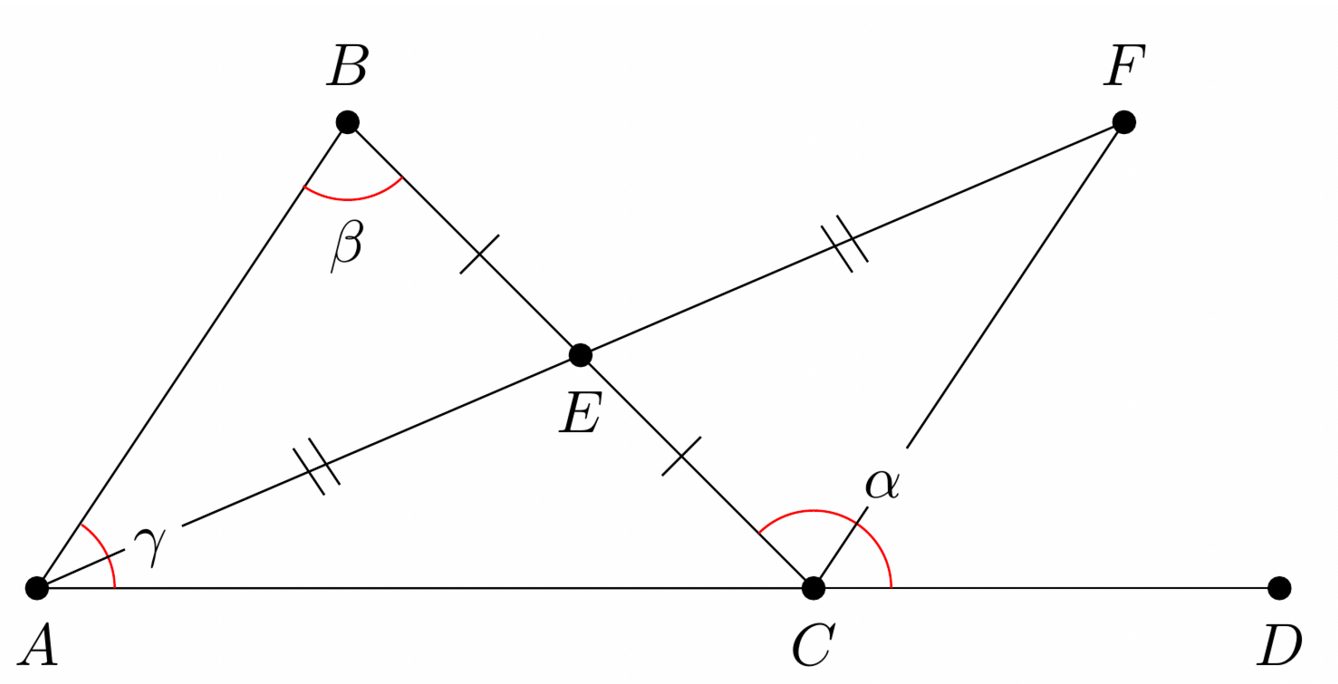
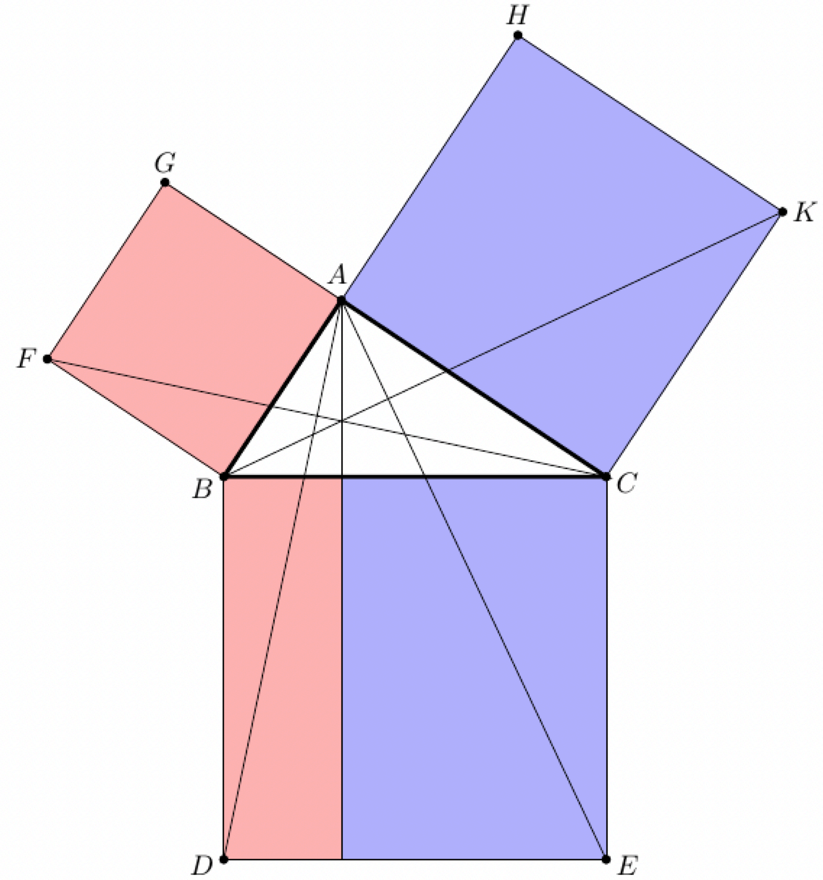
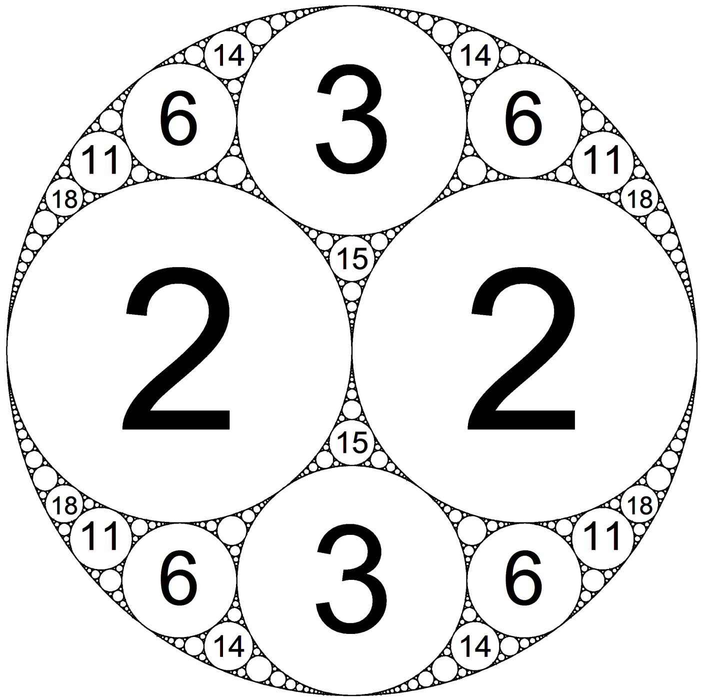




Chapter 4: Euclidean Geometry



Greek Math

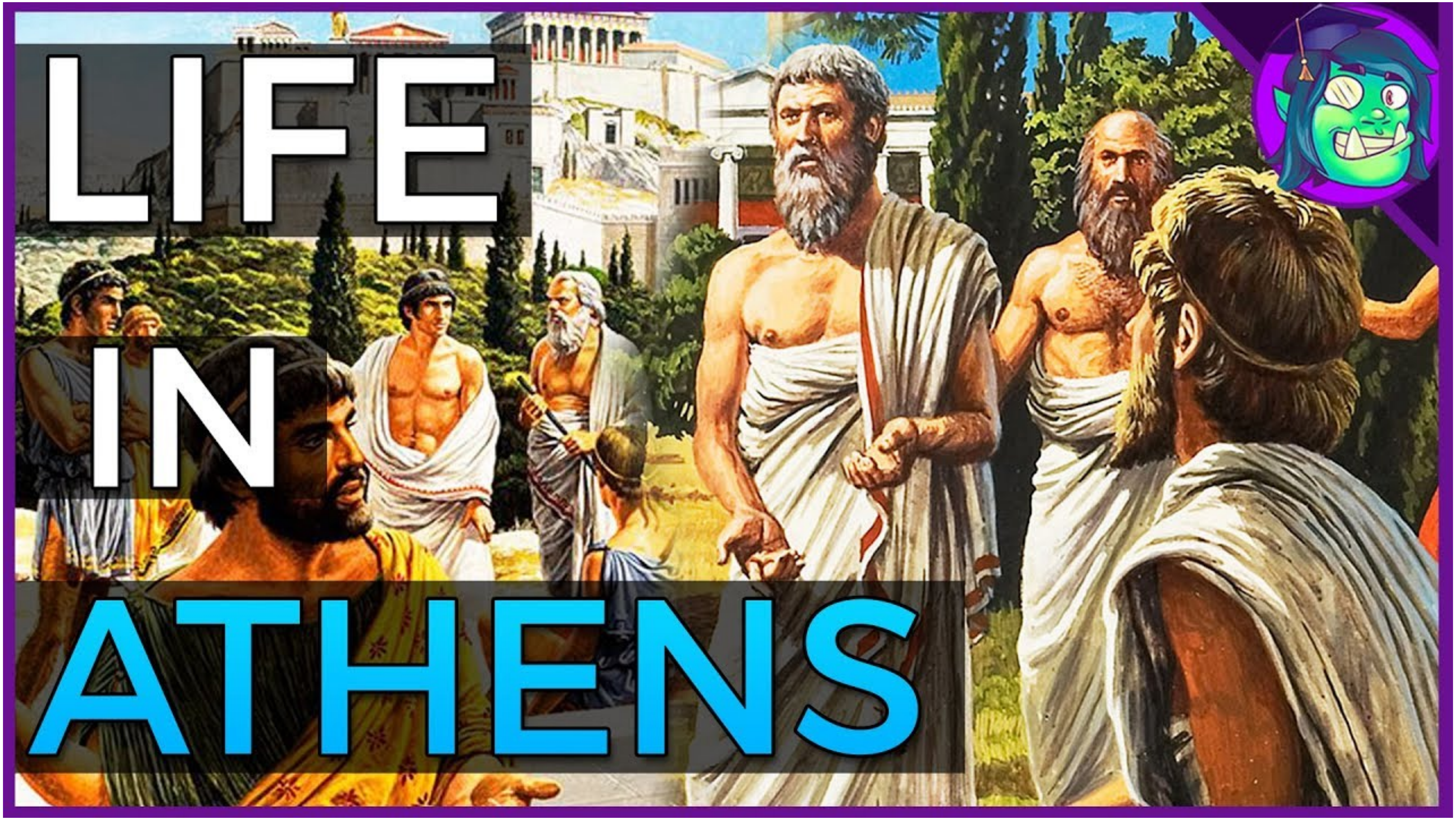
- Pythagoras died ~ 500BC. Euclid born ~325BC. Between them lived Socrates, Plato and Alexander the Great.

- Plato established the Academy in Athens ~387BC, giving scholars time, resources and collaborators. Legend says that above the entrance was “Let no man ignorant of geometry enter here.”

- Many great Greek mathematicians studied at the Academy. Greatest of them was Eudoxus of Cnidus.

Academy in Athens

Life in Ancient Athens



The Elements

- Euclid wrote the *Elements*, which is the most important book in math history. Much of it is not his original work—it is compiled from other sources.
- The major sources were likely the Pythagoreans, Hippocrates and Eudoxus. Many of the proofs are believed to be original to Euclid.
- Its success is due to its logical and axiomatic presentation. This deductive style is the central approach to mathematics today.

The Elements

- The text was the primary math textbook for *two thousand years*.

- It is divided into 13 “books” on topics from geometry, algebra and number theory.

- Book I is devoted to propositions from planar geometry.

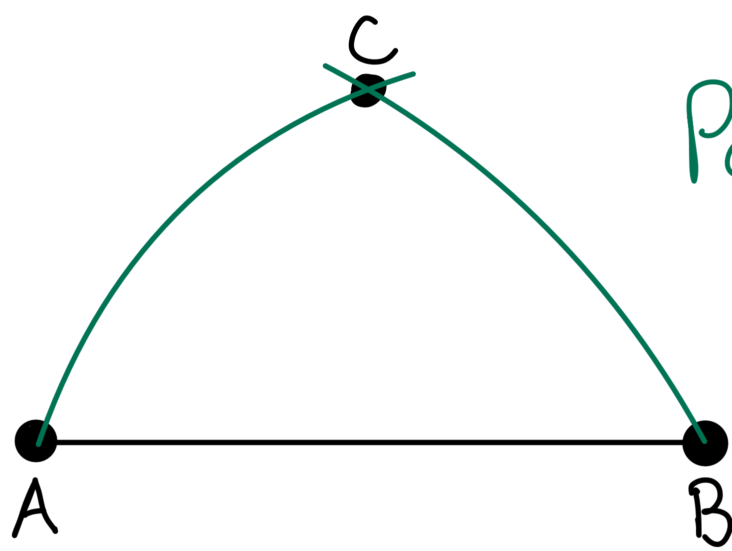
- Euclid’s postulates allow him to use a straightedge and compass, which play a central role.

Definitions, Common Notions and Postulates

Proposition Book 1 - postulate 1

On a given finite line, one can construct an equilateral triangle.

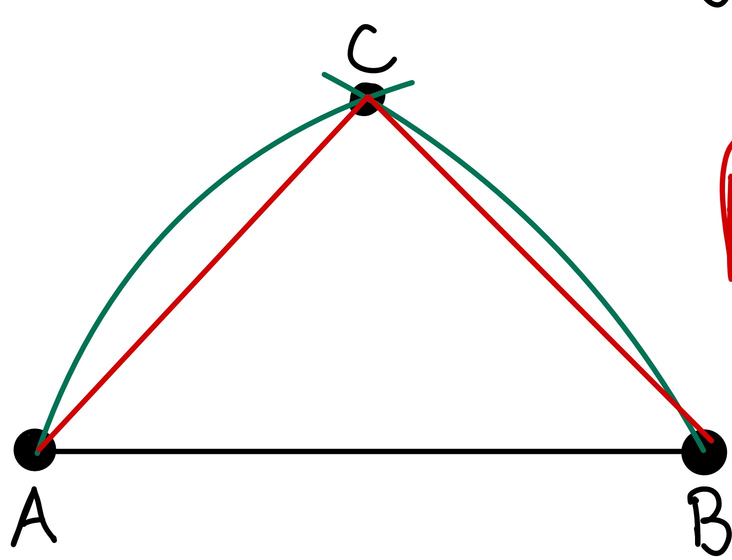
Proof



Postulate 3
(Twice)

Postulate 3 (twice)

[It is possible] to describe a circle with any center and distance



Postulate 1

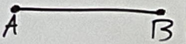
Postulate 1

[It is possible] to draw a straight line from any point to any [other] point

Therefore, $\overline{AB} = \overline{AC}$

re line,

n



ostulate 3
(twice)

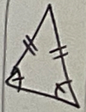
$\overline{AB} = \overline{AC}$ and $\overline{AB} = \overline{BC}$ by definition of a circle.

$\overline{AC} = \overline{BC}$ by Common Notion 1. So, ΔABC is equilateral by definition.

Q.E.D.

Proposition I.4.

SAS triangle Congruence



Propositions I.5 and I.6

A triangle is isosceles if and only if its base angles are Congruent.

Proposition I.8.

SSS triangle Congruence.

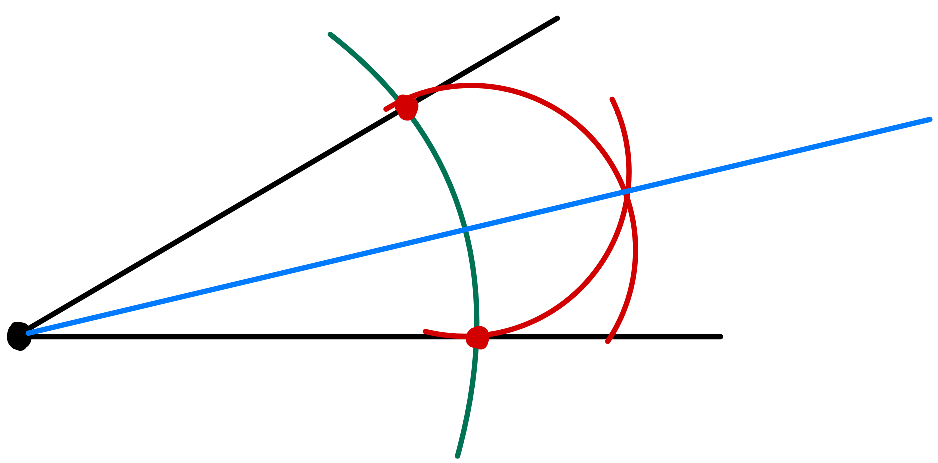
Proposition Book 1 - postulate 4: SAS triangle congruence

Proposition Book 1 - postulate 5 and 6: A triangle is isosceles if and only if its base angles are congruent.

