

Vertex coloring, chromatic number_____

A **k -coloring** of a graph G is a labeling $f : V(G) \rightarrow S$, where $|S| = k$. The labels are called **colors**; the vertices of one color form a **color class**.

A k -coloring is **proper** if adjacent vertices have different labels. A graph is **k -colorable** if it has a proper k -coloring.

The **chromatic number** is

$$\chi(G) := \min\{k : G \text{ is } k\text{-colorable}\}.$$

A graph G is **k -chromatic** if $\chi(G) = k$. A proper k -coloring of a k -chromatic graph is an **optimal coloring**.

Examples. $K_n, K_{n,m}, C_5$, Petersen

A graph G is **k -color-critical** (or **k -critical**) if $\chi(H) < \chi(G) = k$ for every *proper* subgraph H of G .

Characterization of 1-, 2-, 3-critical graphs.

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Lower bounds_____

Simple lower bounds

$$\chi(G) \geq \omega(G)$$

$$\chi(G) \geq \frac{n(G)}{\alpha(G)}$$

Examples for $\chi(G) \neq \omega(G)$:

- **odd cycles** of length at least 5,

$$\chi(C_{2k+1}) = 3 > 2 = \omega(C_{2k+1})$$

- **complements of odd cycles** of order at least 5,

$$\chi(\overline{C}_{2k+1}) = k + 1 > k = \omega(\overline{C}_{2k+1})$$

- **random graph** $G = G(n, \frac{1}{2})$, almost surely

$$\chi(G) \approx \frac{n}{2 \log n} > 2 \log n \approx \omega(G)$$

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Examples for $\chi(G) = \omega(G)$ _____

- cliques, bipartite graphs
- *interval graphs*

An **interval representation** of a graph is an assignment of an interval to the vertices of the graph, such that two vertices are adjacent iff the corresponding intervals intersect. A graph having such a representation is called an **interval graph**.

Proposition. If G is an interval graph, then

$$\chi(G) = \omega(G).$$

Proof. Order vertices according to left endpoints of corresponding intervals and color *greedily*.

- *perfect graphs*

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Perfect graphs_____

Definition (Berge) A graph G is **perfect**, if $\chi(H) = \omega(H)$ for every induced subgraph $H \subseteq G$.

Conjectures of Berge (1960)

Weak Perfect Graph Conjecture. G is perfect iff \overline{G} is perfect.

Strong Perfect Graph Conjecture. G is perfect iff G does not contain an induced subgraph isomorphic to an odd cycle of order at least 5 or the complement of an odd cycle of order at least 5.

The first conjecture was made into the Weak Perfect Graph Theorem by Lovász (1972)

The second conjecture was made into the Strong Perfect Graph Theorem by Chudnovsky, Robertson, Seymour, Thomas (2002)

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Upper bounds_____

Proposition $\chi(G) \leq \Delta(G) + 1$.

Proof. Algorithmic; Greedy coloring.

A graph G is **d -degenerate** if every subgraph of G has minimum degree at most d .

Claim. G is d -degenerate iff there is an ordering of the vertices v_1, \dots, v_n , such that $|N(v_i) \cap \{v_1, \dots, v_{i-1}\}| \leq d$

Proposition. For a d -degenerate G , $\chi(G) \leq d + 1$.
In particular, for every G , $\chi(G) \leq \max_{H \subseteq G} \delta(H) + 1$.

Proof. Greedy coloring.

Brooks' Theorem. (1941) Let G be a connected graph. Then $\chi(G) = \Delta(G) + 1$ iff G is a **complete graph** or an **odd cycle**.

Proof. Trickier, but still greedy coloring...

Create ordering v_1, v_2, \dots, v_n for Greedy by a reversed BFS of a rooted spanning tree.

Only v_n (the root) could receive color $\Delta(G) + 1$.

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Proof of Brooks' Theorem. Cases._____

Case 1. G is not regular.

Let the root be a vertex with degree $< \Delta(G)$.

Case 2. G has a cut-vertex.

Let the root be the cut-vertex.

Assume G is k -regular and $\kappa(G) \geq 2$.

Case 3. $k \leq 2$. Then $G = C_l$ or K_2 .

Assume $k \geq 3$. We need a root v_n with nonadjacent neighbors v_1, v_2 , such that $G - \{v_1, v_2\}$ is connected. Let x be a vertex of degree less than $n(G) - 1$.

Case 4. $\kappa(G - x) \geq 2$.

