Polyhedra: Plato, Archimedes, Euler

Robert L. Benedetto
Amherst College

MathPath at Mount Holyoke College

Tuesday, July 15, 2014
Regular Polygons

Definition
A **polygon** is a planar region $R$ bounded by a finite number of straight line segments that together form a loop.

If all the line segments are congruent, and all the angles between the line segments are also congruent, we say $R$ is a **regular polygon**.
Polyhedra

Definition

A **polyhedron** is a spatial region $S$ bounded by a finite number of polygons meeting along their edges, and so that the interior is a single connected piece.

So these are not polyhedra:

But these are:
Regular Polyhedra

Definition
Let $S$ be a polyhedron. If

- all the faces of $S$ are regular polygons,
- all the faces of $S$ are congruent to each other, and
- all the vertices of $S$ are congruent to each other,

we say $S$ is a **regular polyhedron**.

Cube (Regular Hexahedron)  Regular Octahedron
Another Regular Polyhedron

Regular Tetrahedron
Two More Regular Polyhedra

Regular Dodecahedron

Regular Icosahedron
And They’re Dual:
Some Ancient History (of Regular Polyhedra)

- **Pythagoras of Samos**, c.570–c.495 BCE: Knew about at least three, and possibly all five, of these regular polyhedra.

- **Theaetetus** (Athens), 417–369 BCE: Proved that there are exactly five regular polyhedra.

- **Plato** (Athens), c.426–c.347 BCE: Theorizes four of the solids correspond to the four elements, and the fifth (dodecahedron) to the universe/ether.

- **Euclid** (Alexandria), 3xx–2xx BCE: Book XIII of *The Elements* discusses the five regular polyhedra, and gives a proof (presumably from Theaetetus) that they are the only five.

For some reason, the five regular polyhedra are often called the **Platonic solids**.
There Can Be Only Five: Setup

Given a regular polyhedron $S$ whose faces are regular $n$-gons, and with $k$ polygons meeting at each vertex:

1. $k \geq 3$ and $n \geq 3$.
2. $S$ is completely determined by the numbers $k$ and $n$.
3. $S$ must be **convex**: For any two points in $S$, the whole line segment between the two points is contained in $S$.
4. Since $S$ is convex, the total of angles meeting at a vertex of $S$ is less than 360 degrees.
5. Each angle of a regular $n$-gon has measure $\left(\frac{180(n - 2)}{n}\right)^\circ$.

[Triangle: $60^\circ$, Square: $90^\circ$, Pentagon: $108^\circ$, Hexagon: $120^\circ$.]
There Can Be Only Five: Payoff

From Previous Slide: The regular polyhedron $S$ is determined by $n \geq 3$ (faces are regular $n$-gons) and $k \geq 3$ (number at each vertex). But total angles at each vertex must be less than $360^\circ$.

- **Triangles** ($n = 3$):
  - $k = 3$ triangles at each vertex: **Tetrahedron**
  - $k = 4$ triangles at each vertex: **Octahedron**
  - $k = 5$ triangles at each vertex: **Icosahedron**
  - $k \geq 6$ triangles at each vertex: Angles total $\geq 360^\circ$. NO!

- **Squares** ($n = 4$):
  - $k = 3$ squares at each vertex: **Cube**
  - $k \geq 4$ squares at each vertex: Angles total $\geq 360^\circ$. NO!

- **Pentagons** ($n = 5$):
  - $k = 3$ pentagons at each vertex: **Dodecahedron**
  - $k \geq 4$ pentagons at each vertex: Angles total $> 360^\circ$. NO!

- **$n$-gons** ($n \geq 6$):
  - $k \geq 3$ $n$-gons at each vertex: Angles total $\geq 360^\circ$. NO!
The Five Regular Polyhedra

Tetrahedron \( \{3, 3\} \)  
Cube \( \{4, 3\} \)  
Octahedron \( \{3, 4\} \)  
Dodecahedron \( \{5, 3\} \)  
Icosahedron \( \{3, 5\} \)
But What About This Solid?

- Known to Plato
- Definitely not regular (squares and triangles), but:
  - All faces are regular polygons, and
  - All the vertices are congruent to each other.
Semiregular Polyhedra

**Definition**
Let $S$ be a polyhedron. If
- all the faces of $S$ are regular polygons, and
- all the vertices of $S$ are congruent to each other,
we say $S$ is a **semiregular polyhedron**.

[Same as definition of regular polyhedron, except the faces don’t need to be congruent to each other.]

**Natural Question**: How many (non-regular) semiregular polyhedra are there?  
**Answer**: Infinitely many.
Prisms

Definition
Let $n \geq 3$. An $n$-gonal prism is the solid obtained by connecting two congruent regular $n$-gons by a loop of $n$ squares.

Modified Question: How many (non-regular) semiregular polyhedra are there besides the prisms?

Answer: Still infinitely many.
Antiprisms

Definition
Let $n \geq 3$. An $n$-gonal antiprism is the solid obtained by connecting two congruent regular $n$-gons by a loop of $2n$ equilateral triangles.

Re-Modified Question: How many semiregular polyhedra are there besides the regular polyhedra, prisms, and antiprisms?

