

# Knots and Fractals

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# Outline

- 1 Knot
- 2 Knot
- 3 Application of Knots
- 4 Fractals
- 5 Embedding into Menger Sponge
- 6 Embedding into Sierpinski Tetrahedron

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## What is a knot



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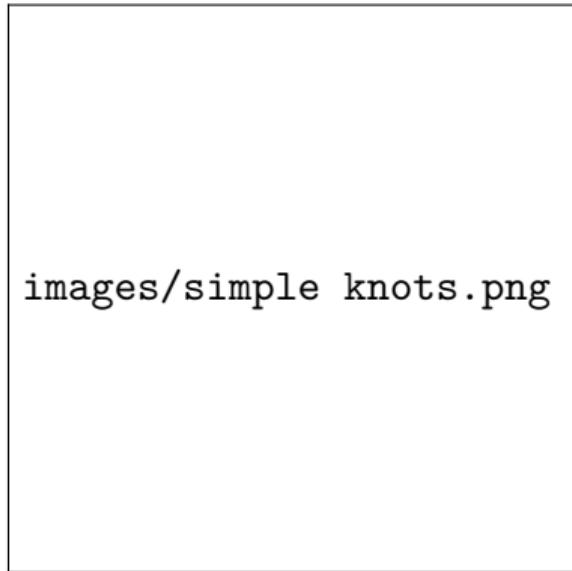
## What is a knot

- ▶ To study knots rigorously, we need to connect the two ends of the rope.

Definition In mathematics, a knot is an embedding of the circle  $S^1$  into 3-dimensional Euclidean space,  $\mathbf{R}^3$ .

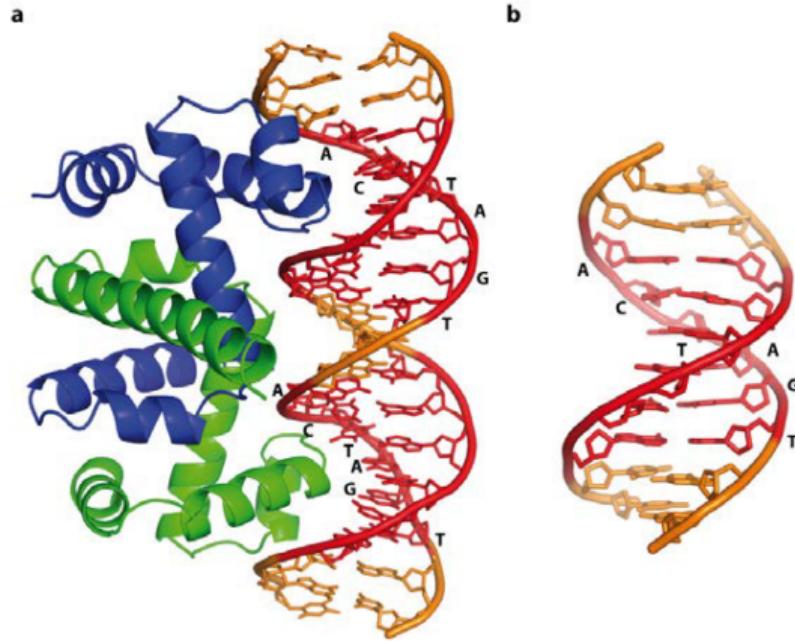
## Motivation

- ▶ Peter Guthrie Tait and Lord Kelvin (19th century): During the research on composition of atoms, they conjectured that atoms are made out of vortex ring of ether.



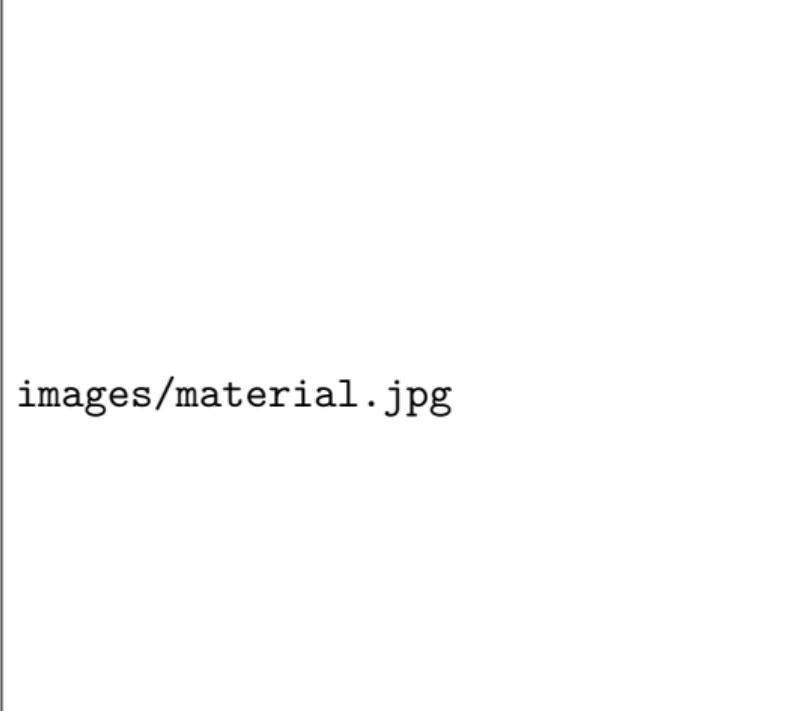
# Motivation

- ▶ The structure of protein and DNA



# Motivation

- ▶ The knot structure of material



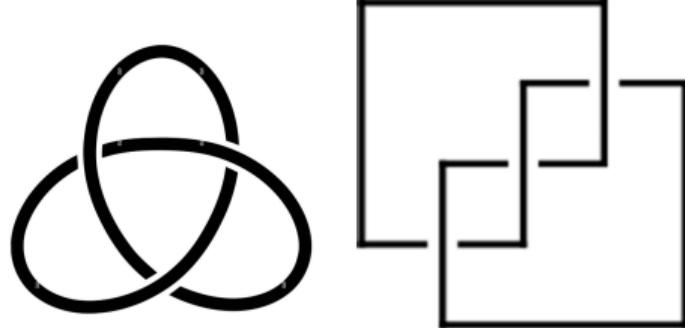
images/material.jpg

## Diagram

- ▶ How to represent a knot? Regular projection.
- ▶ A knot projection is called a regular projection if no three points on the knot project to the same point, and no vertex projects to the same point as any other point on the knot.

## Diagram

- ▶ A knot diagram is the regular projection of a knot to the plane with broken lines indicating where one part of the knot undercrosses the other part.



## Reidemeister move

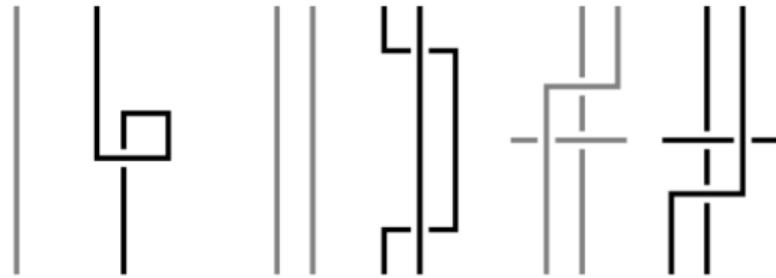
- ▶ Equivalence of knot?



images/equivalence.png

## Reidemeister move

- ▶ A Reidemeister move is an operation that can be performed on the diagram of a knot without altering the corresponding knot.



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## Alternating Knots

In these types of knots, if you follow any strand in any direction you switch between upside and downside at any crossing.

