

Topology – week 7

Math3061

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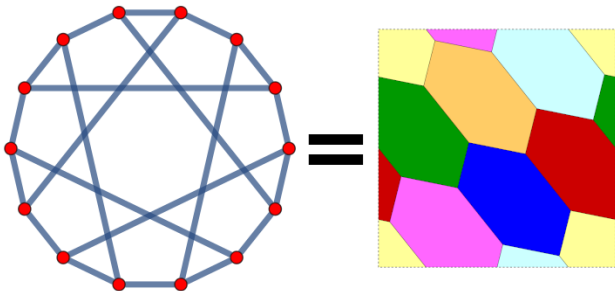
Lecturer Daniel Tubbenhauer

Office hour Zoom (<https://uni-sydney.zoom.us/j/89436493625>) Monday 4:30pm-5:30pm or by appointment (an informal email suffices)

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Web www.dtubbenhauer.com/teaching.html

- I apologize in advances for any typos or other errors on these slides!
- I'd be grateful for any corrections that you send to me or post on Ed



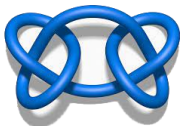
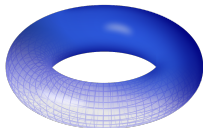
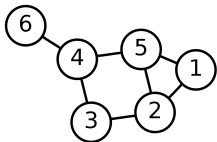
Topology

Unit outline

Topology is the study of properties of spaces that are preserved by **continuous deformation**

We will study:

- Graphs
- Surfaces
- Knots



These are all “topological” objects and we will study all of them by using **invariants** and by approximating them with **graphs**

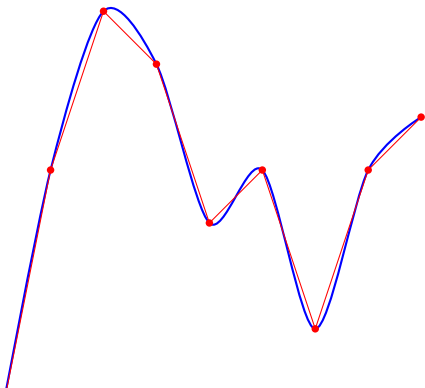
- In topology we are allowed to bend and stretch
- We are **not** allowed to cut, tear or join surfaces together

Underlying theme in this unit

In this course we want to understand **curves** and **surfaces** *but* we allow ourselves to wiggle and stretch the curves and surfaces

Thinking about an arbitrary curve or surface in space is hard, and this is even before we allow them to be continuously deformed

One of the key ideas that we will use is that we can **approximate** curves and surfaces using graphs



Topological equivalences



Topologically, a square and a circle are the same



Topologically, a cube and a sphere are the same

We will see in more detail why these are the same later

...as well as looking at more exotic surfaces



A torus is the same as a coffee mug



Source <https://en.wikipedia.org/wiki/Topology>

Graphs

A (finite) **graph** is an ordered pair $G = (V, E)$, where:

- V is a non-empty finite set of **vertices**
- E is a finite **multiset** of **edges**, which are **unordered** pairs of vertices

The difference between a **set** and a **multiset** is that multisets can have repeated entries

Examples

- $V = \{1, 2, 3\}$ and $E = \{\{1, 1\}, \{1, 1\}, \{1, 1\}, \{2, 3\}\}$
- $V = \{a, b, c, d\}$ and $E = \{\{a, a\}, \{a, b\}, \{a, b\}, \{a, c\}, \{a, d\}\}$

Graphs in the plane

Rather than working with the abstract definition of graphs, it is more intuitive to draw pictures of graphs in the plane where:

vertices = distinct **points** in \mathbb{R}^2 , **edges** = **curves** between the points

This is called a **realization** of the graph in \mathbb{R}^2

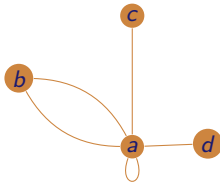
Examples

- $V = \{1, 2, 3\}$ and $E = \{\{1, 1\}, \{1, 1\}, \{1, 1\}, \{2, 3\}\}$



(not **connected**!)

- $V = \{a, b, c, d\}$ and $E = \{\{a, a\}, \{a, b\}, \{a, b\}, \{a, c\}, \{a, d\}\}$



(**connected**!)

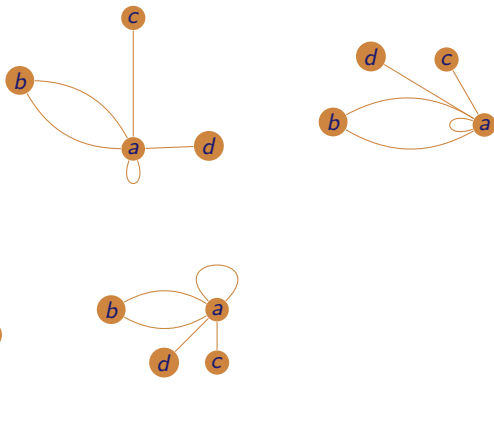
As shown, we allow **loops** and **duplicate edges**

Warning: drawings can be misleading

Drawings of graphs are useful pictorial aids, but be careful:

There are many ways to draw the same graph so we always need to check that whatever are doing does not depend on how the graph is drawn!

Here are four different ways to draw the same graph



Standard graphs

Path graphs P_n , for $n \geq 1$ (also called line graphs)

Vertex set $V = \{1, 2, \dots, n\}$

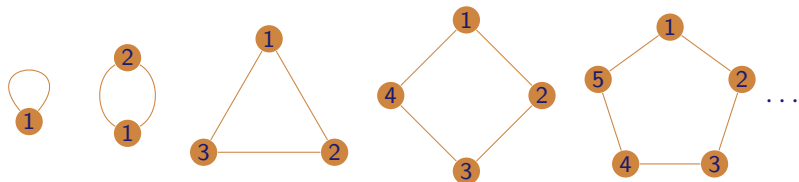
Edge set $E = \{\{1, 2\}, \{2, 3\}, \dots, \{n-1, n\}\}$



Cyclic graphs C_n , for $n \geq 1$

Vertex set $V = \{1, 2, \dots, n\}$

Edge set the multiset $E = \{\{1, 2\}, \{2, 3\}, \dots, \{n-1, n\}, \{n, 1\}\}$

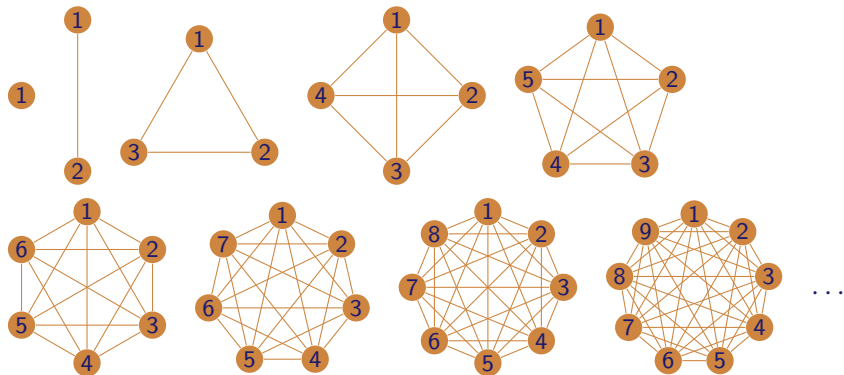


Standard graphs...

Complete graphs K_n , for $n \geq 1$

Vertex set $V = \{1, 2, \dots, n\}$

Edge set $E = \{ \{i, j\} \mid 1 \leq i < j \leq n \}$

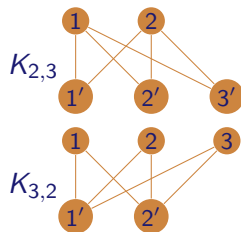


Standard graphs...

Complete bipartite graphs $K_{n,m}$, for $n, m \geq 1$

Vertex set $V = \{1, 2, \dots, n, 1', 2', \dots, m'\}$

Edge set $E = \{ \{i, j'\} \mid 1 \leq i \leq n, 1 \leq j \leq m \}$



Directed graphs

We sometimes use **directed graphs** where we care about the orientation of the edges.

Formally, a (finite) **directed graph** is an ordered pair (V, E) , where:

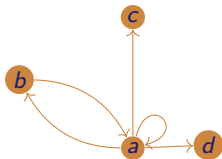
- V is a finite set of **vertices**
- E is a finite **multiset** of **directed edges**, or **ordered pairs** of vertices

Examples

- $V = \{1, 2, 3\}$ and $E = \{(1, 1), (1, 1), (1, 1), (2, 3)\}$



- $V = \{a, b, c, d\}$ and $E = \{(a, a), (a, b), (b, a), (a, c), (a, d)\}$



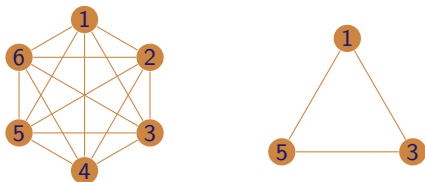
Subgraphs

A **subgraph** of a graph $G = (V, E)$ is a graph $H = (W, F)$ such that
 $W \subseteq V$ and $F \subseteq E$

If (V, E) is a graph and $W \subseteq V$ then the **full subgraph** of (V, E) with vertex set W is the graph (W, F) with $F = \{ \{w, w'\} \in E \mid w, w' \in W \}$

That is, the full subgraph of $G = (V, E)$ with vertex set W is the subgraph of G that contains every edge in G that connects vertices in W .

Example The full subgraph of K_6 with vertex set $W = \{1, 3, 5\}$ is:



That is, $F = \{ \{1, 3\}, \{3, 5\}, \{5, 1\} \}$

Clearly, (W, F) is “the same” as the cyclic graph C_3

...but what does it mean for graphs to be “the same”?

Isomorphic graphs

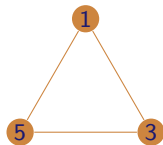
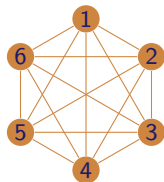
Two graphs $G = (V, E)$ and $H = (W, F)$ are **isomorphic**, written $G \cong H$, if there is a **bijection** $f: V \rightarrow W$ such that the induced map on edges, which sends an edge $\{v, v'\} \in E$ to $\{f(v), f(v')\}$, is also a bijection.

Notice that if $f: G \rightarrow H$ is a graph isomorphism then:

- if $\{v, v'\} \in E$ is an edge of G then $\{f(v), f(v')\} \in F$ is an edge of H
- **Every** edge $\{w, w'\} \in F$ can be written uniquely as $\{f(v), f(v')\}$

Examples

- $G \cong H$ if and only if $H \cong G$
- $K_{n,m} \cong K_{m,n}$
- The full subgraph of K_6 with vertex set $W = \{1, 3, 5\}$ has edge set $F = \{\{1, 3\}, \{3, 5\}, \{5, 1\}\}$



Claim $(W, F) \cong C_3$

For example, define f by

$$f(1) = 1,$$

$$f(3) = 2, \text{ and}$$

$$f(5) = 3$$

Subgraphs of complete graphs

Proposition

Let $G = (V, E)$ be a graph on n vertices that has no loops and no duplicated edges. Then G is isomorphic to a subgraph of K_n .

Proof

Write $V = \{v_1, v_2, \dots, v_n\}$.

Let $N = \{1, 2, \dots, n\}$ be the vertex set of K_n and let

$$E_n = \{ \{i, j\} \mid 1 \leq i < j \leq n \}$$

be its edge set.

Define $H = (N, E_V)$ to be the subgraph of K_n with

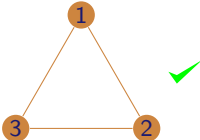
$$E_V = \{ \{i, j\} \mid \{v_i, v_j\} \in E \}.$$

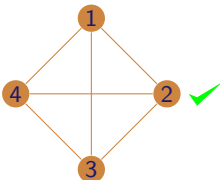
Then the map $f : N \rightarrow V$ given by $f(i) = v_i \in V$ is a graph isomorphism.

Complete graphs are rarely planar

• K_1 

• K_2 

• K_3 

• K_4 

• K_5 

• K_6 

Graph embeddings in \mathbb{R}^3

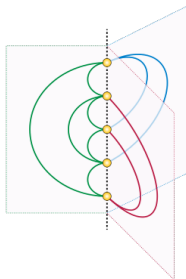
Theorem

Every graph can be embedded (i.e. without edge crossings) in \mathbb{R}^3

Moral Graphs are “low dimensional” objects

Proof First, loops and duplicate edges are easy to treat, so we ignore them. Next, use a book embedding:

A 3-page embedding of K_5 :



In general, one can embed K_n into a book with $\lceil n/2 \rceil$ pages. Since every graph is a subgraph of some K_n , so we are done since books $\subset \mathbb{R}^3$

The degree of a vertex

Let $G = (V, E)$ be a graph. The **degree** of a vertex $v \in V$ is

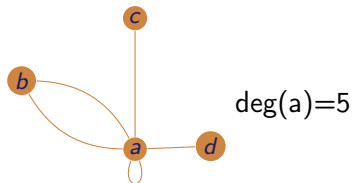
$$\deg(v) = \#\left\{\text{number of edges in } E \text{ that have } v \text{ as an endpoint}\right\}$$

Examples

•



•

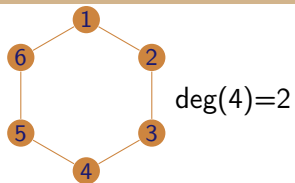


• P_n

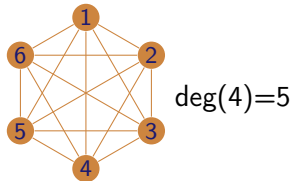


Degrees of vertices in standard graphs; examples

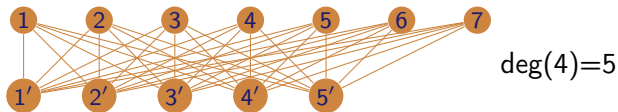
• C_n



• K_n



• $K_{n,m}$



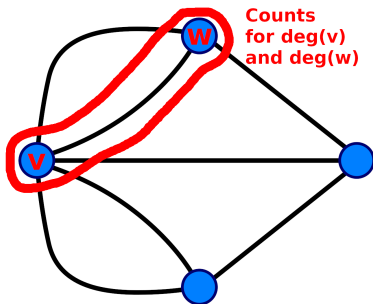
The handshaking lemma

Proposition (Vertex-degree equation = handshaking lemma)

Let $G = (V, E)$ be a finite graph. Then

$$\sum_{v \in V} \deg(v) = 2|E|$$

Proof If I shake your hand, then you shake mine: every edge is adjacent to two vertices, hence each edge contributes twice



The handshaking lemma

Proposition (Vertex-degree equation = handshaking lemma)

Let $G = (V, E)$ be a finite graph. Then

$$\sum_{v \in V} \deg(v) = 2|E|$$

Proof

Strictly speaking, we would use induction on $|E|$:

There is nothing to show if there is no edge, and if $|E| > 0$ remove any edge e use induction for $E' = E \setminus \{e\}$, and add e using the previous observation

The Euler characteristic of a graph

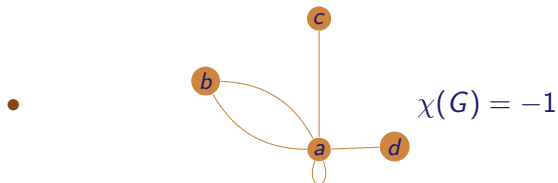
Let $G = (V, E)$ be a graph. The Euler characteristic of G is the integer

$$\chi(G) = |V| - |E|$$

Moral

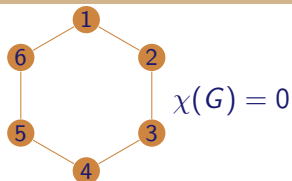
$\chi(G) = \#(\text{degree 0 components of } G) - \#(\text{degree 1 components of } G)$

Examples

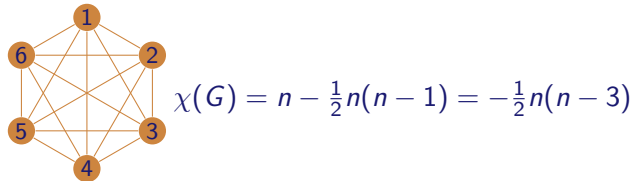


The Euler characteristic of standard graphs

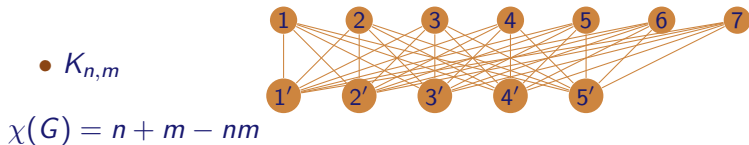
- C_n



- K_n



- $K_{n,m}$

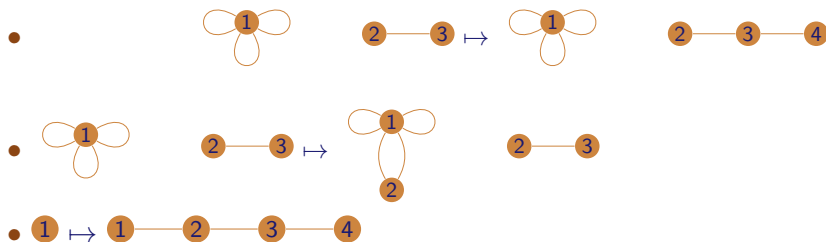


Subdividing graphs

Let $G = (V, E)$. A **subdivision** of G is any graph \hat{G} that is obtained from G by successively replacing V with $V \cup \{u\}$, for $u \notin V$, and E with $E \cup \{\{v, u\}, \{u, w\}\} \setminus \{\{v, w\}\}$, for an edge $\{v, w\} \in E$

That is, we successively replace an edge $v \text{---} w$ with $v \text{---} u \text{---} w$

Examples



Subdivision and Euler characteristic

Proposition

Let \dot{G} be a subdivision of G . Then $\chi(\dot{G}) = \chi(G)$

Proof

The operation



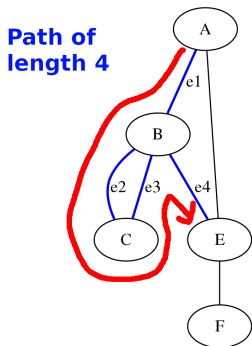
clearly increases V and E by one, so their difference does not change.

Paths in graphs

Let $G = (V, E)$ be a graph and $v, w \in V$. A **path** in G of **length n** from v to w is a sequence of vertices $v = v_0, v_1, \dots, v_n = w$ such that $\{v_i, v_{i+1}\} \in E$, for $0 \leq i < n$.

That is, the path looks like 

Example



Connectivity in graphs

Observations

- Every vertex is a path of length 0
- A path can pass through any edge zero or more times
- A path can go through any vertex zero or more times
- A path $P = (v = v_0 \rightarrow v_2 \rightarrow \cdots \rightarrow v_n = w)$ of length n in a graph is the same as a **graph homomorphism** (not nes. an iso) $f : P_{n+1} \rightarrow G$ with $f(i) = v_{i-1}$, for $1 \leq i \leq n+1$

A graph is **connected** if there is a path between any two vertices

The **connected components** of a graph G are the maximal connected subgraphs of G . That is, $H = (W, F)$ is a connected component of $G = (V, E)$ if H is connected and $\{v, w\} \in F$ whenever $\{v, w\} \in E$ and $w \in W$

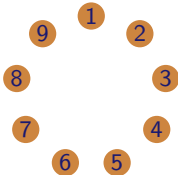
Example



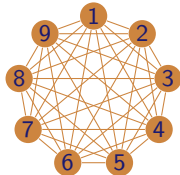
Not connected, two connected components

Connected examples

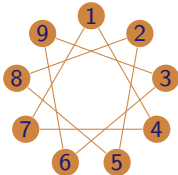
- A fully “disconnected” graph:



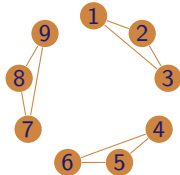
- A fully connected graph:



- Three connected components



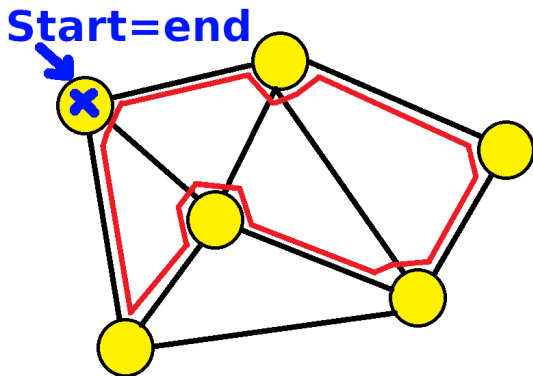
- Three connected components



Circuits

A **circuit** or **cycle** in G is a path from any vertex to itself

Example



Observations about circuits

Observations

- Every vertex is a circuit of length 0
- A circuit can pass through any edge zero or more times
- A circuit can go through any vertex zero or more times
- A circuit $P = (v = v_0 \rightarrow v_2 \rightarrow \cdots \rightarrow v_n = v)$ of length n in a graph is the same as a **graph homomorphism** (not nes. an iso) $f : C_n \rightarrow G$ with $f(i) = v_i$, for $0 \leq i \leq n$
- “Inefficient circuits” backtrack over the same edges and vertices
- We will soon see that the Euler characteristic is closed related to the number of “reduced” circuits in a graph

Contractible circuits

A circuit $v = v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_n = v$ is **contractible** if it contains two consecutive repeated edges $\{v_i, v_{i+1}\} = \{v_{i+1}, v_{i+2}\}$, for some $0 \leq i \leq n-2$

Reduced circuits

A circuit is **reduced** if it is not contractible

Notice that every circuit $v = v_0 \rightarrow v_1 \rightarrow \cdots \rightarrow v_n = v$ can be replaced with a reduced circuit by successively deleting the repeated edges

$$v_i \rightarrow v_{i+1} \rightarrow v_{i+2} = v_i.$$

Observations

- Reduced circuits are “efficient” in the sense that they do not backtrack
- A reduced circuit of length n is not necessarily isomorphic to the cycle graph C_{n+1} because it could, for example, be a figure 8 graph

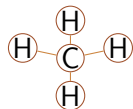
Leaves and trees

A **non-trivial** circuit is a reduced circuit of length $n > 0$

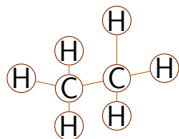
A **tree** is a connected graph that has no non-trivial circuits

Examples

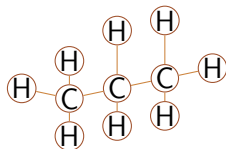
- Saturated hydrocarbons



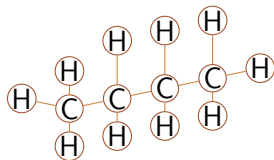
Methane



Ethane

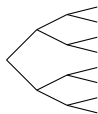


Propane

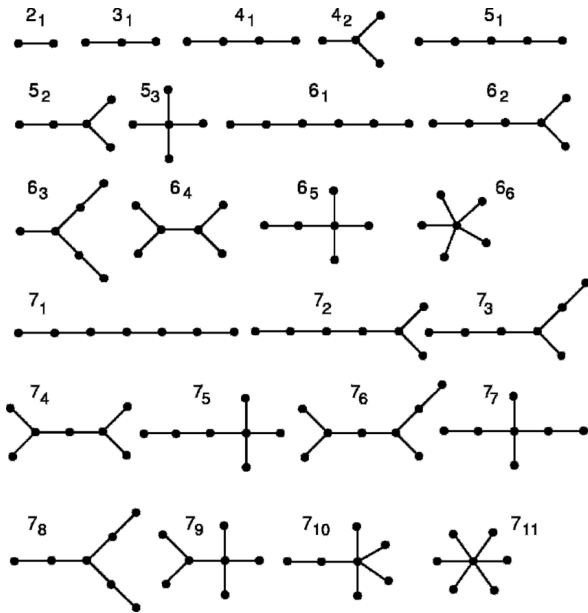


Butane

- A tournament tree



A catalog of small (connected) trees



Trees have leaves

If T is a tree then a leaf in T is any vertex of degree 1

Theorem

Let T be a tree with at least one edge. Then T has at least two leaves.

Remark This result provides an inductive tool for proving facts about trees because removing a leaf gives a tree with one less edge and vertex

Proof Take a longest reduced path P in T , then both endpoints of P are leaves

Why? Say the endpoints are v and w . WLOG suppose v is not a leaf; then v has at least two neighbors and one of them is not in P . (Otherwise we would have a circuit.) Thus one can make P longer. Contradiction

The Euler characteristic of a tree

Theorem

Suppose that T is a tree. Then $\chi(T) = 1$

Proof Argue by induction on the number of edges $|E|$

For $|E|$ small use the previous table.

Otherwise, remove one leaf (which exists by the previous statement). The resulting tree has $\chi(T) = 1$, and adding the leaf back increases V and E by one, so χ remains constant

Number of edges and vertices in a tree

Corollary

Suppose that $T = (V, E)$ is a tree. Then $|V| = |E| + 1$.

Proof By the previous statement

Spanning trees

Proposition

Suppose that $G = (V, E)$ is a connected graph.

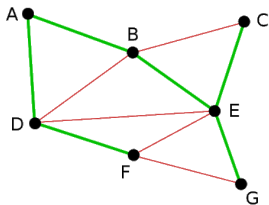
Then G has a subgraph $T = (V, F)$ (same vertices) that is a tree

Proof We remove edges to break circuits

(Formally, use induction on the number of nontrivial circuits of G)

A **spanning tree** of G is any subgraph T of G that is a tree and has the same set of vertices as G

Example



Spanning trees continued

Proposition

Suppose that $G = (V, E)$ is a connected graph.

Then G has a spanning tree $T = (V, F)$ (same vertices)

Proof Remove edges from nontrivial circuit of G to break them; the result is a spanning tree

(Formally, use induction on the number of nontrivial circuit of G)

An upper bound on $\chi(G)$

Corollary

Suppose that G is a connected graph. Then $\chi(G) \leq 1$ with equality if and only if G is a tree.

Proof By the previous statements G has more edges than any of its spanning trees, hence, $\chi(\text{span tree}) = 1$ implies the corollary

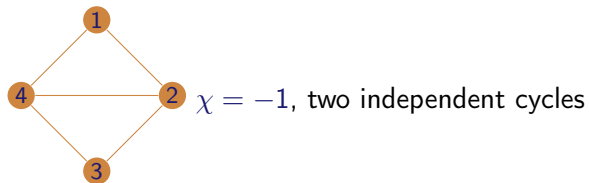
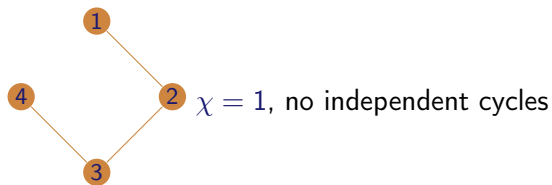
Corollary

Let G be a connected graph. The number of *independent cycles* (defined via example on the next slide) in G is $1 - \chi(G)$

Proof By the previous statements

Independent cycles

Examples



We have $\{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{1, 4\}\} =$
 $\{\{1, 2\}, \{2, 4\}, \{1, 4\}\} + \{\{2, 3\}, \{3, 4\}, \{2, 4\}\} \pmod{2}$

Remark It is possible to construct a vector space of “cycles” that has dimension $1 - \chi(G)$, which shows that the number of independent cycles makes sense. This is beyond the scope of this course.

Topology – week 8

Math3061

Daniel Tubbenhauer, University of Sydney

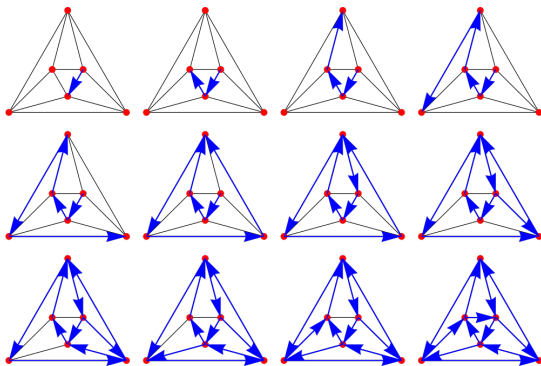
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Eulerian circuits and graphs

A **Eulerian circuit** is a circuit that passes through every **edge** exactly once

A graph is **Eulerian** if it has a Eulerian circuit

Example

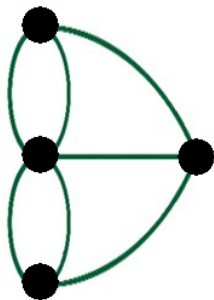
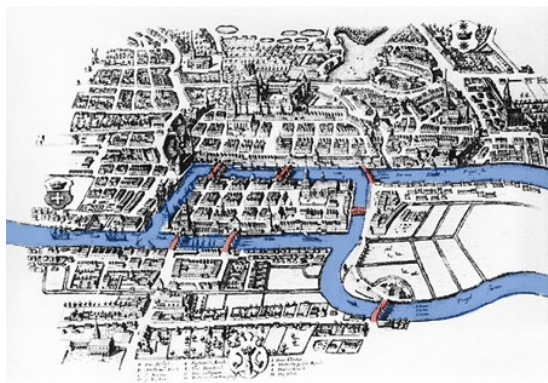


Warning Eulerian graphs do not need to be connected because they may have vertices of degree 0!

Finding Eulerian circuits

In 1736 Euler asked when graphs have Eulerian circuits (without having this terminology)

The motivation was that they wanted to know if it was possible to walk around the city of Königsberg crossing each bridge exactly once



In answering this question Euler laid the foundations of graph theory

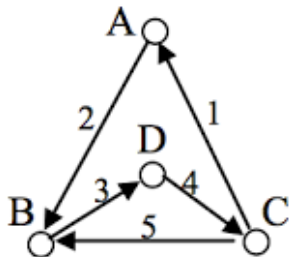
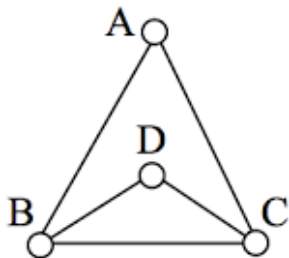
Classifying Eulerian graphs

Theorem

Let $G = (V, E)$ be a connected graph. Then G is Eulerian if and only if every vertex has even degree

Proof

Assume that there is at least one vertex v of odd degree. Since we want to visit every edge exactly once we will eventually get stuck in v or another vertex of odd degree while trying to create an Eulerian cycle. Hence, G can not have an Eulerian cycle



Classifying Eulerian graphs

Proof continued

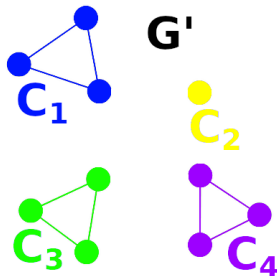
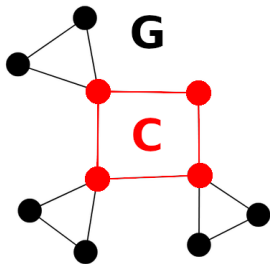
Conversely, if every vertex has even degree, then G is not a tree so contains some circuit C . If C is an Euler circuit we are done, and if not remove all edges of C from G . The resulting (potentially disconnected) graph G' has still even degrees for all of its vertices but fewer edges than G

So we can argue by induction on the number of edges (the base case has no edges and is thus clear), and inductively we can assume that the connected components of G' have Euler circuits C_1, \dots, C_n

Classifying Eulerian graphs

Proof continued

We piece C and C_1, \dots, C_n together into an Euler cycle: we walk along C and whenever we hit a vertex of C_i we take a detour over C_i



Eulerian paths

A **Eulerian path** is a path that is **not** a circuit and which passes through every **edge** exactly once

Corollary

Let $G = (V, E)$ be a connected graph that is not Eulerian. Then G has a Eulerian path if and only if it has exactly two vertices of odd degree

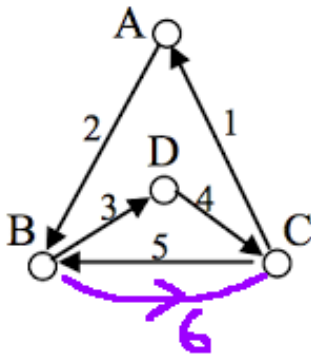
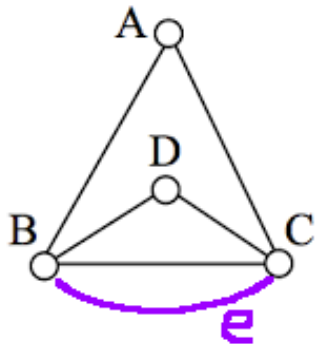
Proof

Only vertices of odd degree can be a start or an end vertex, so we need precisely two of them (all other must be of even degree by the same argument as before)

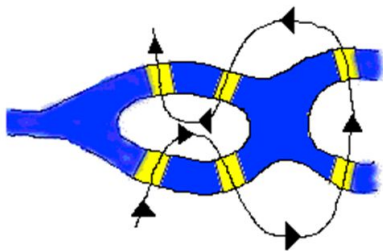
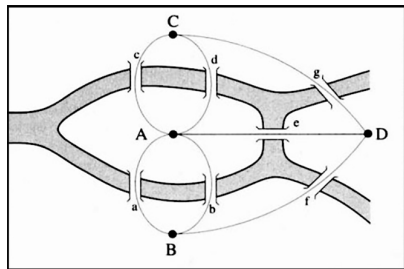
Eulerian paths

Proof continued

Conversely, if v and w are the two vertices of even degree, then we put an additional edge e between them. We get a graph $G' = G \cup \{e\}$ and the previous theorem gives us an Euler circuit C in G' . Then $C \setminus \{e\}$ is an Euler path



What about Königsberg?



