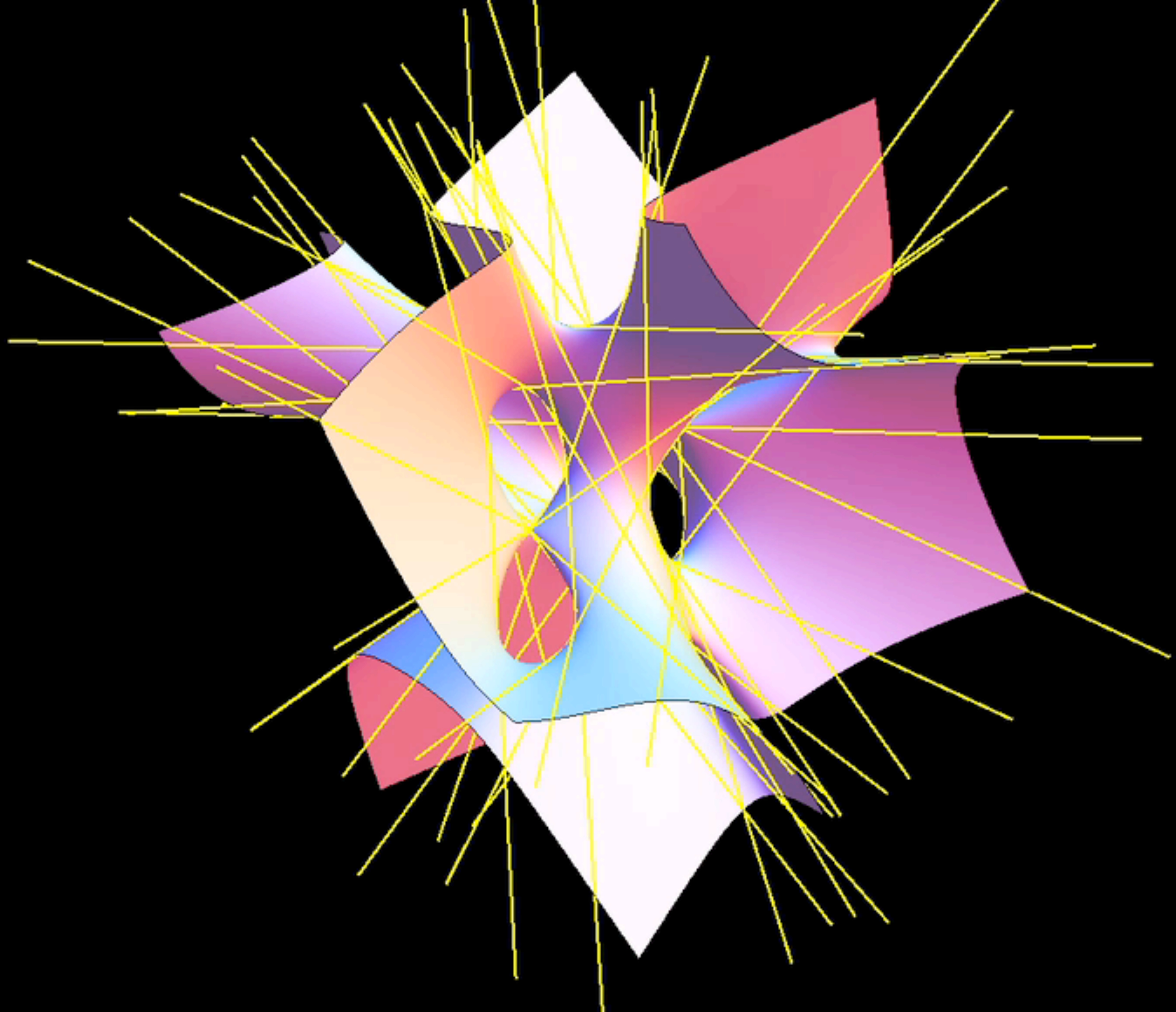

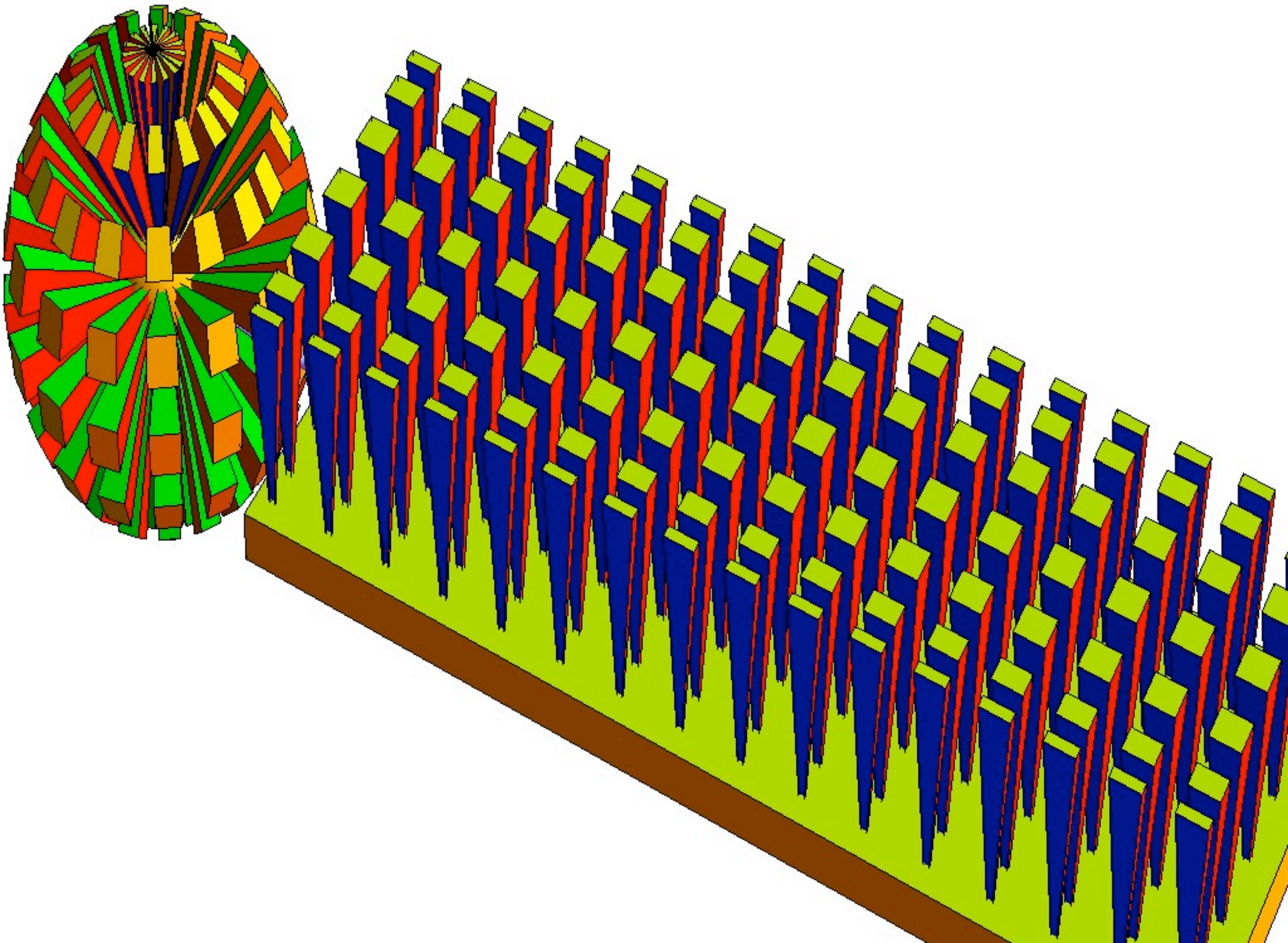

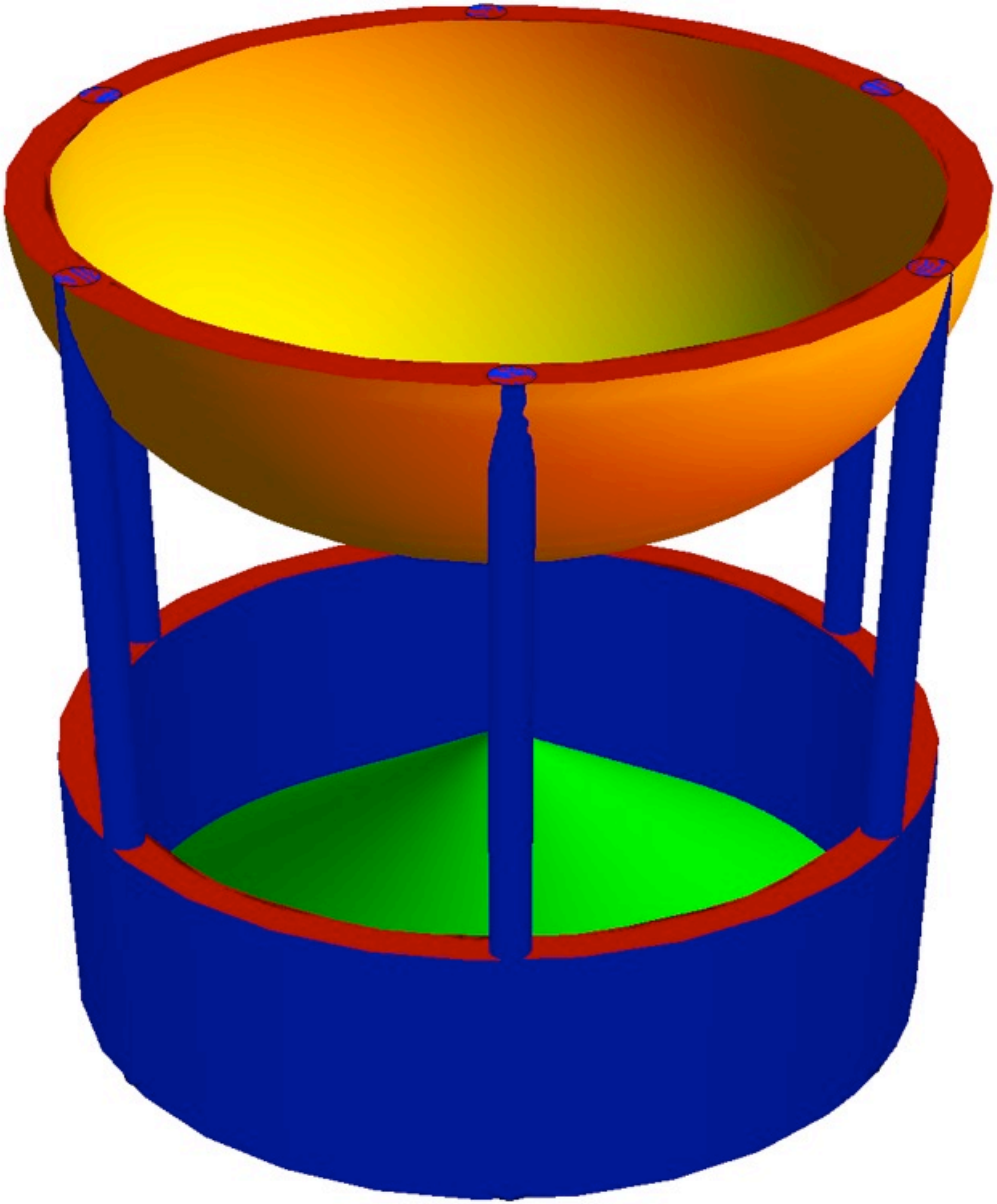