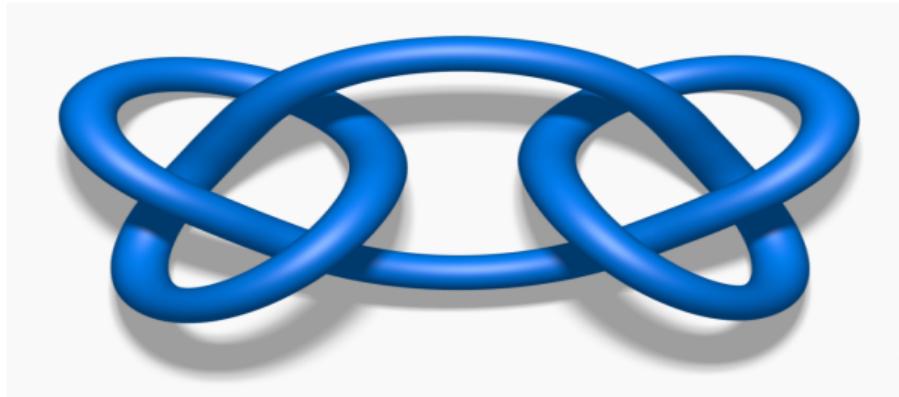


Figure: An alternating knot

(<https://math.stackexchange.com/users/24947/adam-lowrance>), n.d.

## Rational Knots

Rational knots are obtained by closing off the edges of rational tangles. A tangle is a region in a knot that is separated from the knot by a circle and has four outgoing strands crossing the circle.

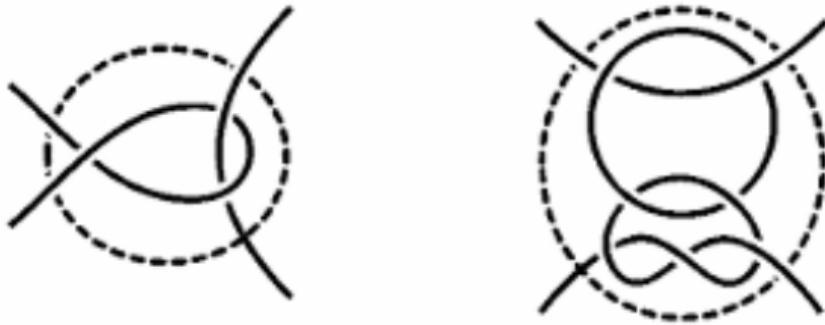
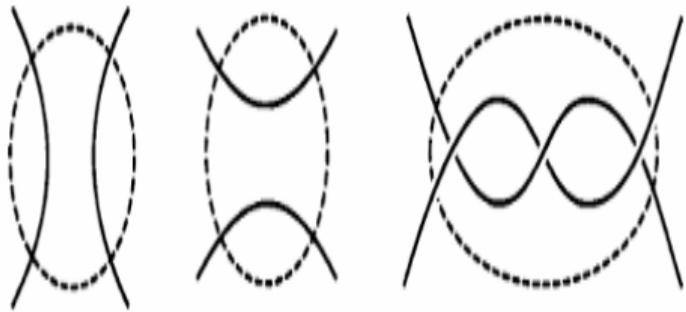


Figure: Tangles

Adams, 2004



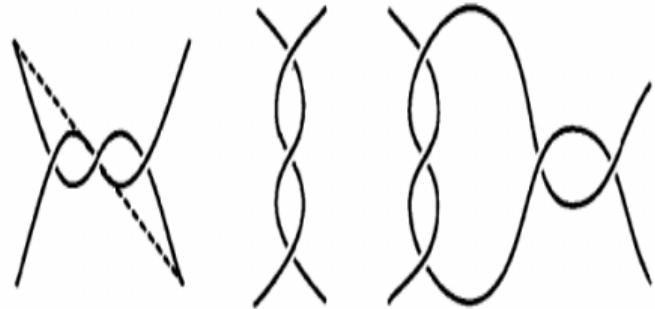
a

b

c

Figure:  $\infty$ , 0 and 3 tangles, they are fundamental

Adams, 2004

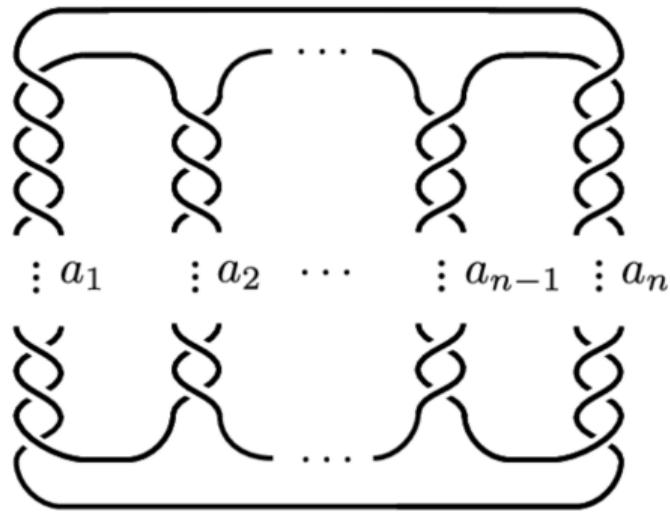


32

Figure: Generating Tangles

## Pretzel Knots

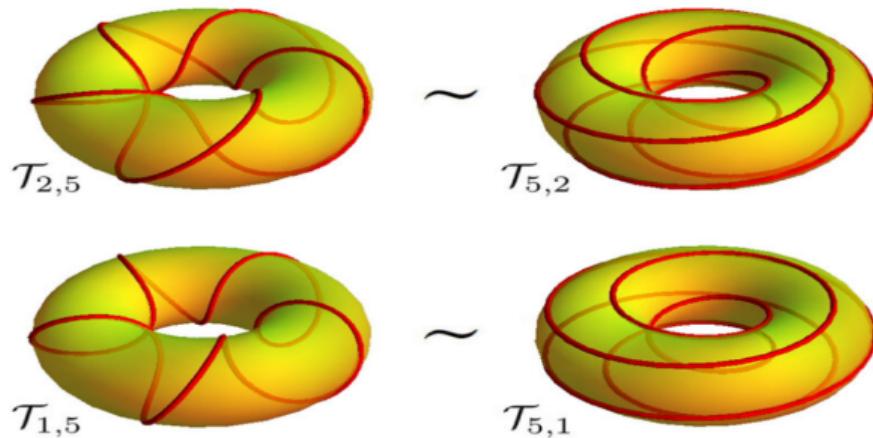
Pretzel knots are rational knots that are obtained by adding up rational tangles. If every term of a rational knot  $klm$  (for instant 311) is multiplied with 0 and the result is a pretzel knot that is denoted by  $k,l,m$  (3,1,1)



Komendarczyk and Michaelides, 2016

## Torus Knots

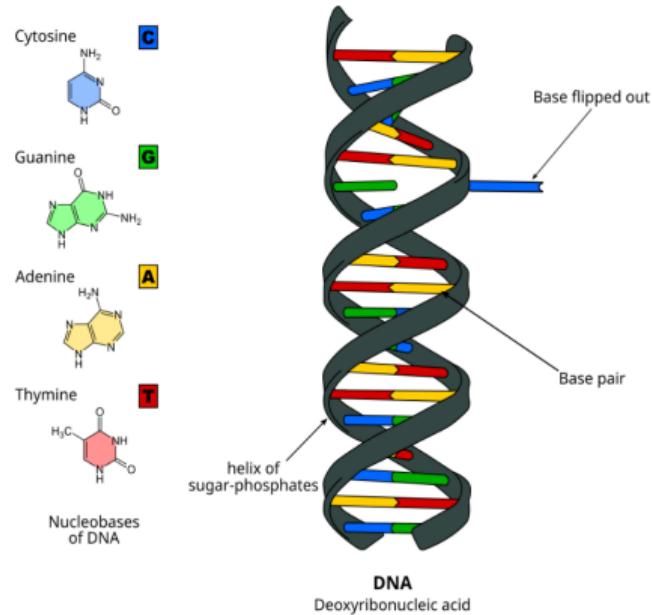
These knots are wrapped around unknotted tori and do not cross themselves as they move around their tori. There are 'short' paths called meridian and 'long' paths called longitude. A  $(p,q)$ -torus knot crosses the longitude  $p$  times and crosses meridians  $q$  times.



