

Knots and Fractals

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Outline

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

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What is a knot



Figure: Knots in daily life (LiveOak, 2024 and et al., 2014)

What is a knot

- ▶ Link

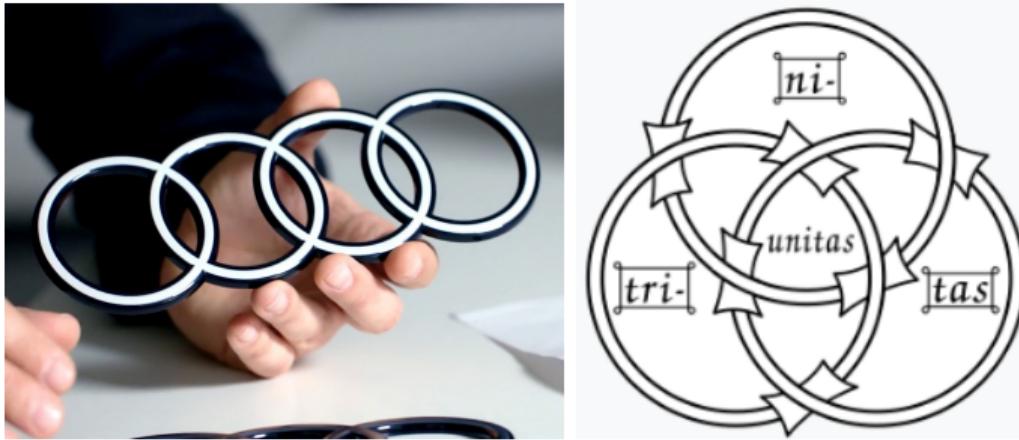


Figure: Links in logos(Gauthier, 2022 and Commons, 2024a)

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.

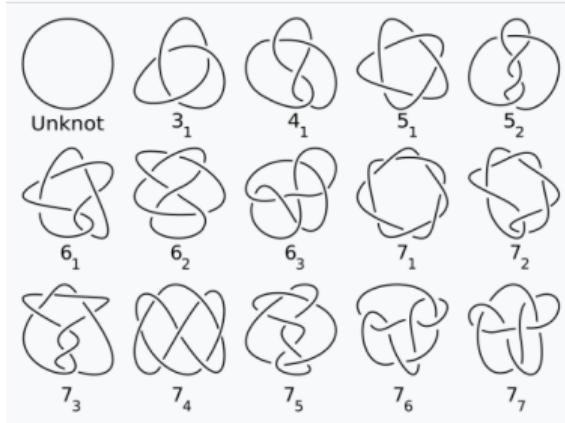


Figure: Simple knots(Wikipedia contributors, 2024c)

Motivation

- ▶ The structure of protein and DNA

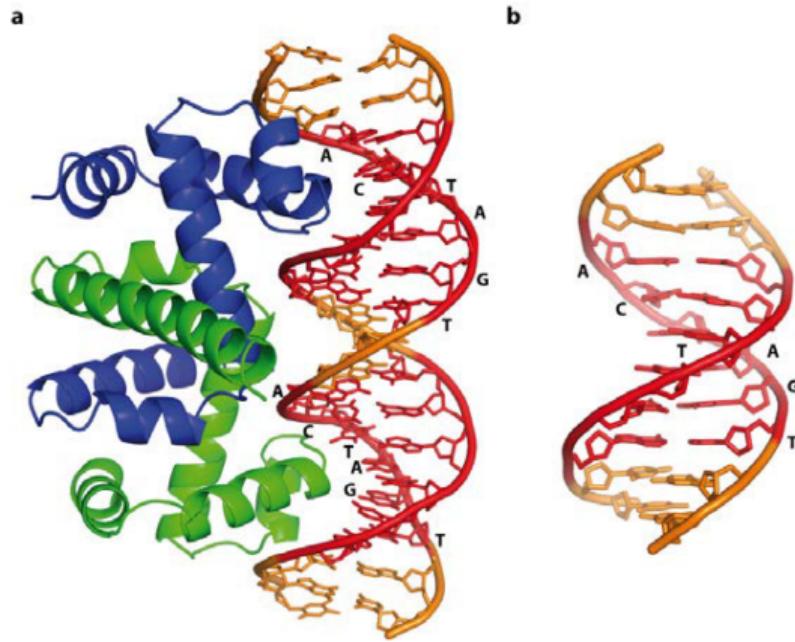


Figure: DNA (Harteis and Schneider, 2014)

Motivation

- The knot structure of chemical compound and material

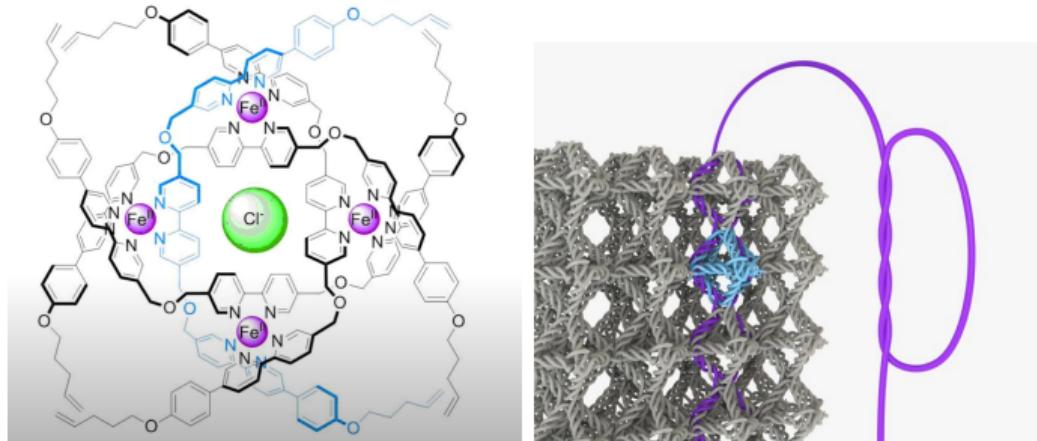


Figure: Tightest synthetic compound (Veritasium, 2024 and Futurology, 2023)

Diagram

- ▶ How to represent a knot? Regular projection.

Definition

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.

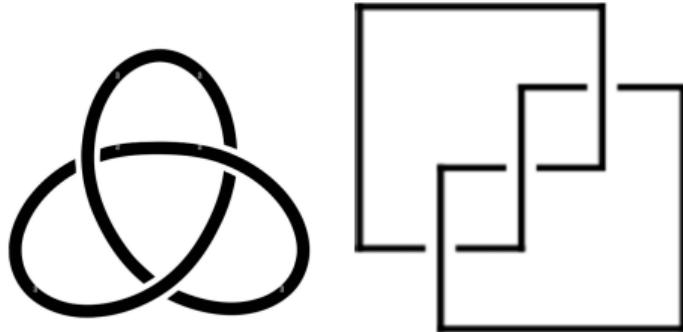


Figure: Trefoil diagram (Wikipedia contributors, 2025)

Equivalence of knots

- Are they equivalent?

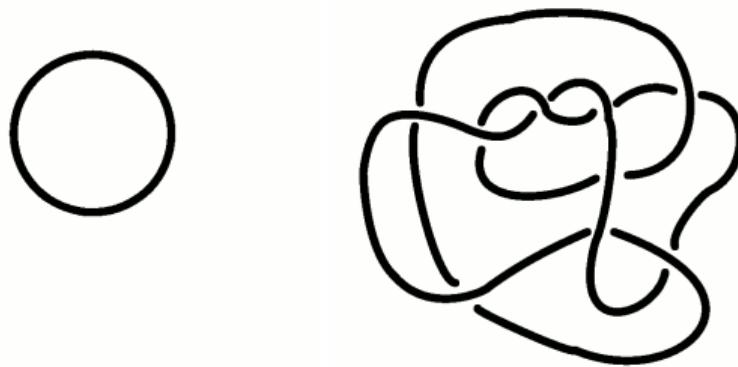


Figure: Knot unfolding (Commons, 2024b)

Reidemeister move

- ▶ Equivalence of knot?

