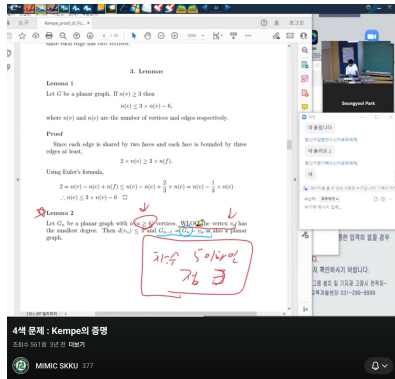


The speaker of
"Six Color Theorem"
in 2018



테라스 비어
2019

Me



"Five Color Theorem"
in 2022

The Four Color Theorem

Hojeon Lee
Sungkyunkwan University

May 12, 2026
Mimic Seminar

History

2021년 10월 18일 월요일



???

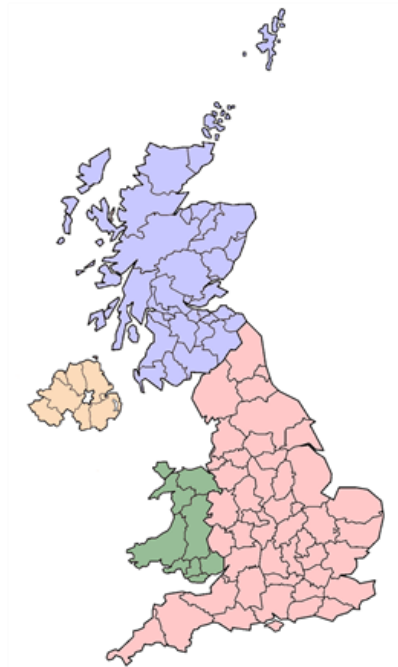
이 편지는 영국에서 최초로 시작되어 일년에 한 바퀴 돌면서 받는 사람에게 행운을 주었고 지금은 당신에게로 옮겨진 이 편지는 4일 안에 당신 곁을 떠나야 합니다. 이 편지를 포함해서 7통을 행운이 필요한 사람에게 보내 주셔야 합니다. 복사를 해도 좋습니다. 혹 미신이라 하실지 모르지만 사실입니다. 영국에서 HGXWCH이라는 사람은 1930년에 이 편지를 받았습니다. 그는 비서에게 복사해서 보내라고 했습니다. 며칠 뒤에 복권이 당첨되어 20억을 받았습니다. 어떤 이는 이 편지를 받았으나 96시간 이내 자신의 손에서 떠나야 한다는 사실을 잊었습니다. 그는 곧 사직되었습니다. 나중해야 이 사실을 알고 7통의 편지를 보냈는데 다시 좋은 직장을 얻었습니다. 미국의 케네디 어느 대통령은 이 편지를 받았지만 그냥 버렸습니다. 결국 9일 후 그는 암살 당했습니다. 기억해 주세요. 이 편지를 보내지 않으면 3년의 불행이 있을 것입니다. 그리고 이 편지를 버리거나 낙서를 해서는 절대로 안됩니다. 7통입니다. 이 편지를 받은 사람은 행운이 깃들 것입니다. 힘들겠지만 좋은 게 좋다고 생각하세요. 7년의 행운을 빌면서..

History

In 1852,

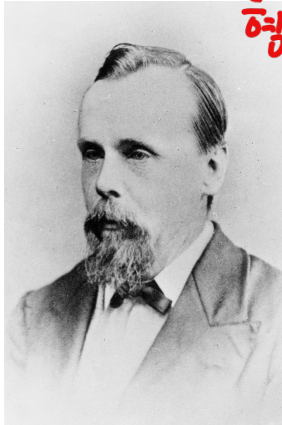


Francis Guthrie



History

In 1852,



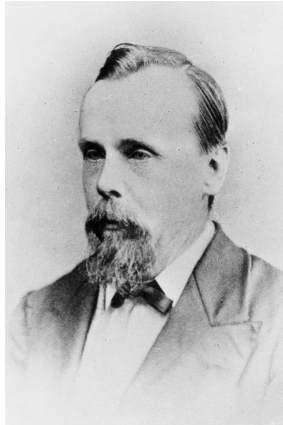
Francis Guthrie



Frederick Guthrie

History

In 1852,



Francis Guthrie



Frederick Guthrie

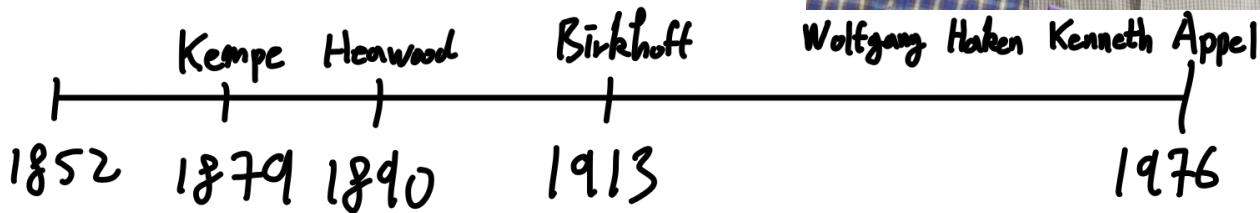


De Morgan

History



John Koch



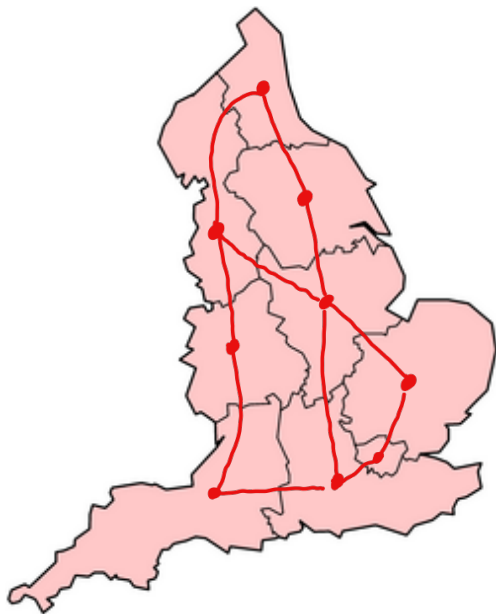
Modeling



Modeling



Modeling



Modeling



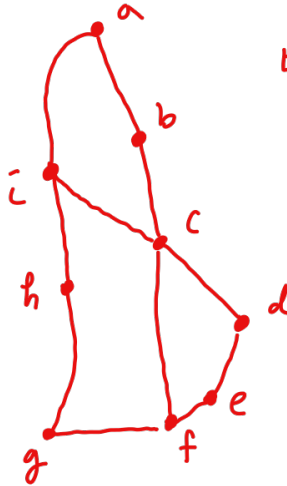
Def) A **graph** is a pair $G = (V, E)$ where
 V : vertices set & E : edge set

Modeling

$$G = (V, E)$$

$$V = \{a, b, c, d, e, f, g, h, i\}$$

$$E = \{ \{a, b\}, \{a, i\}, \{b, c\}, \\ \{c, i\}, \{c, d\}, \{c, f\}, \\ \{d, e\}, \{e, f\}, \{f, g\} \\ \{g, h\}, \{h, i\} \}$$



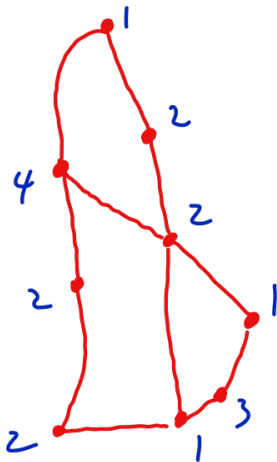
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4-coloring

Def) For a graph $G = (V, E)$

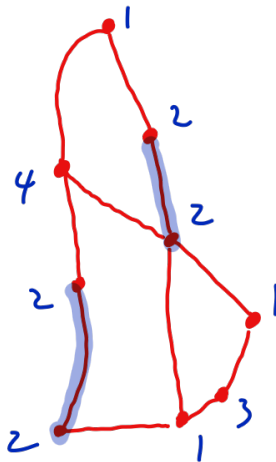
an n -coloring ϕ of G is a map $\phi: V \rightarrow \{1, 2, \dots, n\}$

Modeling

$$G = (V, E)$$

$$V = \{a, b, c, d, e, f, g, h, i\}$$

$$E = \{ \{a, b\}, \{a, c\}, \{b, c\}, \\ \{c, d\}, \{c, f\}, \\ \{d, e\}, \{e, f\}, \{f, g\} \\ \{g, h\}, \{h, c\} \}$$