There is no Eulerian circuit since all vertices have odd degree

There is no Eulerian path since all vertices have odd degree

Solution: Destroy bridge e ;-)

Topological equivalence

Let $X \subseteq \mathbb{R}^m$ and $Y \subseteq \mathbb{R}^n$, for $m, n \geq 1$

Definition

A **homeomorphism** $f: X \rightarrow Y$ is a **continuous** map that has a **continuous inverse** $g: Y \rightarrow X$. The spaces X and Y are **homeomorphic** if there is a homeomorphism $f: X \rightarrow Y$

Remarks

- Homeomorphism is the higher dim analog of isomorphism for graphs
We treat two spaces as being “equal” if they are homeomorphic
- The maps f and g are both bijections with **continuous inverses**
- We have $X \cong X$
- If $X \cong Y$, then $Y \cong X$
- If $X \cong Y$ and $Y \cong Z$, then $X \cong Z$

Examples of homeomorphisms

Proposition

If $a < b$ and $c < d$, then $[a, b] \cong [c, d]$

Proof

Define maps $f : [a, b] \rightarrow [c, d]; x \mapsto c + \frac{d-c}{b-a}(x-a)$
 $g : [c, d] \rightarrow [a, b]; x \mapsto a + \frac{b-a}{d-c}(x-c)$

Exercise Show that $(a, b) \cong (c, d)$ and $(a, b) \cong (c, d) \stackrel{!!!}{\cong} [a, b] \cong [c, d]$

Proposition

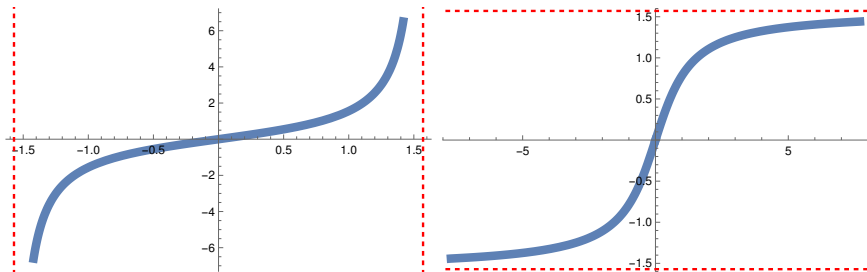
If $a < b$, then $(a, b) \cong \mathbb{R}$

Proof It is enough to show that $(-\frac{\pi}{2}, \frac{\pi}{2}) \cong \mathbb{R}$

Examples of homeomorphisms

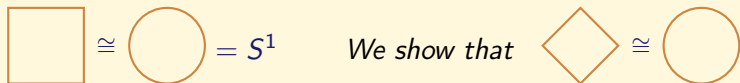
Proof continued

Homeomorphisms are given by $f(x) = \tan(x)$ and $g(x) = \tan^{-1}(x)$



Examples of homeomorphisms...

Proposition



Proof

The square is $\{(x, y) \mid |x| + |y| = 1\}$ and $S^1 = \{(x, y) \mid x^2 + y^2 = 1\}$

Define: $f: \square \rightarrow S^1; (x, y) \mapsto \left(\frac{x}{\sqrt{x^2+y^2}}, \frac{y}{\sqrt{x^2+y^2}}\right)$

$g: S^1 \rightarrow \square; (x, y) \mapsto \left(\frac{x}{|x|+|y|}, \frac{y}{|x|+|y|}\right)$

Note that  $\not\cong$

For free we see that the square and disk are homeomorphic:

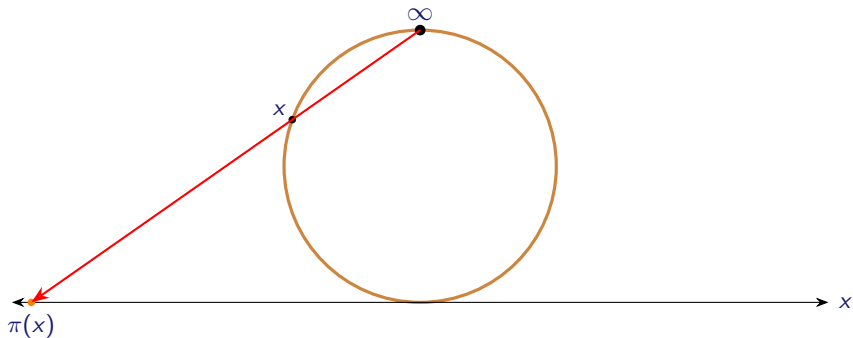
Corollary



Stereographic projection in two dimensions

Think of the north pole of the circle S^1 as ∞

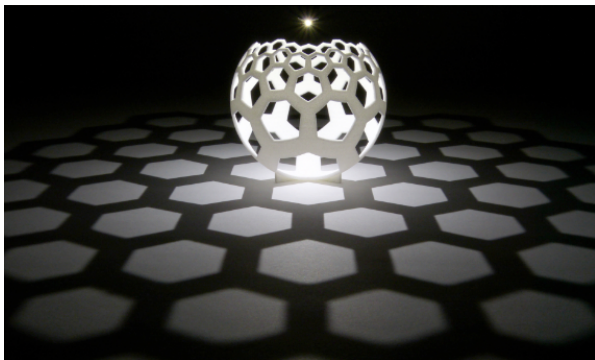
Stereographic projection gives a homeomorphism $\pi: S^1 \setminus \{\infty\} \rightarrow \mathbb{R}$:



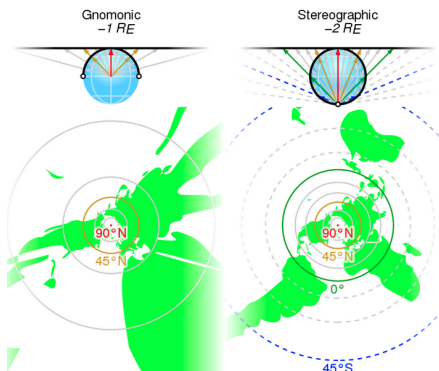
Stereographic projection in three dimensions

Think of the north pole of the circle S^2 as ∞

Stereographic projection gives a homeomorphism $\pi: S^2 \setminus \{\infty\} \rightarrow \mathbb{R}^2$:



Stereographic projection is used to draw maps:



Other projections are also used such as gnomonic projections, conic projections and the Mercator projection, which is a cylindrical projection. Now that we have seen homeomorphisms we are ready to define surfaces.

Surfaces — informal definition

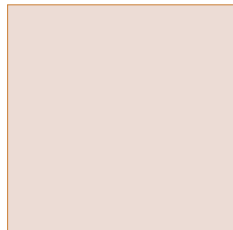
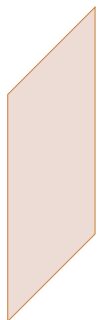
Definition

A **surface** is a subset of \mathbb{R}^n that, locally, is homeomorphic to the graph of the function $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ given by $f(x, y) = z$ / alternatively to a **disc**

Here “locally” means that we can find a “local neighborhood” of every point where the function looks like the plane $f(x, y) = z$ / a **disc**

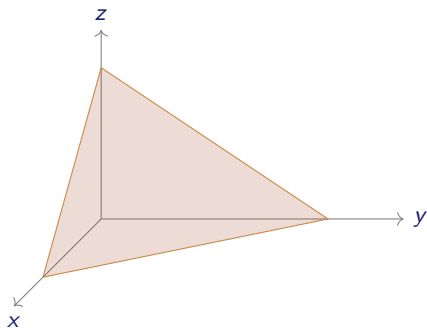
Examples

- A standard xyz -plane in \mathbb{R}^3

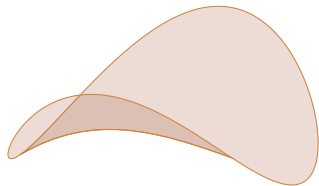


Surfaces — examples...

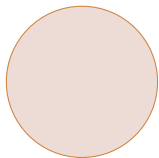
- Non-standard planes in \mathbb{R}^3



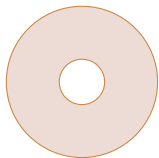
- Curved surfaces in \mathbb{R}^3



- A disk \mathbb{D}^2



- An annulus $\mathbb{A} \cong$ cylinder



\cong

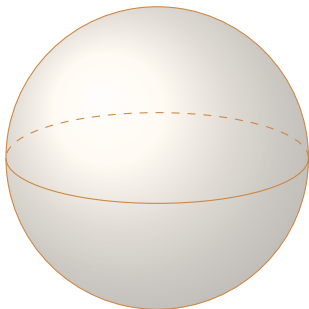


Strictly speaking, these are not surfaces according to our definition because they have a **boundary**, whereas planes in \mathbb{R}^2 do not have boundaries.

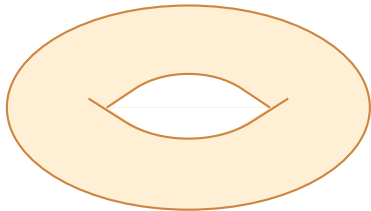
Our rigorous definition of a surface will allow surfaces with boundaries

Surfaces — examples...

- A sphere S^2



- A torus \mathbb{T}



Surfaces — real world examples...

- A sphere $S^2 \cong$ soccer ball



- A torus $\mathbb{T} \cong$ swim ring



Surfaces — real world example...

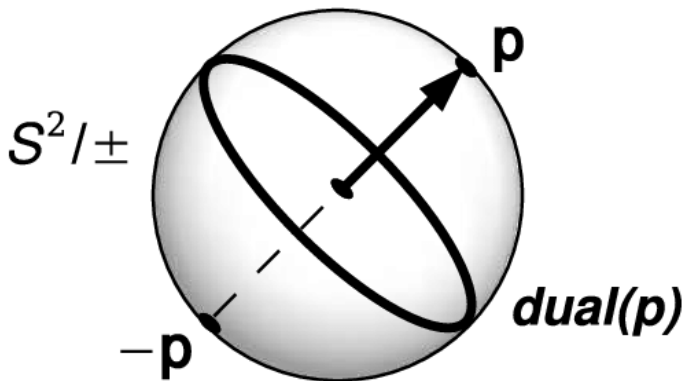
- Here is a surface with boundary:



The patches are examples of neighborhoods which are discs

Surfaces — examples...

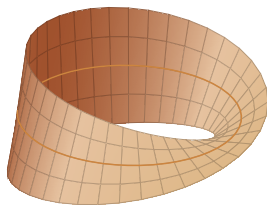
- The real projective plane $\mathbb{P}^2 = S^2/\text{antipode}$



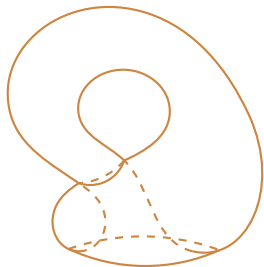
We will see other ways to describe \mathbb{P}^2 later

Surfaces — examples...

- A Möbius band, or Möbius strip, \mathbb{M}



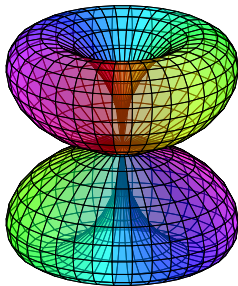
- A Klein bottle \mathbb{K} , also Klein surface



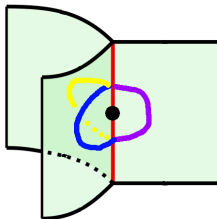
This is a three dimensional “shadow” of a four dimensional object

Surfaces — non-examples

- This is **not** a surface because of the cusp at the origin



- This is **not** a surface because the indicated point has not a disc neighborhood



Identification spaces

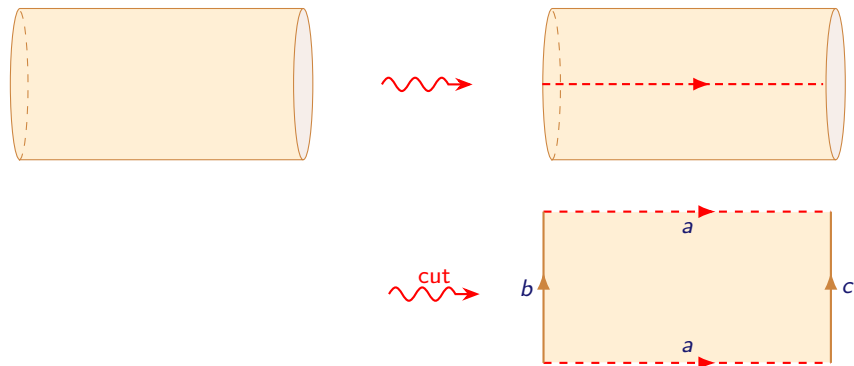
A **partition** of a surface $S \subseteq \mathbb{R}^m$ is a collection X_1, \dots, X_r of subsets of S such that $S = X_1 \cup X_2 \cup \dots \cup X_r$

The space S is an **identification space** for $Y \subseteq \mathbb{R}^n$ if there exists a continuous surjective map $f: S \rightarrow Y$

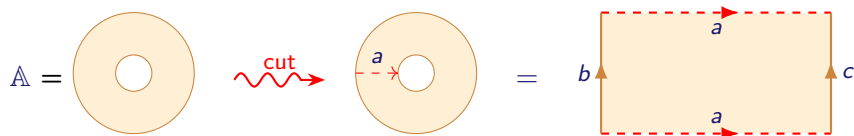
Note $Y = f(X_1) \cup f(X_2) \cup \dots \cup f(X_r)$ and that the map f implicitly **identifies** the points in $f(X_{i_1}) \cap \dots \cap f(X_{i_s})$, for $1 \leq i_1, \dots, i_s \leq r$

This makes it possible to understand Y in terms of, often, easier spaces X_1, \dots, X_r , which we think of as covering Y like a patchwork quilt

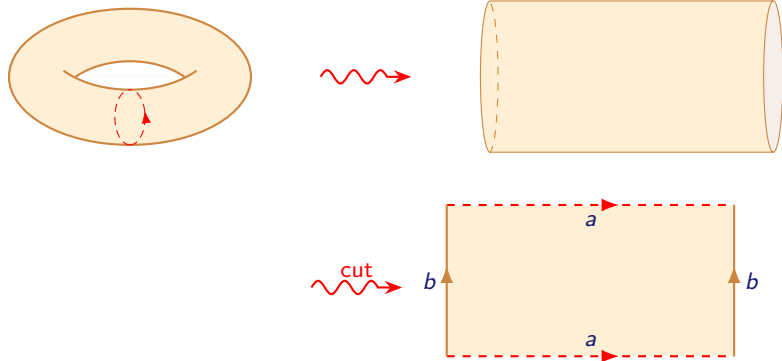
Identification space for a cylinder



That is, the cylinder is the identification space obtained by identifying the top and bottom edges of a suitably sized rectangle

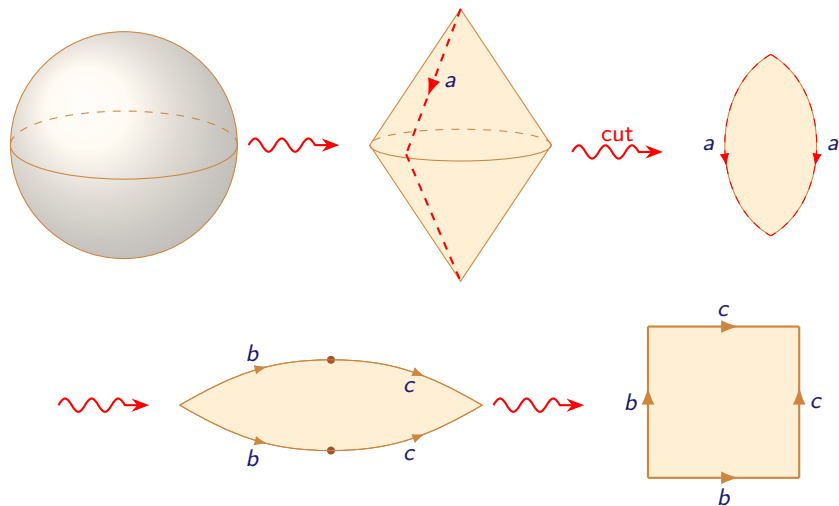


Identification space for a torus



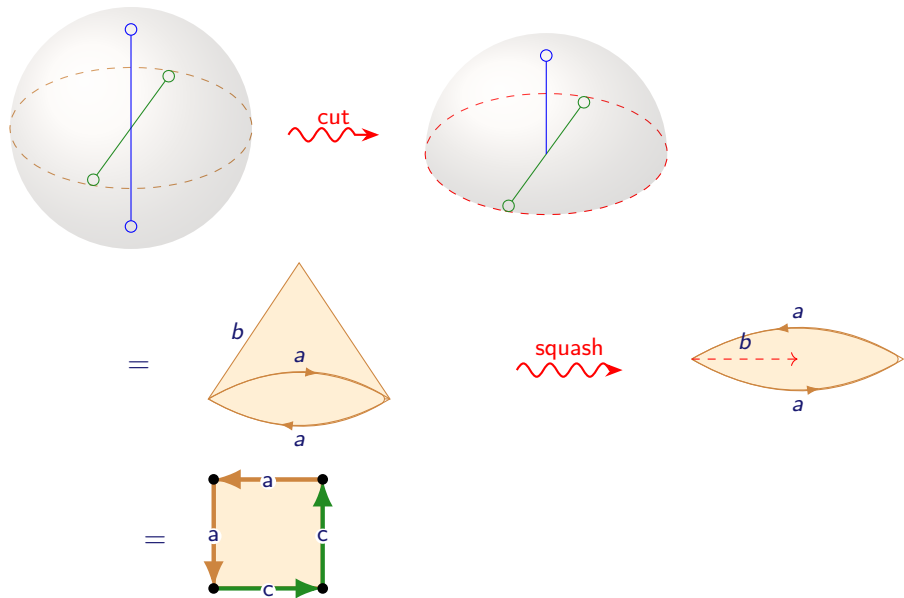
So, the torus \mathbb{T} is obtained by identifying the top and bottom, and the left and right, edges of a rectangle

Identification space for a sphere

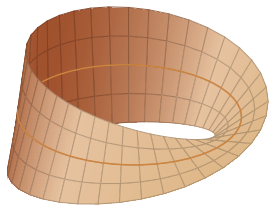


The sphere S^2 is obtained by identifying adjacent sides of a rectangle, or a 2-gon (a polygon with two sides)

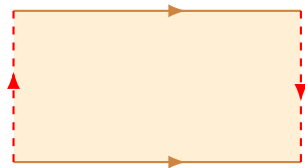
Identification space for the projective plane \mathbb{P}^2



Identification space for a Möbius strip

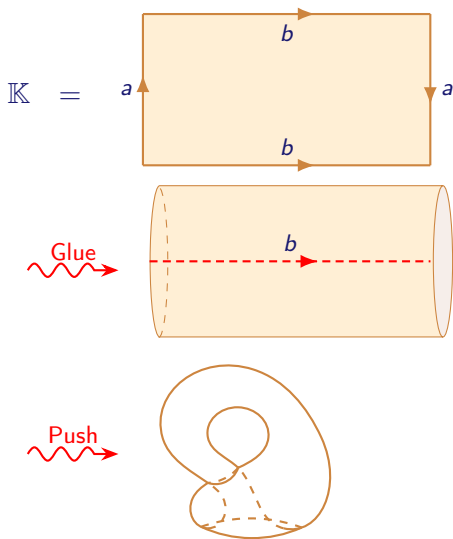


cut

A red wavy arrow pointing to the right, indicating the direction of the cut.

Identification space for a Klein bottle

The Klein bottle is defined to be the identification space



It is not clear how we do the last step in \mathbb{R}^3 and, in fact, we can't!

Polygons in \mathbb{R}^n

We have seen that all of our “standard surfaces” can be viewed as identification spaces using rectangles

A **polygon** is an embedding of the cyclic graph C_m into \mathbb{R}^2 , together with its **face**, such that the vertices of C_m map to distinct points in \mathbb{R}^2 and the images of the edges do not intersect in \mathbb{R}^2

\implies The image of C_n in \mathbb{R}^2 is homeomorphic to the closed disc \mathbb{D}^2



C_2



C_3



C_4



C_5



C_6

...

Remarks

- The image of C_m in \mathbb{R}^2 is an m -gon, or a polygon with m sides
- Polygons are surfaces in \mathbb{R}^2 . They are different from cyclic graphs because they have vertices, edges and one **face**
- The graph C_2 has only **one** edge. When working with surfaces we think of C_2 as having two edges so that its image in \mathbb{R}^2 is a 2-gon

Definition

A **surface** S is an identification space in \mathbb{R}^n that is obtained by gluing together polygons along their edges in such a way that at most two edges meet along any edge

The polygons give a **polygonal decomposition** of the surface S

Remarks

- A surface is an identification space where we identify pairs of edges in polygons. Informally, a surface is a patchwork quilt of polygons
- This essentially agrees with our earlier definition of surfaces because every polygon is homeomorphic to a closed disc \mathbb{D}^2 so, locally, surfaces look like planes / like discs
- A surface can have many seemingly different polygonal decompositions
- A surface with a polygonal decomposition has **vertices**, **edges** and **faces**
- We sometimes write $S = (V, E, F)$, where V is the vertex set, edge set E , and face set F

Identifying edges in polygonal decompositions

Whenever we draw polygonal decompositions we will usually:

- Label all of the edges with letters: a, b, c, \dots
- Use the same color for edges that have the same label
- Fix a direction of every edge (this is important!)

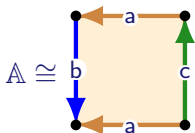
Remarks

- Identifying edges implicitly identifies vertices
- Colouring the edges is not strictly necessary but makes it easier to see how the edges are identified in the polygonal decomposition
- You do not need to color the edges in your work, but you can if you want to
- It is important to give the correct orientation, or direction, for the paired edges because changing the direction of a paired edge will usually change the surface
- When doing surgery always double check that you do not accidentally change the orientation of an edge

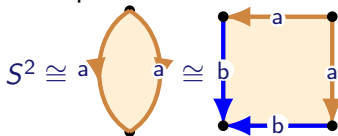
Examples of polygonal decompositions

We have already seen that:

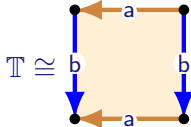
- Annulus



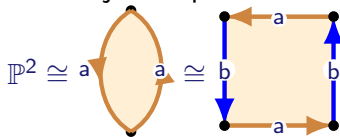
- Sphere



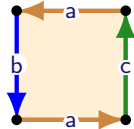
- Torus



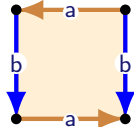
- Projective plane



- Möbius strip

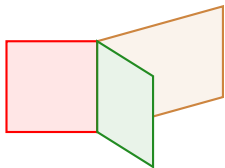


- Klein bottle



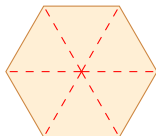
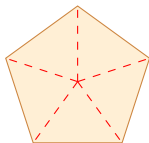
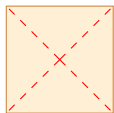
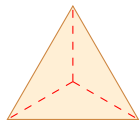
Important facts about polygonal decompositions

- Every polygon is homeomorphic to a closed disk \mathbb{D}^2
- At most two polygons meet in any edge, so



is not polygonal decomposition of a surface

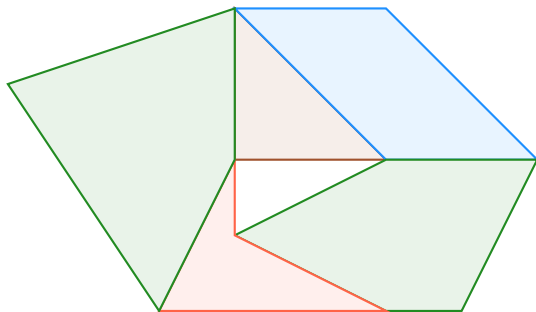
- Any polygonal decomposition can be replaced with one that only uses 3-gons:



\implies Iterating this process, shows that any surface has **infinitely many different** polygonal decompositions!

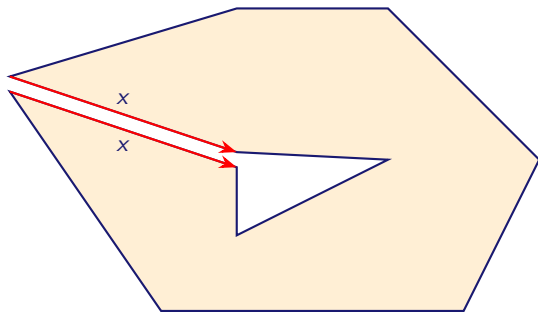
Important facts about polygonal decompositions...

- Every **connected** surface has a polygonal decomposition with one polygon — with identified edges
(A polygonal surface is connected if the underlying graph is connected)



Important facts about polygonal decompositions...

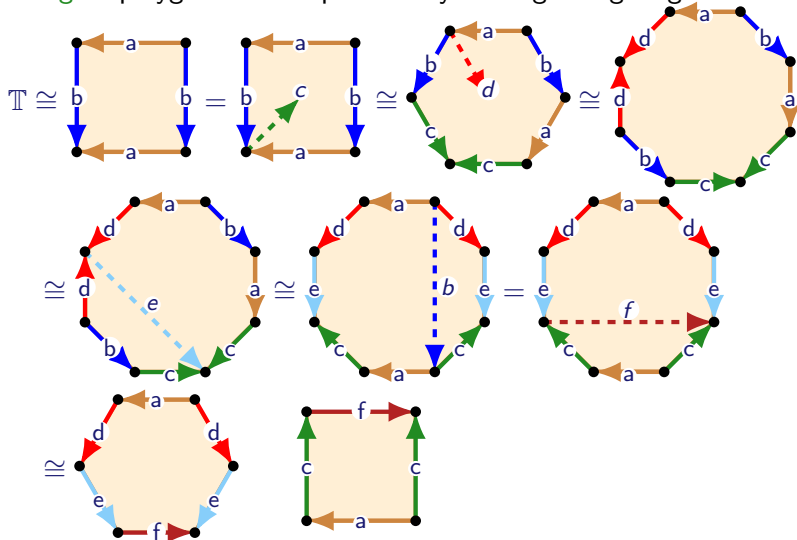
- Every **connected** surface has a polygonal decomposition with one polygon — with identified edges
(A polygonal surface is connected if the underlying graph is connected)



- We have to check that what we are doing does not depend on the **choice** of polygonal decomposition

Surgery: cutting and gluing

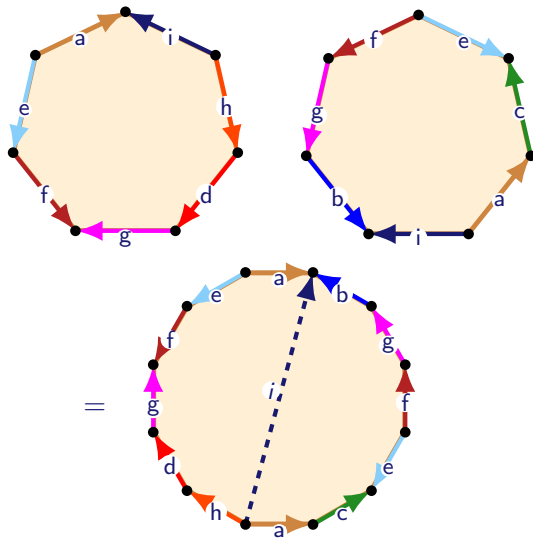
Surgery is our main tool for working with surfaces: it allows us to **change** a polygonal decomposition by cutting and gluing



We want an **easy** way to identify surfaces from polygonal decompositions

Example surface

Exercise Can we describe the following surface?



Answer Not yet! First we need more language and technology.

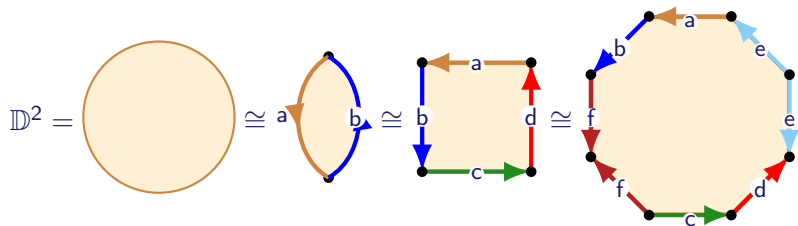
Free and paired edges and the boundary

Let S be a surface with a polygonal decomposition

- An edge is **free** if it occurs only once in the polygonal decomposition
- An edge is **paired** if it occurs twice
- The **boundary of S** is the union of the free edges
- A **boundary circle** is a cycle in the polygonal decomposition in which every edge is free

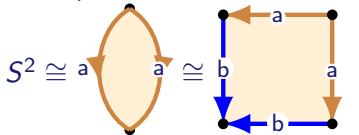
We will show that boundary of S is a disjoint union of boundary circles

Example

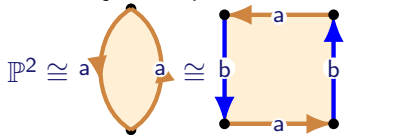


Example boundary circles...

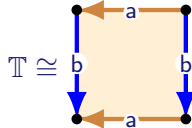
- Sphere



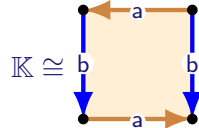
- Projective plane



- Torus

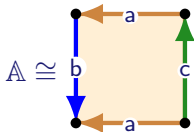


- Klein bottle

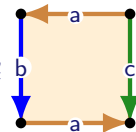


All edges paired \implies no boundary

- Annulus

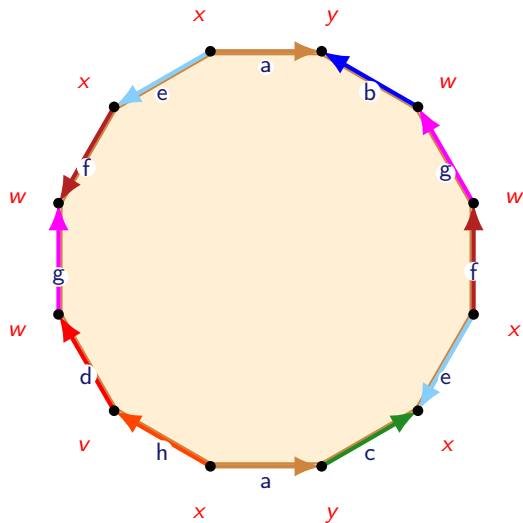


- Möbius $\mathbb{M} \cong$



Example boundary circles...

Exercise What is the boundary of the surface?



Free edges: b, c, d, h

Key observation
Paired edges imply that some vertices are equal

The Euler characteristic of a surface

Let $S = (V, E, F)$ be a surface with a polygonal decomposition

Definition

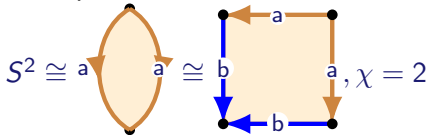
The Euler characteristic of S is $\chi(S) = |V| - |E| + |F|$

Remarks

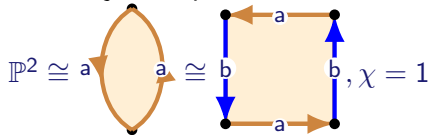
- The Euler characteristic $\chi(S) = |V| - |E| + |F|$ of S is a higher dimensional generalization of the Euler characteristic of a graph $G = (V, E)$, which is $\chi(G) = |V| - |E|$
- The definition of $\chi(S)$ appears to depend on the choice of polygonal decomposition (V, E, F) of S . In fact, we will soon see that $\chi(S)$ is independent of this choice

Euler characteristic of basic surfaces.