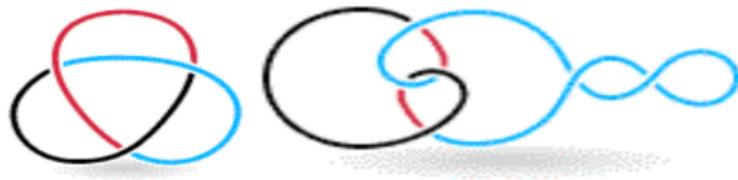


Figure: Equivalence? (Santi, 2002)

- ▶ Formal definition: two knots \mathbf{K}_1 and \mathbf{K}_2 are equivalent if there is an orientation-preserving homeomorphism $h : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ with $h(\mathbf{K}_1) = h(\mathbf{K}_2)$.
- ▶ (1927) Reidemeister's Theorem(et al., 2024b): If two knots are equivalent, their diagrams are related by a sequence of Reidemeister moves.

Reidemeister move

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

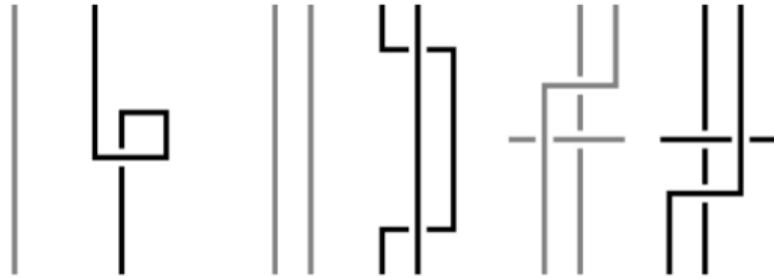


Figure: Equivalence? (et al., 2024b)

Invariant polynomial

- ▶ 1923(James Waddell Alexander)(et al., 2024a): Alexander polynomial ∇ . Reformulated by John Conway in 1969.

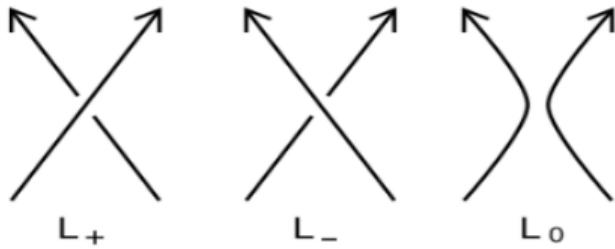


Figure: 3 variations (Wikipedia contributors, 2024a)

$$\nabla(O) = 1$$

$$\nabla(L_+) - \nabla(L_-) = z\nabla(L_0)$$

Invariant polynomial

- ▶ 1984(Vaughan Jones)(et al., 2025): Jones polynomial V . Jones won the field's medal for this discovery in 1990.

$$V(L_0) = 1$$

$$t^{-1}V(L_+) - tV(L_-) = (t^{\frac{1}{2}} - t^{-\frac{1}{2}})V(L_0)$$

- ▶ 1985(multiple authors): HOMFLY-PT polynomial P : A generalization of the above invariants.

$$P(L_0) = 1$$

$$tP(L_+) + t^{-1}P(L_-) + mP(L_0) = 0$$

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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

Fielden et al., 2017

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.

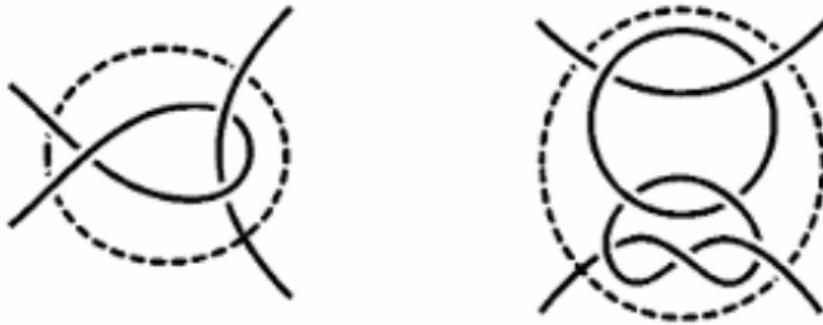
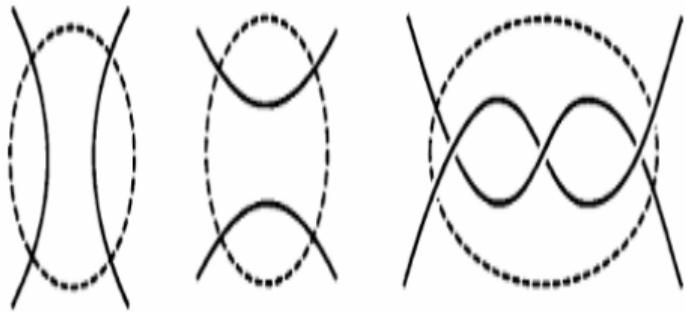


Figure: Tangles

Adams, 2004



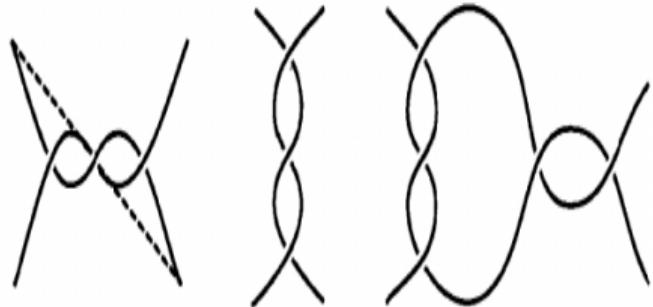
a

b

c

Figure: ∞ , 0 and 3 tangles, they are fundamental

Adams, 2004

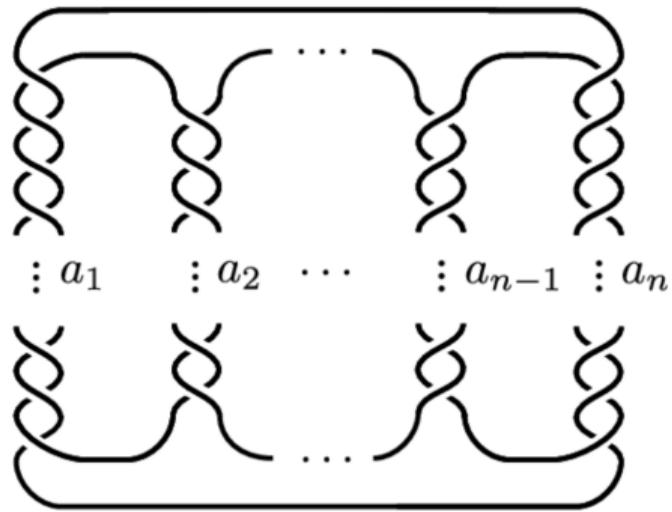


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Figure: Generating Tangles

Pretzel Knots

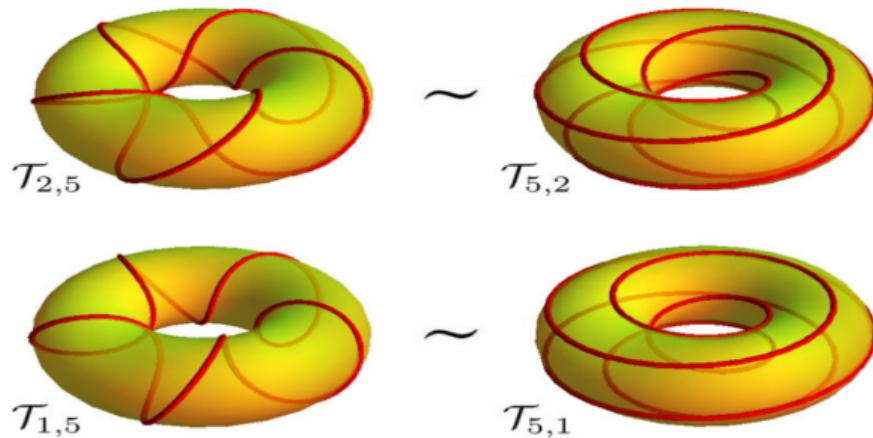
Pretzel knots are rational knots that are obtained by adding up rational tangles. If every term of a rational knot klm (for instant 311) is multiplied with 0 and then added altogether, the result is a pretzel knot that is denoted by k,l,m (3,1,1)