4-coloring

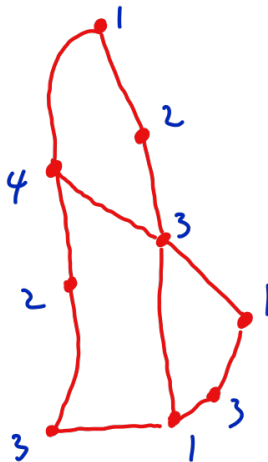
Def) An n -coloring ϕ is **proper** if " $\phi(u) \neq \phi(v)$
whenever $\{u, v\} \in E$ "

Modeling

$$G = (V, E)$$

$$V = \{a, b, c, d, e, f, g, h, i\}$$

$$E = \{ \{a, b\}, \{a, i\}, \{b, c\}, \\ \{c, i\}, \{c, d\}, \{c, f\}, \\ \{d, e\}, \{e, f\}, \{f, g\} \\ \{g, h\}, \{h, i\} \}$$



proper 4-coloring

Def) An n -coloring ϕ is proper if " $\phi(u) \neq \phi(v)$
whenever $\{u, v\} \in E$ "

Modeling

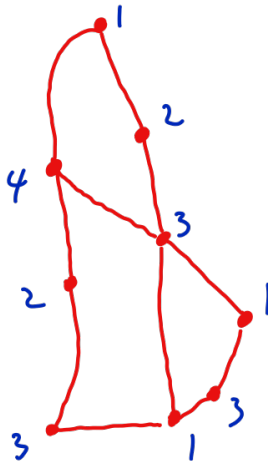
We do not consider multiple edges



$$G = (V, E)$$

$$V = \{a, b, c, d, e, f, g, h, i\}$$

$$E = \{ \{a, b\}, \{a, i\}, \{b, c\}, \\ \{c, i\}, \{c, d\}, \{c, f\}, \\ \{d, e\}, \{e, f\}, \{f, g\} \\ \{g, h\}, \{h, i\} \}$$



proper 4-coloring

Def) An n -coloring ϕ is proper if " $\phi(u) \neq \phi(v)$
whenever $\{u, v\} \in E$ "

Modeling

Maps

Always?
←————→

Graphs

Modeling

Maps

Always?



Yes!



No!

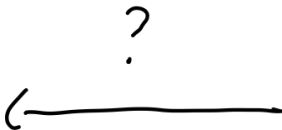


Graphs

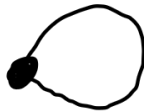
Modeling

~~3~~ map

~~3~~ proper coloring



Loops



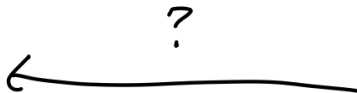
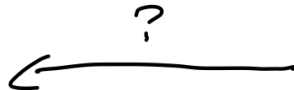
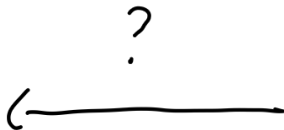
Modeling

~~$\exists$~~ map

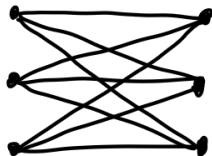
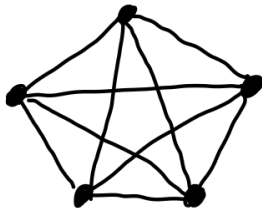
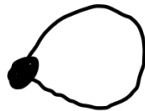
~~$\exists$~~ proper coloring

~~$\exists$~~ map

~~$\exists$~~ map



Loops

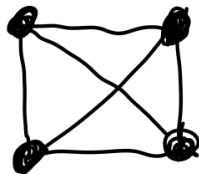


Def) A graph G is planar if G can be embedded in the plane.

Def) A graph G is **planar** if G can be embedded in the plane.

Equivalently,

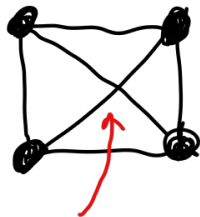
it ~~is~~ crossing edges in some configuration



Def) A graph G is **planar** if G can be embedded in the plane.

Equivalently,

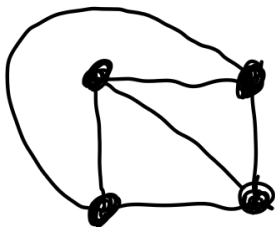
it ~~is~~ crossing edges in some configuration



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Equivalently,

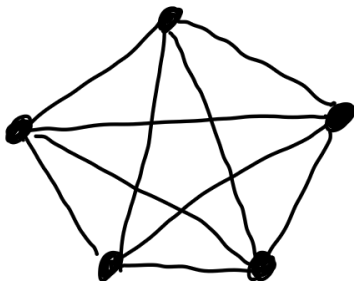
it $\nexists$ crossing edges in some configuration



Def) A graph G is **planar** if G can be embedded in the plane.

Equivalently,

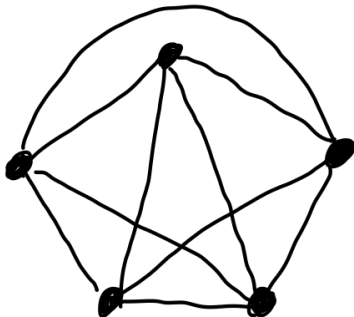
it $\nexists$ crossing edges in some configuration



Def) A graph G is **planar** if G can be embedded in the plane.

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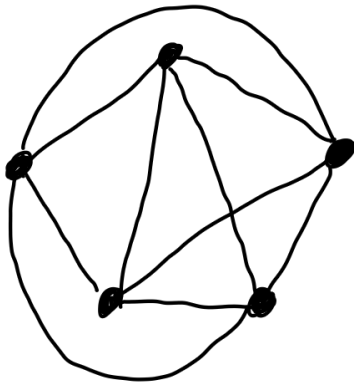
it $\nexists$ crossing edges in some configuration



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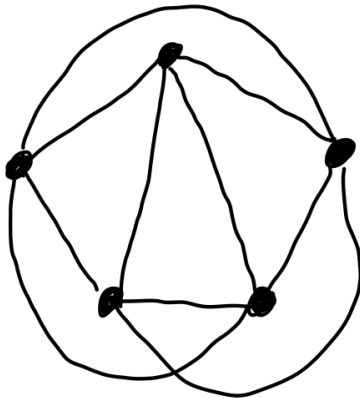
it $\nexists$ crossing edges in some configuration



Def) A graph G is **planar** if G can be embedded in the plane.

Equivalently,

it $\nexists$ crossing edges in some configuration

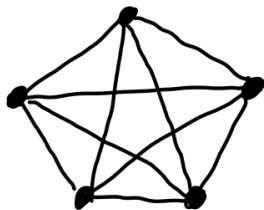


Def) A graph G is **planar** if G can be embedded in the plane.

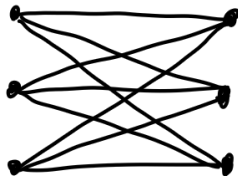
Equivalently, it $\nexists$ crossing edges in some configuration

Thm) A graph G is planar

$\Leftrightarrow G$ does not contain



&



Thm (4CT)

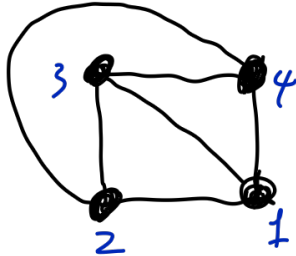
Every simple planar graph has a proper 4-coloring.

loopless & no multiple edges

Thm (4CT)

Every simple planar graph has a proper 4-coloring.
loopless & no multiple edges

Why 4?



Upper bound?

Upper bound?

Thm (6CT) by De Morgan

Every simple planar graph has a proper 6-coloring.

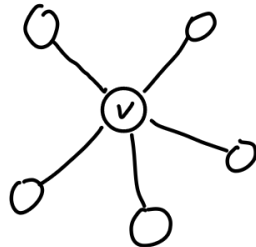
Upper bound?

Thm (6CT) by De Morgan

Every simple planar graph has a proper 6-coloring.

Fact: For a simple planar graph $G = (V, E)$,

if $|V| \geq 6$ then $\exists$ vertex v s.t. $\deg(v) \leq 5$



Upper bound?

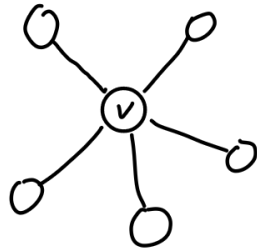
Thm (6CT) by De Morgan

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Fact: For a simple planar graph $G = (V, E)$,

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Using an induction on $|V|$!



Upper bound?

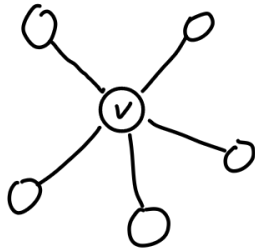
Thm (6CT) by De Morgan

Every simple planar graph has a proper 6-coloring.