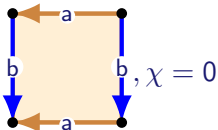
• Sphere



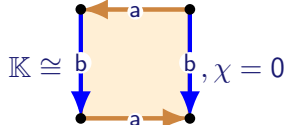
• Projective plane



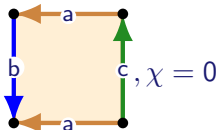
• Torus $\mathbb{T} \cong$



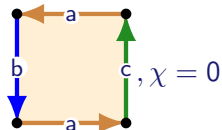
• Klein bottle



• Annulus $\mathbb{A} \cong$



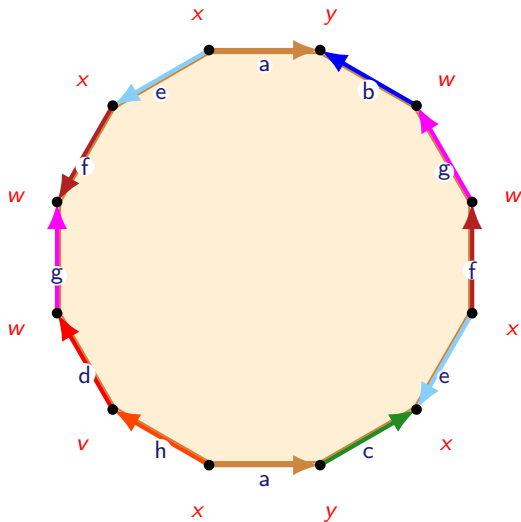
• Möbius $\mathbb{M} \cong$



Euler characteristic example

Example What is the Euler characteristic of the surface:

$S =$



$$\implies \chi(S) = -3$$

Subdivision of a surface

Let S be a surface with a polygonal decomposition

A **subdivision** of S is any polygonal decomposition that is obtained from S by successively applying the following operations:

- **Subdividing an edge** by adding a new vertex



- **Subdividing a face** by adding a new edge



Remarks

- The subdivision of a subdivision of S is a subdivision of S
- If \dot{S} has a polygonal decomposition that is a subdivision of a polygonal decomposition of S then $S \cong \dot{S}$

Subdividing and Euler characteristic

Proposition

Let \dot{S} be a subdivision of S . Then $\chi(S) = \chi(\dot{S})$

Proof It is enough to check this for the two subdivision operations:

- Subdividing an edge:



- Subdividing a face:



Both operations preserve χ

Subdividing and boundary circles

Proposition

Let \dot{S} be a subdivision of S . Then S and \dot{S} have the same number of boundary circles

Proof It is enough to check this for the two subdivision operations:

- Subdividing an edge:



- Subdividing a face:

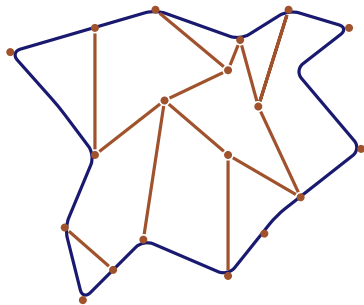
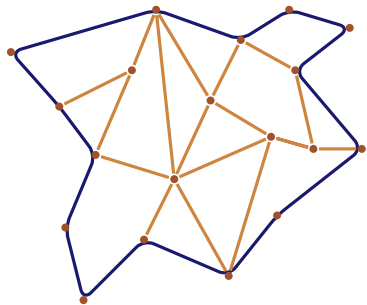


Common subdivisions

Theorem

Let S be a surface and suppose that S has polygonal decomposition $P_1 = (V_1, E_1, F_1)$ and $P_2 = (V_2, E_2, F_2)$. Then S has a polygonal decomposition (V, E, F) that is a common subdivision of P_1 and P_2

Proof Merge the two subdivisions

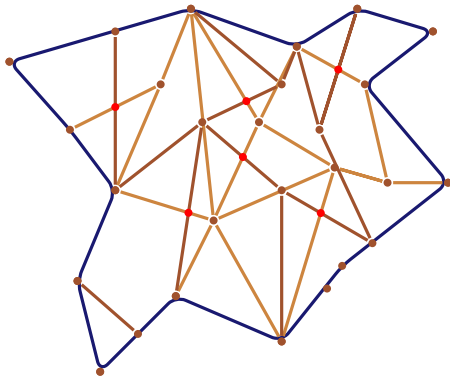


Common subdivisions

Theorem

Let S be a surface and suppose that S has polygonal decomposition $P_1 = (V_1, E_1, F_1)$ and $P_2 = (V_2, E_2, F_2)$. Then S has a polygonal decomposition (V, E, F) that is a common subdivision of P_1 and P_2

Proof Merge the two subdivisions — adding extra vertices as necessary



Two invariants

Corollary

Suppose that S and T are homeomorphic surfaces that have polygonal decompositions. Then $\chi(S) = \chi(T)$ and S and T have the same number of boundary circles.

Proof Since $S \cong T$ there is a continuous map $f: S \rightarrow T$ with a continuous inverse $g: T \rightarrow S$

Observe that if P is a polygonal decomposition of S then $f(P)$ is a polygonal decomposition of T . Similarly, if Q is a polygonal subdivision of T then $g(Q)$ is a polygonal decomposition of S

By the theorem we can assume that S and T have the same polygonal decomposition in the sense that $P = g(Q)$ and $Q = f(P)$

$$\implies \chi(S) = \chi_P(S) = \chi_{f(P)}(T) = \chi_Q(T) = \chi(T).$$

Similarly, S and T have the same number of boundary circles

Why are invariants useful?

Question

Let S and T be surfaces. Is $S \cong T$?

To show that S and T are homeomorphic is, in principle, easy: we find a continuous map $f : S \rightarrow T$ with a continuous inverse $g : T \rightarrow S$

Showing that $S \not\cong T$ is harder as we need to show that no such maps exist

Using **invariants** makes this easier because $S \cong T$ **only if** $\chi(S) = \chi(T)$ **and** if S and T have the same number of boundary circles

\implies if $\chi(S) \neq \chi(T)$, or if S and T have a different number of boundary circles, **then** $S \not\cong T$

Exercise Using what we know so far, deduce that the surfaces

$$S^2, \mathbb{A}, \mathbb{D}^2, \mathbb{K}, \mathbb{M}, \mathbb{P}^2$$

are pairwise non-homeomorphic (see Tutorial 9)

Topology – week 9

Math3061

Daniel Tubbenhauer, University of Sydney

© Semester 2, 2023

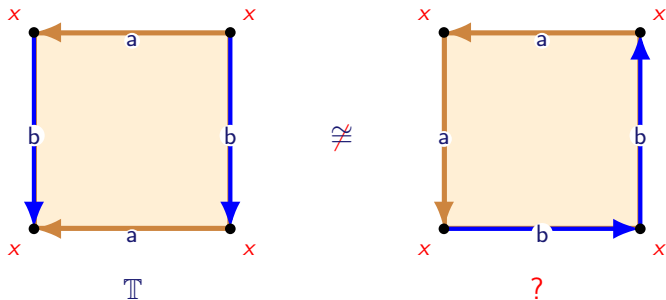
Classifying surfaces using invariants

We have seen that homeomorphic surfaces must have:

- The same Euler characteristic
- The same number of boundary circles

These two **invariants** are both easy to compute but, by themselves, they are not enough to distinguish between all surfaces

Example

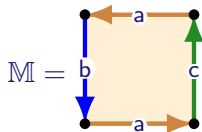


Definition

A surface S is **non-orientable** if it contains a Möbius strip \mathbb{M}
If S does **not** contain a Möbius strip it is **orientable**

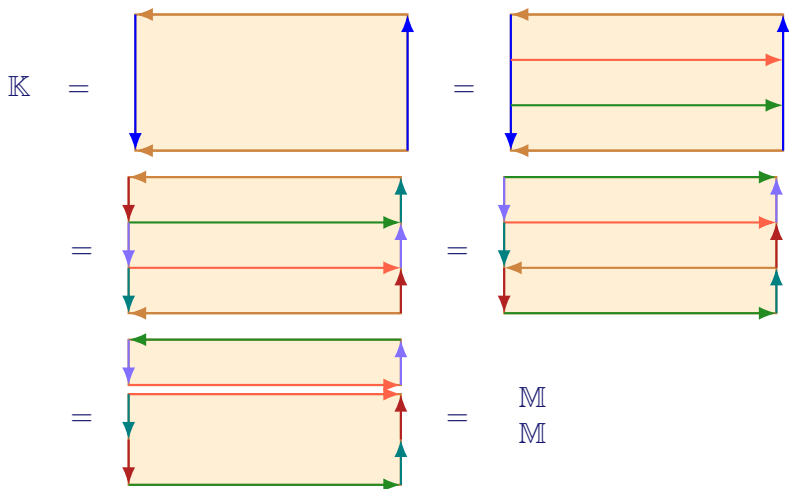
Remarks

- Even though this looks hard to apply we will see it isn't
- Clearly, \mathbb{M} is non-orientable, but there are no other "easy" examples



- Are S^2 , \mathbb{A} , \mathbb{D}^2 , \mathbb{T} , \mathbb{P}^2 , \mathbb{K} , ... orientable or non-orientable?
- Can a surface be orientable and non-orientable for different polygonal decompositions? (That would be bad!)

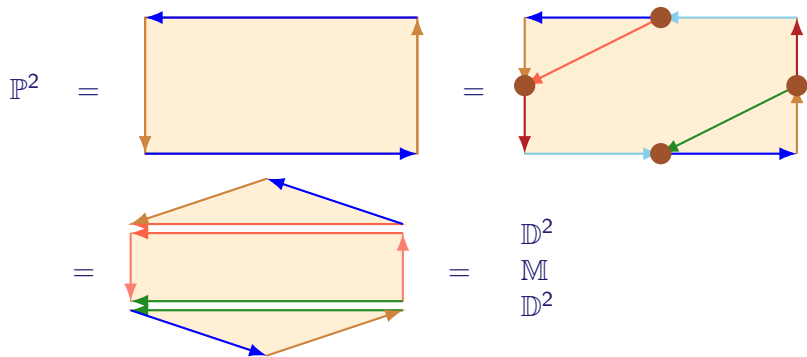
The Klein bottle \mathbb{K}



\implies The Klein bottle \mathbb{K} is non-orientable!

... although it might be more accurate to say that the Klein bottle is a Möbius strip without boundary

The projective plane \mathbb{P}^2



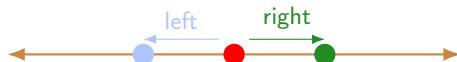
\implies The projective plane \mathbb{P}^2 is non-orientable

... or maybe \mathbb{P}^2 and not \mathbb{K}
is a Möbius strip without boundary?

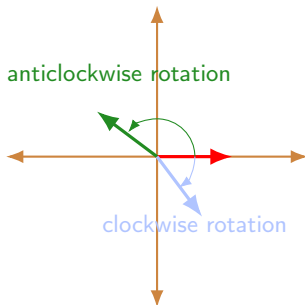
What does orientability mean?

Orientability is a generalisation of **direction** to higher dimensions

- One dimension \mathbb{R}



- Two dimensions \mathbb{R}^2



- Three dimensions \mathbb{R}^3 ???
- Higher dimensions \mathbb{R}^n , for $n \geq 3$???

Direction in higher dimensions

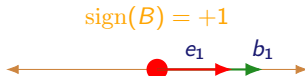
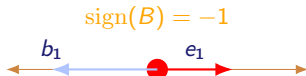
To generalise **direction**, choose an **ordered basis** $B = \{b_1, b_2, \dots, b_n\}$ of \mathbb{R}^n

The **order** of the basis elements is the key to understanding direction

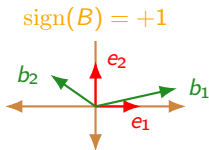
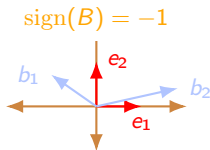
We can compare B to the **standard basis** $E = \{e_1, e_2, \dots, e_n\}$ of column vectors by computing the **sign** of the determinant

$$\det(B) = \det \begin{pmatrix} \vdots & \vdots & \dots & \vdots \\ b_1 & b_2 & \dots & b_n \\ \vdots & \vdots & \dots & \vdots \end{pmatrix} \rightsquigarrow \text{sign}(B) = \pm 1$$

- One dimension \mathbb{R}



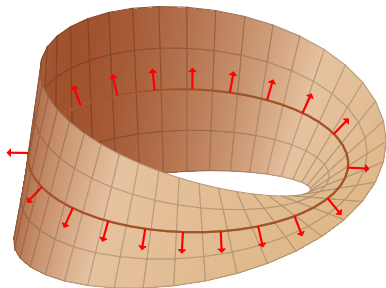
- Two dimensions \mathbb{R}^2



Direction on the Möbius strip

Pick a point $m \in \mathbb{M}$ on the Möbius strip and an ordered basis $B = \{b_1, b_2, b_3\}$ positioned at m with $b_3 = b_1 \times b_2$ pointing outwards

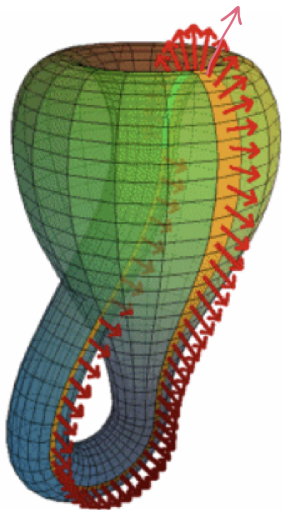
Now imagine m , and the coordinate axes moving, continuously around the Möbius strip so that the xyz -coordinate axes around \mathbb{M}



Initially, b_3 is pointing outwards but after one rotation it is pointing inwards

The vector b_3 is always normal to the surface of the Möbius strip. The direction of b_3 can change from pointing outside to inside because the Möbius strip is a surface with a boundary that only has one side

Direction on the Klein bottle \mathbb{K}



We can do the same experiment with the Klein bottle and we see the same phenomenon: the vector b_3 changes from pointing **outside** to pointing **inside** the surface

This time is slightly different because \mathbb{K} is a surface **without boundary**

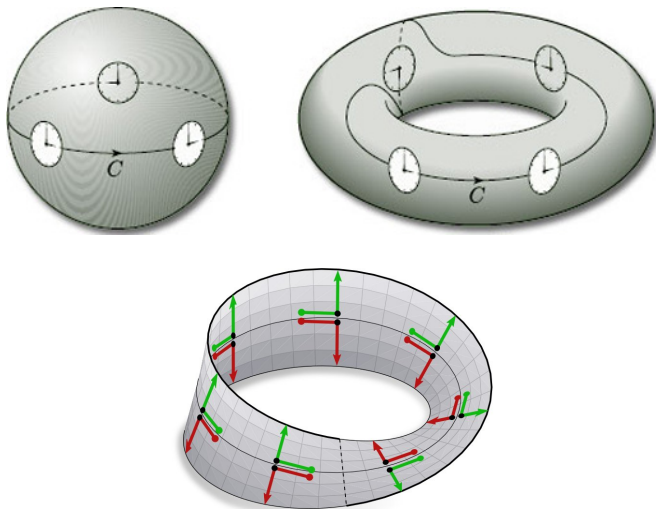
⇒ The Klein bottle \mathbb{K} does **not** have an inside and an outside !!

In contrast, orientable surfaces **without boundary** like S^2 and \mathbb{T} **do** have an inside and an outside

Warning: this is a drawing of \mathbb{K} in \mathbb{R}^3 but it is **not** the actual Klein bottle! Similarly, the pictures of the sphere S^2 in \mathbb{R}^3 are not really the sphere!

Alternative description

Alternatively, think of an orientation as a consistent of a coordinate system for each point:



Orienable surfaces

Theorem

Suppose that S is a connected surface without boundary that embeds in \mathbb{R}^3 . Then S is orientable.

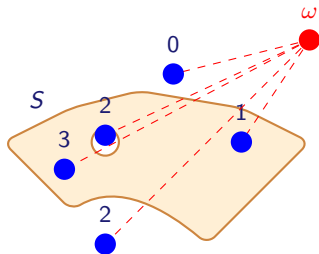
Proof Embed S in \mathbb{R}^3 and pick a point ω a “long” way from S

For each point $x \in \mathbb{R}^3$ draw a line from ω to x and define $s(x)$ to be the number of times this line crosses the boundary of S

Set $V_{\text{in}} = \{x \in \mathbb{R}^3 \mid x \notin S \text{ and } s(x) \text{ is odd}\}$
 $V_{\text{out}} = \{x \in \mathbb{R}^3 \mid s(x) \text{ is even}\}$

$$\implies \mathbb{R}^3 = S \cup V_{\text{in}} \cup V_{\text{out}} \quad (\text{disjoint union})$$

Notice that since S is a **closed surface** it does not have boundary, so the “circle” in the picture, which contains a point x with $s(x) = 2$, should be interpreted as a tube through the surface



Orientable surfaces...

Now suppose that S is non-orientable, so that it contains a Möbius strip M

Pick a point $m \in S$ that is on this Möbius strip and fix an ordered basis $\{b_1, b_2, b_3\}$ with b_1 and b_2 tangential to m and $b_3 = b_1 \times b_2$.

Replacing b_3 with $-b_3$, if necessary, we assume that b_3 points out of S

Now move m , and $B = \{b_1, b_2, b_3\}$, continuously around S

$\implies \det(B)$ changes continuously as m moves around S

By moving m around the Möbius strip in M , we can move m to a point where b_3 now points inside S

\implies By continuity, at some point b_3 must have been in the plane spanned by b_1 and b_2

$\implies \det(B) = 0$ $\color{red}{\llcorner \llcorner \llcorner}$ since B is linearly independent!

Corollary

Let S be a non-orientable closed surface. Then S does not embed in \mathbb{R}^3 .

You can't fill a liquid into the Klein bottle



Strictly speaking the liquid is neither in- nor outside

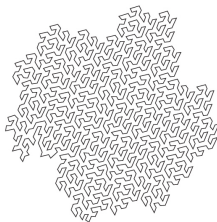
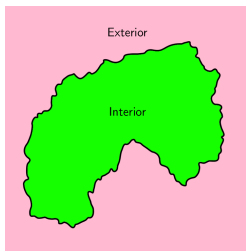
Jordan curve theorem

This argument used to prove theorem can be made rigorous for surfaces with **finite** polygonal decompositions but for “general surfaces” it is difficult to prove that $\mathbb{R}^3 = S \cup V_{in} \cup V_{out}$.

The corresponding result for curves in \mathbb{R}^2 is known as the **Jordan Curve Theorem**, which says that any **closed curve** C in \mathbb{R}^2 gives rise to a decomposition $\mathbb{R}^2 = C \cup V_{in} \cup V_{out}$ (disjoint union)

This is **really hard** to prove!

To appreciate why this is a nontrivial result consider:



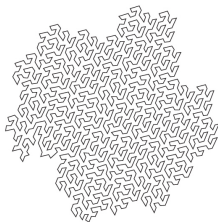
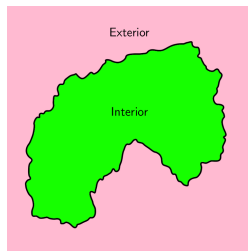
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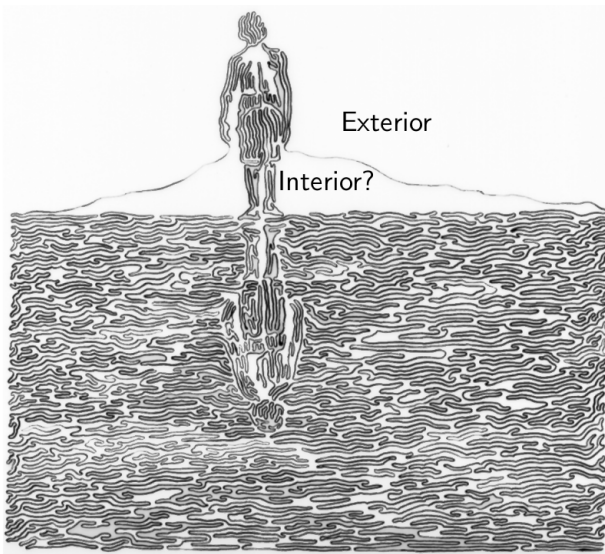
To appreciate why this is a nontrivial result consider:



The left is easy, but can you tell for the right what is “in” or “out”?

Jordan curve theorem - 2

The main meat is that one needs to deal with “crazy” curves:



Embedding the projective plane in \mathbb{R}^4

The projective plane \mathbb{P}^2 is non-orientable, so it does not embed in \mathbb{R}^3

By definition, the projective plane is defined by identifying antipodal points on the sphere S^2 :

$$\mathbb{P}^2 = \{ (x, y, z) \in \mathbb{R}^3 \mid x^2 + y^2 + z^2 = 1 \} / (x, y, z) \sim (-x, -y, -z)$$

We can embed \mathbb{P}^2 into \mathbb{R}^4 using the continuous map:

$$(x, y, z) \mapsto (xy, xz, yz, y^2 - z^2)$$

It is not hard to check that this is a well-defined injective function

$\implies \mathbb{P}^2$ is homeomorphic to the image of this map in \mathbb{R}^4

Remark

We will soon see that every non-orientable surface can be constructed using projective planes, so this implies that every non-orientable surface embeds in \mathbb{R}^4

In contrast, every orientable surface embeds in \mathbb{R}^3

Connected sums

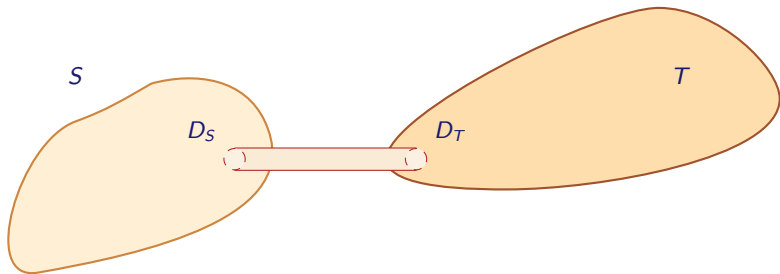
We need a way to build new surfaces from old surfaces

The **boundary** of a surface is the union of its **boundary circles**, or **free edges**. The **interior** of a surface is anything not on the boundary

Definition

The **connected sum** of surfaces S and T is the surface $S \# T$ obtained by

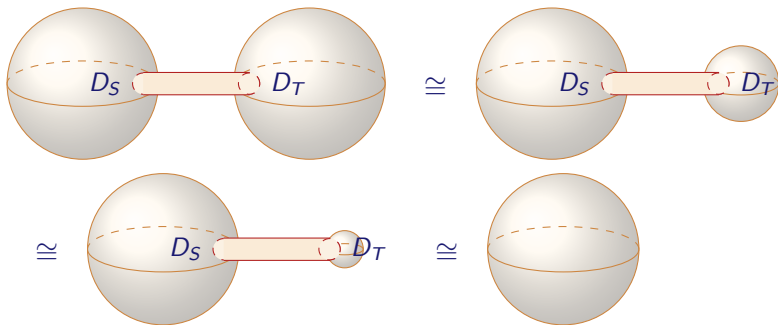
- 1 cutting disks D_S and D_T out of the interiors of S and T , respectively
- 2 identifying the boundary circles of D_S and D_T



Identifying D_S and D_T is the same as connecting them with a cylinder

Connected sums with spheres

- What is $S^2 \# S^2$?



Hence, $S^2 \# S^2 \cong S^2$

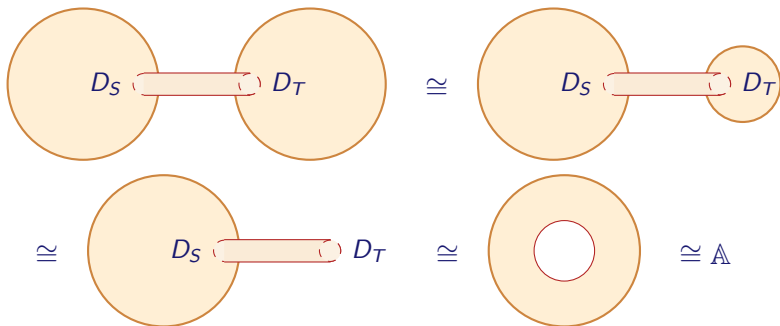
- If T is any surface then $T \# S^2 \cong T$

This follows by exactly the same calculation!

So S^2 is the unit under the operation $\#$

Connected sums with disks

- What is $\mathbb{D}^2 \# \mathbb{D}^2$?



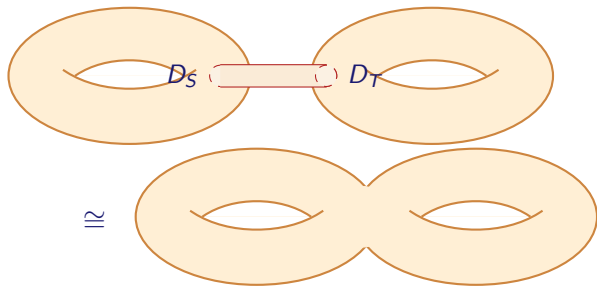
Hence, $\mathbb{D}^2 \# \mathbb{D}^2 \cong \mathbb{A}$, which is the annulus or cylinder

- If T is any surface then $T \# \mathbb{D}^2$ puts a **puncture**, or hole, in T
This follows by exactly the same calculation!

$\implies T \# \underbrace{\mathbb{D}^2 \# \dots \# \mathbb{D}^2}_{d \text{ times}} = T \# \#^d \mathbb{D}^2$ is equal to T with d **punctures** or, equivalently, T with d additional **boundary circles**

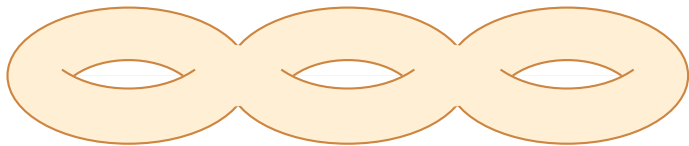
Connected sums with tori

- What is $\mathbb{T} \# \mathbb{T}$?



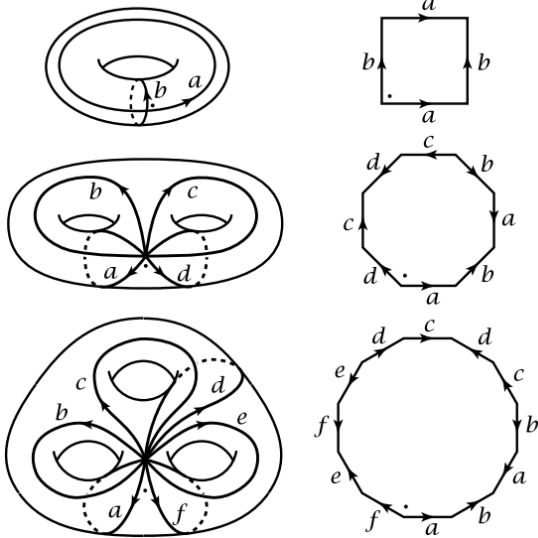
The double torus
 $\mathbb{T} \# \mathbb{T} = \#^2 \mathbb{T}$

Similarly, there are triple tori $\#^3 \mathbb{T}$



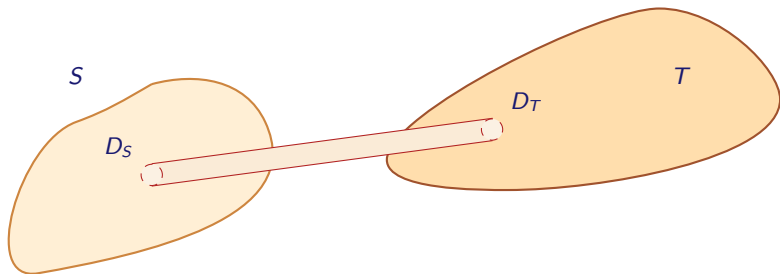
... and, more generally, t -tori $\#^t \mathbb{T}$

We already know t -tori



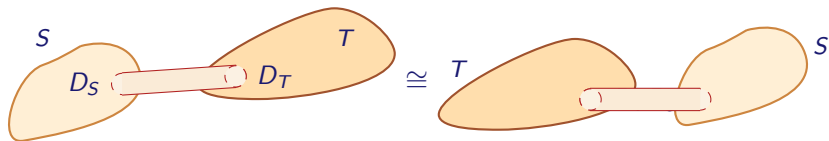
Properties of connected sums

- $S \# T$ is independent of the location of the disks D_S and D_T



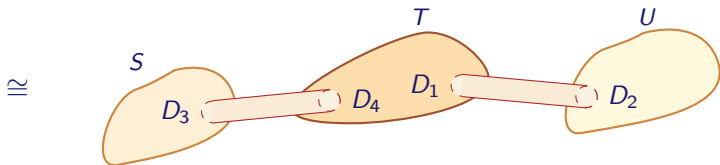
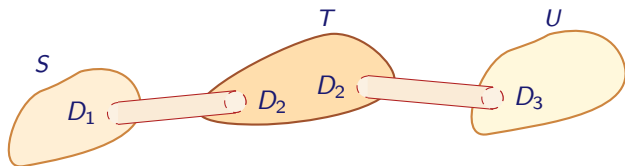
As long as D_S stays in the interior of S , and D_T in the interior of T , the surface $S \# T$ is unchanged up to homeomorphism

- $S \# T \cong T \# S$



Associativity of connected sums...

- $S \# (T \# U) \cong (S \# T) \# U$



In these diagrams, D_1 and D_2 are cut first and then D_3 and D_4

$\implies \#$ is a “surface addition or multiplication”

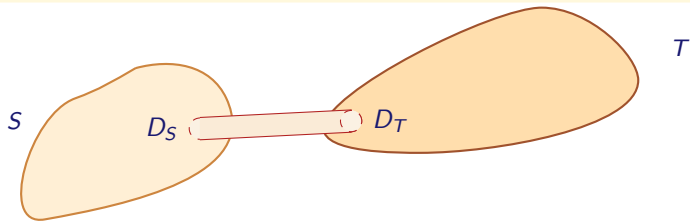
Connected sums of Euler characteristic

Theorem

Let S and T be surfaces with polygonal decompositions. Then

$$\chi(S \# T) = \chi(S) + \chi(T) - 2$$

Proof



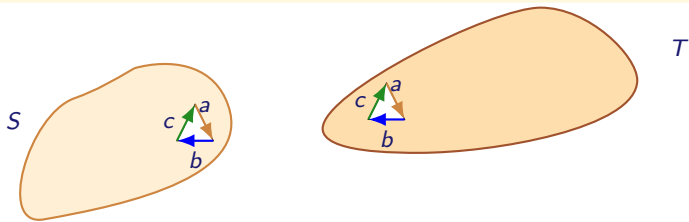
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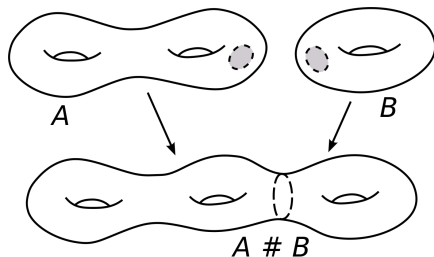


$$\implies \chi(S \# T) = (\chi(S) - (3 - 3 + 1)) + (\chi(T) - (3 - 3 + 1))$$

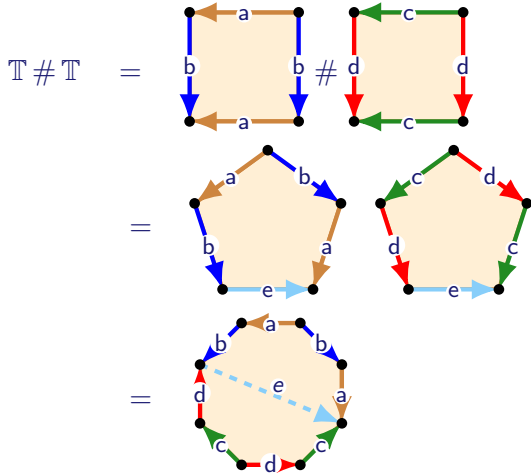
Moral The -2 comes from cutting out **two** disks

Examples

- If S is any surface then $S \cong S \# S^2$
 $\implies \chi(S) = \chi(S) + \underbrace{\chi(S^2)}_{=2} - 2 = \chi(S)$
- $\mathbb{A} \cong \mathbb{D}^2 \# \mathbb{D}^2 \implies \chi(\mathbb{A}) = \chi(\mathbb{D}^2) + \chi(\mathbb{D}^2) - 2 = 1 + 1 - 2 = 0$
- $\chi(\mathbb{T} \# \mathbb{T} \# \mathbb{T}) = (\chi(\mathbb{T}) + \chi(\mathbb{T}) - 2) + \chi(\mathbb{T}) - 2 = -4$



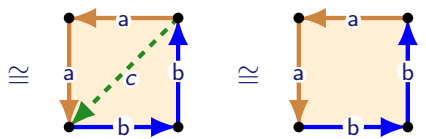
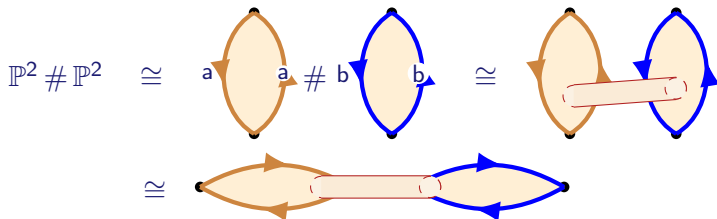
Connected sums and polygonal decompositions



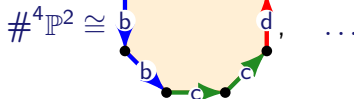
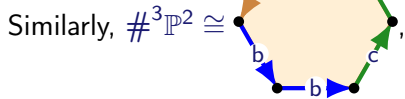
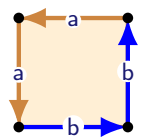
\implies For surfaces without a boundary you can cut the disks anywhere!

Connected sums with projective planes

- What is $\mathbb{P}^2 \# \mathbb{P}^2$?



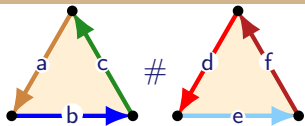
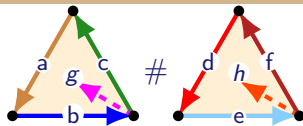
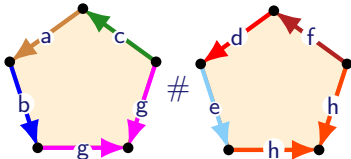
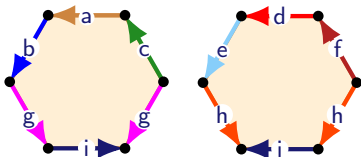
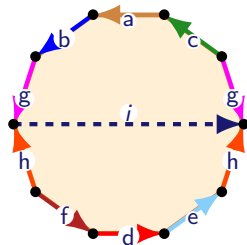
\cong



...

