COMP9020

Foundations of Computer Science
Term 3, 2024

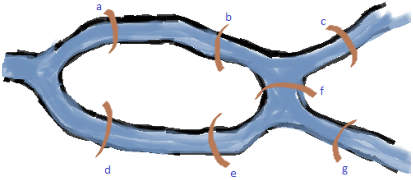
Lecture 16-17: Graph Theory

Outline

Outline

Graph theory: Historical Motivation

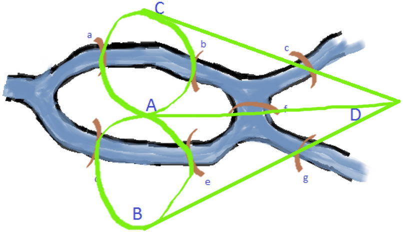
Bridges of Königsberg problem



Can you find a route which crosses each bridge exactly once?

Graph theory: Historical Motivation

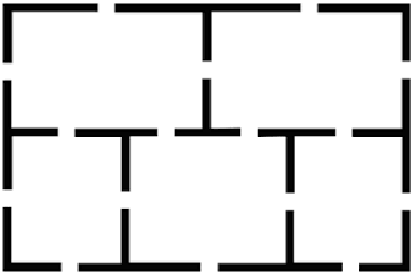
Bridges of Königsberg problem



Can you find a route which crosses each bridge exactly once?

Graph theory: Motivation

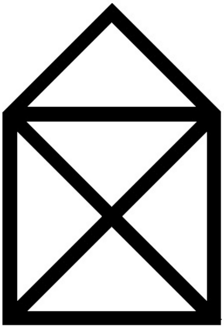
Five rooms problem



Can you find a route which passes through each door exactly once?

Graph theory: Motivation

Crossed house problem



Can you draw this without taking your pen off the paper?

Graph theory: Motivation

Three utilities problem

Can you connect all utilities to all houses without crossing connections?

Graph theory: Motivation

The following table describes several subjects and the students taking them:

Potions	**Charms**	**Herbology**	**Astronomy**	**Transfiguration**
Harry	Ron	Harry	Hermione	Hermione
Ron	Luna	George	Neville	Fred
Malfoy	Ginny	Neville	Seamus	Luna

How many examination timeslots are needed so that no student has two (or more) exams at the same time?

Graphs in Computer Science

Applications of graphs in Computer Science are abundant, e.g.

- route planning in navigation systems, robotics
- optimisation, e.g. timetables, utilisation of network structures, bandwidth allocation
- compilers using "graph colouring" to assign registers to program variables
- circuit layout (Untangle game)
- determining the significance of a web page (Google's pagerank algorithm)
- modelling the spread of a virus in a computer network or news in social network

Outline

Graphs

Terminology (the most common; there are many variants):

Graph — pair (V, E) where V – set of vertices (or nodes)
E – set of edges

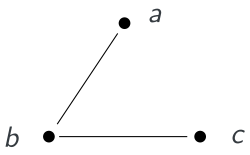
Undirected graph: Every edge $e \in E$ is a two-element set of vertices, i.e. $e = \{x, y\} \subseteq V$ where $x \neq y$

Directed graph: Every edge (or arc) $e \in E$ is an ordered pair of vertices, i.e. $e = (x, y) \in V \times V$, note x may equal y.

Graph representations

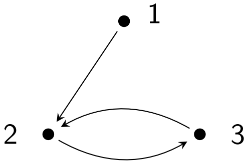
Graph:
$V = \{a, b, c\}$
$E = \{\{a, b\}, \{b, c\}\}$

Pictorially:



Directed graph:
$V = \{1, 2, 3\}$
$E = \{(1, 2), (2, 3), (3, 2)\}$

Pictorially:



Graph representations

Graph:
$V = \{a, b, c\}$
$E = \{\{a, b\}, \{b, c\}\}$

Adjacency matrix:

$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

Directed graph:
$V = \{1, 2, 3\}$
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Graph representations

Graph:
$V = \{a, b, c\}$
$E = \{\{a, b\}, \{b, c\}\}$

Adjacency list:

$$\begin{array}{ll} a: & b \\ b: & a, c \\ c: & b \end{array}$$

Directed graph:
$V = \{1, 2, 3\}$
$E = \{(1, 2), (2, 3), (3, 2)\}$

Adjacency list:

$$\begin{array}{ll} 1: & 2 \\ 2: & 3 \\ 3: & 2 \end{array}$$

Graph representations

Graph:
$V = \{a, b, c\}$
$E = \{\{a, b\}, \{b, c\}\}$

Incidence matrix (vertices=rows, edges=columns):

$$\begin{pmatrix} 1 & 0 \\ 1 & 1 \\ 0 & 1 \end{pmatrix}$$

Directed graph:
$V = \{1, 2, 3\}$
$E = \{(1, 2), (2, 3), (3, 2)\}$

Incidence matrix (vertices=rows, edges=columns):

$$\begin{pmatrix} -1 & 0 & 0 \\ 1 & -1 & 1 \\ 0 & 1 & -1 \end{pmatrix}$$

Paths

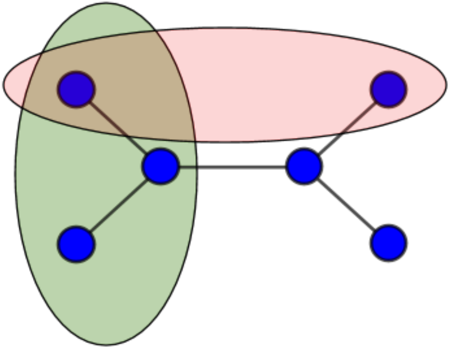
- A **(directed) walk** in a (directed) graph (V, E) is a sequence of edges that link up

$$v_0 \xrightarrow{\{v_0,v_1\}} v_1 \xrightarrow{\{v_1,v_2\}} \ldots \xrightarrow{\{v_{n-1},v_n\}} v_n$$

  where $e_i = \{v_{i-1}, v_i\} \in E$ (or $e_i = (v_{i-1}, v_i) \in E$)
- A **trail** is a walk where no edge is repeated.
  $(\forall i, j \in [n], e_i \neq e_j)$
- A **path** is a walk where no vertex is repeated
  $(\forall i, j \in \{0, \ldots n-1\}, v_i \neq v_j)$
- **length** of a walk is the number of edges: n
  neither the vertices nor the edges have to be all different
- Subpath\subwalk of length r: $(e_m, e_{m+1}, \ldots, e_{m+r-1})$
- Path of length 0: single vertex v_0

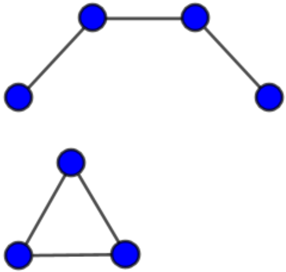
Connectedness

- **Connected set/graph (undirected)** — each pair of vertices joined by a path
- **Strongly connected set/graph (directed)** — each pair of vertices joined by a directed path in both directions



Connectedness

- Given a graph $G = (V, E)$, we call a set of vertices $U \subseteq V$ a **connected component** of G, if every pair of vertices $u, v \in U$ is connected by some path, and U is maximal with this property.



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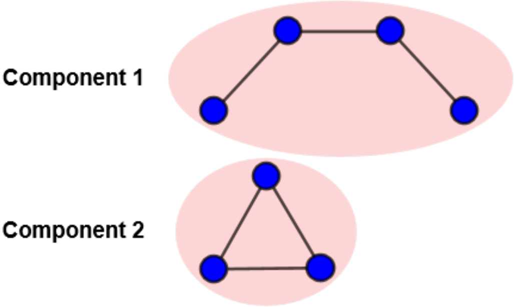


Vertex Degrees (Undirected graphs)

- **Degree** of a vertex

$$\mathrm{deg}(v) = |\{ w \in V : \{v, w\} \in E \}|$$

  i.e., the number of edges attached to the vertex

- **Regular graph** — all degrees are equal
- **Degree sequence** $D_0, D_1, D_2, \ldots, D_k$ of graph $G = (V, E)$, where D_i = no. of vertices of degree i

Question

What is $D_0 + D_1 + \ldots + D_k$?

Fact

$\sum_{v \in V} \mathrm{deg}(v) = 2 \cdot |E|$; *so the sum of vertex degrees is always even.*

Corollary

There is an even number of vertices of odd degree.

Vertex Degrees (Directed graphs)

- **Out-degree** of a vertex

$$outdeg(v) = |\{ w \in V : (v, w) \in E \}|$$

i.e., the number of edges going out of the vertex

- **In-degree** of a vertex

$$indeg(v) = |\{ w \in V : (w, v) \in E \}|$$

i.e., the number of edges going in to the vertex

Fact

$\sum_{v \in V} outdeg(v) = \sum_{v \in V} indeg(v) = |E|$.

Exercises

Exercises

$\boxed{\text{RW: 6.1.13(a)}}$ Draw a connected, regular graph on four vertices, each of degree 2

$\boxed{\text{RW: 6.1.13(b)}}$ Draw a connected, regular graph on four vertices, each of degree 3

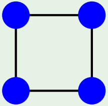
$\boxed{\text{RW: 6.1.13(c)}}$ Draw a connected, regular graph on five vertices, each of degree 3

$\boxed{\text{RW: 6.1.14(a)}}$ Graph with 3 vertices and 3 edges

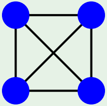
$\boxed{\text{RW: 6.1.14(b)}}$ Two graphs each with 4 vertices and 4 edges

Exercises

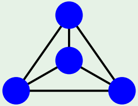
$\boxed{\text{RW: 6.1.13}}$ Connected, regular graphs on four vertices



(a)



(b)



(b)

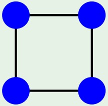
none

(c)

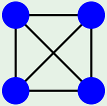
Exercises

Exercises

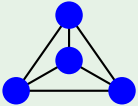
$\boxed{\text{RW: 6.1.13}}$ Connected, regular graphs on four vertices



(a)



(b)

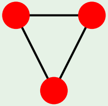


(b)

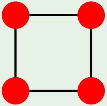
none

(c)

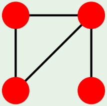
$\boxed{\text{RW: 6.1.14}}$ Graphs with 3 vertices and 3 edges must have a *cycle*



(a) the only one



(b)



(b)

Exercises

Take Notice

We use the notation
$n = v(G) = |V|$ *for the no. of vertices of graph* $G = (V, E)$
$m = e(G) = |E|$ *for the no. of edges of graph* $G = (V, E)$

Exercises

$\boxed{\text{RW: 6.1.20(a)}}$ Graph with $e(G) = 21$ edges has a degree sequence
$D_0 = 0, D_1 = 7, D_2 = 3, D_3 = 7, D_4 = ?$
Find $v(G)$

$\boxed{\text{RW: 6.1.20(b)}}$ How would your answer change, if at all, when
$D_0 = 6$?