Fact: For a simple planar graph $G = (V, E)$,

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Basic case: $|V| \leq 6$ Done



Upper bound?

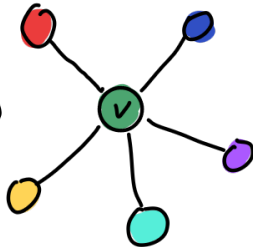
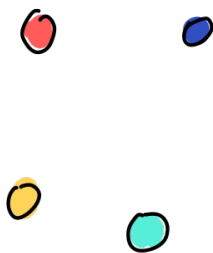
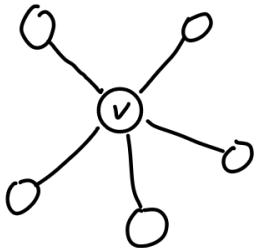
Thm (6CT) by De Morgan

Every simple planar graph has a proper 6-coloring.

Fact: For a simple planar graph $G = (V, E)$,

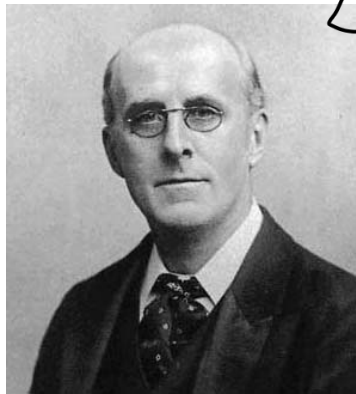
if $|V| \geq 6$ then $\exists$ vertex v s.t. $\deg(v) \leq 5$

$|V| > 6$



In 1879

I proved it!

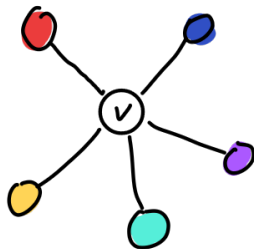


Thm 15CT)

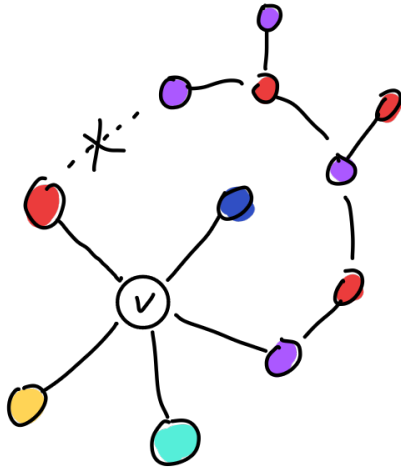
Every simple planar graph has a
proper 5-coloring

Alfred Kempe

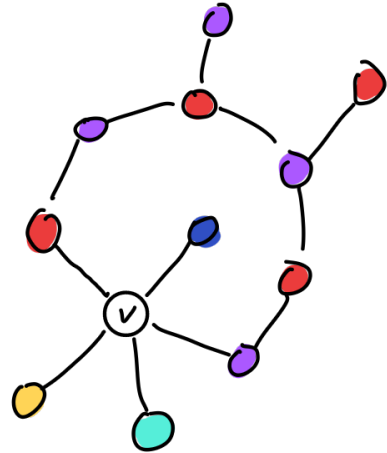
Using "Kempe chains"



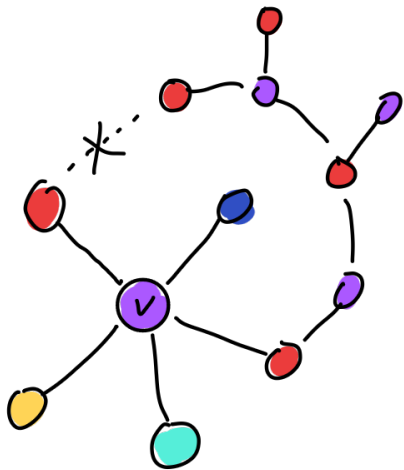
Case 1



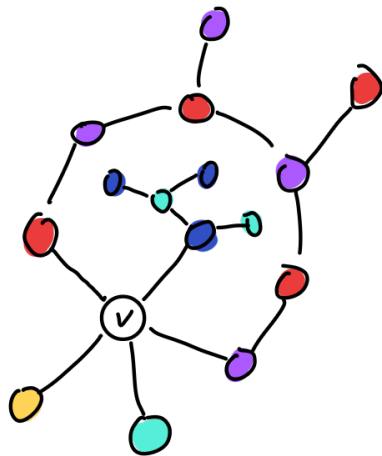
Case 2



Case 1

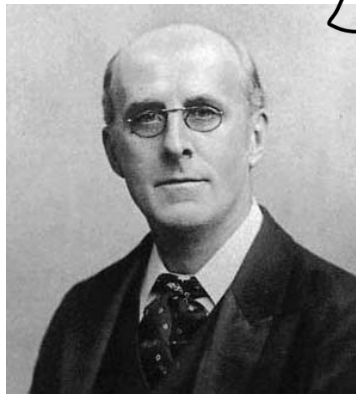


Case 2



In 1879

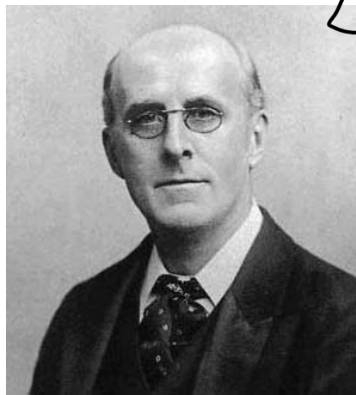
We can do the same thing
to prove 4CT



Alfred Kempe

Using "Kempe chains"

In 1879



Alfred Kempe

We can do the same thing
to prove 4CT

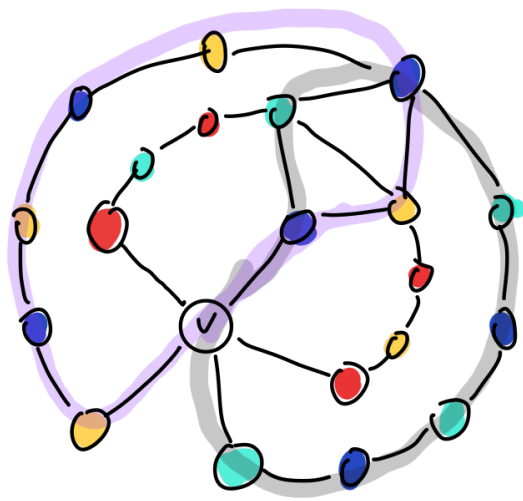
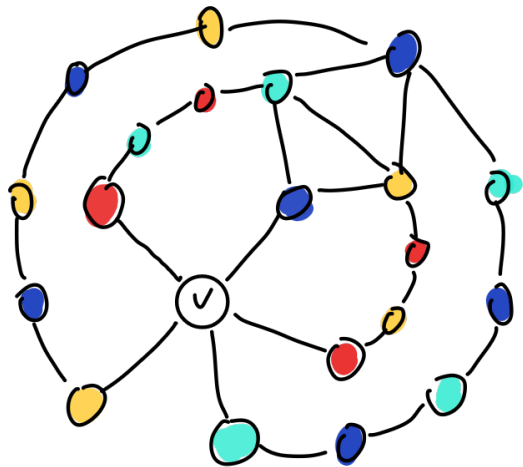
Nope!

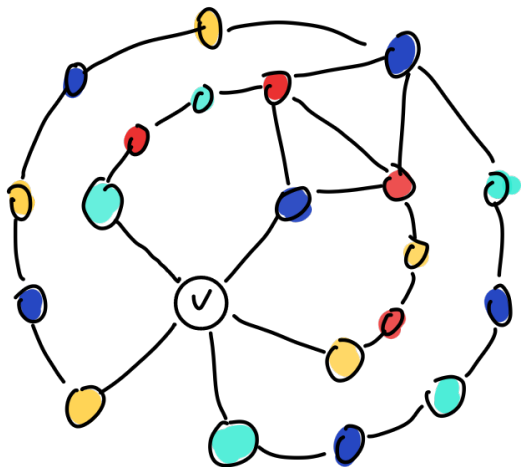
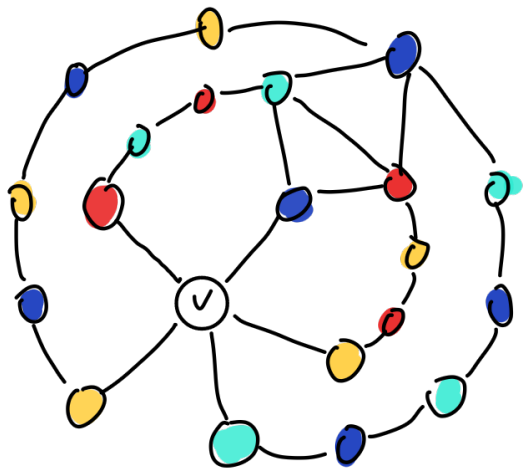
in 1890

