



Elements of Graph Theory



Quick review of Chapters 9.1... 9.4, 9.7

New topics

- connectivity in **directed** graphs
- Euler tours and Hamiltonian paths (Chapter 9.5)
- we will mostly skip shortest paths (Chapter 9.6), as that was covered in Data Structures
- we will talk about graph colourings (Chapter 9.8)
- flows in graphs, maximal bipartite matching (from elsewhere)



Applications of Graphs



Applications of Graphs: Potentially anything (graphs can represent relations, relations can describe the extension of any predicate).

Applications in networking, scheduling, flow optimization, circuit design, path planning.

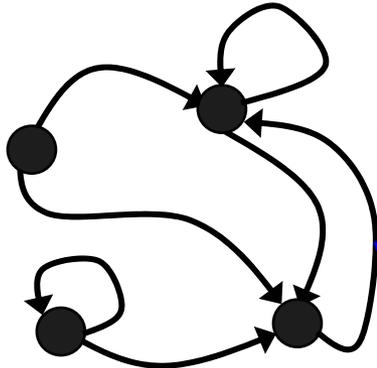
More applications: Geneology analysis, computer game-playing, program compilation, object-oriented design, ...



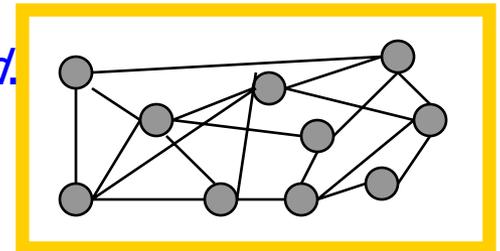
Simple Graphs

Simple Graphs: Correspond to symmetric, irreflexive binary relations R .

- A *simple graph* $G=(V,E)$ consists of:
 - a set V of *vertices* or *nodes* (V corresponds to the universe of the relation R),
 - a set E of *edges* / *arcs* / *links*: unordered pairs of [distinct] elements $u,v \in V$, such that uRv .
- A *directed graph* (V,E) consists of a set of vertices V and a binary relation (need not be symmetric) E on V .



u, v are *adjacent* / *neighbors* / *connected*.
Edge e is *incident* with vertices u and v .
Edge e *connects* u and v .
Vertices u and v are *endpoints* of edge e .



*Visual Representation
of a Simple Graph*



Degree of a Vertex

- Let G be an undirected graph, $v \in V$ a vertex.
 - The *degree* of v , $\deg(v)$, is its number of incident edges. (Except that any self-loops are counted twice.)
 - A vertex with degree 0 is called *isolated*.
 - A vertex of degree 1 is called *pendant*.

Handshaking Theorem: Let G be an undirected (simple, multi-, or pseudo-) graph with vertex set V and edge set E . Then

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

Corollary: Any undirected graph has an even number of vertices of odd degree.



Directed Degree

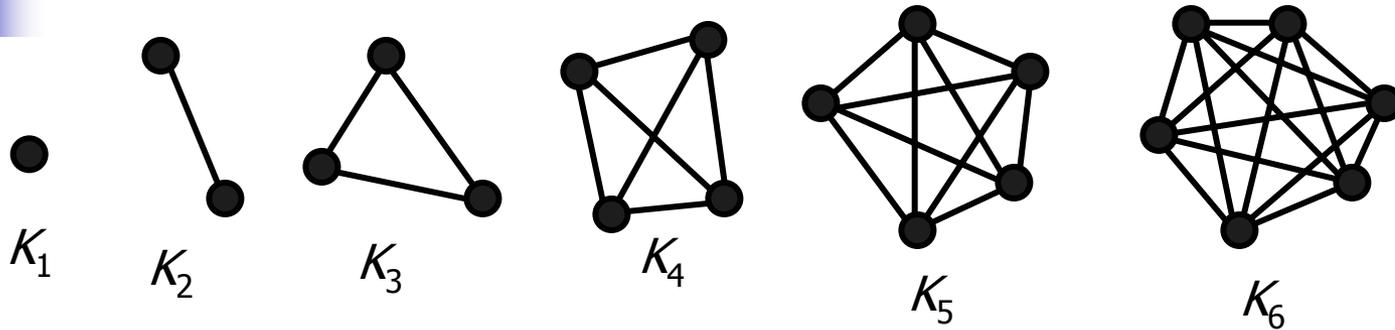


- Let G be a directed graph, v a vertex of G .
 - The *in-degree* of v , $\deg^-(v)$, is the number of edges going to v .
 - The *out-degree* of v , $\deg^+(v)$, is the number of edges coming from v .
 - The *degree* of v , $\deg(v) := \deg^-(v) + \deg^+(v)$, is the sum of v 's in-degree and out-degree.
- **Directed Handshaking Theorem:**