Exercises

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Find $v(G)$

$\sum_v \deg(v) = 2|E|$; here
$7 \cdot 1 + 3 \cdot 2 + 7 \cdot 3 + x \cdot 4 = 2 \cdot 21$ giving $x = 2$, thus
$v(G) = \sum D_i = 19$.

$\boxed{\text{RW: 6.1.20(b)}}$ How would your answer change, if at all, when $D_0 = 6$?

Exercises

Take Notice

We use the notation
$n = v(G) = |V|$ *for the no. of vertices of graph* $G = (V, E)$
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Exercises

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Find $v(G)$

$\sum_v \deg(v) = 2|E|$; here
$7 \cdot 1 + 3 \cdot 2 + 7 \cdot 3 + x \cdot 4 = 2 \cdot 21$ giving $x = 2$, thus
$v(G) = \sum D_i = 19$.

$\boxed{\text{RW: 6.1.20(b)}}$ How would your answer change, if at all, when
$D_0 = 6$?
No change to D_4; $v(G) = 25$.

Cycles

Recall walks $v_0 \xrightarrow{e_1} v_1 \xrightarrow{e_2} \ldots \xrightarrow{e_n} v_n$

- *closed walk* — $v_0 = v_n$
- **cycle** — closed walk of length 3 or more (2 or more in directed graphs) whose vertices are distinct except v_0 and v_n.
- *acyclic walk* (equivalent to path) — $v_i \neq v_j$ for *all* vertices in the path ($i \neq j$)

Take Notice

1. *$C = (e_1, \ldots, e_n)$ is a cycle iff removing any single edge leaves a path. (Show that the 'any' condition is needed!)*
2. *C is a cycle if it has the same number of edges and vertices and no proper subwalk has this property.*
   (Show that the 'subwalk' condition is needed, i.e., there are graphs G that are **not** *cycles and $|E_G| = |V_G|$; every such G must contain a cycle!)*

Trees

- **Acyclic graph** — graph that doesn't contain any cycle
- **Tree** — connected acyclic [undirected] graph
- A graph is acyclic *iff* it is a *forest* (collection of disjoint trees)

Take Notice

Graph G is a tree iff

$\Leftrightarrow$ *it is acyclic and $|V_G| = |E_G| + 1$.*
(Show how this implies that the graph is connected!)

$\Leftrightarrow$ *there is exactly one path between any two vertices.*

$\Leftrightarrow$ *G is connected, but becomes disconnected if any single edge is removed.*

$\Leftrightarrow$ *G is acyclic, but has a cycle if any single edge on already existing vertices is added.*

Trees

A tree with one vertex designated as its *root* is called a *rooted tree*.

It imposes a direction on the edges: 'away' from the root — from parent nodes to children. It also defines a *level number* (or: *depth*) of a node as its distance from the root.

Another very common notion in Computer Science is that of a *DAG* — a *directed, acyclic graph*.

Exercise (Supplementary)

Exercises

$\boxed{\text{RW: 6.7.3}}$ (Supp) Tree with n vertices, $n \geq 3$.

Always true, false or could be either?

(a) $e(T) \stackrel{?}{=} n$

(b) at least one vertex of degree exactly 2?

(c) at least two v_1, v_2 s.t. $\deg(v_1)=\deg(v_2)$

(d) exactly one path from v_1 to v_2

Exercise (Supplementary)

Exercises

$\boxed{\text{RW: 6.7.3}}$ (Supp) Tree with n vertices, $n \geq 3$.
Always true, false or could be either?

(a) $e(T) \stackrel{?}{=} n$ False

(b) at least one vertex of degree exactly 2? Could be either

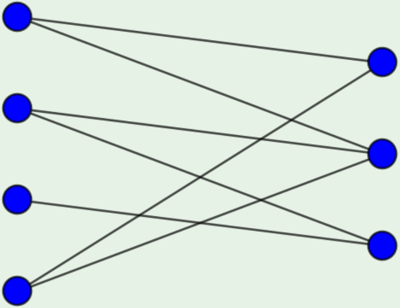
(c) at least two v_1, v_2 s.t. $\deg(v_1) = \deg(v_2)$ True

(d) exactly one path from v_1 to v_2 True (characterises a tree)

Bipartite Graphs

- Can divide the vertices into two disjoint sets, $V = V_1 \cup V_2$
- Each edge must connect a vertex from V_1 to a vertex from V_2

Example



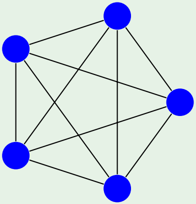
Special Graphs

- **Complete graph** K_n
  n vertices, all pairwise connected, $\frac{n(n-1)}{2}$ edges.
- **Complete bipartite graph** $K_{m,n}$
  Has $m + n$ vertices, partitioned into two (disjoint) sets, one of n, the other of m vertices.
  All vertices from different parts are connected; vertices from the same part are disconnected. No. of edges is $m \cdot n$.
- **Complete k-partite graph** $K_{m_1,\ldots,m_k}$
  Has $m_1 + \ldots + m_k$ vertices, partitioned into k disjoint sets, respectively of $m_1, m_2, \ldots$ vertices.
  No. of edges is $\sum_{i<j} m_i m_j = \frac{1}{2} \sum_{i \neq j} m_i m_j$
  - These graphs generalise the complete graphs $K_n = K_{\underbrace{1,\ldots,1}_{n}}$

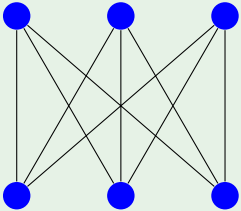
Special Graphs

Example

K_5 :



$K_{3,3}$:



Graph Isomorphisms

$\phi : G \longrightarrow H$ is a *graph isomorphism* if

(i) $\phi : V_G \longrightarrow V_H$ is a bijection

(ii) $(x, y) \in E_G$ iff $(\phi(x), \phi(y)) \in E_H$

Two graphs are called *isomorphic* if there exists (at least one) isomorphism between them.

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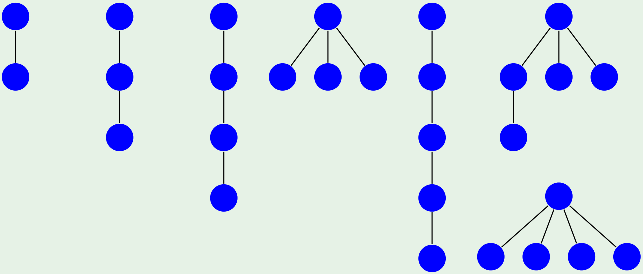
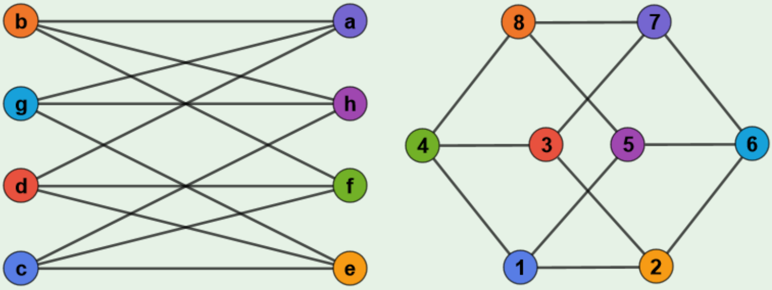
Example

All nonisomorphic trees on $2, 3, 4$ and 5 vertices.



Graph Isomorphisms

Example



Outline

Graph exploration

Often it is useful to "explore" a graph: visit vertices in some order and examine each one.

- **Search**: Explore the graph until a particular vertex is discovered.
- **Traversal**: Examine all the vertices of the graph

Graph exploration

Two common graph exploration algorithms are **Depth-first search/traversal** (DFS) and **Breadth-first search/traversal** (BFS).