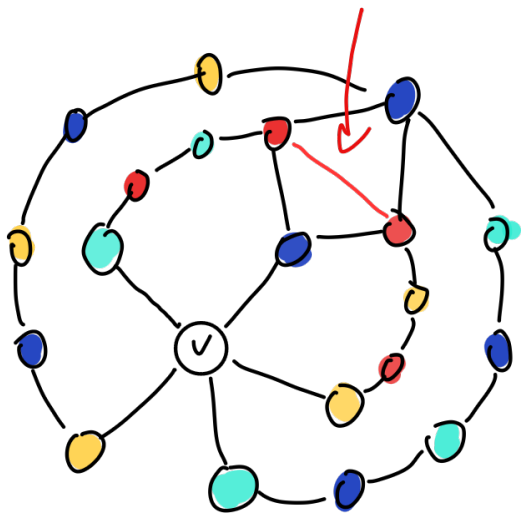
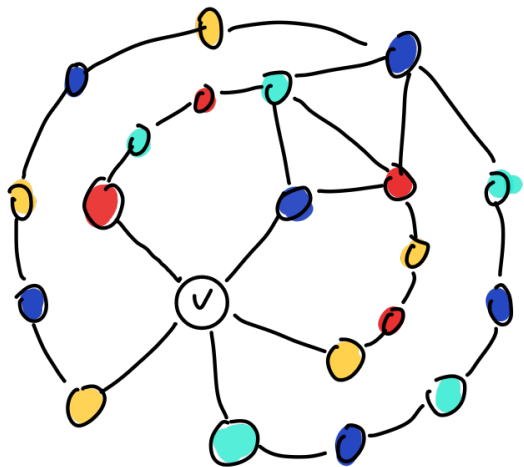


Percy Heawood

Using "Kempe chains"









Induction

Contradiction

~~Induction~~

Contradiction



In 1913



George Birkhoff

In 1913

Let's consider plane triangulations



George Birkhoff

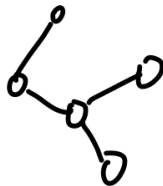
In 1913

Let's consider plane triangulations



George Birkhoff

Triangulation



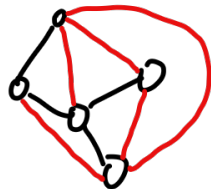
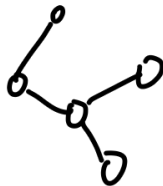
In 1913

Let's consider plane triangulations



George Birkhoff

Triangulation



In 1913

Let's consider plane triangulations



George Birkhoff

Why Triangulation?

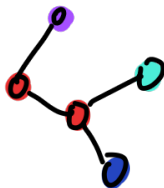
In 1913

Let's consider plane triangulations

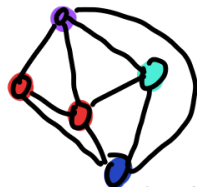


George Birkhoff

Why Triangulation?



Not 4-colorable



Not 4-colorable

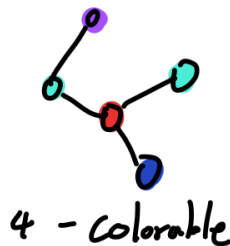
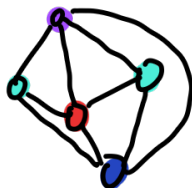
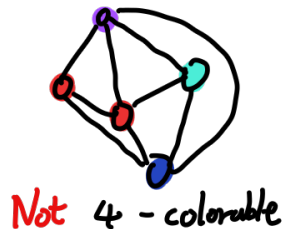
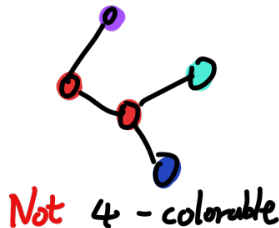
In 1913

Let's consider plane triangulations



George Birkhoff

Why Triangulation?



In 1913

Suppose that $\exists G$ s.t. **Not** 4-colorable.



George Birkhoff

In 1913

Suppose that $\exists G$ s.t. **Not** 4-colorable.



George Birkhoff

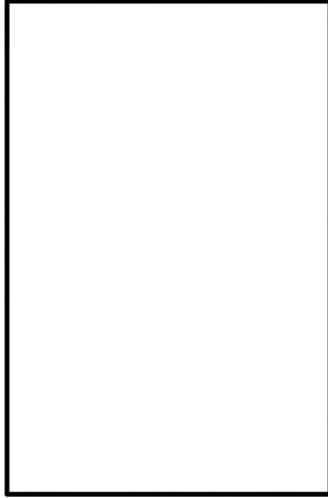
Def) A plane triangulation G is a **minimal counterexample** if

G is not 4-colorable, but if we remove one or more vertex then it is 4-colorable.

Birkhoff program



George Birkhoff



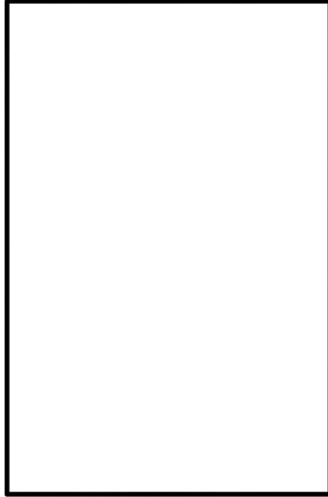
Daniel Lewis

Birkhoff - Lewis
equation

Birkhoff program



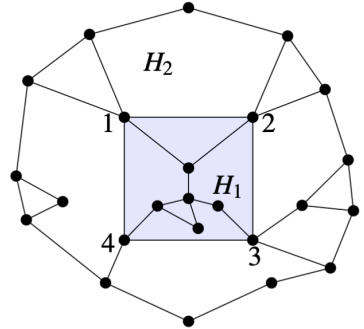
George Birkhoff



Daniel Lewis

Birkhoff - Lewis
equation

$$G = H_1 \cup H_2$$
$$H_1 \cap H_2 = J_4$$



In 1955~ Suppose that $\exists G$ s.t. **Not** 4-colorable.



Heinrich Heesch

Minimal counterexamples



Discharging



Reducibility

In 1955~ Suppose that $\exists G$ s.t. **Not** 4-colorable.



Heinrich Heesch

Minimal counterexamples



Discharging



Reducibility

Every minimal counterexample
contains at least one configuration

from $\left\{ \begin{array}{l} 1. \\ 2. \\ 3. \\ \vdots \end{array} \right.$

In 1955~ Suppose that $\exists G$ s.t. **Not** 4-colorable.



Heinrich Heesch

Minimal counterexamples



Discharging



Reducibility

G

reducing ↓

smaller G'

→ $\chi(G')$
4-colorable

In 1955~ Suppose that $\exists G$ s.t. **Not** 4-colorable.



Heinrich Heesch

Minimal counterexamples



Discharging



Reducibility

$G \dashrightarrow K(G)$

reducing ↓

smaller G'

↑ recover

$\xrightarrow{4\text{-colorable}} K(G')$

In 1976



Wolfgang Haken Kenneth Appel

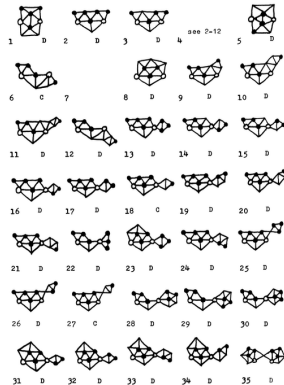
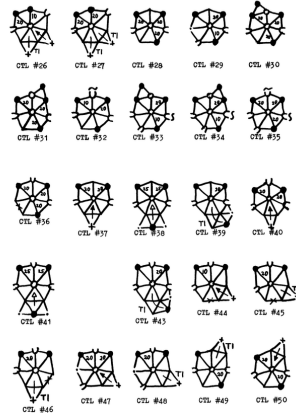


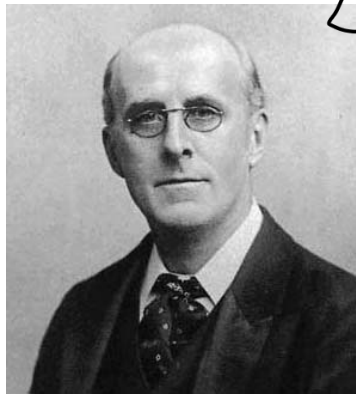
Figure 21

Discharging

Reducibility

Generalization

We can do the same thing
to prove 4CT



Alfred Kempe

Using "Kempe chains"

Nope!

in 1890



Percy Heawood

Generalization



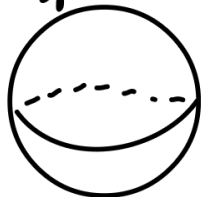
Percy Heawood

Generalization

Plane



Sphere



$g=0$



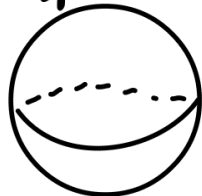
Percy Heawood

Generalization

Plane



Sphere



$g=0$



$g=1$



$g=2$

...