Connected sums and polygonal decompositions...

$$\mathbb{D}^2 \# \mathbb{D}^2$$

 \cong

 \cong

 $=$

 $=$

 $=$


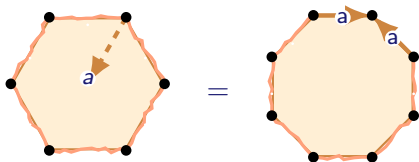
\implies For surfaces with a boundary, you can cut into the interior, if necessary, to form the connected sum

Surgery

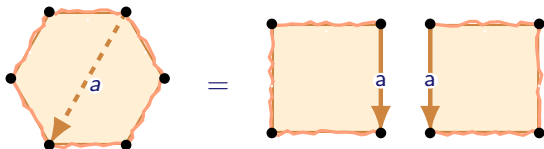
We have already seen that it is possible to change one polygonal decomposition into another using **surgery**

There are two basic operations:

- Adding and removing edges:



- Cutting and gluing



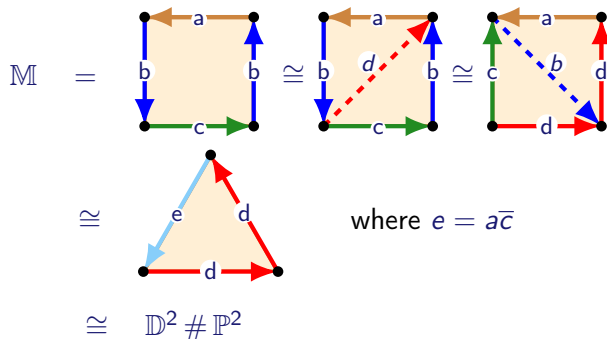
Perhaps surprisingly, these two operations and subdivision are all that we need

Surgery on the Möbius strip

Lemma

$$\mathbb{M} \cong \mathbb{D}^2 \# \mathbb{P}^2 \quad (= a \text{ punctured projective plane})$$

Proof



\implies A Möbius strip is a punctured projective plane

\implies Every non-orientable surface contains the projective plane

Surgery on the Klein bottle

Lemma

$$\mathbb{K} \cong \mathbb{P}^2 \# \mathbb{P}^2 \cong \#^2 \mathbb{P}^2$$

Proof

$$\begin{aligned} \mathbb{K} &= \begin{array}{c} \bullet \xleftarrow{a} \bullet \\ \downarrow b \quad \uparrow b \\ \bullet \xleftarrow{a} \bullet \end{array} = \begin{array}{c} \bullet \xleftarrow{a} \bullet \\ \downarrow b \quad \nearrow c \\ \bullet \xleftarrow{a} \bullet \end{array} = \begin{array}{c} \bullet \xleftarrow{a} \bullet \\ \downarrow a \quad \nearrow b \\ \bullet \xleftarrow{c} \bullet \end{array} \\ &\cong \begin{array}{c} \bullet \xleftarrow{c} \bullet \\ \downarrow a \quad \uparrow a \\ \bullet \xleftarrow{c} \bullet \end{array} \# \begin{array}{c} \bullet \xleftarrow{a} \bullet \\ \downarrow a \quad \uparrow a \\ \bullet \xleftarrow{a} \bullet \end{array} \\ &\cong \mathbb{P}^2 \# \mathbb{P}^2 \end{aligned}$$

The diagrammatic proof shows the following steps:

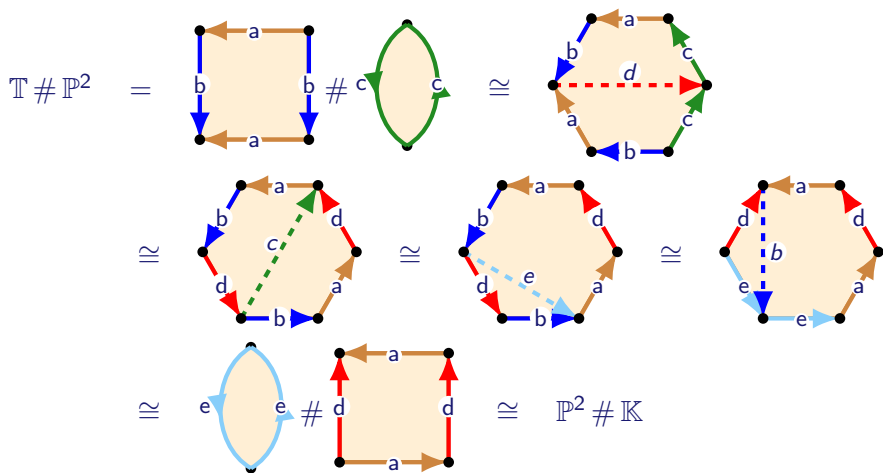
- Step 1:** A square representing the Klein bottle with boundary segments labeled a (horizontal, left-to-right) and b (vertical, top-to-bottom).
- Step 2:** The same square with a dashed green diagonal line labeled c from the bottom-left to the top-right.
- Step 3:** The square with a dashed blue diagonal line labeled b from the top-left to the bottom-right.
- Step 4:** Two projective planes, each represented as a lens-shaped region with boundary segments labeled a and c .
- Step 5:** The final result, two projective planes connected by a point, denoted as $\mathbb{P}^2 \# \mathbb{P}^2$.

Surgery on a torus and projective plane

Theorem

$$\mathbb{T} \# \mathbb{P}^2 \cong \mathbb{K} \# \mathbb{P}^2$$


Proof



Projective planes dominate

On the last slide we saw that $\mathbb{T} \# \mathbb{P}^2 \cong \mathbb{K} \# \mathbb{P}^2$

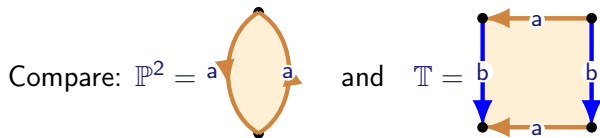
$$\implies \mathbb{T} \# \mathbb{P}^2 \cong \#^3 \mathbb{P}^2 \text{ since } \mathbb{K} \cong \#^2 \mathbb{P}^2$$

 suggests that the connected sum of any surface with a projective plane is non-orientable

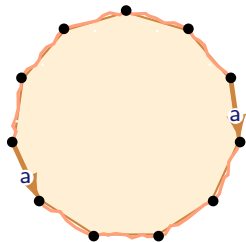
Warning Connected sums do **not** cancel since $\mathbb{T} \not\cong \mathbb{K}$

Why? \mathbb{T} embeds in \mathbb{R}^3 but \mathbb{K} does not!

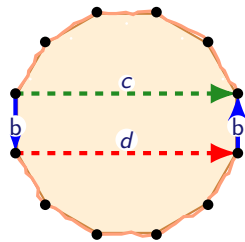
Oriented and unoriented edges



Paired edges on a polygon are **oriented** if they point in **opposite** directions and **unoriented** if they point in the same direction



Oriented



Unoriented

\mathbb{M}

Oriented edges can be folded together without twisting whereas unoriented edges can only be brought together if the surface is twisted

Classification of connected surfaces

Theorem

Let S be a connected surface. Then there exist non-negative integers d , p and t such that

- 1 $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$
- 2 the boundary of S is the disjoint union of d circles
- 3 S is orientable if and only if $p = 0$

Moreover, we can assume that $pt = 0$, in which case S is uniquely determined up to homeomorphism by (d, p, t)

Remark If $d + p + t \neq 0$ we can omit the sphere S^2

Proof We argue by induction on the number of edges in a polygonal decomposition of S with one face to first prove 1

Base case: If S has one edge then either

$$S = a \begin{array}{c} \curvearrowright \\ \curvearrowleft \end{array} a \cong S^2 \quad \text{or} \quad S = b \begin{array}{c} \curvearrowright \\ \curvearrowright \end{array} b \cong \mathbb{P}^2$$

\implies The theorem is true in this case

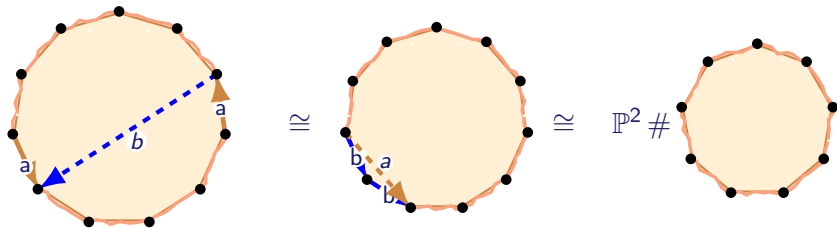
Proof of the classification theorem

Now suppose that S has at least two edges and that the theorem is true whenever all surfaces that have a polygonal decomposition with one face and fewer edges

If S has only **free edges** then $S \cong \mathbb{D}^2$ and the theorem holds

Hence, we can assume that S has at least one **paired edge**

Case I: S has an unoriented edge



$$\implies S \cong \mathbb{P}^2 \# T$$

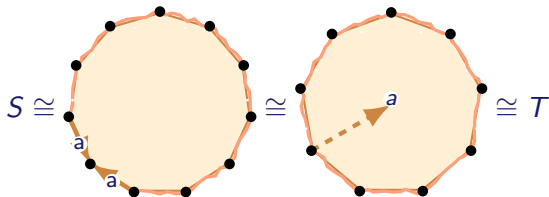
By induction, $T \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$ since T has fewer edges

$$\implies S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^{p+1} \mathbb{P}^2 \# \#^t \mathbb{T} \text{ as required}$$

Proof of the classification theorem...

Case II: All paired edges in S are oriented

If S has adjacent oriented edges then



$\implies S \cong T \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$ by induction

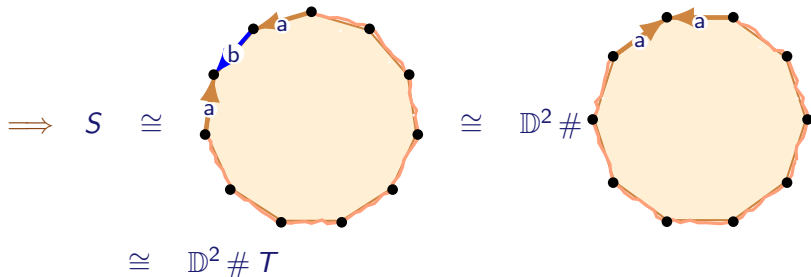
Hence, we can assume that the paired edges are not adjacent

Similarly, we can assume that S does not have any adjacent free edges as such edges can be replaced with a single free edge

Fix an (oriented) paired edge a such that the number of edges between the two copies of a is **minimal**

Proof of the classification theorem...

Case IIa: All edges on one side of a are free



By induction, $T \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t T$

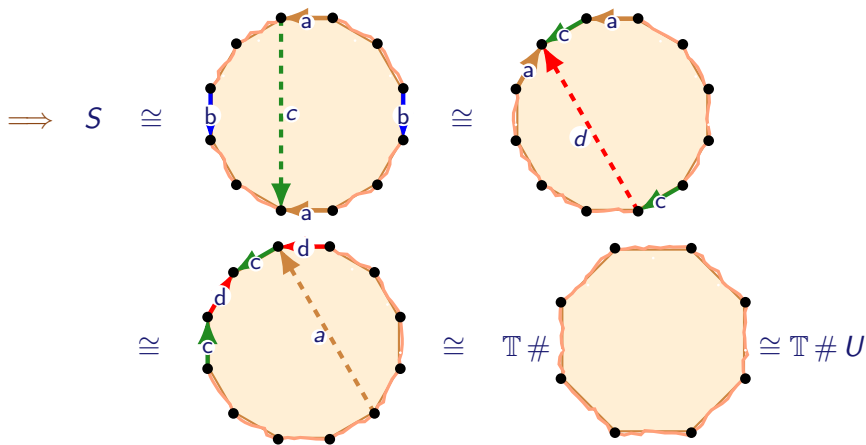
$$\implies S \cong \mathbb{D}^2 \# T \cong S^2 \# \#^{d+1} \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t T$$

Hence, we can assume that there are paired edges on **both** sides of a

Proof of the classification theorem...

Case IIb: There are paired edges on both sides of a

The number of edges between the ends of a is minimal, so



By induction, $U \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$

$\implies S \cong \mathbb{D}^2 \# U \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^{t+1} \mathbb{T}$

Proof of the classification theorem...

We have now proved that every surface can be written in the form

$$S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$$

for non-negative integers d , p and t

The proof so far shows that d is the number of boundary circles

Next, note that if $p > 0$ then \mathbb{P}^2 is contained in S

$\implies S$ is non-orientable if $p \neq 0$

On the other hand, $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^t \mathbb{T} \hookrightarrow \mathbb{R}^3$ is orientable if $p = 0$

$\implies S$ is orientable if and only if $p = 0$

We have now proved ①, ② and ③ from the theorem!

Next, observe that if $p \neq 0$ and $t \neq 0$ then S contains $\mathbb{P}^2 \# \mathbb{T} \cong \#^3 \mathbb{P}^2$

$\implies \#^t \mathbb{T} \# \mathbb{P}^2 \cong \#^{t-1} \mathbb{T} \# \#^3 \mathbb{P}^2 \cong \dots \cong \#^{2t+1} \mathbb{P}^2$

\implies Hence, we can assume $t = 0$ if $p \neq 0$

That is, we can assume $pt = 0$ — equivalently, $p = 0$ or $t = 0$

Proof of the classification theorem...

It remains to prove if $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$ with $tp = 0$ then S is uniquely determined up to homeomorphism by (d, p, t)

Let $T = S^2 \# \#^e \mathbb{D}^2 \# \#^q \mathbb{P}^2 \# \#^s \mathbb{T}$, with $sq \neq 0$

\implies We need to show that $S \cong T$ if and only if $(d, p, t) = (e, q, s)$

If $(d, p, t) = (e, q, s)$ there is nothing to prove, so suppose $S \cong T$

- $d = e$ as homeomorphisms preserve boundary circles
- $p \neq 0 \Leftrightarrow q \neq 0$ as homeomorphisms preserve orientability
- Homeomorphisms preserve Euler characteristic. By tutorial 9,
 - ▶ $\chi(S^2 \# \#^a \mathbb{D}^2 \# \#^b \mathbb{P}^2) = 2 - a - b$
 - ▶ $\chi(S^2 \# \#^a \mathbb{D}^2 \# \#^c \mathbb{T}) = 2 - a - 2c$

$\implies (d, p, t) = (e, q, s)$ since $\chi(S) = \chi(T)$

All parts of the classification theorem are now proved!!

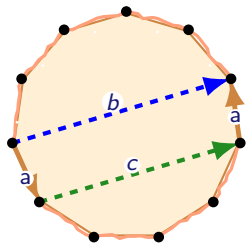
Hence, we now know **all** surfaces up to homeomorphism!

Orientability

Corollary

A surface S is non-orientable if and only if its polygonal decomposition contains an unoriented edge

Proof Any unoriented edge gives a Möbius band inside S :



Conversely, $S = S^2 \# \#^d \mathbb{D}^2 \# \#^t \mathbb{T}$ embeds in \mathbb{R}^3 , so it is orientable. Hence, a polygonal decomposition of S can only contain oriented edges

It is now not hard to find an explicit polygonal decomposition of

$$S = S^2 \# \#^d \mathbb{D}^2 \# \#^t \mathbb{T}$$

and check that surgery cannot create unoriented edges in S

Theorem

Let S be a connected surface. Then there exist non-negative integers d , p and t with $pt = 0$ such that

- 1 $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$
- 2 the boundary of S is the disjoint union of d circles
- 3 S is orientable if and only if $p = 0$

The surface S is in **standard form** when written as

$$S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$$

with $pt = 0$ — that is, $p = 0$ or $t = 0$

- The standard form **uniquely identifies** S
- S is **orientable** if and only if $p = 0$
- S has d **boundary circles**
- S has **Euler characteristic** $\chi(S) = 2 - d - p - 2t$ (tutorials!)

The standard form of a surface that is not connected has each component in standard form

Corollary of classification

Corollary

A connected surface is uniquely determined, up to homeomorphism by

- 1 the number of *boundary circles*
- 2 its *orientability*
- 3 its *Euler characteristic*

Proof Write $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$ in standard form with $tp = 0$

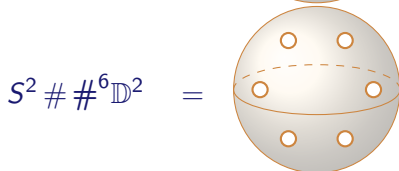
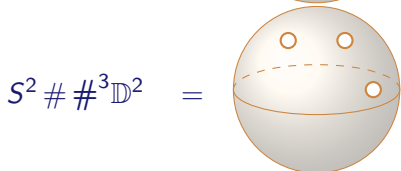
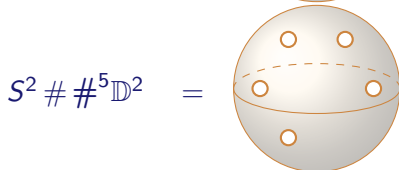
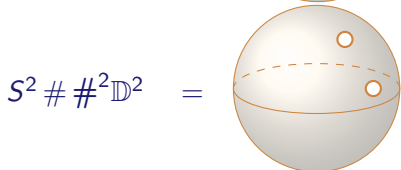
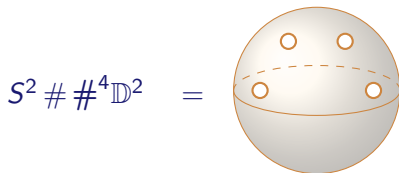
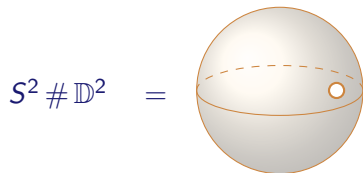
$$\implies \chi(S) = 2 - d - p - 2t$$

Hence, the standard form uniquely determines the number of boundary circles, orientability and Euler characteristic of S

Conversely, these three characteristics of S determine (d, p, t)

Spheres with punctures

- $S^2 \# \#^d \mathbb{D}^2$ is a sphere with d punctures



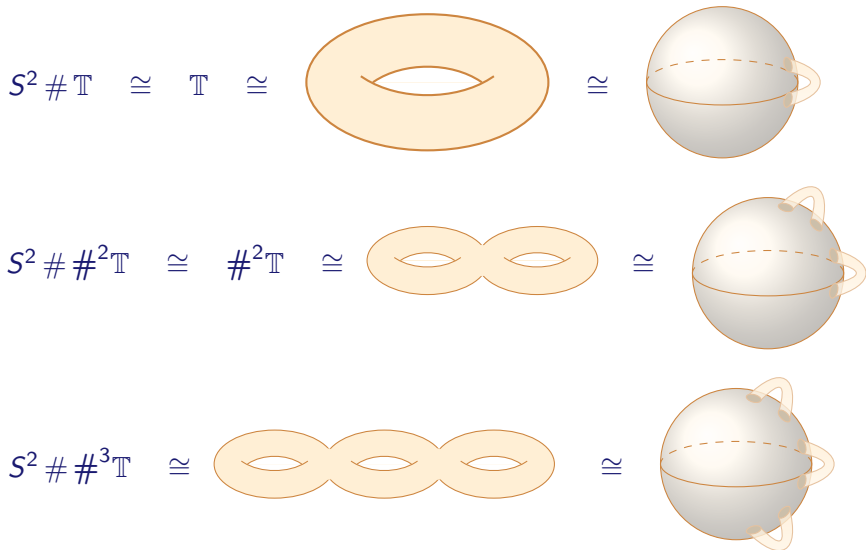
More generally, $S \# \#^d \mathbb{D}^2$ is S with d punctures

A spheres with zero and one puncture

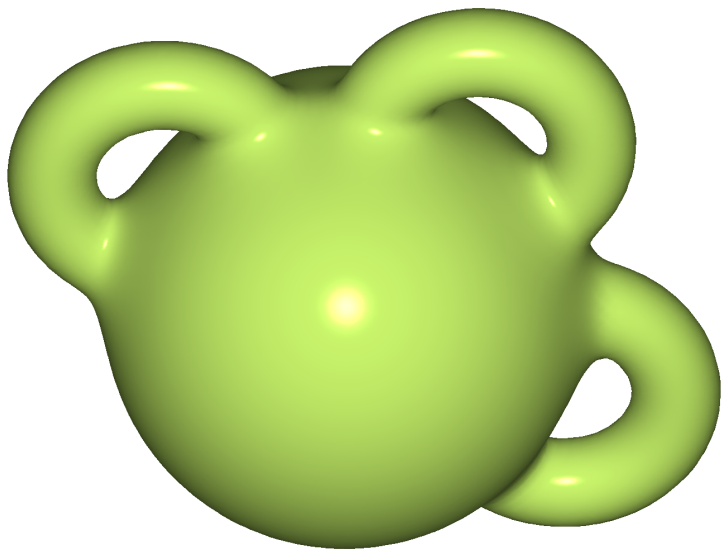


Spheres with handles

- $S^2 \# \#^t \mathbb{T}$ is a sphere with t handles



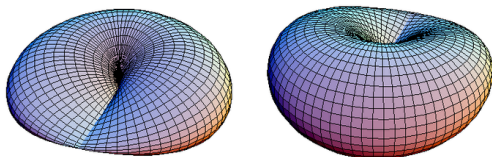
Continuing like this constructs a sphere with t -handles $\#^t \mathbb{T}$



Sphere with cross-caps

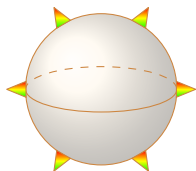
- $S^2 \# \#^p \mathbb{P}^2$ is a sphere with p cross-caps

A **cross-cap** is what you get when you sew a Möbius strip onto the sphere
This shape lives in \mathbb{R}^4 , so difficult to visualize but Wikipedia draws it as:



In \mathbb{R}^3 this surface self-intersects. We draw surfaces with cross caps as:

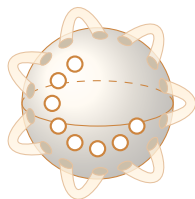
$$S^2 \# \#^6 \mathbb{P}^2 \cong$$



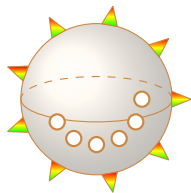
What do standard surfaces look like?

We can combine the pictures above to draw all of the standard surfaces:

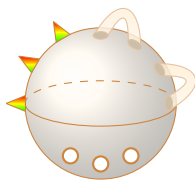
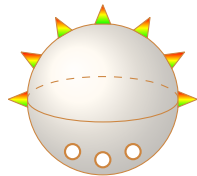
$$\#^8 \mathbb{D}^2 \# \#^7 \mathbb{T} \cong \mathbb{R}^3$$



$$\#^6 \mathbb{D}^2 \# \#^9 \mathbb{P}^2 \cong \mathbb{R}^3$$



$$\#^3 \mathbb{D}^2 \# \#^2 \mathbb{T} \# \#^3 \mathbb{P}^2 \cong \mathbb{R}^3$$


$$\cong \mathbb{R}^3$$


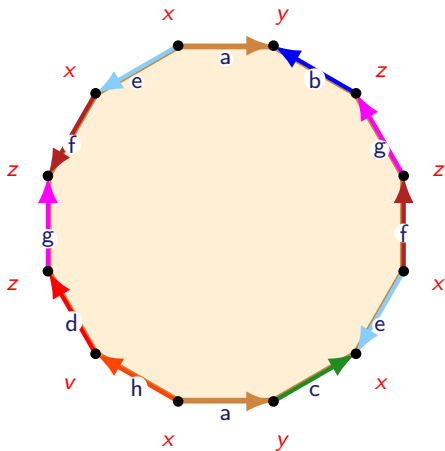
Putting a surface in standard form

Given a polygonal decomposition for a surface we can put it in standard form by:

- Find all of the vertices (identified edges implicitly identify vertices)
- Count the number d of boundary circles
- S is orientable ($p = 0$) if all edges are oriented otherwise it is non-orientable ($t = 0$)
- Compute $\chi(S) = 2 - d - p - 2t$ to determine the missing variable, which is t if S is orientable and or p if non-orientable

Example 1

What is the surface with the below polygonal decomposition?

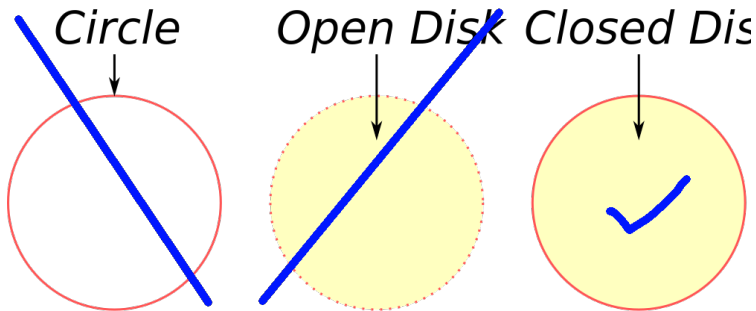
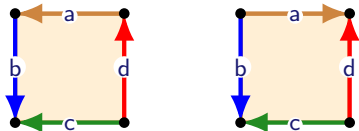


$a c \bar{e} f g b \bar{a} e f \bar{g} d \bar{h}$ (overline=opposite direction)

\implies This is $\#^1 \mathbb{D}^2 \# \#^0 \mathbb{T} \# \#^4 \mathbb{P}^2$

Example 2

What is the standard form of the surface with polygonal decomposition?



Topology – week 10

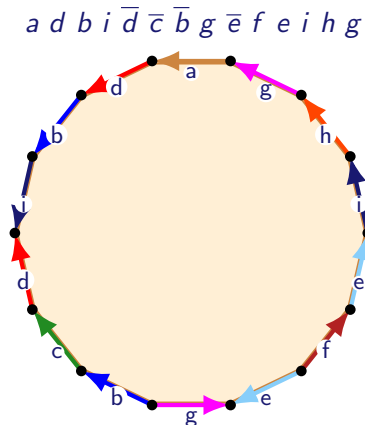
Math3061

Daniel Tubbenhauer, University of Sydney

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Words for surfaces


A polygonal decomposition for a surface that has **one face** can be encoded in a **word**



- ▶ write x for an edge pointing **anticlockwise**
- ▶ write \bar{x} for an edge pointing **clockwise**
- ▶ We always read the word in **anticlockwise** order


Words for basic surfaces

• $S^2 = a \overline{a}$



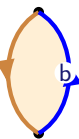
$= a \bar{a}$

• $\mathbb{P}^2 = a a$



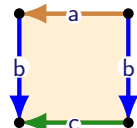
$= a a$

• $\mathbb{D}^2 = a b$



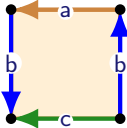
$= a b$

• $\mathbb{A} = a b \bar{c} \bar{b}$



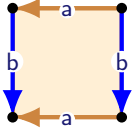
$= a b \bar{c} \bar{b}$

• $\mathbb{M} = a b \bar{c} b$



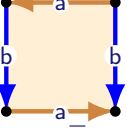
$= a b \bar{c} b$

• $\mathbb{T} = a b \bar{a} \bar{b}$



$= a b \bar{a} \bar{b}$

• $\mathbb{K} = a b a \bar{b}$



$= a b a \bar{b}$

Properties of words

- Words **encode** orientability
 - ▶ Orientable: $\dots a \dots \bar{a} \dots$ or $\dots \bar{a} \dots a \dots$
 - ▶ Non-orientable: $\dots a \dots a \dots$ or $\dots \bar{a} \dots \bar{a} \dots$
- Words give a compact and easily readable way of describing surfaces
- Words can be read in **clockwise** or **anticlockwise** order (we always read in **anticlockwise** order)
- The word of a surface is well-defined only up to **cyclic permutation** and **reversing** the direction of any edge

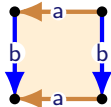
Example The following words are all words for the torus \mathbb{T} :

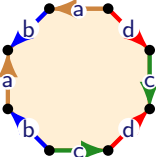
$$\begin{array}{cccc} a b \bar{a} \bar{b} & b \bar{a} \bar{b} a & \bar{a} \bar{b} a b & \bar{b} a b \bar{a} \\ a \bar{b} \bar{a} b & \bar{b} \bar{a} b a & \bar{a} b a \bar{b} & b a \bar{b} \bar{a} \end{array}$$

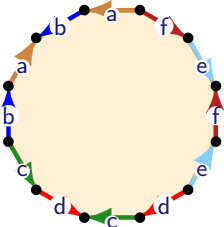
- The word of a surface can be used to give generators and relations for the first **homotopy group** of the surface — this generalises **independent cycles** and are beyond the scope of this unit

Standard words for closed orientable surfaces

- Connected sums of tori: $\#^t \mathbb{T}$

▶ $\mathbb{T} =$  $= a b \bar{a} \bar{b}$

▶ $\#^2 \mathbb{T} =$  $= a b \bar{a} \bar{b} c d \bar{c} \bar{d}$

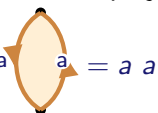
▶ $\#^3 \mathbb{T} =$  $= a b \bar{a} \bar{b} c d \bar{c} \bar{d} e f \bar{e} \bar{f}$

▶ ... $\#^t \mathbb{T} = a_1 b_1 \bar{a}_1 \bar{b}_1 a_2 b_2 \bar{a}_2 \bar{b}_2 \dots a_t b_t \bar{a}_t \bar{b}_t$

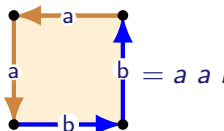
Words for closed non-orientable surfaces

- Connected sums of projective planes $\#^p \mathbb{P}^2$

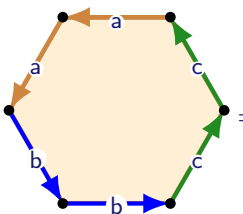
▶ $\mathbb{P}^2 = a a = a a$



▶ $\#^2 \mathbb{P}^2 = a a b b = a a b b$



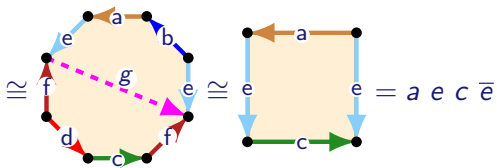
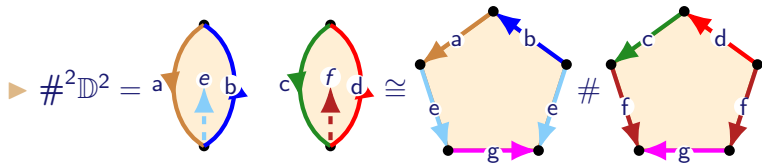
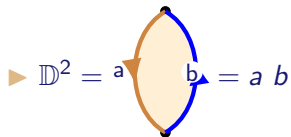
▶ $\#^3 \mathbb{P}^2 = a a b b c c = a a b b c c$



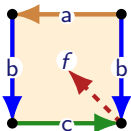
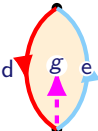
▶ ... $\#^p \mathbb{P}^2 = a_1 a_1 a_2 a_2 \dots a_p a_p$

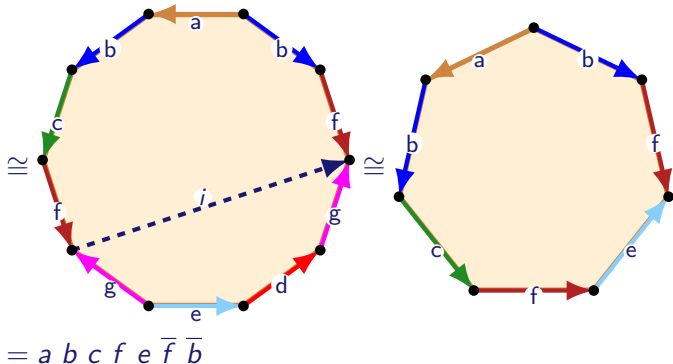
Standard words for surfaces with boundary

• $\#^d \mathbb{D}^2$



Standard words for surfaces with boundary

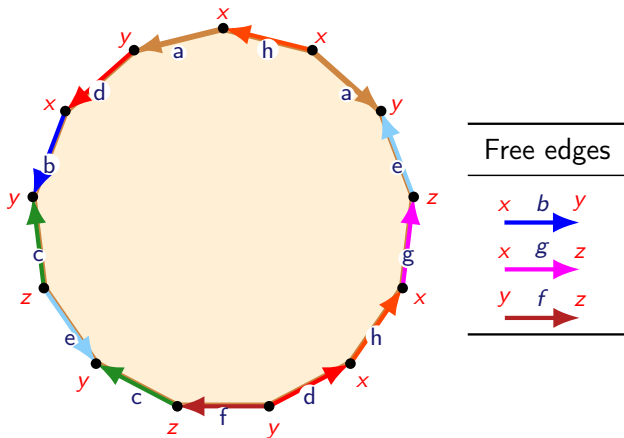
$\triangleright \#^3 \mathbb{D}^2 = \#^2 \mathbb{D}^2 \# \mathbb{D}^2 \cong$

 $\#$




$\triangleright \#^d \mathbb{D}^2 = a_1 b_1 a_2 b_2 \dots b_{d-1} a_d \bar{b}_{d-1} \dots \bar{b}_2 \bar{b}_1$

Words to surfaces

What **standard surface** is given by the word $a d b \bar{c} e \bar{c} \bar{f} d h g e \bar{a} h$?



$$\implies d = 1 \text{ and } \chi(S) = 3 - 8 + 1 = -4$$

$$\implies S \cong \mathbb{D}^2 \# \#^5 \mathbb{P}^2$$

$$\implies S = a b b c c d d e e f f$$

The vertex-degree equation revisited

When we looked at graphs we proved the **vertex-degree equation**:

$$\sum_{v \in V} \deg(v) = 2|E| \quad \text{for } G = (V, E) \text{ a graph}$$

The best way to understand this formula is to note that each edge $\{x, y\} \in E$ contributes 2 to both sides of this equation

- +1 to each of $\deg(x)$ and $\deg(y)$ on the left-hand side
- +2 = $2 \cdot 1$ to the right-hand side for the edge $\{x, w\}$

We want similar formulas for a surface $S = (V, E, F)$ with a polygonal decomposition

Question What is the correct definition of **degree** in S ?

The problem

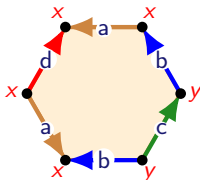
We are identifying edges in S and hence implicitly identifying vertices

- ▶ Do we identify edges and vertices when computing $\deg(v)$ and $|E|$?

Answer Yes and no!