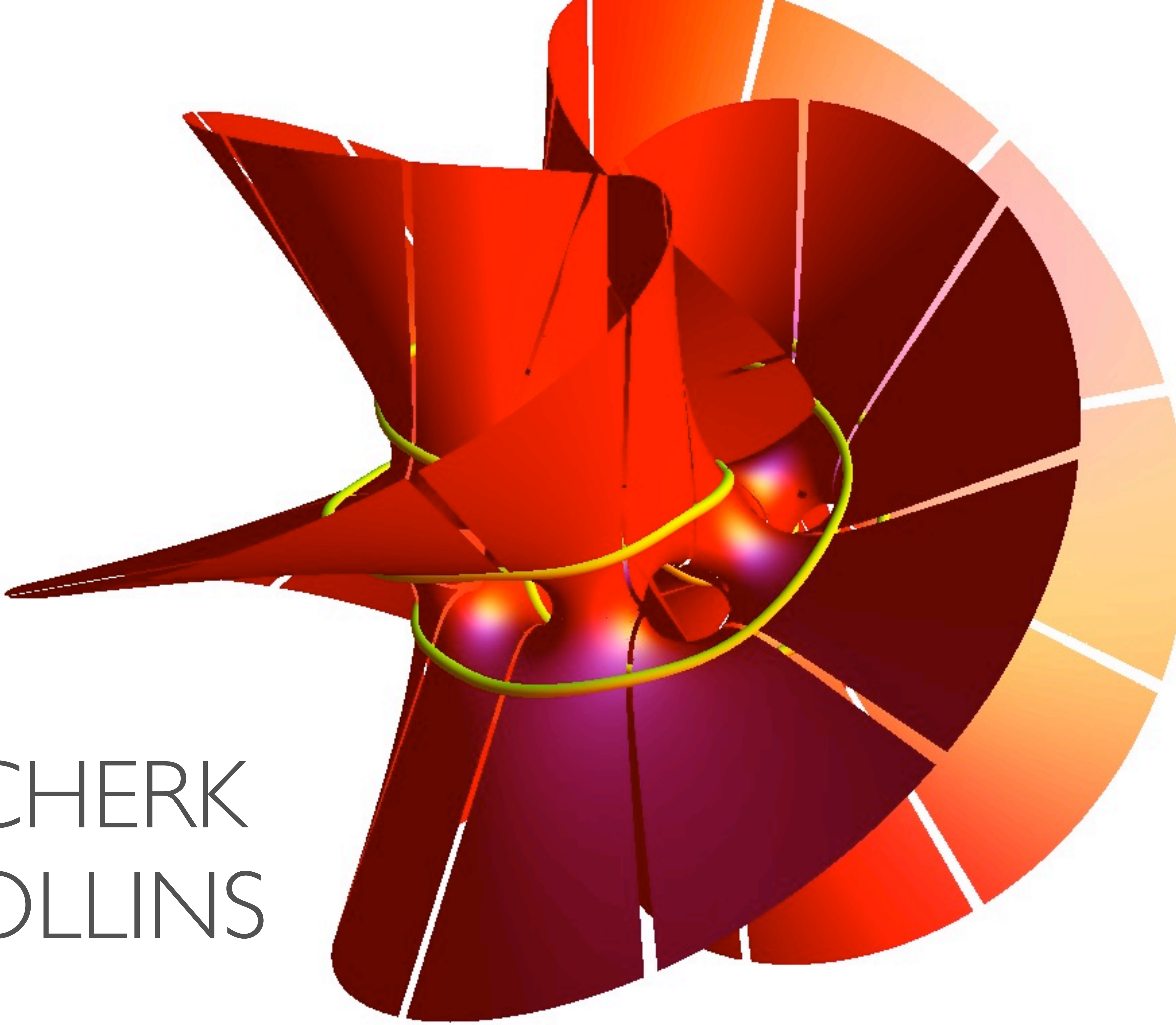

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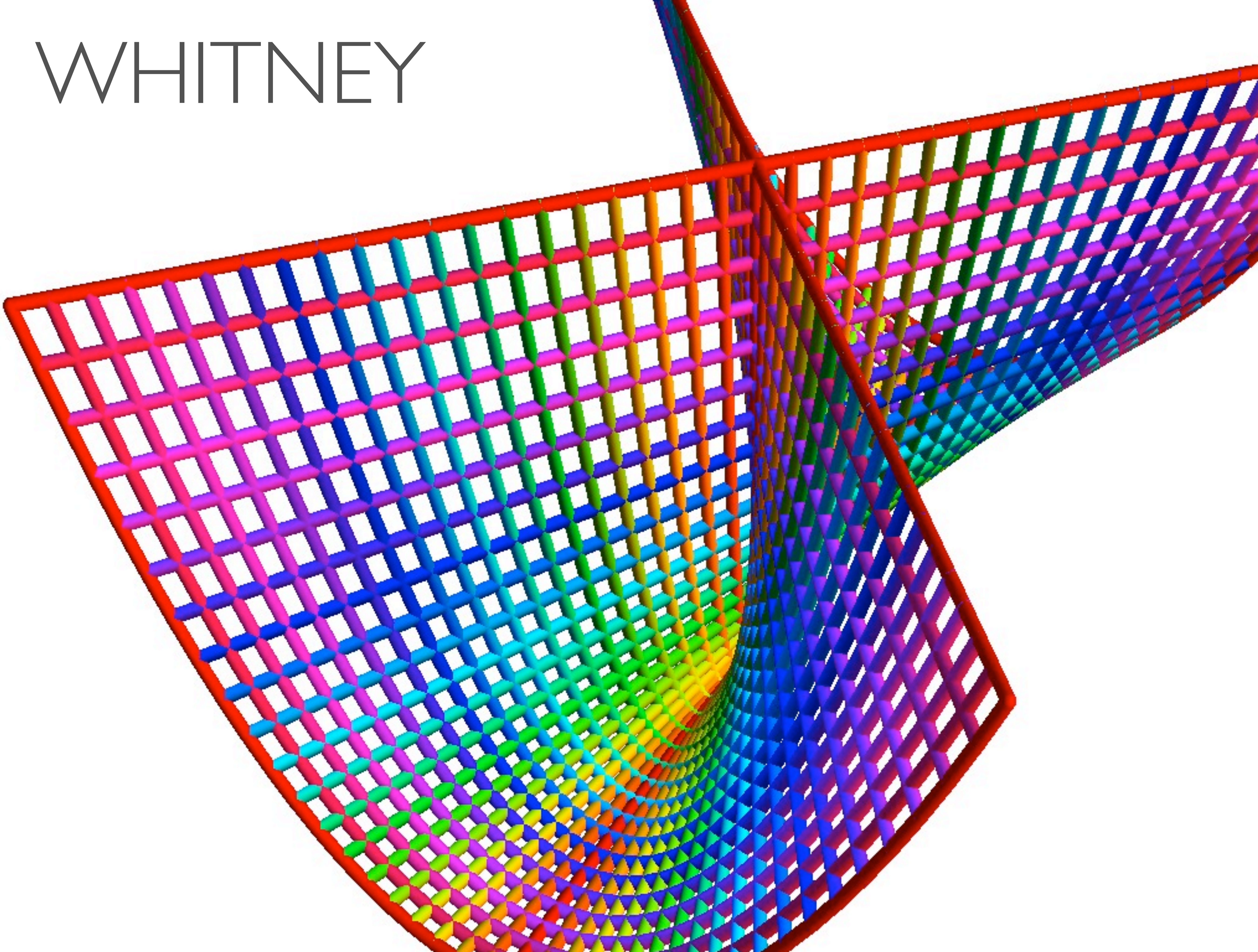