Komendarczyk and Michaelides, 2016

Torus Knots

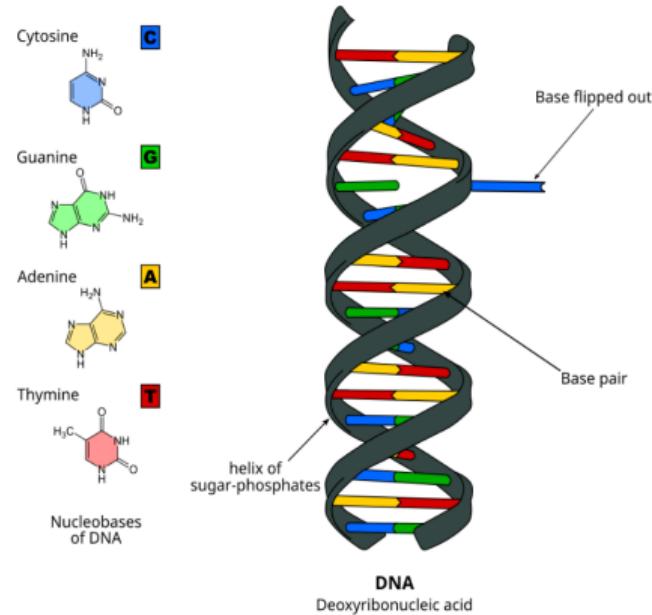
These knots are wrapped around unknotted tori and do not cross themselves as they move around their tori. There are 'short' paths called meridian and 'long' paths called longitude. A (p,q) -torus knot travels the longitude p times and travels meridians q times.



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

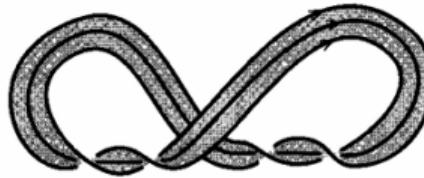
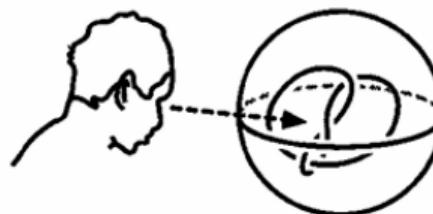


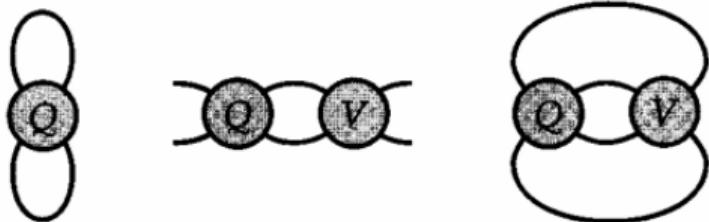
Figure: Axis

Adams, 2004

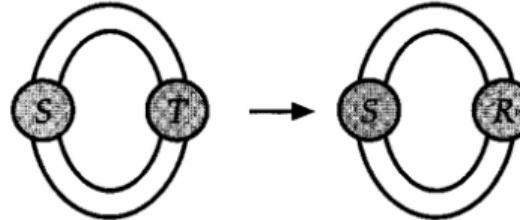


Adams, 2004

- ▶ 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

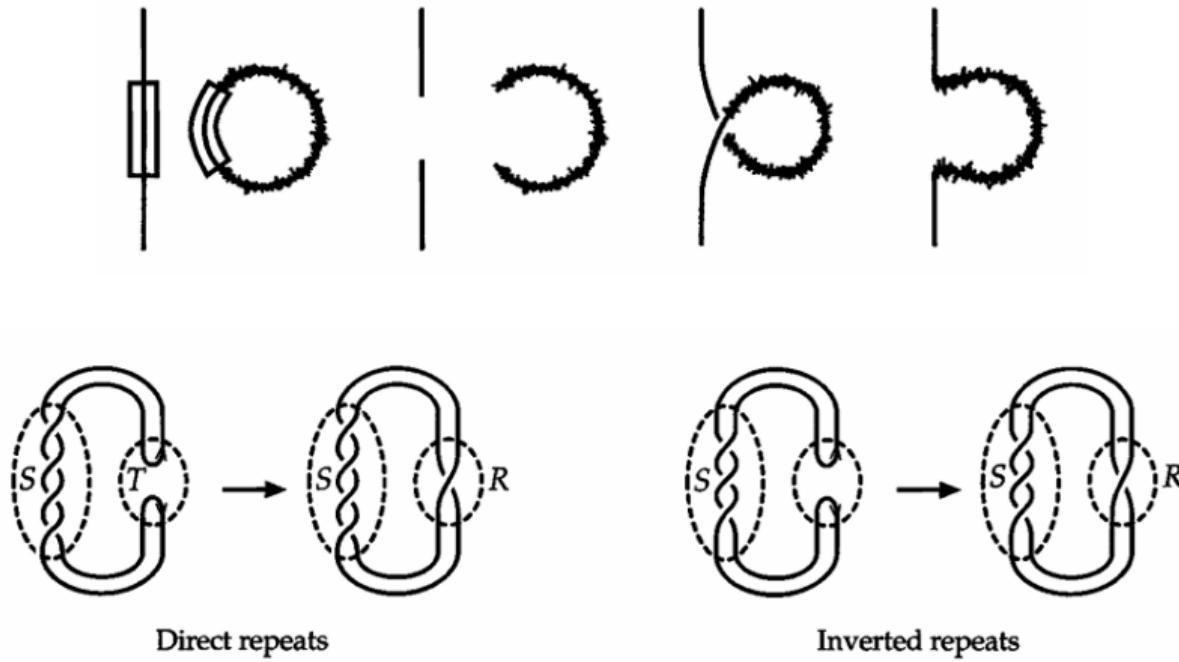


Figure: Effects of Int enzyme

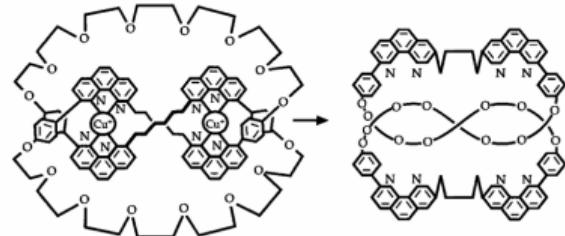
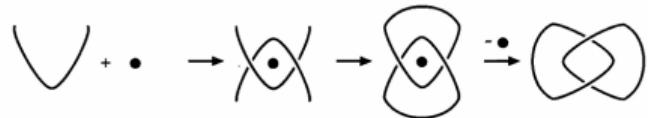
Adams, 2004

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.

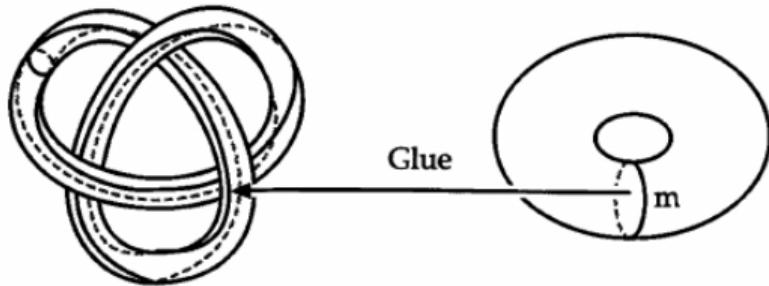


Figure: Dehn Surgery

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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Fractals

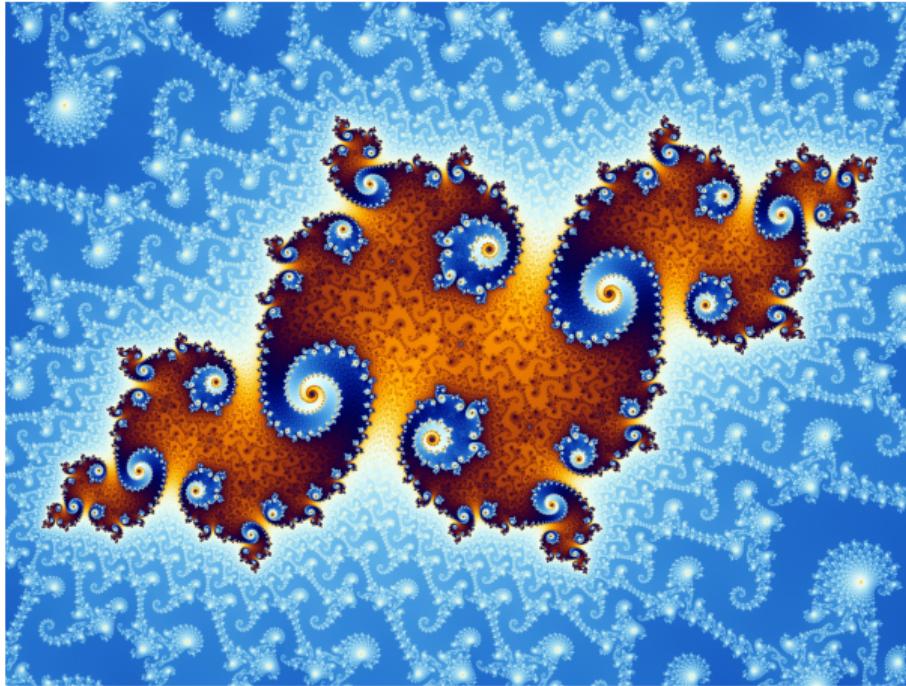


Figure: Fractal (Wikipedia, 2023)