Both follow the same structure:

- Examine a vertex v
- Discover new vertices (neighbours of v)
- Move to the next discovered but not yet examined vertex

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- DFS: Examine vertices by most recently discovered

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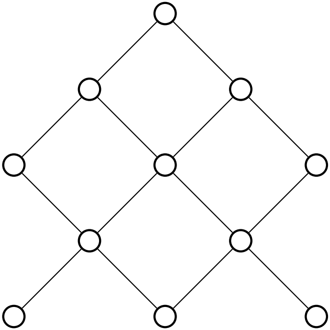
Both follow the same structure:

- Examine a vertex v
- Discover new vertices (neighbours of v)
- Move to the next discovered but not yet examined vertex

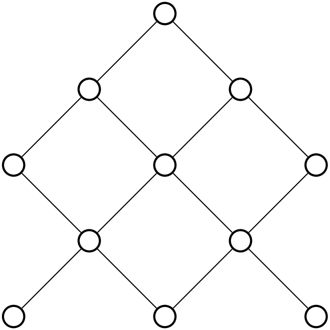
- DFS: Examine vertices by most recently discovered
- BFS: Examine vertices by least recently discovered

DFS vs BFS

DFS

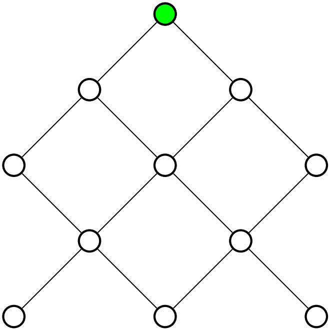


BFS

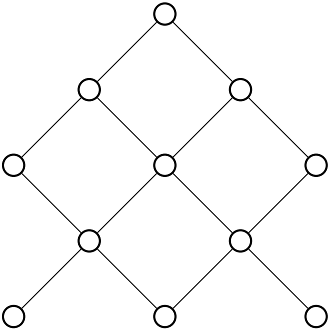


DFS vs BFS

DFS

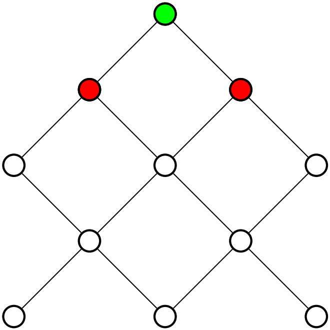


BFS

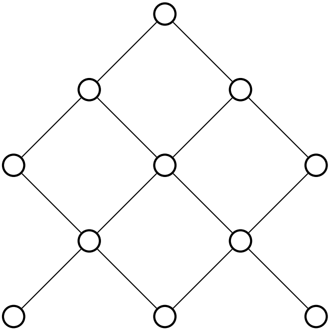


DFS vs BFS

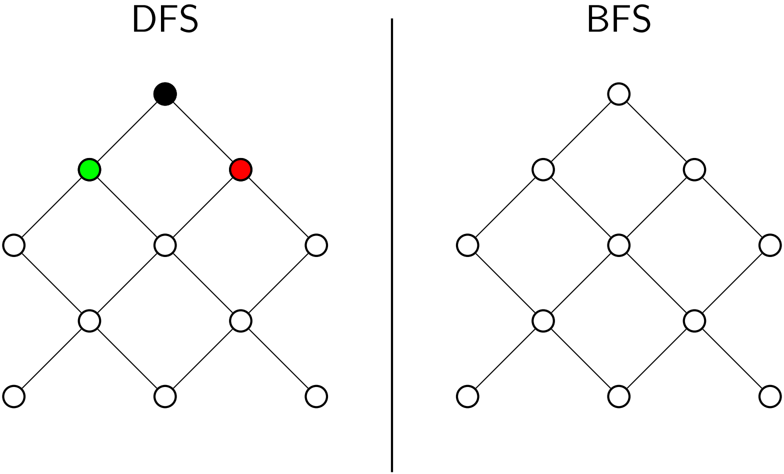
DFS



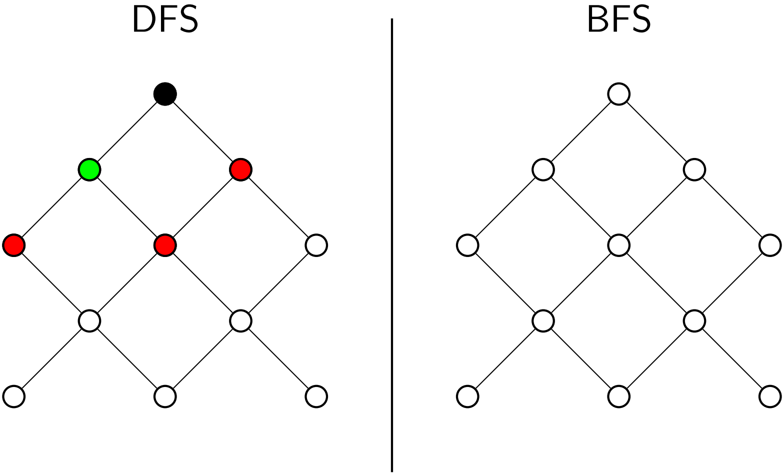
BFS



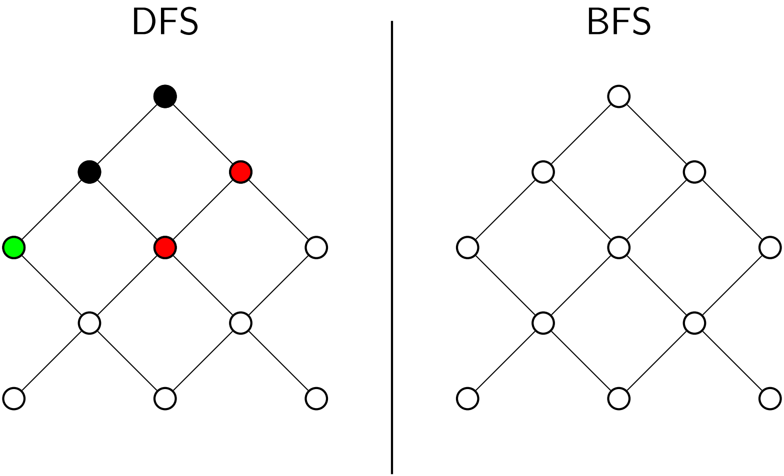
DFS vs BFS



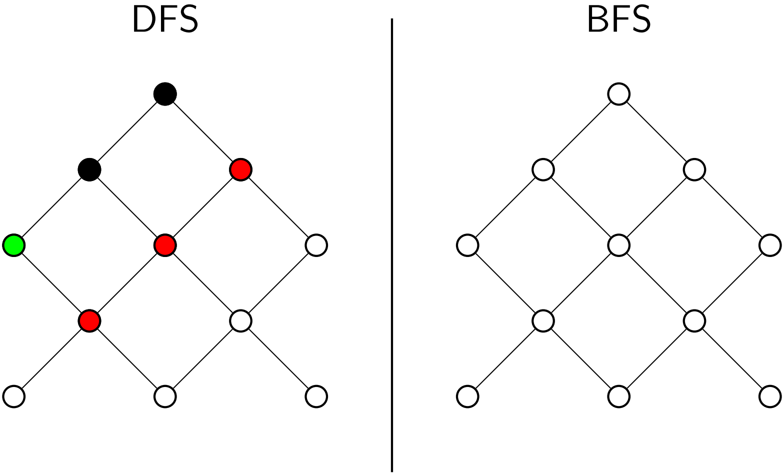
DFS vs BFS



DFS vs BFS



DFS vs BFS



DFS vs BFS

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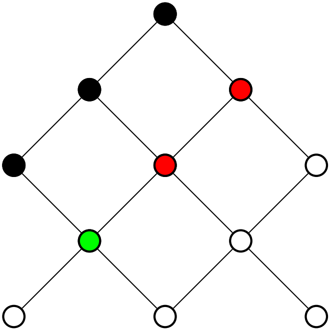

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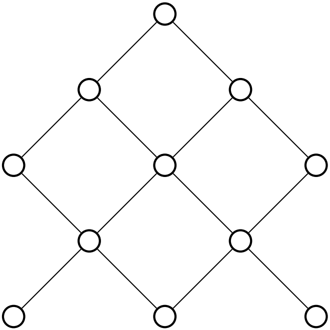

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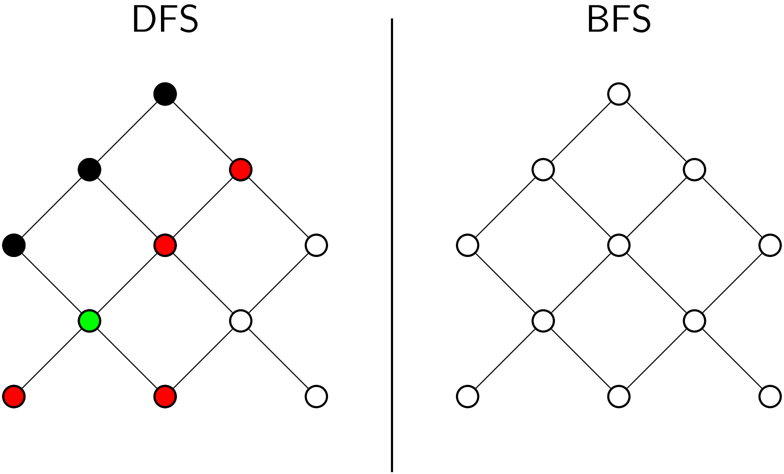

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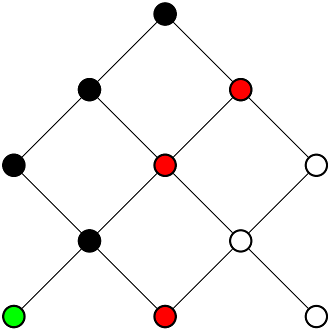

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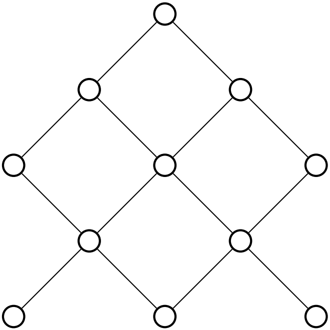

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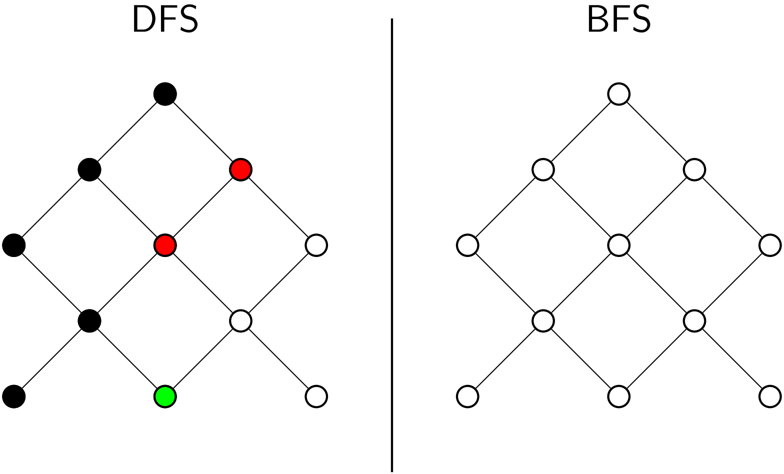

