

# Discrete Mathematics in Computer Science

## C1. Introduction to Graphs

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## C1.1 Graphs and Directed Graphs

## C1.2 Induced Graphs and Degree Lemma

## C1.1 Graphs and Directed Graphs

## Graphs

**Graphs** (of various kinds) are ubiquitous in Computer Science and its applications.

Some examples:

- ▶ Boolean circuits in hardware design
- ▶ control flow graphs in compilers
- ▶ pathfinding in video games
- ▶ computer networks
- ▶ neural networks
- ▶ social networks

## Graph Theory

- ▶ **Graph theory** was founded in 1736 by Leonhard Euler's study of the **Seven Bridges of Königsberg** problem.
- ▶ It remains one of the main areas of discrete mathematics to this day.

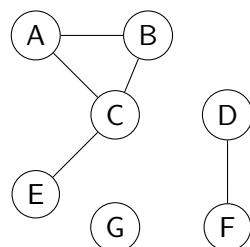
More on Euler and the Seven Bridges of Königsberg:



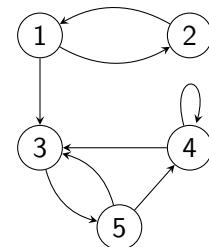
- ▶ The Seven Bridges of Königsberg – Numberphile.  
<https://youtu.be/W18FDEA1jRQ>

## Graphs and Directed Graphs – Pictorially

often described pictorially:



graph  $(V, E)$



directed graph  $(N, A)$

- ▶  $V = \{A, B, C, D, E, F, G\}$
- ▶  $E = \{\{A, B\}, \{A, C\}, \{B, C\}, \{C, E\}, \{D, F\}\}$

- ▶  $N = \{1, 2, 3, 4, 5\}$
- ▶  $A = \{(1, 2), (1, 3), (2, 1), (3, 5), (4, 3), (4, 4), (5, 3), (5, 4)\}$

## Graphs and Directed Graphs – Definitions

### Definition (Graph)

A **graph** (also: **undirected graph**) is a pair  $G = (V, E)$ , where

- ▶  $V$  is a finite set called the set of **vertices**, and
- ▶  $E \subseteq \{\{u, v\} \subseteq V \mid u \neq v\}$  is called the set of **edges**.

German: Graph, ungerichtet Graph, Knoten, Kanten

### Definition (Directed Graph)

A **directed graph** (also: **digraph**) is a pair  $G = (N, A)$ , where

- ▶  $N$  is a finite set called the set of **nodes**, and
- ▶  $A \subseteq N \times N$  is called the set of **arcs**.

German: gerichteter Graph, Digraph, Knoten, Kanten/Pfeile

## Relationship to Relations

graphs vs. directed graphs:

- ▶ edges are **sets** of two elements, arcs are **pairs**
- ▶ arcs can be **self-loops**  $(v, v)$ ; edges cannot (why not?)

(di-)graphs vs. relations:

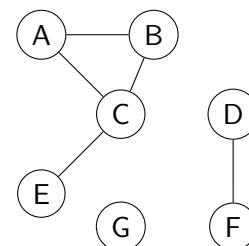
- ▶ A directed graph  $(N, A)$  is essentially identical to (= contains the same information as) an **arbitrary relation**  $R_A$  over the finite set  $N$ :  
 $u R_A v$  iff  $(u, v) \in A$
- ▶ A graph  $(V, E)$  is essentially identical to an **irreflexive symmetric** relation  $R_E$  over the finite set  $V$ :  
 $u R_E v$  iff  $\{u, v\} \in E$

## Other Kinds of Graphs

many variations exist, for example:

- ▶ self-loops may be allowed in edges ("non-simple" graphs)
- ▶ labeled graphs: additional information associated with vertices and/or edges
- ▶ weighted graphs: numbers associated with edges
- ▶ multigraphs: multiple edges between same vertices allowed
- ▶ mixed graphs: both edges and arcs allowed
- ▶ hypergraphs: edges can involve more than 2 vertices
- ▶ infinite graphs: may have infinitely many vertices/edges

## Graph Terminology – Examples



endpoints, incident, adjacent, neighbours, degree

## Graph Terminology

### Definition (Graph Terminology)

Let  $(V, E)$  be a graph.

- ▶  $u$  and  $v$  are the **endpoints** of the edge  $\{u, v\} \in E$
- ▶  $u$  and  $v$  are **incident** to the edge  $\{u, v\} \in E$
- ▶  $u$  and  $v$  are **adjacent** if  $\{u, v\} \in E$
- ▶ the vertices adjacent with  $v \in V$  are its **neighbours**  $\text{neigh}(v)$ :  
 $\text{neigh}(v) = \{w \in V \mid \{v, w\} \in E\}$
- ▶ the number of neighbours of  $v \in V$  is its **degree**  $\text{deg}(v)$ :  
 $\text{deg}(v) = |\text{neigh}(v)|$

German: Endknoten, inzident, adjazent/benachbart, Nachbarn, Grad

## Directed Graph Terminology

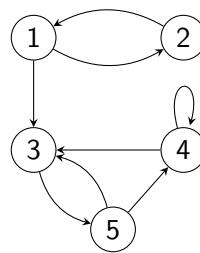
### Definition (Directed Graph Terminology)

Let  $(N, A)$  be a directed graph.