Proposition Book 1 - postulate 8: SSS triangle congruence

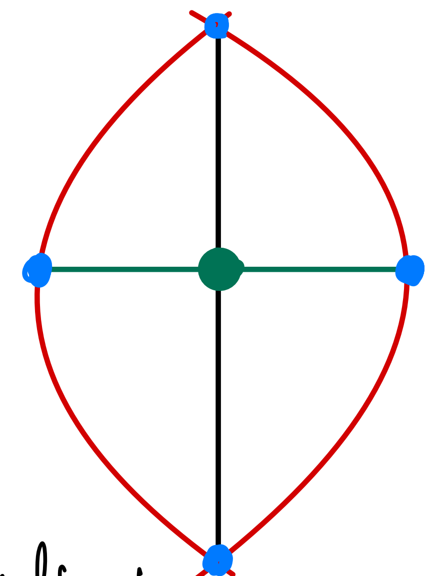
4 constructions

Book I.9

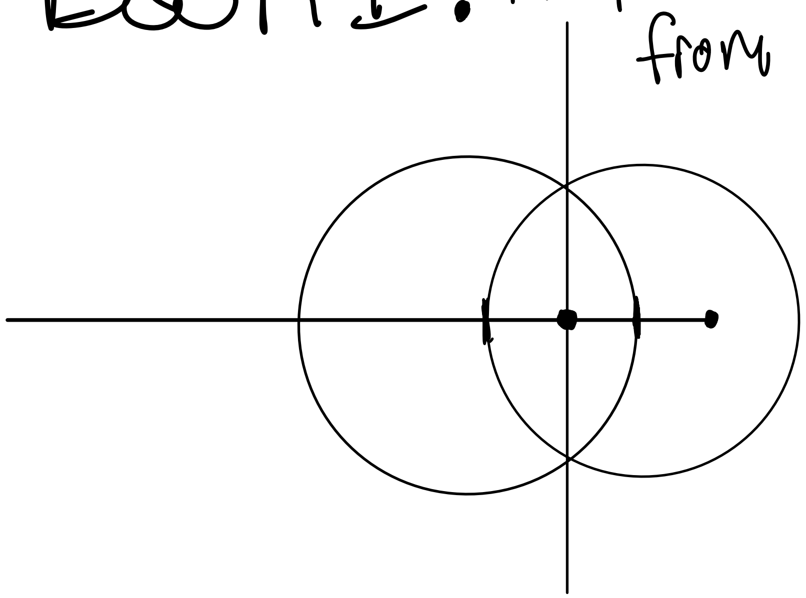


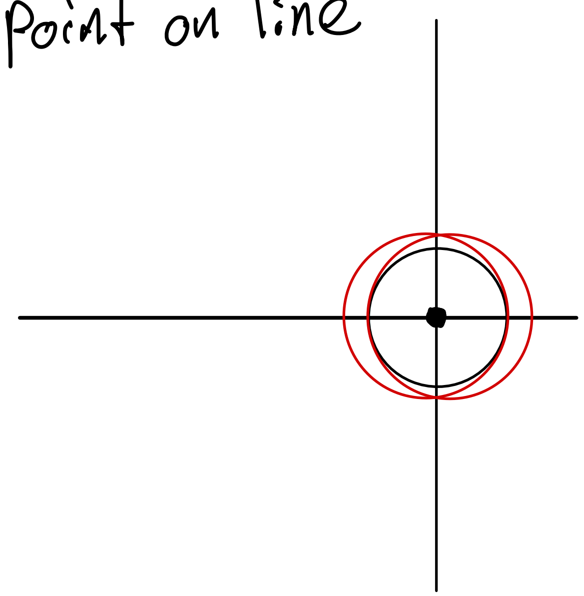
Book I.10

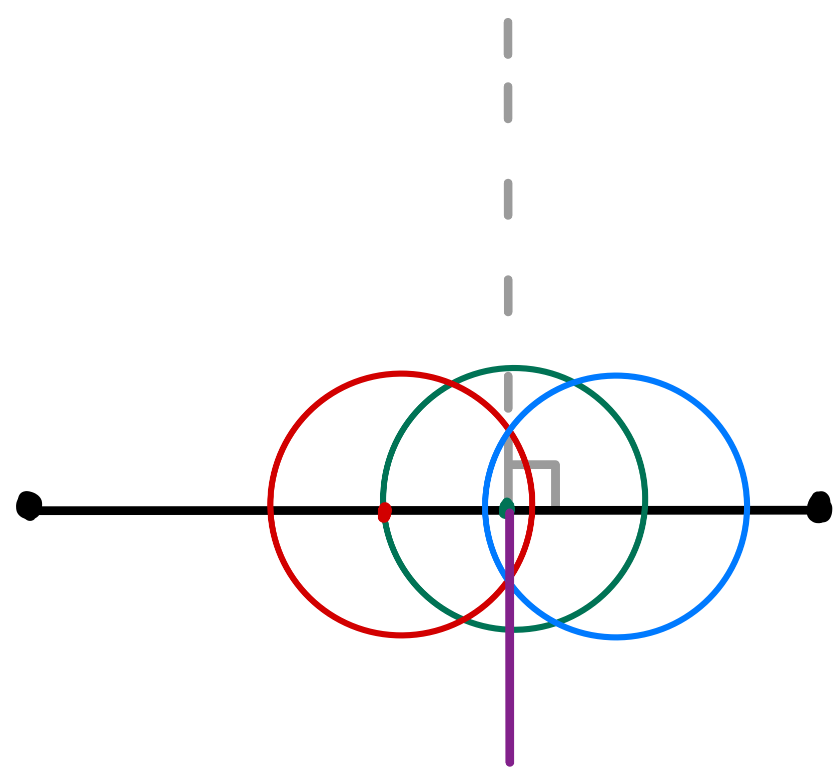
Bisect a line



Book I. Proposition 2 Perpendicular from point on line



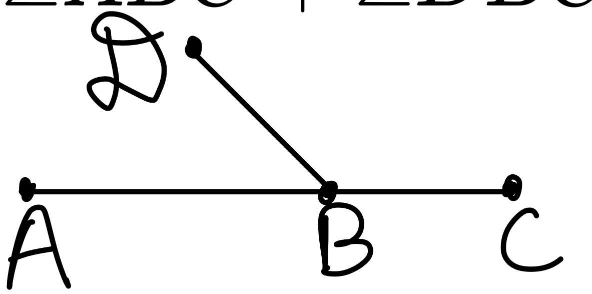




Propositions I.13 + I.14

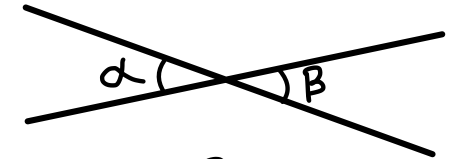
ABC is a straight line if and only if

$$\angle ABC + \angle DBC = \text{Two right angles (i.e. } 180^\circ)$$



Proposition I.15

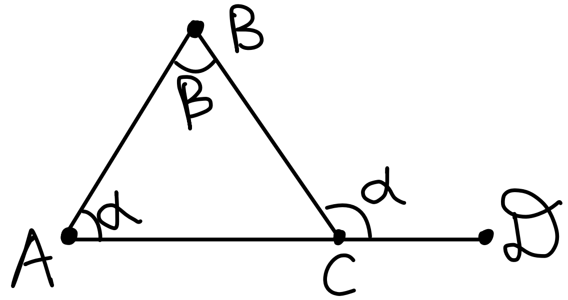
Vertical angles are equal



$\alpha = \beta$

Proposition I.16 (Exterior angle theorem)

An exterior angle of any triangle is greater than either of the opposite angles.



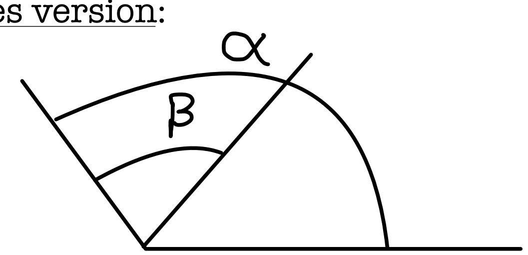
Claim: $\alpha > \beta$

$\alpha > \gamma$

Proof Idea. Common Notion 5:

The whole is greater than the part.

Angles version:



$\Rightarrow \alpha > \beta$

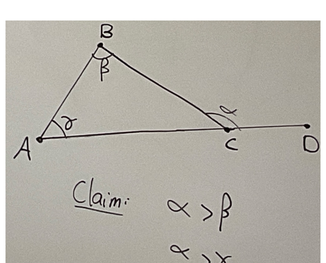
Proof that alpha > beta

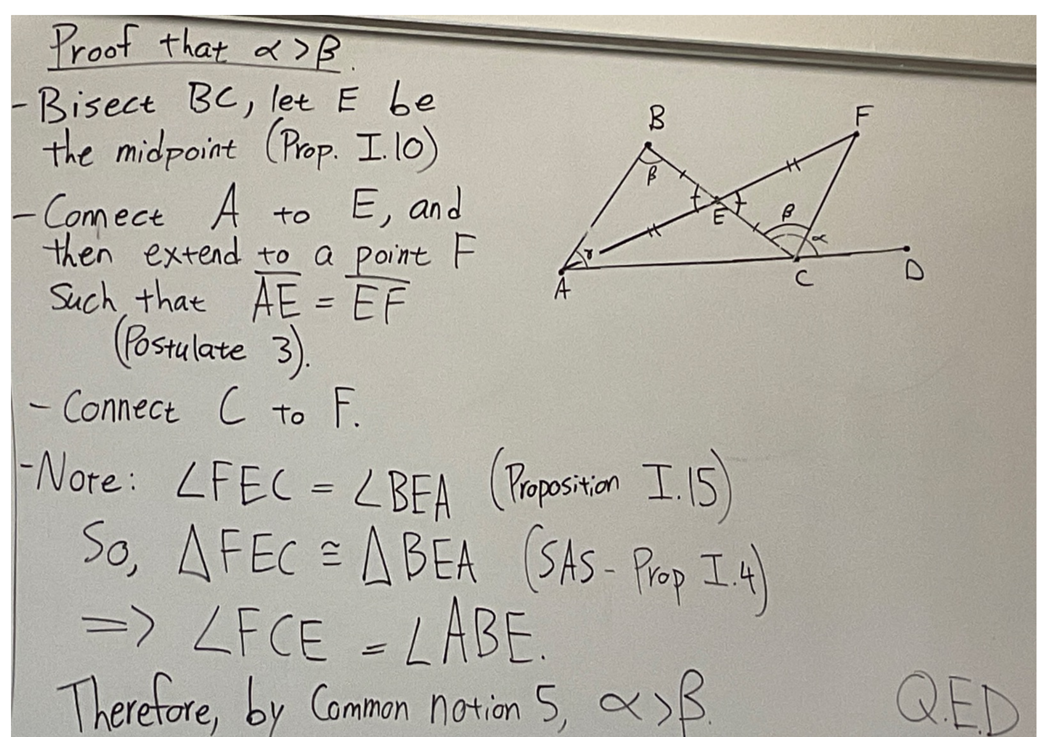
- Bisect BC, let E be the midpoint (prop. I.10)
- Connect A to E, and then extend to a point F such that AE = EF (Postulate 3)
- Connect C to F.
- Note: <FEC = <BEA (Proposition I.15).

So, ΔFEC ~= ΔBEA (SAS - Prop I.4)

=> <FCE = <ABE.

Therefore by common notion 5, alpha > beta





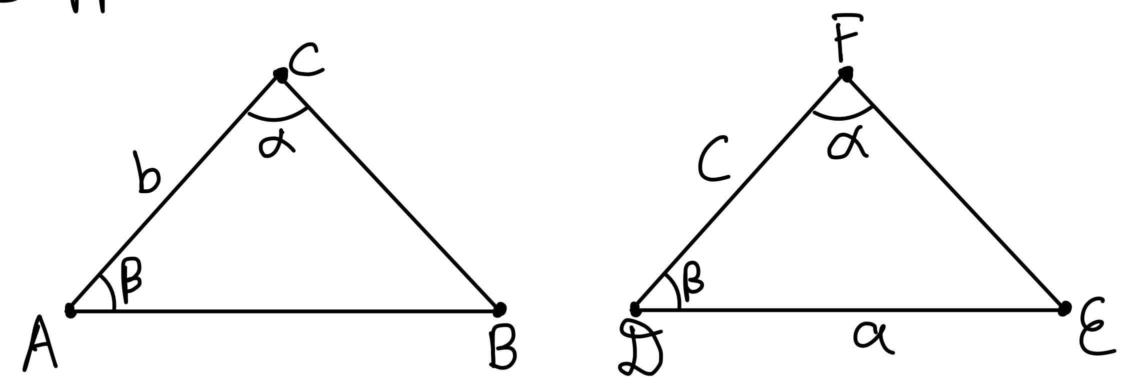
Prop I.20

Shortest distance between points is a straight line

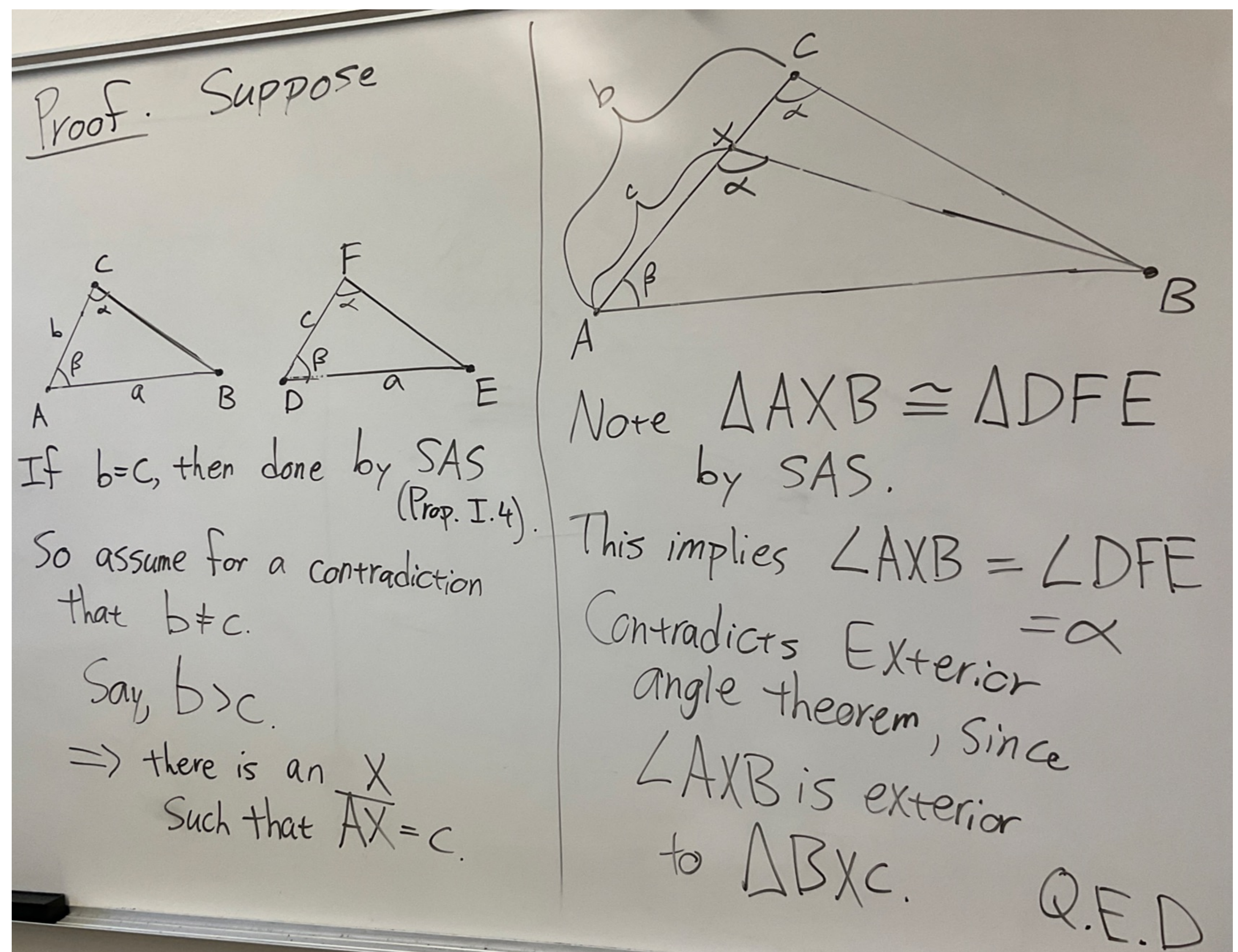
Prop I.26

AAS triangle congruence.

Proof. Suppose

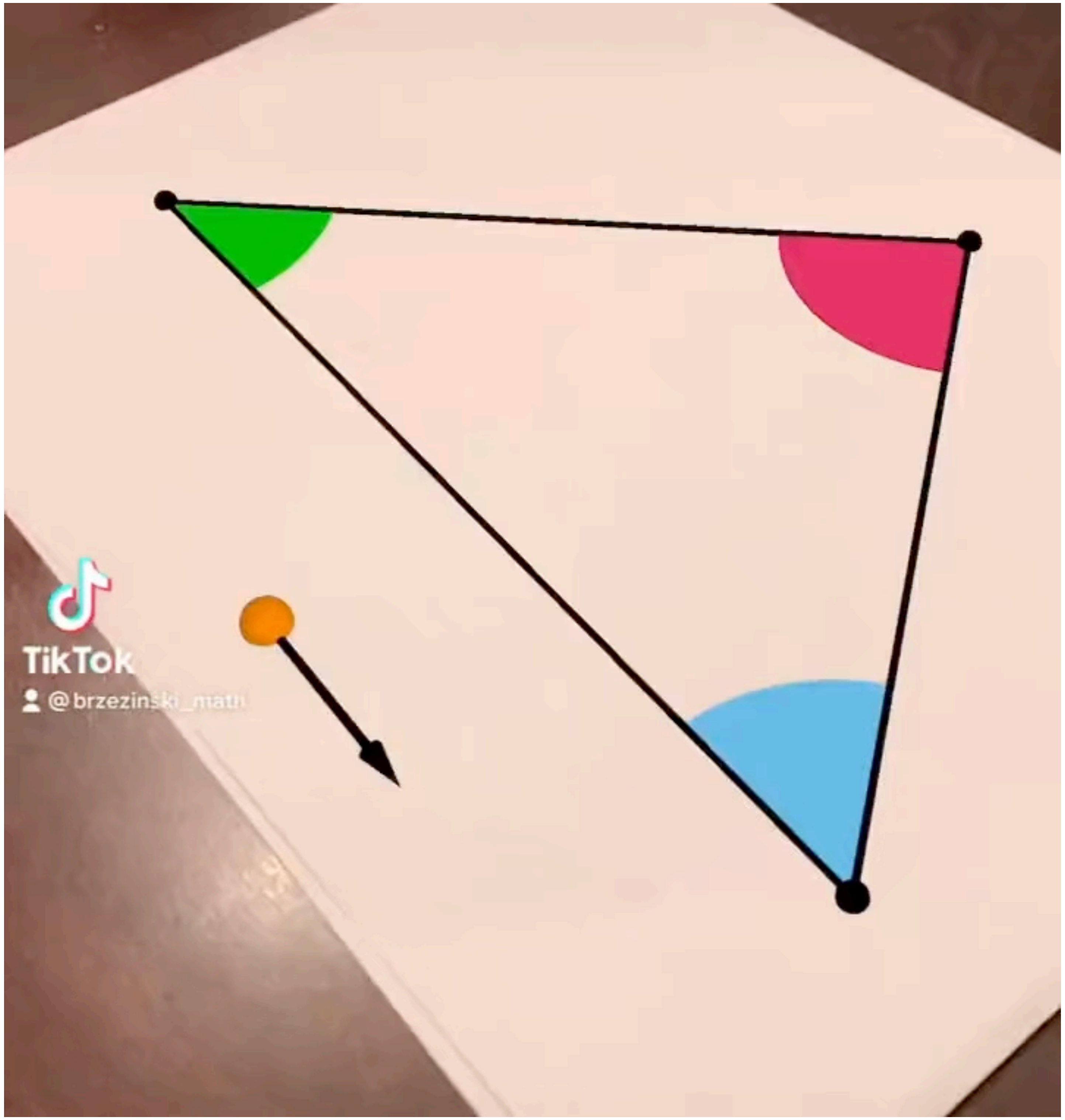


If b = c, then done by SAS (Prop. I.4)
So assume for a contradiction than b ≠ c.
Say, b > c.
=> there is a x such that AX = C



Proving Propositions

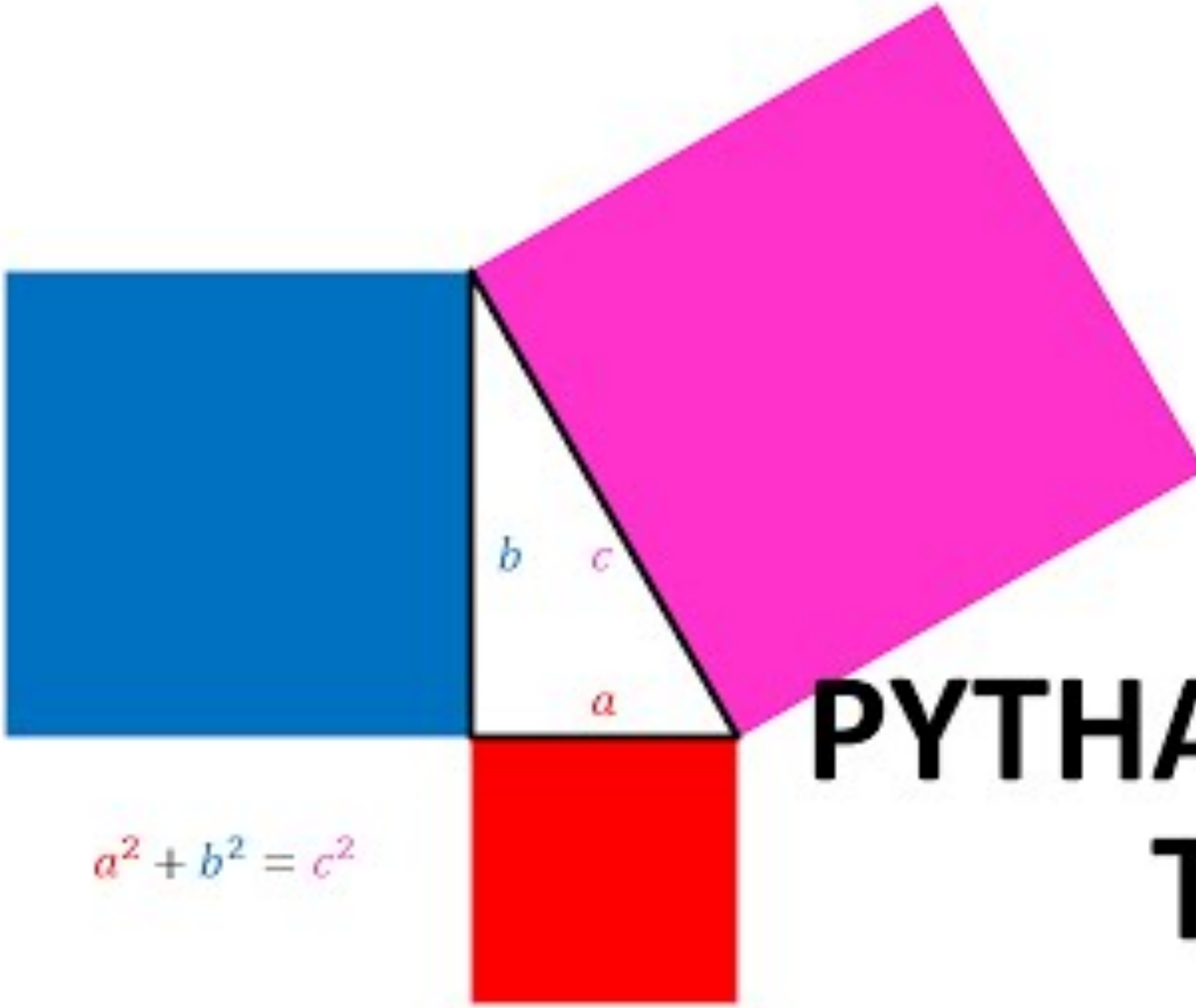
Triangle Angle Sum



Link

https://www.geogebra.org/m/atx3asep

PYTHAGOREAN THEOREM



$a^2 + b^2 = c^2$

The Aftermath

- Book I showed how to construct an equilateral triangle and a square.