Oberti and Ricca, 2017

# Knots and Biology

en.wikipedia.org, n.d.



Adams, 2004



- ▶  $\text{Tw}(R)$ : Twist of the ribbon. Average of crossings over the axis
- ▶  $\text{Wr}(R)$ : Writhe of the ribbon. Average of crossings of the axis from every projection it is

$$\frac{\int \text{signed-crossover-number} \cdot dA}{\int dA}$$

- ▶  $\text{Lk}(R)$ : Linking number
- ▶  $\text{Lk}(R) = \text{Tw}(R) + \text{Wr}(R)$

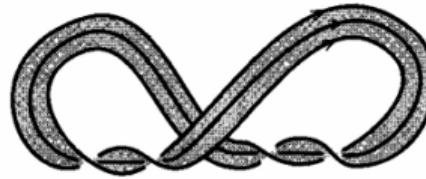
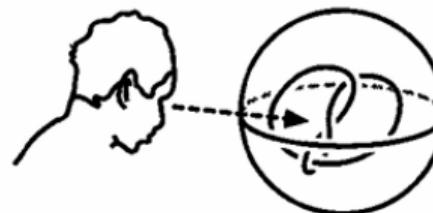


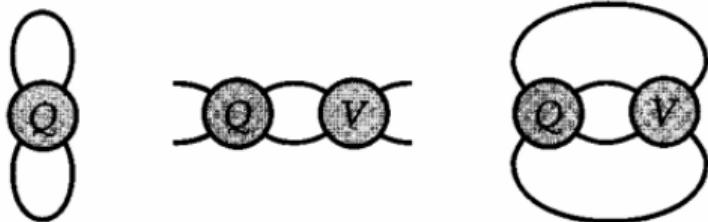
Figure: Axis

Adams, 2004

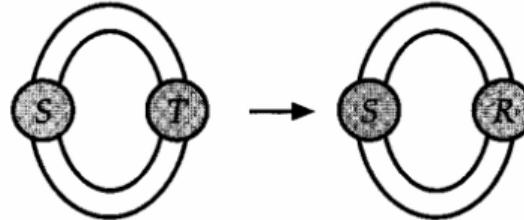


Adams, 2004

- ▶ S: Substrat tangle
- ▶ T: Site tangle
- ▶ R: Recombination tangle
- ▶ N(Q): Converting tangle to a knot or a link
- ▶  $N(S + T) = N(1)$  (unknot)
- ▶  $N(S + R) = N(2)$  (Hopf link)
- ▶  $N(S + R + R) = N(211)$  (figure-eight knot)
- ▶  $N(S + R + R + R) = N(1111)$   
(Whitehead link)



Adams, 2004



Adams,

2004

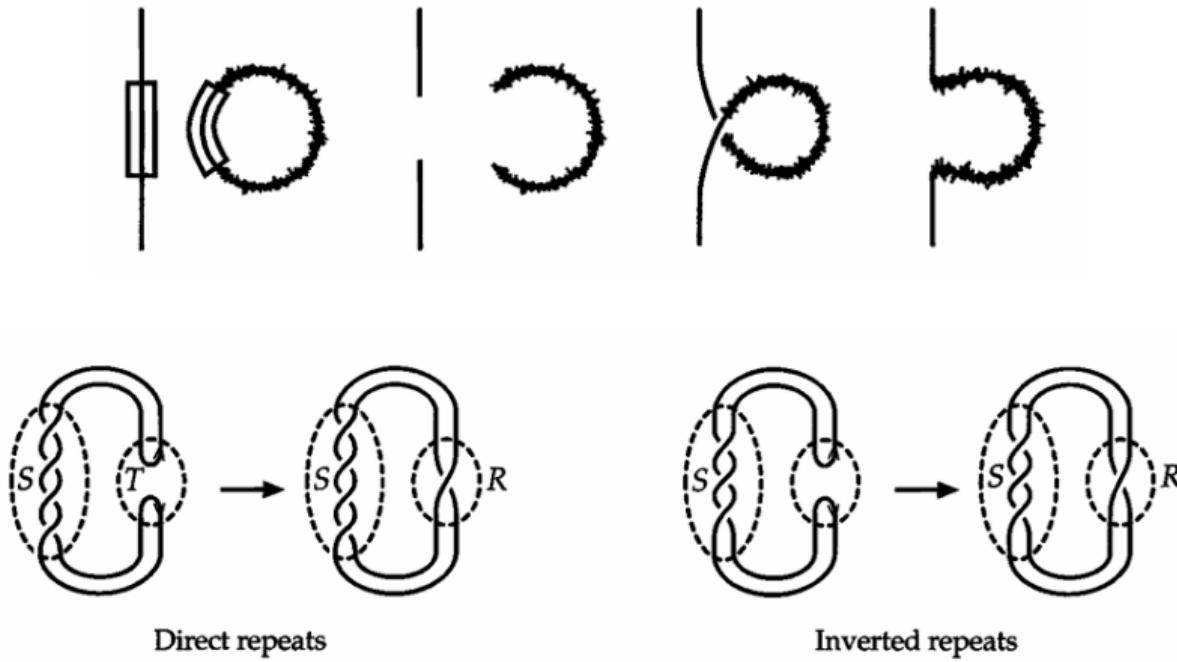


Figure: Effects of Int enzyme

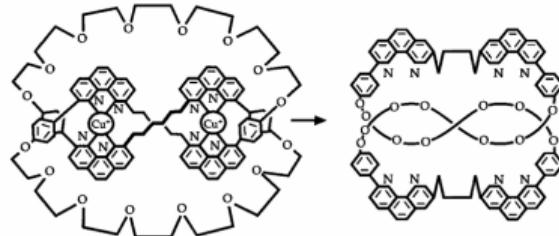
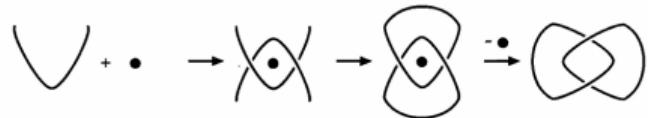
Adams, 2004

# Knots and Chemistry



Figure: Homeomorphic but not isotopic molecules

Adams, 2004



Adams, 2004

## Knots and Topology

Poincaré Conjecture: Every three-dimensional topological manifold which is closed, connected, and has trivial fundamental group is homeomorphic to the three-dimensional sphere.

