Discrete Mathematics in Computer Science
C4. Further Topics in Graph Theory

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C4.1 Subgraphs

C4.2 Isomorphism

C4.3 Planarity and Minors

C4.1 Subgraphs

Overview

▶ We conclude our discussion of (di-) graphs by giving
a brief tour of some further topics in graph theory
that we do not have time to discuss in depth.

▶ In the interest of brevity (and hence wider coverage of topics),
we do not give proofs for the results in this chapter.

Subgraphs

Definition (subgraph)

A subgraph of a graph (V, E) is a graph (V', E')
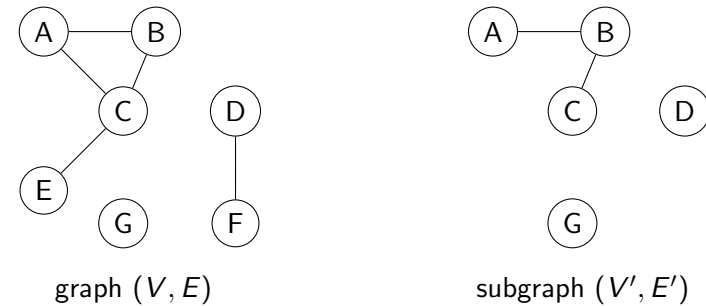with $V' \subseteq V$ and $E' \subseteq E$.

A subgraph of a digraph (N, A) is a digraph (N', A')
with $N' \subseteq N$ and $A' \subseteq A$.

German: Teilgraph/Untergraph

Question: Can we choose V' and E' arbitrarily?

The subgraph relationship defines a partial order on graphs
(and on digraphs).

Subgraphs – Example

graph (V, E) subgraph (V', E')

Induced Subgraphs (1)

Definition (induced subgraph)

Let $G = (V, E)$ be a graph, and let $V' \subseteq V$.
The subgraph of G induced by V' is the graph (V', E')
with $E' = \{\{u, v\} \in E \mid u, v \in V'\}$.

We say that G' is an induced subgraph of $G = (V, E)$ if G' is
the subgraph of G induced by V' for any set of vertices $V' \subseteq V$.

German: induzierter Teilgraph (eines Graphen)

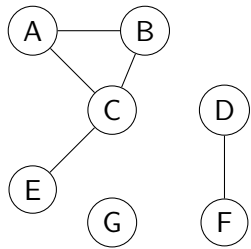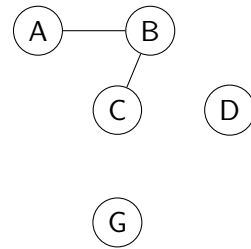# Induced Subgraphs (2)

Definition (induced subgraph)

Let $G = (N, A)$ be a digraph, and let $N' \subseteq N$.
The subgraph of G induced by N' is the digraph (N', A')
with $A' = \{(u, v) \in A \mid u, v \in N'\}$.

We say that G' is an induced subgraph of $G = (N, A)$ if G' is
the subgraph of G induced by N' for any set of nodes $N' \subseteq N$.
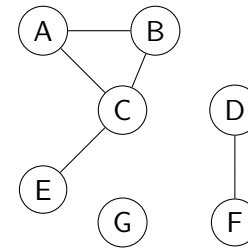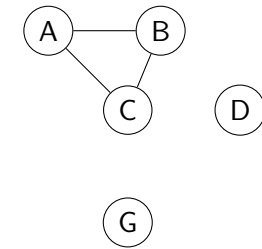
German: induzierter Teilgraph (eines gerichteten Graphen)

Induced Subgraphs – Example

graph (V, E) Is this an induced subgraph?

Induced Subgraphs – Example

graph (V, E) This is an induced subgraph.

Induced Subgraphs – Discussion

▶ Induced subgraphs are subgraphs.
▶ They are the largest (in terms of the set of edges) subgraphs
  with any given set of vertices.
▶ A typical example is a subgraph induced by
  one connected component of a graph.
▶ The subgraphs induced by the connected components
  of a forest are trees.

Counting Subgraphs

▶ How many subgraphs does a graph (V, E) have?
▶ How many induced subgraph does a graph (V, E) have?

For the second question, the answer is $2^{|V|}$.