The degree of a vertex

Consider the surface with polygonal decomposition



Using identified vertices and edges + count with multiplicities

$$\implies \deg(x) = 5, \deg(y) = 3, \text{ so } \deg(x) + \deg(y) = 8 = 2|E|$$

Not using identified edges or vertices (i.e. as a graph, ignoring the face)

$$\implies \text{six vertices of degree } 2 \text{ and six edges, so } 12 = 2 \cdot 6$$

The vertex-degree equation holds using either identified or non-identified edges and vertices because in both cases the **degree** of a vertex is defined to be the **number of incident edges to the vertex**

The surface degree-vertex equation

Proposition

Let $S = (V, E, F)$ be a surface with polygonal decomposition. Then

$$\sum_{v \in V} \deg(v) = 2|E|$$

Proof The proof is the same as before: the edge $\{x, y\}$ contributes $+2$ to both sides of this equation because edge contributes $+1$ to $\deg(x)$ and $+1$ to $\deg(y)$.

Therefore, we have two degree-vertex equations:

- The **graph degree-vertex equation** where we **do not identify** edges and vertices in S
- The **surface degree-vertex equation** where we **do identify** edges and vertices in S

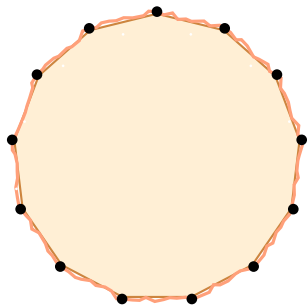
The degree of a face

Let $S = (V, E, F)$ be a surface with polygonal decomposition

Let $f \in F$ be a face of S . The **degree** of f is

$\deg(f)$ = number of edges (count with multiplicities) incident with f

Examples Suppose that $f \in F$ is an n -gon



$$\implies \deg(f) = n$$

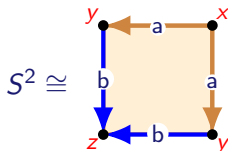
Notice that faces are never identified in the polygonal decomposition

Question How are $\sum \deg(f)$ and $2|E|$ related?

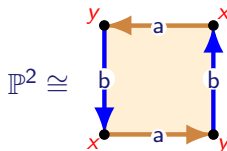
Face degrees of basic surfaces

In all cases $\text{deg}(\text{face}) = 4$ as there are 4 non-identified edges

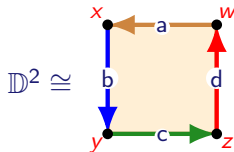
- Sphere



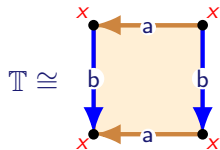
- Projective plane



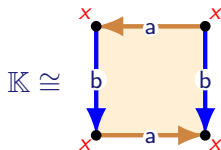
- Disk



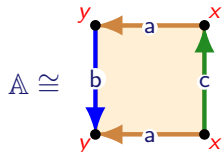
- Torus



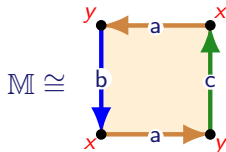
- Klein bottle



- Annulus



- Möbius band



The face-degree equation

Recall that for any graph $G = (V, E)$ we proved that $\sum_{v \in V} \deg(v) = 2|E|$

Let (V, E, F) be a polygonal decomposition

The degree of a face $f \in F$ is $\deg(f) = n$ if P is an n -gon

Proposition (The surface face-degree equation)

Let $S = (V, E, F)$ be a closed surface (no boundary). Then

$$\sum_{f \in F} \deg(f) = 2|E|,$$

Proof By definition, $\deg(f) = n$ if f is an n -gon

Since S is a closed surface, every edge meets two faces (potentially the same face), so it contributes $+2$ to both sides of this equation

$$\implies \sum_{f \in F} \deg(f) = 2|E|$$

Remark To use this formula we need to know the number of identified edges in the polygonal decomposition

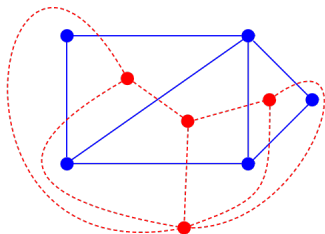
Dual surfaces

Let $S = (V, E, F)$ be a closed surface with a polygonal decomposition such that the vertices around each polygon are distinct

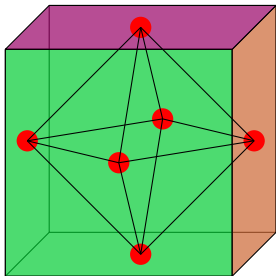
The **dual surface** S^* has polygonal decomposition (V^*, E^*, F^*) , where

- the **vertex** set of S^* is $V^* = F$, the set of **faces** of S
- there is an **edge** between two vertices f and f' of S^* if the faces f and f' in S are **separated by an edge**
 \implies the **faces** of S^* are the **vertices** of S

Examples



The dual of the cube



⇒ the dual surface to the cube is the octahedron

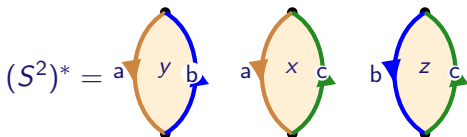
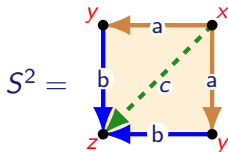
Dual surfaces and the degree equations

Taking the dual of a surface swaps the vertices and faces

\implies if $v \in V$ then $v \in F^*$ and $\deg_S(v) = \deg_{S^*}(v)$

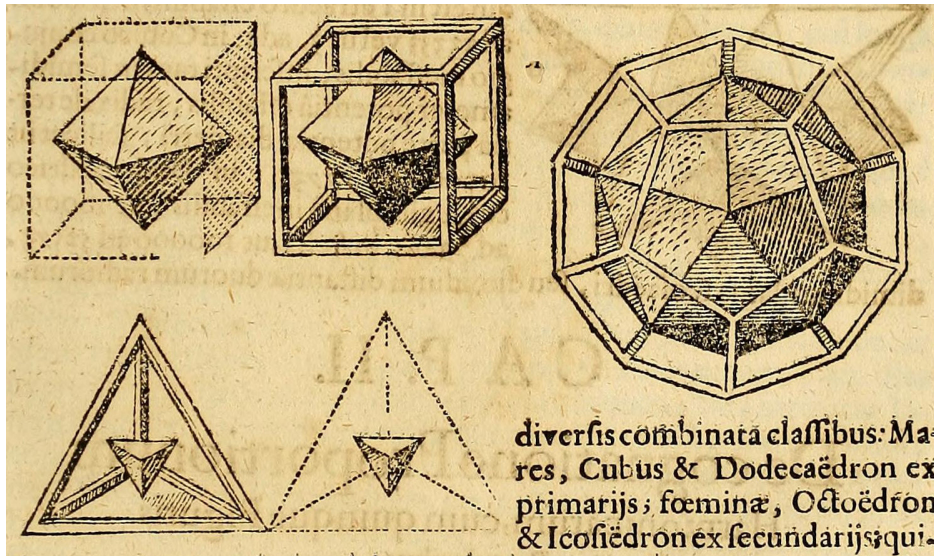
\implies the vertex-degree equation for S is the same as the face-degree equation for S^*

Example



We will see better examples when we look at Platonic solids

Kepler's Harmonices Mundi



Graphs on surfaces

Recall that a graph G is **planar** if it can be drawn in \mathbb{R}^2 without edge crossings

Let S be a surface and $x, y \in S$. A **path** from x to y on S is a **continuous** map $p: [0, 1] \rightarrow S$ such that $p(0) = x$ and $p(1) = y$

Let $\mathcal{P}(S)$ be the set of all paths on S

If S is **any** surface and $G = (V, E)$ is a graph then an **embedding of G in S** is a pair of maps

$$f: V \rightarrow S \quad \text{and} \quad p: E \rightarrow \mathcal{P}(S)$$

such that:

- The map f is injective
- If $e = \{v, w\} \in E$ then $p(e) \in \mathcal{P}(S)$ is an injective path from $f(v)$ to $f(w)$
- If $e, e' \in E$ then the paths $F(e)$ and $F(e')$ can intersect only at the images of their endpoints

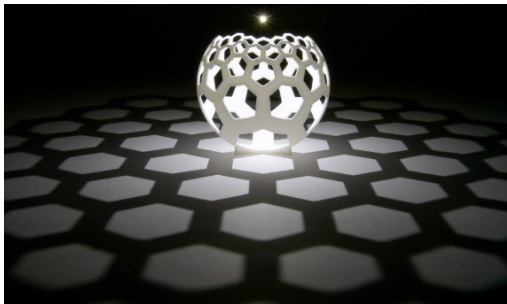
Planar graphs

Theorem

Let G be a (finite) graph. Then the following are equivalent.

- 1 There is an embedding of G in \mathbb{R}^2 (= the graph is planar)
- 2 There is an embedding of G in \mathbb{D}^2
- 3 There is an embedding of G in S^2

Proof Stereographic projection! (Move G away from ∞ .)



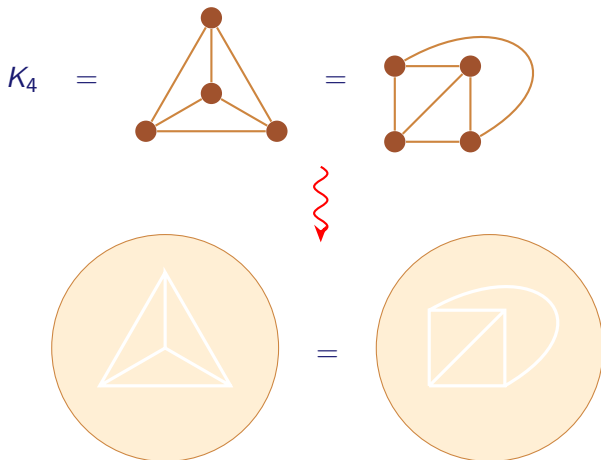
Faces of embedded graphs

Suppose that G has an embedding on a surface S

Identify G with its image in S

The **faces** of G are the connected components of $S \setminus G$

Example Taking $S = \mathbb{D}^2$ and $G = K_4$ gives four faces:



Theorem

Let G be a connected planar graph without leaves.

Then G gives a polygonal decomposition of S^2 where the polygons correspond to the non-trivial cycles in G

Proof Since G is connected, and S^2 does not have a boundary, $S^2 \setminus G$ is a disjoint union of a finite number of regions each of which is bounded by a non-trivial cycle in G .

Every vertex v in G has degree at least 2 and, by assumption, every edge is included in a non-trivial cycle in G

\implies there are two faces adjacent to every edge in G

\implies the embedding of G in S^2 induces a polygonal decomposition on S^2

Remark The argument cheats slightly because we are implicitly assuming that the edges are “nice” curves. This allows us to side-step issues connected with the **Jordan curve theorem**

Theorem

Let $G = (V, E)$ be a connected planar graph with face set F .

Then $2 = |V| - |E| + |F|$

Proof Use the previous theorem or argue by induction on $|E|$

Case 1 G is a tree

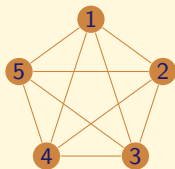
Combine $|V| - |E| = 1$ (previous lectures) and that there is only one face

Case 2 G is not a tree

By $\chi(S^2) = 2$ and the previous theorem

Proposition

The complete graph $K_5 =$



is not planar

Proof Assume that K_5 is planar with $|F|$ faces

We have $|V| = 5$ and $|E| = 10$, so $2 = |V| - |E| + |F| \implies |F| = 7$

Let's count the number of faces in this polygonal decomposition differently

- The faces correspond to cycles in K_5
- Every face has at least 3 edges, so by the degree-face equation

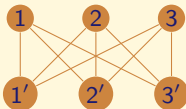
$$\implies 2|E| = \sum_{f \in F} \deg(f) \geq 3|F|$$

$$\implies 2|E| = 20 \geq 21 = 3|F| \quad \color{red}{\downarrow \downarrow \downarrow}$$

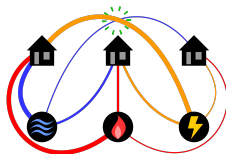
Hence, the complete graph K_5 is not planar

Planarity of bipartite graphs

Proposition

The bipartite graph $K_{3,3} =$  is not planar

Proof Tutorials



Theorem (Kuratowski)






Let G be a graph. Then G is planar if and only if it has no subgraph isomorphic to a **subdivision** of K_5 or $K_{3,3}$

The proof is out of the scope of this unit!

Platonic solids

A **Platonic solid** is a surface that has a polygonal decomposition that is constructed using regular n -gons of the **same shape and size** such that the **same number of polygons meet at every vertex**

Examples

	Tetrahedron	Cube	Octahedron	Dodecahedron	Icosahedron
					
n	3	4	3	5	3
$ V $	4	8	6	20	12
$ E $	6	12	12	30	30
$ F $	4	6	8	12	20

Questions

- Are there any others?
- Can we understand them as polygonal decompositions of the sphere?

Vertices, edges and faces of Platonic solids

Let P be a polygonal decomposition of S^2 obtained by gluing together (regular) n -gons so that p polygons meet at each vertex

Suppose there are $|V|$ vertices, $|E|$ edges and $|F|$ faces

\implies each vertex has degree p and each face degree n

$\implies p|V| = 2|E|$ by the **vertex-degree** equation

$\implies 2|E| = n|F|$ by the **face-degree** equation

$\implies 2 = \chi(S^2) = |V| - |E| + |F| = \frac{2|E|}{p} - |E| + \frac{2|E|}{n}$

$\implies \frac{1}{2} + \frac{1}{|E|} = \frac{1}{p} + \frac{1}{n}$

$\implies \frac{1}{p} + \frac{1}{n} = \frac{1}{2} + \frac{1}{|E|} > \frac{1}{2}$

We require $p \geq 3$, $n \geq 3$ and $|E| \geq 2$

The equations above give:

$$|E| = \left(\frac{1}{p} + \frac{1}{n} - \frac{1}{2} \right)^{-1}, \quad |V| = \frac{2|E|}{p} \quad \text{and} \quad |F| = \frac{2|E|}{n}$$

Classification of Platonic solids

Theorem

The complete list of Platonic solids is:

p	n	$\frac{1}{p} + \frac{1}{n}$	$e = \left(\frac{1}{p} + \frac{1}{n} - \frac{1}{2}\right)^{-1}$	$v = \frac{2e}{p}$	$f = \frac{2e}{n}$	Platonic solid
3	3	$\frac{2}{3}$	6	4	4	Tetrahedron
3	4	$\frac{7}{12}$	12	8	6	Cube
3	5	$\frac{8}{15}$	30	20	12	Dodecahedron
4	3	$\frac{7}{12}$	12	6	8	Octahedron
5	3	$\frac{8}{15}$	30	12	20	Isosahedron

Proof Since $\frac{1}{p} + \frac{1}{n} > \frac{1}{2}$ and $p, n \geq 3$ we get $n < 6$ since $\frac{1}{3} + \frac{1}{6} = \frac{1}{2}$.
Case-by-case we then get the above values for p, n as the **only possible** values for Platonic solids.

To prove **existence** we need to actually construct them

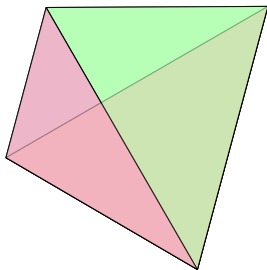
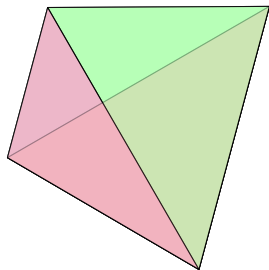
Classification of Platonic solids

Proof Continued Their construction is well-known:

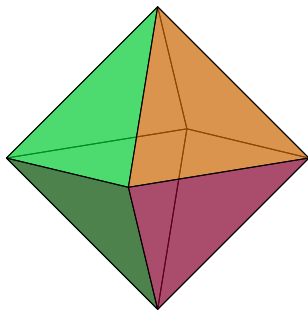
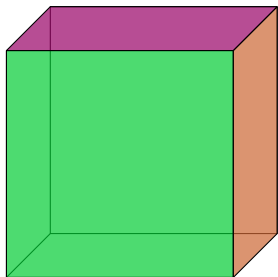


Dual tetrahedron = tetrahedron

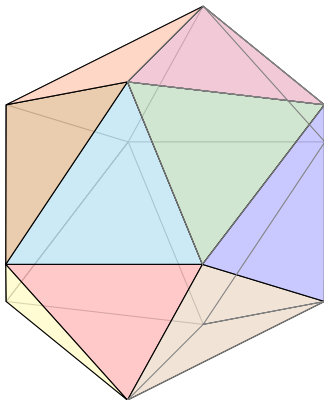
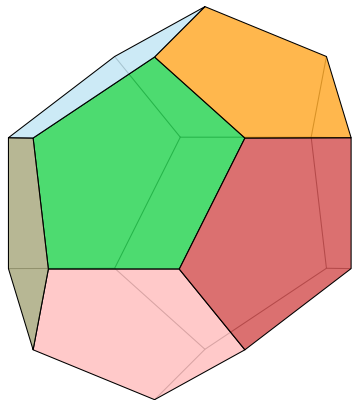
There is a symmetry in the Platonic solids given by $(p, n) \leftrightarrow (n, p)$. This corresponds to taking the dual surface



Cube and octahedron



Dodecahedron and icosahedron



Platonic soccer balls

Here are two dodecahedral decompositions of S^2



Soccer ball

Example A ball is made by gluing together **triangles** and **octagons** so that each octagon is connected to four non-touching triangles. Determine the number of octagons and triangles used

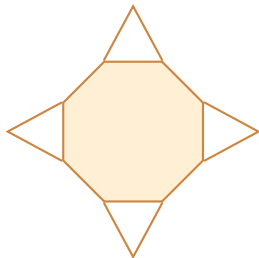
Let there be $|V|$ vertices, $|E|$ edges and $|F|$ faces

Write $|F| = o + t$, where $o = \#$ octagons and $t = \#$ triangles

$$\implies 2 = |V| - |E| + o + t$$

We have:

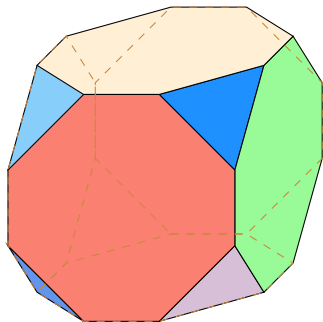
- vertex-degree equation: $3|V| = 2|E|$
- face-degree equation: $2|E| = 3t + 8o$
- Every octagon meets 4 triangles,
 $\implies 3t = 4o \implies 2|E| = 12o$
 $\implies 2 = o\left(4 - 6 + 1 + \frac{4}{3}\right) = \frac{o}{3}$
 $\implies o = 6$ and $t = 8$
 $\implies |E| = 36$ and $|V| = 24$



The octacube

As with the Platonic solids, we have only shown that if such a surface exists then there are 6 octagons, 8 triangles, 24 vertices and 36 edges **but** we have not shown that such a surface exists!

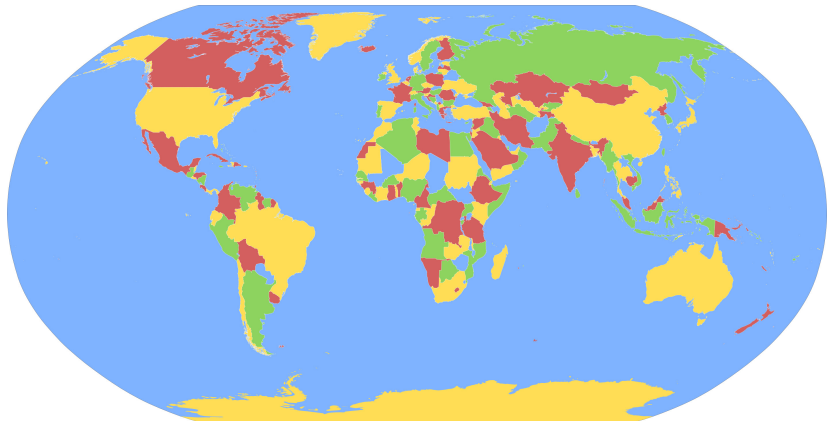
In fact, this surface does exist and it can be constructed by cutting triangular corners off a cube



Coloring maps

Question

How many different colors do you need to color a map so that adjacent countries have different colors?



A map is a polygonal decomposition. The answer to this question involves the same ideas we used to understand Platonic solids

Chromatic number of (connected – assumed from now on) surfaces

Let $P = (V, E, F)$ be a polygonal decomposition of a surface S

Polygons in P are **adjacent** if they are separated by an edge

Let $C_P(S)$ be the **minimum number of colours** needed to colour the polygons in P such that adjacent polygons have **different colors**

Definition

The **chromatic number** of S is $C(S) = \max\{ C_P(S) \mid P \text{ is a "map" on } S \}$

We still need to say what a map in in terms of polygonal decompositions

That is, $C(S)$ is the smallest number of colors that we need to be able to color any polygonal decomposition, or “map”, on S

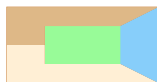
Examples



$$C_P(\mathbb{D}^2) = 2$$



$$C_P(\mathbb{D}^2) = 3$$



$$C_P(\mathbb{D}^2) = 4$$

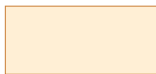
$$\implies C(\mathbb{D}^2) \geq 4$$

For maps of the world we are most interested in $C(\mathbb{D}^2) = C(S^2)$

Map colouring assumptions

A **map** on a surface S is a polygonal decomposition such that:

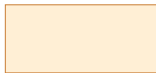
- All vertices have degree at least 3
- No region (i.e. face or polygon) has a border with itself



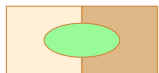
- No region contains a hole



- No region is completely surrounded by another



- No internal region has only two borders (i.e. edges)



These assumptions are purely for convenience because, in each case, we can colour these maps using the same number of colours

Understanding map colourings

The basic idea is to use the Euler characteristic and the degree-vertex and degree-face equations to understand colourings

Let $M = (V, E, F)$ be a map on a surface S . Set

- $\partial_V = \frac{2|E|}{|V|}$, the average vertex-degree
- $\partial_F = \frac{2|E|}{|F|}$, the average face-degree

By definition, $\partial_V|V| = 2|E| = \partial_F|F|$

Moreover,

- ▶ $\partial_V \geq 3$ since vertices have degree at least 3
- ▶ $\partial_F \leq |F| - 1$ as no region borders itself

Remark For a Platonic solid that is made from n -gons with p polygons meeting at each vertex we have $\partial_V = p$ and $\partial_F = n$

Bounding the face degree

Lemma

Suppose that M is a map on a closed surface S . Then

$$\partial_F = \left(1 - \frac{\chi(S)}{|F|}\right) / \left(\frac{1}{2} - \frac{1}{\partial_V}\right)$$

Proof This is a simple calculation with the Euler characteristic:

$$\chi(S) = |V| - |E| + |F| = \frac{|F|\partial_F}{\partial_V} - \frac{|F|\partial_F}{2} + |F|$$

$$\implies \frac{\chi(S)}{|F|} = \frac{\partial_F}{\partial_V} - \frac{\partial_F}{2} + 1$$

$$\implies \partial_F = \left(1 - \frac{\chi(S)}{|F|}\right) / \left(\frac{1}{2} - \frac{1}{\partial_V}\right)$$

Corollary

Let M be a map on a closed surface S . Then $\partial_F \leq 6\left(1 - \frac{\chi(S)}{|F|}\right)$

Proof By assumption, $\partial_V \geq 3 \implies \frac{1}{2} - \frac{1}{\partial_V} \geq \frac{1}{2} - \frac{1}{3} = \frac{1}{6}$

$\implies \partial_F \leq 6\left(1 - \frac{\chi(S)}{|F|}\right)$ as required

Corollary

Let M be a map on S^2 or \mathbb{P}^2 . Then $\partial_F < 6$

Proof By the last corollary, $\partial_F \leq 6 \left(1 - \frac{\chi(S)}{|F|}\right)$

Hence the result follows since $\chi(S^2) = 2$ and $\chi(\mathbb{P}^2) = 1$

Remarks

- 1 A Platonic solid constructed out of n -gons is a special type of map on S^2 . As $\partial_F = n$ this reproves the fact that Platonic solids only exist when $3 \leq n \leq 5$
- 2 If the average face degree $\partial_F < 6$ then there must be at least one face f with $\deg(f) \leq 5$
This observation will be important when we prove the **Five color theorem** (not quite the four color theorem)

Topology – week 11

Math3061

Daniel Tubbenhauer, University of Sydney

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Map coloring assumptions

A **map** on a surface S is a polygonal subdivision such that:

- All vertices have degree at least 3
- No region (i.e. face or polygon) has a border with itself



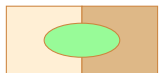
- No region contains a hole



- No region is completely surrounded by another



- No internal region has only two borders (i.e. edges)



The last three assumptions are purely for convenience because, in each case, we can color these maps using the same number of colors

Recall: Notation for map colorings

The basic idea is to use the Euler characteristic and the degree-vertex and degree-face equations to understand colorings

Let $M = (V, E, F)$ be a map on a surface S .

Set

- $\partial_V = \frac{2|E|}{|V|}$, the average vertex-degree
- $\partial_F = \frac{2|E|}{|F|}$, the average face-degree

By definition, $\partial_V|V| = 2|E| = \partial_F|F|$

Moreover,

- ▶ $\partial_V \geq 3$ since vertices have degree at least 3
- ▶ $\partial_F \leq |F| - 1$ because no region borders itself
- ▶ If M is a map on a closed surface S , then we proved that

$$\partial_F \leq 6 \left(1 - \frac{\chi(S)}{|F|} \right)$$

Maps on surfaces with $\chi(S) \leq 0$

Lemma

Let M be a map on a closed surface S with $\chi(S) \leq 0$. Then

$$\partial_F \leq \frac{1}{2} \left(5 + \sqrt{49 - 24\chi(S)} \right)$$

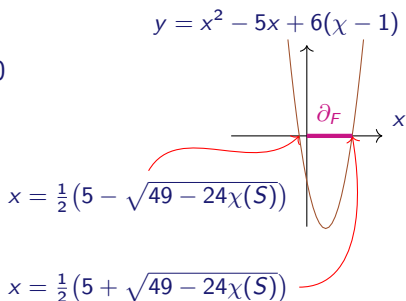
Proof Recall that $\partial_F < |F|$ since no region bounds itself

$$\partial_F < |F| \implies |F| \geq \partial_F + 1$$

Using the corollary from last lecture, and the fact that $\chi(S) \leq 0$,

$$\begin{aligned} \partial_F &\leq 6 \left(1 - \frac{\chi(S)}{|F|} \right) \leq 6 \left(1 - \frac{\chi(S)}{1 + \partial_F} \right) \\ \iff \partial_F^2 - 5\partial_F + 6(\chi(S) - 1) &\leq 0 \end{aligned}$$

$$\begin{aligned} \implies \partial_F &\leq \frac{1}{2} \left(5 + \sqrt{49 - 24\chi(S)} \right) \\ &\text{as required} \end{aligned}$$

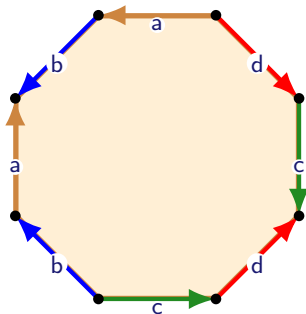


Average face degree for the double torus

Example Let $S = \#^2\mathbb{T}$.

$$\implies \partial_F \leq \frac{1}{2}(5 + \sqrt{49 - \chi(S)}) = \frac{1}{2}(5 + \sqrt{49 - 24(-2)}) \approx 7.4$$

The standard polygonal decomposition for $S = \#^2\mathbb{T}$ is



This has $\partial_F = 8$!?

This is **not** a contradiction because we are assuming that no region has a border with itself, which is never true for a polygonal decomposition that has only one face

Heawood's theorem

Theorem

Suppose that S is a closed surface. Then

$$C(S) \leq \begin{cases} 6, & \text{if } S = S^2 \text{ or } S = \mathbb{P}^2, \\ \frac{7 + \sqrt{49 - 24\chi(S)}}{2}, & \text{otherwise} \end{cases}$$

Proof Let c be the integer part of the right-hand side. Then:

- If $S = S^2$ or $S = \mathbb{P}^2$ then $\partial_F < 6 = c$ by last week's discussion
 - Otherwise, $\partial_F \leq \frac{1}{2}(5 + \sqrt{49 - 24\chi(S)}) = c - 1 < c$ by the last lemma
- $\implies \partial_F < c$ for all S

Claim If M is a map on S then $C_M(S) \leq c$

We argue by induction on $|F|$

- If $|F| \leq 6$ then M has at most 6 faces, so $C_M(S) \leq 6 \leq c$
- Assume now that $|F| > 6$ and that the claim holds for smaller $|F|$

Since $\partial_F < c$ there is at least one face f with $\deg(f) < c$

Proof of Heawood's theorem...

We are now assuming that $|F| > 6$ and f is a face with $\deg(f) < c$

We construct a new map N by shrinking f to a point x :



This gives a new map N on S with $|F| - 1$ faces

$\implies C_N(S) \leq c$ by induction

Since $\deg(f) < c$ we need at most $c - 1$ colors around x :



As we used at most $c - 1$ colors around x , we can color the map M with c colors $\implies C_M(S) \leq c \implies C(S) \leq c$

Chromatic numbers

Heawood's theorem gives an **upper bound** for the chromatic number $C(S)$

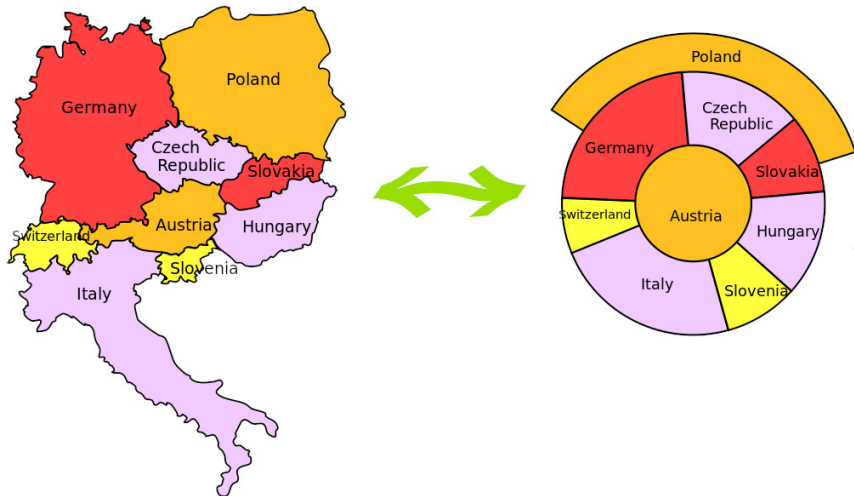
This estimate is **exactly right** except when $S = S^2$ or $S = \mathbb{K}$

Surface	Heawood's bound	real $C(S)$
S^2	6	4
\mathbb{K}	7	6
$S \neq S^2, \mathbb{K}$	$c = \left\lfloor \frac{7 + \sqrt{49 - 24\chi(S)}}{2} \right\rfloor$	c

Remarks

- 1 To prove this for $S \neq S^2, \mathbb{K}$ it is necessary to construct maps that **require** this many colors **and** show no more colors are ever needed
- 2 It is easy to see that $C(S^2) \geq 4$ but it is **really hard** to show that $C(S^2) = 4$: the first proofs of the **Four color theorem** used complicated reductions and then exceedingly long brute force computer calculations
- 3 If $S = S^2$ then $\chi(S^2) = 2$ so $\frac{7 + \sqrt{49 - 24\chi(S)}}{2} = 4$!?