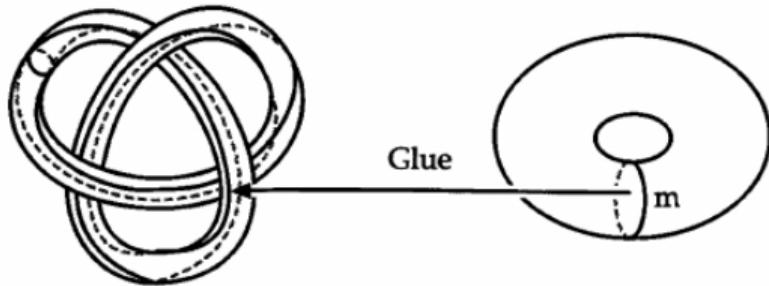


Figure: Dehn Surgery

Adams, 2004

## Open Problems

- ▶ Could there be a constant  $c$  such that for any knot  $K$  and for any two projections  $P_1$  and  $P_2$  of  $K$ , each with no more than  $n$  crossings, one can get from one projection to the other by Reidemeister moves without ever having more than  $n + c$  crossings at any intermediate stage?
- ▶ Find all of the 14-crossing prime knots.
- ▶ Show that the number of distinct prime  $(n + 1)$ -crossing knots is greater than the number of distinct prime  $n$ -crossing knots, for each positive integer  $n$ .
- ▶ Is it true that a knot with unknotting number  $n$  cannot be a composite knot with  $n + 1$  factor knots?
- ▶ Show that the crossing number of a composite knot is the sum of the crossing numbers of the factor knots, that is,  $c(K_1 K_2) = c(K_1) + c(K_2)$

Adams, 2004

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6 Embedding into Sierpinski Tetrahedron

# Application

- ▶ Medicine
  - Identifying tumors in brain MR images Iftekharuddin et al., 2003
  - Diabetic retinopathy, etc. : blood vessel's diameter Uahabi and Atounti, 2015
- ▶ Economics
  - Market properties, price fluctuation, money flow. Takayasu and Takayasu, 2009
- ▶ Geology and Ecology
  - Landscape patterns, vegetation structure, animal habitats. Loehle and Li, 1996
- ▶ Computer science
  - Image encryption. Sangavi and Thangavel, 2019
  - Computer graphics. Sala, 2021
- ▶ Architecture
  - Combining aesthetics and functionality. Lorenz, 2002

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## Knots Inside the Menger Sponge

What is a knot in the Menger Sponge?

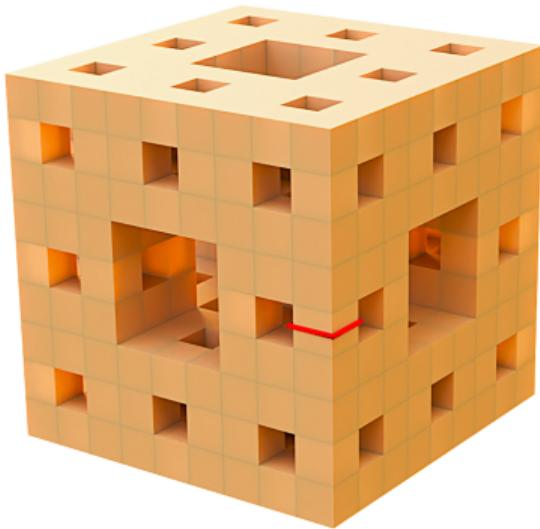
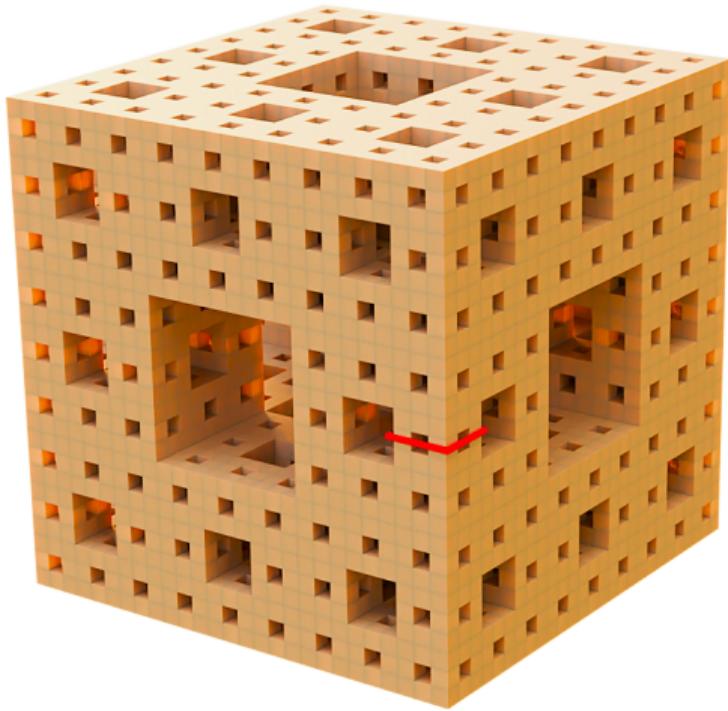


Figure: The Unknot?

# Not a Knot!



## Knot or Not?

- ▶ Does the following knot live on the fractal?

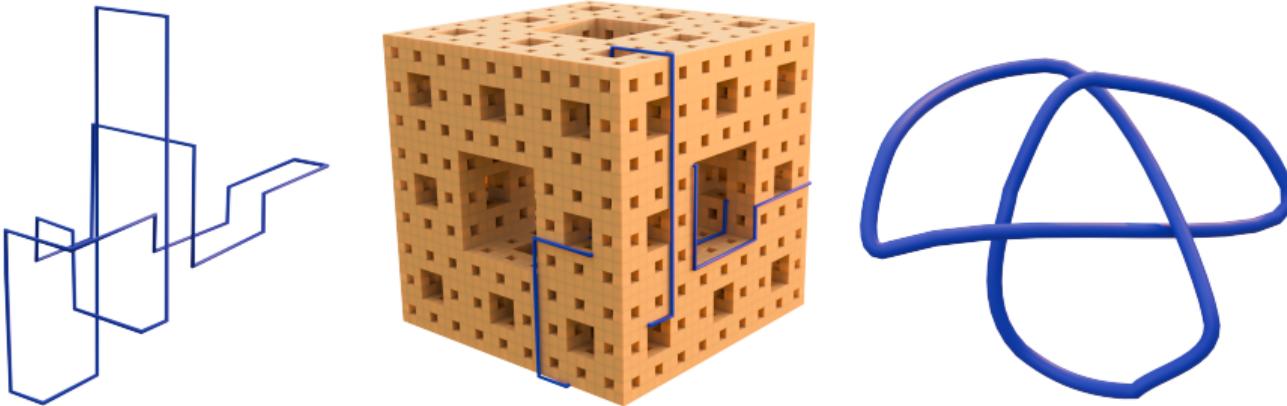


Figure: Enter Caption

- ▶ What possible knots can we find in this fractal?

## The Positive Answer

This is the question asked by highschoolers Niko Voth (top right), Joshua Broden (bottom right) and Noah Nazareth under the supervision of Malors

- ▶ In 2024 they were able to show that you could find every possible knot embedded in the Menger Sponge!
- ▶ Published a paper on ArXiv.



Figure: Barber, 2024

## The Cantor Set

- ▶ Split the interval  $[0, 1]$  into thirds and remove the middle third
- ▶ Repeat on each remaining interval

A point  $x \in [0, 1]$  is in the Cantor set if it does not have a 1 in its ternary expansion.