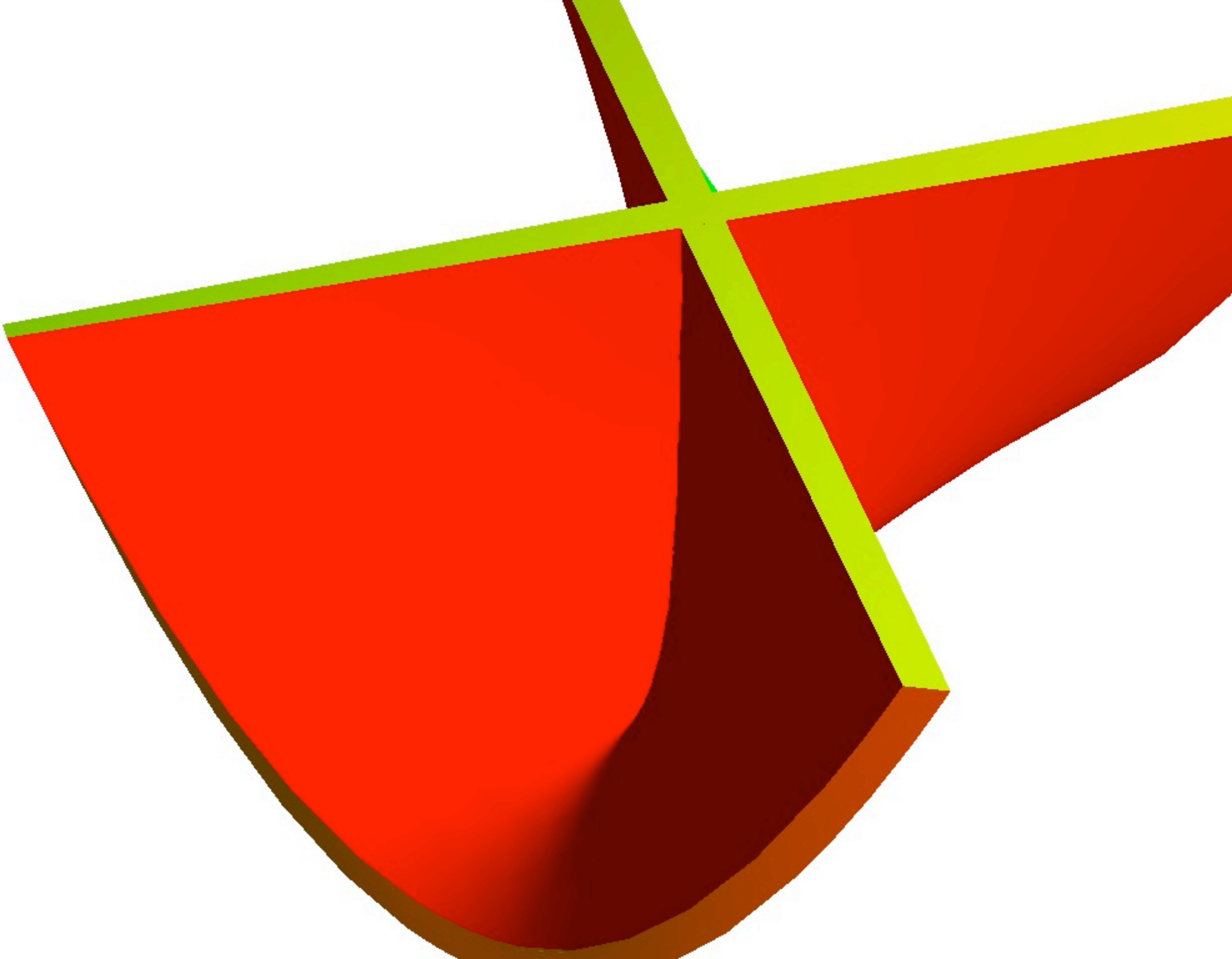

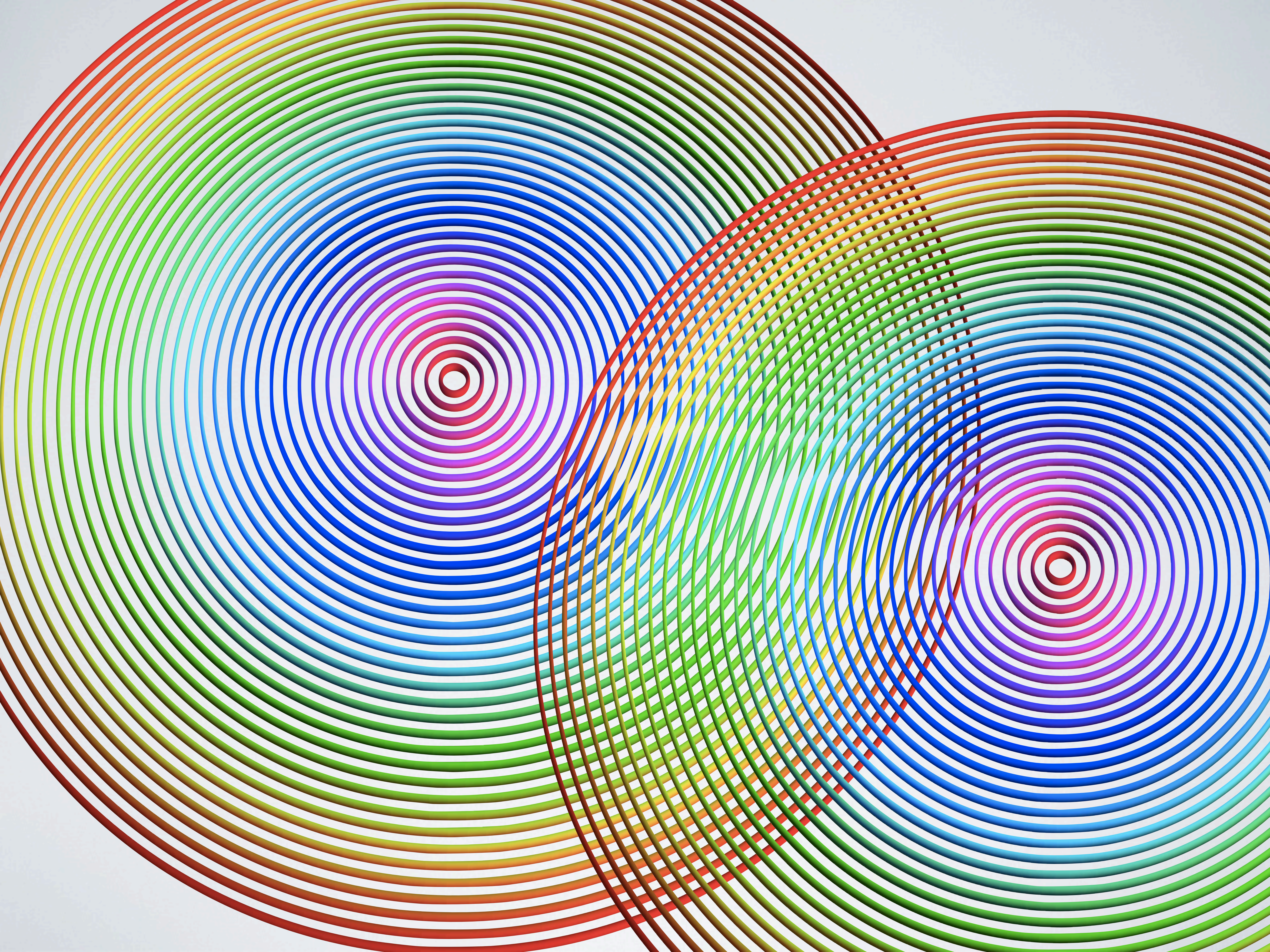

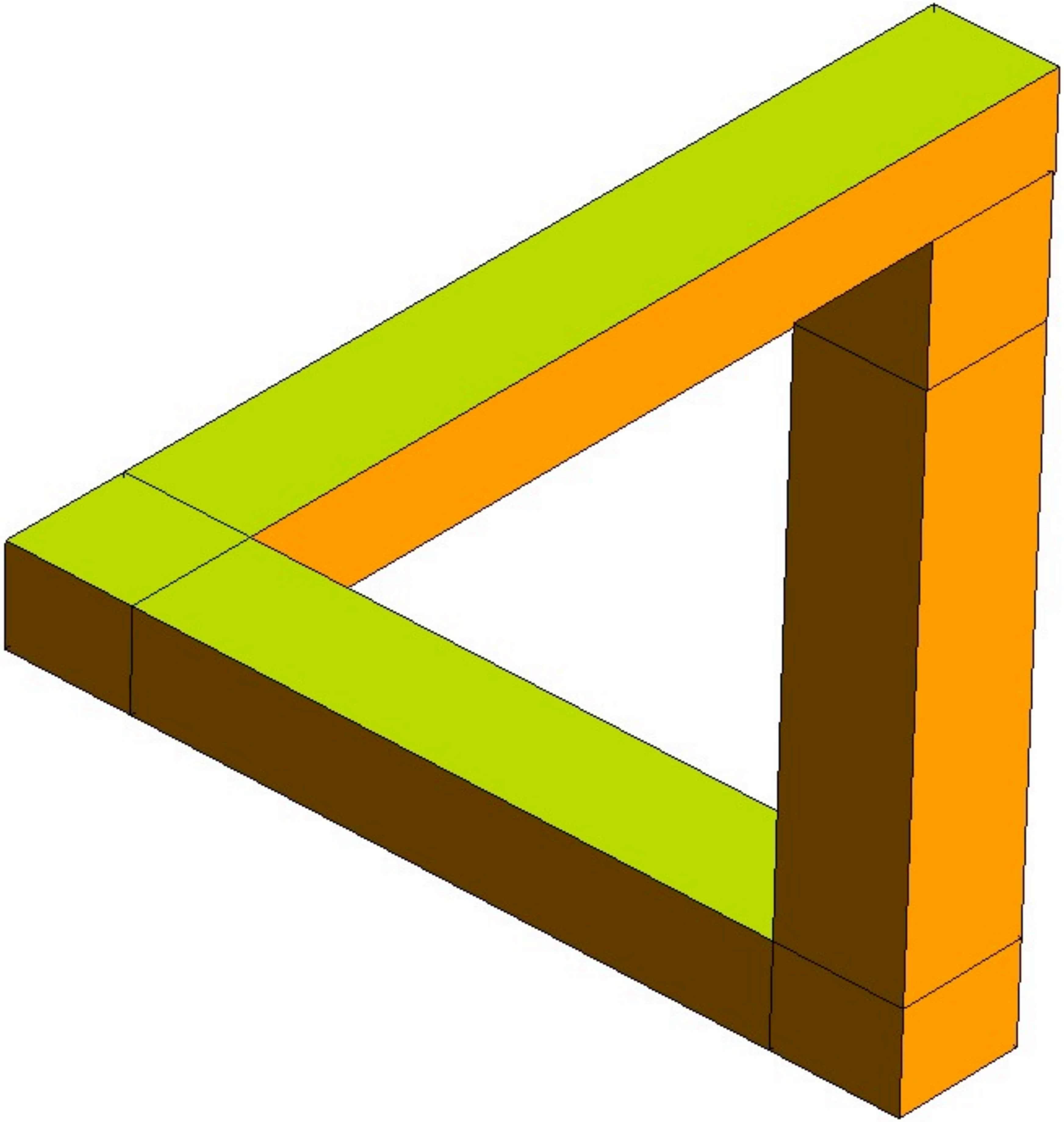