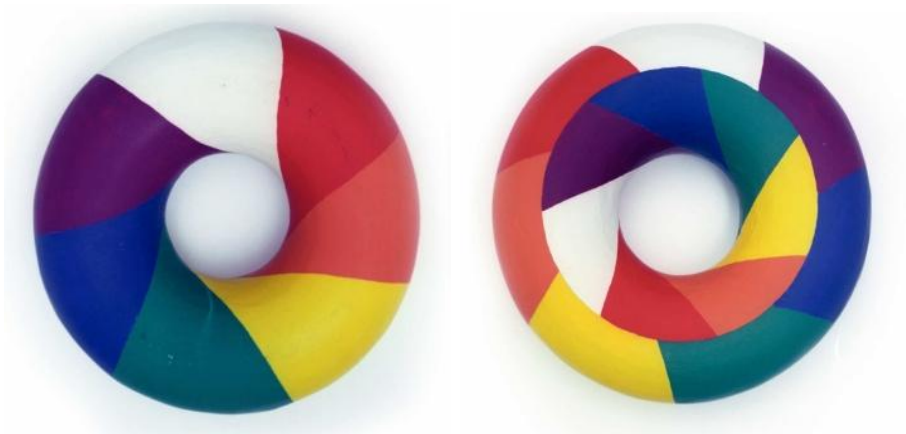
Why is $C(S^2) \geq 4$ easy to see? Well:



Coloring the torus

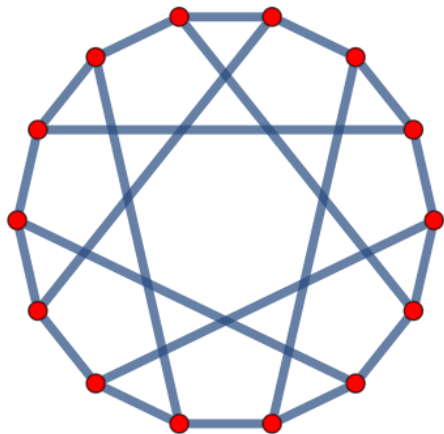
Heawood's estimate for the torus is $C(\mathbb{T}) \leq \frac{7 + \sqrt{49 - 24\chi(\mathbb{T})}}{2} \leq 7$

Here is a map on the torus that requires 7 colors

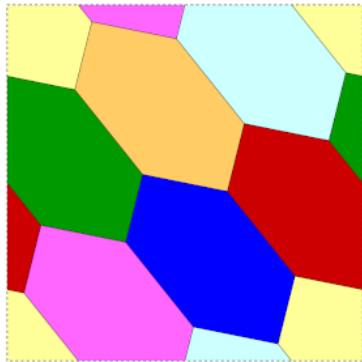


Hence, $C(\mathbb{T}) = 7$ (see the tutorials)

Hexagons on the torus



=

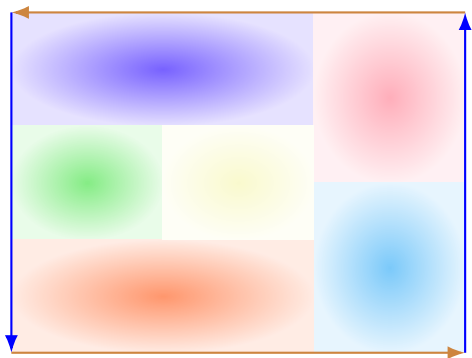


Coloring the projective plane

Heawood's estimate for the projective plane \mathbb{P}^2 is

$$C(\mathbb{P}^2) \leq \frac{7 + \sqrt{49 - 24\chi(\mathbb{P}^2)}}{2} \leq 6$$

Here is a map on \mathbb{P}^2 that requires 6 colors:



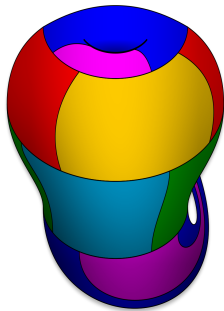
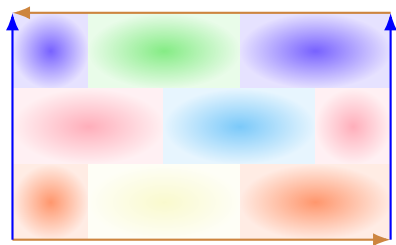
Hence, $C(\mathbb{P}^2) = 6$

Coloring the Klein bottle

Heawood's estimate for the Klein bottle is

$$C(\mathbb{K}) \leq \frac{7 + \sqrt{49 - 24\chi(\mathbb{K})}}{2} \leq 7$$

In fact, Franklin (1930) proved that $C(\mathbb{K}) = 6$



Using these maps you can show that $C(\mathbb{K}) \geq 6$

The four color theorem

Theorem

Every map on \mathbb{D}^2 can be colored using *four* colors.

That is, $C(\mathbb{D}^2) = C(\mathbb{R}^2) = C(S^2) = 4$

Remark All known proofs have a computational component

There were several incorrect proofs published before Appel and Haken proved this result. One of the incorrect proofs was due to Kempe and 11 years later Heawood found a counterexample to their proof. In doing this, Heawood gave their upper bound for the chromatic number $C(S)$ of any closed surface and he gave a conjecture for coloring surfaces and graphs, which was finally proved in 1968 by Ringel and Young.

At the same time, Heawood proved the *Five color theorem*

Theorem

Every map on \mathbb{D}^2 can be colored with *five* colors

By stereographic projection, it is enough to show that $C(S^2) \leq 5$

Proof of Heawood's Five color Theorem

Let $M = (V, E, F)$ be a map on S^2 . We argue by induction on $|F|$

If $|F| \leq 5$ then we can color M with $|F|$ colors, starting the induction

Suppose then that $|F| > 5$. Recall that we have proved $\partial_F < 6$

$\implies M$ has a face f with $\deg(f) \leq 5$

As we did in the proof of Heawood's theorem, construct a new map N by shrinking f to a point:



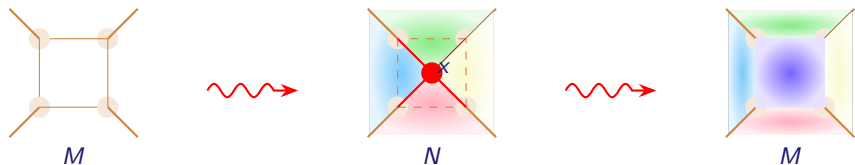
By induction the new map N is 5-colorable

As in the proof of Heawood's theorem, the idea is now to modify the 5-coloring on N to give a 5-coloring on M . This time the proof is more complicated and there are several cases to consider

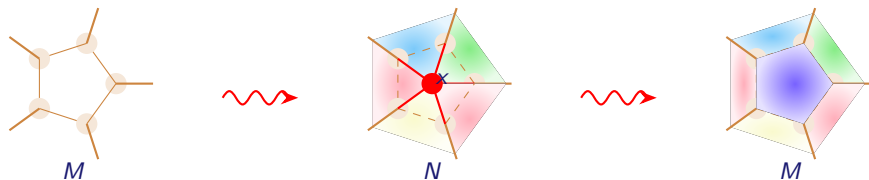
Proof of the Five color Theorem 2

Case 1: $\deg(f) < 5$

If $\deg(f) < 5$ then the 5-coloring of N has at most 4 colors for the faces in N around $x \implies M$ is 5-colorable:

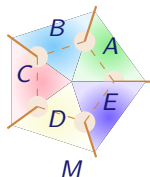


Case 2: $\deg(f) = 5$ and the colors around x are not distinct



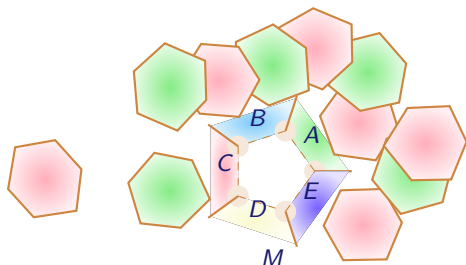
As we have used at most 4 colors in N around x , it follows that M is 5-colorable

Case 3: $\deg(f) = 5$ and all of the colors in N around x are different

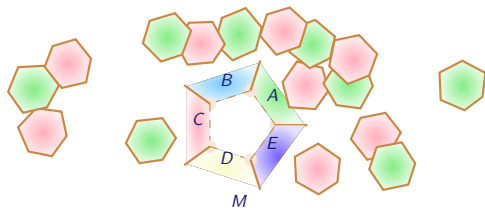


Label the regions $A-E$ as shown.

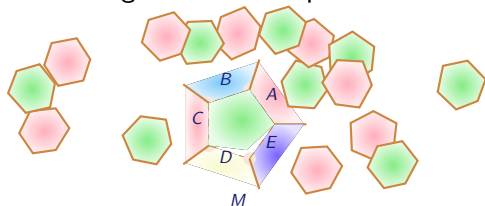
Consider the polygonal decomposition P contained in N that has these five faces together with all of the regions in N that have the same colors as the faces A and C



Case 3a: The regions A and C are not connected in P



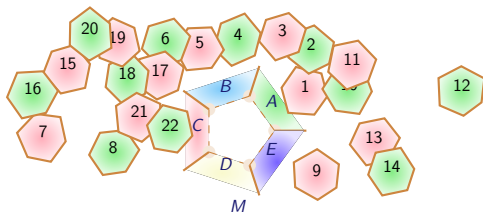
\implies Swapping the colors A and C in the connected component of P that contains A gives a new map N' with a valid coloring



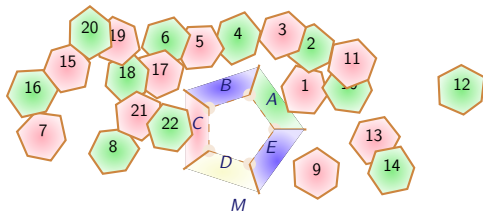
\implies A and C now have the same color and we are back in Case 2

\implies The map M is 5-colorable

Case 3b: The regions A and C are connected in P



\implies As A and C are connected, B and E cannot be connected!
 Swap colors B and E in the “color connected component” containing D



\implies We are back in Case 2, so M is 5-colorable
 This completes the proof of the Five color Theorem

Knots

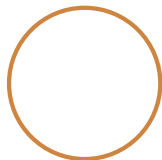
Intuitive definition A **knot** is a piece of string with the ends tied together

Definition

A **knot** is the image of an **injective continuous map** from S^1 into \mathbb{R}^3 , where $S^1 = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 = 1\}$ is the unit circle in \mathbb{R}^2

Equivalently, a knot is a **closed path** in \mathbb{R}^3 that has no **self-intersections**

Examples



Unknot



Trefoil



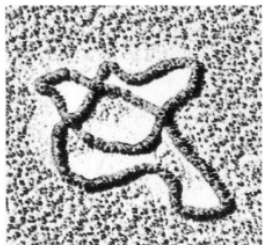
Reverse trefoil



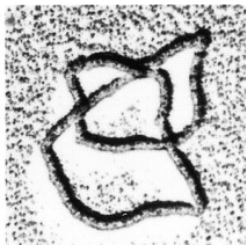
Heart knot

Knot theory is a beautiful mathematical subject with applications in mathematics, computer science, computer chip design, biology, ...

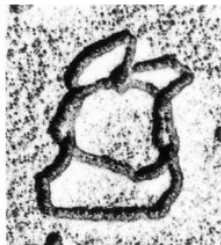
A picture of life



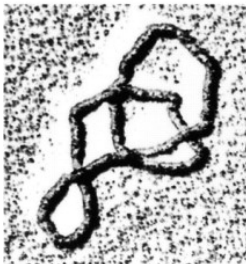
(+) 3



(+) 3



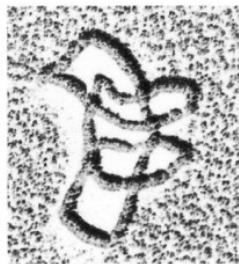
(+) 5 torus



(+) 3



(+) 3

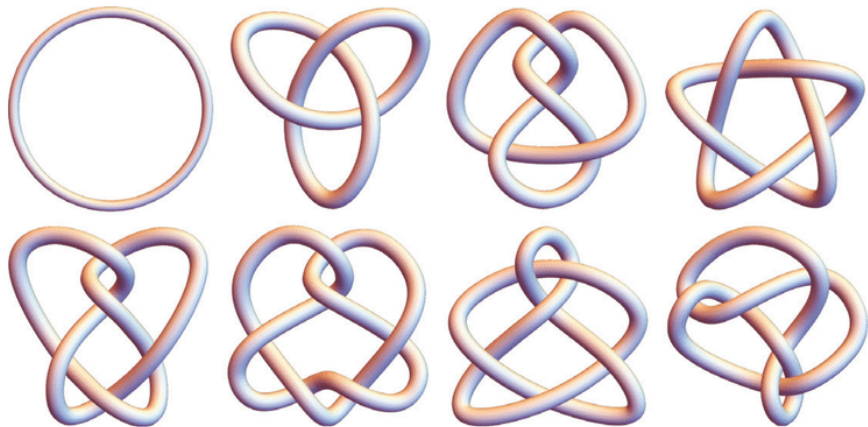


(+) 6 granny

Another picture of life



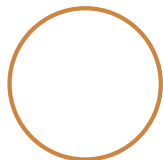
More knots



Basic question in knot theory

Question

When is a knot the unknot?

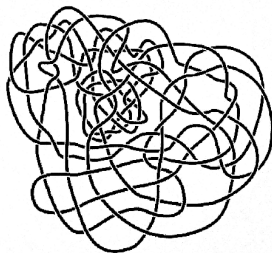


Unknot



Another unknot

It is difficult to tell if
a knot is the unknot



When are two knots the same?

- Can we tell when two knots are equal?
- What does it even mean for two knots to be equal?

Question Is being homeomorphic enough?

No! Every knot is homeomorphic to S^1

\implies Homeomorphism is **not** the right equivalence relation for knots!

Definition

Two knots K and L are **equivalent**, and we write $K \cong L$, if there exists a continuous map, or **ambient isotopy**, $f : \mathbb{R}^3 \times [0, 1] \rightarrow \mathbb{R}^3$ such that

- 1 for each $t \in [0, 1]$ the map $\mathbb{R}^3 \rightarrow \mathbb{R}^3; x \mapsto f(x, t)$ is a homeomorphism
- 2 if $x \in K$ then $f(x, 0) = x$, and
- 3 there is a homeomorphism $K \rightarrow L$ given by $x \mapsto f(x, 1)$

Intuitively, f **continuously deforms** $K = f(K, 0)$ into the knot $L = f(K, 1)$

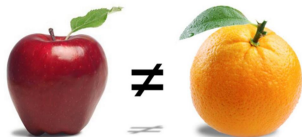
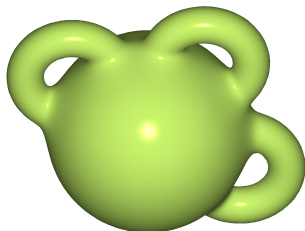
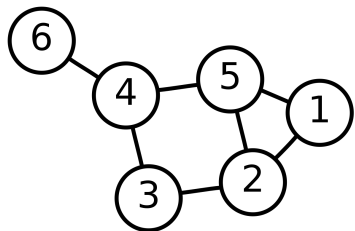
In practice, we will never use this definition but you should see it

A knot K is **trivial** if it is equivalent to the unknot otherwise it is **non-trivial**

Different notions of “equal”

Objects	Graphs	Surfaces	Knots
Equivalence	Isomorphism of graphs	Homeomorphism	Equivalence of knots

In other words, graphs, surfaces and knots should never be directly compared – they are different beasts



Polygonal knots

A **polygonal knot** is a finite union of (straight) line segments in \mathbb{R}^3 that is homeomorphic to S^1



just like the polygonal decompositions of surfaces, polygonal knots reduce the study of knots to **combinatorics**

Examples



Unknot



Trefoil



Figure eight

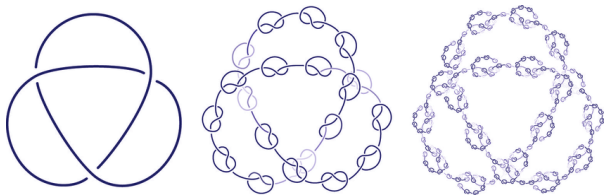
Remark Two polygonal knots K and L are **equivalent** if they have a common subdivision

Only polygonal knots

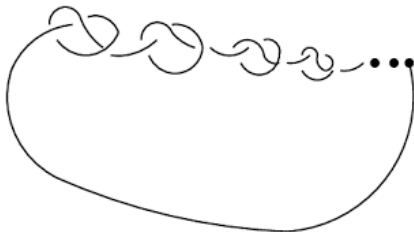
From now on **all** knots are polygonal knots and we drop the adjective polygonal

This is **not** a huge restriction: anything you can draw is polygonal. Any “finite thing” is a polygonal knot, but “limits” are not so we ignore them

Good (but the limit is not):



Not good:



Polygonal knots avoid pathologies

These are not polygonal knots:



Knot projections

Question What do our drawings of knots actually mean?

A **knot projection** is a drawing of a knot in \mathbb{R}^2 such that:

- crossings only involve **two** string **segments**, or **connected components**
- **over** and **under** crossings indicate relative string placement

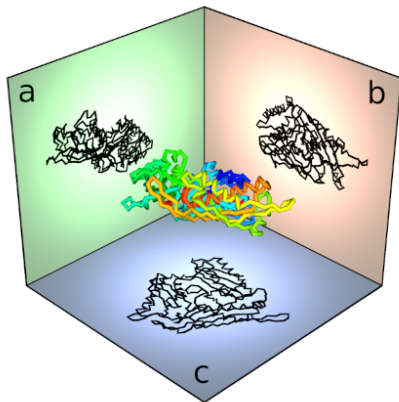
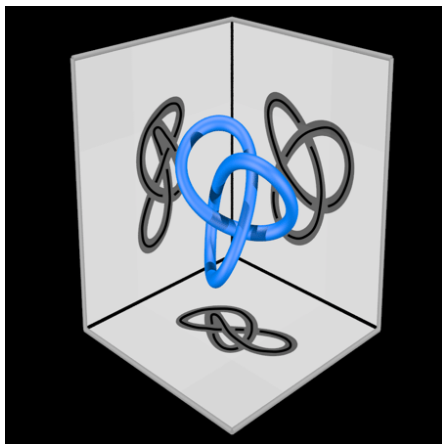


Warning!

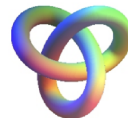
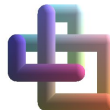
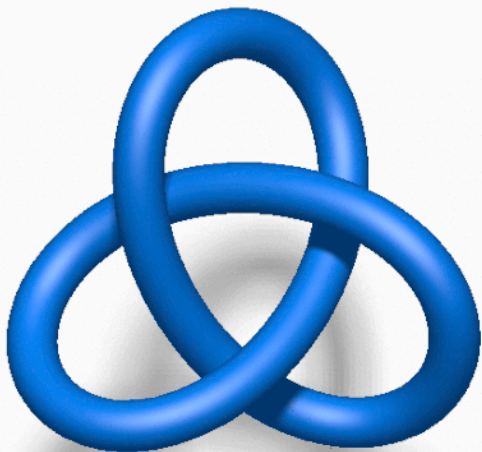
Knot projections are a convenient way of drawing knots but they involve a **choice** of projection

- ⇒ Knot projections can be misleading so we have to check that our constructions are independent of the choice of knot projection

Projections = shadows



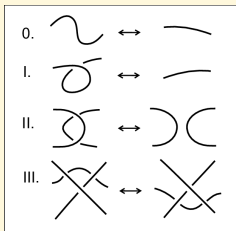
The trefoil knot times nine



Reidemeister's theorem

Theorem

Two knot diagrams represent the same knot if and only if they are related by a (finite) sequence of moves of the following three types

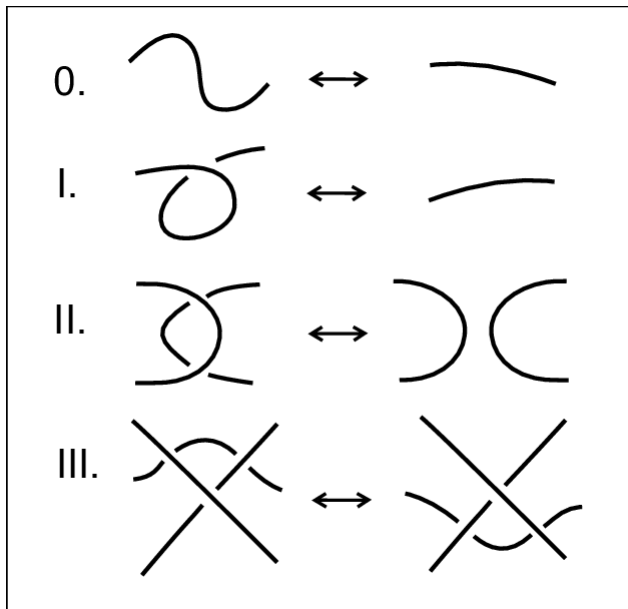


Here the 0th move is usually used silently

We won't prove Reidemeister's theorem in this lecture - the proof is a bit technical and **uses the definition of equivalence of knots**

The point: Reidemeister's theorem **reduces topology to combinatorics of diagrams**

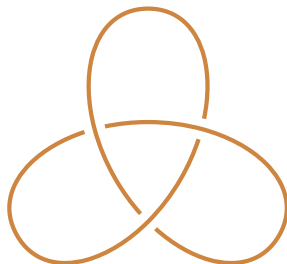
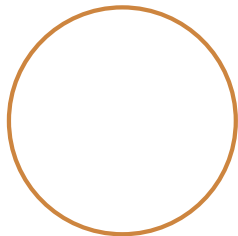
The Reidemeister moves on one slide



The knotty trefoil

Question

Is the trefoil knot *equivalent* to the unknot?

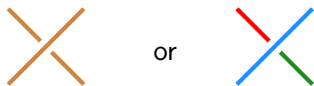


It seems clear that these two knots are different but, so far, we have not seen an easy way to distinguish between them

Knot colorings

Definition

A **coloring** of a knot (projection) is the assignment of colors to the different segments, or connected components, so that at each crossing all segments have either the **same color** or they all have **different colors** and at least **two colors** are used



or

\implies If a knot (projection) is **3-colorable** then it has a coloring that uses **exactly 3** colors

Let $C_3(K)$ be the number of different colorings of K using 3 colors

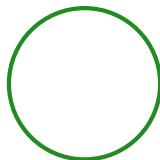
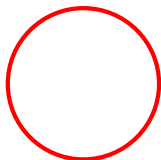
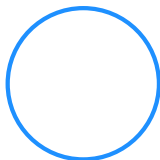
Remark

- A knot can always be colored using a single color, so $C_3(K) \geq 3$ for all knots K
- As soon as more than one color is used we must use all three colors, so K is 3 colorable if and only if $C_3(K) > 3$

Three colorings

As the unknot has no crossings, it has only one segment that must always be colored using the same color

$\implies C_3(\text{Unknot}) = 3$ and the Unknot is **not** 3-colorable



Which of the following are knots are 3-colorable?



coloring the trefoil knot

Question What is $C_3(T)$ if T is the trefoil knot?

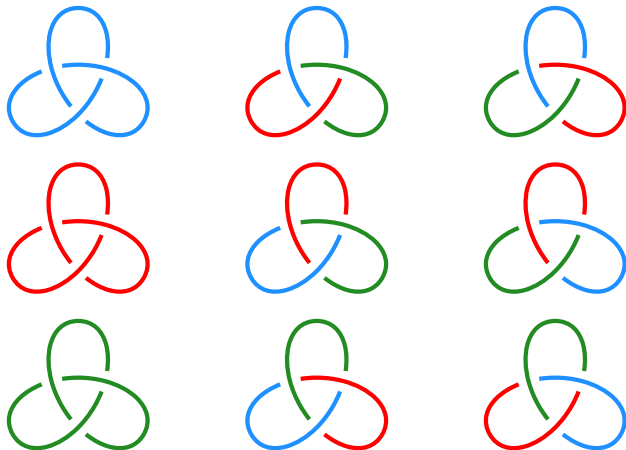


Claim $C_3(T) = 9$ since the components of T can be colored independently

coloring the trefoil knot

Question What is $C_3(T)$ if T is the trefoil knot?

Claim $C_3(T) = 9$ since the components of T can be colored independently



Three colorability

Theorem

The integer $C_3(K)$ is a knot invariant





That is, $C_3(K)$ depends only on K , up to ambient isotopy, and it is independent of the choice of knot projection

Corollary

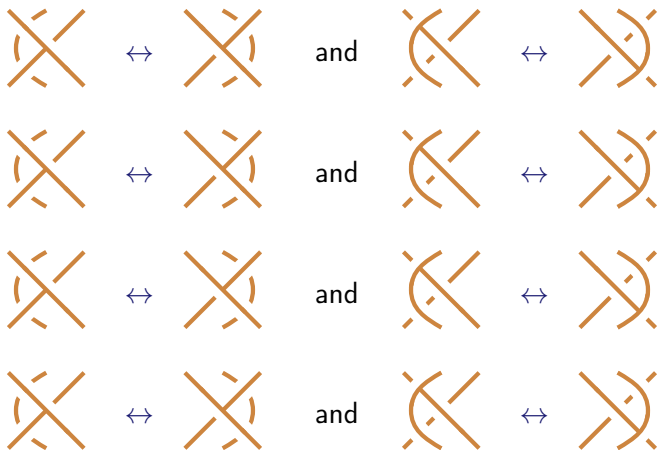
Being 3-colorable is a knot invariant

The corollary follows because K is 3-colorable if and only if $C_3(K) > 3$

To prove the theorem it suffices to check that $C_3(K)$ is invariant under the three Reidemeister moves

- Twisting  and 
- Looping  and 

- Braiding



Key point For each Reidemeister move there is a unique way to complete any coloring given the existing colors of the segments going in and out

Topology – week 12

Math3061

Daniel Tubbenhauer, University of Sydney

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Reidemeister moves are powerful but might be tricky

This is the unknot: $K =$

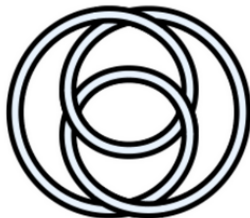


These two knots
are equivalent:

$K =$



, $K' =$



How to show that? Use Reidemeister moves (this is a **strongly recommended exercise**). But that might be tricky in general, so invariants is what we want.

Connected sums of knots

We used **connected sums** to construct and classify surfaces

We want an analog of connected sums for knots

Definition

Given two knots K and L their **connected sum** is the knot $K\#L$ that is obtained by cutting both knots and splicing them together



Remarks

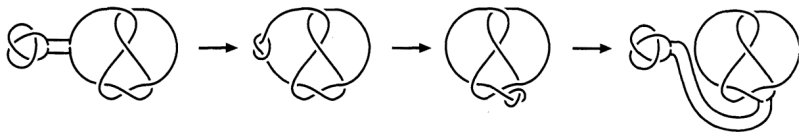
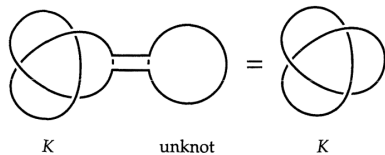
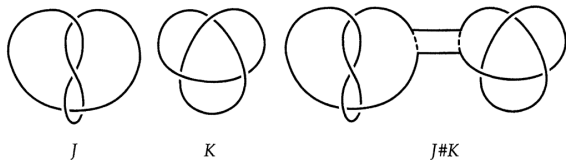
▶ $\#$ does not depend on the choice of knot projections or where you cut either knot, and it is an “addition” or “multiplication”:

▶ $K\#\bigcirc \cong K$

▶ $K\#L \cong L\#K$

▶ $(K\#L)\#M \cong K\#(L\#M)$

Examples of



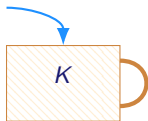
Three colorability and connected sums

Proposition

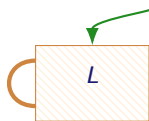
Let K and L be knots. Then $C_3(K\#L) = \frac{1}{3}C_3(K) \cdot C_3(L)$

Proof We need to count the possible colorings of $K\#L$

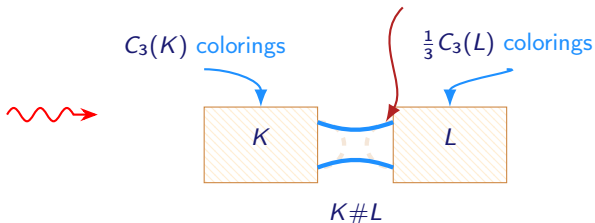
$C_3(K)$ colorings



$C_3(L)$ colorings



The color of these two strings is fixed by K



Since the colors of the connecting strands are fixed, there are only $\frac{1}{3}C_3(L)$ ways to 3-color the strands of L inside $K\#L$

How many knots are there?

Corollary

There are infinitely many inequivalent knots

Proof Since $C_3(K)$ is a knot invariant, it is enough to find an infinite family of knots that have a different number of 3-colorings

Let T be the trefoil knot

$$\implies C_3(T) = 9 = 3^2 > 3$$

\implies if $n \geq 1$ then

$$\begin{aligned} C_3(\#^k T) &= \frac{1}{3} C_3(T) \cdot C_3(\#^{k-1} T) = \frac{1}{3} \cdot 9 \cdot C_3(\#^{k-1} T) \\ &= 3 C_3(\#^{k-1} T) \\ &= 3^2 C_3(\#^{k-2} T) \dots = 3^{k-1} C_3(T) = 3^{k+1} \end{aligned}$$

Therefore, the knots $T, \#^2 T, \#^3 T, \dots$ are all inequivalent because they all have a different number of 3-colorings

More generally, the same argument shows that if K is 3-colorable then the knots $K, \#^2 K, \#^3 K, \dots$ are all inequivalent

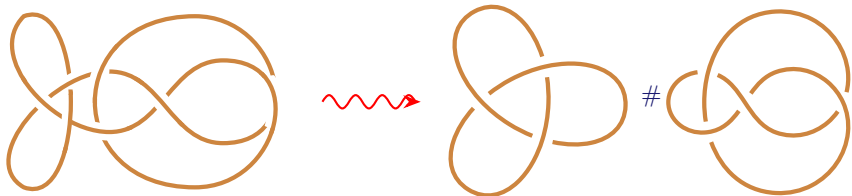
Prime knots

Definition

The knot K is a **composite** knot if it has a **factorisation** $K = L \# M$, where L and M are **not** the unknot

A knot K is **prime** if it is not composite

Example



Remark The definition of prime knots is hard to apply because it is difficult to tell when a knot is not the unknot!

In fact, we don't yet know that the figure eight knot is not the unknot!!

The crossing number of a knot

Definition

The **crossing number** of a **projection** is the number of crossings you see. The **crossing number** $\text{cross}(K)$ of a **knot** K is the **smallest** number of crossings in **any** knot projection

This is obviously a knot invariant but **not** obvious how to compute it !!!

Examples

- $\text{cross}(\bigcirc) = 0$. In fact, $\text{cross}(K) = 0$ if and only if K is the unknot
- $\text{cross}(\text{trefoil}) = 3$

Lemma

Let K and L be knots. Then $\text{cross}(K\#L) \leq \text{cross}(K) + \text{cross}(L)$

Remark It is a big open question if $\text{cross}(K\#L) = \text{cross}(K) + \text{cross}(L)$

This is only known to be true for certain types of knots such as **alternating knots**, which we will meet soon

The crossing number and prime knots

Lemma

Let K and L be knots. Then $\text{cross}(K\#L) \leq \text{cross}(K) + \text{cross}(L)$

Proof Note that $K\#L$ has a projection with $\text{cross}(K) + \text{cross}(L)$ crossings

Corollary

Let K be a knot. Then $K = P_1\#\dots\#P_n$, for prime knots P_1, \dots, P_n

Proof Immediate by induction on $\text{cross}(K)$, the minimal number of crossings in K

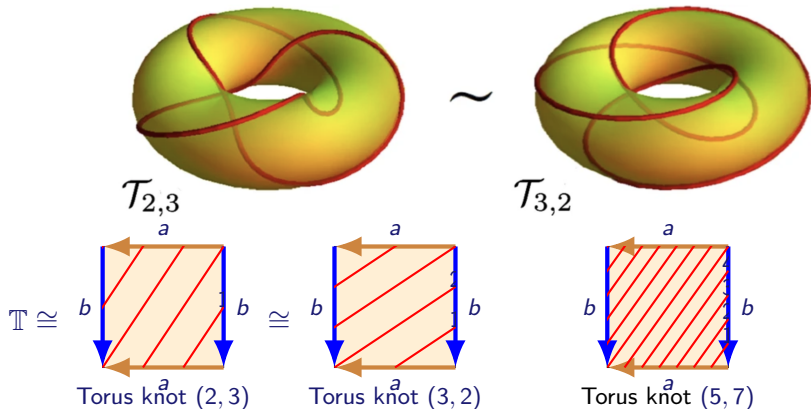
Conversely, we can ask how many prime knots there are

Torus knots

For $a, b \in \mathbb{R}$ write $a \equiv b$ if $a - b \in \mathbb{Z} \iff$ same fractional part

Definition

Then the (p, q) -torus knot $\mathcal{T}_{p,q}$ is the closed path $\{(x, y) \in T \mid py \equiv qx\}$ on the standard polygonal decomposition of the torus on the unit square, where $p, q \in \mathbb{N}$ and $\gcd(p, q) = 1$



Torus knots are prime knots

Theorem

Suppose that $\gcd(p, q) = 1$. Then the (p, q) -torus knot is prime

This is intuitively clear because whenever we try to write a torus knot as the connected sum of two smaller knots, each of the smaller knots is the unknot; we sketch the proof momentarily

Corollary

There are an infinite number of prime knots

Proof If $p < q$ then $\text{cross}(\mathcal{T}_{p,q}) = (p-1)q$ — true but won't prove
 \implies the torus knots $\mathcal{T}_{2,q}$ with $q > 2$ odd are all inequivalent

The number of prime knots with n -crossings

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	0	1	1	2	3	7	21	49	165	552	2176	9988	46972

As is common, knots and their mirror images are only counted once

Torus knots are prime - proof sketch

Proof

For $p, q \geq 2$ let the (p, q) -torus knot K lie on an unknotted torus $T \subset S^3$ and let the 2-sphere S define a decomposition of K . We assume that S and T are in general position, that is, $S \cap T$ consists of finitely many disjoint simple closed curves.

Such a curve either meets K , is parallel to it or it bounds a disk D on T with $D \cap K = \emptyset$. Choose γ with $D \cap S = \partial D = \gamma$. Then γ divides S into two disks D', D'' such that $D \cup D'$ and $D \cup D''$ are spheres, $(\cup D') \cap (\cup D'') = D$; hence, D' or D'' can be deformed into D by an isotopy of S^3 which leaves K fixed. By a further small deformation we get rid of one intersection of S with T .

Proof Continued

Consider the curves of $S \cap T$ which intersect K . There are one or two curves of this kind since K intersects S in two points only. If there is one curve it has intersection numbers $+1$ and -1 with K and this implies that it is either isotopic to K or nullhomotopic on T . In the first case K would be the trivial knot. In the second case it bounds a disk D_0 on T and $D_0 \cap T$, plus an arc on S , represents one of the factor knots of K ; this factor would be trivial, contradicting the hypothesis.