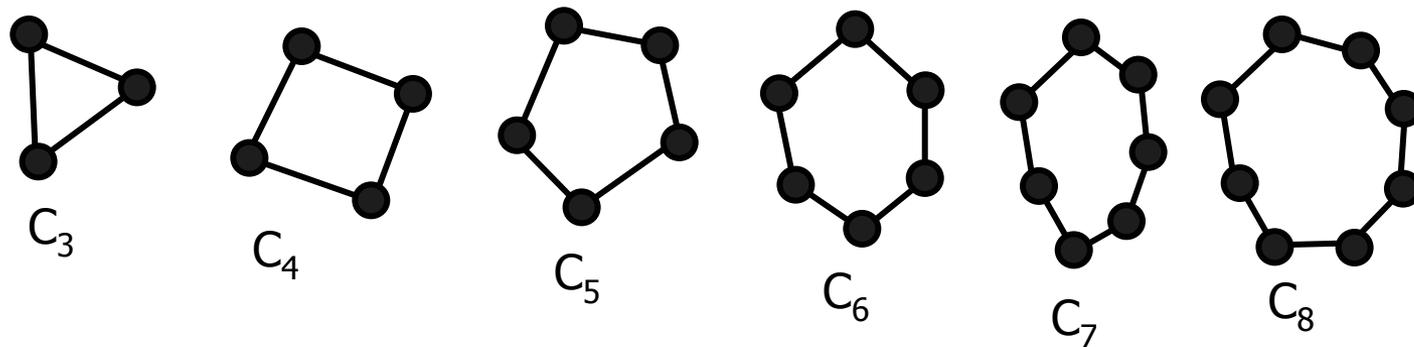
$$\sum_{v \in V} \deg^-(v) = \sum_{v \in V} \deg^+(v) = \frac{1}{2} \sum_{v \in V} \deg(v) = |E|$$



Special Graph Structures



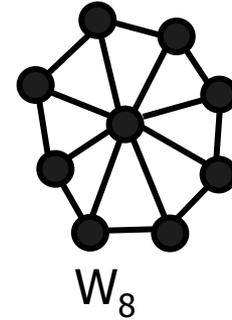
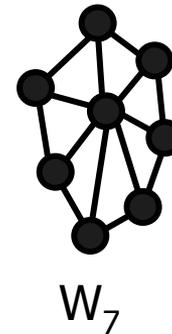
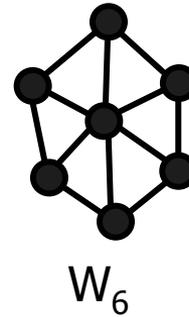
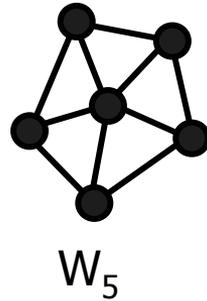
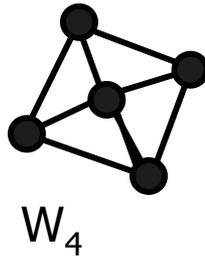
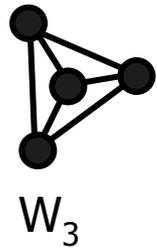
Complete graphs K_n



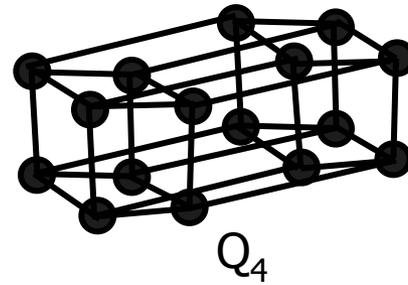
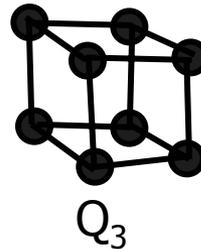
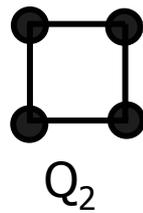
Cycles C_n



Special Graph Structures



Wheels W_n



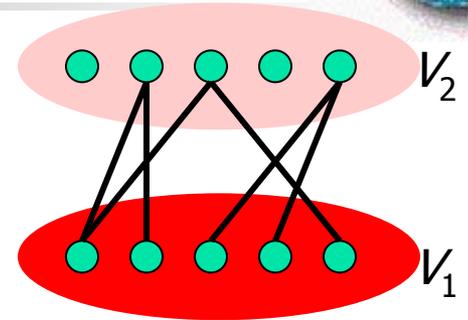
n -Cubes Q_n

Number of vertices: 2^n . Number of edges?

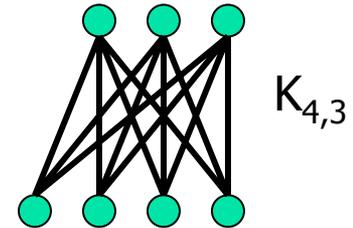


Bipartite Graphs

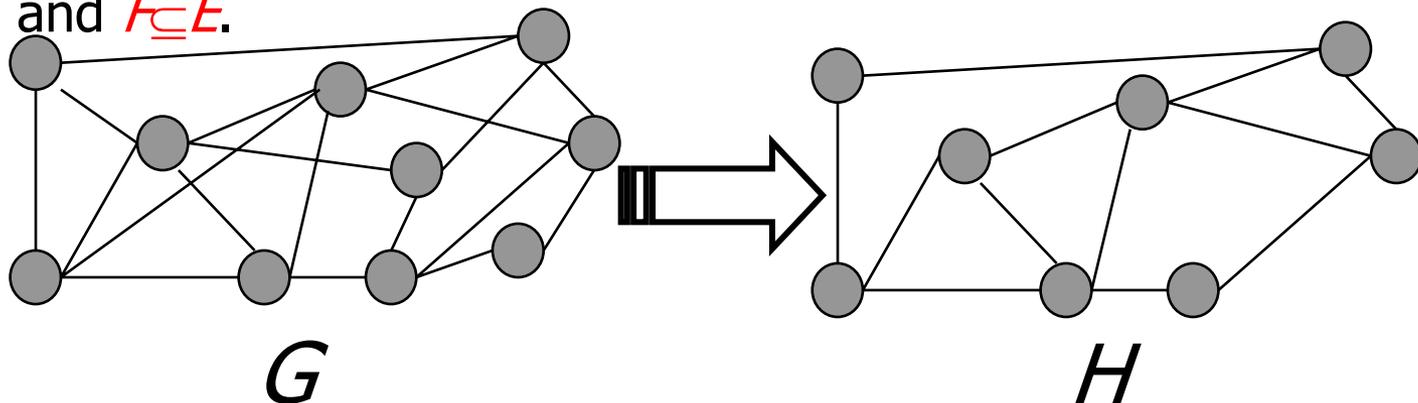
A graph $G=(V,E)$ is *bipartite* (two-part) iff
 $V = V_1 \cup V_2$ where $V_1 \cap V_2 = \emptyset$ and $\forall e \in E$:
 $\exists v_1 \in V_1, v_2 \in V_2: e = \{v_1, v_2\}$.