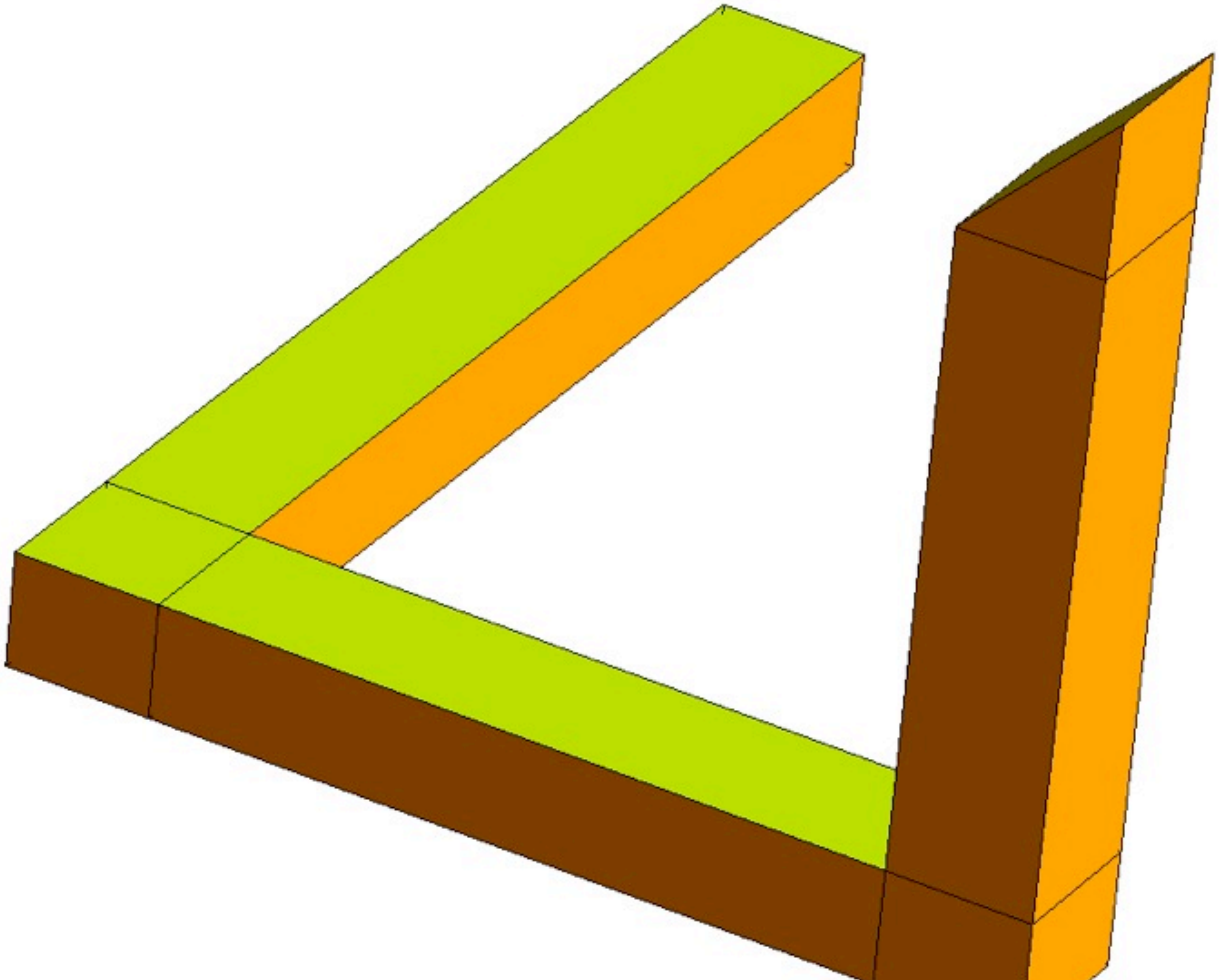

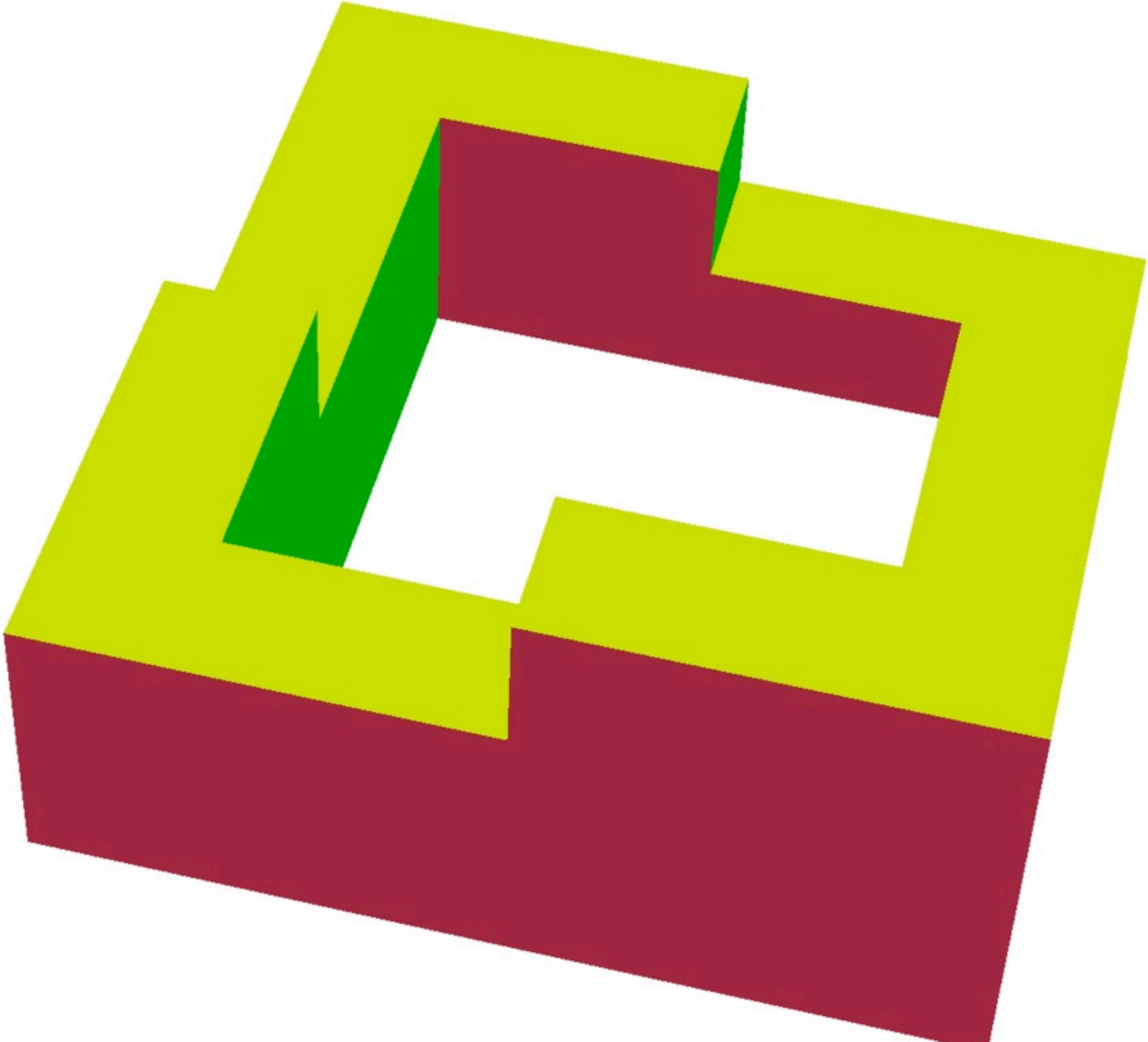