- Ancient Greeks also know how to construct a regular pentagon, and given a regular polygon with m sides, they could construct a regular polygon with $2m$ sides.

- Major open question: For which values of n is the regular n-gon constructible with a straightedge and compass?

The Aftermath

- There was no progress made until 1796, which a 19-year-old named Carl Friedrich Gauss used some beautiful algebra to find a construction of the regular 17-gon.

- Then, at 24, he entirely classified which regular polygons are constructible.

- He did not prove one direction of his theorem, though. That was done by Pierre Wantzel.

The Aftermath

- The Gauss-Wantzel theorem says this:

- A regular n-gon can be constructed with straightedge and compass if and only if n is a power of 2 or the product of a power of 2 and any number of distinct Fermat primes.

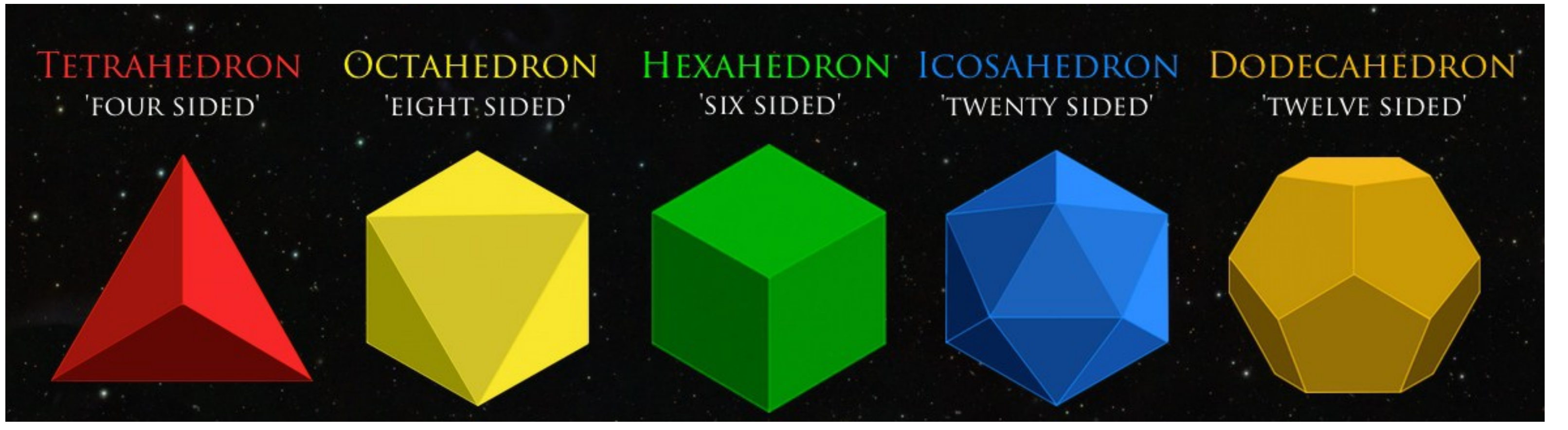
- A Fermat prime is a prime of the form $2^{2^k} + 1$.

The Elements

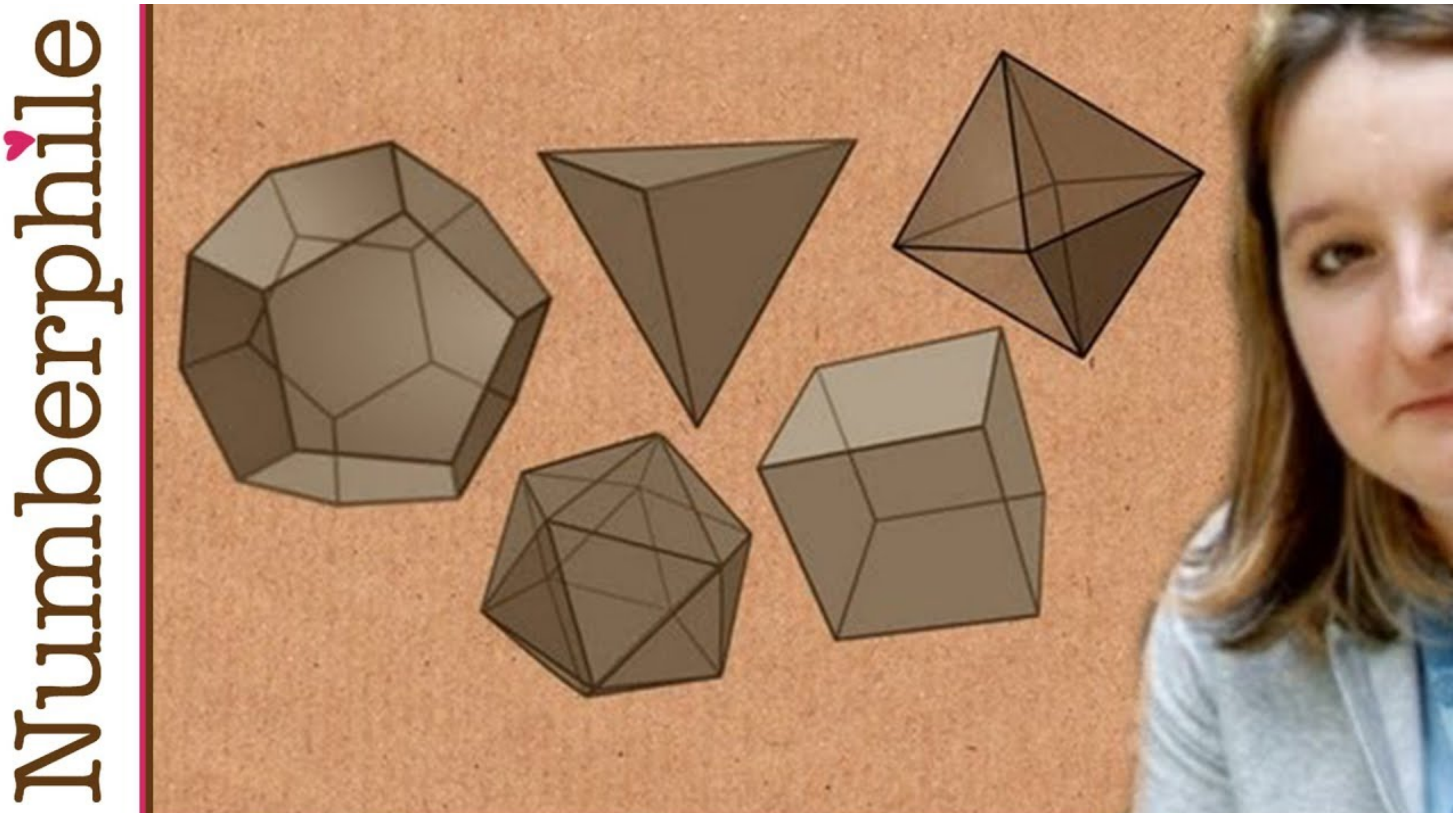
- Book I: Planar geometry
- Book II: Algebraic geometry
- Book III: Circles
- Book IV: Inscribing and circumscribing
- Book V: Magnitudes, ratios and rules of arithmetic
- Book VI: Proportions between lines and shapes

The Elements

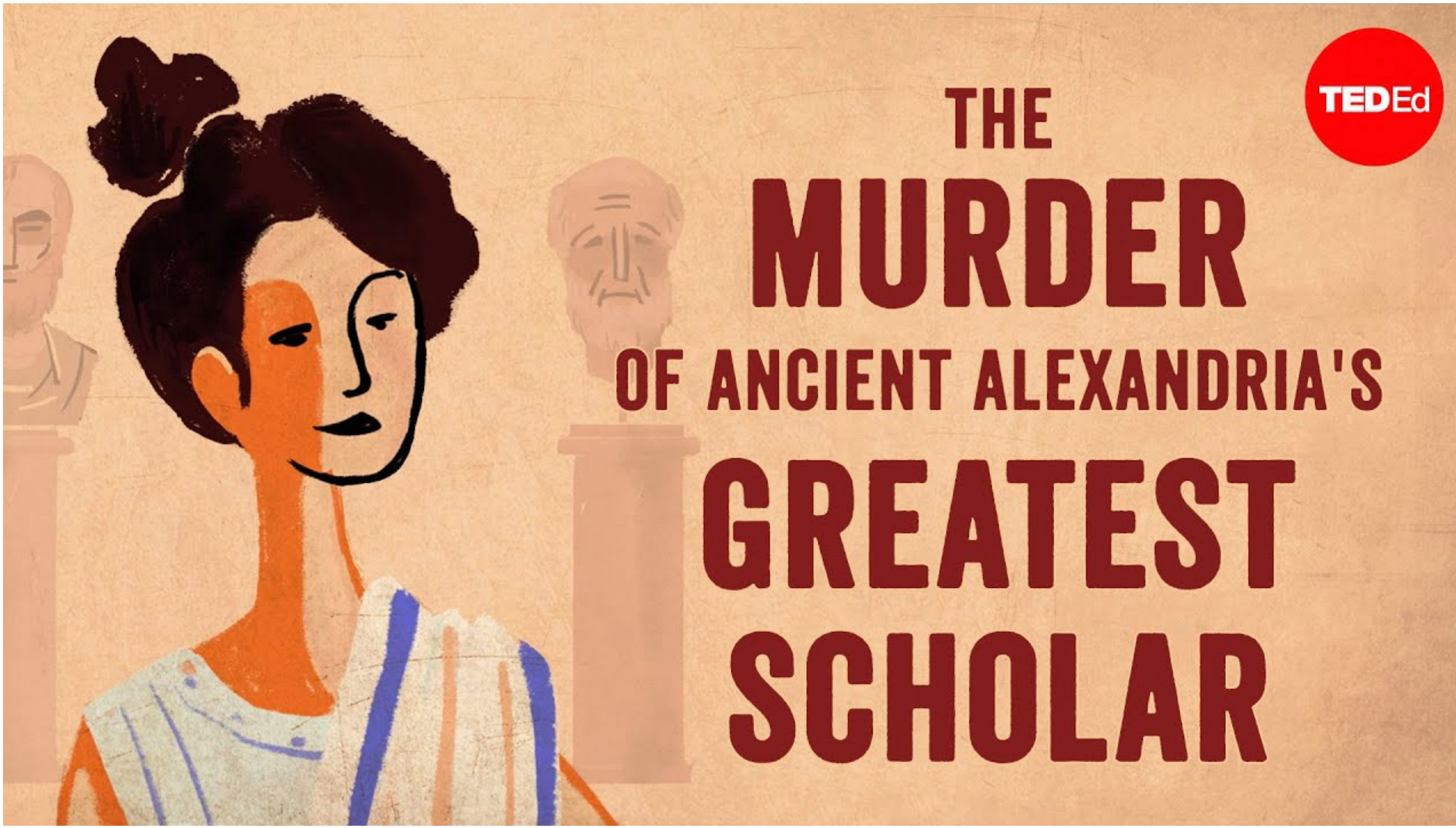
- Book VII, VIII and IX: Number theory
- Book X: Square roots
- Book XI: Solid figures
- Book XII: Volume
- Book XIII: Platonic solids



Platonic solids



Hypatia



Hypatia

- Hypatia is the first woman in math history that we know a lot about.

- She was a first-class thinker and highly respected philosopher, mathematician and teacher.

- Her life ended in tragedy, as she was brutally murdered for defending religious freedom.

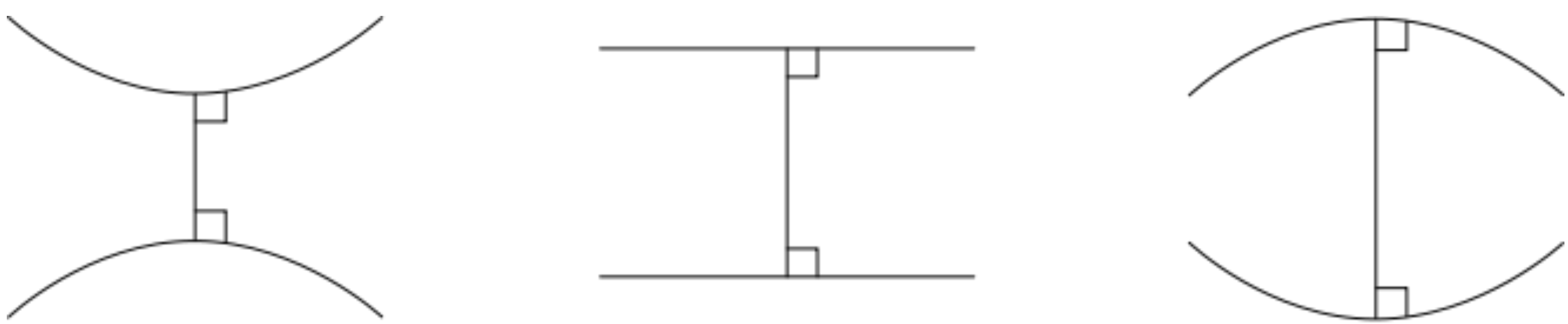
The Legacy of Axiomatic Thinking

The Aftermath

- Recall that Euclidean geometry was built from 5 axioms, the final of which was *the parallel postulate*. This one was slightly controversial.
- Can that postulate be deduced from the other four? Unfortunately, no.
- In this way, the parallel postulate is *undecidable* if your axioms are only the first four.

The Aftermath

- This implies that there exist non-Euclidean geometries. Instead of the parallel postulate, you can have an axiom saying that if ℓ is a line and P is a point off of ℓ, then there are 2+ lines through P that are parallel to ℓ. Or no lines that are parallel.



Hyperbolic Euclidean Elliptic

The Aftermath

- Our set theory today is built from the *ZFC axioms*. These are 8 completely basic axioms about sets, plus the slightly-controversial *axiom of choice*.

- From these, not only is set theory built, but number theory, too.

- Kurt Gödel proved that every set of axioms that leads to number theory must have undecidable statements. There must be statements that can neither be proven nor disproven.

Approximating $\sqrt{2}$

- This chapter is on geometry and the next chapter is on number theory. A bridge between these topics is using geometry to approximate $\sqrt{2}$.

- We previously learned about the Indian geometry from their *sulbasutras*. These also contained an approximation:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Approximating $\sqrt{2}$

- This chapter is on geometry and the next chapter is on number theory. A bridge between these topics is using geometry to approximate $\sqrt{2}$.

- We previously learned about the Indian geometry from their *sulbasutras*. These also contained an approximation:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

$$1.414213\ldots$$

Approximating $\sqrt{2}$

- This chapter is on geometry and the next chapter is on number theory. A bridge between these topics is using geometry to approximate $\sqrt{2}$.

- We previously learned about the Indian geometry from their *sulbasutras*. These also contained an approximation:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

$1.414215\ldots$

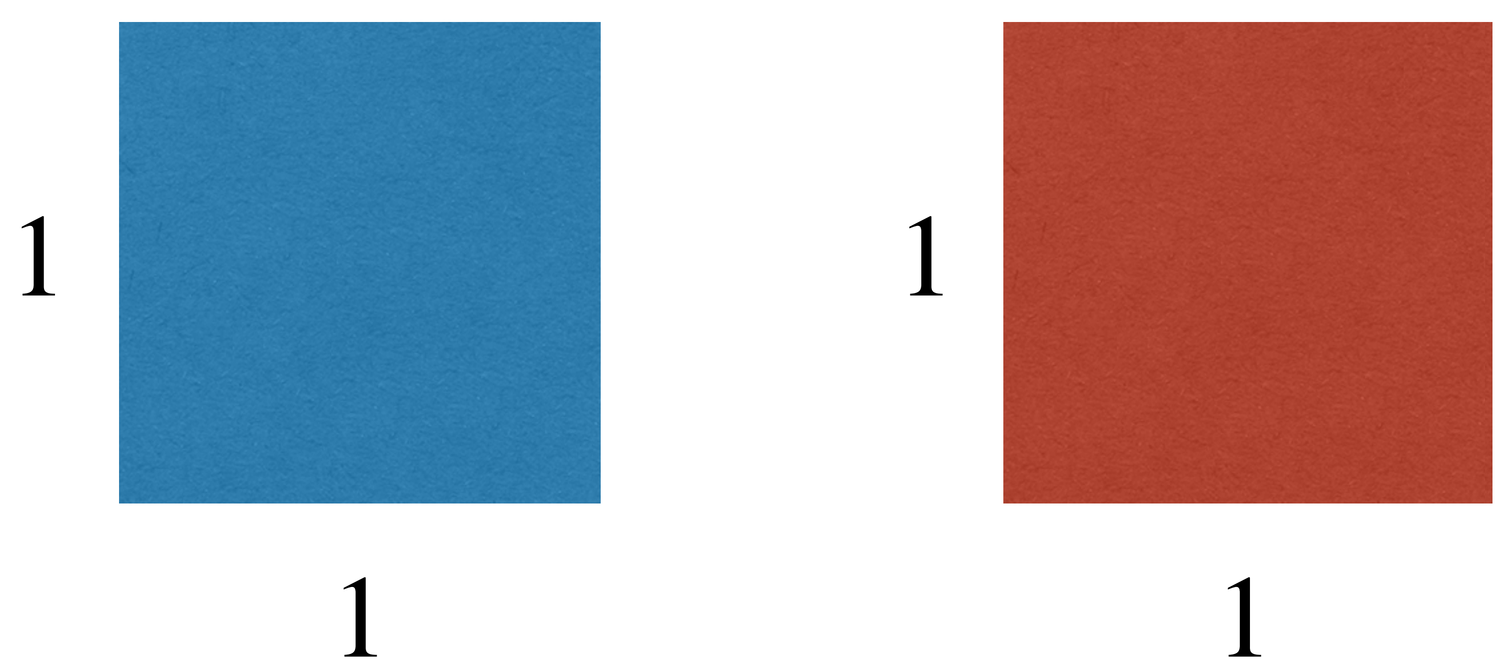
$1.414213\ldots$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares



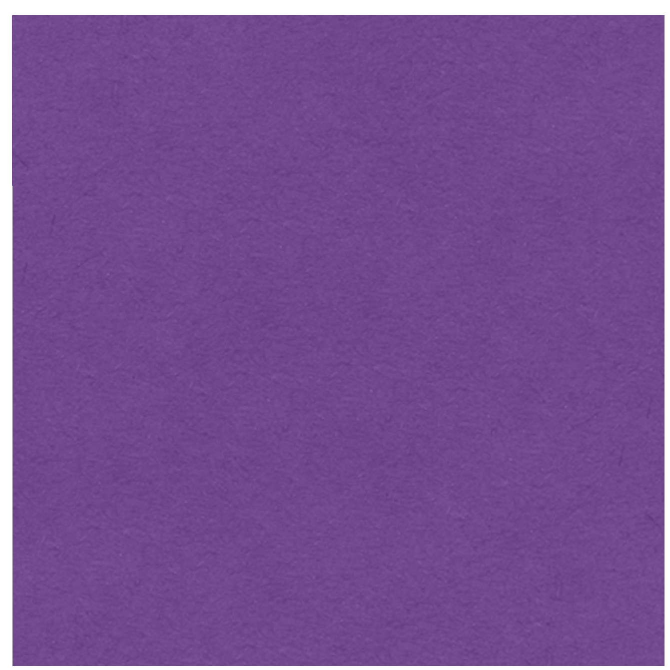
Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