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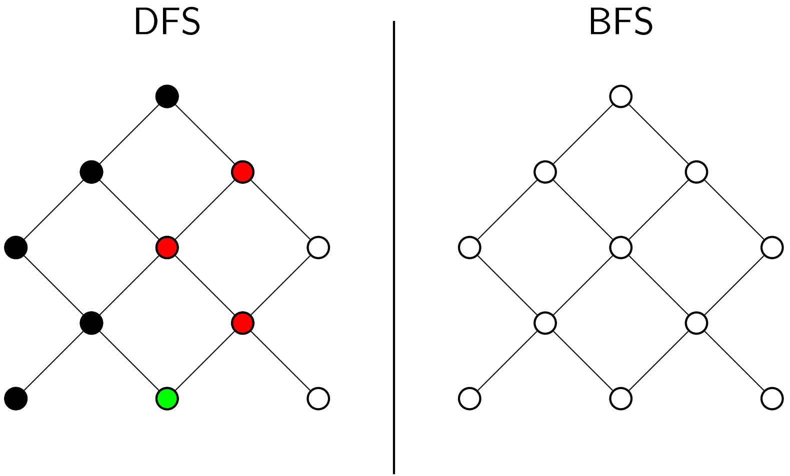

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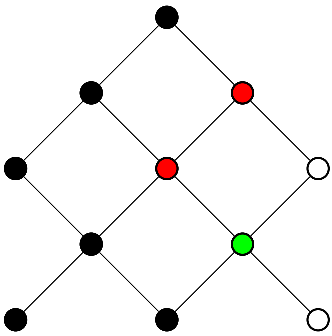

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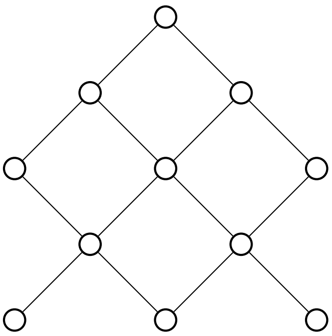

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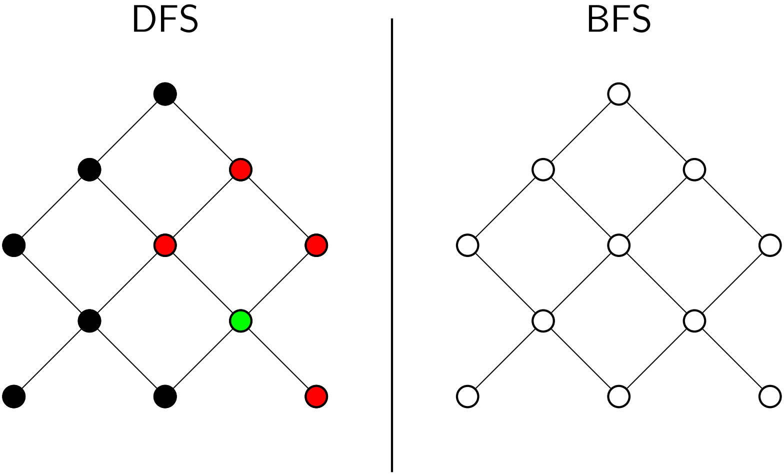

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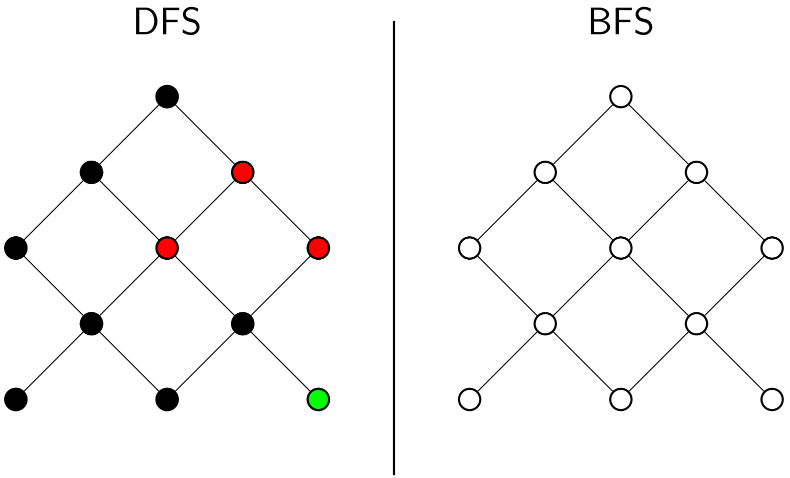

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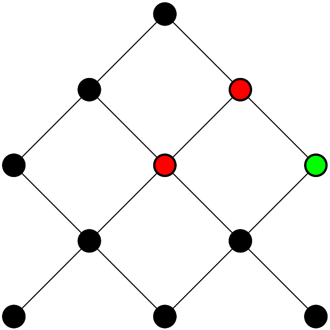

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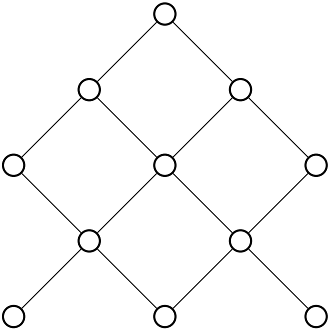

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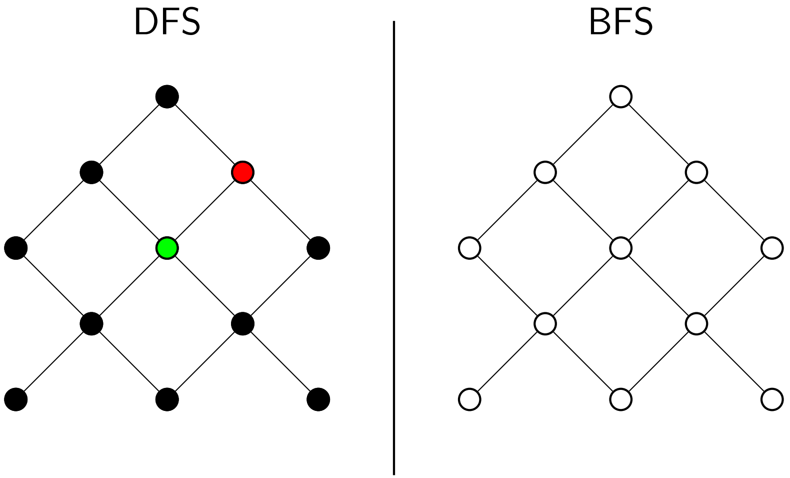

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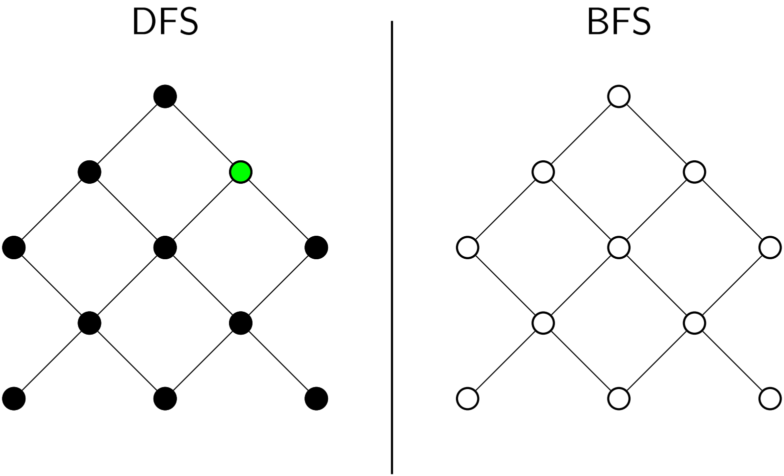

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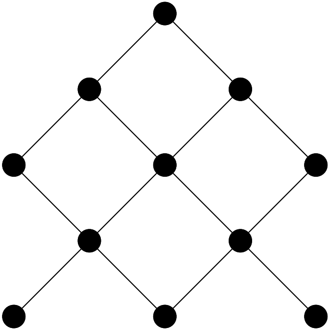

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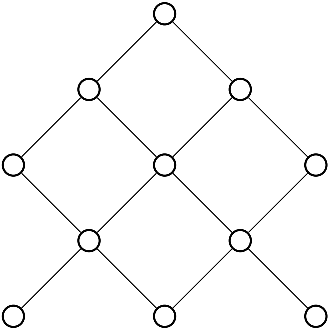

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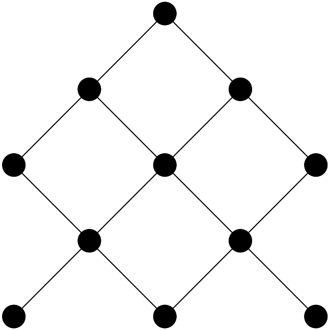

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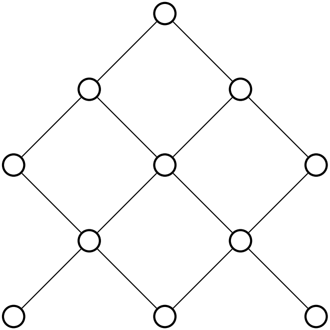