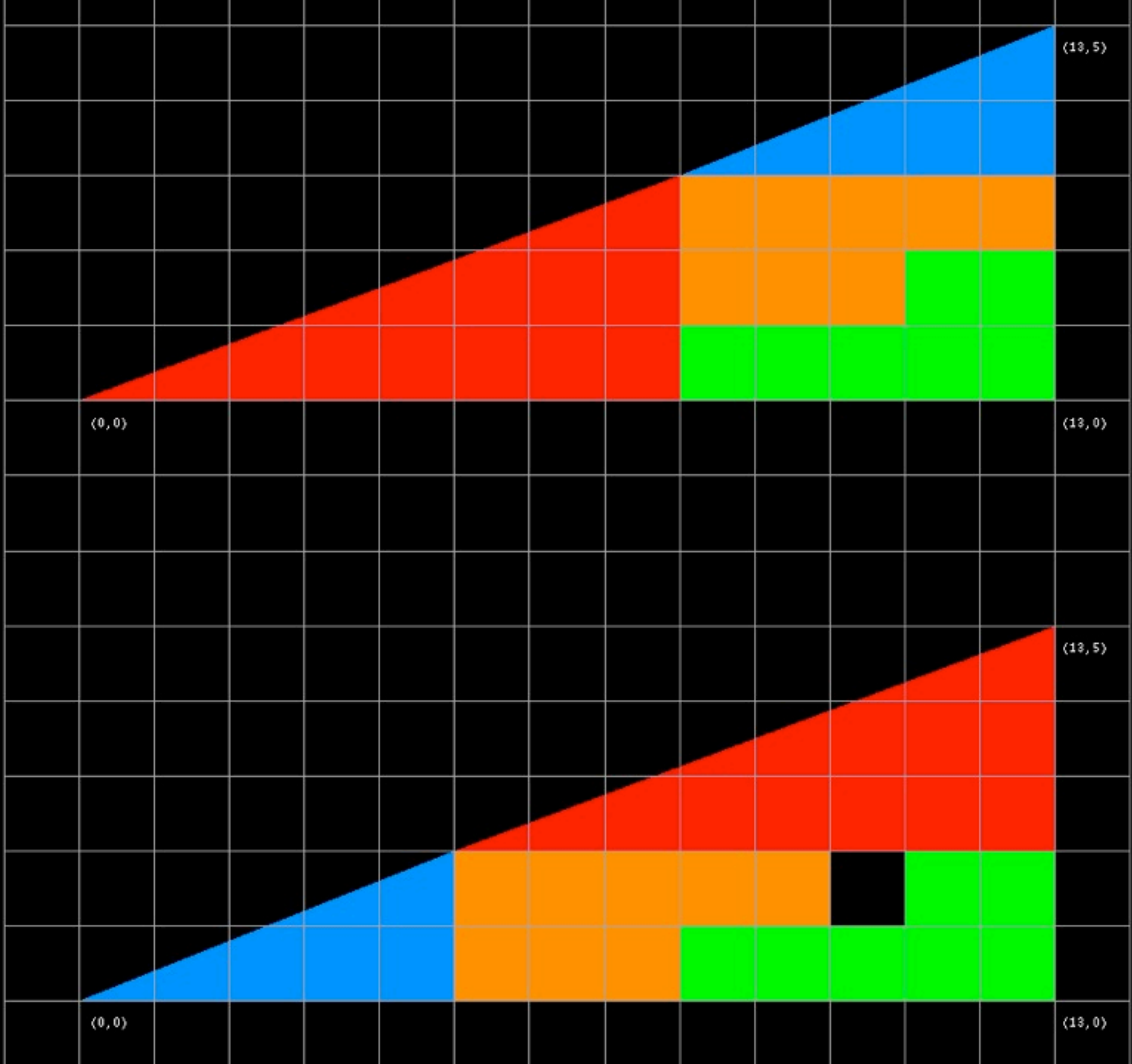
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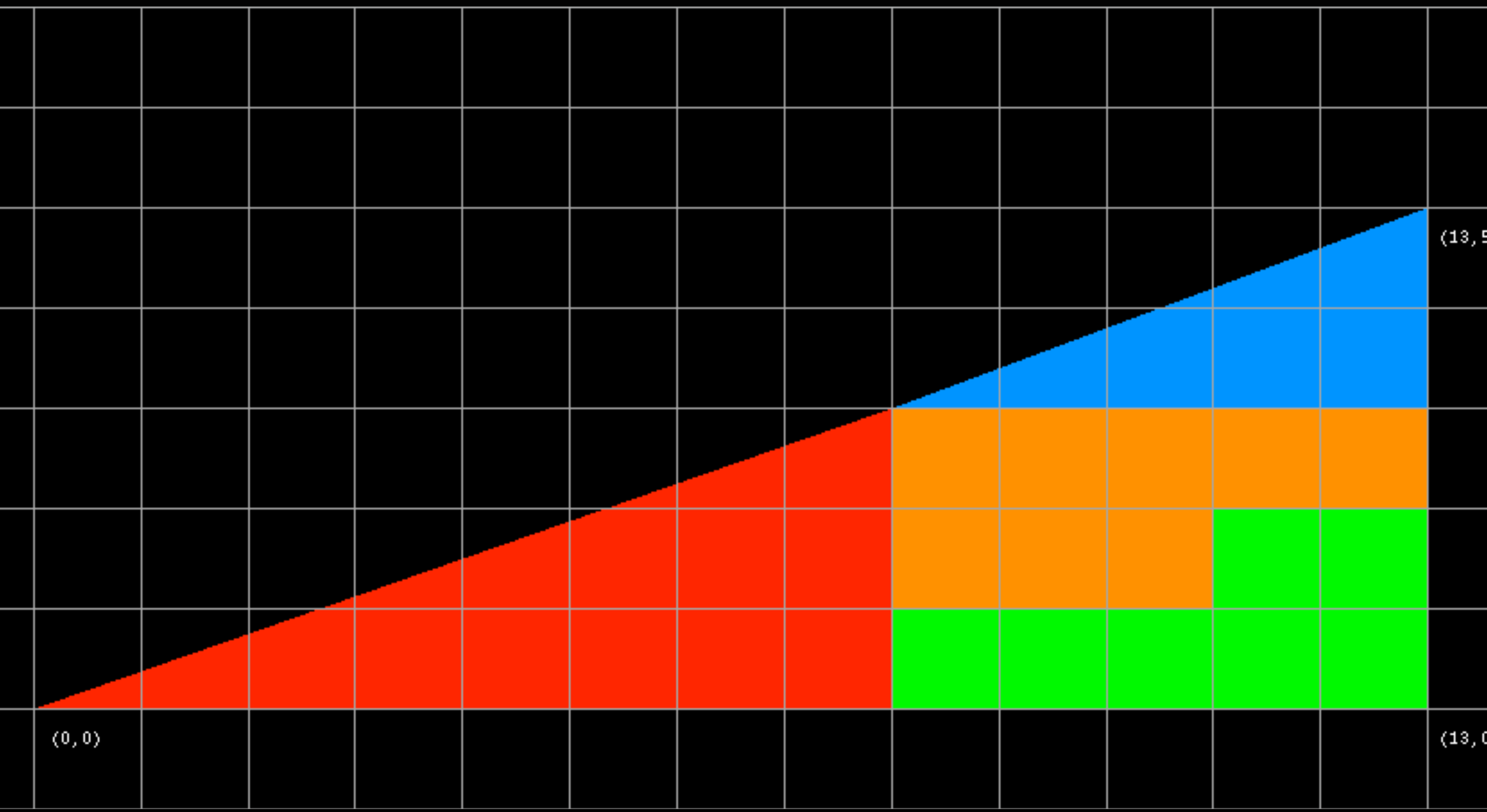