The first question is in general not easy to answer because
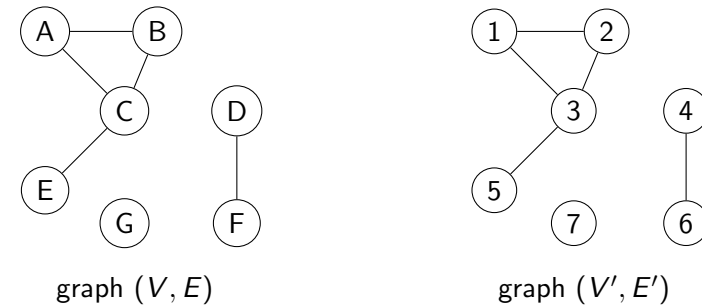vertices and edges of a subgraph cannot be chosen independently.

Example (subgraphs of a complete graph)

A complete graph with n vertices (i.e., with all possible $\binom{n}{2}$ edges)
has $\sum_{k=0}^{n} \binom{n}{k} 2^{\binom{k}{2}}$ subgraphs. (Why?)

for $n = 10$: 1024 induced subgraphs, 35883905263781 subgraphs

C4.2 Isomorphism

Motivation

graph (V, E) graph (V', E')

What is the difference between these graphs?

Isomorphism

- In many cases, the "names" of the vertices of a graph do not have any particular semantic meaning.
- Often, we care about the structure of the graph, i.e., the relationship between the vertices and edges, but not what we call the different vertices.
- This is captured by the concept of isomorphism.

Isomorphism – Definition

> **Definition (Isomorphism)**
>
> Let $G = (V, E)$ and $G' = (V', E')$ be graphs.
>
> An isomorphism from G to G' is a bijective function $\sigma : V \to V'$ such that for all $u, v \in V$:
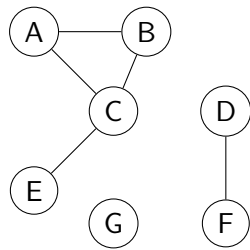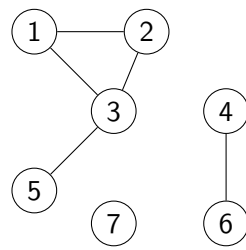>
> $$\{u, v\} \in E \quad \text{iff} \quad \{\sigma(u), \sigma(v)\} \in E'.$$
>
> If there exists an isomorphism from G to G', we say that they are isomorphic, in symbols $G \cong G'$.

German: Isomorphismus, isomorph

- derives from Ancient Greek for "equally shaped/formed"
- analogous definition for digraphs omitted

## Isomorphism – Example

graph (V, E) graph (V', E')

- $\sigma = \{A \mapsto 1, B \mapsto 2, C \mapsto 3, D \mapsto 4, E \mapsto 5, F \mapsto 6, G \mapsto 7\}$
- for example: $\{A, B\} \in E$ and $\{\sigma(A), \sigma(B)\} = \{1, 2\} \in E'$
- for example: $\{A, D\} \notin E$ and $\{\sigma(A), \sigma(D)\} = \{1, 4\} \notin E'$

Isomorphism – Discussion

- The identity function is an isomorphism.
- The inverse of an isomorphism is an isomorphism.
- The composition of two isomorphisms is an isomorphism (when defined over matching sets of vertices)

It follows that being isomorphic is an equivalence relation.
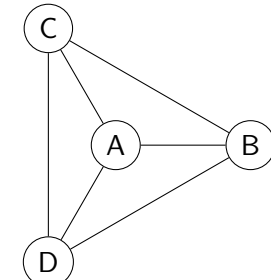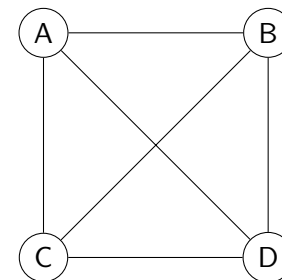
Isomorphic or Not? (1)
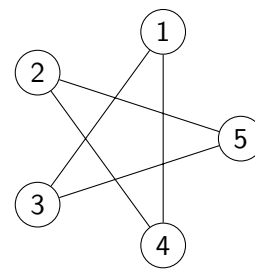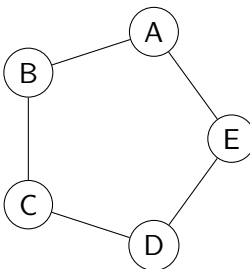
isomorphic
$\sigma = \{A \mapsto 1, B \mapsto 3, C \mapsto 5, D \mapsto 2, E \mapsto 4\}$
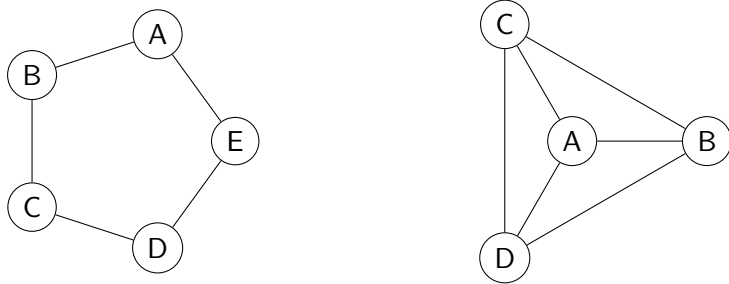
Isomorphic or Not? (2)