If you could combine them into a single square, it would be a $\sqrt{2} \times \sqrt{2}$ square

$\sqrt{2}$



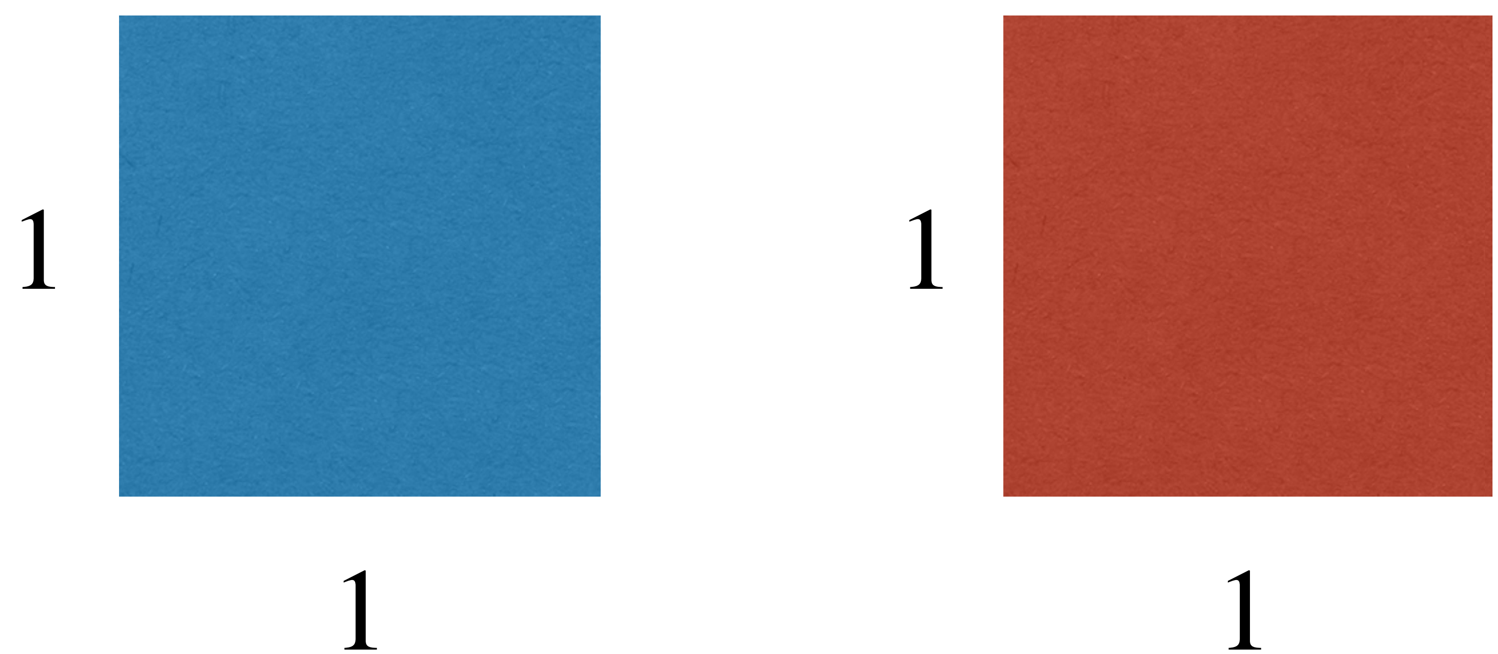
$\sqrt{2}$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

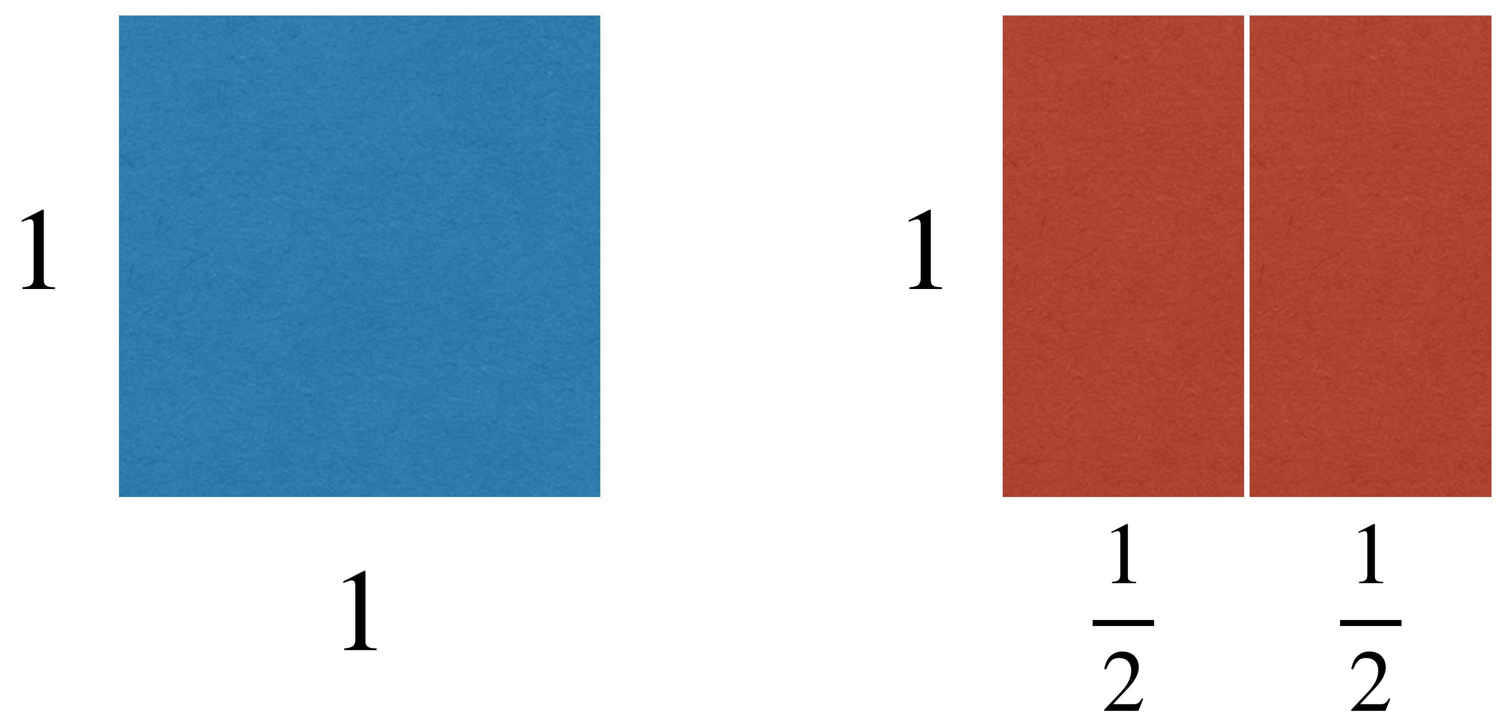


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

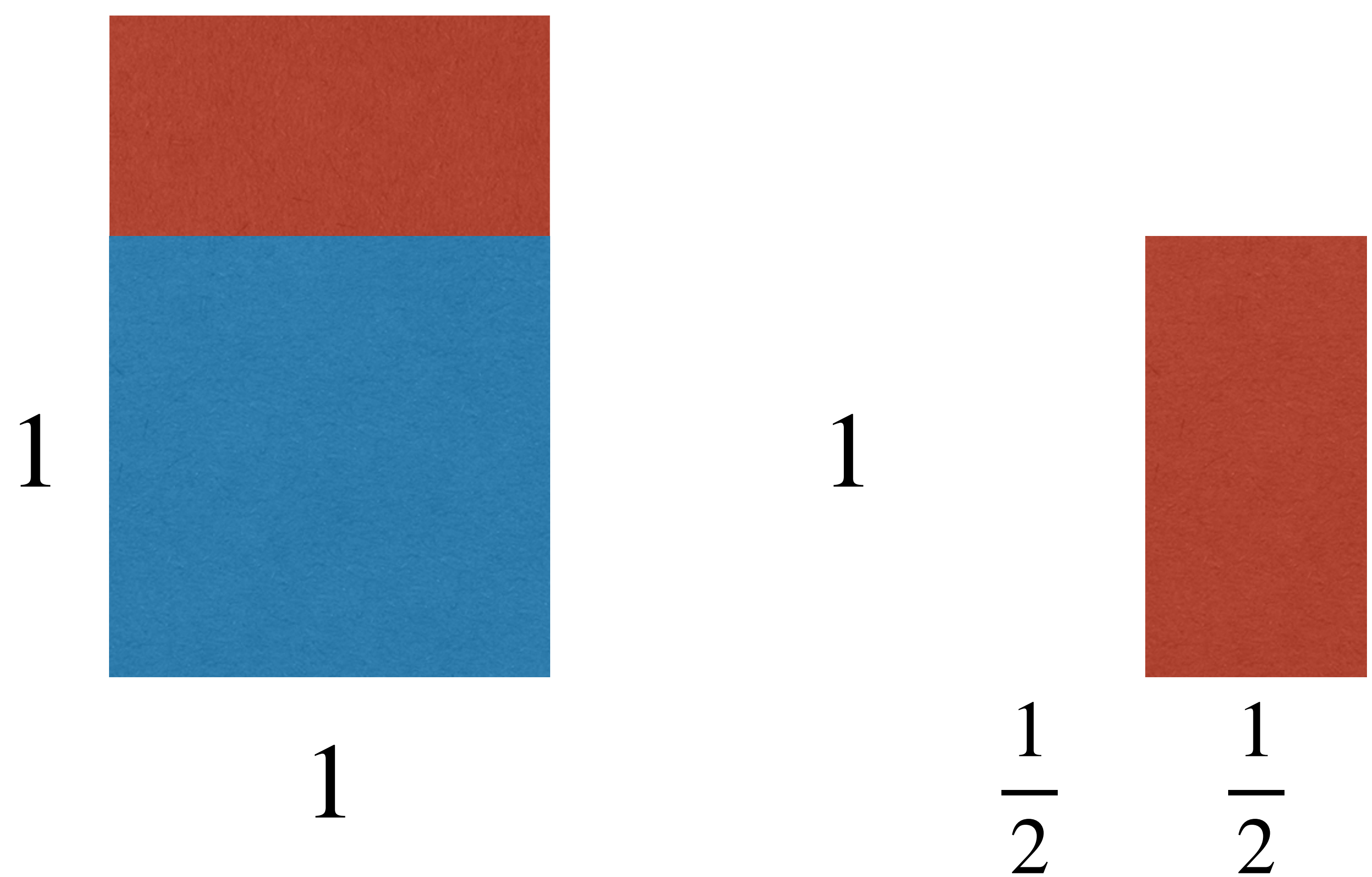


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

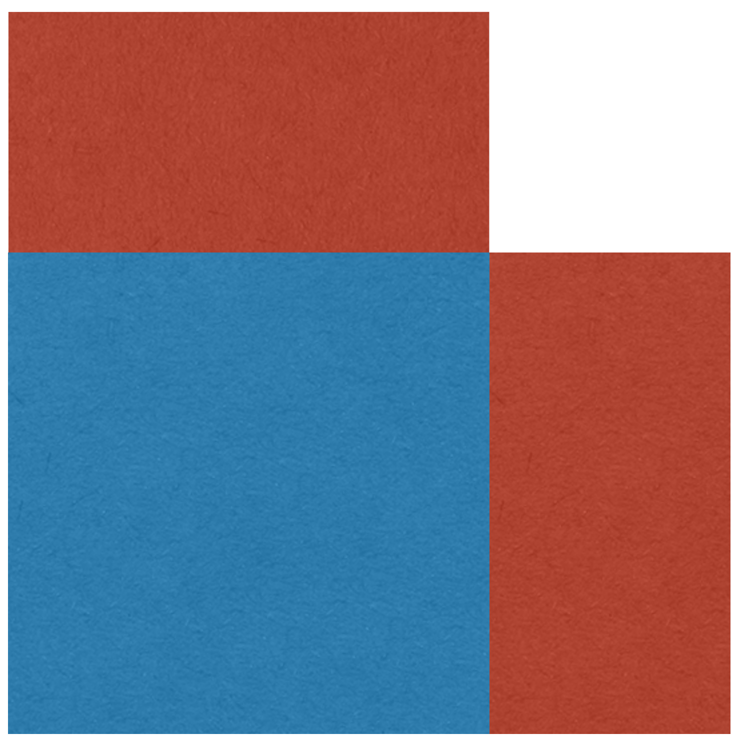


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares



1 1

1

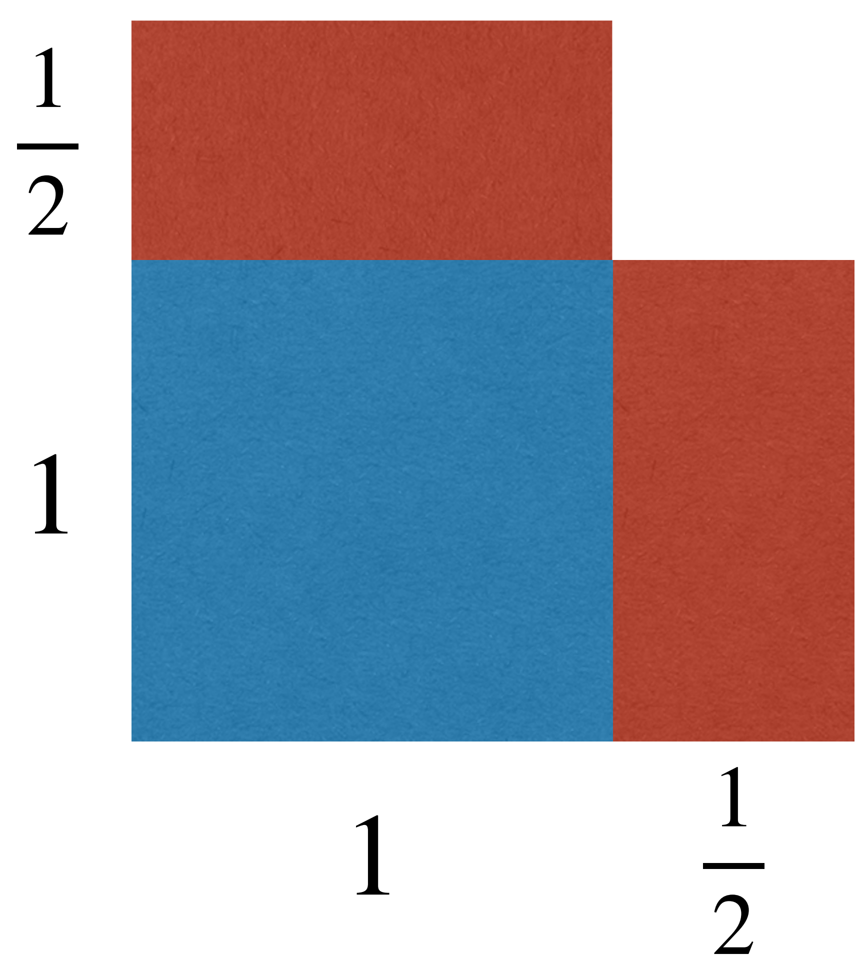
$\frac{1}{2}$ $\frac{1}{2}$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