Figure: Cantor Set - Commons, 2025

## Cantor Dust

Cantor dust is a 2 dimensional fractal and is the cartesian product of 2 cantor sets

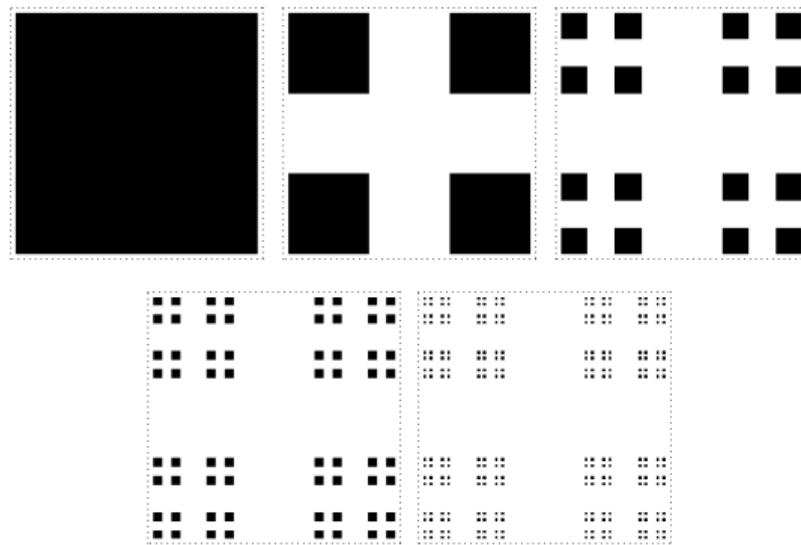


Figure: Enter Caption

## Relation With Sierpienski Carpet

Cantor dust is a 2 dimensional fractal and is the cartesian product of 2 cantor sets

### Lemma

$(x, y)$  lies on the Sierpinski carpet if and only if  $x$  and  $y$  share no digit 1 in their ternary expansion.

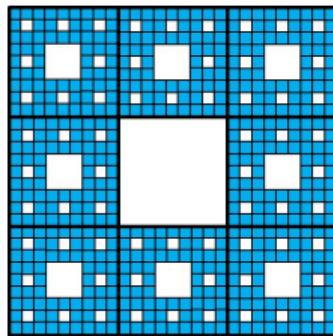


Figure: Illustrative-Mathematics, 2016

# Which Points Lie on the Menger Sponge?

## Lemma

Let  $(x, y)$  be a Cantor Dust point, then  $(x, y, z) \in M$  for all  $0 \leq z \leq 1$ .

## Proof.

Consider the first 2 stages where regions not in black have a hole behind them.



Figure: Stage 0 and Stage 1



## Which Points Lie on the Menger Sponge?

### Proof (Cont.)

- ▶ In the next iteration of the sponge we need only consider the black regions as it is never possible to fill in a hole.
- ▶ However, each black region occurs at a square of dimension  $\frac{1}{3} \times \frac{1}{3}$  and so can be viewed as Stage 0 when zoomed in.
- ▶ Repeating this argument inductively we see that the black areas precisely align with points of the Cantor Dust fractal.

□



## Arc Presentation of Knot

### Definition

An Arc Presentation in grid form is an ordered list of  $n$  unordered pairs  $\{a_1, b_1\}, \dots, \{a_n, b_n\}$ , such that  $a_1, \dots, a_n$  and  $b_1, \dots, b_n$  are permutations of  $1, \dots, n$  and  $a_i, b_i$ , for  $i \in \{1, \dots, n\}$

### Example

An Arc Presentation of the Eight Knot  $4_1$  is

$$\{3, 5\}, \{6, 4\}, \{5, 2\}, \{1, 3\}, \{2, 6\}, \{4, 1\}.$$

## Arc Presentation and Arc Index

An arc presentation of a link  $L$  is an embedding of  $L$  in finitely many pages of the open-book decomposition so that each of these pages meets  $L$  in a single simple arc

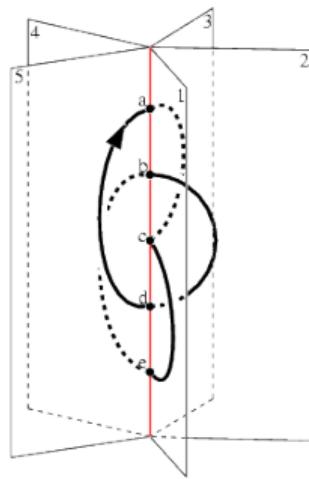


Figure: Arc Presentation Trefoil

# Arc Presentation and Arc Index

## Definition

The minimum number of pages required to represent a knot is called its arc index

## Example

The arc index of a  $(p, q)$  torus knot is  $p + q$ . This was shown using techniques from contact geometry.

## Knot Game

Before we start the proof we will play a quick game! The goal is to guess the correct knot inside the sponge.

## Knots in The Menger Sponge

We now give the proof that every knot can be found in a finite iteration of the merger sponge.

- ▶ Given a knot  $K$  we let  $\{a_1, b_1\}, \dots, \{a_n, b_n\}$  be its arc presentation.
- ▶ Take an iteration of the Cantor set  $C$ , with at least  $n$  endpoints and pick  $n$  of these points  $p_1, \dots, p_k \in C$ .
- ▶ We now re-write the arc presentation as  $\{p_{a_1}, p_{b_1}\} \dots \{p_{a_n}, p_{b_n}\}$
- ▶ This does not change the knot!

## Knots in The Menger Sponge

- ▶ We notice if  $x_0 \in C$  then  $(x_0, y, 0)$  lies entirely on the front face of the sponge for  $0 \leq y \leq 1$
- ▶ Similarly if  $y_0 \in C$   $(x, y_0, 0)$  lies entirely on the front face of the sponge for  $0 \leq x \leq 1$
- ▶ We conclude the entire knot diagram induced by the given arc presentation lies on the front face of the sponge

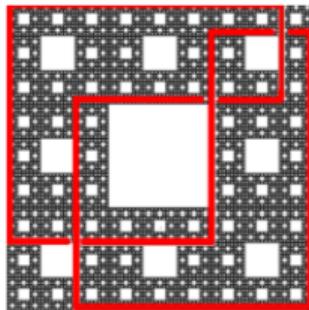


Figure: Enter Caption

## Push Through the Sponge!

The last big idea is to push the knot through the sponge

- ▶ We draw the vertical lines on the front face and the horizontal lines on the back face.
- ▶ We connect them through the sponge.
- ▶ This is possible as the points  $(x_0, y_0)$  were cantor dust points!
- ▶ The knot is our original knot as the projection onto the front face recovers our knot diagram.

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- ② Knot
- ③ Application of Knots
- ④ Fractals
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- ⑥ Embedding into Sierpinski Tetrahedron

## Difficulties

Menger Sponge	Sierpinski Tetrahedron
Easily understandable representation	Difficulties caused by tetrahedrons
arc representation	?

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Menger Sponge	Sierpinski Tetrahedron
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Solution:

- ▶ Combinatorial representation of the Sierpinski Tetrahedron
- ▶ Pretzel knots

## Combinatorial representation of the Tetrahedron

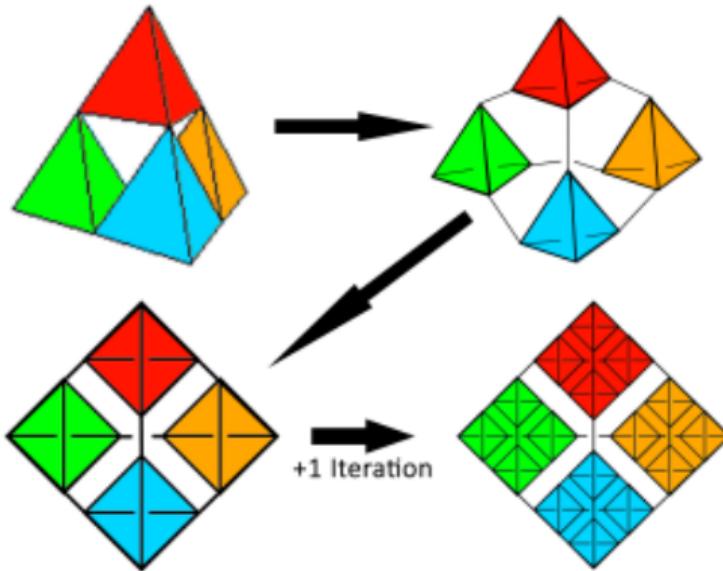


Figure: Combinatorial representation of the Tetrahedron Broden et al., 2024

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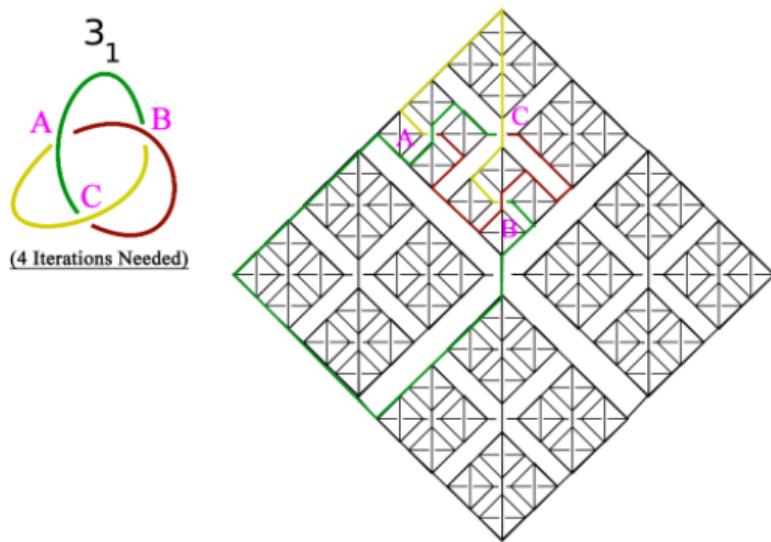


Figure: Example  $3^1$  knot Broden et al., 2024

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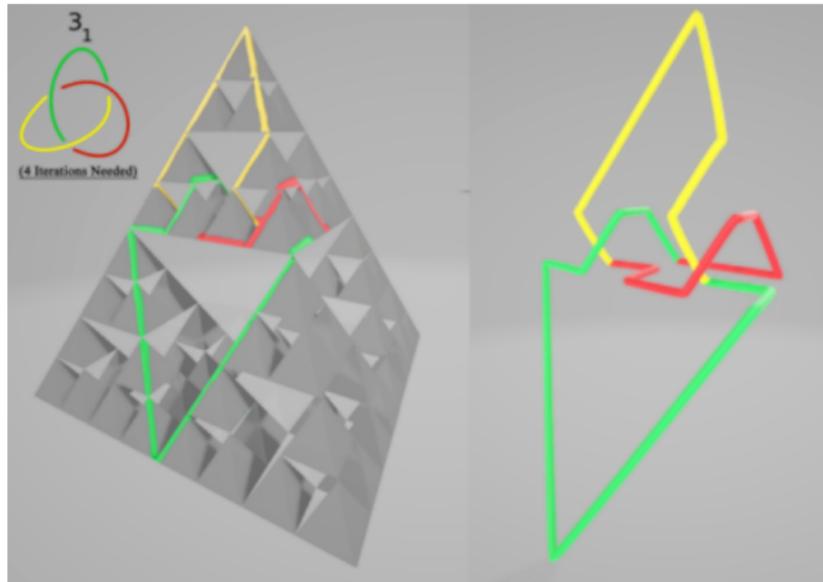


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# Sierpinski Tetrahedron

## Theorem

*All Pretzel Knots are inside a finite iteration of the Sierpinski Tetrahedron. Broden et al., 2024*

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To finish the proof they showed, that the helices can be connected as required. □

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To finish the proof they showed, that the helices can be connected as required. □

- ▶ It is easy to follow that a certain Pretzel knot in which iteration can be embedded.

# Sierpinski Tetrahedron

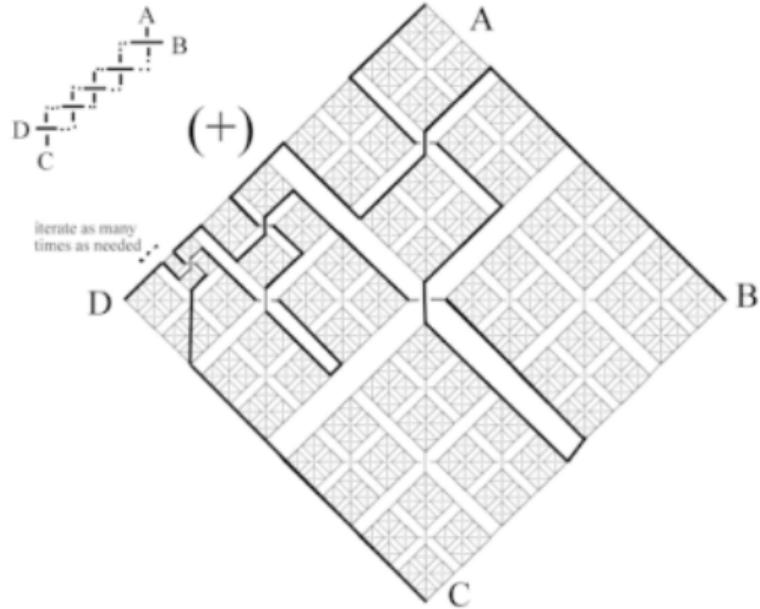
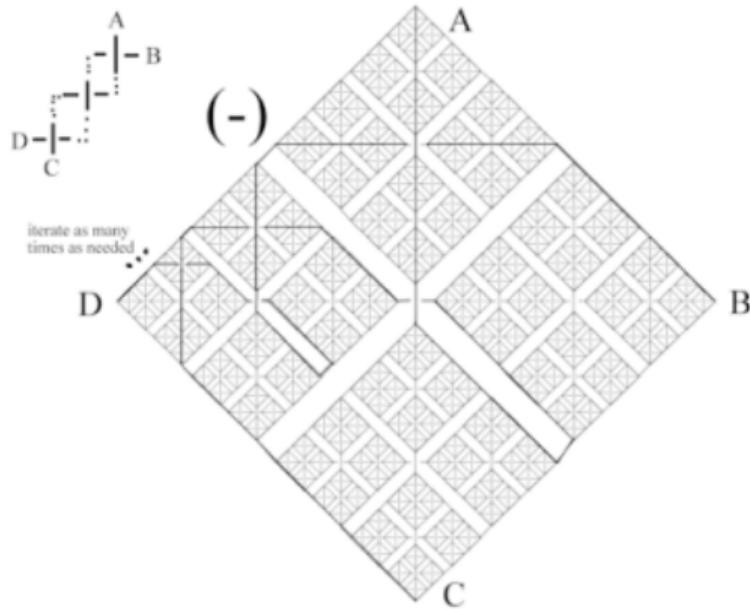


Figure: Helices in a certain iteration. Broden et al., 2024

# Sierpinski Tetrahedron

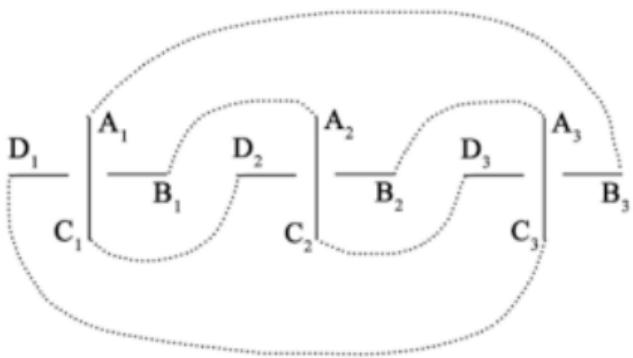


Figure: Every Pretzel Knot can be simplified to the above form. Broden et al., 2024