For $m, n \in \mathbf{N}$, the *complete bipartite graph* $K_{m,n}$
is a bipartite graph where $|V_1| = m$, $|V_2| = n$,
and $E = \{\{v_1, v_2\} \mid v_1 \in V_1 \wedge v_2 \in V_2\}$.



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





§8.3: Graph Representations & Isomorphism

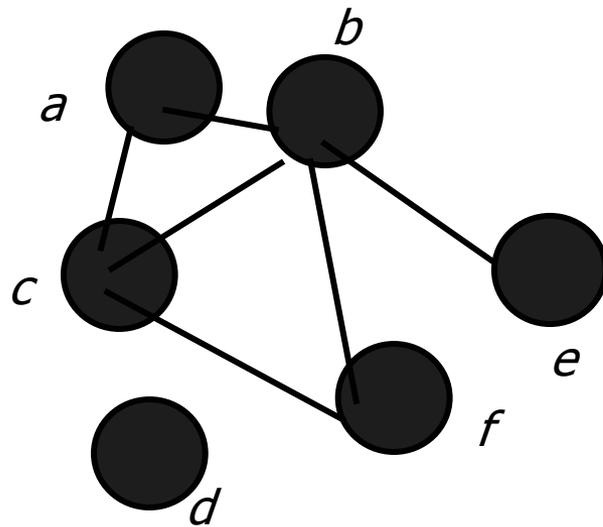


- Graph representations:
 - Adjacency lists.
 - Adjacency matrices.
 - Incidence matrices.
- Graph isomorphism:
 - Two graphs are isomorphic iff they are identical except for their node names.



Adjacency Lists

Adjacency Lists: A table with 1 row per vertex, listing its adjacent vertices.



<i>Vertex</i>	<i>Adjacent Vertices</i>
<i>a</i>	<i>b, c</i>
<i>b</i>	<i>a, c, e, f</i>
<i>c</i>	<i>a, b, f</i>
<i>d</i>	
<i>e</i>	<i>b</i>
<i>f</i>	<i>c, b</i>

Directed Adjacency Lists: 1 row per node, listing the terminal nodes of each edge incident from that node.



Adjacency Matrices



- A way to represent simple graphs
 - possibly with self-loops.
- Matrix $\mathbf{A}=[a_{ij}]$, where a_{ij} is 1 if $\{v_i, v_j\}$ is an edge of G , and is 0 otherwise.
- Can extend to pseudographs by letting each matrix elements be the number of links (possibly >1) between the nodes.



Graph Isomorphism



Formal definition:

- Simple graphs $G_1=(V_1, E_1)$ and $G_2=(V_2, E_2)$ are *isomorphic* iff \exists a bijection $f: V_1 \rightarrow V_2$ such that $\forall a, b \in V_1$, a and b are adjacent in G_1 iff $f(a)$ and $f(b)$ are adjacent in G_2 .
- f is the “renaming” function between the two node sets that makes the two graphs identical.
- This definition can easily be extended to other types of graphs.

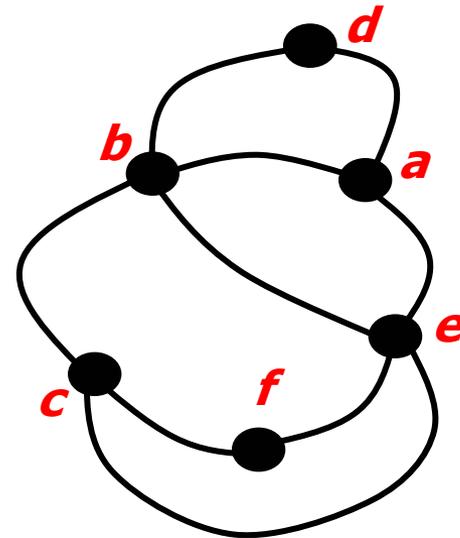
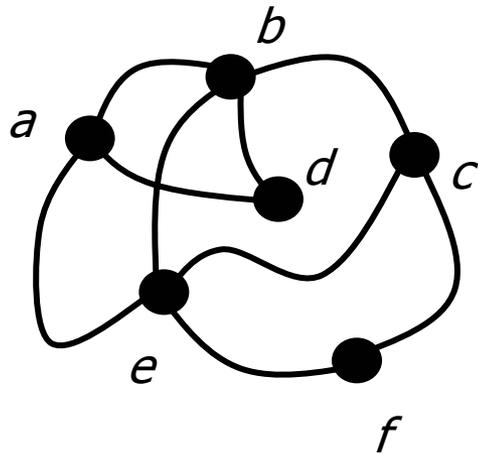
Necessary but not *sufficient* conditions for $G_1=(V_1, E_1)$ to be isomorphic to $G_2=(V_2, E_2)$:

- We must have that $|V_1|=|V_2|$, and $|E_1|=|E_2|$.
- The number of vertices with degree n is the same in both graphs.
- For every proper subgraph g of one graph, there is a proper subgraph of the other graph that is isomorphic to g .