...



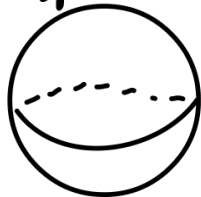
Percy Heawood

Generalization

Plane



Sphere



$g=0$



$g=1$



$g=2$

...

...

$$p = \left\lfloor \frac{7 + \sqrt{1+48g}}{2} \right\rfloor$$



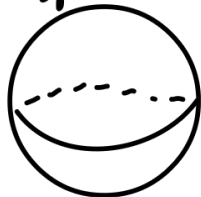
Percy Heawood

Generalization

Plane



Sphere



$$g=0$$

$$= 4$$



$$g=1$$

$$\leq 7$$



$$g=2$$

$$\leq 8$$

...

...

...

$$p = \left\lfloor \frac{7 + \sqrt{1 + 48g}}{2} \right\rfloor$$



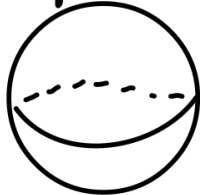
Percy Heawood

In 1968

Plane



Sphere



$$g=0$$

$$= 4$$

$$p = \left\lfloor \frac{7 + \sqrt{1 + 48g}}{2} \right\rfloor$$



$$g=1$$

$$= 7$$



$$g=2$$

$$= 8$$

...

...

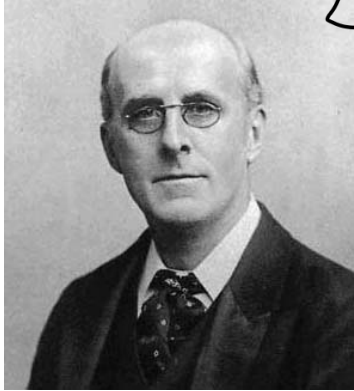
...



Gerhard Rindler



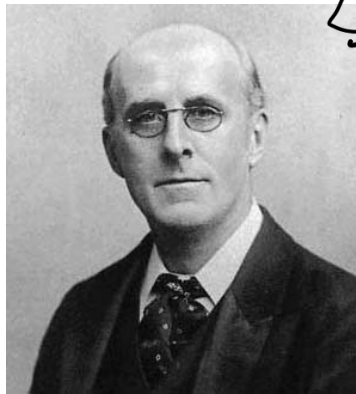
John William T. Youngs



Me again...?

Alfred Kempe

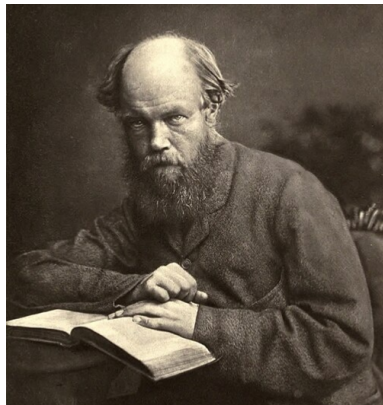
Another approach



Alfred Kempe

Phew...

Another mathematician
who believed he had
solved the Four Color Theorem.

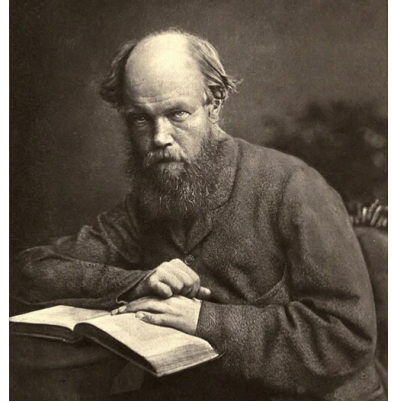


Peter Tait

Another approach

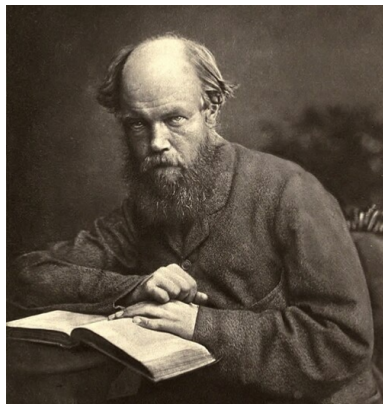
"Edge coloring"

Another mathematician
who believed he had
solved the Four Color Theorem.



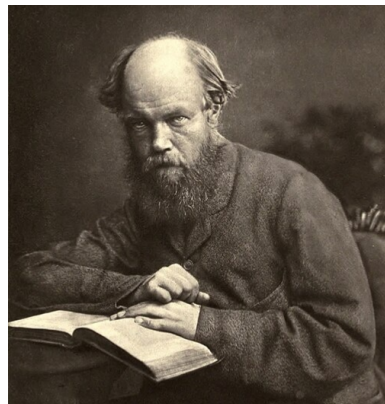
Peter Tait

In 1890



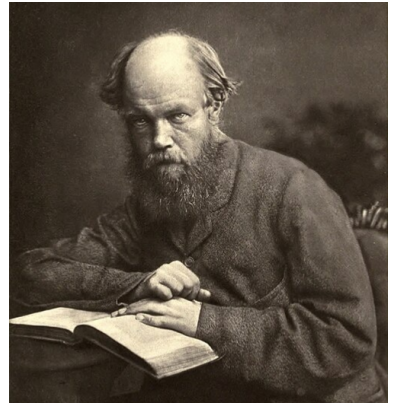
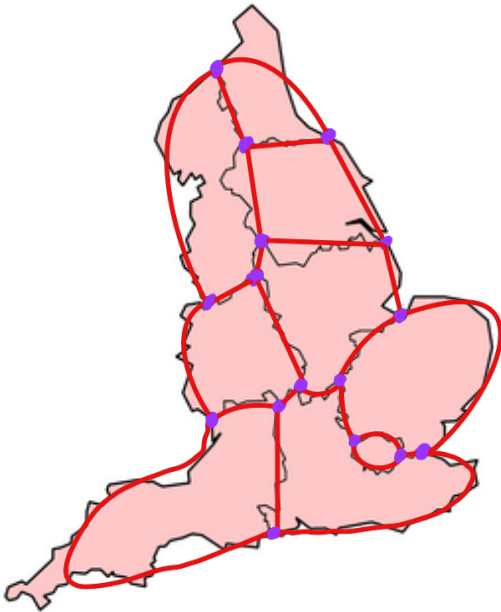
Peter Tait

In 1890



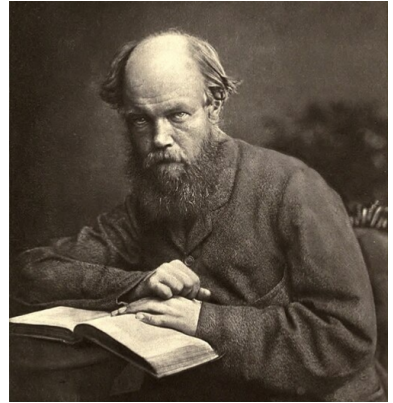
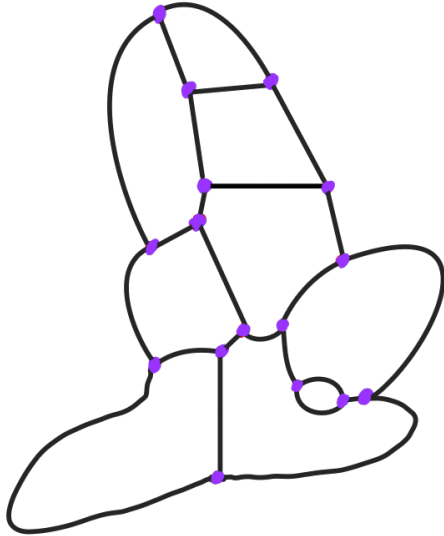
Peter Tait