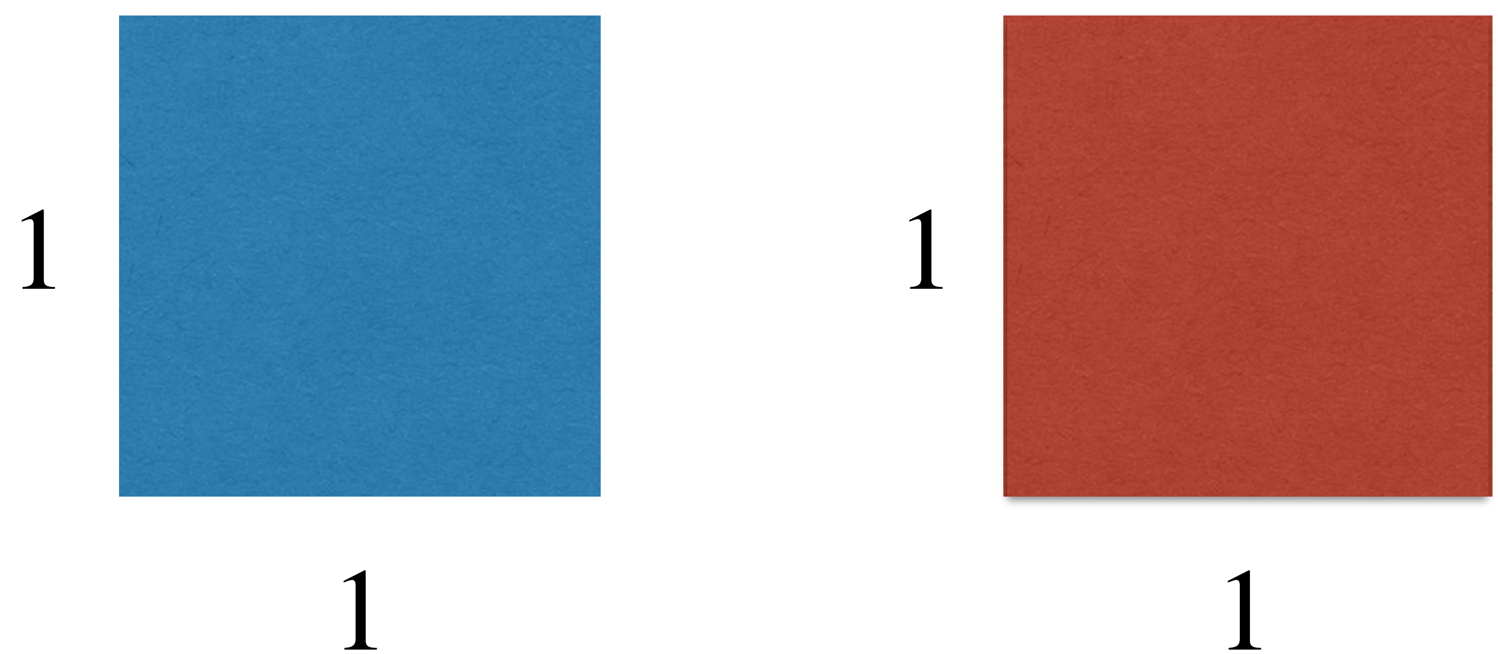


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

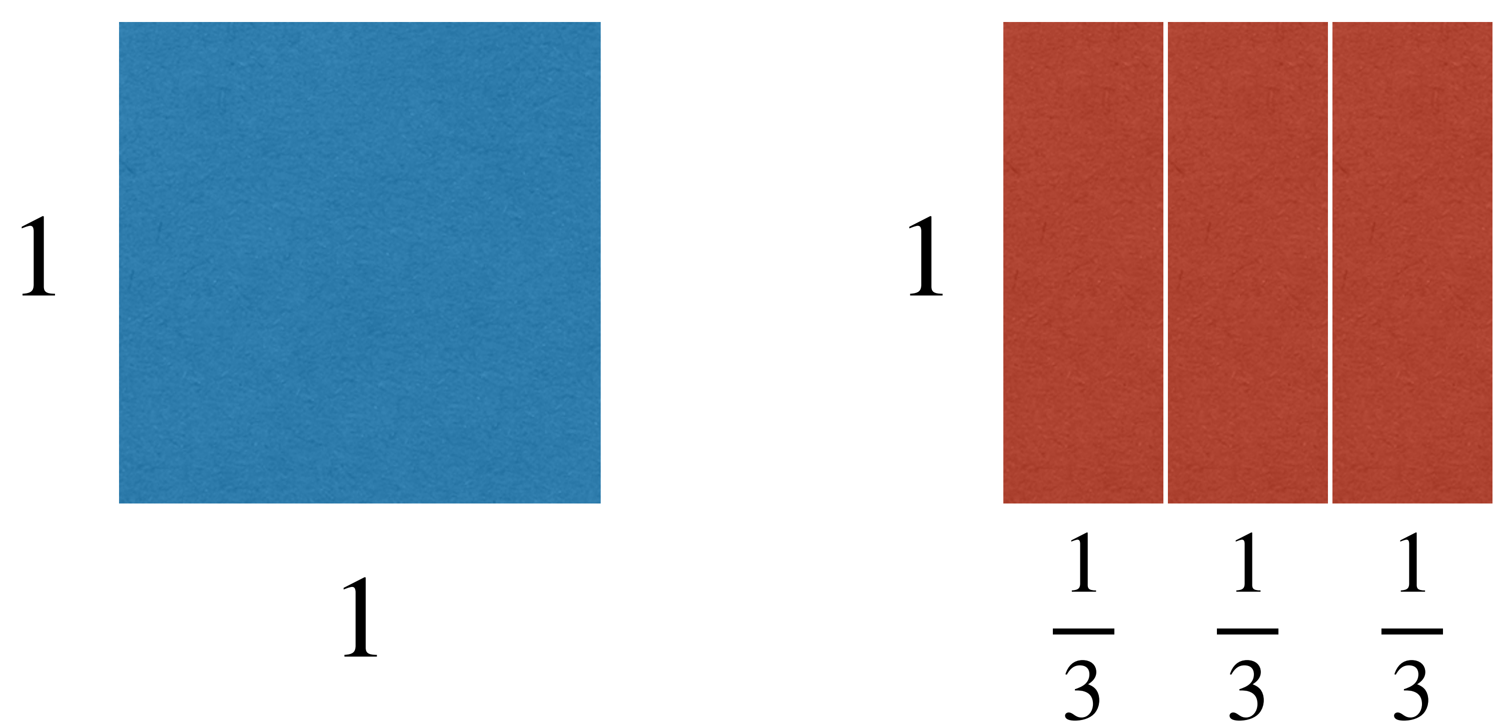


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares



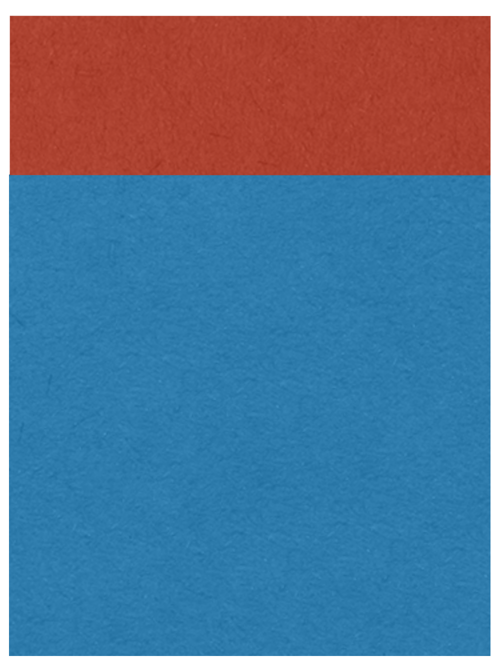
Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

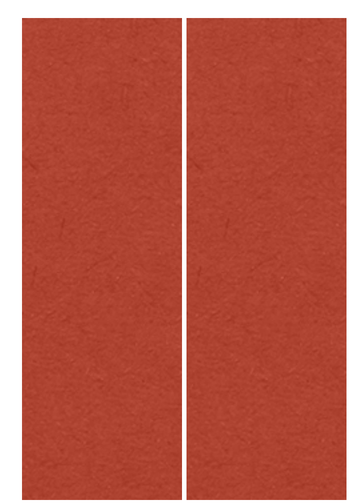
Suppose you have two 1×1 squares

1



1

1



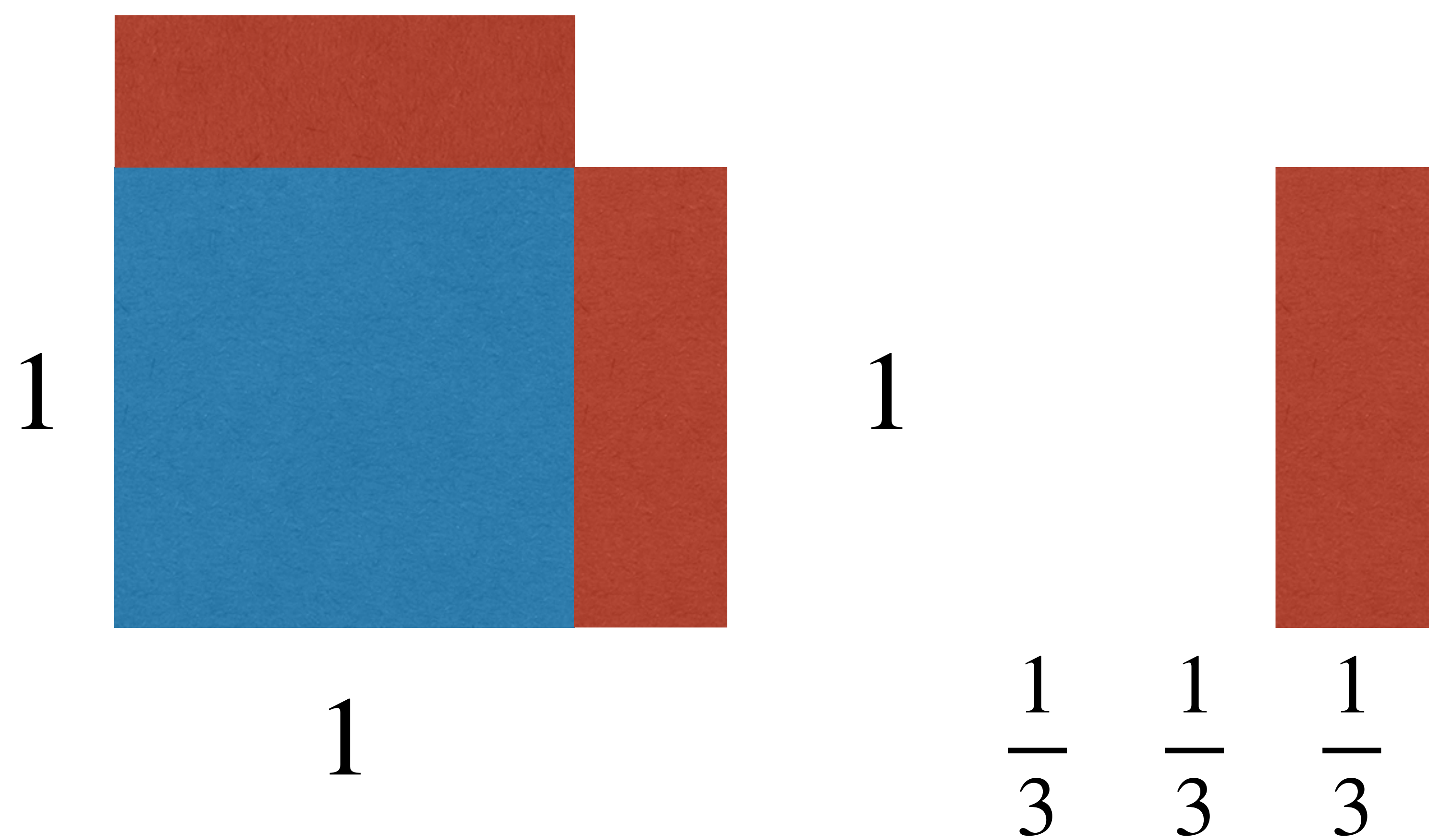
$\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

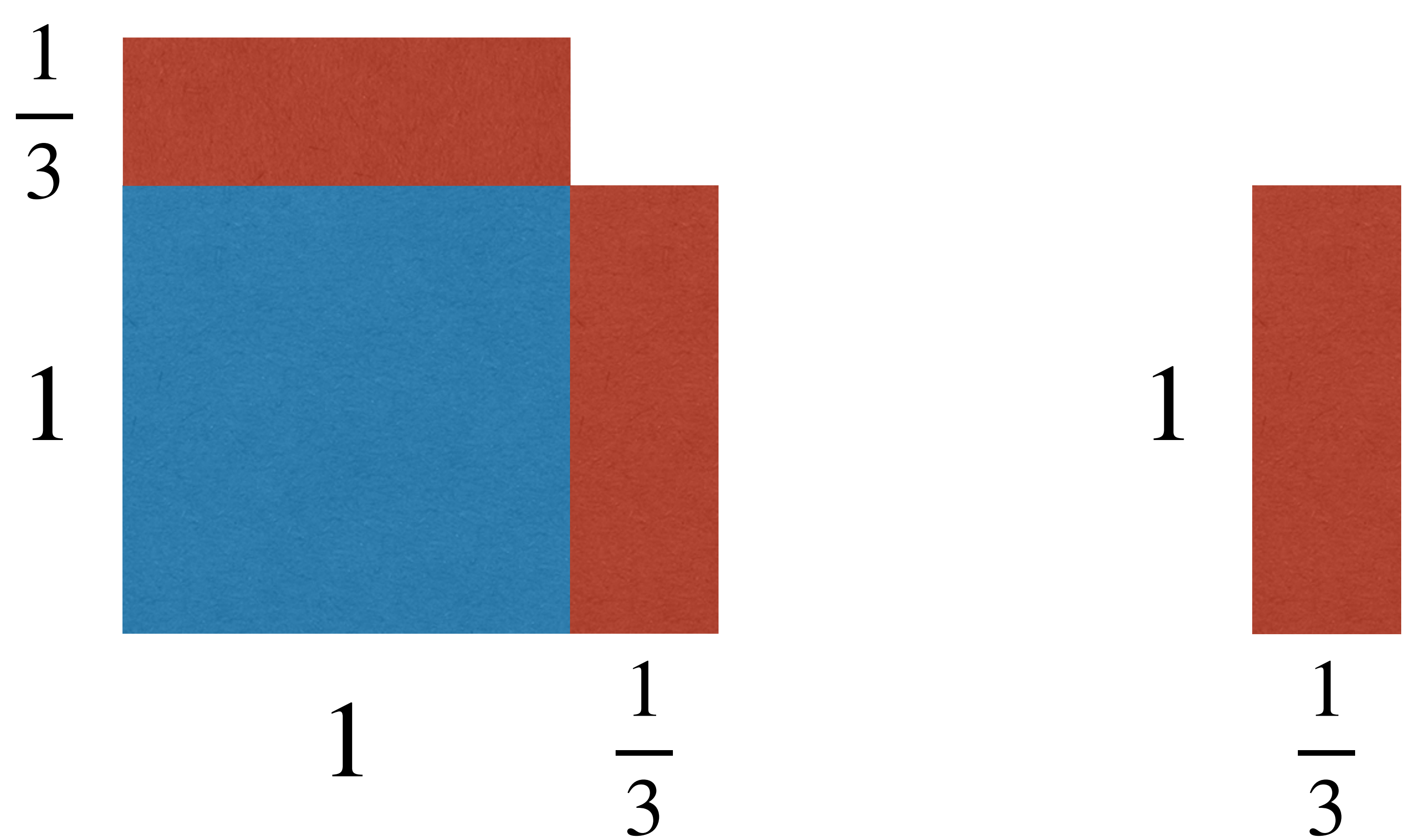


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

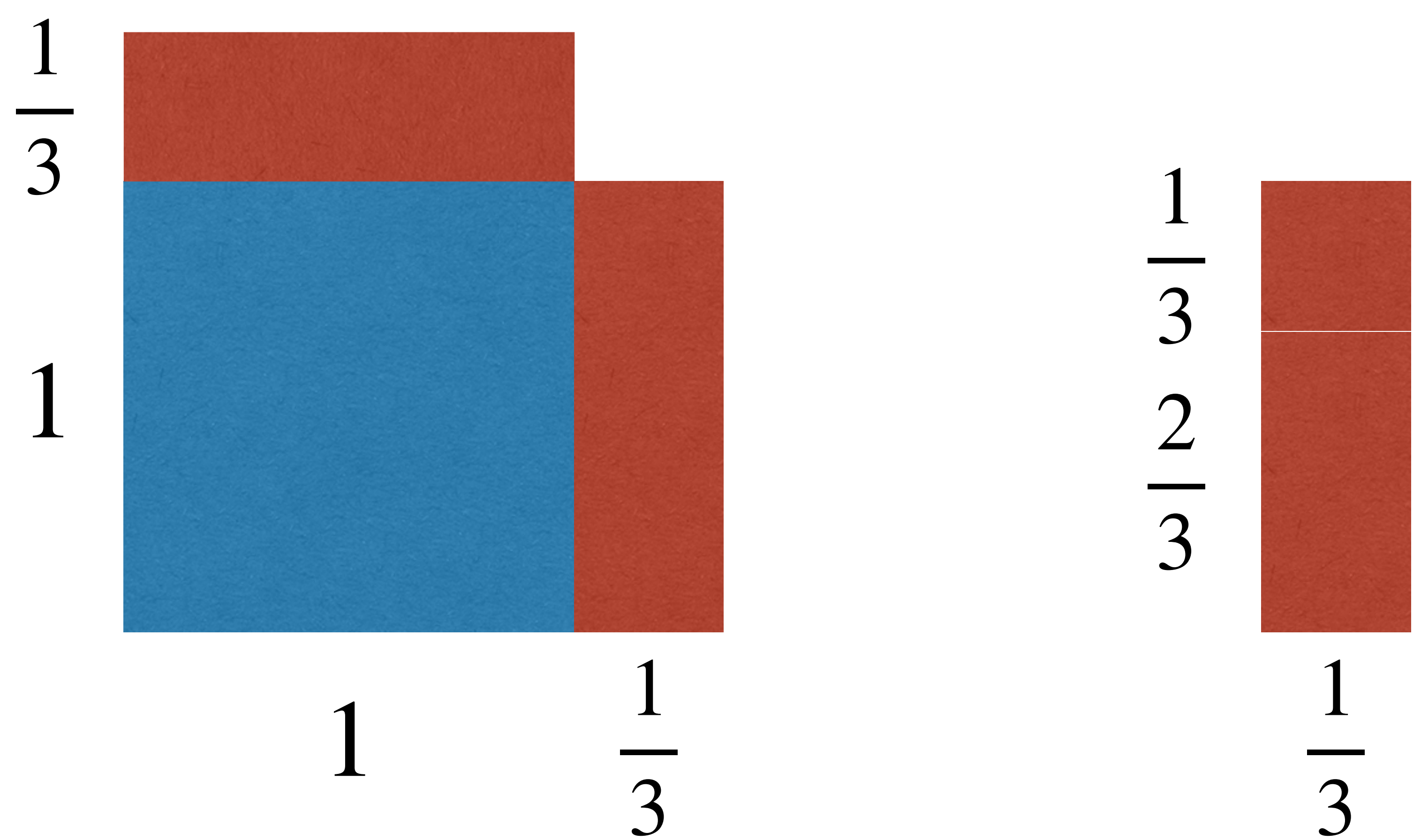


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

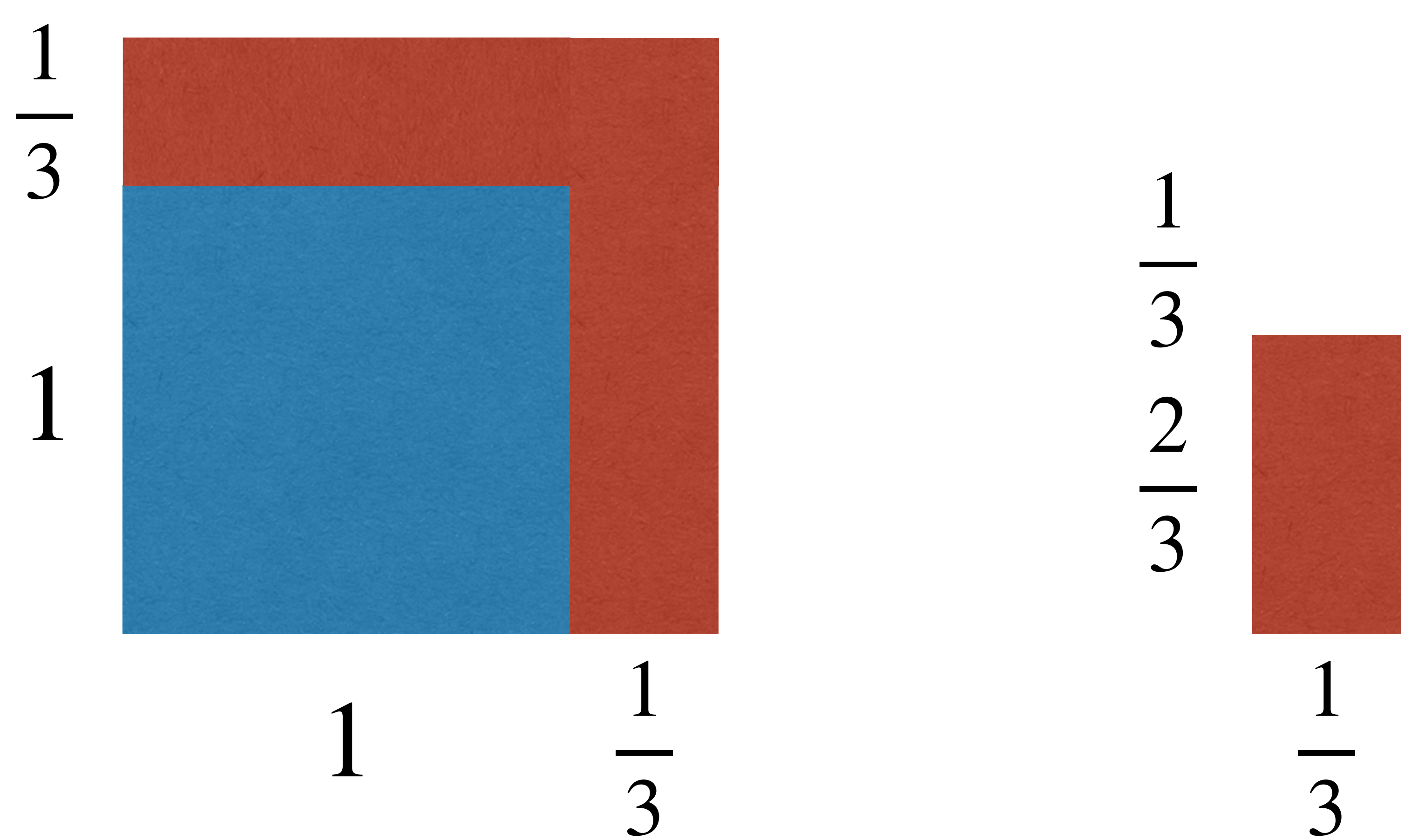


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

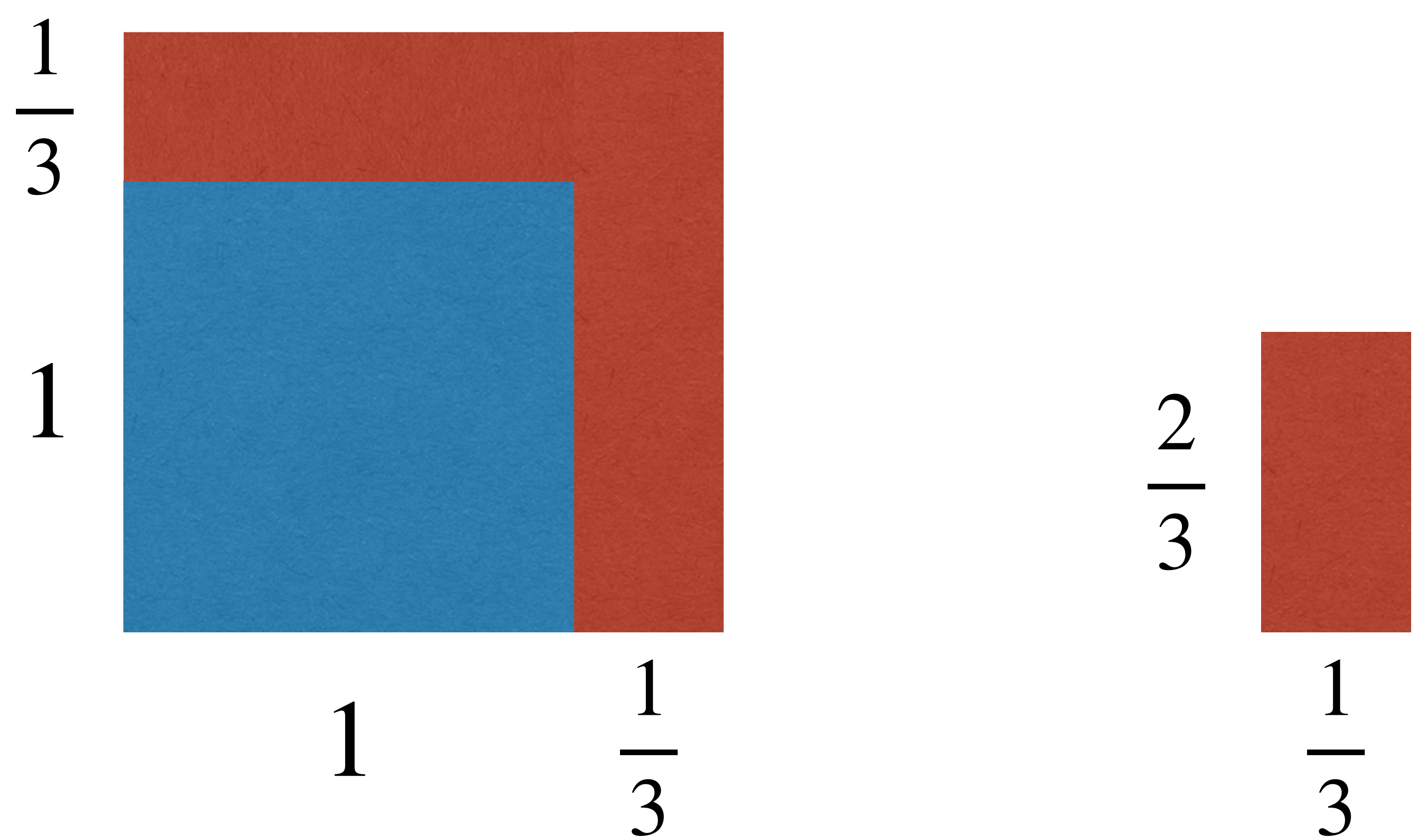


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Suppose you have two 1×1 squares

