

Tricolorings of Knots

Lucas Meyers

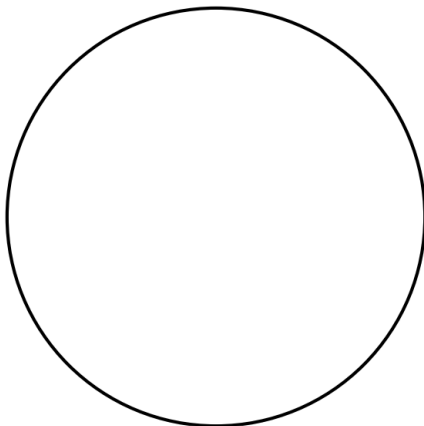
Department of Mathematics
Louisiana State University

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Knot Definition

- A *Knot* is a simple closed curve in S^3 ($\mathbb{R}^3 \cup \{\infty\}$)

Unknot



Trefoil

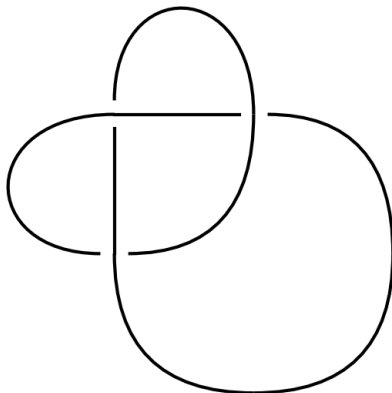
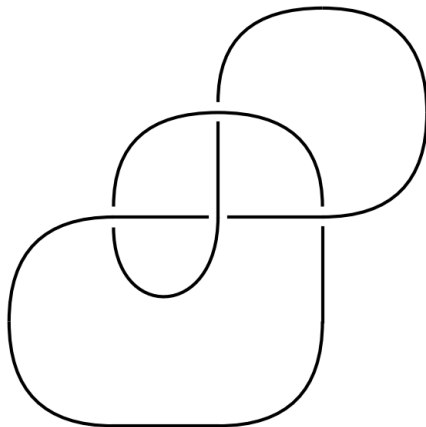


Figure-Eight

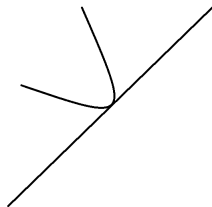


Equivalence

- All knots are homeomorphic to S^1 .
- Two knots K and J are *Ambient Isotopic* if there is a homotopy $H : S^3 \times [0, 1] \rightarrow S^3$ such that
 - $H(x, 0)$ is the identity on S^3
 - The image $H(K, 1)$ is J
 - For each fixed $t \in [0, 1]$ the map $H(x, t)$ is a homeomorphism.

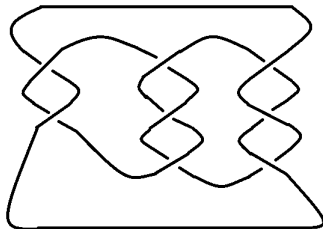
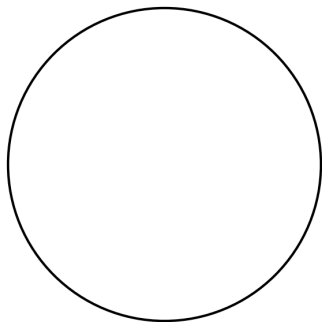
Diagrams

- A *diagram* D of a knot K is a projection of K to a plane such that
 - We preserve over and under crossing information
 - Only two points or fewer may be projected to the same point
 - All crossings must be either overcrossings or undercrossings.



Reidmeister Moves

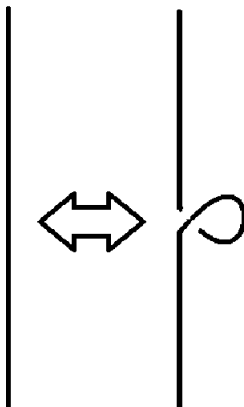
- Diagrams for a knot are not unique.