Motivation

- ▶ Coastline
- ▶ Lungs



Figure: Coastline and lung (Birnir, 2004 and el al., 2010)

Motivation

- ▶ 1872: Karl Weierstrass constructed a function that is continuous but nowhere differentiable:

$$f(x) = \sum_{n=0}^{\infty} a^n \cos(b^n \pi x)$$

- ▶ 1904: Helge von Koch devised a geometric method to construct pathological curves.
- ▶ 1915: Wacław Sierpiński introduced Sierpiński triangle.
- ▶ 1918: Gaston Julia Pierre Fatou studied iteration of complex functions.

Geometric Fractals

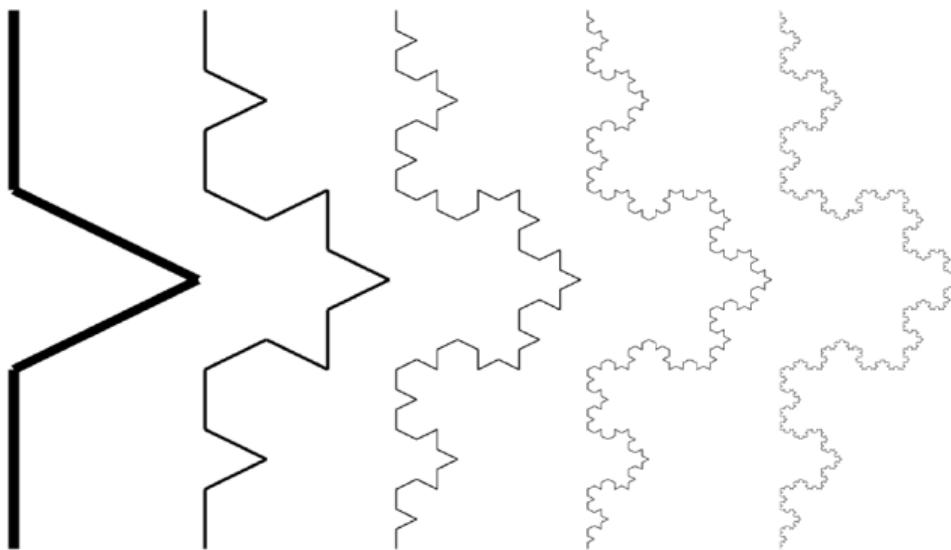


Figure: Koch curve (**frac**)

Algebraic Fractals

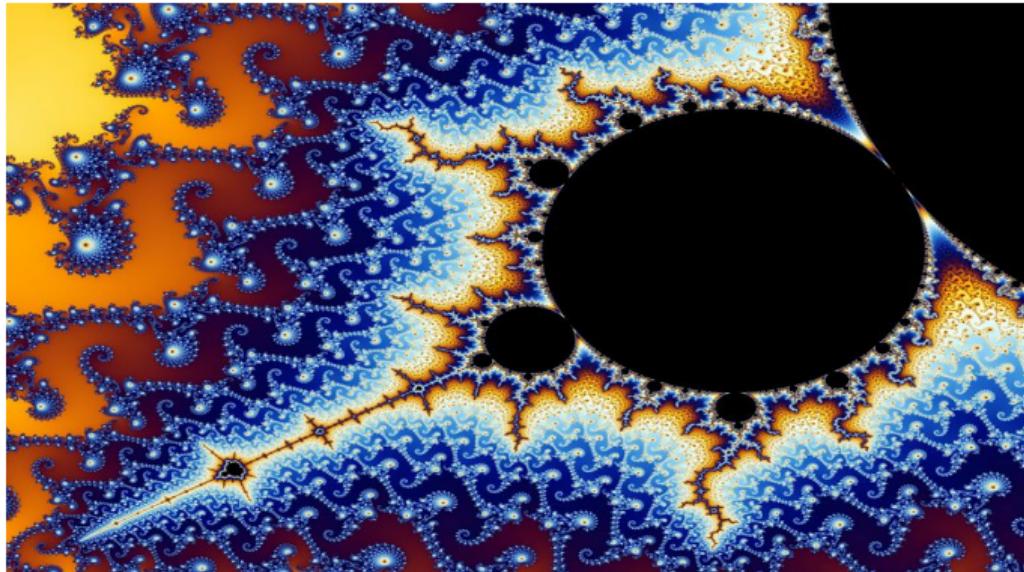


Figure: Section of a Mandelbrot set ([wiki:xxx](#))

Fractal Dimension

- ▶ Key Question: How does the object scale?

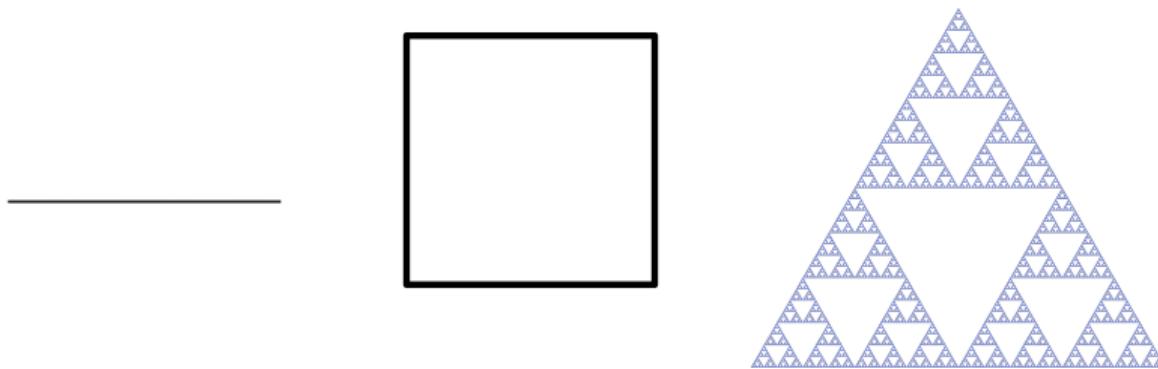


Figure: Wikipedia, [accessed 3-April-2025](#)

Box-Counting Dimension

- ▶ Place our fractal in grid of "boxes"
- ▶ How does the number of boxes change as they get smaller?

$$N \approx N_0 s^{-d} \implies \dim_{\text{box}}(S) = \lim_{s \rightarrow 0} \frac{\log(N(s))}{\log(s^{-1})}$$

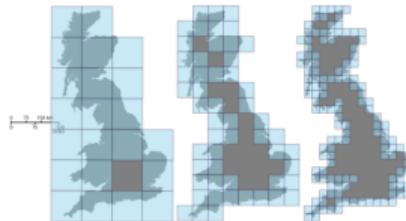


Figure: Dimension of UK coastline is approx 1.25, (Mandelbrot, 1983, Wikipedia, 2025)

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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The Menger Sponge, Menger, 1926

- Universal - Contains every curve

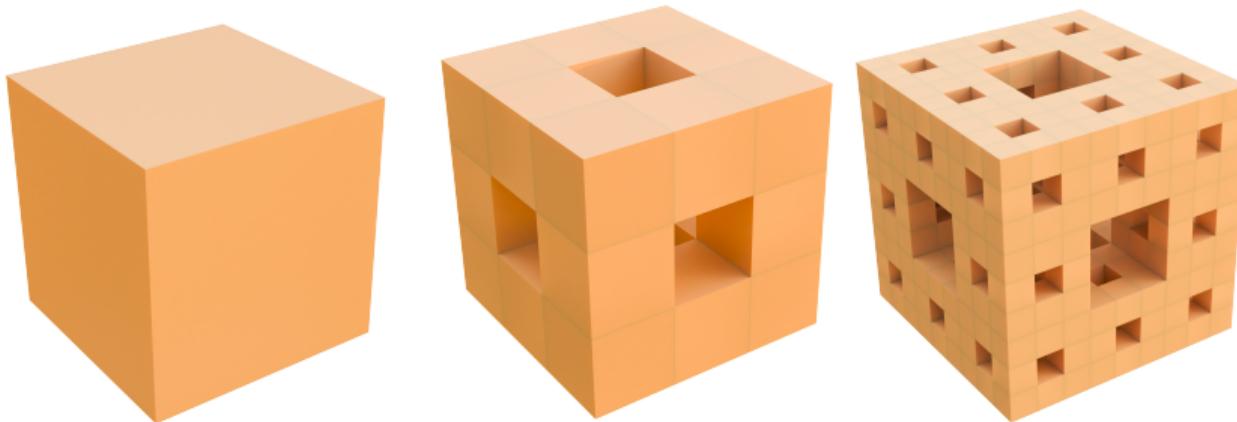


Figure: Michael McGloin (2025)

Knots Inside the Menger Sponge

What is a knot in the Menger Sponge?