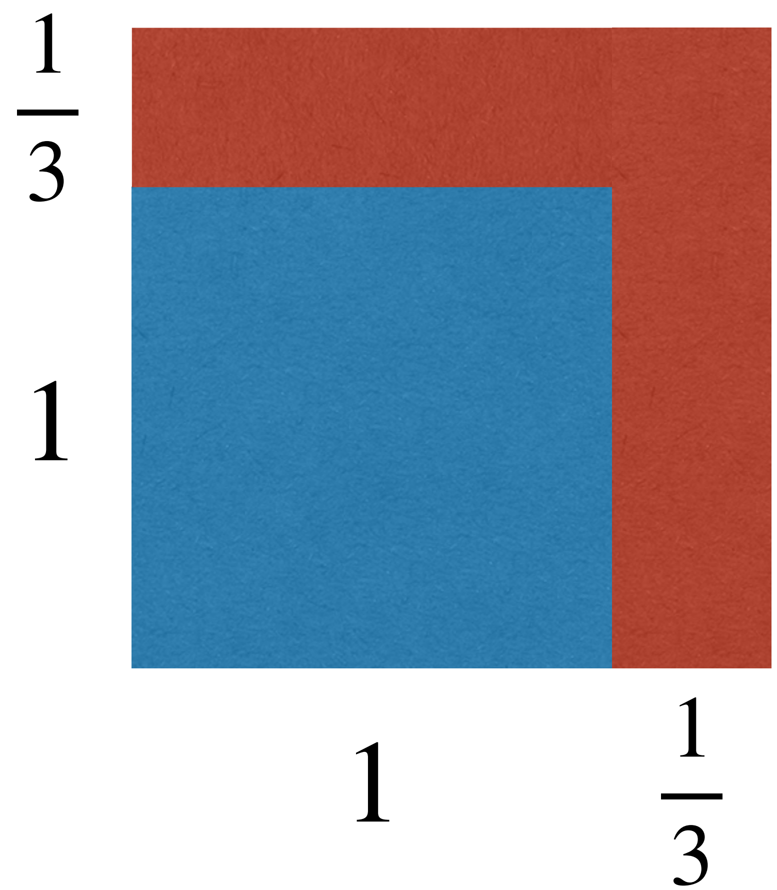


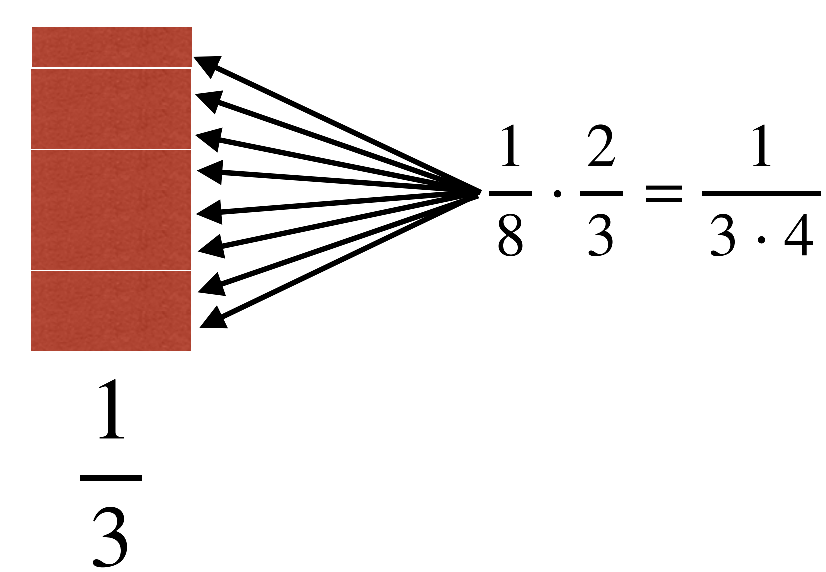
Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}\,.$$

Divide into 8 pieces



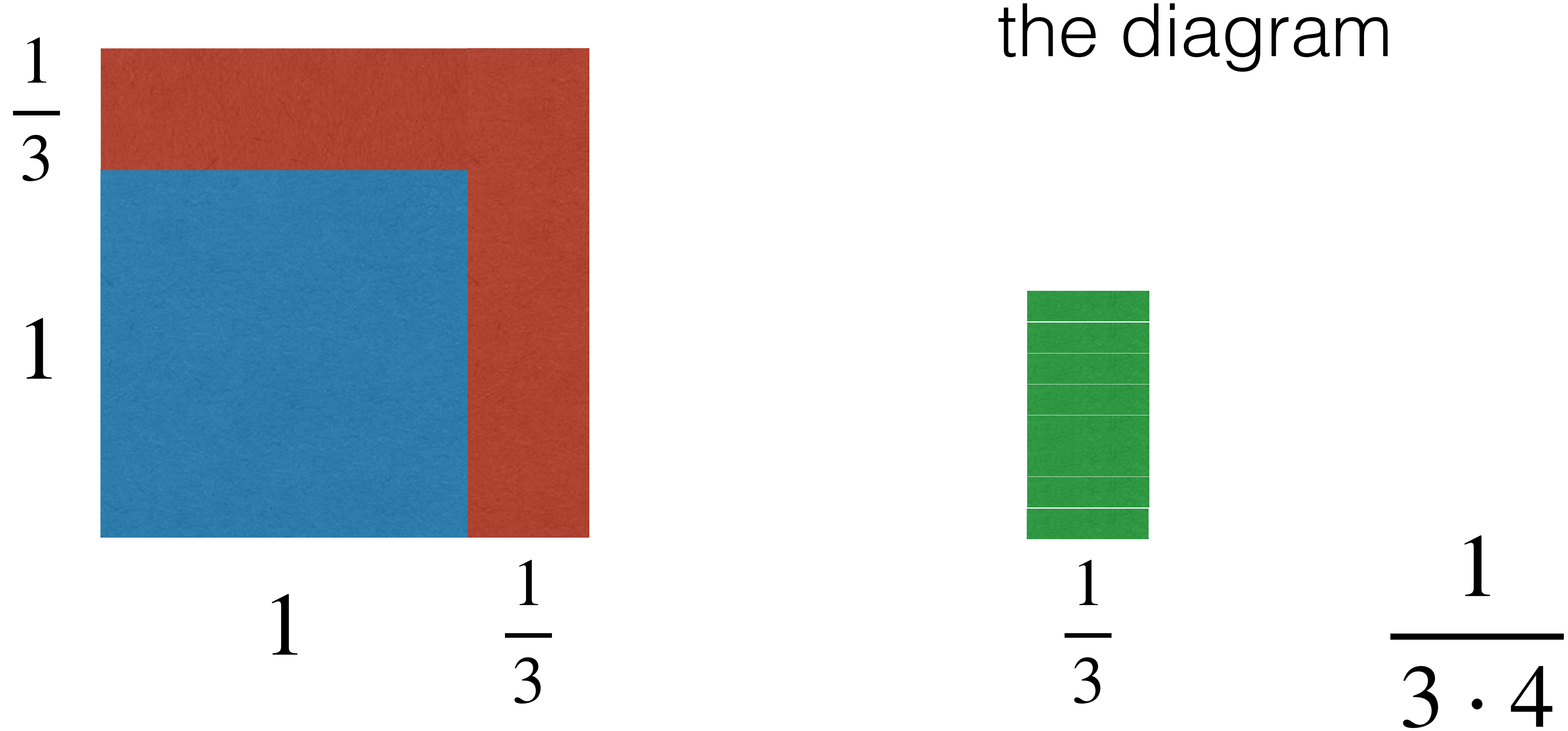


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Place them on the diagram

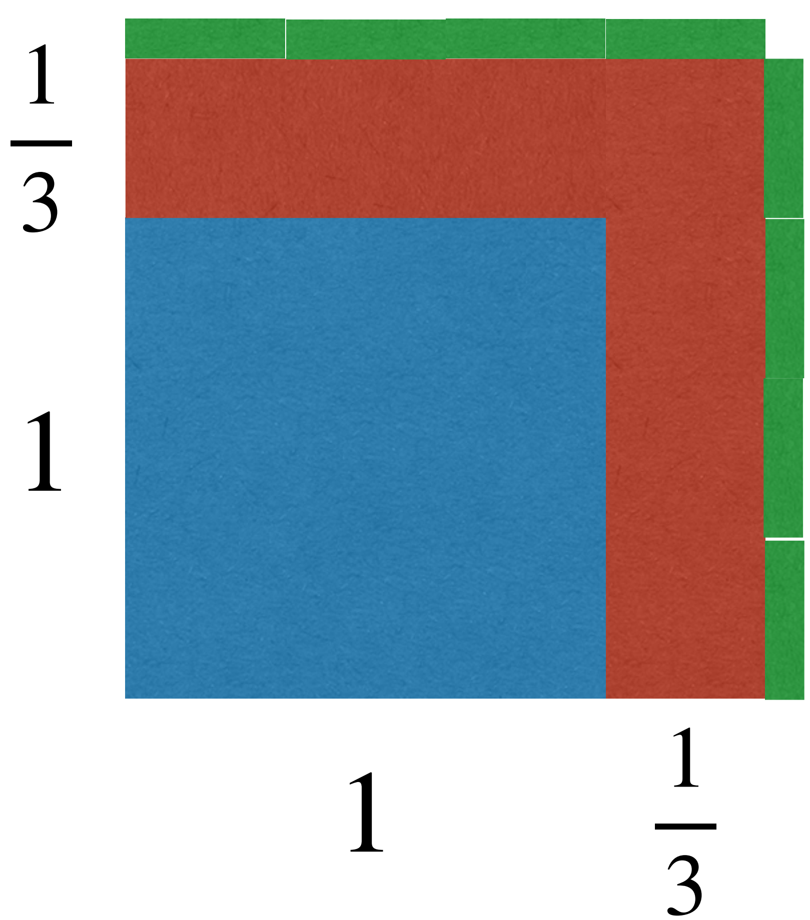


Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

Place them on the diagram

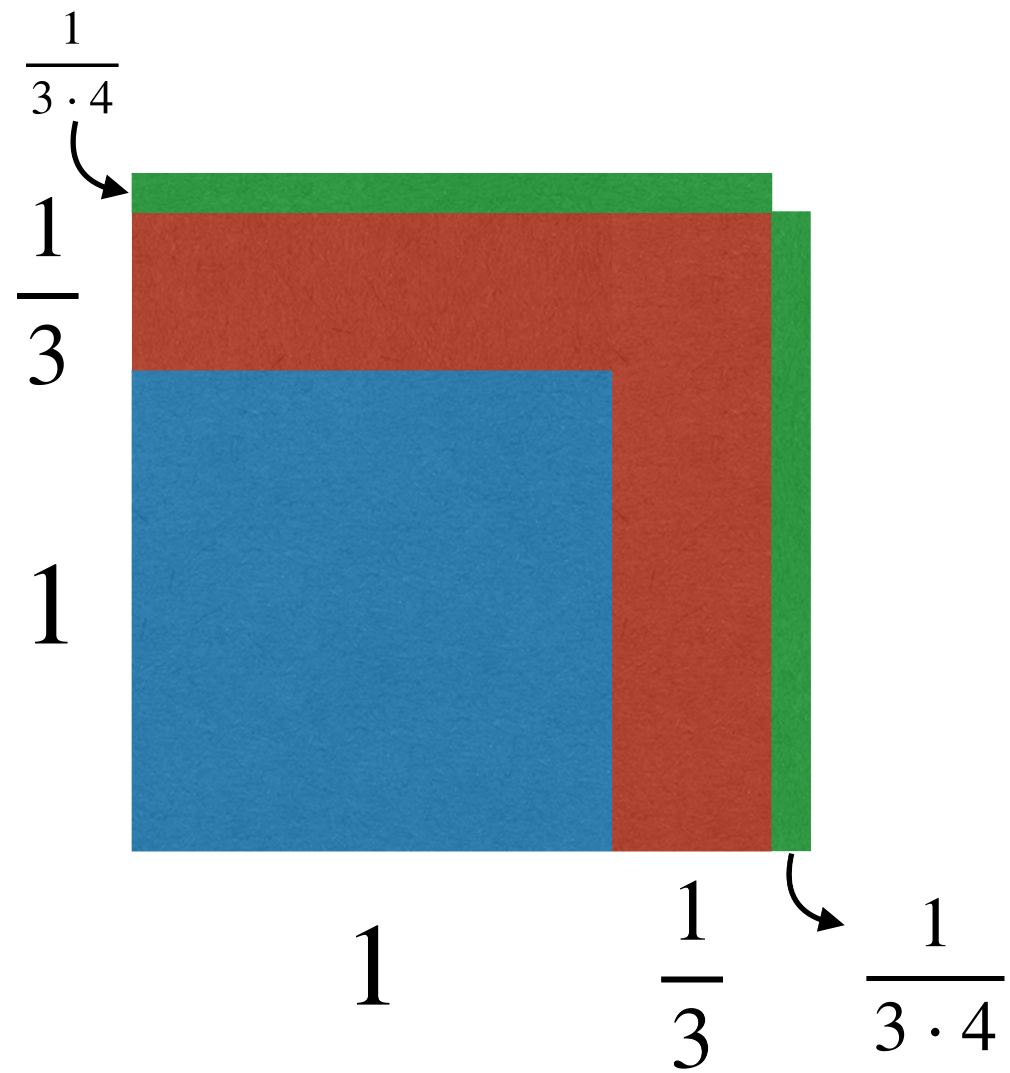


$\frac{1}{3}$ $\frac{1}{3 \cdot 4}$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