Let v_n be a neighbor of x , which has a neighbor y , such that y and x are non-neighbors. Then let $v_1 = x$ and $v_2 = y$.

Case 5. $\kappa(G - x) = 1$.

Then x has a neighbor in every leaf-block of $G - x$. Let $v_n = x$ and v_1, v_2 be two neighbors of x in different leaf blocks of $G - x$.

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Block-decomposition of connected graphs_____

Maximal induced subgraph of G with no cut-vertex is called **block** of G .

Lemma. Two blocks intersect in **at most** one vertex.

Proof. If B_1 and B_2 have no cut-vertex and share at least two vertices then $B_1 \cup B_2$ has no cut-vertex either.

The **Block/Cut-vertex graph** of G is a bipartite graph with vertex set

$$\{B : B \text{ is a block}\} \cup \{v : v \text{ is a cut-vertex}\}.$$

Block B is adjacent to cut-vertex v iff $v \in V(B)$.

Proposition. The Block/Cut-vertex graph of a connected graph is a **tree**.

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Mycielski's Construction_____

The bound $\chi(G) \geq \omega(G)$ could be arbitrarily bad.

Construction. Given graph G with vertices v_1, \dots, v_n , we define supergraph $M(G)$.

$$V(M(G)) = V(G) \cup \{u_1, \dots, u_n, w\}.$$

$$E(M(G)) = E(G) \cup \{u_i v : v \in N_G(v_i)\} \cup \{w\}.$$

Theorem.

(i) If G is triangle-free, then so is $M(G)$.

(ii) If $\chi(G) = k$, then $\chi(M(G)) = k + 1$.

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Forced subdivision_____

G contains a $K_k \Rightarrow \chi(G) \geq k$

G contains a $K_k \not\Leftarrow \chi(G) \geq k$ (already for $k \geq 3$)

Hajós' Conjecture

G contains a K_k -subdivision $\stackrel{?}{\Leftarrow} \chi(G) \geq k$

An **H-subdivision** is a graph obtained from H by successive edge-subdivisions.

Remark. The conjecture is true for $k = 2$ and $k = 3$.

Theorem (Dirac, 1952) Hajós' Conjecture is true for $k = 4$.

Homework. Hajós' Conjecture is **false** for $k \geq 7$.

Hadwiger's Conjecture

G contains a K_k -minor $\stackrel{?}{\Leftarrow} \chi(G) \geq k$

Proved for $k \leq 6$. Open for $k \geq 7$.

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Proof of Dirac's Theorem_____

Theorem (Dirac, 1952) If $\chi(G) \geq 4$ then G contains a K_4 -subdivision.

Proof. Induction on $n(G)$. $n(G) = 4 \Rightarrow G = K_4$.

W.l.o.g. G is 4-critical.

Case 0. $\kappa(G) = 0$ would **contradict** 4-criticality

Case 1. $\kappa(G) = 1$ would **contradict** 4-criticality

Case 2. $\kappa(G) = 2$. Let $S = \{x, y\}$ be a cut-set.

$xy \in E(G)$ would **contradict** 4-criticality

Hence $xy \notin E(G)$.

$\chi(G) \geq 4 \Rightarrow G$ must have an S -lobe H , such that $\chi(H + xy) \geq 4$. Apply induction hypothesis to $H + xy$ and find a K_4 -subdivision F in $H + xy$. Then modify F to obtain a K_4 -subdivision in G .

Let $S \subseteq V(G)$. An **S -lobe** of G is an induced subgraph of G whose vertex set consists of S and the vertices of a component of $G - S$.

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Proof of Dirac's Theorem— Continued_____

Case 3. $\kappa(G) \geq 3$. Let $x \in V(G)$. $G - x$ is 2-connected, so contains a cycle C of length at least 3.

Claim. There is an x, C -fan of size 3.

Proof. Add a new vertex u to G connecting it to the vertices of C . By the Expansion Lemma the new graph G' is 3-connected. By Menger's Theorem there exist three p.i.d x, u -paths P_1, P_2, P_3 in G' . \square

Given a vertex x and a set U of vertices, and x, U -fan is a set of paths from x to U such that any two of them share only the vertex x .

Fan Lemma. G is k -connected iff $|V(G)| \geq k + 1$ and for every choice of $x \in V(G)$ and $U \subseteq V(G)$, $|U| \geq k$, G has an x, U -fan.

Then $C \cup P_1 \cup P_2 \cup P_3 - u$ is K_4 -subdivision in G .

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