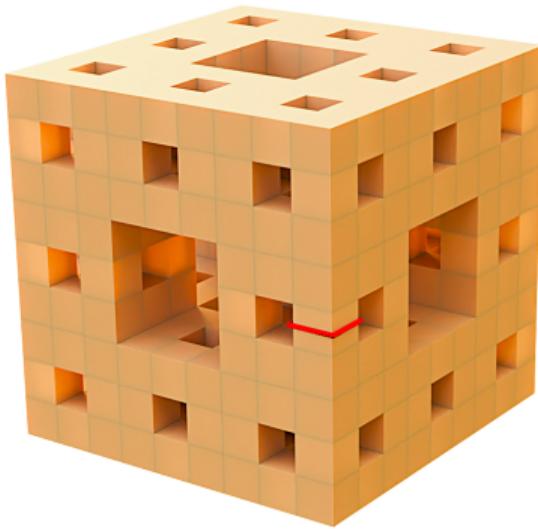
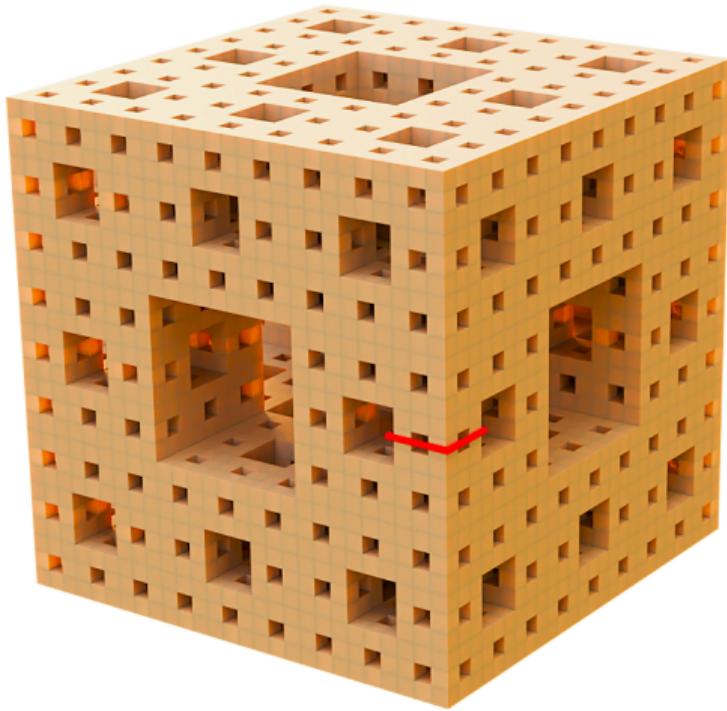


Figure: The Unknot? - Michael McGloin (2025)

Not a Knot!



Knot or Not?

- ▶ Does the following knot live on the fractal?

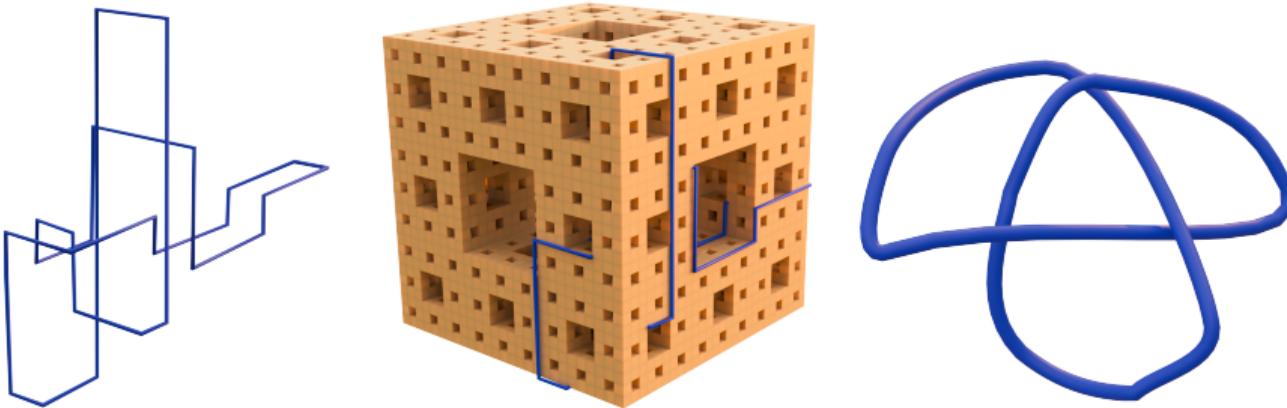


Figure: Trefoil Knot in Sponge - Michael McGloin (2025)

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

The Positive Answer

- ▶ This is the question asked by a group of highschoolers.
- ▶ 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: Niko Voth (top right), Joshua Broden (bottom right) and Noah Nazareth under the supervision of Malors. Barber, 2024

The Cantor Set

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



Figure: Cantor Set - Commons, 2025

Cantor Dust

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

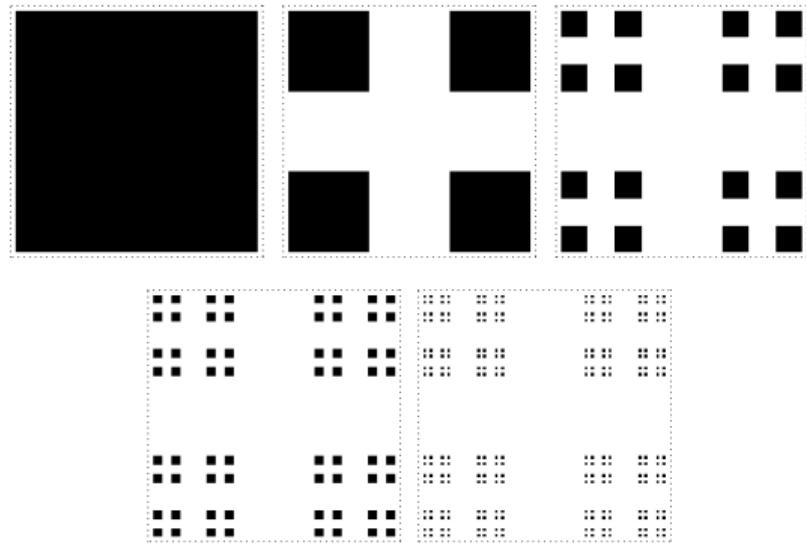


Figure: Dickau, 2014

Relation With Sierpienski Carpet

Lemma

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

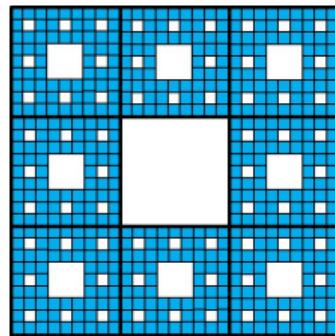


Figure: Sierpinski Carpet, Illustrative-Mathematics, 2016

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 Broden et al., 2024



Cantor Dust!