Isomorphism Example

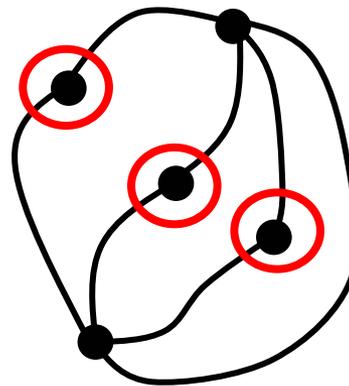
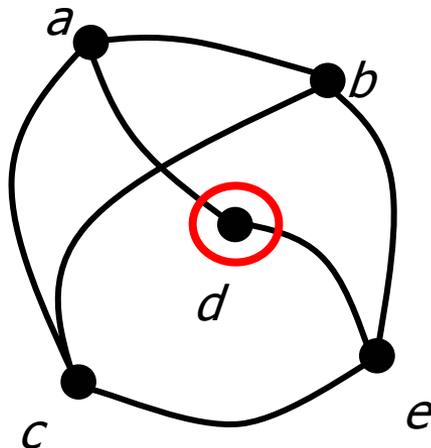
If isomorphic, label the 2nd graph to show the isomorphism, else identify difference.





Are These Isomorphic?

- If isomorphic, label the 2nd graph to show the isomorphism, else identify difference.



- *Same # of vertices*
- *Same # of edges*
- *Different # of vertices of degree 2! (1 vs 3)*



§8.4: Connectivity



- In an undirected graph, a *path* of length n from u to v is a sequence of adjacent edges going from vertex u to vertex v .
- A path is a *circuit* if $u=v$.
- A path *traverses* the vertices along it.
- A path is *simple* if it contains no edge more than once.
- **Paths in Directed Graphs:** Same as in undirected graphs, but the path must go in the direction of the arrows.

An undirected graph is *connected* iff there is a path between every pair of distinct vertices in the graph.

There is a *simple* path between any pair of vertices in a connected undirected graph.

Connected component: connected subgraph

A *cut vertex* or *cut edge* separates 1 connected component into 2 if removed



Directed Connectedness

- A directed graph is *strongly connected* iff there is a directed path from a to b for any two vertices a and b .
- It is *weakly connected* iff the underlying *undirected* graph (*i.e.*, with edge directions removed) is connected.
- Note *strongly* implies *weakly* but not vice-versa.

Note that connectedness, and the existence of a circuit or simple circuit of length k are graph invariants with respect to isomorphism.

Counting different paths: the number of different paths from a vertex i to a vertex j is the (i, j) entry in \mathbf{A}^r , where A is the adjacency matrix of the graph

proof by induction on r



§8.5: Euler & Hamilton Paths



- An ***Euler circuit*** in a graph G is a simple circuit containing every edge of G .
- An ***Euler path*** in G is a simple path containing every edge of G .
- A ***Hamilton circuit*** is a circuit that traverses each vertex in G exactly once.
- A ***Hamilton path*** is a path that traverses each vertex in G exactly once.



Euler and Hamiltonian Tours



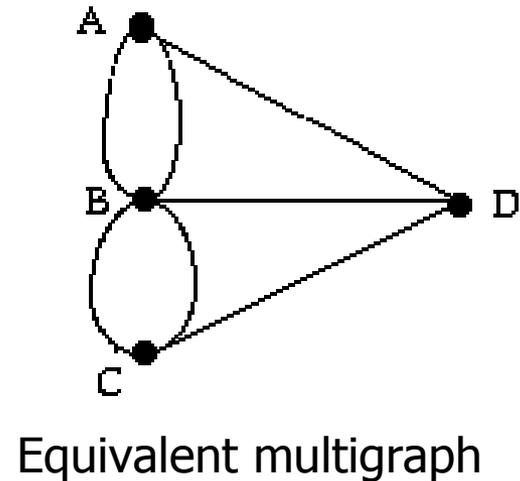
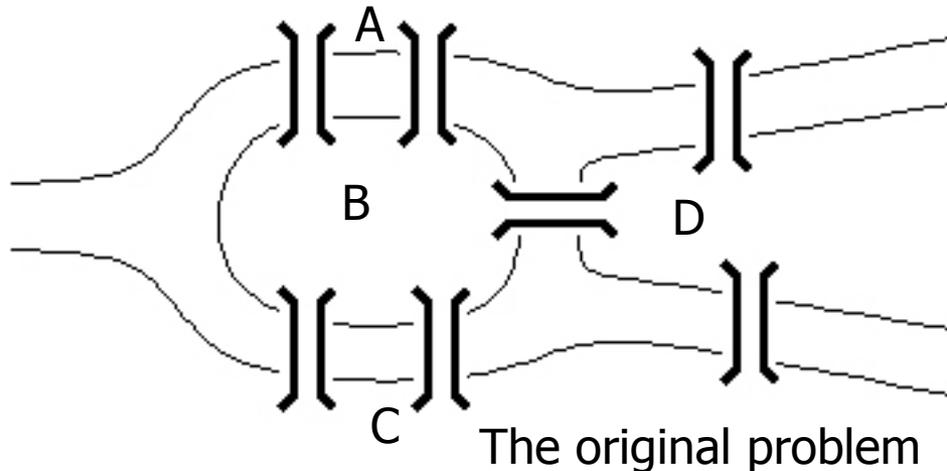
Chinese postman problem

- find a shortest tour in a non-Euler graph
- some edges will be traversed twice
- corresponds to finding the cheapest set of paths connecting matching vertices of odd degree
 - the number of odd-degree vertices is even
 - the paths are edge-disjoint



Bridges of Königsberg Problem

Can we walk through town, crossing each bridge exactly once, and return to start?