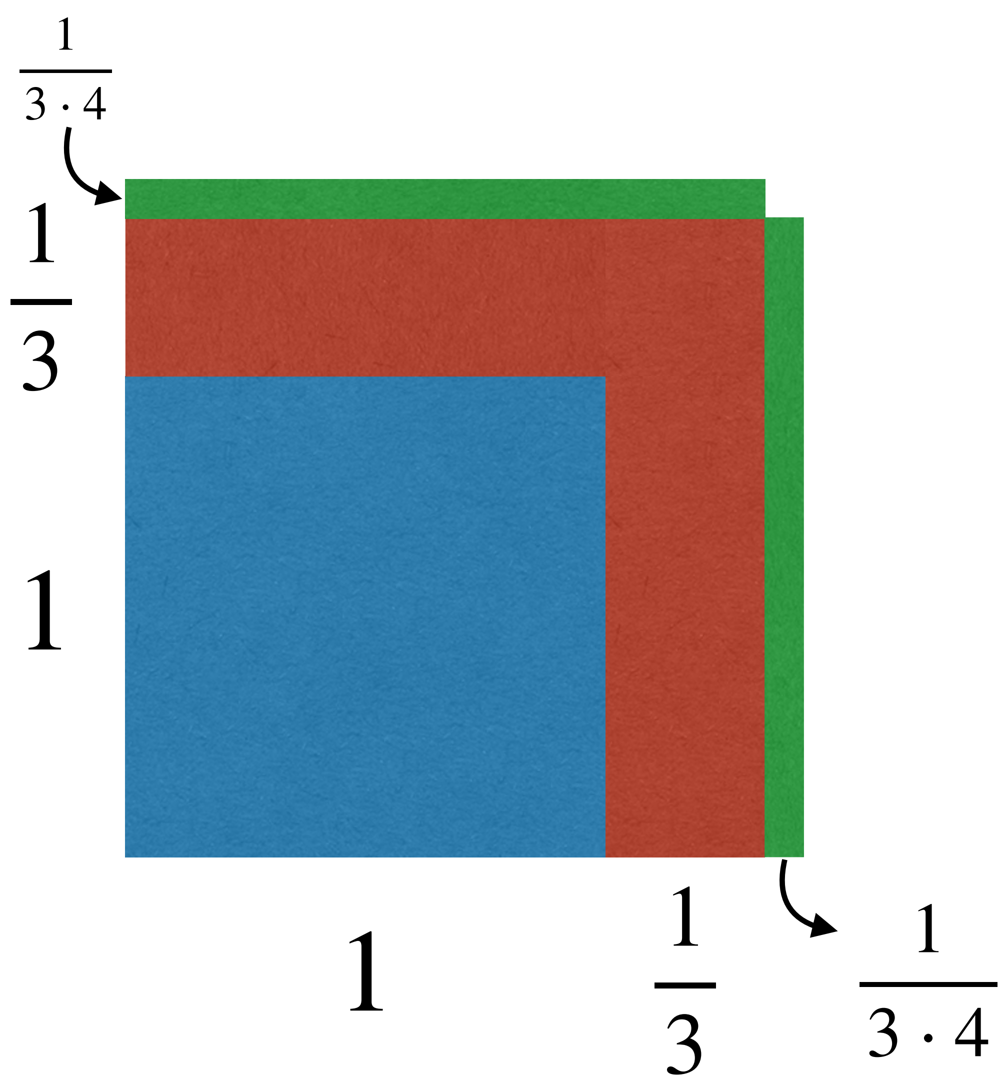


Place them on the diagram

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

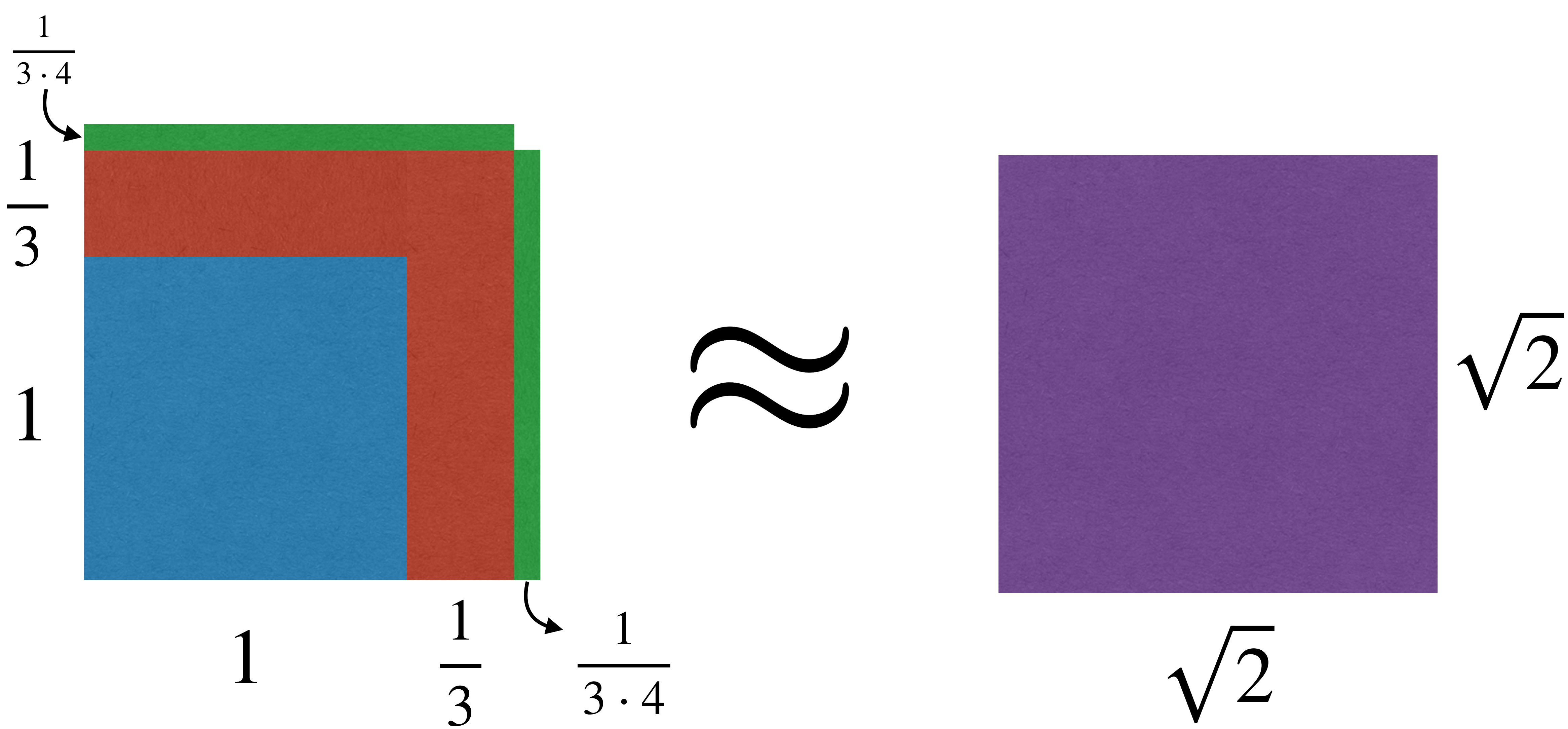


This is not a square, but it's close. And it does use all of the original two squares.

Approximating $\sqrt{2}$

- Goal:

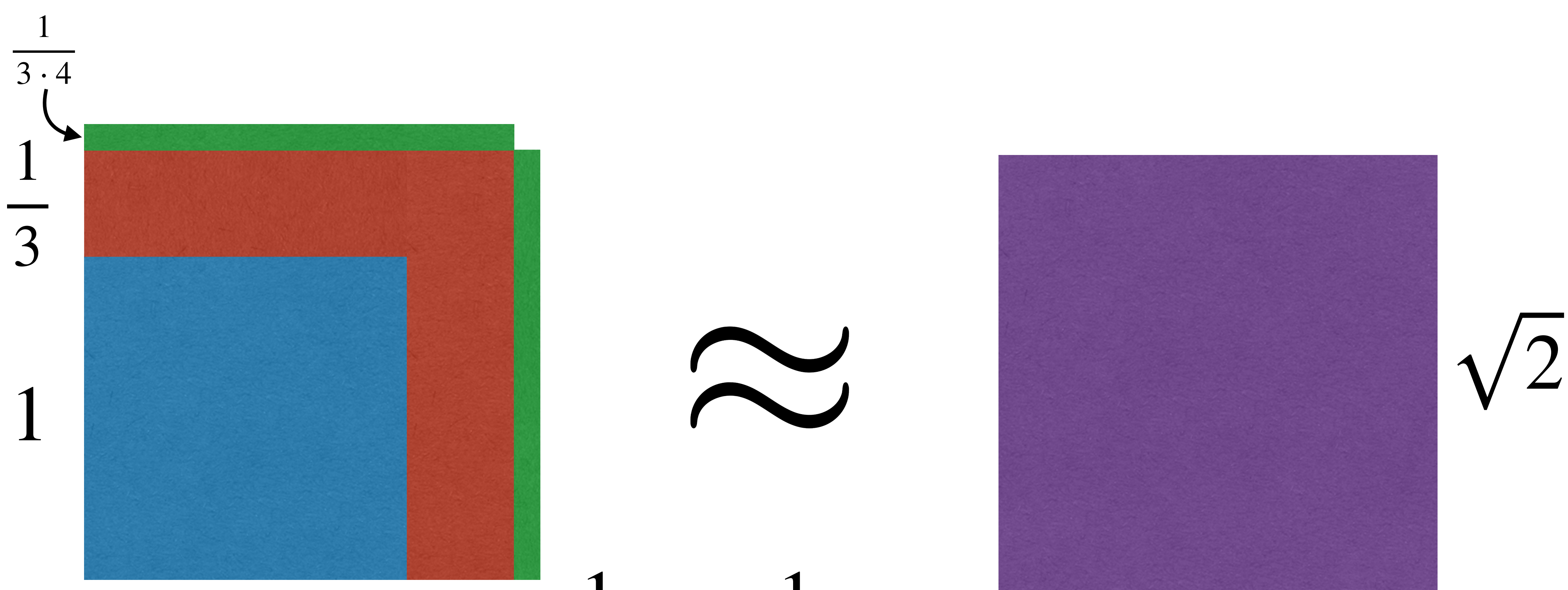
$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}\,.$$



Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}\,.$$

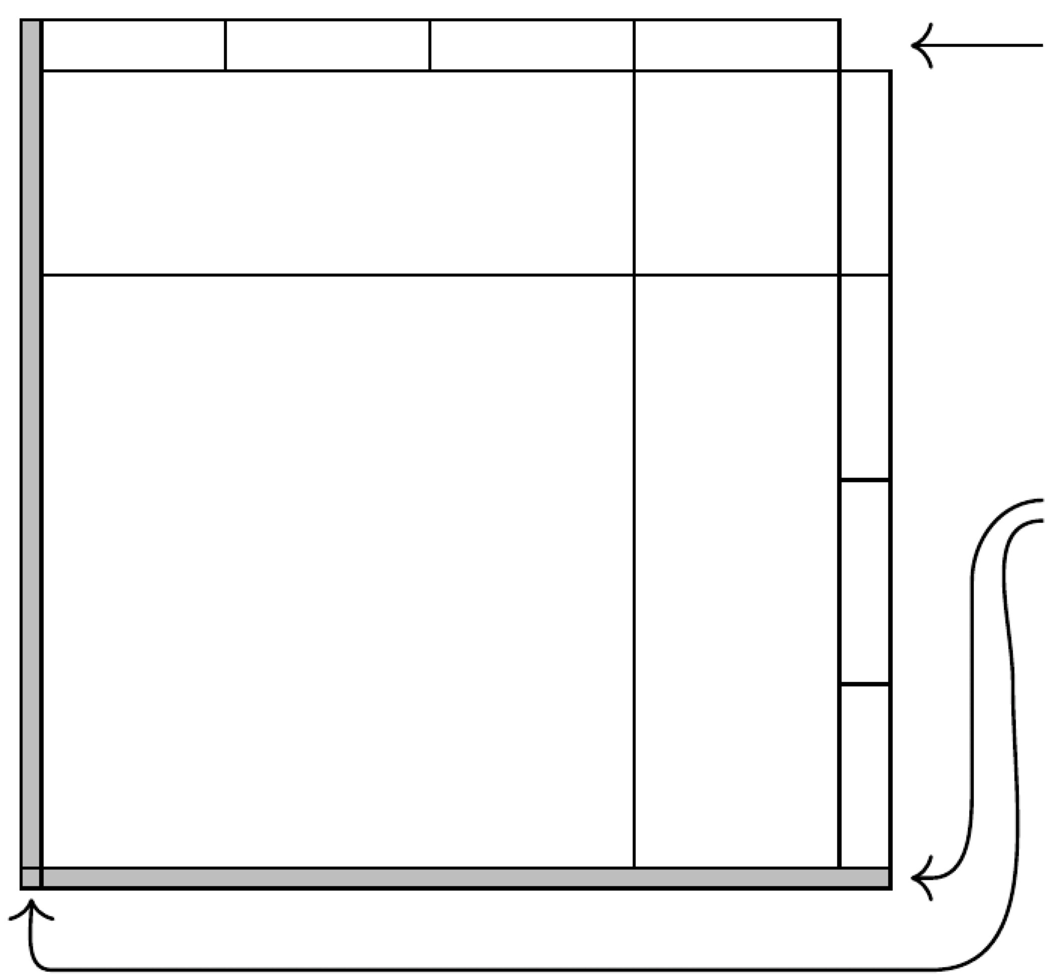


$$1 + \frac{1}{3} + \frac{1}{3 \cdot 4} \approx \sqrt{2}$$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$



$\longleftarrow$ Missing $\frac{1}{3\cdot4} \times \frac{1}{3\cdot4}$ square

Two shaded strips to cut off, to equal the area of the missing square

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

$$2 \cdot W \times \left(1 + \frac{1}{3} + \frac{1}{3 \cdot 4}\right) - W^2 = \frac{1}{3 \cdot 4} \times \frac{1}{3 \cdot 4}$$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}\,.$$

$$2 \cdot W \times \left(1 + \frac{1}{3} + \frac{1}{3 \cdot 4}\right) = \frac{1}{3 \cdot 4} \times \frac{1}{3 \cdot 4}$$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

$$2 \cdot W \times \left(1 + \frac{1}{3} + \frac{1}{3 \cdot 4}\right) = \frac{1}{3 \cdot 4} \times \frac{1}{3 \cdot 4}$$

$$\frac{2W(12 + 4 + 1)}{3 \cdot 4} = \frac{1}{3 \cdot 4 \cdot 3 \cdot 4}$$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}\,.$$

$$2 \cdot W \times \left(1 + \frac{1}{3} + \frac{1}{3 \cdot 4}\right) = \frac{1}{3 \cdot 4} \times \frac{1}{3 \cdot 4}$$

$$\frac{2W(12 + 4 + 1)}{3 \cdot 4} = \frac{1}{3 \cdot 4 \cdot 3 \cdot 4}$$

$$34W = \frac{1}{3 \cdot 4}$$

Approximating $\sqrt{2}$

- Goal:

$$\sqrt{2} \approx 1 + \frac{1}{3} + \frac{1}{3 \cdot 4} - \frac{1}{3 \cdot 4 \cdot 34}.$$

$$2 \cdot W \times \left(1 + \frac{1}{3} + \frac{1}{3 \cdot 4}\right) = \frac{1}{3 \cdot 4} \times \frac{1}{3 \cdot 4}$$

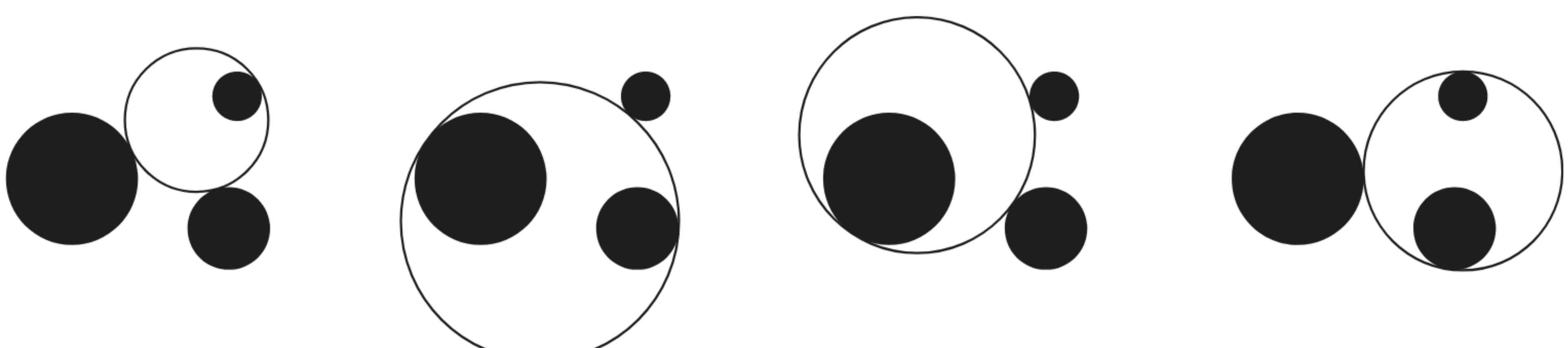
$$\frac{2W(12+4+1)}{3 \cdot 4} = \frac{1}{3 \cdot 4 \cdot 3 \cdot 4}$$

$$34W = \frac{1}{3 \cdot 4}$$

$$W = \frac{1}{3 \cdot 4 \cdot 34}. \quad \checkmark$$

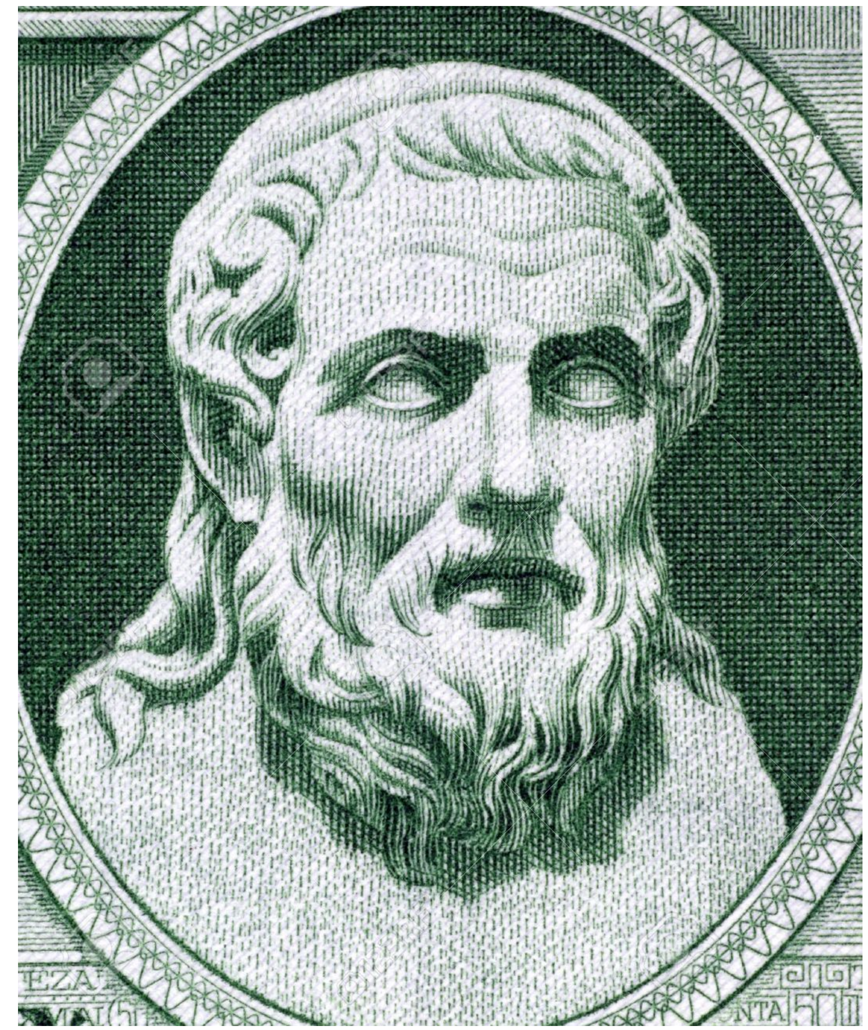
Shout-outs!

- Apollonius lived ~262-190 BC, modern-day Turkey.
- Wrote the text *Conic*. A major study in ellipses, parabolas, hyperbolas, and tangent lines.
- Apollonius problem: Given 3 circles, find a 4th circle tangent to all 3. (Solved in 1956.)

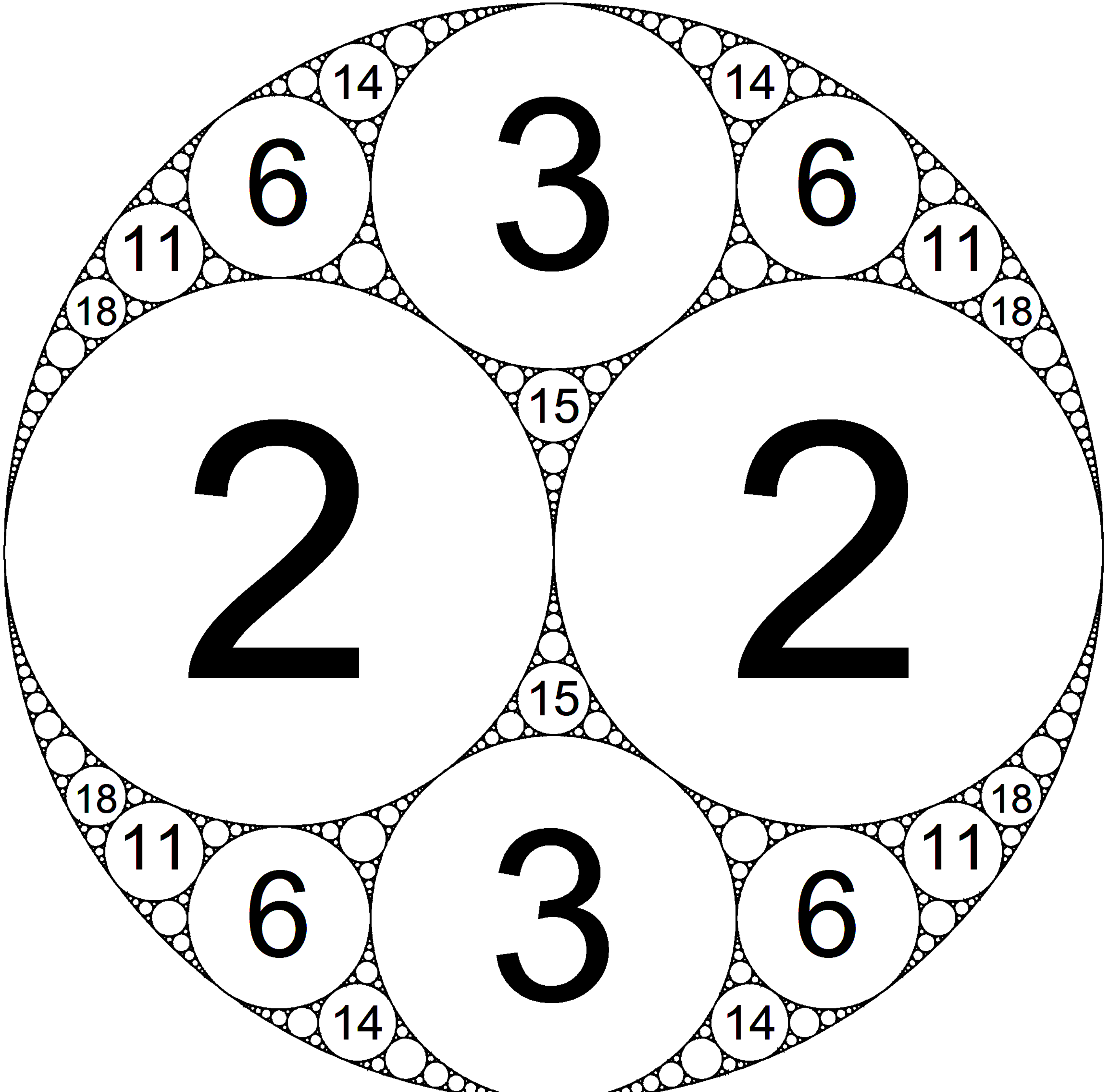


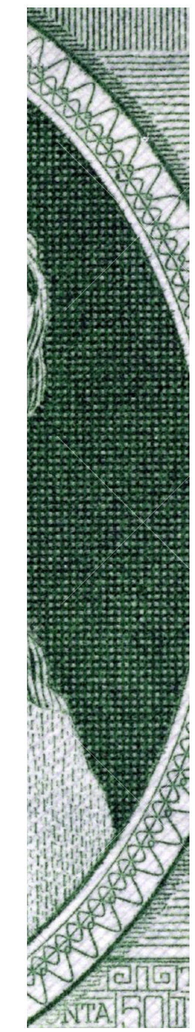
Shout-outs!