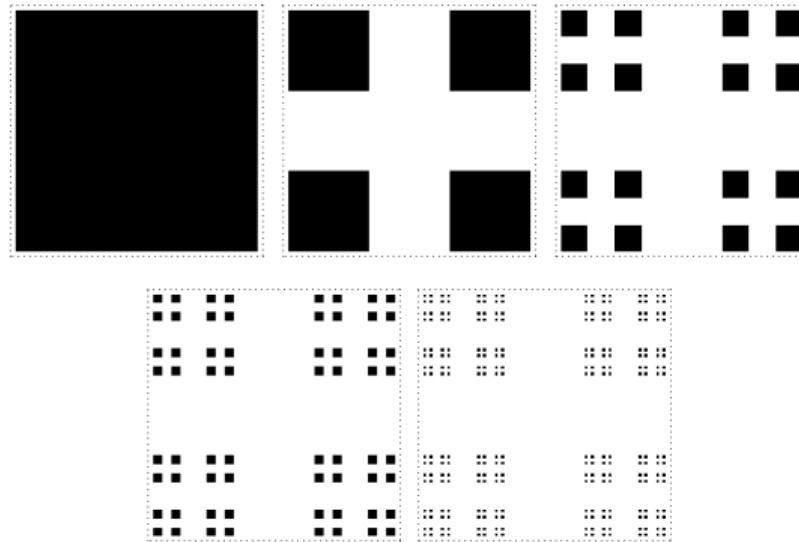
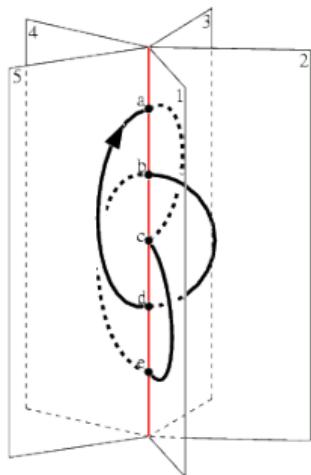


Figure: Dickau, 2014

Arc Presentation and Arc Index

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



$$K = \{3, 5\}, \{2, 4\}, \{1, 3\}, \{2, 5\}, \{1, 4\}$$

Figure: Arc Presentation Trefoil, Cromwell, 1996

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. (Etnyre and Honda, 2000)

Knots in The Menger Sponge

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

- ▶ Let $K = \{a_1, b_1\}, \dots, \{a_n, b_n\}$ be its arc presentation.
- ▶ Take n endpoints, p_1, \dots, p_n of Cantor Set.
- ▶ We now re-write $K = \{p_{a_1}, p_{b_1}\} \dots \{p_{a_n}, p_{b_n}\}$

Knots in The Menger Sponge

- ▶ We notice if $x_0 \in C$ then vertical line through x_0 on sponge.
- ▶ Same with vertical lines for y_0
- ▶ Can draw our knot diagram on the face!

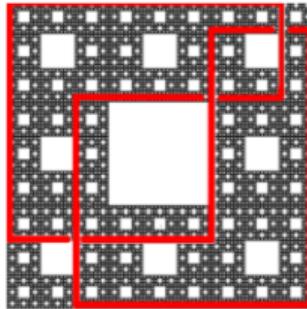


Figure: Broden et al., 2024

Push Through the Sponge!

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

- ▶ Vertical lines on front face.
- ▶ Horizontal Lines on back face.
- ▶ We connect them through the sponge.
- ▶ The knot is our original knot as the projection onto the front face recovers our knot diagram.

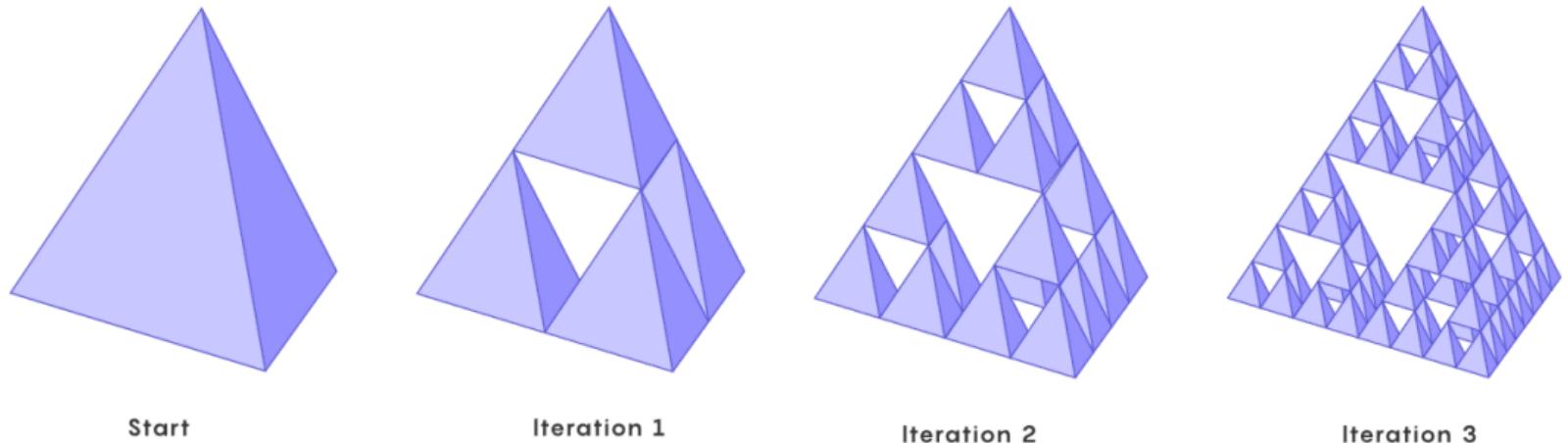
Knot Game

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

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Construction of Sierpinski Tetrahedron Barber, 2024



- ▶ Similar construction like the construction of the Menger Sponge.
- ▶ Each face is an iteration of the Sierpinski Triangle.