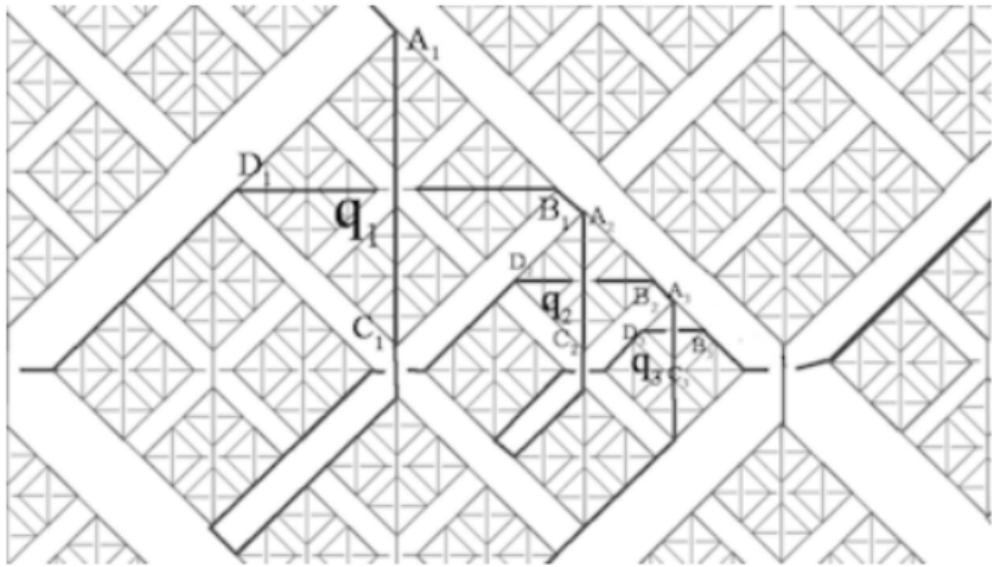


Figure: It is possible to connect the helices in the required order. Broden et al., 2024

## Comparison between Fractals

Denote with  $M_n$  and  $S_n$  the one-skeleton of the  $n^{th}$  iteration of the Menger sponge and the Sierpinski Tetrahedron.

Let  $M(K) = \min n$ , such that  $K \subset M_n$ . Similarly  $S(K) = \min n, s.t. K \subset S_n$ .

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### Theorem

*Let  $K$  be a knot, then we have*

$$M(K) \leq S(K),$$

*whenever  $S(K)$  is defined. Broden et al., 2024*

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### Proof.

Shortly: The one-skeleton of the  $i^{th}$  iteration of the Sierpinski Tetrahedron can be embedded into the one-skeleton of the  $i^{th}$  iteration of the Menger Sponge. This embedding preserves the knot type. □

## Comparison between Fractals

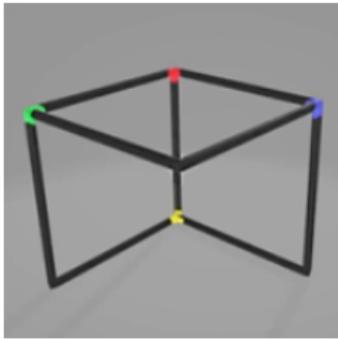


Figure:  $S_0$  in  $M_0$

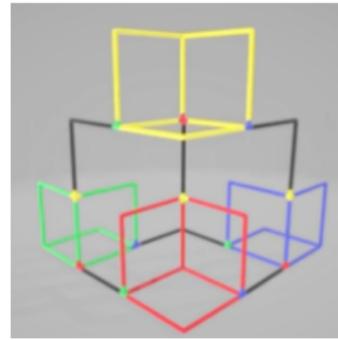


Figure:  $S_1$  in  $M_1$

## Comparison between Fractals

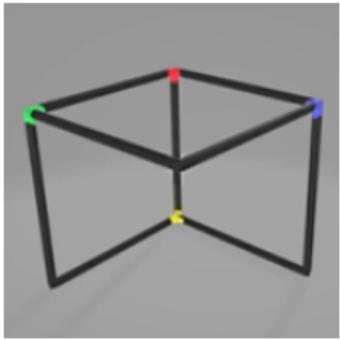


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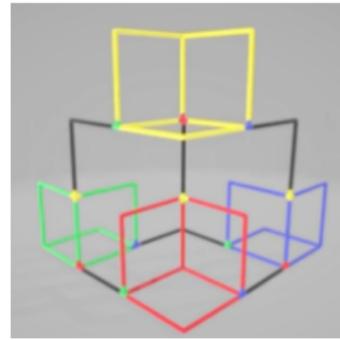


Figure:  $S_1$  in  $M_1$

What next?

## Comparison between Fractals

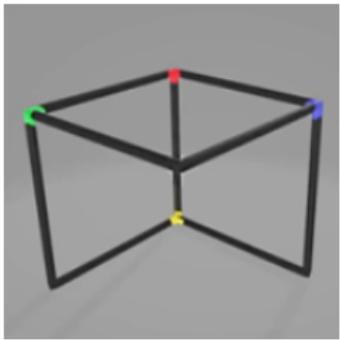


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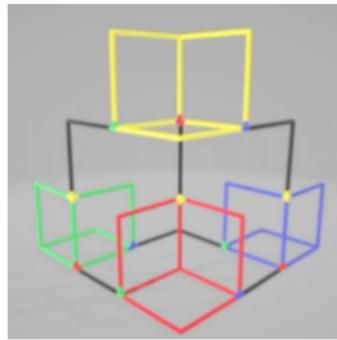


Figure:  $S_1$  in  $M_1$

What next?

- ▶ To get  $S_2$  in  $M_2$ : replace every  $S_0$  in  $S_1$  by  $S_1$ .

## Comparison between Fractals

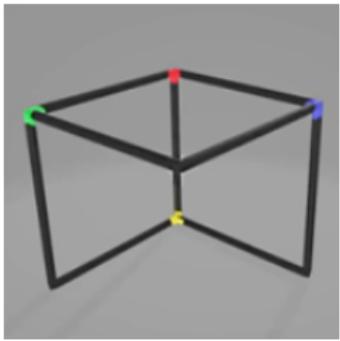


Figure:  $S_0$  in  $M_0$

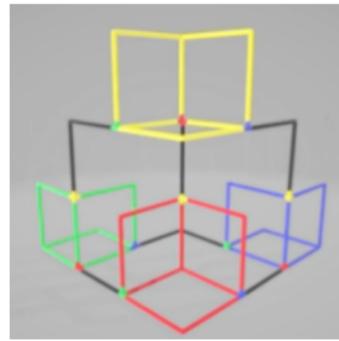


Figure:  $S_1$  in  $M_1$

What next?

- ▶ To get  $S_2$  in  $M_2$ : replace every  $S_0$  in  $S_1$  by  $S_1$ .
- ▶ To get  $S_{n+1}$  in  $M_{n+1}$ : replace every  $S_0$  in  $S_n$  by  $S_1$ .

## Comparison between Fractals

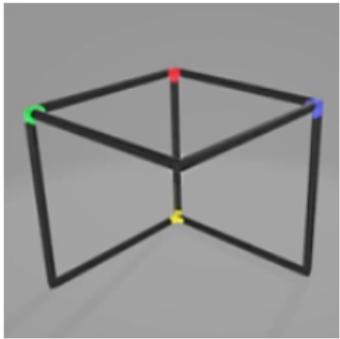


Figure:  $S_0$  in  $M_0$

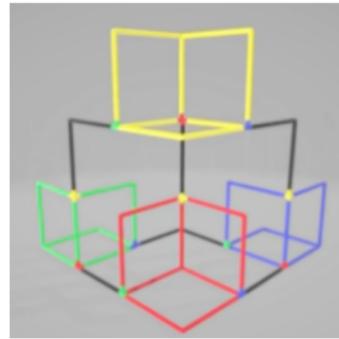


Figure:  $S_1$  in  $M_1$

What next?