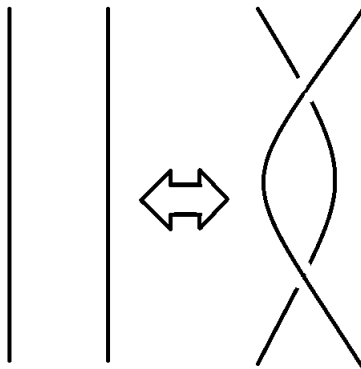
Reidmeister Moves

- **Theorem:** Two knots K and J are ambient isotopic if, and only if, their diagrams are related by a finite sequence of Reidmeister moves and planar isotopy.

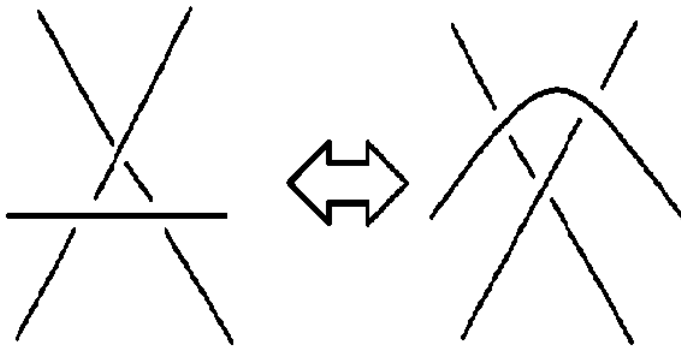
Type I



Type II



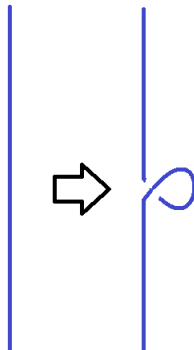
Type III



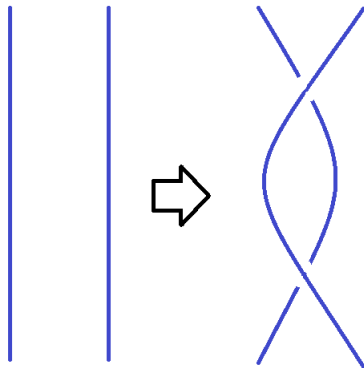
Tricoloring

- A *tricoloring* of a diagram is an assignment of one of three colors to each arc such that for all crossings
 - Only a single color is present
 - All three colors are present
- A tricoloring is *nontrivial* if at least two colors are used
- **Theorem:** The existence of a non-trivial tricoloring is a knot invariant. Such a knot is called tricolorable (or 3-colorable).