Torus knots are prime - proof sketch

Proof Continued

The case remains where $S \cap T$ consists of two simple closed curves intersecting K exactly once. These curves are parallel and bound disks in one of the solid tori bounded by T . But this contradicts $p, q \geq 2$

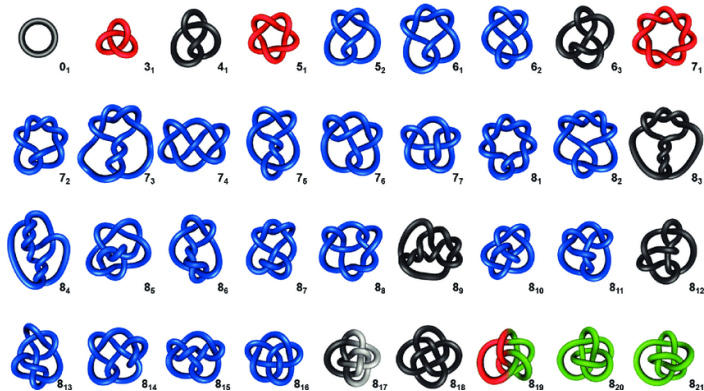
Prime factorisation of knots

Theorem

Suppose that K is not the unknot. Then $K = P_1 \# P_2 \# \dots \# P_n$, for prime knots P_1, \dots, P_n . Moreover, the multiset of prime knots is a knot invariant

This can be proved using **Seifert surfaces** (that we meet later)

Here is a table of the unknot and the first 36 prime knots:



Question

Is the figure eight knot the unknot?

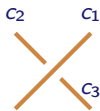
\implies We need another knot invariant to show that the figure eight knot is not the unknot

To do this we first need to better understanding 3-colorings

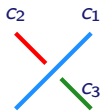
Rather than colors, lets color the segments with 0, 1 and 2

Question

What can we say about $c_1 + c_2 + c_3$ for a 3-coloring?

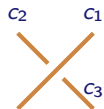


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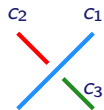


Possible colorings and the values of $c_1 + c_2 + c_3$

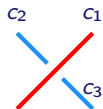
Allowed colorings



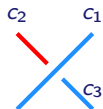
or



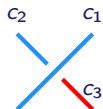
Disallowed colorings



or



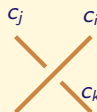
or



Knot colorings with p -colors

Definition

Let $p \in \mathbb{N}$. A p -coloring of a knot K is a coloring of the segments of K that using colors from $\{0, 1, \dots, p-1\}$ such that


$$\implies 2c_i \equiv c_j + c_k \pmod{p}$$

Let $C_p(K)$ be the number of p -colorings of K .

A knot is p -colorable if it has a p -coloring that uses at least two colors

- $a \equiv b \pmod{p} = a - b$ is divisible by p . When $p = 3$ this agrees with the previous definition of 3-coloring

- As with 3-coloring this depends on the choice of knot projection

- For any p the constant coloring is a p -coloring

$$\implies C_p(K) \geq p$$

$$\implies K \text{ is } p\text{-colorable if and only if } C_p(K) > p$$

Colorability is a knot invariant

Theorem

Suppose that $p \geq 3$. Then $C_p(K)$ and p -colorability are both knot invariants

Proof Repeat the argument used for 3-colorings to show that $C_p(K)$ is unchanged by the Reidemeister moves and hence is a knot invariant

\implies p -colorability is a knot invariant since K is p -colorable if and only if $C_p(K) > p$

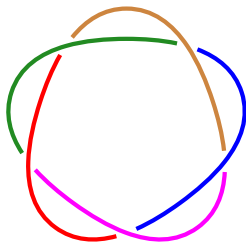
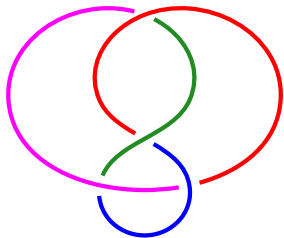
Similarly, $C_p(K \# L) = \frac{1}{p} C_p(K) C_p(L)$, for knots K and L

Question

Is there an easy way to tell if a knot is p -colorable?

Examples of p -colorings

Are the following knots 4-colorable, 5-colorable, ... ?



We **need** a better way to determine if a knot is p -colorable!



Use **linear algebra**!

The trefoil knot is knotted!

Corollary

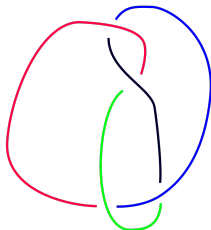
The trefoil knot is not the unknot

Proof The trefoil is 3-colorable and the unknot is not

Corollary

The trefoil knot is not equivalent to the figure eight knot

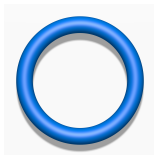
Proof The trefoil is 3-colorable and the figure eight knot is not



The trefoil knot in comparison



\neq



or



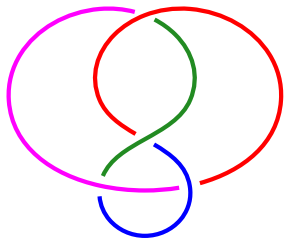
Colorful linear algebra

Consider the figure eight knot.

Label the segments c_1, c_2, c_3, c_4 in traveling order around the knot

⇒ We require:

$$\begin{array}{cccc} 2c_1 & & -c_3 & -c_4 & \equiv 0 \\ -c_2 & 2c_2 & & -c_4 & \equiv 0 \\ -c_1 & -c_2 & 2c_3 & & \equiv 0 \\ & -c_2 & -c_3 & 2c_4 & \equiv 0 \end{array}$$



In matrix form this becomes $M_K \underline{C} \equiv \underline{0} \pmod{p}$, where

$$M_K = \begin{bmatrix} 2 & 0 & -1 & -1 \\ -1 & 2 & 0 & -1 \\ -1 & -1 & 2 & 0 \\ 0 & -1 & -1 & 2 \end{bmatrix} \quad \text{and} \quad \underline{C} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix}$$

That is, \underline{C} is a p -coloring $\iff M_K \underline{C} \equiv 0 \pmod{p}$

We have reduced finding c_1, \dots, c_4 to linear algebra!

The knot matrix

Let K be knot projection with n crossings.

\implies Each segment starts and ends at a crossing, and each crossing has two under-crossings, so the knot projection has n segments.

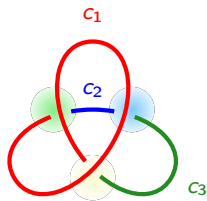
Traveling around the knot in an anti-clockwise direction let the colors of the segments be c_1, \dots, c_n and let the crossings be x_1, \dots, x_n

The **knot matrix** of K is the matrix $M_K = (m_{ij})$, where m_{ij} is the **sum** of the contributions of the j th segment of color c_j to the i th crossing x_i with

$$\begin{cases} +2, & \text{for over-crossings} \\ -1, & \text{for under-crossings} \end{cases}$$

\implies **crossings label rows** and **segments label columns**

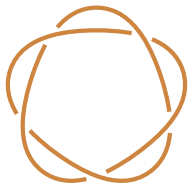
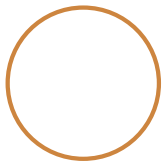
An atypical example



$$M_K = \begin{bmatrix} c_1 & c_2 & c_3 \\ 2 & -1 & 0 \\ 2 & -1 & -1 \\ 2 & -1 & 0 & -1 \end{bmatrix}$$

Alternating knots

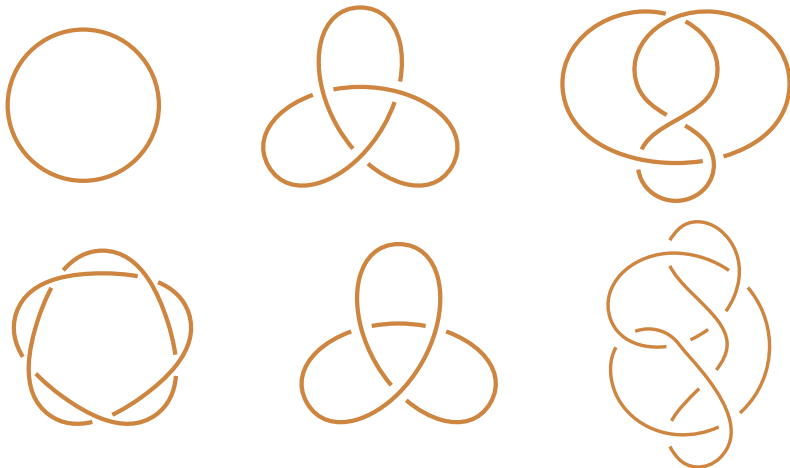
We mainly consider colorings of alternating knots



Alternating knots

We mainly consider colorings of **alternating knots**

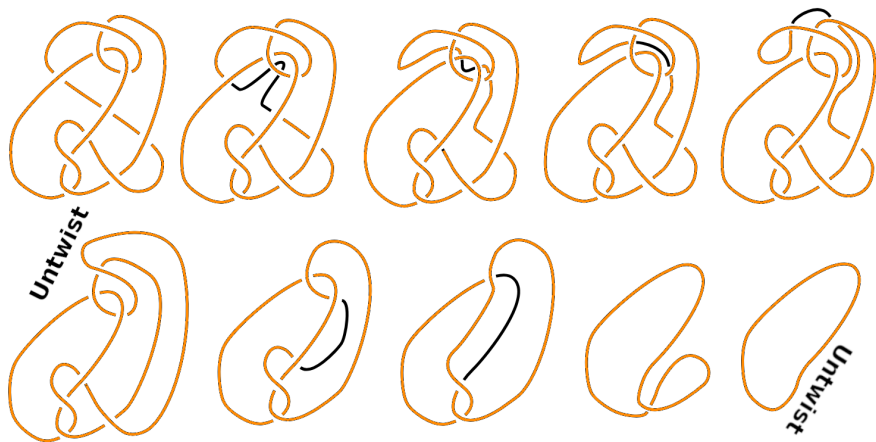
A knot **projection** is **alternating** if the crossings alternate between over and under crossings as you travel around the knot in an anti-clockwise direction



⇒ Being alternating is **not** a knot invariant

Alternating knots – careful with projections

The unknot is alternating, but it can have non-alternating projections:



Similarly, for other knots

Knot matrices for alternating knots

If K is an **alternating knot** then:

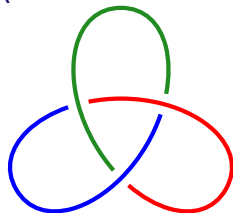
- ⇒ every segment starts as an under-string, becomes an over-string and finishes as an under-string
- ⇒ when read in traveling order the segments and crossings alternate as $c_1, x_2, c_2, x_2, \dots, c_n, x_n$
- ⇒ if K is alternating and no segment meets itself then each row of M_K will contain one 2 and two -1 's
- ⇒ if K is alternating the row and column sums of M_K are all 0

We will mainly consider colorings of alternating knots

Knot matrix examples

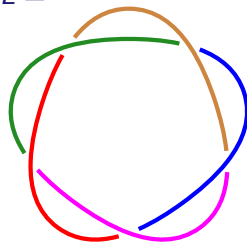
$$M_K = \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}$$

$K =$



$$M_L = \begin{pmatrix} 2 & 0 & 0 & -1 & -1 \\ -1 & 2 & 0 & 0 & -1 \\ -1 & -1 & 2 & 0 & 0 \\ 0 & -1 & -1 & 2 & 0 \\ 0 & 0 & -1 & -1 & 2 \end{pmatrix}$$

$L =$



Properties of the knot matrix

Lemma

Let K be an alternating knot.

① The row and column sums of M_K are all 0

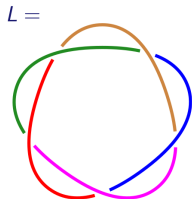
② $M_K \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} = \underline{0}$

③ $\det M_K = 0$

Proof

(1) Since the knot is alternating every colored strand contributes 2 once and -1 twice (see below) and dually from crossings

$$M_L = \begin{pmatrix} 2 & 0 & 0 & -1 & -1 \\ -1 & 2 & 0 & 0 & -1 \\ -1 & -1 & 2 & 0 & 0 \\ 0 & -1 & -1 & 2 & 0 \\ 0 & 0 & -1 & -1 & 2 \end{pmatrix}$$



Proof Continued

(2) By (1), the respective vector is an eigenvector with eigenvalue zero

(3) By (2) there is a zero eigenvector, so the kernel is nontrivial

Minors of a matrix

The (r, c) -minor of an $n \times n$ matrix M is the $(n - 1) \times (n - 1)$ -matrix M_{rc} obtained by deleting row r and column c from M

$$M = \begin{bmatrix} a_{11} & \cdots & a_{1c} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{r1} & \cdots & a_{rc} & \cdots & a_{rn} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nc} & \cdots & a_{nn} \end{bmatrix}$$



$$M_{rc} = \begin{bmatrix} a_{11} & \cdots & a_{1c} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ a_{r1} & \cdots & a_{rc} & \cdots & a_{rn} \\ \vdots & \ddots & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nc} & \cdots & a_{nn} \end{bmatrix}$$

The knot determinant

Definition

Let K be a knot. The **knot determinant** of K is $\det(K) = |\det(M_K)_{11}|$

Lemma

Let $M = (m_{rc})$ be an $n \times n$ matrix with zero row and column sums. Then $\det M_{rc} = \pm \det M_{11}$, for $1 \leq r, c \leq n$

Proof Let \mathbb{I} be the $n \times n$ -matrix with every entry equal to 1

$$\begin{aligned} \text{Then } \det(M + \mathbb{I}) &= n^2 \det \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & m_{22}+1 & \cdots & m_{1n}+1 \\ \vdots & \ddots & \ddots & \vdots \\ 1 & m_{n2}+1 & \cdots & m_{nn}+1 \end{bmatrix} \\ &= n^2 \det \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 0 & m_{22} & \cdots & m_{1n} \\ \vdots & \ddots & \ddots & \vdots \\ 0 & m_{n2} & \cdots & m_{nn} \end{bmatrix} \end{aligned}$$

By the same argument, if $1 \leq r, c \leq n$ then

$$\det(M + \mathbb{I}) = (-1)^{r+c} n^2 \det M_{rc}$$

The knot determinant

Definition

Let K be an alternating knot. The **knot determinant** of a knot K is
 $\det(K) = |\det(M_K)_{11}|$ — can take **any minor** of M_K

Theorem

Let K be an alternating knot and $p \geq 3$ be a prime. Then K is p -colorable if and only if p divides the knot determinant $\det(K)$

Proof

By definition, K is p -colorable if and only if there exist c_1, \dots, c_n such that $M_K \begin{bmatrix} c_1 \\ \vdots \\ c_n \end{bmatrix} \equiv \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \pmod{p}$.

Now $\begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$ is a 0-eigenvector of M_K , so if $d \in \mathbb{Z}$ then

$$M_K \begin{bmatrix} c_1 \\ \vdots \\ c_n \end{bmatrix} = M_K \begin{bmatrix} c_1+1 \\ \vdots \\ c_n+1 \end{bmatrix} = M_K \begin{bmatrix} c_1+2 \\ \vdots \\ c_n+2 \end{bmatrix} = \dots = M_K \begin{bmatrix} c_1+d \\ \vdots \\ c_n+d \end{bmatrix}$$

Proof Continued

\implies We can assume that $c_1 = 0$ by taking $d = -c_1$

Hence, K is p -colorable if and only if and only if there exist c_2, \dots, c_n such that

$$M_K \begin{bmatrix} 0 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} \equiv 0 \pmod{p} \iff (M_K)_{11} \begin{bmatrix} c_2 \\ \vdots \\ c_n \end{bmatrix} \equiv 0 \pmod{p}$$

$$\iff \det(K) \not\equiv 0 \pmod{p}$$

Remarks

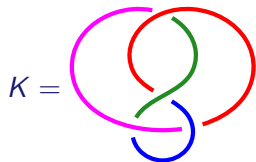
- 1 The Reidemeister moves show that the knot matrix M_K is not a knot invariant but $\det(K) = |\det(M_K)_{11}|$ is a knot invariant
- 2 If K and L are knots then $\det(K\#L) = \det(K)\det(L)$
 \implies if $\det(K\#L) = p$ is prime, then either $\det(K) = p$ or $\det(L) = p$
- 3 If K is not alternating then the row sums of M_K are still 0. Therefore, the argument used to prove the theorem shows that K is p -colorable if and only if p divides $(M_K)_{rc}$, for some r, c .

Colorability of the figure eight knot

Summary of how to determine p -colorability

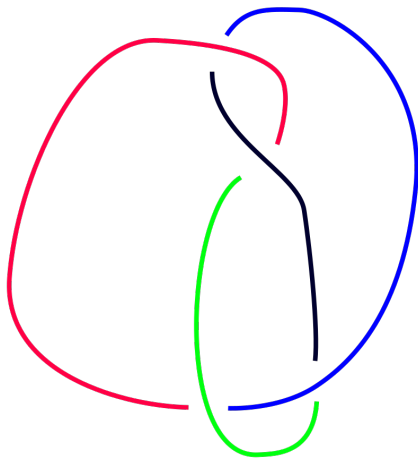
- 1 Label the segments in traveling order
- 2 Compute the entries of the knot matrix M_K
- 3 Compute the knot determinant $\det(K) = |\det(M_K)_{11}|$
- 4 Check if p divides $\det(K)$

$$M_K = \begin{pmatrix} 2 & -1 & -1 & 0 \\ -1 & 0 & 2 & -1 \\ -1 & -1 & 0 & 2 \\ 0 & 2 & -1 & -1 \end{pmatrix}$$



The determinant is five, so the figure eight knot is five-colorable (and only five colorable)

Colorability of the figure eight knot – part 2



Thus, the figure eight knot is not trivial (it has **strictly more than five 5-colorings**) and also not the trefoil knot

Seifert surfaces

Definition

A **Seifert surface** for a knot K is an orientable surface that has K as its boundary

Theorem

Every knot has a Seifert surface

Remark In general, a Seifert surface is **not** unique

We will prove this result by giving an algorithm for constructing a Seifert surface for any knot

Constructing Seifert surfaces

Proof Real world version

Take a knot, build out of wire, and put it into soap



The minimal surface you get is a Seifert surface

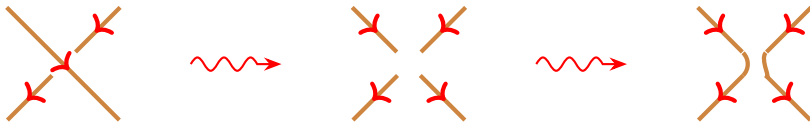
Constructing Seifert surfaces

Proof Math version

Step 1 Pick an **orientation** of the knot

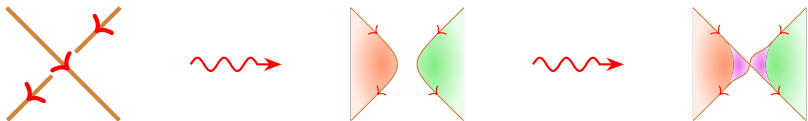
That is, fix a direction to travel around the knot

Step 2 At each crossing cut the over-string and join the incoming and outgoing strings; the knot is then a disjoint union of **Seifert circles**

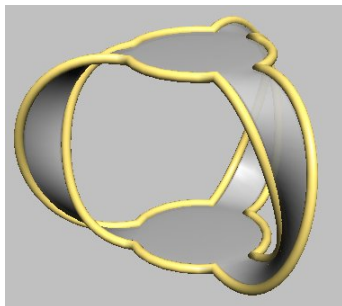
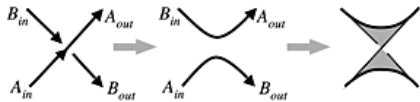
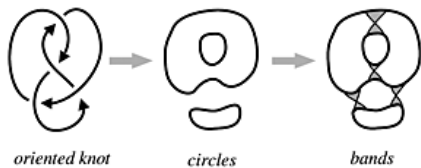


Step 3 Imagine the Seifert circles as being at different heights and glue a disk onto each one of the Seifert circles

Step 4 Now each crossing in K , glue on a **twisted** strip that has the crossing as a boundary



The platform construction

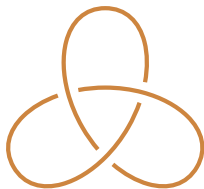


Examples of Seifert surfaces

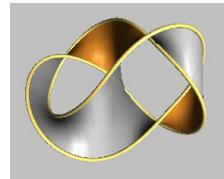
- Unknot:



- Trefoil



- Figure eight



More examples of Seifert surfaces

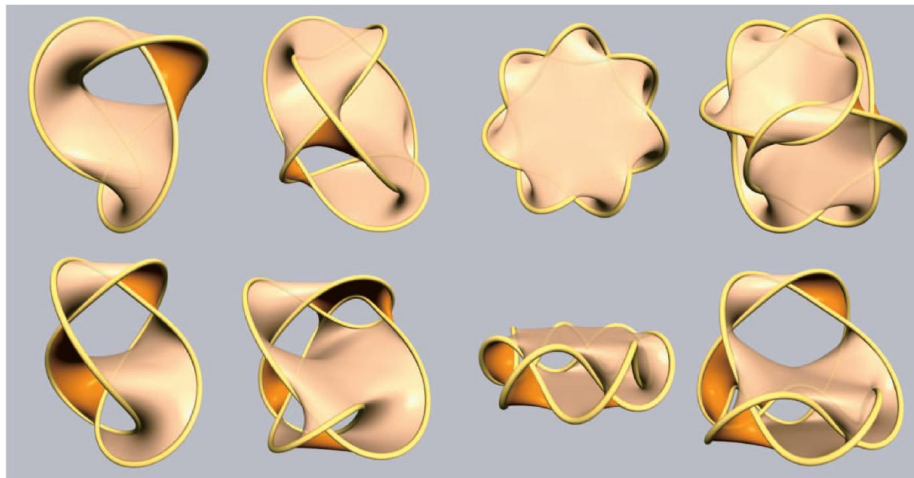


Figure 8 = 4_1

6_1

7_1

8_5

The genus of a knot

Let S be a Seifert surface of a knot K

$\implies S$ is orientable + has one boundary circle since it embeds in \mathbb{R}^3

$\implies S \cong \mathbb{D}^2 \# \#^t \mathbb{T}$, where $t = \frac{1-\chi(S)}{2} \geq 0$

Definition


The **genus** of K is $g(K) = \min \left\{ \frac{1-\chi(S)}{2} \mid S \text{ a Seifert surface of } K \right\}$

Remark Used to prove uniqueness of factorization of prime knots

Example (with proof!)

• $K = \bigcirc \implies g(K) = 0$ as $S \cong \mathbb{D}^2$ and g **cannot be smaller**, so just checking this one diagram \bigcirc is sufficient

Fact $g(K) = 0 \iff K = \bigcirc$

Problem K is the trefoil:  ... not very clear how to calculate $g(K)$!

Calculating the knot genus

Proposition

Let S be the Seifert surface with s Seifert circles that is constructed from a knot projection for a knot K with c crossings.

Then $\chi(S) = s - c$ and $g(K) \leq \frac{1+c-s}{2}$

Proof Recall from tutorials that $\chi(A \cup B) = \chi(A) + \chi(B) - \chi(A \cap B)$

Write $S = A \cup B$, where A the union of the Seifert circles and B the union of the twists in S

$\implies A \cap B$ is a union of c pairs



$\implies \chi(S) = \chi(A) + \chi(B) - \chi(A \cap B) = s + c - 2c = s - c$

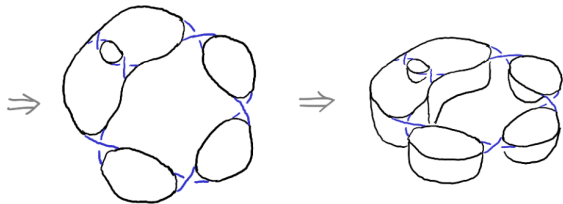
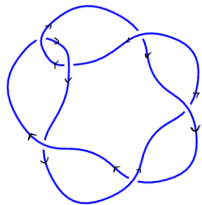
Hence, $g(K) \leq \frac{1-\chi(S)}{2} = \frac{1+c-s}{2}$

Genus of trefoil and figure eight knots

If K has c crossings and s Seifert circles then $g(K) \leq \frac{1+c-s}{2}$



$$\text{So } g(K) \leq \frac{1+4-3}{2} = 1$$



genus=1

Genus of alternating knots

Bad news: It can happen that $g(K) < \frac{1-\chi(S)}{2}$!!

The good news is that there is no bad news for alternating knots

Theorem

Let S be the Seifert surface constructed from an *alternating* knot projection of K . Then $g(K) = \frac{1-\chi(S)}{2}$

Proof Nontrivial and omitted!

Knot genus is additive

Theorem

Let K and L be knots. Then $g(K\#L) = g(K) + g(L)$

Start of proof It is not hard to see that $S_{K\#L} \cong S_K \#_{\text{strip}} S_L$ (connected sum along a strip connecting the surfaces **and** boundary cycles). This implies that $g(K\#L) \leq g(K) + g(L)$. The reverse implication is **much** harder!

The theorem gives another proof that the trefoil and figure eight knots are non-trivial because both knots have genus 1

Corollary

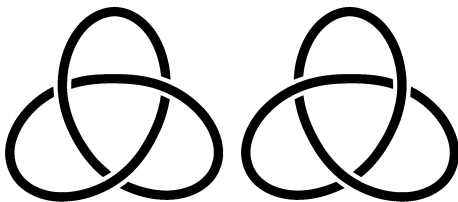
Let K and L be knots, which are not the unknot. Then $K \not\cong (K\#L)\#M$ for any knot M

Proof If such a knot M existed then

$$\begin{aligned} g(K) &= g((K\#L)\#M) = g(K) + g(L) + g(M) \\ \implies g(M) &= -g(L) < 0 \quad \color{red}{\lll} \end{aligned}$$

Left = right-handed trefoil? No idea...

No method we have seen distinguishes these two fellows:

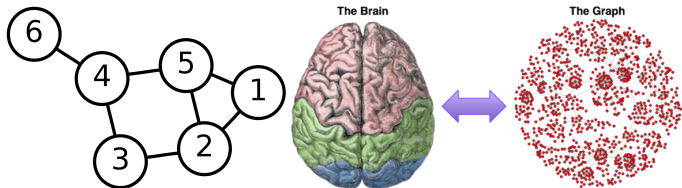


But that has to wait for another time...

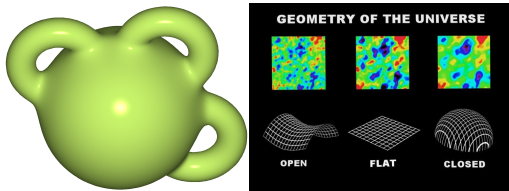


A few take away pictures

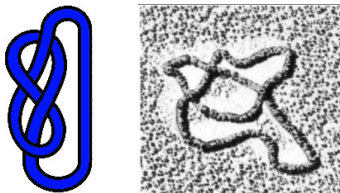
Topic 1: graphs!



Topic 2: surfaces!



Topic 3: knots!



This was my last slide!



Topology – recollection

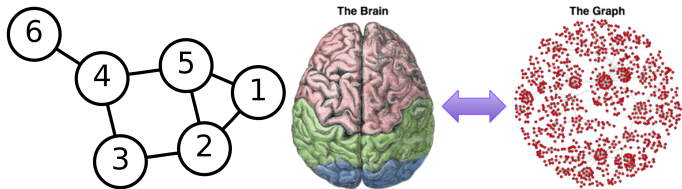
Math3061

Daniel Tubbenhauer, University of Sydney

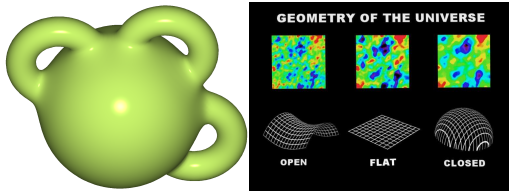
© Semester 2, 2023

The three main topics

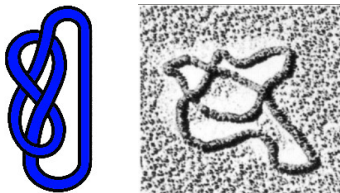
Topic 1: graphs!



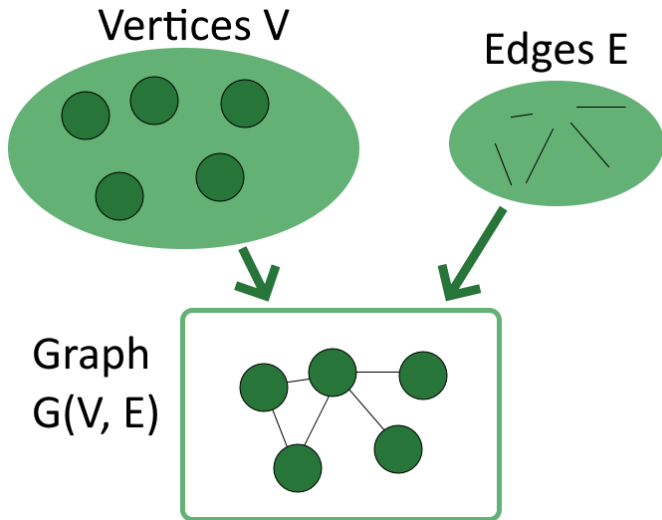
Topic 2: surfaces!



Topic 3: knots!



Topic 1: graphs!



Questions we ask about a graph G

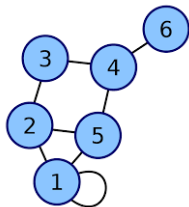
- 1 Have we seen G before? Is it one of the standard ones (lines, cycles, complete graphs, complete bipartite graphs)?
- 2 How many vertices and edges does G have?
- 3 What is its Euler characteristic?
- 4 Is G connected? How many connected components does G have?
- 5 Is G a tree? If not, then can we find a spanning tree?
- 6 What are its paths (start and endpoint might be different)? What are its circuits?
- 7 Does G have an Eulerian circuit? Does G have an Eulerian path?
- 8 Is G planar, i.e. does it embed into the plane = the disc = S^2 ?
- 9 Does G embed into other surfaces?
- 10 How many colors do we need to color maps defined by G ?

Let us answer 1-10 for the [Pappus graph](#)

But before, let us recall what the above are!

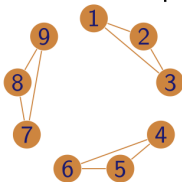
Basics

A connected graph with $|V| = 6$, $|E| = 8$, $\chi = -2$ and one loop:

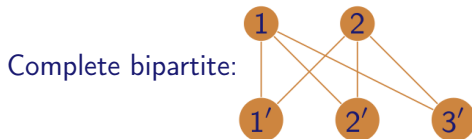
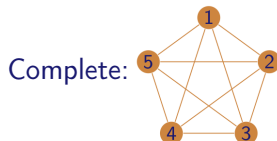
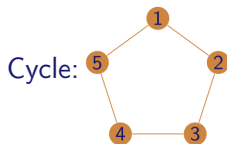


A non-connected graph with $|V| = 9$, $|E| = 9$, $\chi = 0$:

Three connected components

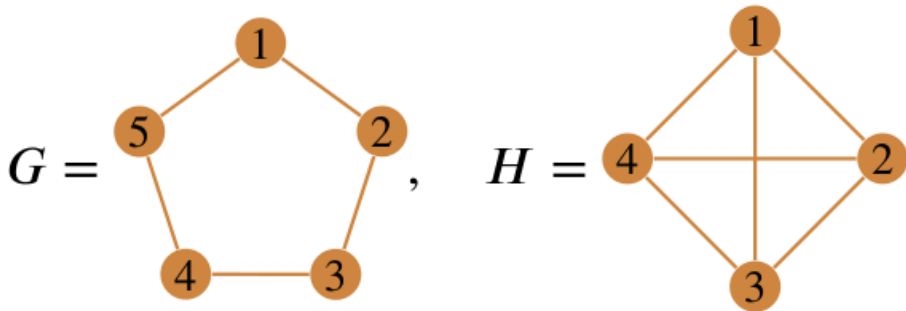


Standard graphs



Standard graphs – part 2

Exercise Check whether you understand how the various standard graphs are related and what properties they have. For example, which ones are subgraphs, which ones are planar etc.



Trees are **acyclic**, so only the right graph below is a tree:

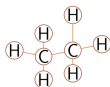
A **tree** is a connected graph that has no non-trivial circuits

Examples

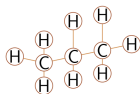
- Saturated hydrocarbons



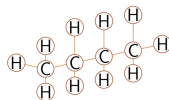
Methane



Ethane



Propane



Butane

Cyclic Graph



Acyclic Graph



Trees satisfy many properties and are always amenable for induction, e.g. prove the following as an **exercise**:

Corollary

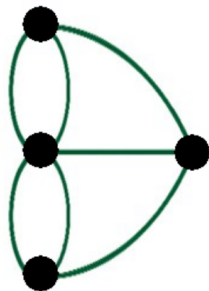
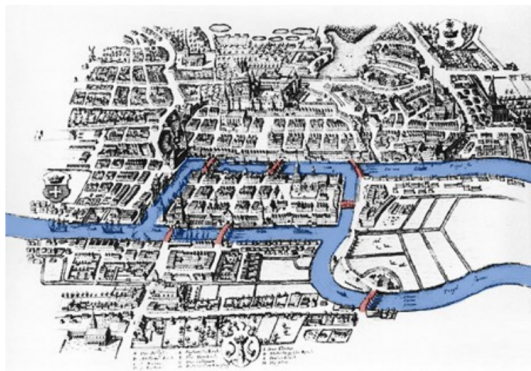
Suppose that $T = (V, E)$ is a tree. Then $|V| = |E| + 1$.