Answer: FINALLY that’s the right question. Archimedes says: 13.
Archimedean Solids

Definition
An Archimedean solid is a semiregular polyhedron that is not regular, a prism, or an antiprism.

- **Archimedes of Syracuse**, 287–212 BCE: Among his many mathematical contributions, described the 13 Archimedean solids. But this work is lost. We know of it only through:

- **Pappus of Alexandria**, c.290–c.350 CE: One of the last ancient Greek mathematicians. Describes the 13 Archimedean solids in Book V of his *Collections*.

- **Johannes Kepler** (Germany and Austria), 1571–1630 CE: Rediscovered the 13 Archimedean solids; gave first surviving proof that there are only 13.
Cuboctahedron and Icosidodecahedron
Adding Some Squares

Rhombicuboctahedron  Rhombicosidodecahedron
To **truncation** a polyhedron means to slice off its corners.

- **Truncated Tetrahedron**
- **Truncated Cube**
More Truncated Regular Polyhedra

Truncated Octahedron

Truncated Dodecahedron
Truncated Icosahedron
Truncation FAIL

If you truncate, say, the cuboctahedron, you don’t quite get regular polygons — the sliced corners give **non-square** rectangles.
Fixing a Failed Truncation

But if you squish the rectangles into squares, you can get regular polygons all around. Same deal for truncating the icosidodecahedron:

Truncated Cuboctahedron   Truncated Icosidodecahedron
a.k.a.
Great Rhombicuboctahedron,   Great Rhombicosidodecahedron
And Two More

Adding more triangles to the cuboctahedron (or cube) and to the icosidodecahedron (or dodecahedron) gives:

Snub Cube

Snub Dodecahedron

Note: Unlike all the others, these two are not mirror-symmetric.
Why Are There Only Thirteen?

Kepler’s proof for Archimedean solids is similar in spirit to Theaetetus’ proof for Platonic solids, but of course it’s longer and more complicated.

I’ll give a sketch based on the description of Kepler’s proof in Chapter 4 of *Polyhedra*, by Peter Cromwell. (Cambridge U Press, 1997).

**Goal**: Given a semiregular polyhedron $S$, we want to show the arrangement of polygons around each vertex agrees with one of the specific examples we already know about.
Some Notation

To describe the arrangement of polygons at a vertex, let’s write

\[[a, b, c, \ldots]\]

to indicate that there’s an \(a\)-gon, then a \(b\)-gon, then a \(c\)-gon, etc., as we go around the vertex.

**Example:** The truncated cube is \([8, 8, 3]\), and the icosidodecahedron is \([3, 5, 3, 5]\).

Warning: the order matters, but only up to rotating. So

\[[8, 8, 3] = [8, 3, 8] = [3, 8, 8]\]

and

\[[3, 5, 3, 5] = [5, 3, 5, 3] \neq [3, 3, 5, 5].\]
Three Lemmas

**Lemma 1.** Suppose \([a, b, c]\) is an arrangement for a semiregular polyhedron. If \(a\) is odd, then \(b = c\).

**Lemma 2.** Suppose \([3, 3, a, b]\) is an arrangement for a semiregular polyhedron. Then either \(a = 3\) or \(b = 3\). (Antiprism.)

**Lemma 3.** Suppose \([3, a, b, c]\) is an arrangement for a semiregular polyhedron. If \(a, c \neq 3\), then \(a = c\).
Sketch of the Proof

There are now a whole lot of cases to consider, depending on what sorts of polygonal faces the solid $S$ has:

1. 2 sorts: Triangles and Squares.
2. 2 sorts: Triangles and Pentagons.
3. 2 sorts: Triangles and Hexagons.
4. 2 sorts: Triangles and $n$-gons, with $n \geq 7$.
5. 2 sorts: Squares and $n$-gons, with $n \geq 5$.
6. 2 sorts: Pentagons and $n$-gons, with $n \geq 6$.
7. 3 sorts: Triangles, Squares, and $n$-gons, with $n \geq 5$.
8. 3 sorts: Triangles, $m$-gons, and $n$-gons, with $n > m \geq 5$.
9. 3 sorts: $\ell$-gons, $m$-gons, and $n$-gons, with $n > m > \ell \geq 4$.
10. 2 or 3 sorts, all with $\geq 6$ sides each.
11. $\geq 4$ sorts of polygons.

And most of these cases have multiple sub-cases.
Example: Case 2: Triangles and Pentagons as faces

One pentagon at each vertex:

▶ \([3, 3, 5]\): Impossible by Lemma 1: 3 odd, 3 ≠ 5.
▶ \([3, 3, 3, 5]\): Pentagonal Antiprism
▶ \([3, 3, 3, 3, 5]\): Snub Dodecahedron
▶ ≥ 5 triangles and 1 pentagon: NO; angles total > 360°.

Two pentagons at each vertex:

▶ \([3, 5, 5] = [5, 5, 3]\): Impossible by Lemma 1: 5 odd, 5 ≠ 3.
▶ \([3, 3, 5, 5]\): Impossible by Lemma 2: 5, 5 ≠ 3
▶ \([3, 5, 3, 5]\): Isocidodecahedron
▶ ≥ 3 triangles and 2 pentagons: NO; angles total > 360°.