isomorphic
⇝ in fact, the same graph!
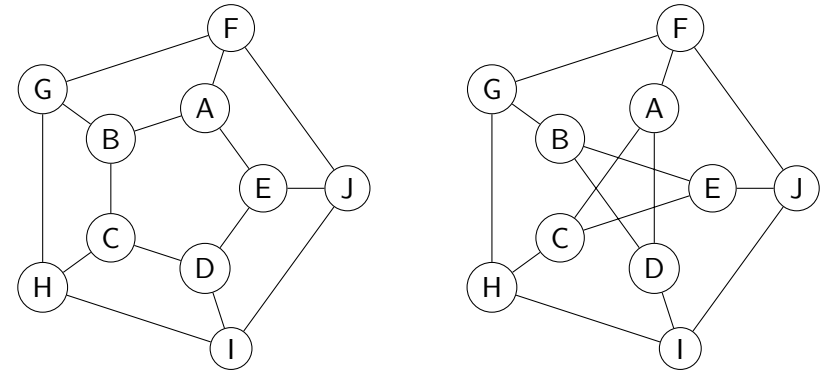$\sigma = \{A \mapsto A, B \mapsto B, C \mapsto C, D \mapsto D\}$

Isomorphic or Not? (3)

not isomorphic

There does not even exist a bijection between the vertices.

Isomorphic or Not? (4)

isomorphic or not?

Proving and Disproving Isomorphism

▶ To prove that two graphs are isomorphic, it suffices to state an isomorphism and verify that it has the required properties.

▶ To prove that two graphs are not isomorphic, we must rule out all possible bijections.
  ▶ With n vertices, there are $n!$ bijections.
  ▶ example $n = 10$: $10! = 3628800$

▶ A common disproof idea is to identify a graph invariant, i.e., a property of a graph that must be the same in isomorphic graphs, and show that it differs.
  ▶ examples: number of vertices, number of edges, maximum/minimum degree, sorted sequence of all degrees, number of connected components

Isomorphic or Not? (5)
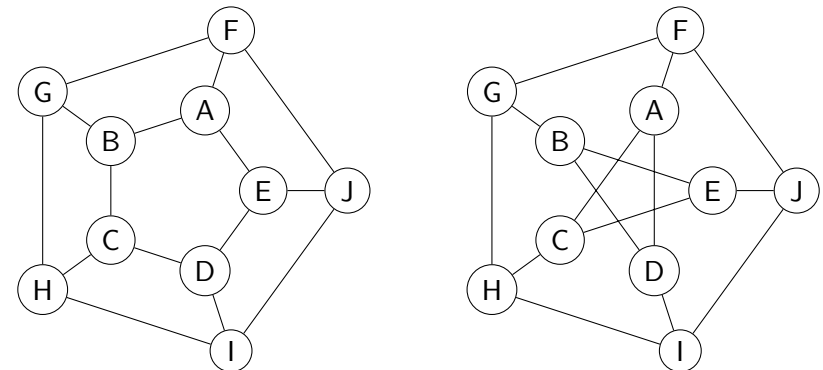
not isomorphic

▶ The left graph has cycles of length 4 (e.g., $\langle A, B, G, F, A \rangle$).

▶ The right graph does not.

▶ Having a cycle of a given length is an invariant.