In 1870



Peter Tait

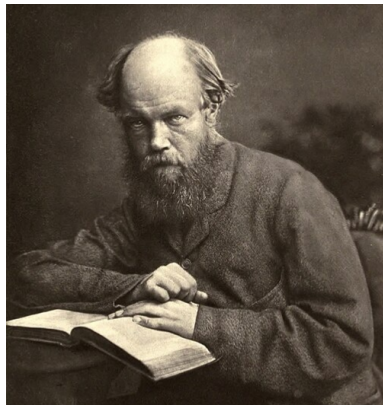
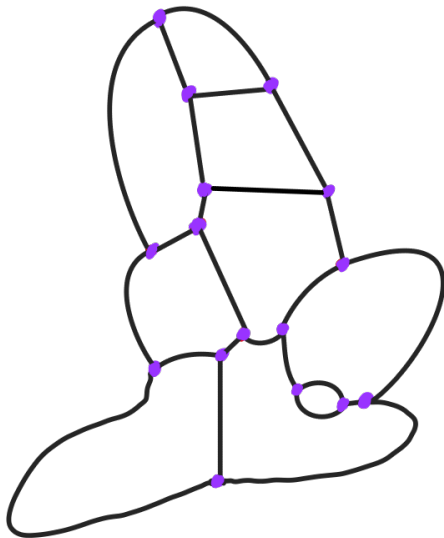
In 1870



Peter Tait

In 1870

Klein 4-group

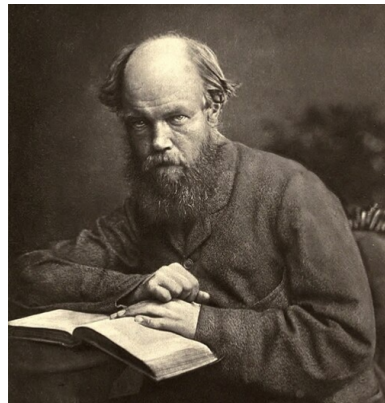
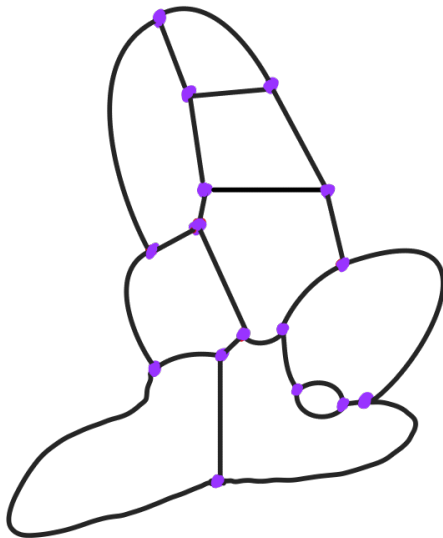


Peter Tait

In 1870

Klein 4-group

↙ +가 잘 정의된 집합



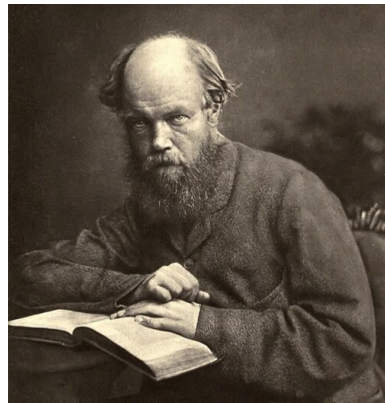
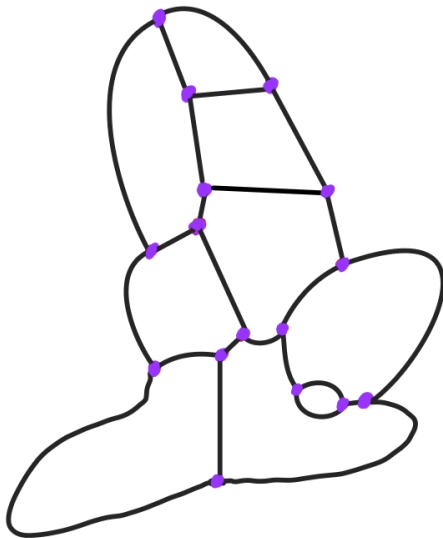
Peter Tait

In 1880

Klein 4-group

↙ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E



Peter Tait

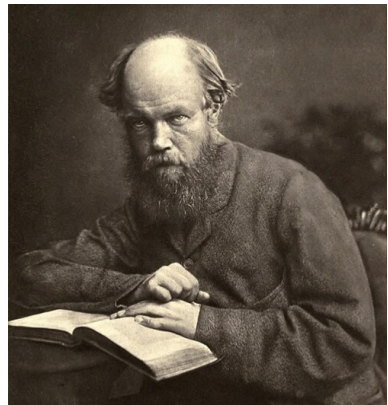
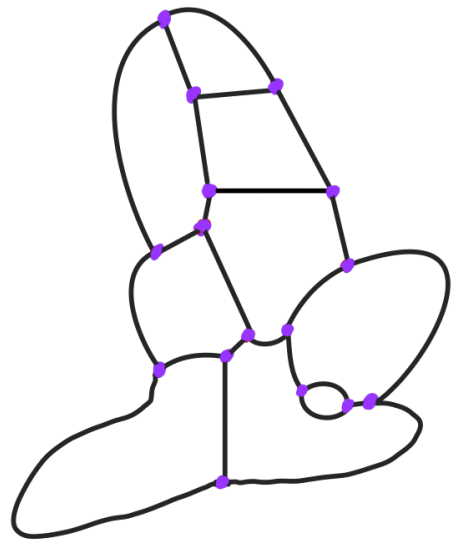
In 1880

Klein 4-group

↙ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$



Peter Tait

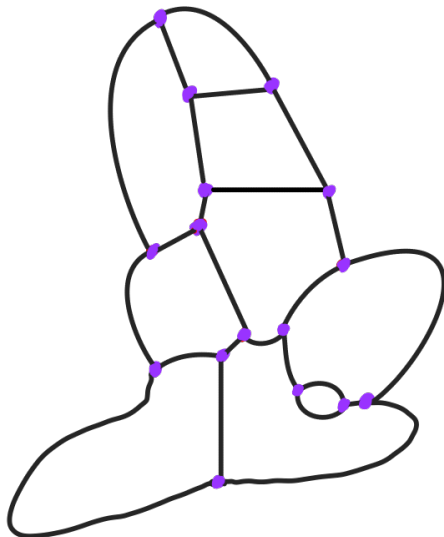
In 1880

Klein 4-group

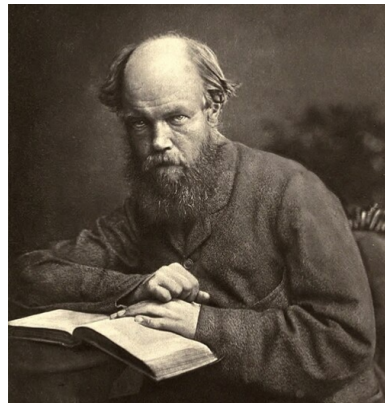
가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$



Edge coloring w/ A, B, C



Peter Tait

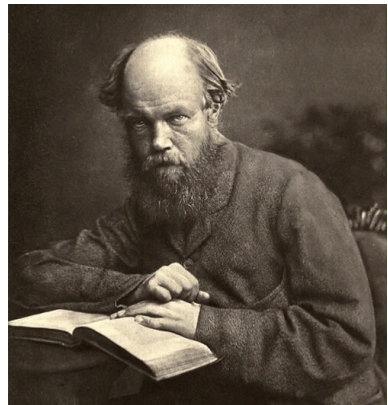
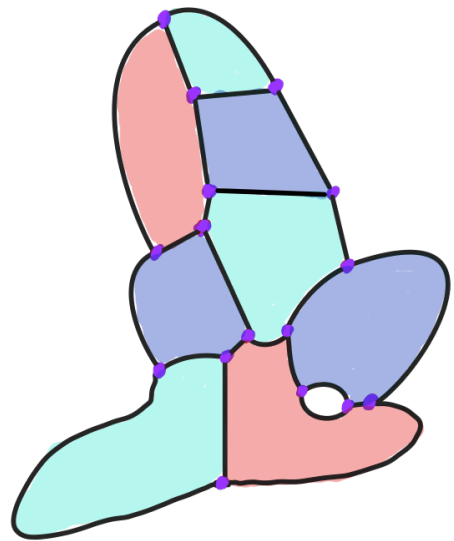
In 1880

Klein 4-group

↙ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$



Peter Tait

Edge coloring w/ A, B, C

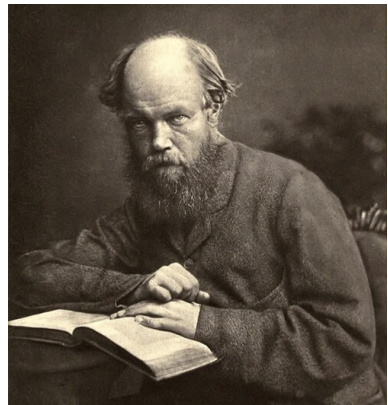
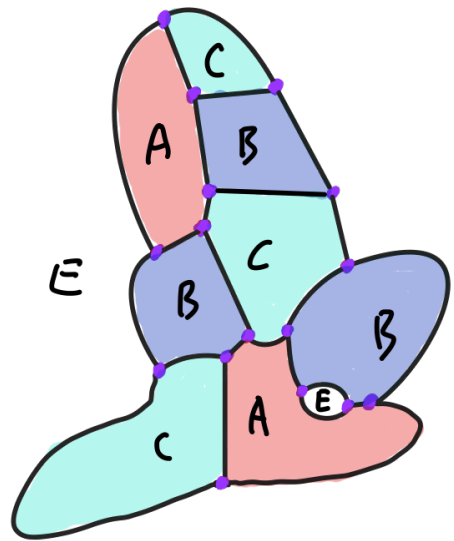
In 1880