Theorem: A connected multigraph has an Euler circuit iff each vertex has even degree.

Proof:

- (\rightarrow) The circuit contributes 2 to degree of each node.
- (\leftarrow) By construction using algorithm on p. 580-581



Euler Path Problem

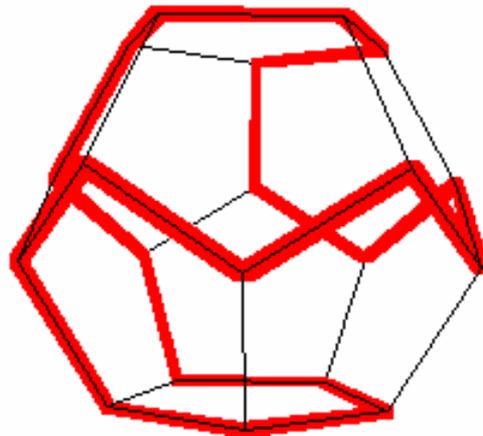
- **Theorem:** A connected multigraph has an Euler path (but not an Euler circuit) iff it has exactly 2 vertices of odd degree.
 - One is the start, the other is the end.
- **Euler tour in a directed graph**
 - in-degrees must match out-degrees in all nodes
- **Euler Circuit Algorithm**
 - Begin with any arbitrary node.
 - Construct a simple path from it till you get back to start.
 - Repeat for each remaining subgraph, splicing results back into original cycle.



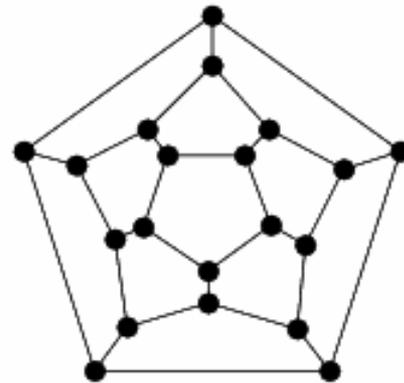
Round-the-World Puzzle



- Can we traverse all the vertices of a dodecahedron, visiting each once?



Dodecahedron puzzle



Equivalent graph



Hamiltonian Path Theorems



- **Dirac's theorem:** If (but not only if) G is connected, simple, has $n \geq 3$ vertices, and $\forall v \deg(v) \geq n/2$, then G has a Hamilton circuit.
- **Ore's corollary:** If G is connected, simple, has $n \geq 3$ nodes, and $\deg(u) + \deg(v) \geq n$ for every pair u, v of non-adjacent nodes, then G has a Hamilton circuit.



Hamiltonian Tours - Applications



Traveling salesmen problem

- in a weighted graph, find the shortest tour visiting every vertex
- we can solve it if we can solve the problem of finding the shortest Hamiltonian path in complete graphs

Gray codes

- find a sequence of codewords such that each binary string is used, but adjacent codewords are close to each other (differ by 1 bit only)
- all binary strings of length n = vertices of n -dimensional hypercube
- edges of the hypercube = vertices that differ by 1 bit
- our problem = find a Hamiltonian circuit in hypercubes
- Gray codes – one particular solution
 - can be defined recursively (as hypercubes are)



§10.1: Introduction to Trees



- A *tree* is a connected undirected graph that contains no circuits.
 - **Theorem:** There is a unique simple path between any two of its nodes.
- A (not-necessarily-connected) undirected graph without simple circuits is called a *forest*.
 - You can think of it as a set of trees having disjoint sets of nodes.
- A *leaf* node in a tree or forest is any pendant or isolated vertex. An *internal* node is any non-leaf vertex (thus it has degree ≥ 2).



Trees as Models



- Can use trees to model the following:
 - Saturated hydrocarbons
 - Organizational structures
 - Computer file systems
- In each case, would you use a rooted or a non-rooted tree?



Some Tree Theorems

- Any tree with n nodes has $e = n - 1$ edges.
 - **Proof:** Consider removing leaves.
- A full m -ary tree with i internal nodes has $n = mi + 1$ nodes, and $\ell = (m - 1)i + 1$ leaves.
 - **Proof:** There are mi children of internal nodes, plus the root. And, $\ell = n - i = (m - 1)i + 1$. \square
- Thus, when m is known and the tree is full, we can compute all four of the values e , i , n , and ℓ , given any one of them.



Some More Tree Theorems



- **Definition:** The *level* of a node is the length of the simple path from the root to the node.
 - The *height* of a tree is maximum node level.
 - A rooted m -ary tree with height h is called *balanced* if all leaves are at levels h or $h-1$.
- **Theorem:** There are at most m^h leaves in an m -ary tree of height h .
 - **Corollary:** An m -ary tree with ℓ leaves has height $h \geq \lceil \log_m \ell \rceil$. If m is full and balanced then $h = \lceil \log_m \ell \rceil$.



§9.2: Applications of Trees



- Binary search trees
 - A simple data structure for sorted lists
- Decision trees
 - Minimum comparisons in sorting algorithms
- Prefix codes
 - Huffman coding
- Game trees



§9.3: Tree Traversal



- Universal address systems
- Traversal algorithms
 - Depth-first traversal:
 - Preorder traversal
 - Inorder traversal
 - Postorder traversal
 - Breadth-first traversal
- Infix/prefix/postfix notation



Planar Graphs



Planar graphs are graphs that can be drawn in the plane without edges having to cross.