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

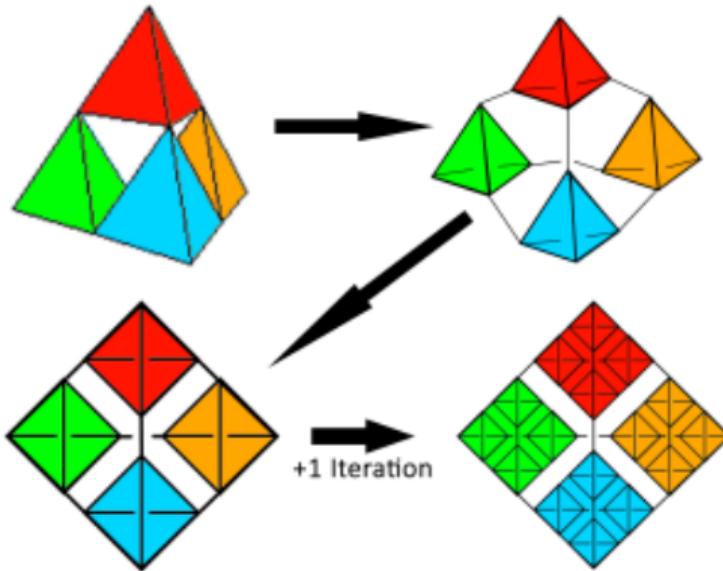


Figure: Combinatorial representation of the Tetrahedron Broden et al., 2024

Combinatorial representation of the Tetrahedron

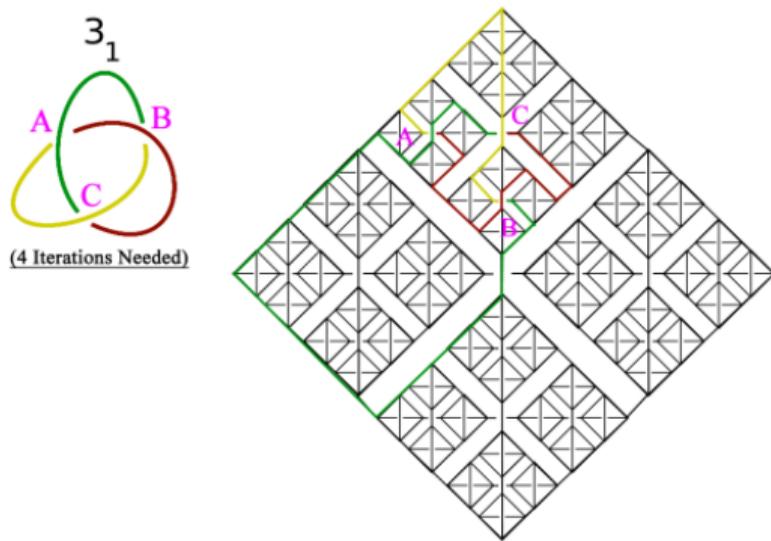


Figure: Example 3^1 knot Broden et al., 2024

Combinatorial representation of the Tetrahedron

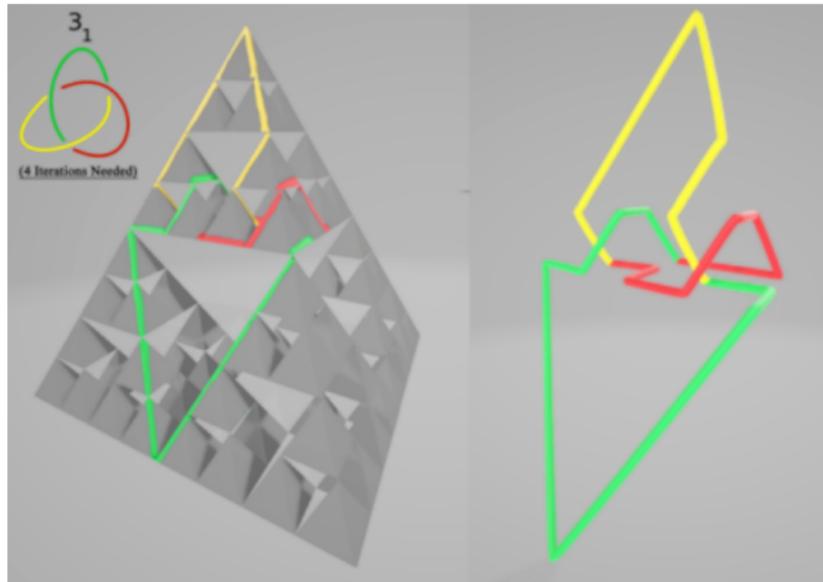


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Sierpinski Tetrahedron

Theorem

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

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Proof.

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Every isolated helix can be put inside a finite iteration of the 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

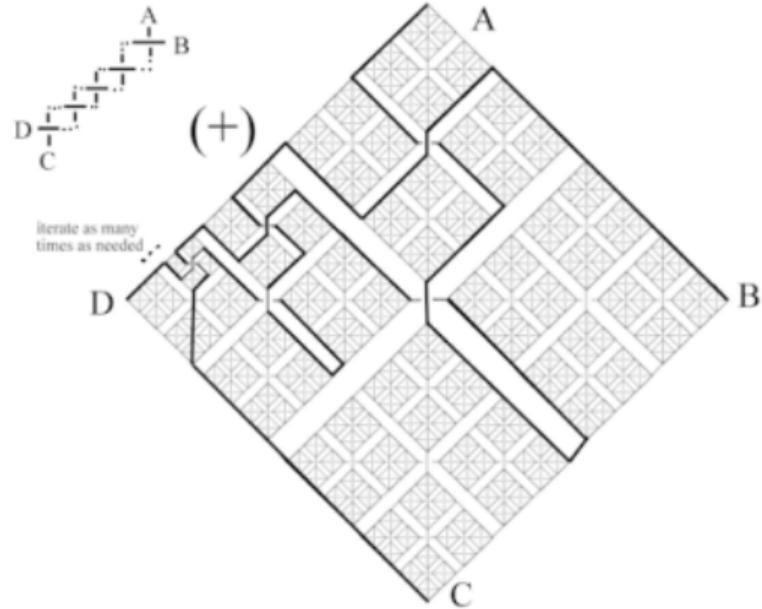
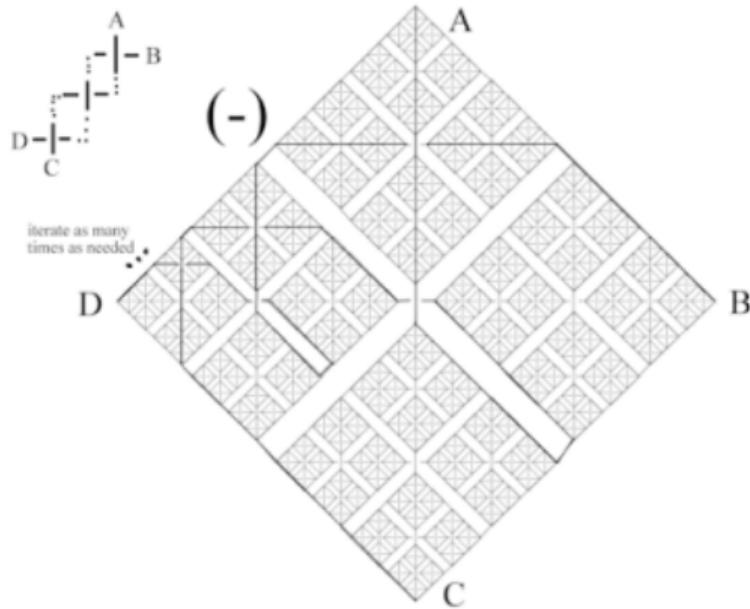


Figure: Helices in a certain iteration. Broden et al., 2024

Sierpinski Tetrahedron

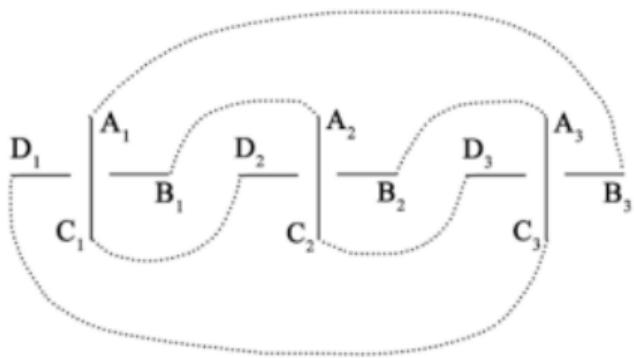


Figure: Every Pretzel Knot can be simplified to the above form. Broden et al., 2024

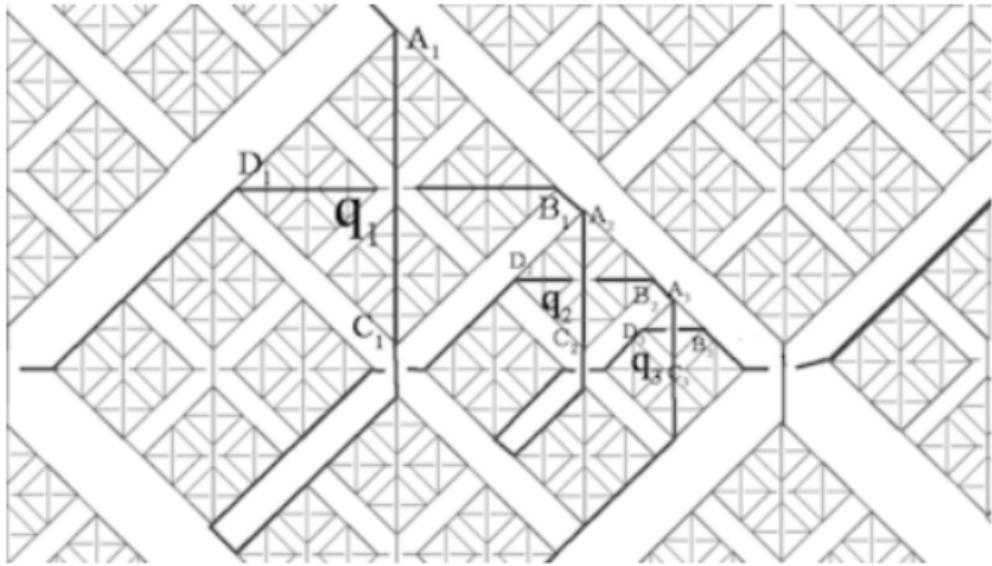


Figure: It is possible to connect the helices in the required order. Broden et al., 2024

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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Let K be a knot, then we have

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

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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