Klein 4-group

↙ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$



Peter Tait

Edge coloring w/ A, B, C

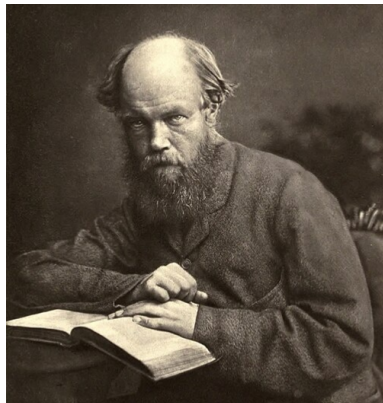
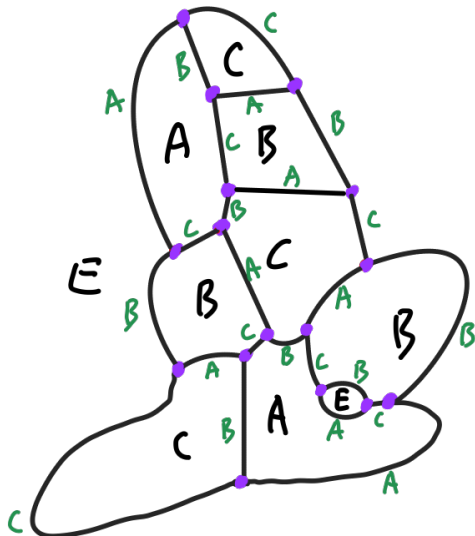
In 1880

Klein 4-group

↙ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$



Peter Tait

Edge coloring w/ A, B, C

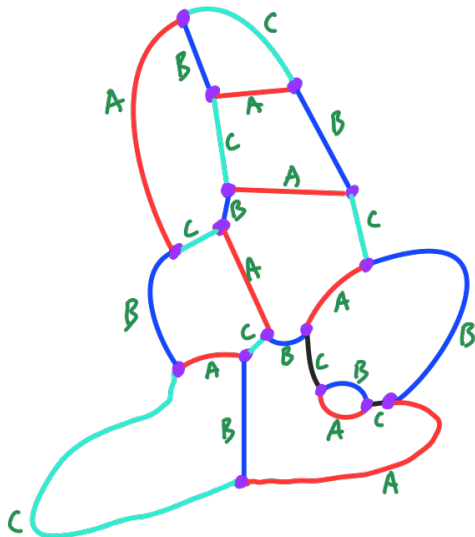
In 1880

Klein 4-group

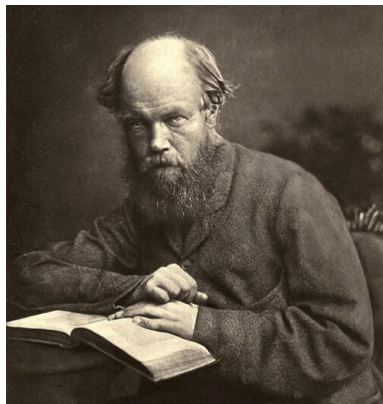
↖ +가 잘 정의된 집합

+	E	A	B	C
E	E	A	B	C
A	A	E	C	B
B	B	C	E	A
C	C	B	A	E

$$A^2 = B^2 = C^2 = E$$

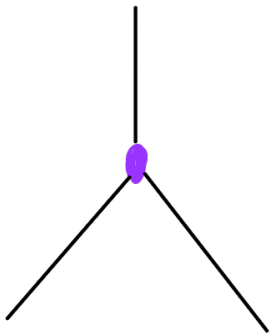


Edge coloring w/ A, B, C

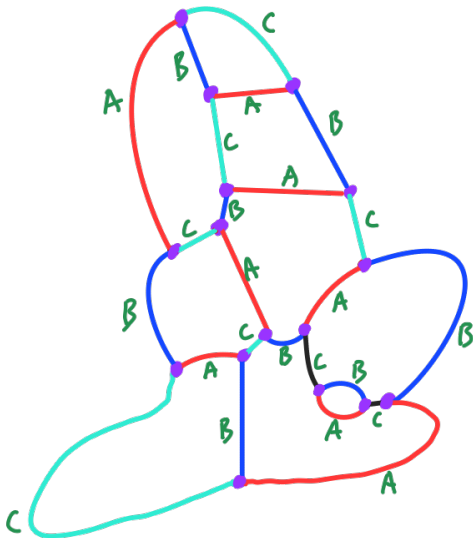


Peter Tait

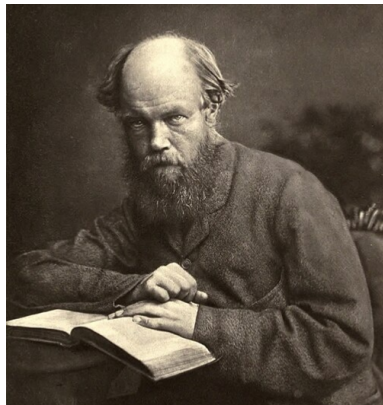
In 1870



Cubic

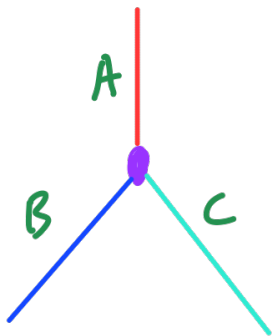


Edge coloring w/ A, B, C

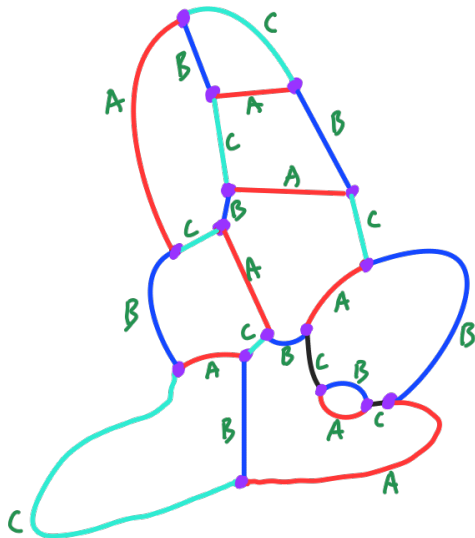


Peter Tait

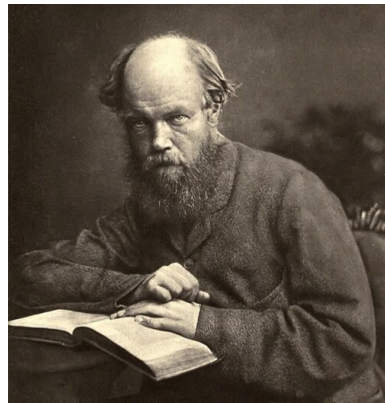
In 1870



proper 3-coloring

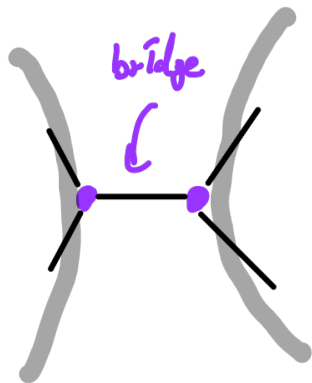


Edge coloring w/ A, B, C

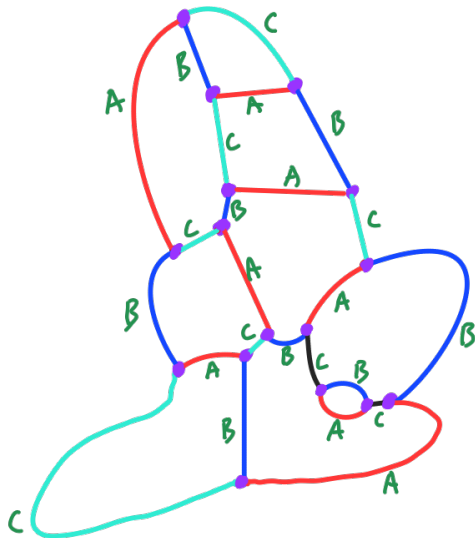


Peter Tait

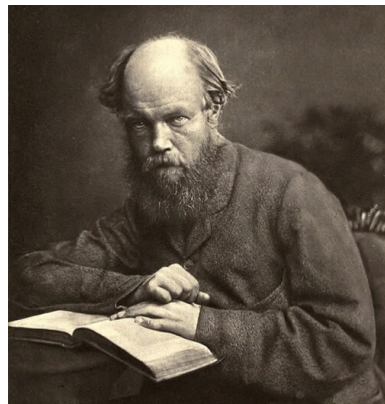
In 1870



bridgeless



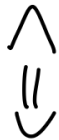
Edge coloring w/ A, B, C



Peter Tait

Thm (4CT)

Every simple planar graph has a proper 4-coloring.