Euler and cycles

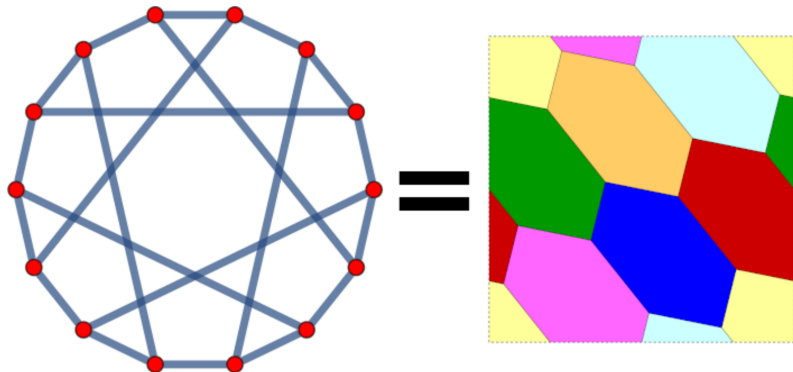
Euler's famous criterion:

Theorem

Let $G = (V, E)$ be a connected graph. Then G is Eulerian if and only if every vertex has even degree



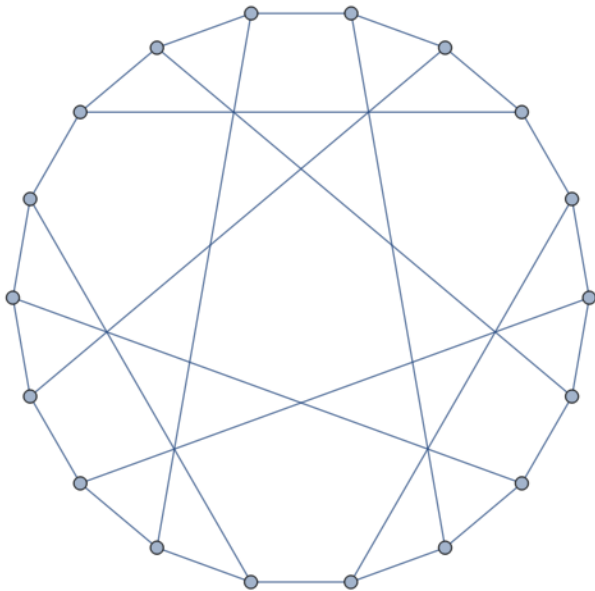
Embeddings on surfaces



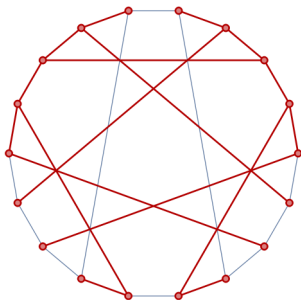
Heawood's coloring formula:

$$C = \left\lfloor \frac{7 + \sqrt{49 - 24\chi(S)}}{2} \right\rfloor$$

The Pappus graph G



The Pappus graph G – answering 1–10, part 1

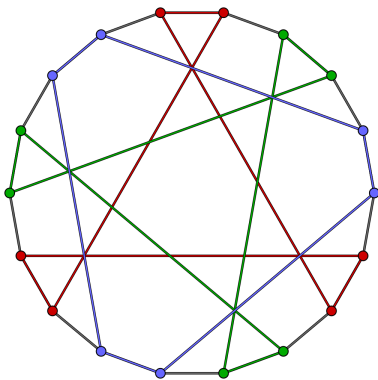


The Pappus graph is not a standard graph – it is neither a line nor a cycle nor complete nor complete bipartite

We clearly have $|V| = 18$ and $|E| = 27$, so that $\chi(G) = |V| - |E| = -9$, and G is connected

The Pappus graph is not a tree and a spanning tree is illustrated above (there are many more spanning trees)

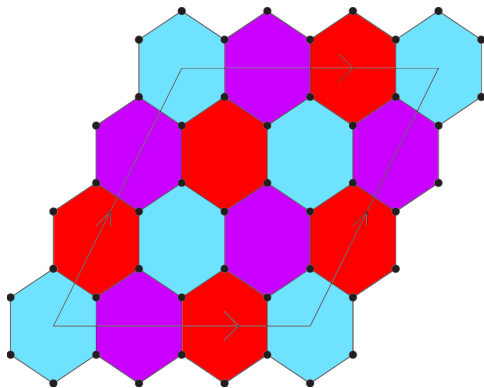
The Pappus graph G – answering 1–10, part 2



The Pappus graph has many cycles that are hexagons, as illustrated above. In fact, one checks that the length of the smallest cycle is 6

Every vertex in the Pappus graph is of degree 3, so there are neither Eulerian circuits nor paths

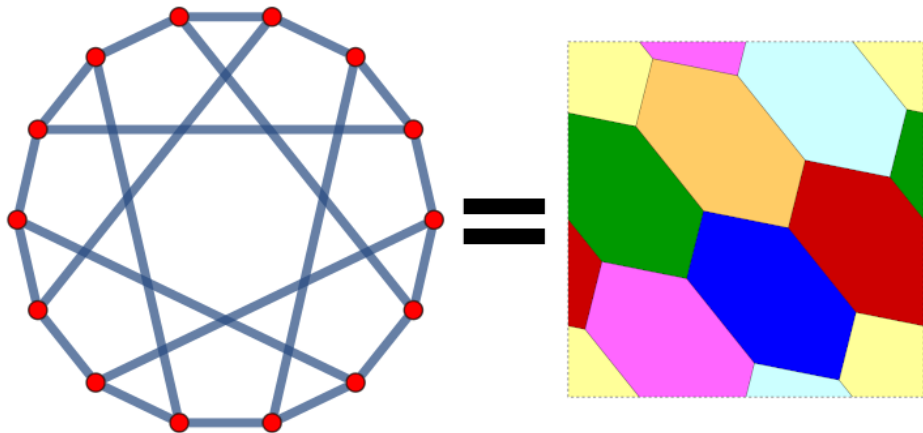
The Pappus graph G – answering 1–10, part 3



The Pappus graph does not embed into S^2

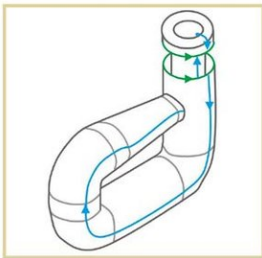
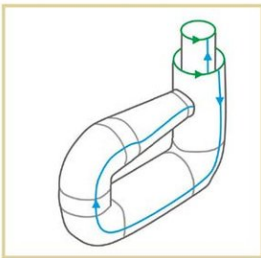
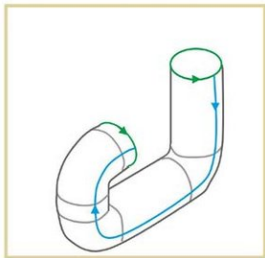
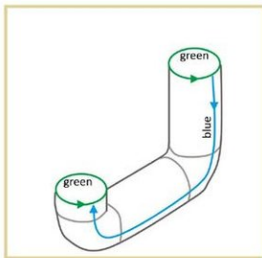
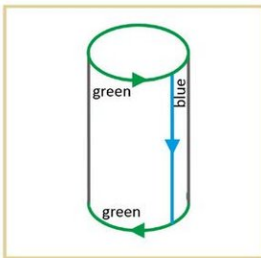
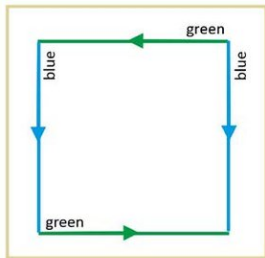
G embeds onto the torus and then needs 3 colors to color it, see above
Heawood's theorem for the torus would give $\lfloor \frac{7+\sqrt{49-24\cdot 0}}{2} \rfloor = 7$ as the
number of colorings needed in the worst case, so G does better

The Heawood graph – answer 1–10 as an exercise



The above graph is called the Heawood graph – **try yourself!**

Topic 2: surfaces!



Questions we ask about a surface S

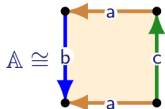
- 1 Have we seen S before? Is it one of the standard ones (sphere, torus, Klein bottle, projective plane etc.)?
- 2 How many boundary cycles = punctures does S have?
- 3 What is its Euler characteristic?
- 4 Is S connected? How many connected components does S have?
- 5 Is S orientable?
- 6 Can we find a polygonal form of S ?
- 7 What is its standard form?
- 8 How many cross-caps are there in standard form?
- 9 How many handles are there in standard form?
- 10 If $d = 0$, then what is the chromatic number of S ?

Let us answer 1-10 for a **randomly generated polygonal form**

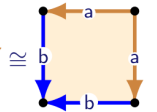
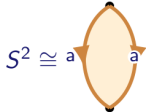
But before, let us recall what the above are!

The standard surfaces in polygonal form

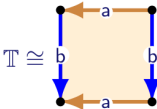
• Annulus $\mathbb{A} \cong$



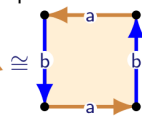
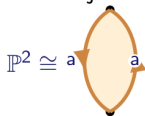
• Sphere $S^2 \cong$



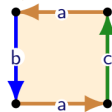
• Torus $\mathbb{T} \cong$



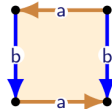
• Projective plane $\mathbb{P}^2 \cong$



• Möbius strip $\mathbb{M} \cong$



• Klein bottle $\mathbb{K} \cong$



These are 2 dimensional objects, e.g. the torus is hollow:

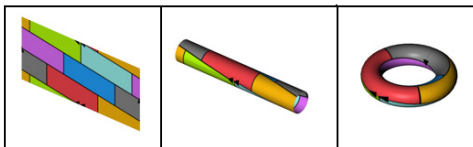
$\mathbb{T} =$



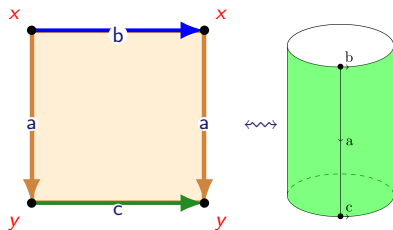
From polygons to surfaces

Recall that one goes from a polygon to a surface by **identifying paired edges**

For the torus that means e.g.



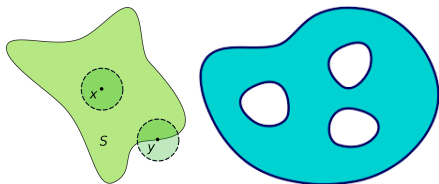
For an annulus one gets



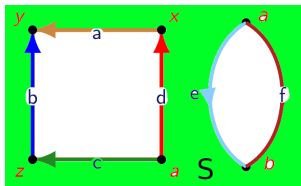
One can build of most these, e.g. a Möbius, strip out of paper

The boundary

Boundary points have neighborhoods that are **half-discs**; all other points have **disc** neighborhoods



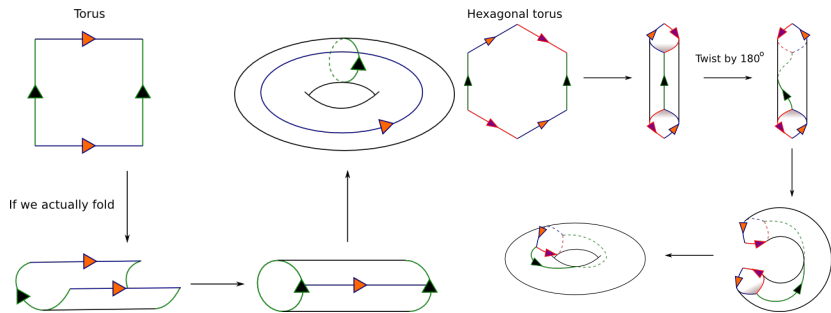
In a polygonal form, the free edges wrap around boundary components:



Note that the surface S is on the outside in these pictures

Euler characteristic

Every surface S has infinitely many polygonal forms and they might look wildly different, e.g.:

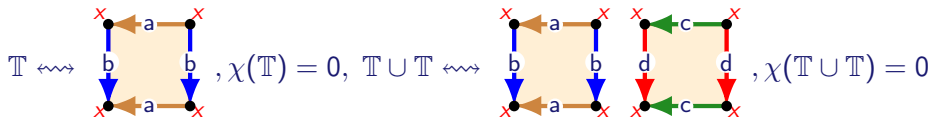


The Euler characteristic $\chi(S) = |V| - |E| + |F|$ is the same for any polygonal form

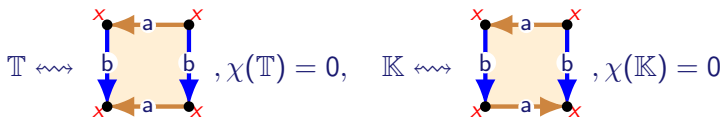
$$\text{left: } \chi(\mathbb{T}) = 1 - 2 + 1 = 0, \quad \text{right: } \chi(\mathbb{T}) = 2 - 3 + 1 = 0$$

Euler characteristic – only **almost** perfect

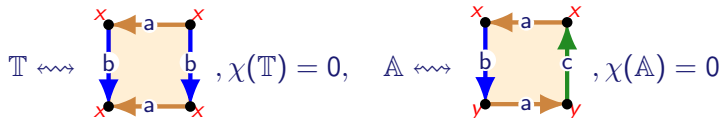
We have $\chi(S) \neq \chi(T) \Rightarrow S \not\cong T$ but the converse is not true:



Fix: check **connectivity**



Fix: check **orientability**

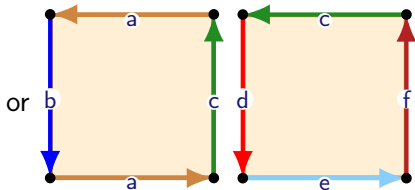
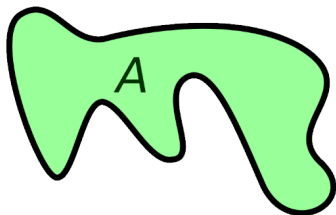


Fix: check **boundary**

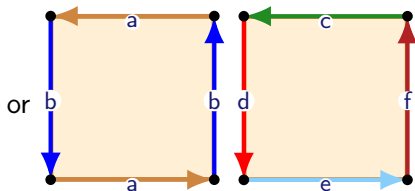
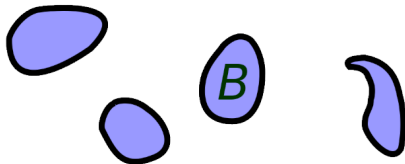
Connectivity – we can eyeball it

Connected = we can go from every point of S to any other point of S

Connected:



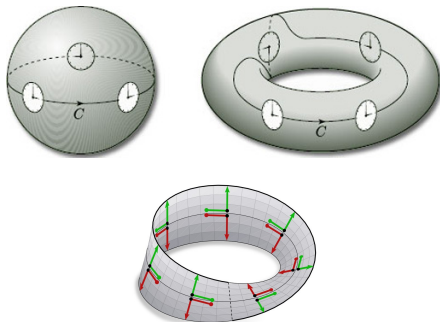
Not connected:



Orientability – we can tell on the words

Orientable = consistent choice of a coordinate system

Top: orientable, bottom: not orientable

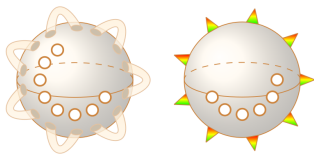


This is hard to check on the surface itself but:

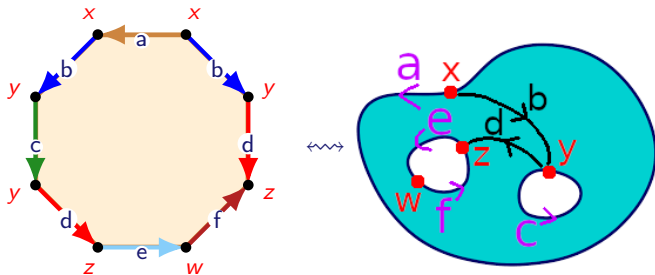
- Words encode orientability
 - ▶ Orientable: $\dots a \dots \bar{a} \dots$ or $\dots \bar{a} \dots a \dots$
 - ▶ Non-orientable: $\dots a \dots a \dots$ or $\dots \bar{a} \dots \bar{a} \dots$

Boundary = punctures = holes

Eight and six boundary components, respectively:



On the polygon this is the **free-edge game**: identify free edges, and check what cycles they form, e.g.:



The classification theorem

Theorem

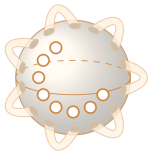
Let S be a connected surface. Then there exist non-negative integers d , p and t such that

- 1 $S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$
- 2 the boundary of S is the disjoint union of d circles
- 3 S is orientable if and only if $p = 0$

Moreover, we can assume that $pt = 0$, in which case S is uniquely determined up to homeomorphism by (d, p, t)

Thus, every surfaces is of either of the following two forms, called **standard**:

$$\#^8 \mathbb{D}^2 \# \#^7 \mathbb{T} \cong$$

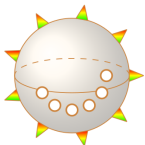


$d \iff$ punctures=boundary=holes

$p \iff$ projective planes=cross caps

$t \iff$ handles=tori

$$\#^6 \mathbb{D}^2 \# \#^9 \mathbb{P}^2 \cong$$

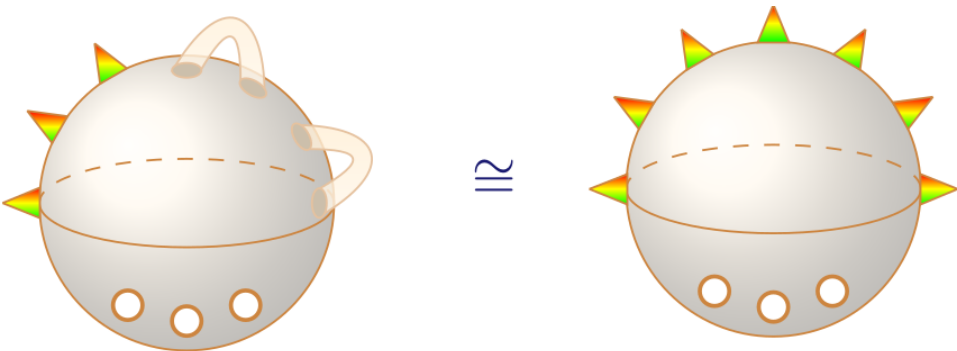


Handles and cross-caps **do not** want to go along

$$\mathbb{T} \# \mathbb{P}^2 \cong \mathbb{K} \# \mathbb{P}^2 \cong \mathbb{P}^2 \# \mathbb{P}^2 \# \mathbb{P}^2 \leftrightarrow "t = 2p"$$

Not true: $\mathbb{T} \cong \mathbb{K}$

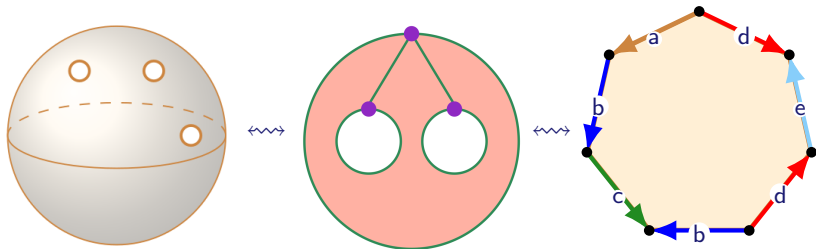
We can use this to always get rid of all tori **in the presence of** \mathbb{P}^2 , e.g.:



The left-hand surface is **not in standard form**

From a surface to a polygon

Here is an example how to find a word for the 3-times punctured sphere:



In general, using the classification theorem, we had **standard words** that we can paste together:

$$\#^t \mathbb{T} = a_1 b_1 \bar{a}_1 \bar{b}_1 a_2 b_2 \bar{a}_2 \bar{b}_2 \dots a_t b_t \bar{a}_t \bar{b}_t$$

$$\#^p \mathbb{P}^2 = a_1 a_1 a_2 a_2 \dots a_p a_p$$

$$\#^d \mathbb{D}^2 = a_1 b_1 a_2 b_2 \dots b_{d-1} a_d \bar{b}_{d-1} \dots \bar{b}_2 \bar{b}_1$$

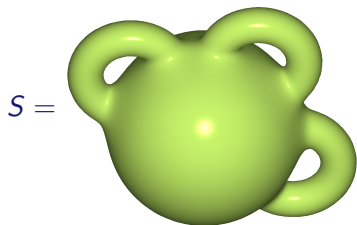
Heawood's exciting theorem

For a connected closed surface $S \not\cong \mathbb{K}$ we have that the chromatic number $C(S)$ is

$$C(S) = \lfloor \frac{1}{2}(7 + \sqrt{49 - 24\chi(S)}) \rfloor$$

Additionally $C(\mathbb{K}) = 6$

Example



$S =$

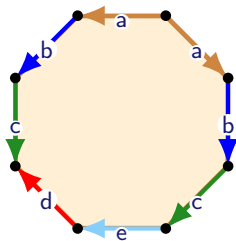
$$, \chi(S) = -4, C(S) = \lfloor 9.5208 \rfloor = 9$$

recall the formula:

$$\chi(S) = 2 - d - p - 2t$$

$$\text{for } S \cong S^2 \# \#^d \mathbb{D}^2 \# \#^p \mathbb{P}^2 \# \#^t \mathbb{T}$$

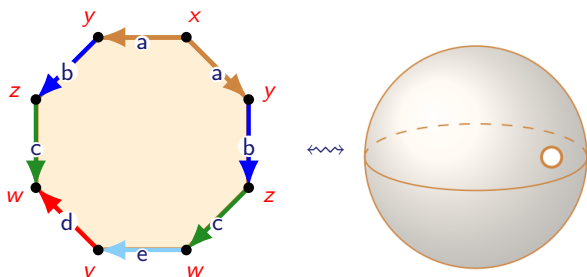
A random example



To find (d, p, t) for S we go through a list of steps:

- 1 Identify vertices and count them $\Rightarrow |V|$
- 2 Count edges and faces $\Rightarrow |E|$ and $|F|$
- 3 Compute $\chi(S) = |V| - |E| + |F|$
- 4 Check how free edges arrange themselves in cycles $\Rightarrow d$
- 5 Check for $a...a$ and $\bar{a}...\bar{a}$; if we find them, then $t = 0$ otherwise $p = 0$
 \Rightarrow we get either p or t
- 6 Use $\chi(S) = 2 - d - p - 2t$ to determine the remaining entry t or p

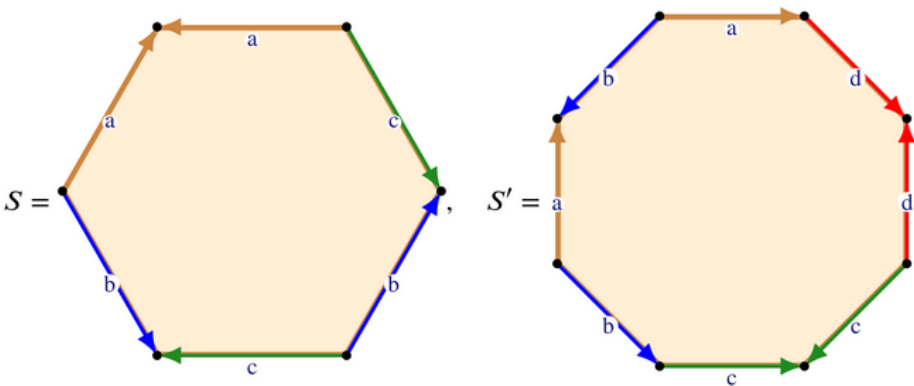
A random example – part 2



Lets do it!

- 1 From the above we get $|V| = 5$
- 2 Counting edges and faces gives $|E| = 5$ and $|F| = 1$
- 3 We get $\chi(S) = |V| - |E| + |F| = 1$
- 4 The only free edges $d: v \rightarrow w$ and $e: w \rightarrow v$ form one cycle, so $d = 1$
- 5 No pairs $a...a$ or $\bar{a}...a$, so $p = 0$
- 6 $1 = \chi(S) = 2 - 1 - 0 - 2t$ gives $t = 0$

More examples – answer 1–10 as an exercise



These two surfaces are well-known and want to be identified – **try yourself!**

Exercise Write down some word representing a polygonal form and identify its corresponding standard form, meaning (d, p, t)

Topic 3: knots!



Questions we ask about a knot K

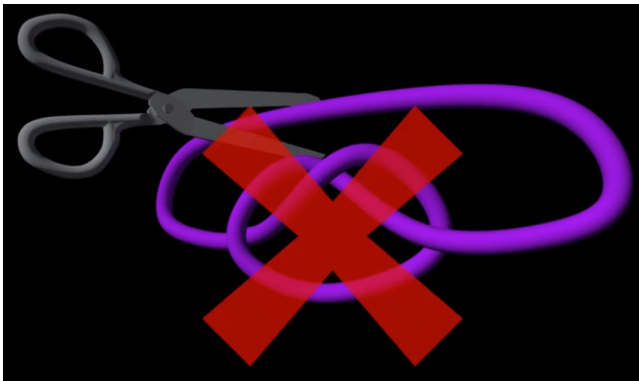
- 1 Have we seen K before? Is it one of the standard ones, i.e. for low crossing number?
- 2 Can the diagram(=projection) of K that we see be simplified?
- 3 Is K the unknot a.k.a. trivial?
- 4 What is the crossing number of K ?
- 5 Is K alternating?
- 6 Is K three colorable?
- 7 Is K p -colorable for $p > 3$?
- 8 What is the knot determinant of K ?
- 9 Can we explicitly compute a Seifert surface for a diagram of K ?
- 10 What is the genus of K ?

Let us answer 1-10 for the [knot \$5_1\$](#)

But before, let us recall what the above are!

Knots





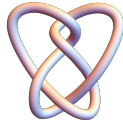
A knot is an embedding of S^1 into \mathbb{R}^3 and we study these up to equivalence, i.e. **continuous deformation without cutting**



Note that **all knots are homeomorphic**, so this is the wrong notion of equivalence for knots

The periodic table of knots

A main point of knot theory is to have a [table of knots](#) up to mirror images:

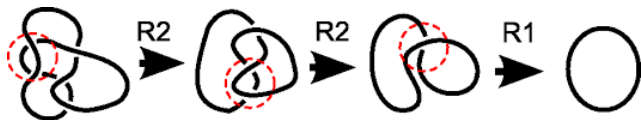
knot					
name	unknot	trefoil	figure 8	cinquefoil	three-twist
notation	0_1	3_1	4_1	5_1	5_2
$cross(K)$	0	3	4	5	5
$det(K)$	1	3	5	5	7
$g(K)$	0	1	1	2	1
prime?	yes	yes	yes	yes	yes
alternating?	yes	yes	yes	yes	yes

Google [The Rolfsen Knot Table](#) or use e.g. KnotData of Mathematica

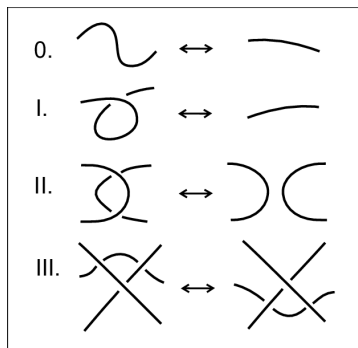
Mirror images (=flipped crossings) **cannot be detected** by our invariants

Simplify diagrams using Reidemeister moves

A first step is to check whether there are any “obvious” simplifications:

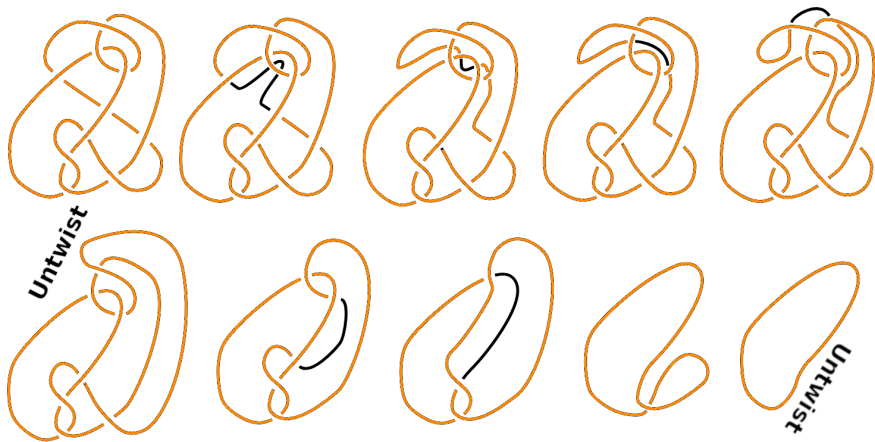


Recall that two knot diagrams represent the same knot **if and only if** we can relate them by the Reidemeister moves:



The culprit

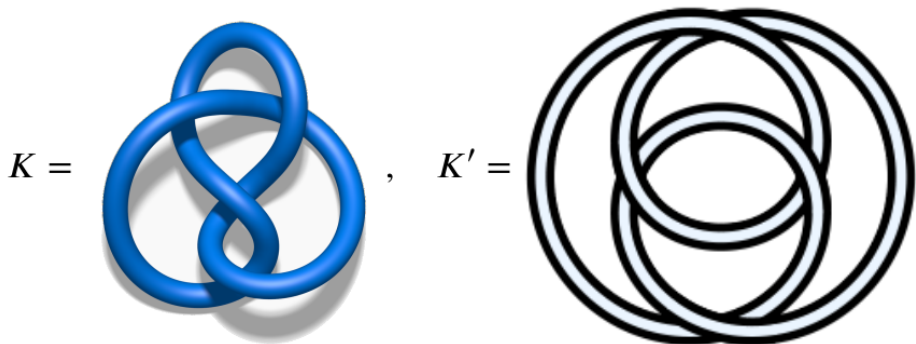
Sometimes diagrams drastically simplify:



Reidemeister moves – practise makes perfect

Exercise Check whether you understand the Reidemeister moves used for the culprit on the previous slide

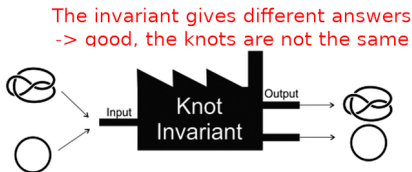
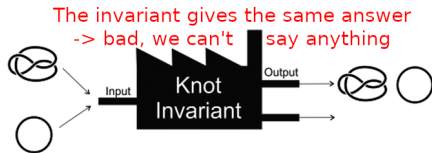
Exercise Check using isotopies and Reidemeister moves whether these two beasts are the same knot:



The main question...

...is always: are two knot diagrams representing the same knot?

We want **knot invariants** to do this!



We had essentially two ways to decide that

- Knot invariant 1: colorability
- Knot invariant 2: genus

p -colorable; here only $p = 3$

Coloring = each segment gets a color such that we have 3-colored crossings or monochromatic crossings



A knot is 3-colorable if it admits a non-monochromatic coloring



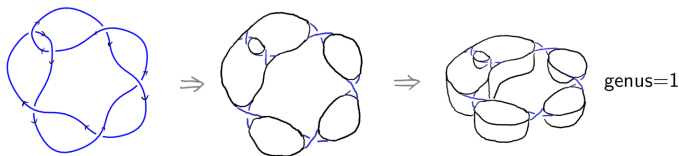
Trefoil knot: tricolorable



Figure-eight knot: NOT tricolorable

The genus: great to check whether a knot is trivial

Genus = the minimal t of all Seifert surfaces; to compute it for an **alternating** knot run Seifert's algorithm:



Then $t = \frac{1}{2}(1 + c - s)$ where c is the number of crossings and s the number of Seifert circles

Cool fact (verify " \Leftarrow " as an **exercise**):

$$g(K) = 0 \Leftrightarrow K \cong \text{unknot}$$

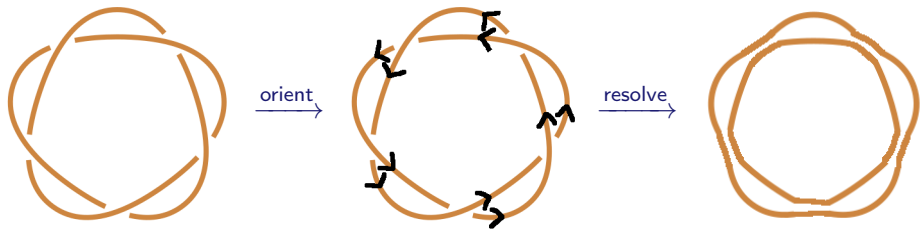
The knot $K = 5_1$



Let us go through the list of steps:

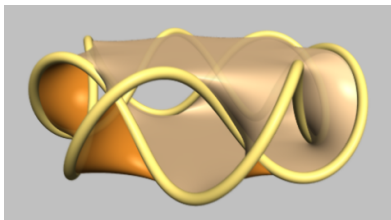
- 1 We have seen it before, it is 5_1
- 2 The diagram cannot be made simpler in any obvious way
- 3 The knot is not trivial, see next slide or coloring above
- 4 Since the diagram is alternating $cross(K) = 5$
- 5 The diagram is clearly alternating
- 6 No, K is not 3-colorable see above
- 7 Yes, K is 5-colorable, see above
- 8 We have $det(K) = 5$ by computation
- 9 Yes, Seifert surfaces are easy to get, see next slide
- 10 $g(K) = 1$, see next slide

The knot $K = 5_1$ – Seifert surfaces and genus

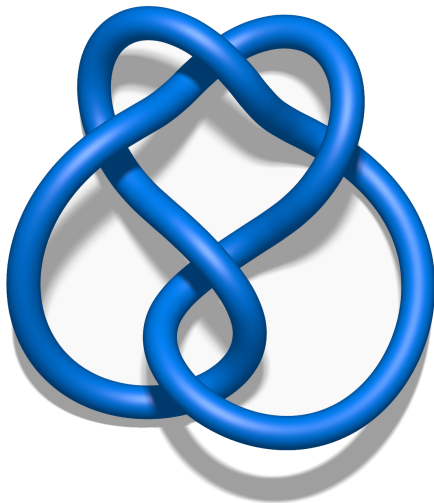


Thus, $c = 5$ and $s = 2$ gives $\chi(S) = s - c = -3$ and $g = \frac{1}{2}(1 - \chi(S)) = \frac{1}{2}(1 + c - s) = 2$

Putting in the twists gives:



Another knot – answer 1–10 as an exercise



This is knot 5_2 – try yourself!

I hope you enjoyed topology!