Understanding planar graph is important:

- Any graph representation of maps/topographical information is planar.
 - graph algorithms often specialized to planar graphs (e.g. traveling salesperson)
- Circuits usually represented by planar graphs



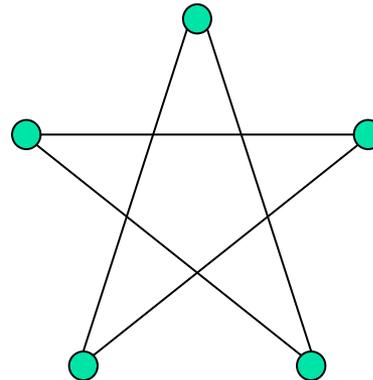
Planar Graphs

-Common Misunderstanding



Just because a graph is drawn with edges crossing doesn't mean it's not planar.

Q: Why can't we conclude that the following is non-planar?



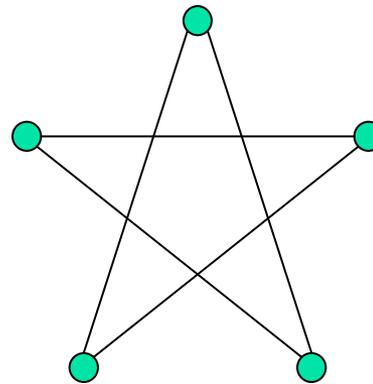


Planar Graphs

-Common Misunderstanding



A: Because it is isomorphic to a graph which *is* planar:



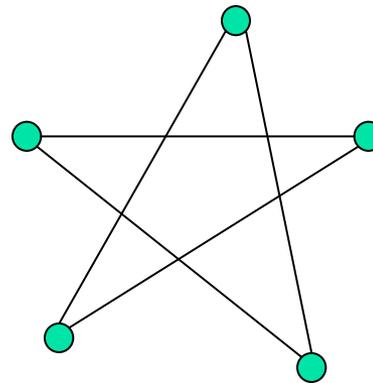


Planar Graphs

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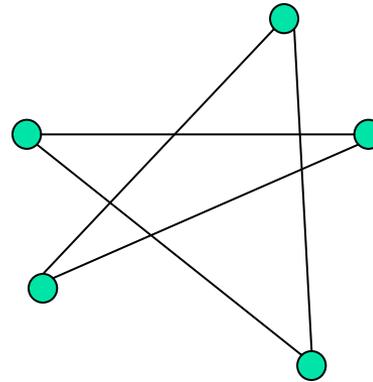


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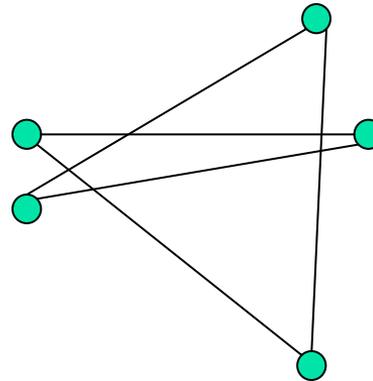


Planar Graphs

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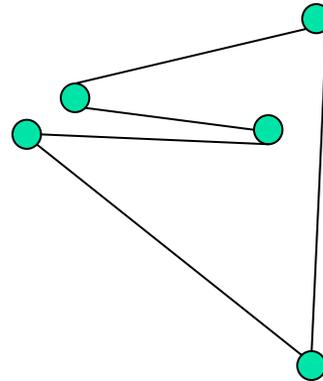


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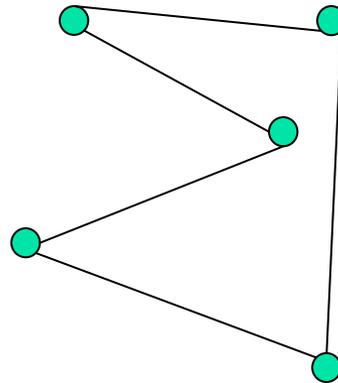


Planar Graphs

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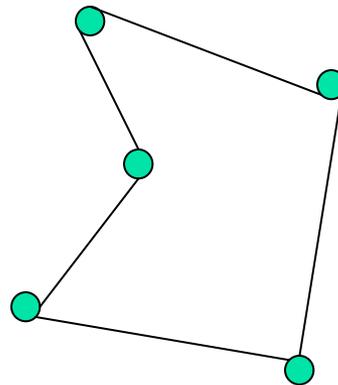


Planar Graphs

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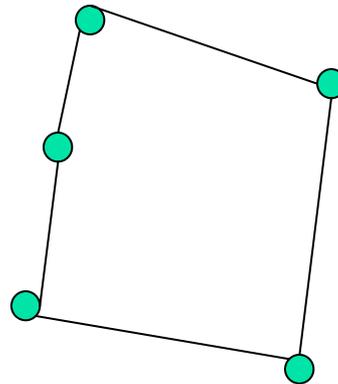


Planar Graphs

-Common Misunderstanding



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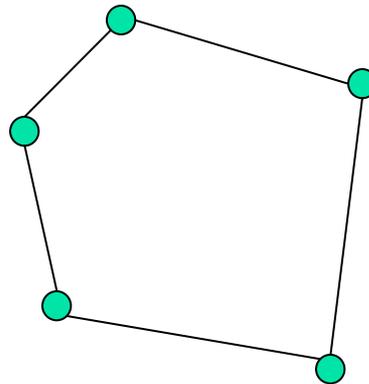