Scientific Pop Culture

- ▶ Determining if two graphs are isomorphic
  is an algorithmic problem that has been famously resistant
  to studying its complexity.
- ▶ For more than 40 years, we have not known if polynomial
  algorithms exist, and we also do not know if it belongs to
  the famous class of NP-complete problems.
- ▶ In 2015, László Babai announced an algorithm
  with quasi-polynomial (worse than polynomial,
  better than exponential) runtime.

> **Further Reading**
> Martin Grohe, Pascal Schweitzer.
> The Graph Isomorphism Problem.
> Communications of the ACM 63(11):128–134, November 2020.
> `https://dl.acm.org/doi/10.1145/3372123`

Symmetries, Automorphisms and Group Theory

- ▶ An isomorphism σ between a graph G and itself
  is called an automorphism or symmetry of G.
- ▶ For every graph, its symmetries are permutations of its vertices
  that form a mathematical structure called a group:
    - ▶ the identity function is a symmetry
    - ▶ the composition of two symmetries is a symmetry
    - ▶ the inverse of a symmetry is a symmetry

Automorphism Group of a Graph
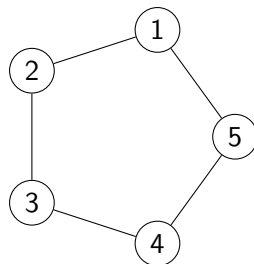
What are the symmetries?

- ▶ one example is the rotation
  $\sigma_1 = \{1 \mapsto 2, 2 \mapsto 3, 3 \mapsto 4, 4 \mapsto 5, 5 \mapsto 1\}$
- ▶ another example is the reflection
  $\sigma_2 = \{1 \mapsto 5, 2 \mapsto 4, 3 \mapsto 3, 4 \mapsto 2, 5 \mapsto 1\}$
- ▶ There are 10 symmetries in total, and they are all
  generated by (= can be composed from) σ_1 and σ_2.
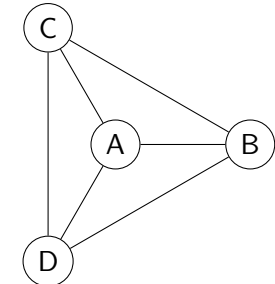

C4.3 Planarity and Minors

Planarity

- ▶ We often draw graphs as 2-dimensional pictures.
- ▶ When we do so, we usually try to draw them
  in such a way that different edges do not cross.
- ▶ This often makes the picture neater
  and the edges easier to visualize.
- ▶ A picture of a graph with no edge crossings
  is called a planar embedding.
- ▶ A graph for which a planar embedding exists is called planar.

Planar Embeddings – Example
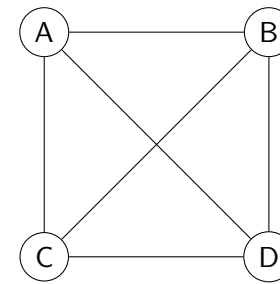
not a planar embedding   planar embedding

The complete graph over 4 vertices is planar.

Planar Graphs

Definition (planar)

A graph $G = (V, E)$ is called planar if there exists
a planar embedding of G, i.e., a picture of G
in the Euclidean plane in which no two edges intersect.

German: planar

Notes:

- ▶ We do not formally define planar embeddings,
  as this is nontrivial and not necessary for our discussion.
- ▶ In general, we may draw edges as arbitrary curves.
- ▶ However, it is possible to show that a graph
  has a planar embedding iff it has a planar embedding
  where all edges are straight lines.

Planar Graphs – Discussion

- ▶ Planar graphs arise in many practical applications.
- ▶ Many computational problems are easier for planar graphs.
  - ▶ For example, every planar graph can be coloured with at most
    4 colours (i.e., we can assign one of four colours to each vertex
    such that two neighbours always have different colours).
- ▶ For this reason, planarity is of great practical interest.
- ▶ How can we recognize that a graph is planar?
- ▶ How can we prove that a graph is not planar?

Planar Graphs – Counterexample (1)
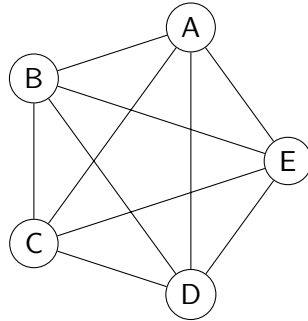
The complete graph K_5 over 5 vertices is not planar.
(We do not prove this result.)