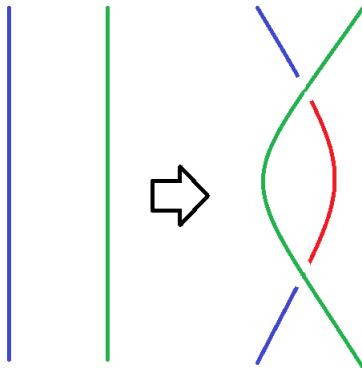
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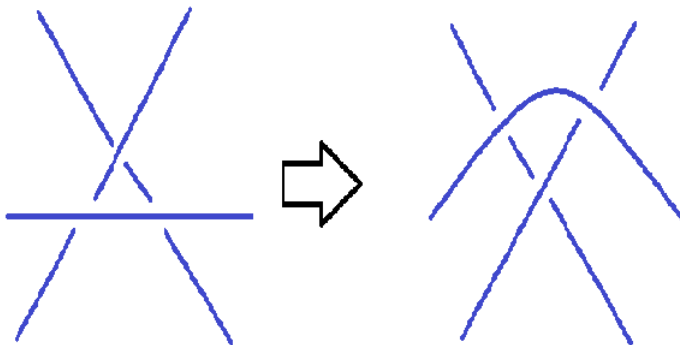
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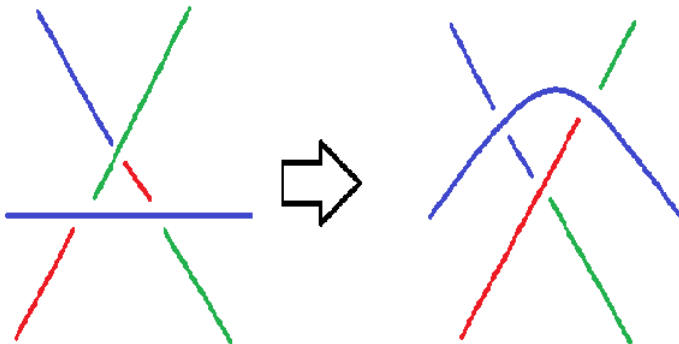
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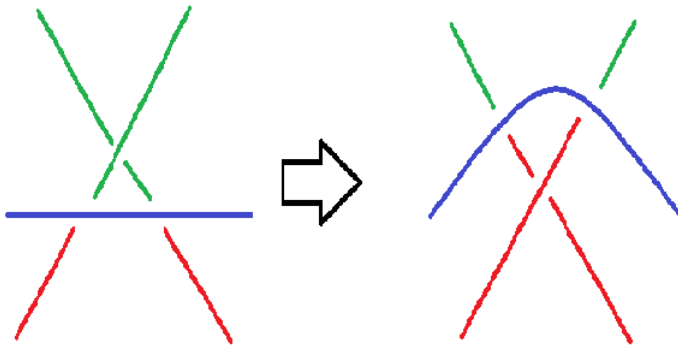
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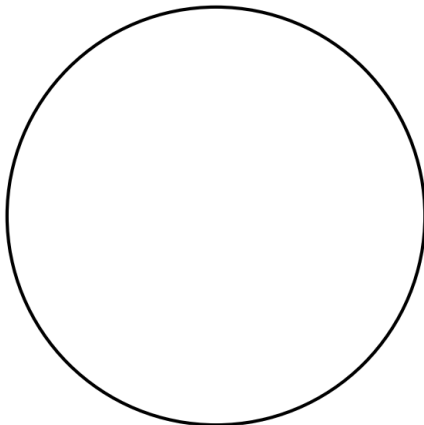
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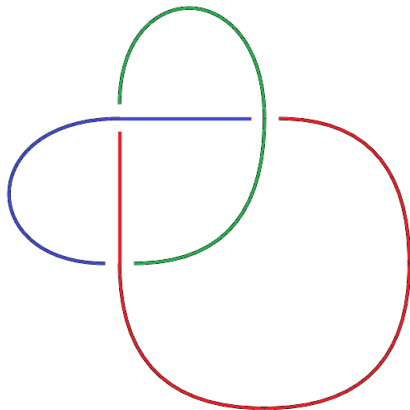
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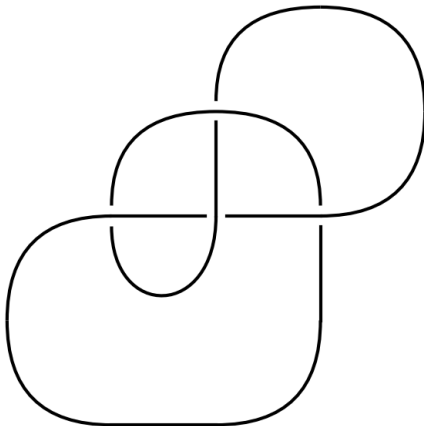
Uncolorability of the Unknot



Colorability of the Trefoil



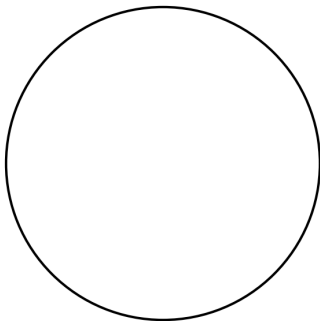
Uncolorability of the Figure-Eight Knot



Knot Group

- Since all knots are homeomorphic to S^1 their fundamental groups are isomorphic to \mathbb{Z} .
- Given a knot K , the *knot group* is the fundamental group of the knots complement $\pi_1(S^3 \setminus K, *)$