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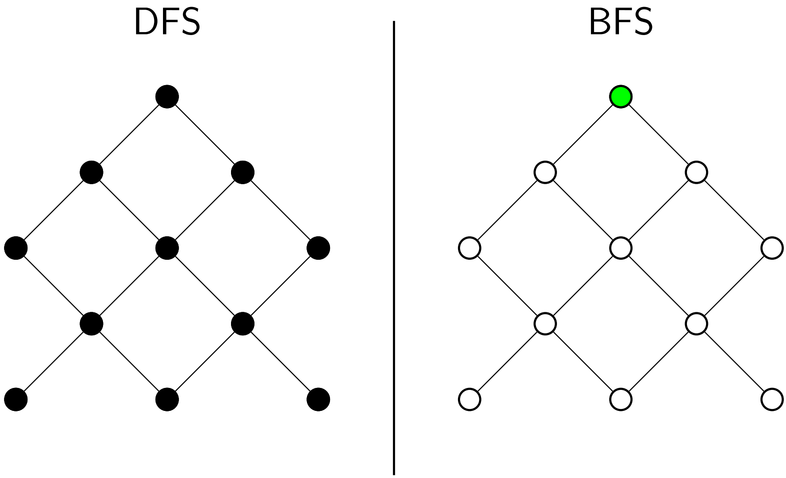

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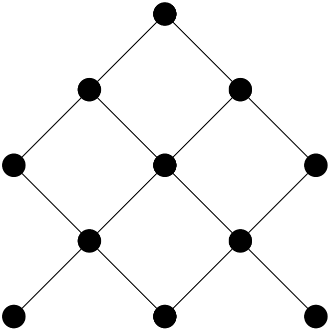

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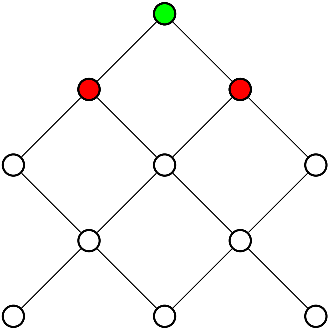

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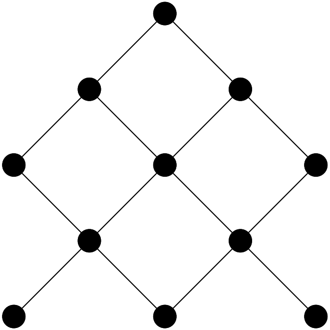

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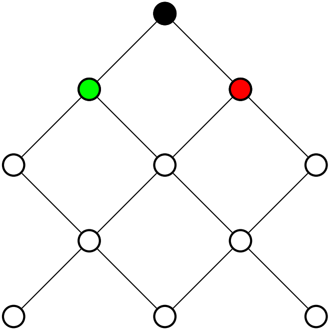

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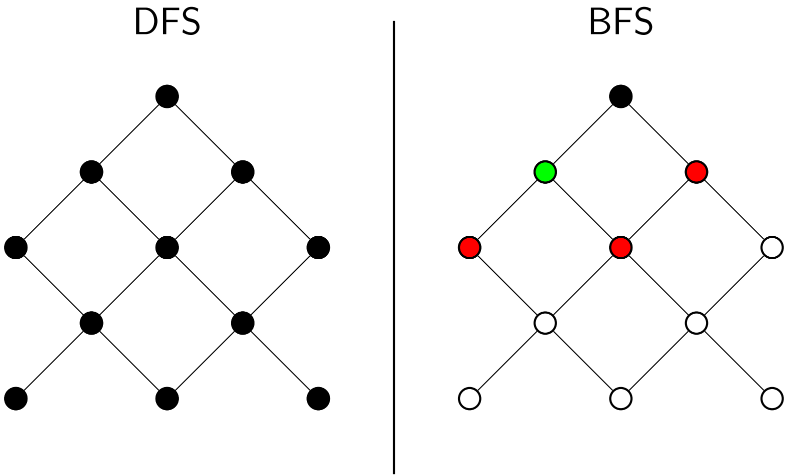

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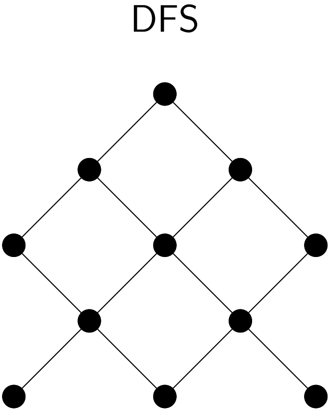

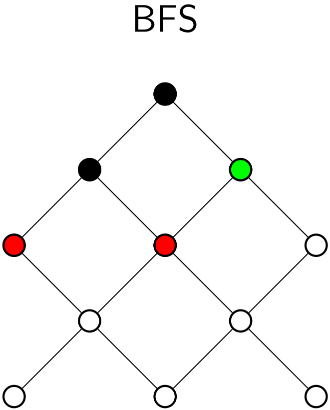

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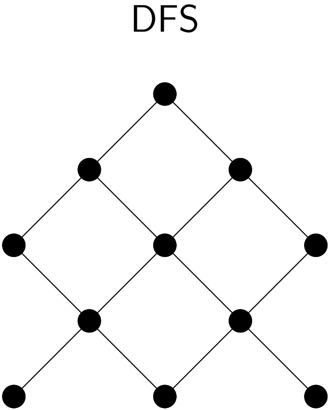

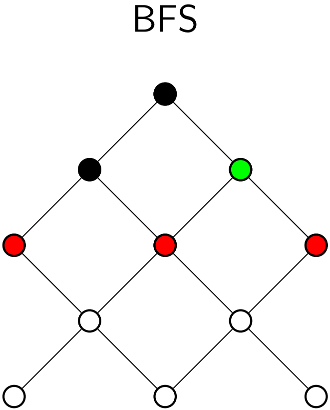

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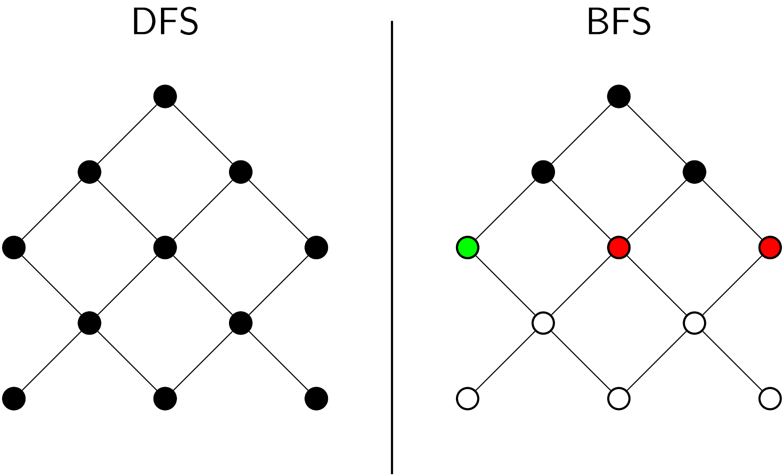

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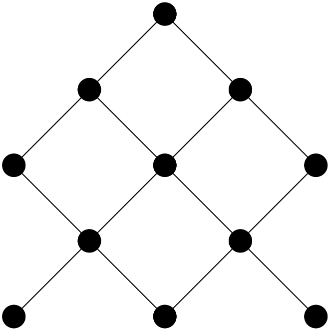

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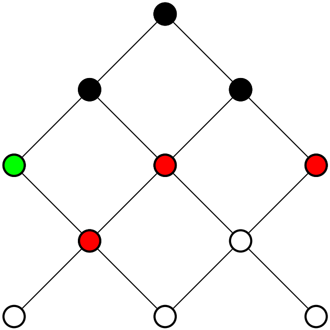

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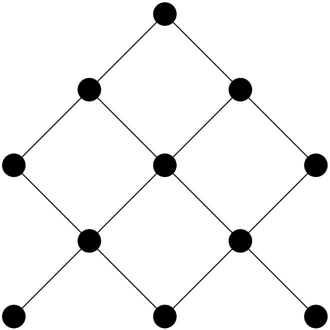

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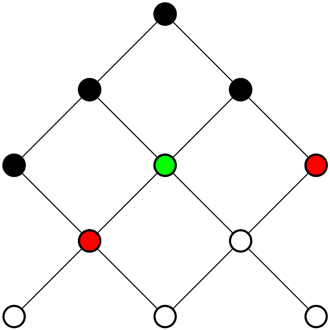

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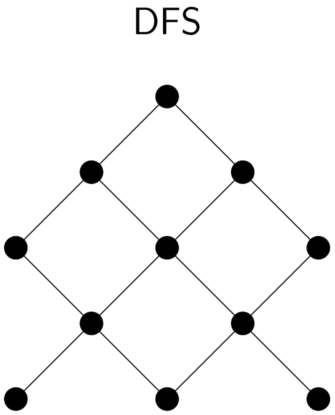

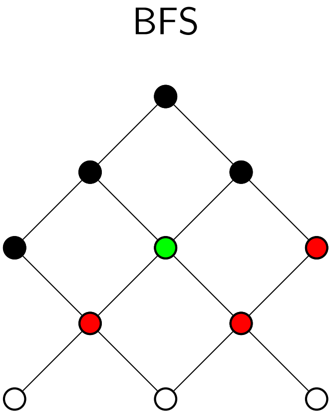

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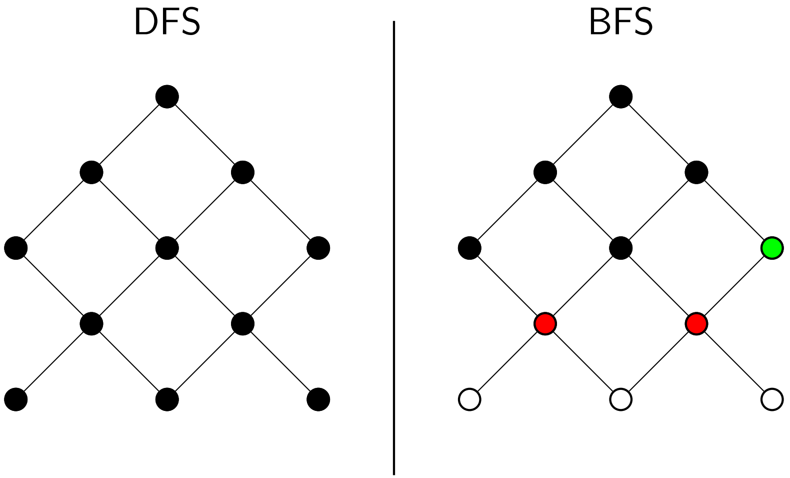