Planar Graphs – Counterexample (2)
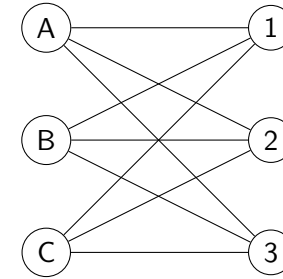
The complete bipartite graph $K_{3,3}$ over $3 + 3$ vertices is not planar.
(We do not prove this result.)

Non-Planarity in General

- ▶ The two non-planar graphs K_5 and $K_{3,3}$ are special:
  they are the smallest non-planar graphs.
- ▶ In fact, something much more powerful holds:
  a graph is planar iff it does not contain K_5 or $K_{3,3}$.
- ▶ The notion of containment we need here is related
  to the notion of subgraphs that we introduced,
 but a bit more complex. We will discuss it next.

Edge Contraction

We say that $G' = (V', E')$ can be obtained from graph $G = (V, E)$
by contracting the edge $\{u, v\} \in E$ if

- ▶ $V' = (V \setminus \{u, v\}) \cup \{uv\}$, where $uv \notin V$ is a new vertex
- ▶ $E' = \{e \in E \mid e \cap \{u, v\} = \emptyset\} \cup$
  $\{\{uv, w\} \mid w \in V \setminus \{u, v\}, \{u, w\} \in E \text{ or } \{v, w\} \in E\}$.

In words, we combine the vertices u and v
(which must be connected by an edge) into a single vertex uv.

The neighbours of uv are the union of the neighbours of u
and the neighbours of v (excluding u and v themselves).

Edge Contraction – Example
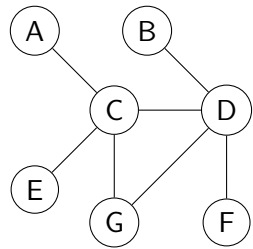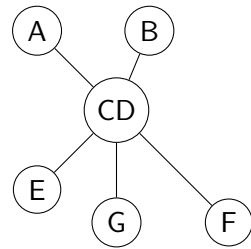
graph (V, E) after contracting $\{C, D\}$

Minor

> ### Definition (minor)
> We say that a graph G' is a minor of a graph G
> if it can be obtained from G through a sequence
> of transformations of the following kind:
> 1. remove a vertex (of degree 0) from the graph
> 2. remove an edge from the graph
> 3. contract an edge in the graph

German: Minor (plural: Minoren)

Notes:

- ▶ If we only allowed the first two transformations,
  we would obtain the regular subgraph relationship.
- ▶ It follows that every subgraph is a minor,
  but the opposite is not true in general.

Wagner's Theorem

> ### Theorem (Wagner's Theorem)
> *A graph is planar iff it does not contain K_5 or $K_{3,3}$ as a minor.*

German: Satz von Wagner

Note: There exist linear algorithms for testing planarity.

Minor-Hereditary Properties

- ▶ Being planar is what is called a minor-hereditary property:
  if G is planar, then all its minors are also planar.
- ▶ There exist many other important such properties.
- ▶ One example is acyclicity.

How could one prove that a property is minor-hereditary?

The Graph Minor Theorem

> **Theorem (Graph minor theorem)**
>
> *Let Π be a minor-hereditary property of graphs.*
>
> *Then there exists a finite set of* forbidden minors *$F(\Pi)$*
> *such that the following result holds:*
>
> *A graph has property Π iff it does not have any graph*
> *from $F(\Pi)$ as a minor.*

German: Minorentheorem

Examples:

- the forbidden minors for planarity are K_5 and $K_{3,3}$
- the (only) forbidden minor for acyclicity is K_3,
  the complete graph with 3 vertices (a.k.a. the 3-cycle graph)

Remarks on the Graph Minor Theorem (1)

- The graph minor theorem is also known as the
  Robertson-Seymour theorem.
- It was proved by Robertson and Seymour in a series
  of 20 papers between 1983–2004, totalling 500+ pages.
- It is one of the most important results in graph theory.

Remarks on the Graph Minor Theorem (2)

- In principle, for every fixed graph H, we can test if H is
  a minor of a graph G in polynomial time in the size of G.
- This implies that every minor-hereditary property
  can be tested in polynomial time.
- However, the constant factors involved in the known general
  algorithms for testing minors (which depend on $|H|$) are so
  astronomically huge as to make them infeasible in practice.