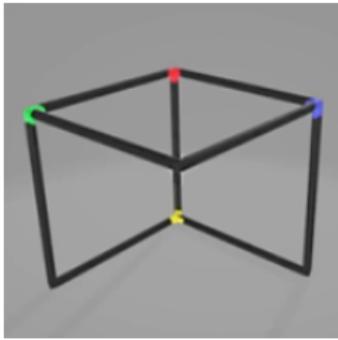


Figure: S_0 in M_0 Broden et al., 2024

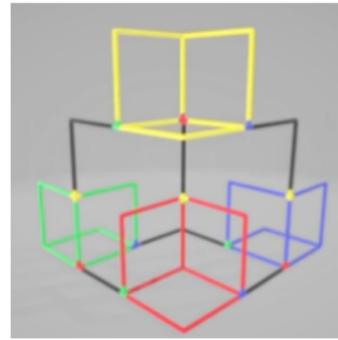


Figure: S_1 in M_1 Broden et al., 2024

Comparison between Fractals

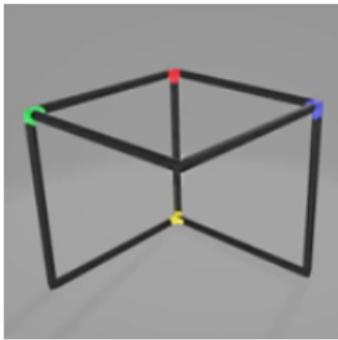


Figure: S_0 in M_0 Broden et al., 2024

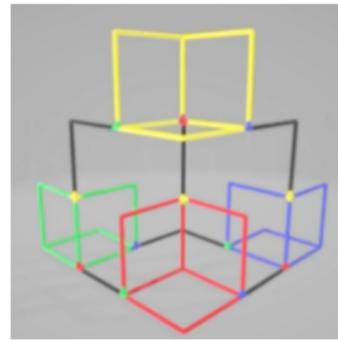


Figure: S_1 in M_1 Broden et al., 2024

What next?

Comparison between Fractals

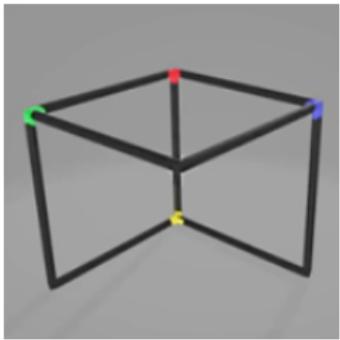


Figure: S_0 in M_0 Broden et al., 2024

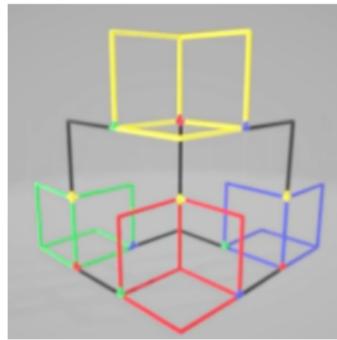


Figure: S_1 in M_1 Broden et al., 2024

What next?

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

Comparison between Fractals

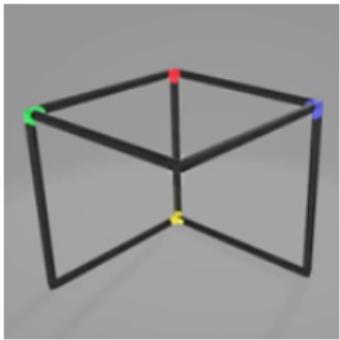


Figure: S_0 in M_0 Broden et al., 2024

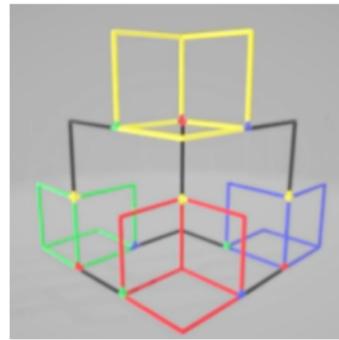


Figure: S_1 in M_1 Broden et al., 2024

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

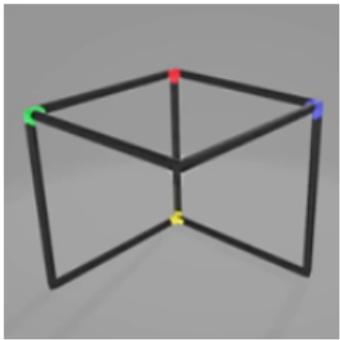


Figure: S_0 in M_0 Broden et al., 2024

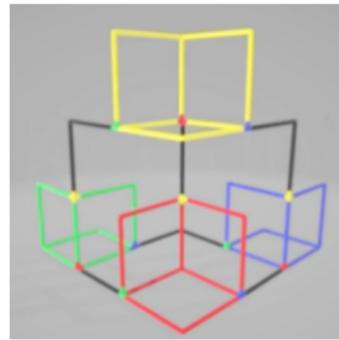


Figure: S_1 in M_1 Broden et al., 2024

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.

Open questions Broden et al., 2024

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

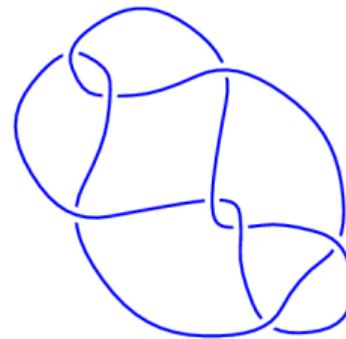


Figure: 8₁₂ knot is not a Pretzel knot Livingston and Moore, 2025

Open questions Broden et al., 2024

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

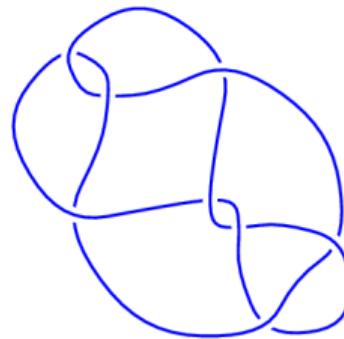


Figure: 8₁₂ knot is not a Pretzel knot Livingston and Moore, 2025

- ▶ 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

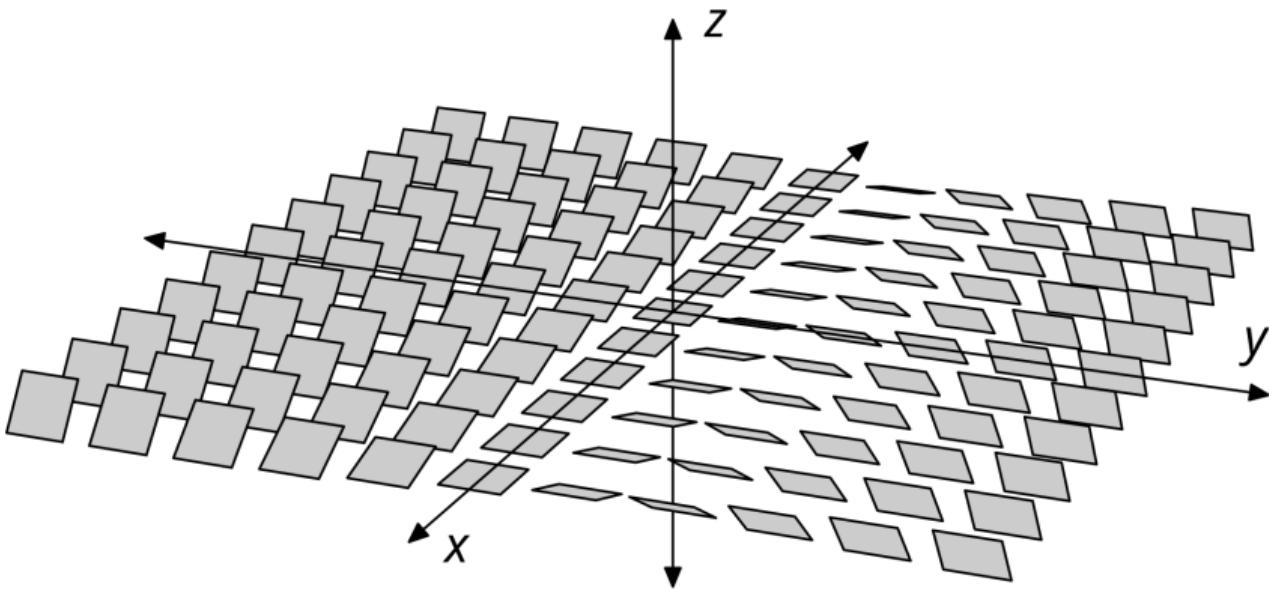


Figure: The standard contact structure on \mathbb{R}^3 . Wikipedia contributors, 2024b