Knot Group of the Unknot



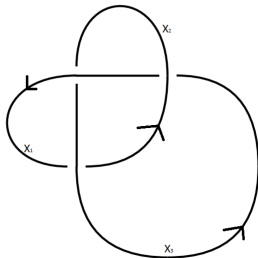
- The knot group of the unknot is $\pi_1(S^3 \setminus K, *) = \mathbb{Z}$ generated by the loop through the unknot's.

Wirtinger Presentation

- For other knots we use a tool called the *Wirtinger Presentation*.
- Let K be a knot and D a diagram for K . Choose an orientation of D . Let x_1, \dots, x_n denote the arcs of D and, for each crossing, give a relation r_1, \dots, r_m such that $r_i \equiv (x_i x_j x_i^{-1})$ where, when approaching x_k is the arc leaving the crossing, the top arc is x_i and the bottom arc entering is x_j .
- Then the knot group of K has presentation

$$\pi_1(S^3 \setminus K) \equiv \langle x_1, \dots, x_n | r_1, \dots, r_m \rangle$$

Knot Group of the Trefoil



- From this diagram the knot group of the trefoil is

$$\langle x_1, x_2, x_3 \mid x_1 x_2 x_1^{-1} = x_3, x_3 x_1 x_3^{-1} = x_2, x_2 x_3 x_2^{-1} = x_1 \rangle$$

- Which simplifies to $\langle x_1, x_2 \mid x_1 x_2 x_1 = x_2 x_1 x_2 \rangle$

Fox 3-Colorings

- A *Fox 3-coloring* is a homomorphism ρ from the knot group to the symmetry group D_6 of an equilateral triangle.
- A Fox 3-coloring is nontrivial if ρ is surjective.

Fox 3-Colorings of the Unknot and Trefoil

- There is no nontrivial Fox 3-coloring of the unknot as D_6 has two generators and the knot group of the unknot, \mathbb{Z} , only has one.
- We can give a nontrivial Fox 3-coloring of the trefoil, $\langle x_1, x_2 | x_1 x_2 x_1 = x_2 x_1 x_2 \rangle$, using the presentation of D_6 as

$$\langle r, s | r^3 = s^2 = 1, srsr = 1 \rangle$$

by mapping x_1 to r and x_2 to s or vice versa.

- This gives us two nontrivial Fox 3-colorings of the trefoil.

Equivalence of Tricoloring and Fox 3-Coloring

- **Theorem:** A Knot K has a 3-coloring if, and only if, there is a Fox 3-coloring of K .

Consequences

- Since for any two groups G and H the homomorphisms $\text{hom}(G, H)$ form a group this implies that colorings of knots also form a group.
- Unlike with tricolorability it more obvious how to extend Fox 3-colorings to an arbitrary number of colors.
 - A *Fox n -coloring* of a knot K is a homomorphism from the knot group of K to D_{2n} .
- Given any group G we can define a *Fox G -coloring* as a homomorphism from the knot group of K to the group G .
 - If G is a finite group then searching for nontrivial G -colorings is very fast to compute.
 - This can be done by sending generators to generators and checking that the relations hold.

Extending Tricolorability

- We can also use the fact that Fox 3-colorings and tricolorability are equivalent to guide us in extending the notion of n -colorings to diagrams as well.
- Instead of assigning colors to each arc we use elements of \mathbb{Z}_n .
- Then a diagram has a nontrivial coloring if at least two numbers are used and for each crossing, if we label the overcrossing arc x and the two undercrossing arcs as y and z , the following equation is satisfied

$$2x - y - z \equiv 0 \pmod{n}$$

5-Coloring of the Figure-Eight Knot

- Recall that the figure-eight knot was not 3-colorable. However it is 5-colorable.