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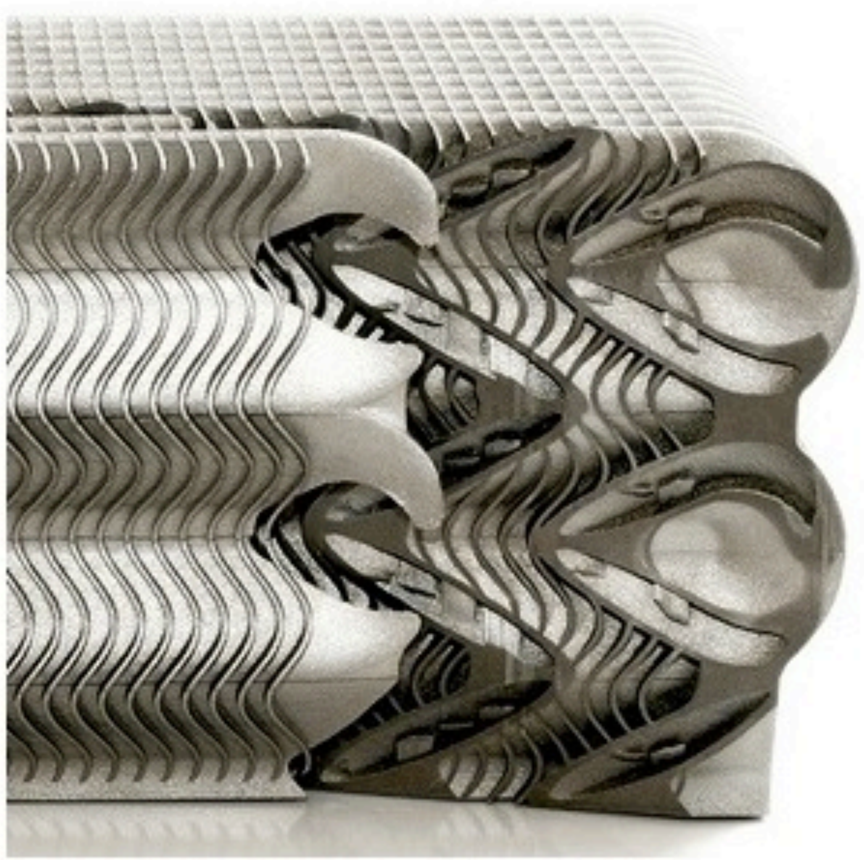
WISH LIST