- ▶ To get  $S_2$  in  $M_2$ : replace every  $S_0$  in  $S_1$  by  $S_1$ .
- ▶ To get  $S_{n+1}$  in  $M_{n+1}$ : replace every  $S_0$  in  $S_n$  by  $S_1$ .
- ▶ Substitutions are in disjoint regions, so the embedding preserves the knot type.

## Open questions Broden et al., 2024

- ▶ Every knot can be embedded into the Sierpinski tetrahedron.

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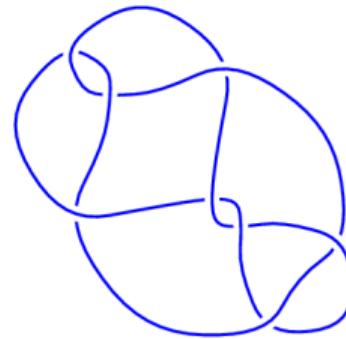


Figure: 8<sub>12</sub> knot is not a Pretzel knot Livingston and Moore, 2025

## Open questions Broden et al., 2024

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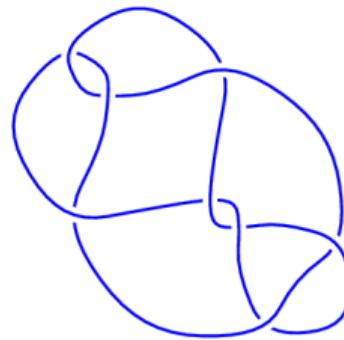


Figure: 8<sub>12</sub> knot is not a Pretzel knot Livingston and Moore, 2025

- ▶ Is there a fractal defined by iterative steps that doesn't admit all of the knots? If it is so, what does this tell us about the fractal?

## Conclusion

- ▶ Knot theory
- ▶ Fractals
- ▶ Intersection: Knots inside Fractals
- ▶ Open questions

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# Fantastic Knots and Where to Find Them

## KnotInfo: Table of Knots

About   Database Download   KnotFinder   LinkInfo   More   Please Cite KnotInfo

Check the desired boxes in the sections below and then click SUBMIT to produce your desired table.

Select knots by crossing number

3-6    7    8    9    10    11    12    3-12    13a    13n

Nomenclature

<input type="checkbox"/> Name	<input type="checkbox"/> DT Name	<input type="checkbox"/> Conway Name	<input type="checkbox"/> Gauss Notation
<input type="checkbox"/> Name Rank	<input type="checkbox"/> DT Notation	<input type="checkbox"/> Conway Notation	<input type="checkbox"/> Tetrahedral Census Name
<input type="checkbox"/> PD Notation	<input type="checkbox"/> DT Rank		

3D Presentations and Properties

<input type="checkbox"/> Adequate	<input type="checkbox"/> Braid Notation	<input type="checkbox"/> Monodromy	<input type="checkbox"/> Seifert Matrix
<input type="checkbox"/> Almost Alternating	<input type="checkbox"/> Fibred	<input type="checkbox"/> Montesinos Notation	<input type="checkbox"/> Small or Large
<input type="checkbox"/> Alternating	<input type="checkbox"/> Geometric Type	<input type="checkbox"/> Pretzel Notation	<input type="checkbox"/> Symmetry Type
<input type="checkbox"/> Boundary Slopes	<input type="checkbox"/> Grid Notation	<input type="checkbox"/> Quasialternating	<input type="checkbox"/> Two-Bridge Notation

3D Numeric Invariants

<input type="checkbox"/> Arc Index	<input type="checkbox"/> Crosscap Number	<input type="checkbox"/> Nakanishi Index	<input type="checkbox"/> Torsion Numbers
<input type="checkbox"/> Braid Index	<input type="checkbox"/> Crossing Number	<input type="checkbox"/> Ribbon Number	<input type="checkbox"/> Tunnel Number
<input type="checkbox"/> Braid Length	<input type="checkbox"/> Determinant	<input type="checkbox"/> Ropelength	<input type="checkbox"/> Turaev Genus
<input type="checkbox"/> Bridge Index	<input type="checkbox"/> Genus-3D	<input type="checkbox"/> Stick Number	<input type="checkbox"/> Unknotting Number
<input type="checkbox"/> Clasp Number	<input type="checkbox"/> Mosaic/Tile-Number	<input type="checkbox"/> Super Bridge Index	<input type="checkbox"/> Unknotting Number (Alg.)
<input type="checkbox"/> Cosmetic Crossing	<input type="checkbox"/> Morse-Novikov Number	<input type="checkbox"/> Thurston-Bennequin Number	<input type="checkbox"/> Width

Figure: Knot table Livingston and Moore, 2025

## Contact geometry

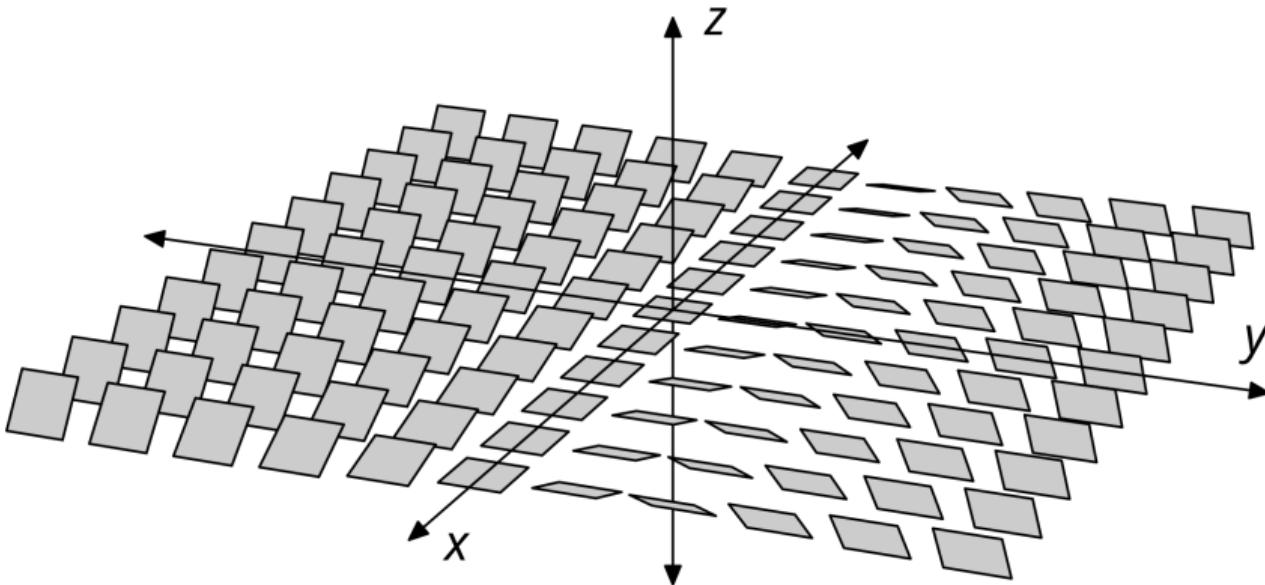


Figure: The standard contact structure on  $\mathbb{R}^3$ . Wikipedia contributors, 2024