Every bridgeless cubic graph has
a proper 3-edge coloring

Penrose polynomial



Roger Penrose

Penrose polynomial



Roger Penrose

$$[\text{X}] = [\text{) } [] - [\text{X}]$$

$$[O] = 3$$

Relations

$$\text{[Diagram: two circles connected by a vertical line, with a dot at the intersection]} \sim \text{) } [$$

$$\text{[Diagram: a circle with a dot inside]} \sim \text{) }$$

$$\text{[Diagram: a triangle with dots at its vertices and a dot at its center]} \sim \text{[Diagram: a Y-shape with a dot at its center and a circle at its base]}$$

$$\text{[Diagram: a triangle with dots at its vertices and a dot at its center, with lines extending from the vertices]} \sim \text{[Diagram: a Y-shape with a dot at its center and a circle at its base, with lines extending from the branches]}$$

Penrose polynomial

$$[\bigcirc] = 6$$

$$[\text{X}] = [\text{) } (] - [\text{X}]$$

$$[\bigcirc] = 3$$

Relations

$$[\text{X}] \sim [\text{) } (]$$

$$[\text{X}] \sim [\text{) } (]$$

$$[\text{X}] \sim [\text{X}]$$

$$[\text{X}] \sim [\text{X}]$$

Penrose polynomial

$$\left[\text{Diagram: a circle with two dots on a vertical line, enclosed in a red dashed rectangle} \right] = 6$$

$$[X] = [\text{Diagram: a circle with two dots on a vertical line}] - [\text{Diagram: a circle with two dots on a vertical line, crossed out}]$$

$$[O] = 3$$

Relations

$$[\text{Diagram: a circle with two dots on a vertical line, crossed out}] \sim [\text{Diagram: a circle with two dots on a vertical line}]$$

$$[\text{Diagram: a circle with two dots on a vertical line, crossed out}] \sim [\text{Diagram: a circle with two dots on a vertical line}]$$

$$[\text{Diagram: a triangle with dots at vertices and midpoints, crossed out}] \sim [\text{Diagram: a triangle with dots at vertices and midpoints}]$$

$$[\text{Diagram: a triangle with dots at vertices and midpoints, crossed out}] \sim [\text{Diagram: a triangle with dots at vertices and midpoints, crossed out}]$$

Penrose polynomial

$$[\text{diagram}] = 6$$


$$[0 \ 0] - [\text{diagram}]$$


$$[\text{diagram}] = [\text{diagram}] [\text{diagram}] - [\text{diagram}]$$




$$[0] = 3$$

Relations

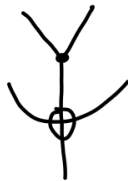
$$[\text{diagram}] \sim [\text{diagram}] [\text{diagram}]$$

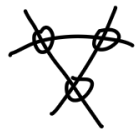



$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



Penrose polynomial

$$[\text{diagram}] = 6$$

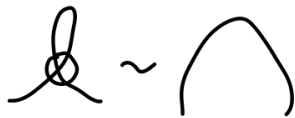

$$[\text{O} \text{O}] - [\text{O}]$$

$$[\text{X}] = [\text{) } [\text{ (}] - [\text{X}]$$

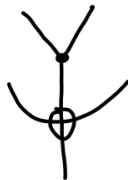

$$[\text{O}] = 3$$

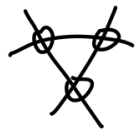
Relations

$$[\text{diagram}] \sim [\text{) } [\text{ (}]$$


$$[\text{diagram}] \sim [\text{) } [\text{ (}]$$


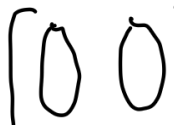
$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



Penrose polynomial

$$[\text{diagram}] = 6$$


$$[\text{diagram}] - [\text{diagram}] = 3^2 - 3 = 6$$



$$[\text{diagram}] = [\text{diagram}] - [\text{diagram}]$$




$$[\text{diagram}] = 3$$


Relations

$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



$$[\text{diagram}] \sim [\text{diagram}]$$



Mathematics > Geometric Topology

[Submitted on 17 Apr 2026]

The Penrose–Kauffman Polynomial

Louis H. Kauffman, Daniel S. Silver, Susan G. Williams

For any cubic graph in a closed orientable surface and a perfect matching, the Penrose–Kauffman polynomial is a sum of chromatic polynomials of a collection of associated graphs. A knot–theoretic perspective affords elementary proofs of old and new results about the polynomial. The Four Color Theorem is shown to be equivalent to a statement about 3–coloring alternating link diagrams in the plane that are reduced and have no bigon regions.

Comments: 33 pages, 28 figures

Subjects: **Geometric Topology (math.GT)**

MSC classes: Primary 05C15, secondary 57M15

Cite as: [arXiv:2604.16635](https://arxiv.org/abs/2604.16635) [math.GT]

(or [arXiv:2604.16635v1](https://arxiv.org/abs/2604.16635v1) [math.GT] for this version)

<https://doi.org/10.48550/arXiv.2604.16635> 

Submission history

From: Susan G. Williams [[view email](#)]

[v1] Fri, 17 Apr 2026 18:46:13 UTC (4,945 KB)

Recent Study

Theorem 4.1. *The Four Color Theorem is equivalent to the statement: Every reduced prime alternating link diagram in the plane has a 3-colorable state.*



Louis Kauffman



Daniel Silver



Susan Williams

Me...?

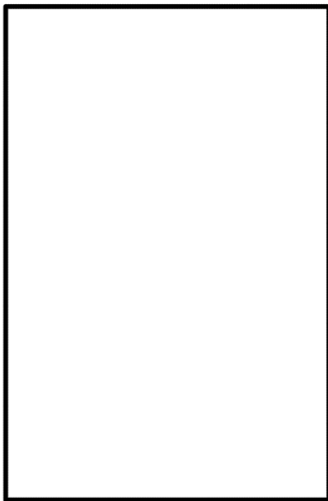


Hojoon Lee

Me...?



George Birkhoff

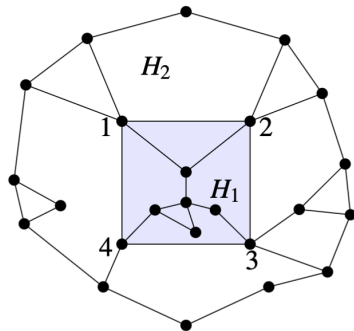


Daniel Lewis

Birkhoff - Lewis
equation

$$G = H_1 \cup H_2$$

$$H_1 \cap H_2 = J_4$$



Me...?

Master's Thesis

Algebraic and Diagrammatic Approaches to the Four Color Theorem

Hojoon Lee

2026학년도 1학기 대학원 석.박사 (예비, 본) 논문심사 일정

연번	구분	심사	날짜	요일	시간	심사자	장소	심사위원장	심사위원	지도교수
1	석사	본심	2026.05.20	수	10:00~11:00	이호준	31317	김승현	오재성	김광수
2	석박사통합	본심	2026.05.21	목	15:00~16:00	홍기남	31351A	서이혁	정윤모 최요정 허정규	윤석배
3	박사	본심	2026.05.21	목	16:00~16:30	JAVANTABERA	32356A	김광수	우서진 김석진(건국대), Xu Chunlei(Mongolia Minzu University)	권대원드라다스
4	박사	본심	2026.05.21	목	16:30~17:00	810연	32356A	김광수	우서진 김석진(건국대), Xu Chunlei(Mongolia Minzu University)	권대원드라다스
5	석박사통합	본심	2026.05.26	화	15:00~16:00	송우근	31319	김광현	권순학	김광수
6	석사	본심	2026.05.26	화	16:00~17:00	김강희	32356A	권순학	허석문	김광현
7	석사	본심	2026.05.28	목	15:00~15:30	김민혁	95712	정윤모	최우철	허정규
8	석사	본심	2026.05.28	목	15:30~16:00	최해린	95712	정윤모	허정규	최우철
9	석사	본심	2026.06.04	목	10:00~11:00	이상훈	31319	임선혁	오재성	김승현