≥ 3 pentagons at each vertex:

▶ ≥ 1 triangle(s) and ≥ 3 pentagons: NO; angles total > 360°.
A Twist

OK, so the proof is done. But what about this:

This new solid has only squares and triangles for faces, and each vertex has 3 squares and 1 triangle, with the same set of angles between them.

It is called the **Elongated Square Gyrobicupola** or **Pseudorhombicuboctahedron**.
The Pseudorhombicuboctahedron

First known appearance in print: Duncan Sommerville, 1905.
Rediscovered by J.C.P. Miller, 1930. (Sometimes called “Miller’s solid”).
Did Kepler know of it? He once referred to 14 Archimedean solids, rather than 13.
But it’s not usually considered an Archimedean solid.
Two Questions

1. Why did Kepler's proof miss the PRCOH?
A: Unlike regular polyhedra, a convex polyhedron with the same arrangement of regular polygons at each vertex is not completely determined by the arrangement of polygons around each vertex.

2. So why isn't the PRCOH considered semiregular?
A: Because we (like the ancients) were vague about what “all vertices are congruent” means.
  - Is it just the faces meeting at the vertex that look the same?
  - Or is that the whole solid looks the same if you move one vertex to where another one was?

Although terminology varies, there is general agreement that the nice class (usually called either “semiregular” or “uniform”) should use the “whole solid” definition. So the PRCOH is not an Archimedean solid.
Let's count how many vertices, edges, and faces these solids have:

<table>
<thead>
<tr>
<th></th>
<th>V</th>
<th>E</th>
<th>F</th>
<th></th>
<th>V</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>T.TH</td>
<td>12</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Cu</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td>T.Cu</td>
<td>24</td>
<td>36</td>
<td>14</td>
</tr>
<tr>
<td>OH</td>
<td>6</td>
<td>12</td>
<td>8</td>
<td>T.OH</td>
<td>24</td>
<td>36</td>
<td>14</td>
</tr>
<tr>
<td>DH</td>
<td>20</td>
<td>30</td>
<td>12</td>
<td>T.DH</td>
<td>60</td>
<td>90</td>
<td>32</td>
</tr>
<tr>
<td>IH</td>
<td>12</td>
<td>30</td>
<td>20</td>
<td>T.IH</td>
<td>60</td>
<td>90</td>
<td>32</td>
</tr>
<tr>
<td>COH</td>
<td>12</td>
<td>24</td>
<td>14</td>
<td>IDH</td>
<td>30</td>
<td>60</td>
<td>32</td>
</tr>
<tr>
<td>RCOH</td>
<td>24</td>
<td>48</td>
<td>26</td>
<td>RIDH</td>
<td>60</td>
<td>120</td>
<td>62</td>
</tr>
<tr>
<td>T.COH</td>
<td>48</td>
<td>72</td>
<td>26</td>
<td>T.IDH</td>
<td>120</td>
<td>180</td>
<td>62</td>
</tr>
<tr>
<td>S.Cu</td>
<td>24</td>
<td>60</td>
<td>38</td>
<td>S.DH</td>
<td>60</td>
<td>150</td>
<td>92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>V</th>
<th>E</th>
<th>F</th>
<th></th>
<th>V</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Pr</td>
<td>2n</td>
<td>3n</td>
<td>n + 2</td>
<td>n-APr</td>
<td>2n</td>
<td>4n</td>
<td>2n + 2</td>
</tr>
</tbody>
</table>

Euler observes: \( V - E + F = 2 \).
Euler’s Theorem

Leonhard Euler (Switzerland, Russia, Germany), 1707–1783 CE: Among many, many, **MANY** other things, proved:

**Theorem**

Let $S$ be a convex polyhedron, with $V$ vertices, $E$ edges, and $F$ faces. Then $V - E + F = 2$.

**Key idea of proof:** If you change a polyhedron by:

- adding a vertex somewhere in the middle of an edge,
- cutting a face in two by connecting two nonadjacent vertices with a new edge,
- reversing either of the above two kinds of operations, or
- bending or stretching it,

the quantity $V - E + F$ remains unchanged.
Regular Polyhedra Revisited

Let $S$ be a regular polyhedron with $m$ faces, and with $k$ regular \textit{n}-gons meeting at each vertex. Then:

\[ V = \frac{mn}{k}, \quad E = \frac{mn}{2}, \quad F = m. \]

So

\[ 2 = V - E + F = \frac{mn}{k} - \frac{mn}{2} + m = \frac{m(2n - kn + 2k)}{2k}. \]

In particular, $2n - kn + 2k > 0$, i.e., $\frac{1}{n} + \frac{1}{k} > \frac{1}{2}$. And it’s not hard to show that the only pairs of integers $(k, n)$ with $k, n \geq 3$ that give $\frac{1}{n} + \frac{1}{k} > \frac{1}{2}$ are:

![Tetrahedron (3, 3), Cube (4, 3), Octahedron (3, 4), Dodecahedron (5, 3), Icosahedron (3, 5)]