- ▶  $u$  is the **tail** and  $v$  is the **head** of the arc  $(u, v) \in A$ ;  
we say  $(u, v)$  is an arc **from**  $u$  **to**  $v$
- ▶  $u$  and  $v$  are **incident** to the arc  $(u, v) \in A$
- ▶  $u$  is a **predecessor** of  $v$  and  $v$  is a **successor** of  $u$  if  $(u, v) \in A$
- ▶ the predecessors and successor of  $v$  are written as  
 $\text{pred}(v) = \{u \in N \mid (u, v) \in A\}$  and  
 $\text{succ}(v) = \{w \in N \mid (v, w) \in A\}$
- ▶ the number of predecessors/successors of  $v \in N$  is its **indegree/outdegree**:  $\text{indeg}(v) = |\text{pred}(v)|$ ,  
 $\text{outdeg}(v) = |\text{succ}(v)|$

German: Fuss, Kopf, inzident, Vorgänger, Nachfolger, Eingangs-/Ausgangsgrad

## Directed Graph Terminology – Examples



head, tail, predecessors, successors, indegree, outdegree

## C1.2 Induced Graphs and Degree Lemma

### Induced Graph of a Directed Graph

#### Definition (undirected graph induced by a directed graph)

Let  $G = (N, A)$  be a directed graph.

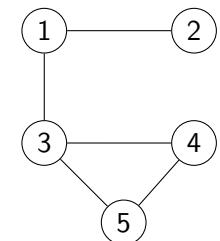
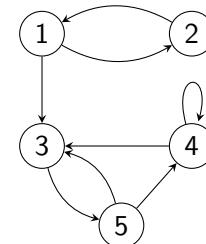
The (undirected) **graph induced by  $G$**  is the graph  $(N, E)$  with  $E = \{ \{u, v\} \mid (u, v) \in A, u \neq v \}$ .

German: induziert

Questions:

- ▶ Why require  $u \neq v$ ?
- ▶ If  $|N| = n$  and  $|A| = m$ , how many vertices and edges does the induced graph have?
- ▶ How does the answer change if  $G$  has no self-loops?

### Induced Graph of a Directed Graph – Example



- ▶  $N = \{1, 2, 3, 4, 5\}$
- ▶  $A = \{(1, 2), (1, 3), (2, 1), (3, 5), (4, 3), (4, 4), (5, 3), (5, 4)\}$
- ▶  $V = \{1, 2, 3, 4, 5\}$
- ▶  $E = \{\{1, 2\}, \{1, 3\}, \{3, 4\}, \{3, 5\}, \{4, 5\}\}$

## Degree Lemma

### Lemma (degree lemma for directed graphs)

Let  $(N, A)$  be a directed graph.

Then  $\sum_{v \in N} \text{indeg}(v) = \sum_{v \in N} \text{outdeg}(v) = |A|$ .

**Intuitively:** every arc contributes 1 to the indegree of one node and 1 to the outdegree of one node.

### Lemma (degree lemma for undirected graphs)

Let  $(V, E)$  be a graph.

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

**Intuitively:** every edge contributes 1 to the degree of two vertices.

### Corollary

Every graph has an even number of vertices with odd degree.

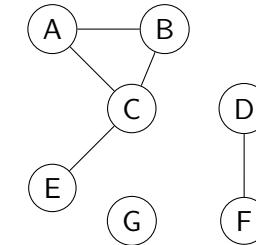
## Degree Lemma – Proof (1)

### Proof of degree lemma for directed graphs.

$$\begin{aligned}
 \sum_{v \in N} \text{indeg}(v) &= \sum_{v \in N} |\text{pred}(v)| \\
 &= \sum_{v \in N} |\{u \mid u \in N, (u, v) \in A\}| \\
 &= \sum_{v \in N} |\{(u, v) \mid u \in N, (u, v) \in A\}| \\
 &= \left| \bigcup_{v \in N} \{(u, v) \mid u \in N, (u, v) \in A\} \right| \\
 &= |\{(u, v) \mid u \in N, v \in N, (u, v) \in A\}| \\
 &= |A|.
 \end{aligned}$$

$\sum_{v \in N} \text{outdeg}(v) = |A|$  is analogous. □

## Degree Lemma – Example



$$\begin{aligned}
 \sum_{v \in V} \deg(v) &= \deg(A) + \deg(B) + \deg(C) + \deg(D) + \deg(E) + \deg(F) + \deg(G) \\
 &= 2 + 2 + 3 + 1 + 1 + 1 + 0 \\
 &= 10 = 2 \cdot 5 = 2|E|
 \end{aligned}$$

4 vertices with odd degree

## Degree Lemma – Proof (2)

We omit the proof for undirected graphs, which can be conducted similarly.

One possible proof strategy that reuses the result we proved:

- ▶ Define **directed** graph  $(V, A)$  from the graph  $(V, E)$  by orienting each edge into an arc arbitrarily.
- ▶ Observe  $\deg(v) = \text{indeg}(v) + \text{outdeg}(v)$ , where  $\deg$  refers to the graph and  $\text{indeg}/\text{outdeg}$  to the directed graph.
- ▶ Use the degree lemma for directed graphs:
 
$$\begin{aligned}
 \sum_{v \in V} \deg(v) &= \sum_{v \in V} (\text{indeg}(v) + \text{outdeg}(v)) = \\
 &= \sum_{v \in V} \text{indeg}(v) + \sum_{v \in V} \text{outdeg}(v) = |A| + |A| = 2|A| = 2|E|
 \end{aligned}$$