Wanted: A Print Button for 3-D Objects

A lack of accessible design tools is holding back 3-D printing.

By Antonio Regalado on April 24, 2013



Detail oriented: A metal heat exchanger created using additive manufacturing contains small contours and internal shapes that would be hard to make

The largest companies in 3-D printing are racing to simplify design software so that it can become as easy to make an object as it is to send a document to a printer.

Interest in 3-D printing, also known as additive manufacturing, is exploding due to the falling cost of machines that can lay down finely targeted layers of plastic to make simple products, like jewelry or sculptures, much as a traditional printer sprays ink onto paper. The idea is that 3-D printers could democratize design and eventually manufacturing by letting anyone make physical things in small quantities, without the expense of an assembly line.

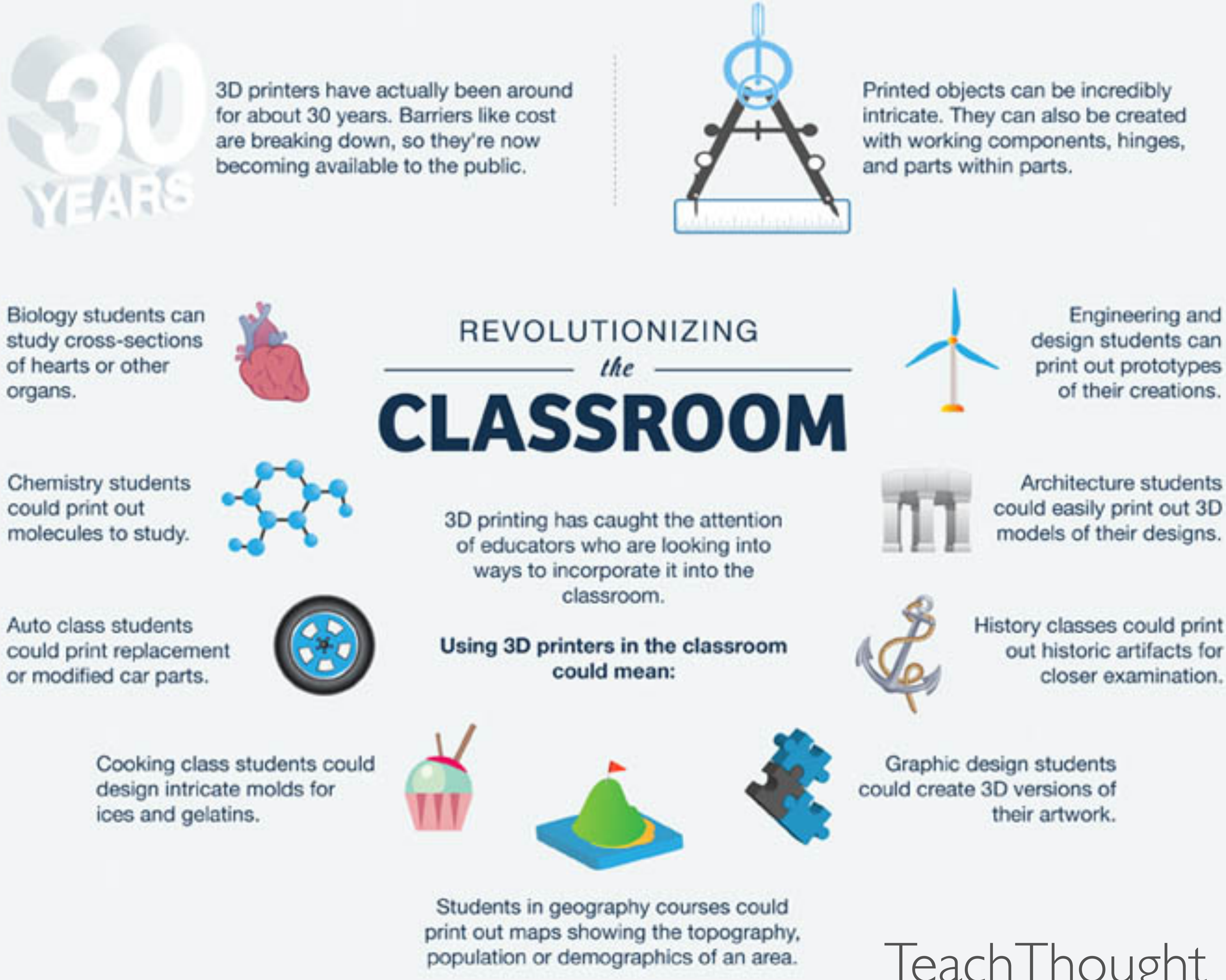
The technology still has a ways to go – making objects on consumer printers is slow and expensive. To print a solid plastic apple on MakerBot's $2,000 consumer printer, for instance, takes seven hours and costs $50 in supplies, so it's no competition for cheap plastic goods made in China.

WHY IT MATTERS

One day 3-D printing could cheaply create customized objects that would be prohibitively expensive with traditional manufacturing methods.


SPECIAL REPORT
How to Make the Next Big Thing
The Future of Manufacturing
Robot Bosses
Next-Gen Materials
3-D Printing
Nanotech Machines