Planar Graphs

-Common Misunderstanding



A: Because it is isomorphic to a graph which *is* planar:





Proving Planarity

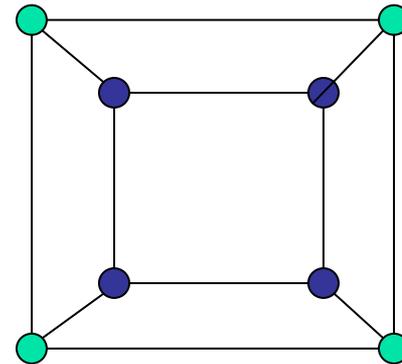
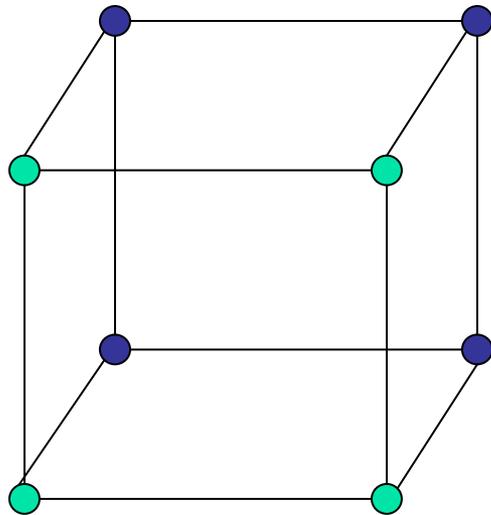


To prove that a graph is planar amounts to redrawing the edges in a way that no edges will cross. May need to move vertices around and the edges may have to be drawn in a very indirect fashion.

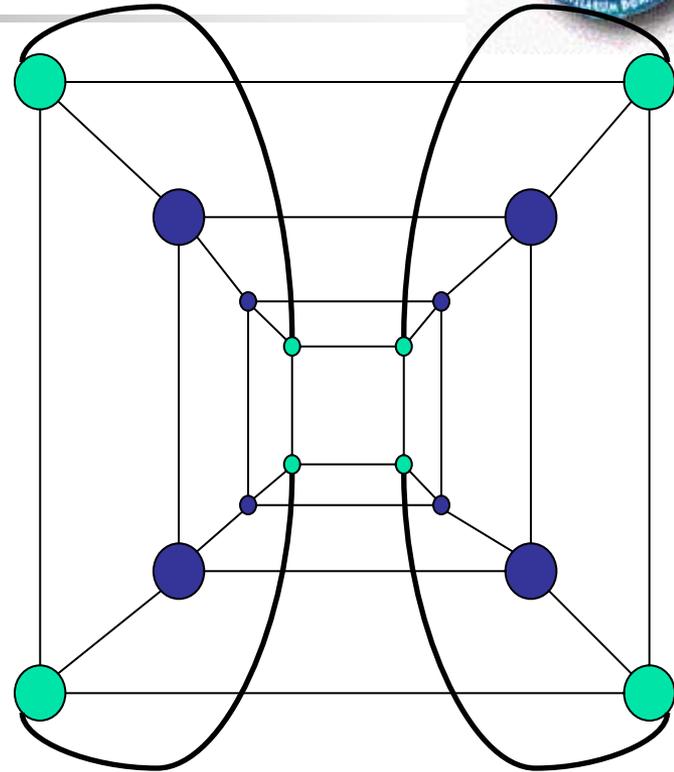
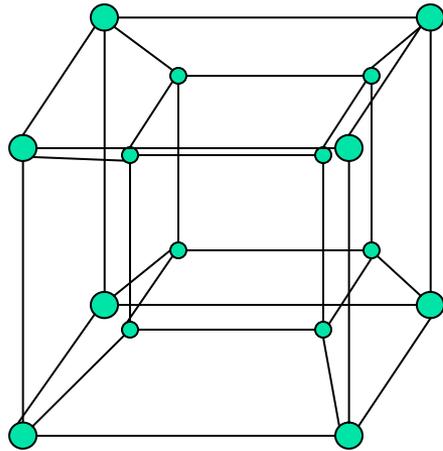
E.G. show that the 3-cube is planar:



Proving Planarity 3-Cube



Proving Planarity? 4-Cube



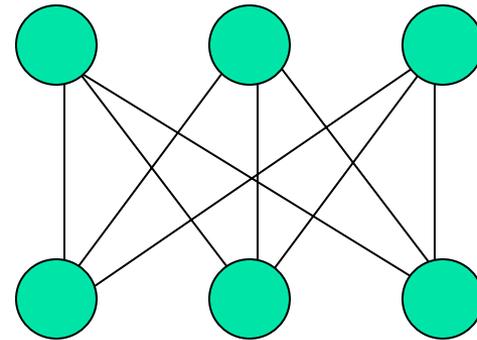
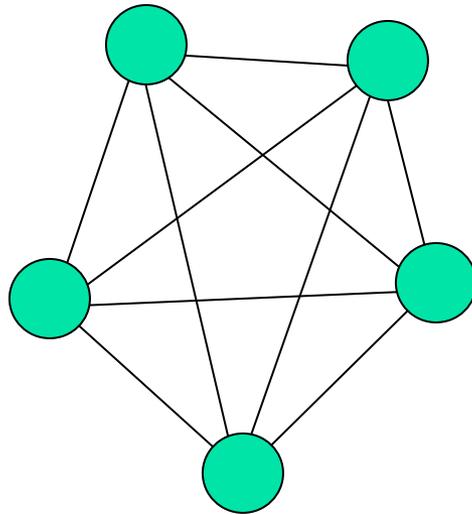
Seemingly not planar, but how would one prove this!