- A related problem is one of my favorite in all of math.

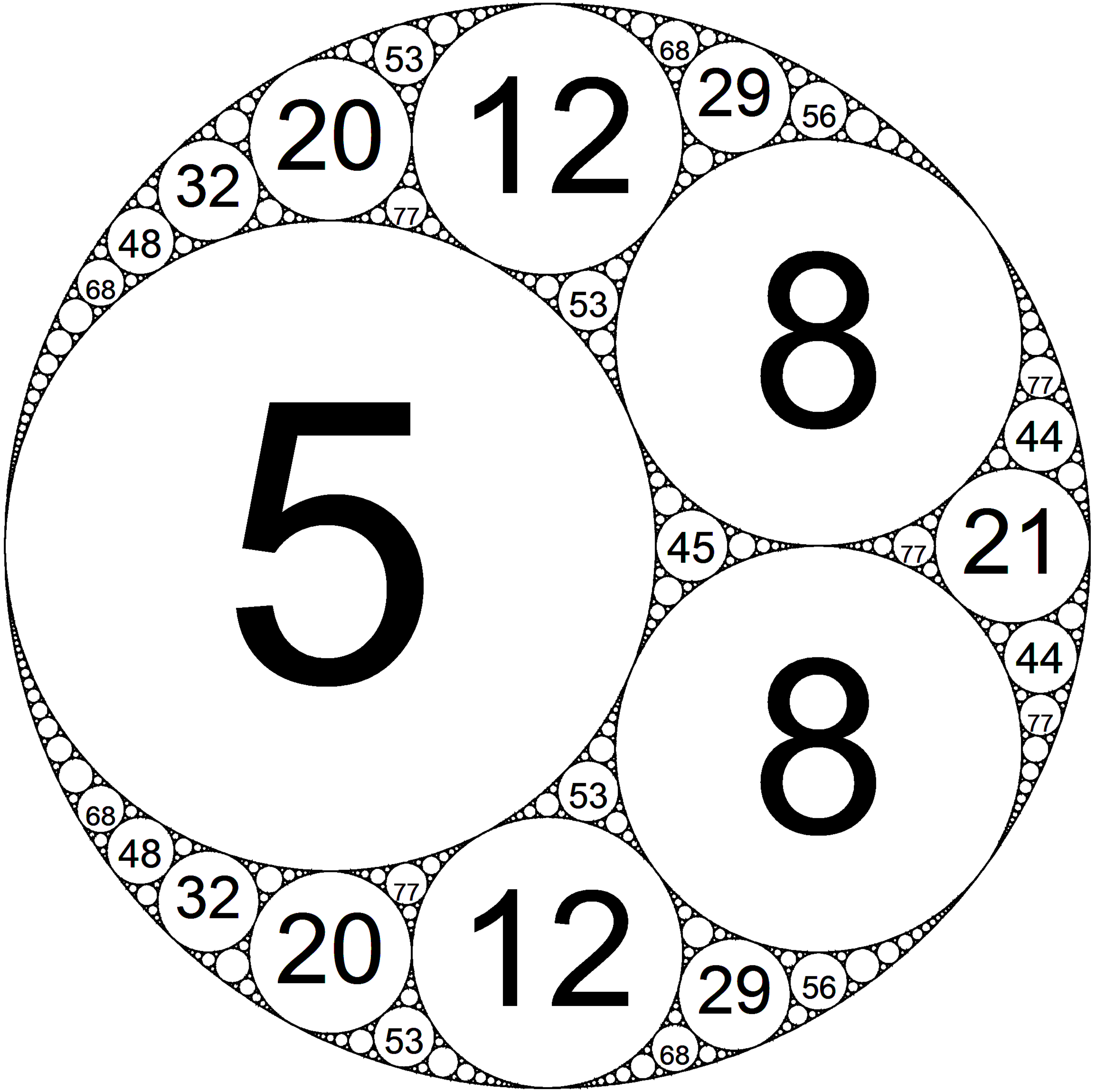


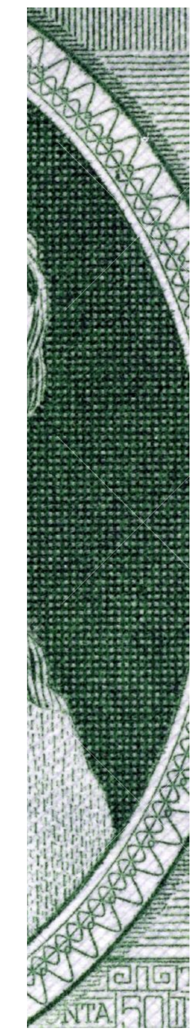
- A
  r



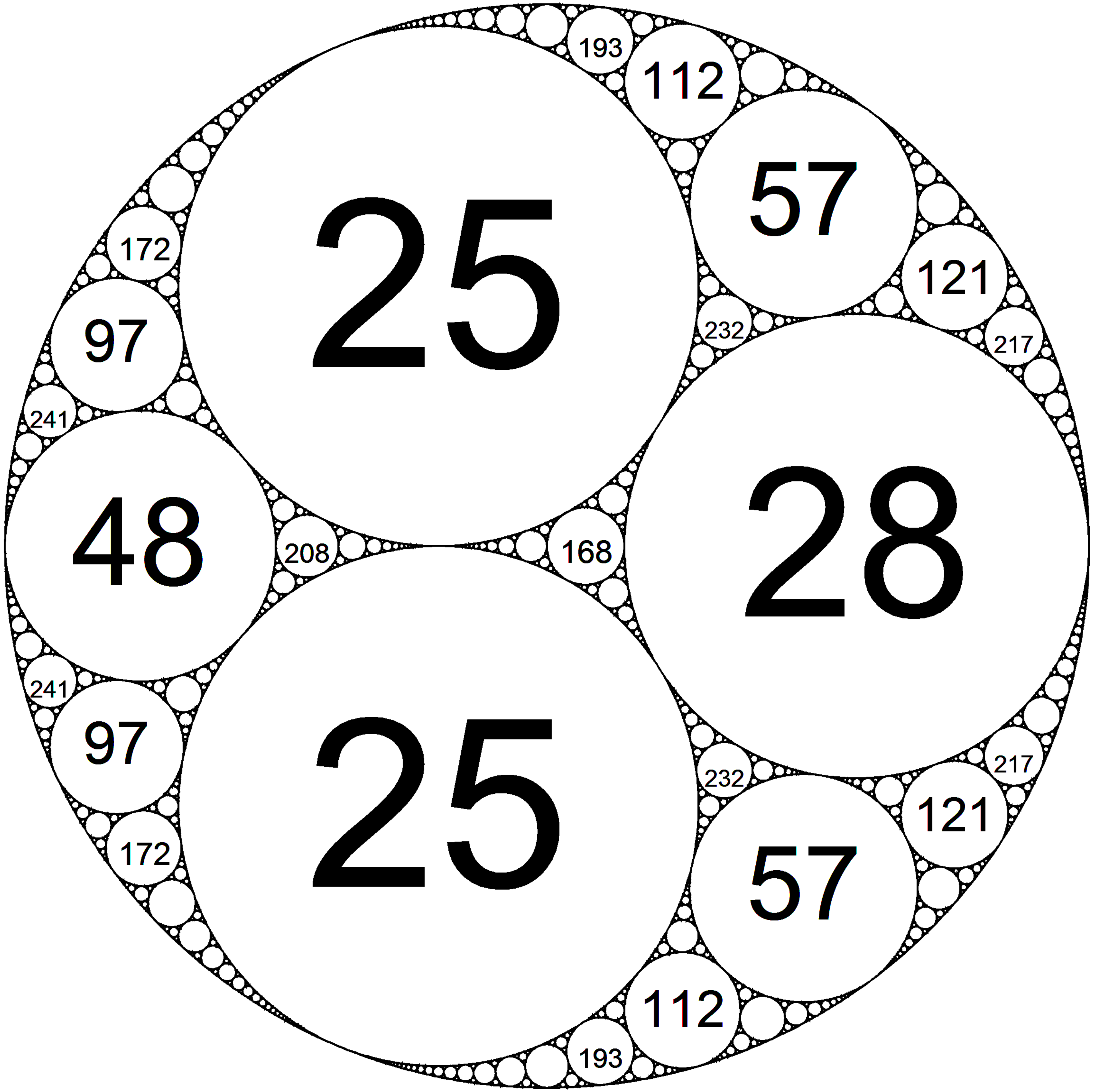


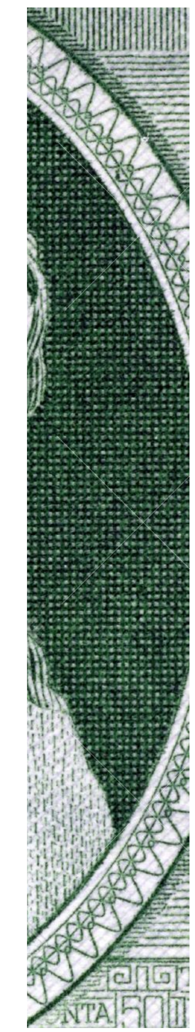
- A
  r


53
68
12
20
29
56
32
77
48
68
53
8
5
77
44
45
77
21
44
77
53
68
48
32
77
20
12
29
56
53
68

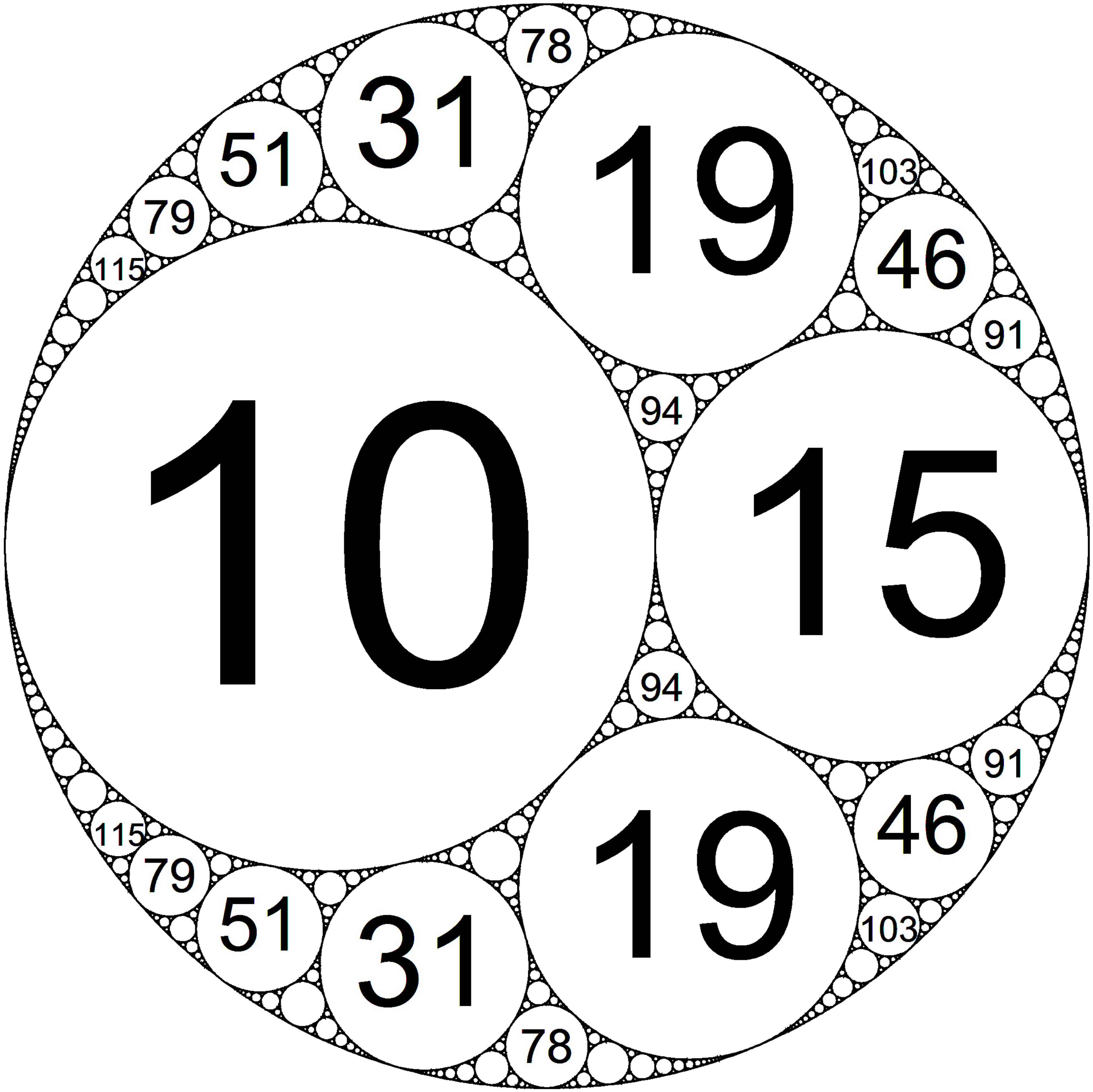

NTA

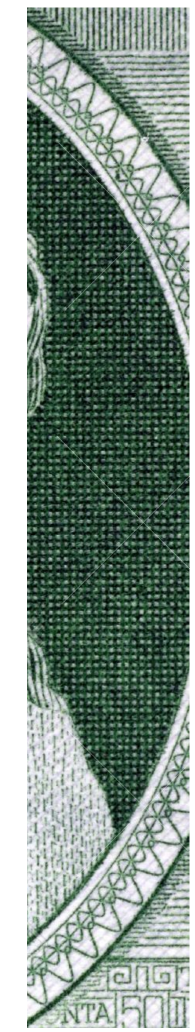
- A r


193
112
25
57
172
121
232
97
217
241
48
208
168
28
241
97
25
217
232
121
172
57
112
193

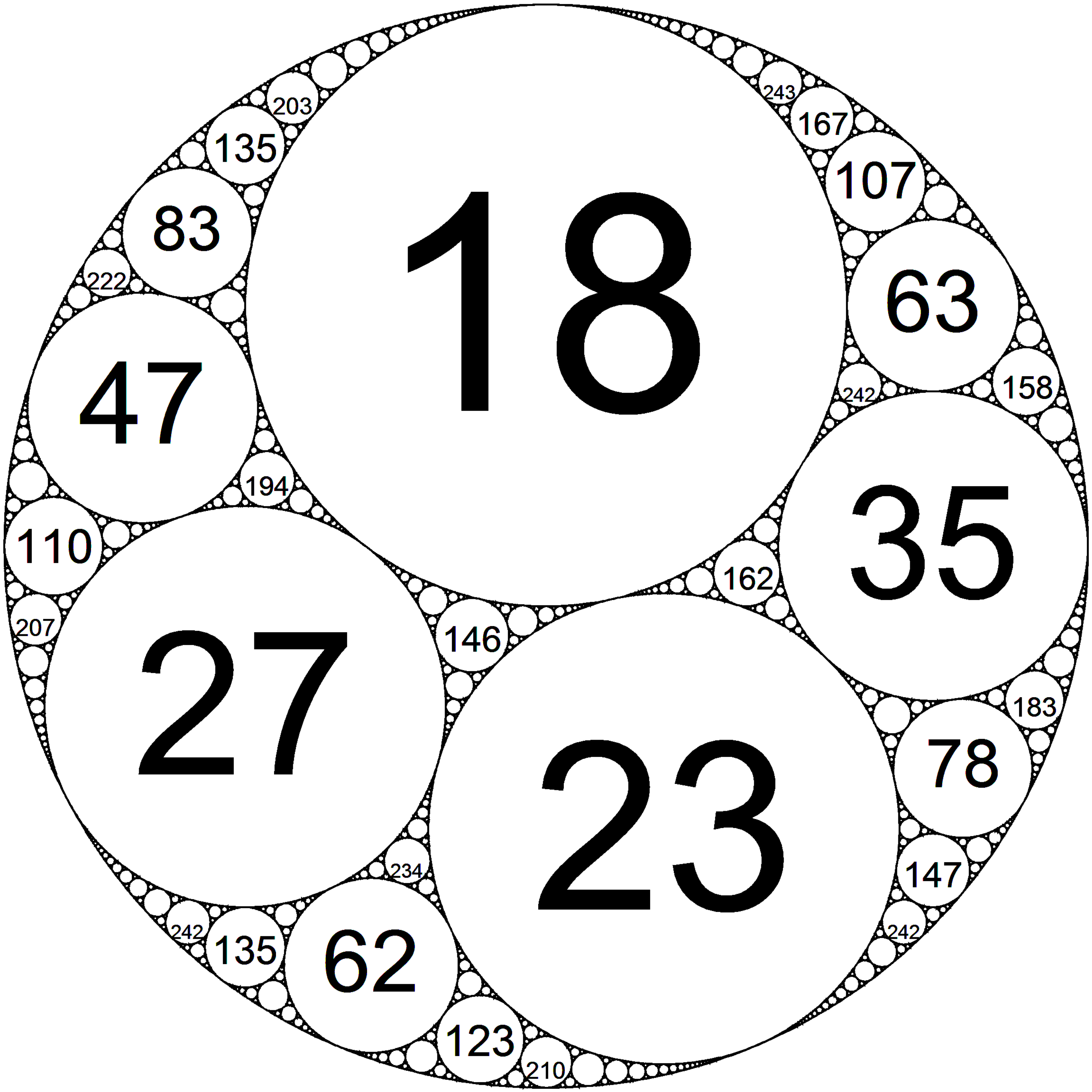


- A
  r

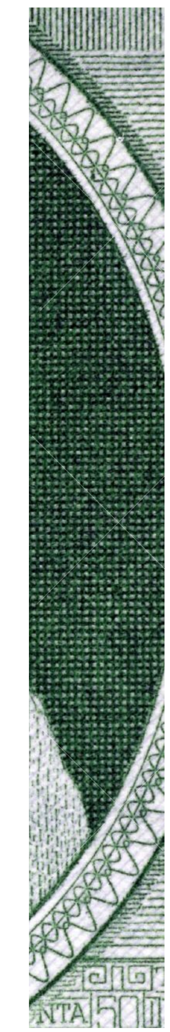




- A
  m



18
23
27
35
47
63
62
83
78
107
110
123
135
135
146
147
158
162
167
183
194
203
207
210
222
234
242
242
242
243



Shout-outs!

- Packing problems are still important areas of study.
- In the 17th century, Johannes Kepler conjectured that the most efficient way to pack spheres will result in about 75% of the volume being filled.
- This was proved in 1998 by Thomas Hales.

Shout-outs!

- In 2017, Maryna Viazovska generalized this to higher dimensions.

- Example: in 8 dimensions, only 25% of your space can be filled with hyperspheres. In 24 dimensions, only 0.1% of your space can be filled with hyperspheres.

- For her work, Viazovska won the 2022 Fields medal. She was the second woman in history to win it.

School of Athens

People’s History

People's History of Geometries