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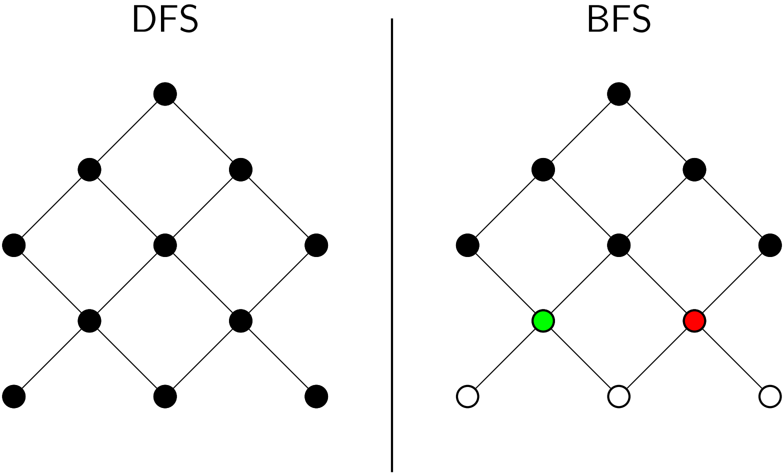

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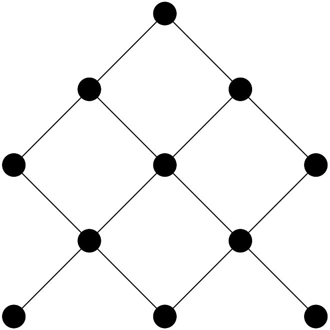

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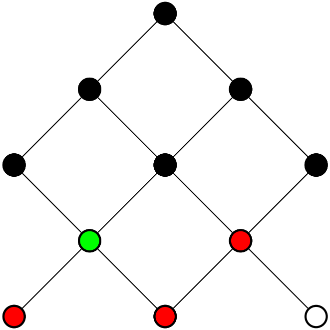

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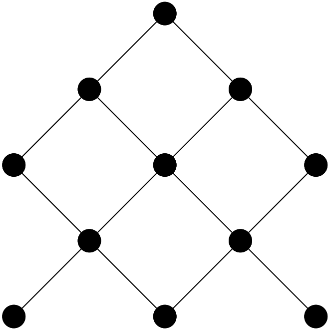

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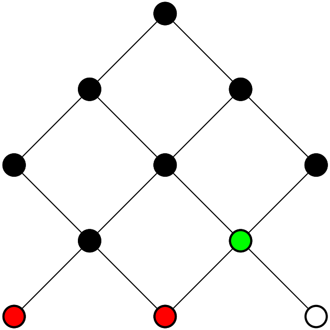

DFS vs BFS

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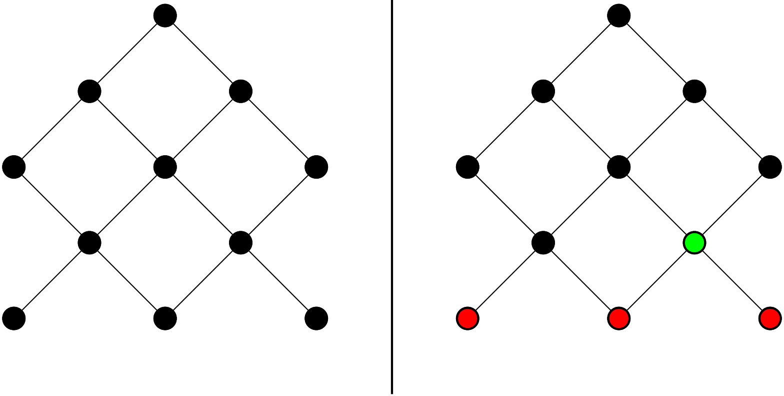

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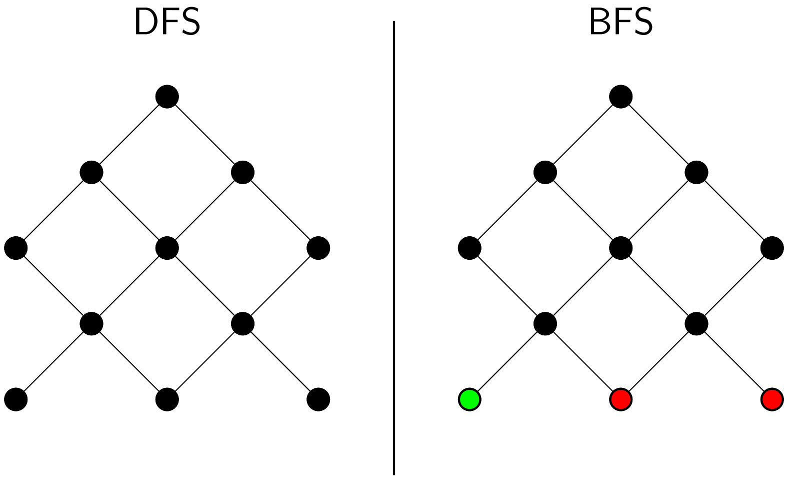

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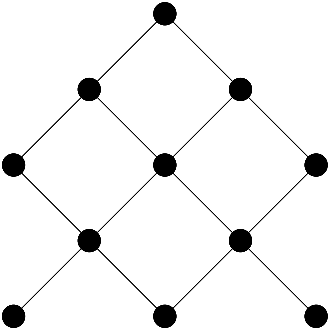

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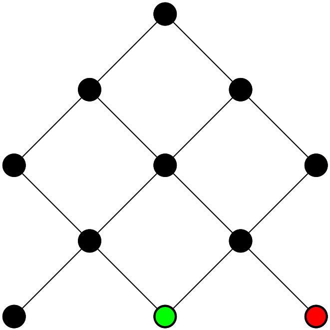

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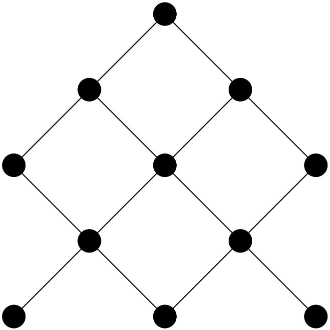

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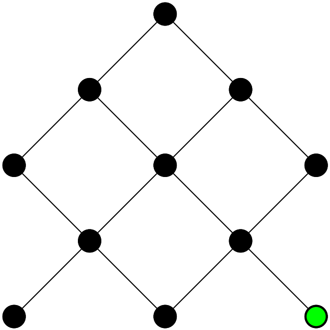

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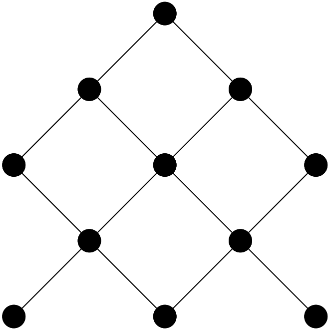

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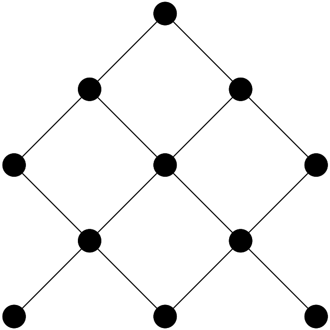


Special types of traversals

Often we are interested in traversals that have a certain property. For example:

- Eulerian traversals: Visit all the edges exactly once
- Hamiltonian traversals: Visit all the vertices exactly once

Take Notice

In any given graph, these traversals may or may not exist. Establishing the existence of such a traversal (decision problem) vs finding one if it exists (search problem) are subtly different problems.

Edge Traversal

Definition

For a graph $G = (V, E)$.

- **Euler trail** — trail containing every edge in E exactly once
- **Euler circuit** — closed Euler trail

Characterisations

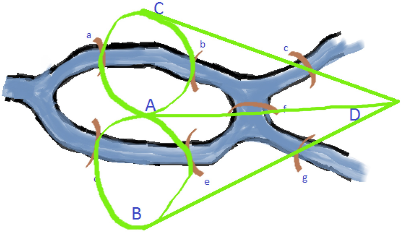
- Suppose G is connected. Then G has an Euler circuit iff $\deg(v)$ is even for all $v \in V$.
- Suppose G is connected. Then G has an Euler trail iff either it has an Euler circuit or it has exactly two vertices of odd degree.