Media in the Classroom

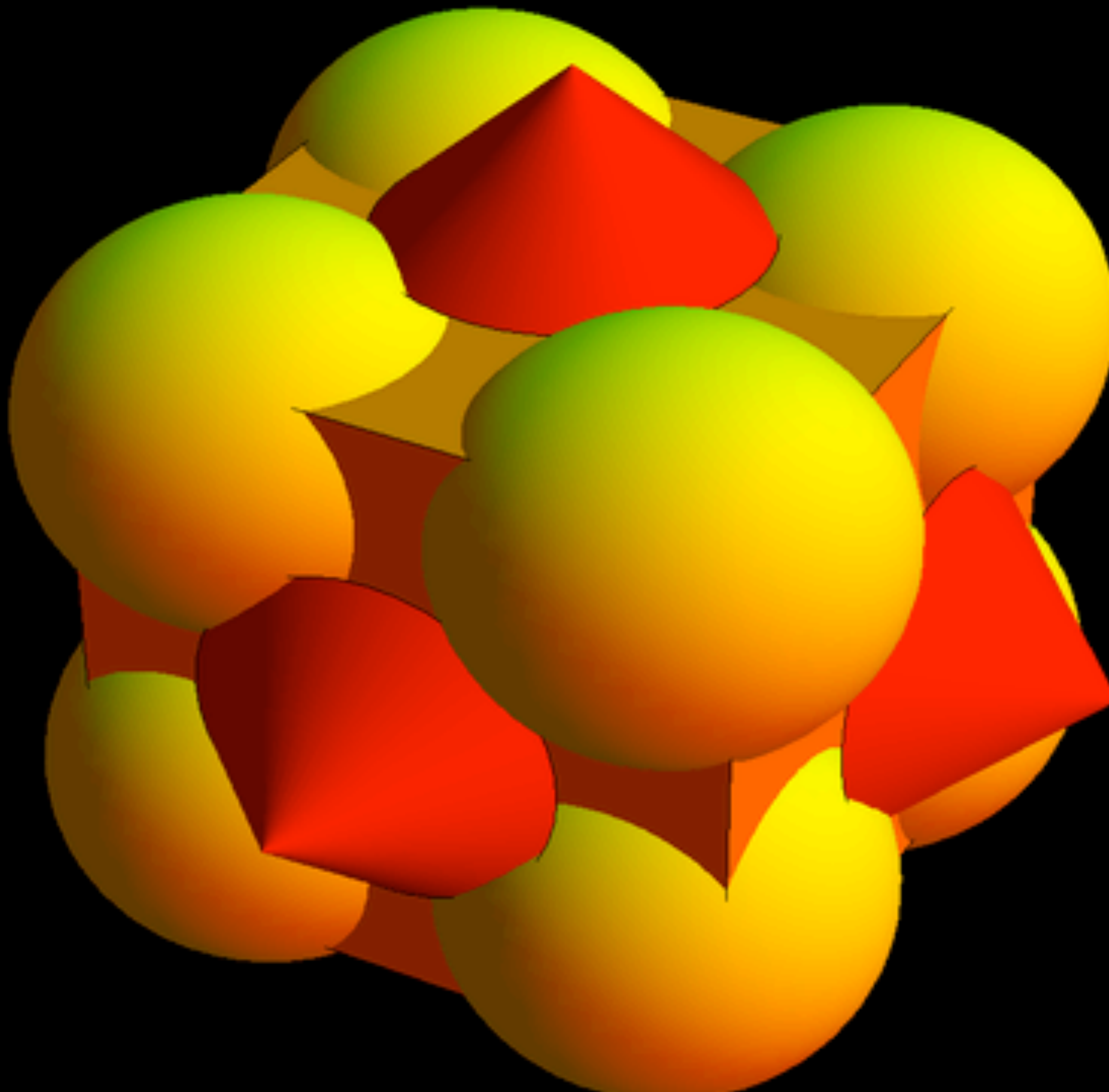

30 YEARS
3D printers have actually been around for about 30 years. Barriers like cost are breaking down, so they're now becoming available to the public.
Printed objects can be incredibly intricate. They can also be created with working components, hinges, and parts within parts.
REVOLUTIONIZING the CLASSROOM
Biology students can study cross-sections of hearts or other organs.
Engineering and design students can print out prototypes of their creations.
Chemistry students could print out molecules to study.
Architecture students could easily print out 3D models of their designs.
3D printing has caught the attention of educators who are looking into ways to incorporate it into the classroom.
Auto class students could print replacement or modified car parts.
Using 3D printers in the classroom could mean:
History classes could print out historic artifacts for closer examination.
Cooking class students could design intricate molds for ices and gelatins.
Graphic design students could create 3D versions of their artwork.
Students in geography courses could print out maps showing the topography, population or demographics of an area.
TeachThought


How to
Make
the Next
Scientific american

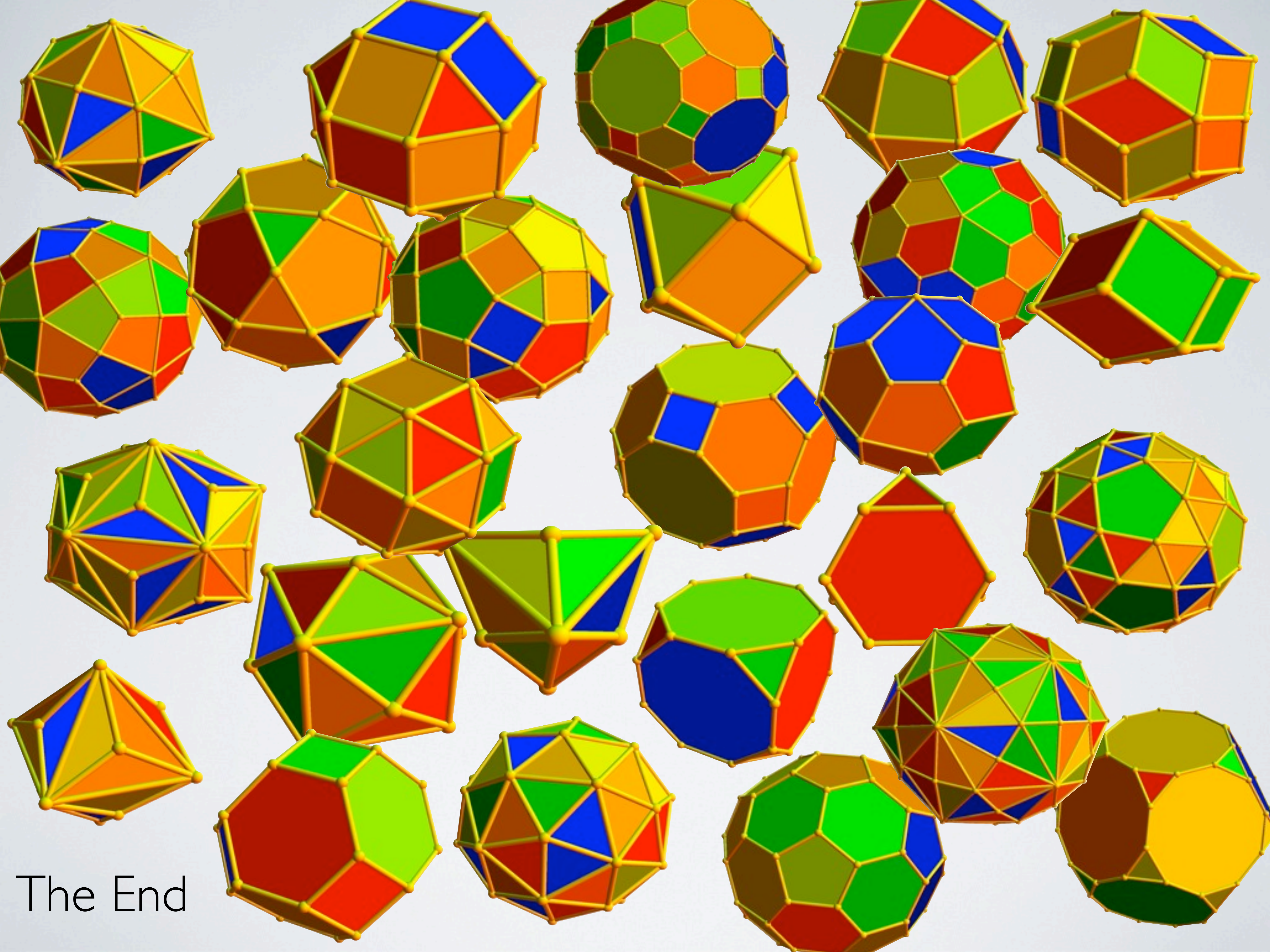
PHYSICS EXPERIMENTS

WISH LIST

- More open source conversion systems
- Computer algebra support of 3D printing
- More libraries with objects



Math 21a Class Fall 2012



The End