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We can color v with a color not used to color the neighbors of v, and we have a proper 6-coloring of G, contradicting the definition of G.

The Five Color Theorem

Theorem. Let G be a planar graph.
There exists a proper 5-coloring of G.

Proof. Let G be a the smallest planar graph (by number of vertices) that has no proper 5-coloring.

By Theorem 8.1.7, there exists a vertex v in G that has degree five or less. $G \setminus v$ is a planar graph smaller than G, so it has a proper 5-coloring.

Color the vertices of $G \setminus v$ with five colors; the neighbors of v in G are colored by at most five different colors.

If they are colored with only four colors,
we can color v with a color not used to color the neighbors of v, and we have a proper 5-coloring of G, contradicting the definition of G.

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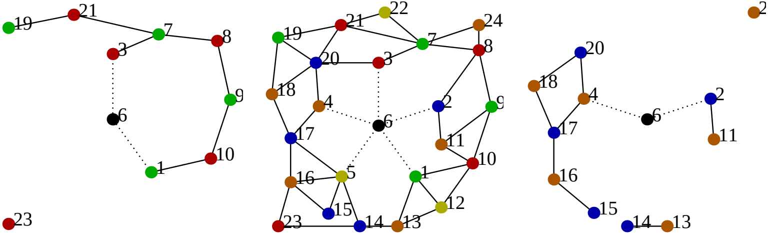
Consider the subgraphs $H_{1,3}$ and $H_{2,4}$ of $G \setminus v$ constructed as follows:
Let $V_{1,3}$ be the set of vertices in $G \setminus v$ colored with colors 1 or 3.
Let $V_{2,4}$ be the set of vertices in $G \setminus v$ colored with colors 2 or 4.
Let $H_{1,3}$ be the induced subgraph of G on $V_{1,3}$. (Define $H_{2,4}$ similarly)



The Kempe Chains Argument

Definition: A **Kempe chain** is a path in $G \setminus v$ between two non-consecutive neighbors of v such that the colors on the vertices of the path *alternate* between the colors on those two neighbors.

In the example above, $3 \to 7 \to 8 \to 9 \to 10 \to 1$ is a Kempe chain: the colors alternate between red and green and 1&3 not consecutive.

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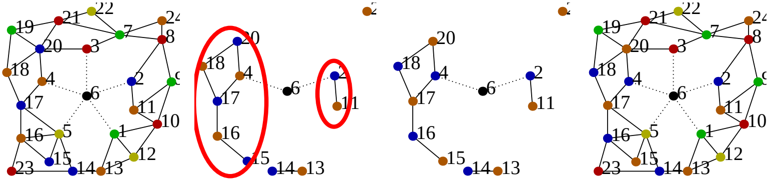
Either v_1 and v_3 are in the same component of $H_{1,3}$ or not.
If they are, there is a Kempe chain between v_1 and v_3.
If they are not, (say v_1 is in component C_1 and v_3 is in C_3) then swap colors 1 and 3 in C_1. (Here we show C_2 and C_4)



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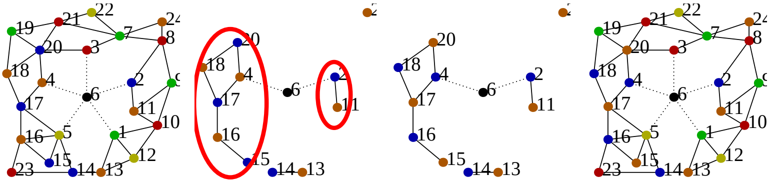
In C_1, there are only vertices of color 1 and 3 and recoloring does not change that no two adjacent vertices are colored differently.

And, by construction, no vertex adjacent to a vertex in C_1 is colored 1 or 3. This is true before AND after recoloring. □



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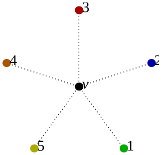
So **either** there is a Kempe chain between v_1 and v_3 **or** we can swap colors so that v's neighbors are colored only using four colors.

Similarly, **either** there is a Kempe chain between v_2 and v_4 **or** we can swap colors to color v's neighbors with only four colors.

Question. Can we have both a v_1-v_3 and a v_2-v_4 Kempe chain?



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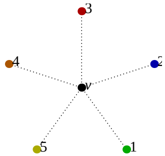

There are no edge crossings in the graph drawing, so there would exist a vertex__________________________________.
This can not exist, so it must be possible to swap colors and be able to place a fifth color on v, contradicting the definition of G.

Modifications of Graphs

Definition: **Deletion**

$G \setminus v$ (G delete v): Remove v from the graph and all incident edges.

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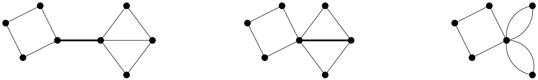
G/e (G contract e): If $e = vw$, coalesce v and w into a super-vertex adjacent to all neighbors of v and w. [*This may produce a multigraph.*]



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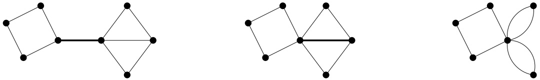

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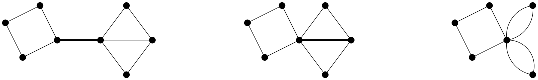

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Note. Any subgraph of G is also a minor of G.

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Note. The converse is not necessarily true.

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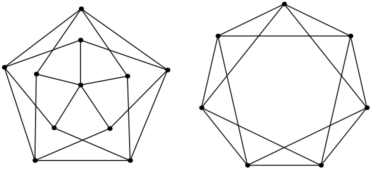

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- To prove that a graph G is planar, find a planar embedding of G.
- To prove that a graph G is non-planar, **(a)** Use $q \leq 3p - 6$, or **(b)** find a subgraph of G that is isomorphic to a subdivision of K_5 or $K_{3,3}$, or **(b)** successively delete and contract edges of G to show that K_5 or $K_{3,3}$ is a minor of G.
- Practice on the Petersen graph. (Here, have some copies!)