Take Notice

- *These characterisations apply to graphs with loops as well*
- *For directed graphs the condition for existence of an Euler circuit is* $indeg(v) = outdeg(v)$ *for all* $v \in V$

Bridges of Köngisberg

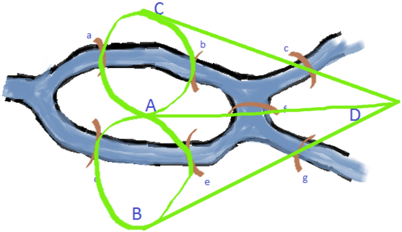
Bridges of Königsberg problem



Q. Can you find a route which crosses each bridge exactly once?

Bridges of Köngisberg

Bridges of Königsberg problem

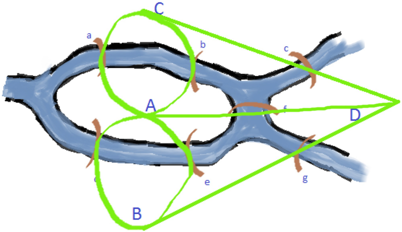


Q. Can you find a route which crosses each bridge exactly once?

Q. In other words, does this multigraph have an Euler trail?

Bridges of Köngisberg

Bridges of Königsberg problem

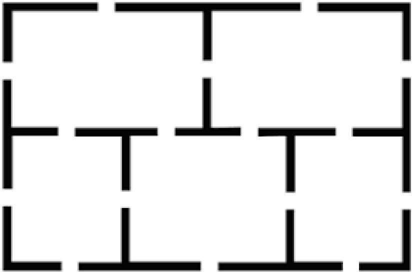


Q. Can you find a route which crosses each bridge exactly once?

Q. In other words, does this multigraph have an Euler trail?

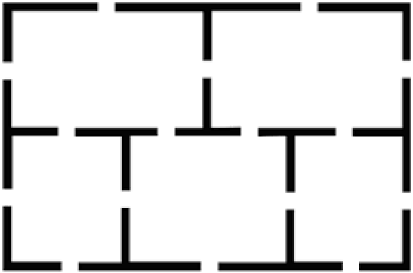
A. No.

Five rooms problem



Q. Can you find a route which passes through each door exactly once?

Five rooms problem



Q. Can you find a route which passes through each door exactly once?

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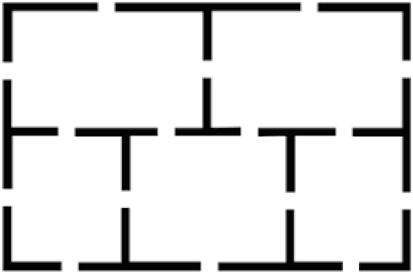
Five rooms problem

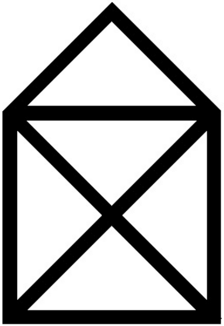


Q. Can you find a route which passes through each door exactly once?

Q. In other words, does the corresponding multigraph have an Euler trail?

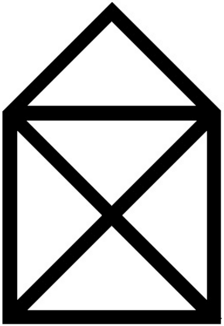
A. No.

Crossed house problem



Q. Can you draw this without taking your pen off the paper?

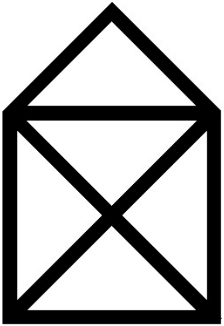
Crossed house problem



Q. Can you draw this without taking your pen off the paper?

Q. In other words, does this graph have an Euler trail?

Crossed house problem



Q. Can you draw this without taking your pen off the paper?

Q. In other words, does this graph have an Euler trail?

A. Yes.

Exercises

$\boxed{\text{RW: 6.2.11}}$ Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two coordinates.

(a) How many components does this graph have?

(b) How many vertices of each degree?

(c) Euler circuit?

$\boxed{\text{RW: 6.2.12}}$ As Ex. 6.2.11 but with an edge between vertices if they differ in two or three coordinates.

Solution to first exercise

Exercises

$\boxed{\text{RW: 6.2.11}}$ Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two coordinates.

(a) How many components does this graph have?

(b) How many vertices of each degree?

(c) Euler circuit?

Solution

Solution to first exercise

Exercises

RW: 6.2.11 Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two coordinates.

(a) How many components does this graph have?

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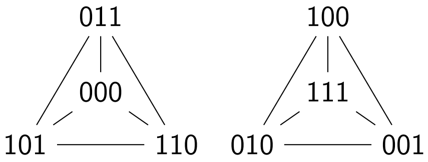
Solution

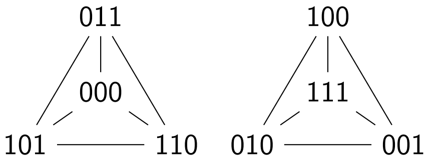


Solution to first exercise

Exercises

RW: 6.2.11 Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two coordinates.
(a) How many components does this graph have?
(b) How many vertices of each degree?
(c) Euler circuit?

Solution



a) It has 2 disjoint components. b) All 8 vertices have degree 3. c) No Euler circuit, as the graph is disconnected.

Note. This graph consists of all the *face diagonals* of a cube.

Solution to second exercise

Exercises

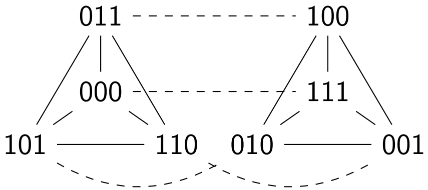
$\boxed{\text{RW: 6.2.12}}$ Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two <u>or three</u> coordinates.

(a) How many components does this graph have?

(b) How many vertices of each degree?

(c) Euler circuit?

Solution

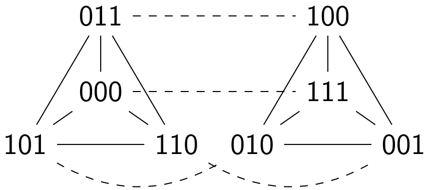


Solution to second exercise

Exercises

$\boxed{\text{RW: 6.2.12}}$ Construct a graph with vertex set $\{0,1\} \times \{0,1\} \times \{0,1\}$ and with an edge between vertices if they differ in exactly two <u>or three</u> coordinates.
(a) How many components does this graph have?
(b) How many vertices of each degree?
(c) Euler circuit?

Solution



a) It has 1 component. b) All 8 vertices have degree 4. c) Yes, it has an Euler circuit. (Why?)

Exercises

Exercises

RW: 6.2.14

1. Which complete graphs K_n have an Euler circuit?
2. Which bipartite complete graphs have an Euler circuit?
3. Which 3-partite complete graphs have an Euler circuit?

Exercises

Exercises

RW: 6.2.14

1. Which complete graphs K_n have an Euler circuit?
2. Which bipartite complete graphs have an Euler circuit?
3. Which 3-partite complete graphs have an Euler circuit?

Solution

1. K_n has an Euler circuit when n is odd.
2. $K_{m,n}$ — when both m and n are even.
3. $K_{p,q,r}$ — when $p+q, p+r, q+r$ are all even, i.e. when p, q, r are all even or all odd

Vertex Traversal

Definition

- **Hamiltonian path** visits every vertex of graph exactly once
- **Hamiltonian cycle** visits every vertex exactly once except the last one, which duplicates the first

Take Notice

Finding such a cycle, or proving it does not exist, is a difficult problem — the worst case is NP-complete.

Examples (where the Hamiltonian cycle exists)

- All five regular polyhedra (verify!)
- n-cube; Hamiltonian circuit = *Gray code*
- K_m for all m; $K_{m,n}$ iff $m = n$; $K_{a,b,c}$ iff a, b, c satisfy the triangle inequalities: $a + b \geq c$, $a + c \geq b$, $b + c \geq a$
- Knight's tour on a chessboard (incl. rectangular boards)

Examples when a Hamiltonian cycle does not exist are much harder to construct.

Also, given such a graph, it is nontrivial to verify that there is no Hamiltonian cycle. There is nothing obvious to specify that could assure us about this property. We have to check all possibilities.

In contrast, if a cycle is given, it is immediate to verify that it is a Hamiltonian cycle.

These situations demonstrate the often enormous discrepancy in difficulty of 'proving' versus (simply) 'checking'.

Exercise

Exercise

RW: 6.5.5(a) How many Hamiltonian cycles does $K_{n,n}$ have?

Solution

Exercise

Exercise

RW: 6.5.5(a) How many Hamiltonian cycles does $K_{n,n}$ have?

Solution

Let $V = V_1 \cup V_2$

- start at any vertex in V_1 (n choices of starting vertex)
- go to any vertex in V_2 (n choices of second vertex)
- go to any *new* vertex in V_1 ($n - 1$ choices for third vertex)
- ......

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- go to any *new* vertex in V_1 ($n-1$ choices for third vertex)
- ......

The number of choices of starting vertex (in V_1) to final vertex are

$$(n)(n)(n-1)(n-1)(n-2)(n-2)\cdots(2)(2)(1)(1) = (n!)^2$$

Similarly if we started in V_2 instead, then there are also $(n!)^2$ orderings of first vertex to last vertex.

So in total there are $2(n!)^2$ choices of first vertex to last vertex of a Hamilton cycle.

(This method counts the same cycle multiple times. Why? How do we fix this?)

Outline

Colouring

Informally: assigning a “colour” to each vertex (e.g. a node in an electric or transportation network) so that the vertices connected by an edge have different colours.
Formally: A mapping $c : V \longrightarrow [1\,..\,t]$ such that for every $e = (v, w) \in E$

$$c(v) \neq c(w)$$

The minimum t sufficient to effect such a mapping is called the **chromatic number** of a graph $G = (E, V)$ and is denoted $\chi(G)$.

Take Notice

This notion is extremely important in operations research, esp. in scheduling.
There is a dual notion of ‘edge colouring’ — two edges that share a vertex need to have different colours. Curiously enough, it is much less useful in practice.

Properties of the Chromatic Number

- $\chi(K_n) = n$
- If G has n vertices and $\chi(G) = n$ then $G = K_n$

Proof.

Suppose that G is 'missing' the edge (v, w), as compared with K_n. Colour all vertices, except w, using $n - 1$ colours. Then assign to w the same colour as that of v. □

- If $\chi(G) = 1$ then G is totally disconnected: it has 0 edges.
- If $\chi(G) = 2$ then G is bipartite.
- For any tree $\chi(T) = 2$.
- For any cycle C_n its chromatic number depends on the parity of n — for n even $\chi(C_n) = 2$, while for n odd $\chi(C_n) = 3$.

Cliques

Graph (V', E') *subgraph* of (V, E) — $V' \subseteq V$ and $E' \subseteq E$.