The smallest graphs that are not planar



- $K_5, K_{3,3}$





Disproving Planarity: Kuratowski / Wagner



- A graph is planar if and only if it does not contain the K_5 and the $K_{3,3}$ as a *homeomorphic subgraph* / as a *minor*.
- Minor: H is a minor of G , if H can be obtained from G by a series of 0 or more deletions of vertices, deletions of edges, and contraction of edges.
- Does not yield fast recognition algorithm!



Euler's theorem



- Let G be a connected plane graph with n vertices, m edges, and f faces. Then $n + f - m = 2$.
- Proof. By induction.
 - True if $m=0$.
 - If G has a circuit, then delete an edge and ...
 - If G has a vertex v of degree 1, then delete v and ...
- ...



Euler's theorem Corollaries



- If G is a connected plane graph with no parallel edges and no self-loops, with $n > 1$, then $m \leq 3n - 6$.
 - Every face 'has' at least three edges; each edge 'is on' two faces, or twice on the same face.
- Every plane graph with no parallel edges and no self-loops has a vertex of degree at most 5.
 - K_5 is not a planar graph
- If G is a planar simple graph with $v \geq 3$ and no cycles of length 3, then $e \leq 2v - 4$
 - $K_{3,3}$ is not planar



Proof of Euler's theorem Corollaries



Suppose that G has at most m edges, consider some plane drawing of G , with f faces. Consider the number of pairs (e, F) where e is one of the edges bounding the face F .

For each edge e , there are at most 2 faces that it bounds. So the total number of these edge face pairs has to be less than $2m$. On the other hand, because G is a simple graph, each face is bounded by at least 3 edges. Therefore, the total number of edge-face pairs is greater than or equal to $3f$. So $3f \leq 2m$

By the Euler Polyhedron Formula, $n - m + f = 2$, so, $3n - 3m + 3f = 6$. Since $3f \leq 2m$, $3f = 6 - 3n + 3m \leq 2m$. Therefore $m \leq 3n - 6$.

If G has no triangles, each face must be bounded by 4 or more edges. Thus $2f \leq m$ and $4 - 2n + 2m \leq m$, therefore $m \leq 2n - 4$.



Euler's theorem Corollaries



Every simple, planar graph has a vertex of degree less than 6.

Proof: $\sum_{v \in V} \deg(v) = 2m \leq 2(3n - 6) = 6n - 12$

Thus the average degree $(6n-12)/n = 6 - 12/n < 6$.

So at least one of the vertices has degree less than 6.



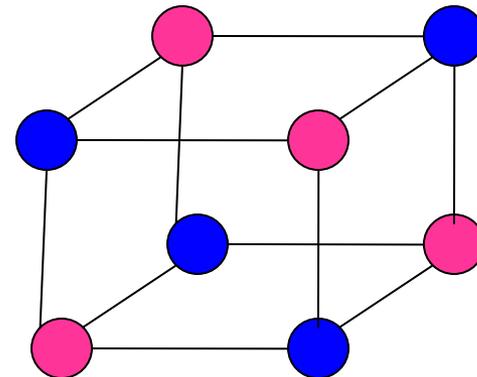
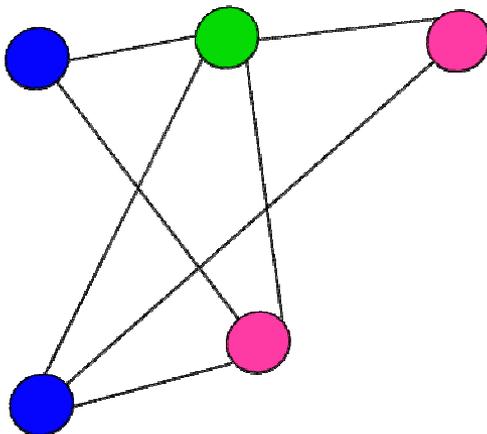
Graph Colorings

Vertex coloring of a graph

- assign a color to each vertex so that adjacent vertices are of different colors
- i.e. find $c: V \rightarrow N$ such that $(u,v) \in E \rightarrow c(u) \neq c(v)$

Chromatic number χ of a graph G

- the least amount of colors needed to color the graph





Graph Colorings



So, what is a chromatic number for

- K_n ?
- C_n ?
- $K_{m,n}$?

Bipartite Graphs

The chromatic number of a graph G is 2 if and only if G is a bipartite graph

Planar Graphs?



The four Color Theorem



The four color theorem: The chromatic number of every simple planar graph is at most four

We can prove that six colors are enough

For general graphs?

only exponential algorithms known
even finding approximation is difficult



Six color Theorem



Proof of the six color theorem: by induction on n , the number of vertices of the graph.

Basis Step: If G has fewer than seven vertices then the result is obvious. Suppose that G has n vertices with $n \leq 7$.

Inductive step: We assume that all simple graphs with $n-1$ vertices are 6 colorable. Because of planarity and Euler's theorem we know that G has a vertex v with degree less than 6. Remove v from G and all adjacent edges to v . The remaining subgraph has $n-1$ vertices and by the induction hypothesis it can be properly colored by 6 colors. Since v has at most 5 adjacent vertices in G , then v can be colored with a color different from all of its neighbours. This ends the proof.



Graph Colorings - Applications



Scheduling exams

- many exams, each student have specified which exams he/she has to take
- how many different exam slots are needed? (a student cannot be at two different exams at the same time)

Vertices: courses

Edges: if there is a student taking both courses

Exam slots: colors

Frequency assignments

- TV channels, mobile networks