Definition

A **clique** in G is a *complete* subgraph of G. A clique of k nodes is called k-*clique*.
The size of the largest clique is called the *clique number* of the graph and denoted $\kappa(G)$.

Theorem

$\chi(G) \geq \kappa(G)$.

Proof.

Every vertex of a clique requires a different colour, hence there must be at least $\kappa(G)$ colours. □

However, this is the only restriction. For any given k there are graphs with $\kappa(G) = k$, while $\chi(G)$ can be arbitrarily large.

Take Notice

This fact (and such graphs) are important in the analysis of parallel computation algorithms.

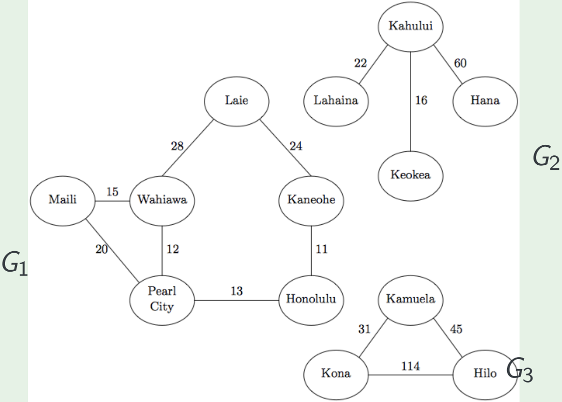
- $\kappa(K_n) = n$, $\kappa(K_{m,n}) = 2$, $\kappa(K_{m_1,\ldots,m_r}) = r$.
- If $\kappa(G) = 1$ then G is totally disconnected.
- For a tree $\kappa(T) = 2$.
- For a cycle C_n
  $\kappa(C_3) = 3, \quad \kappa(C_4) = \kappa(C_5) = \ldots = 2$

The difference between $\kappa(G)$ and $\chi(G)$ is apparent with just $\kappa(G) = 2$ — this does not imply that G is bipartite. For example, the cycle C_n for any odd n has $\chi(C_n) = 3$.

Exercise

Exercise

RW: 9.10.1 (Ullmann)

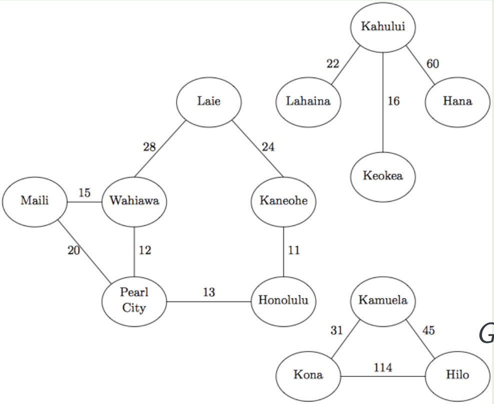


Q. What is $\chi(G_i)$ and $\kappa(G_i)$ for each $i \in \{1, 2, 3\}$?

Exercise

Exercise

$\boxed{\text{RW: 9.10.1}}$ (Ullmann)



G_2

G_1

G_3

A. $\chi(G_1) = \kappa(G_1) = 3$; $\chi(G_2) = \kappa(G_2) = 2$; $\chi(G_3) = \kappa(G_3) = 3$

Exercise

$\boxed{\text{RW: 9.10.3}}$ (Ullmann) Let $G = (V, E)$ be an undirected graph. What inequalities must hold between

- the maximal $deg(v)$ for $v \in V$
- $\chi(G)$
- $\kappa(G)$

Exercise

Exercise

$\boxed{\text{RW: 9.10.3}}$ (Ullmann) Let $G = (V, E)$ be an undirected graph. What inequalities must hold between

- the maximal $deg(v)$ for $v \in V$
- $\chi(G)$
- $\kappa(G)$

Solution

$$\max_{v \in V} deg(v) + 1 \geq \chi(G) \geq \kappa(G)$$

Timetable scheduling

The following table describes several subjects and the students taking them:

Potions	**Charms**	**Herbology**	**Astronomy**	**Transfiguration**
Harry	Ron	Harry	Hermione	Hermione
Ron	Luna	George	Neville	Fred
Malfoy	Ginny	Neville	Seamus	Luna

Q. How many examination timeslots are needed so that no student has two (or more) exams at the same time?

Timetable scheduling

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Harry	Ron	Harry	Hermione	Hermione
Ron	Luna	George	Neville	Fred
Malfoy	Ginny	Neville	Seamus	Luna

Q. How many examination timeslots are needed so that no student has two (or more) exams at the same time?

A. 3 timeslots.

Argument. We model this problem as a graph G where the vertices represent subjects, and there is an edge between two subjects if they have a student in common. Now the number of timeslots required is given by the chromatic number $\chi(G) = 3$.

Planar Graphs

Definition

A graph is **planar** if it can be embedded in a plane without its edges intersecting.

Theorem

If the graph is planar it can be embedded (without self-intersections) in a plane so that all its edges are straight lines.

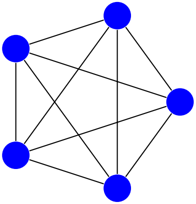
Take Notice

This notion and its related algorithms are extremely important to VLSI and visualizing data.

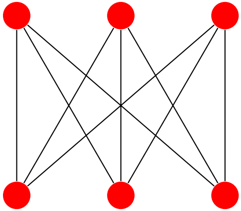
Nonplanar graphs

Two minimal nonplanar graphs

K_5 :



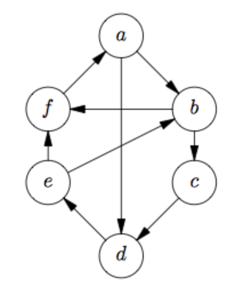
$K_{3,3}$:



Try out K_5
Try out $K_{3,3}$

Exercise

RW: 9.10.2 (Ullmann)



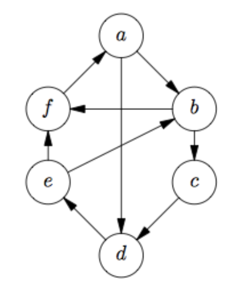
Q. Is (the undirected version of) this graph planar?

Try it out

Exercise

Exercise

RW: 9.10.2 (Ullmann)



Q. Is (the undirected version of) this graph planar?

A. Yes

Try it out

Three utilities problem

Q. Can you connect all utilities to all houses without crossing connections?

Three utilities problem

Q. Can you connect all utilities to all houses without crossing connections?

A. No, because $K_{3,3}$ is not planar.

Testing for nonplanarity

Theorem

If graph G contains, as a subgraph, a nonplanar graph, then G itself is nonplanar.

For a graph, *edge subdivision* means to introduce some new vertices, all of degree 2, by placing them on existing edges.

We call such a derived graph a *subdivision* of the original one.

Theorem

If a graph is nonplanar then it must contain a subdivision of K_5 or $K_{3,3}$.

More nonplanar graphs

Theorem

K_n for $n \geq 5$ is nonplanar.

Proof.

It contains K_5: choose any five vertices in K_n and consider the subgraph they define. $\square$

Theorem

$K_{m,n}$ is nonplanar when $m \geq 3$ and $n \geq 3$.

Proof.

They contain $K_{3,3}$ — choose any three vertices in each of two vertex parts and consider the subgraph they define. $\square$

Exercise

Q. Are all $K_{m,1}$ planar?

Exercise

Exercise

Q. Are all $K_{m,1}$ planar?

A. Yes, they are trees of two levels — the root and m leaves.

Exercise

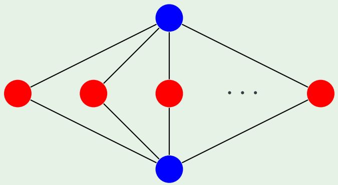
Q. Are all $K_{m,2}$ planar?

Exercise

Exercise

Q. Are all $K_{m,2}$ planar?

A. Yes; they can be represented by "glueing" together two such trees at the leaves.
Sketching $K_{m,2}$

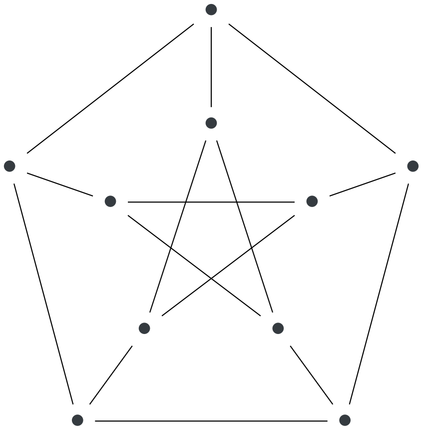


Also, among the k-partite graphs, planar are $K_{2,2,2}$ and $K_{1,1,m}$. The latter can be depicted by drawing one extra edge in $K_{2,m}$, connecting the top and bottom vertices.

Testing nonplanarity

Take Notice

Finding a 'basic' nonplanar obstruction is not always simple



This graph contains a subdivision $K_{3,3}$, but not K_5.

Strategy for finding a subdivision

To show G contains a subdivision of H as a subgraph:
Strategy I:

- Start at H
- Perform the following operations as many times as you need:
  1. Subdivide an edge
  2. Add a vertex
  3. Add an edge
- Finish with G

Take Notice

- *Each operation increases* $|V| + |E|$
- *Can do all (i) first, then all (ii), then all (iii)*

Strategy for finding a subdivision

To show G contains a subdivision of H as a subgraph:
Strategy II:

- Start at G
- Perform the following operations as many times as you need:
  1. Delete an edge
  2. Delete a vertex (and all adjacent edges)
  3. Replace a vertex of degree 2 with an edge connecting its neighbours (contracting a vertex)
- Finish with H

Take Notice

- *Each operation decreases* $|V| + |E|$
- *Can do all (i) first, then all (ii), then all (iii)*

Showing a graph does not contain a subdivision

Question

What does not change when performing the operations?