Lecture 4: Circuits

Shuai Li

John Hopcroft Center, Shanghai Jiao Tong University

https://shuaili8.github.io

https://shuaili8.github.io/Teaching/CS3330/index.html

Eulerian circuit

- A closed walk through a graph using every edge once is called an Eulerian circuit
- A graph that has such a walk is called an Eulerian graph

- Theorem (1.2.26, W) A graph G is Eulerian $\Leftrightarrow$ it has at most one nontrivial component and its vertices all have even degree
- (possibly with multiple edges)
- Proof "$\Longrightarrow$" That G must be connected is obvious.
  Since the path enters a vertex through some edge and leaves by another edge, it is clear that all degrees must be even

Key lemma

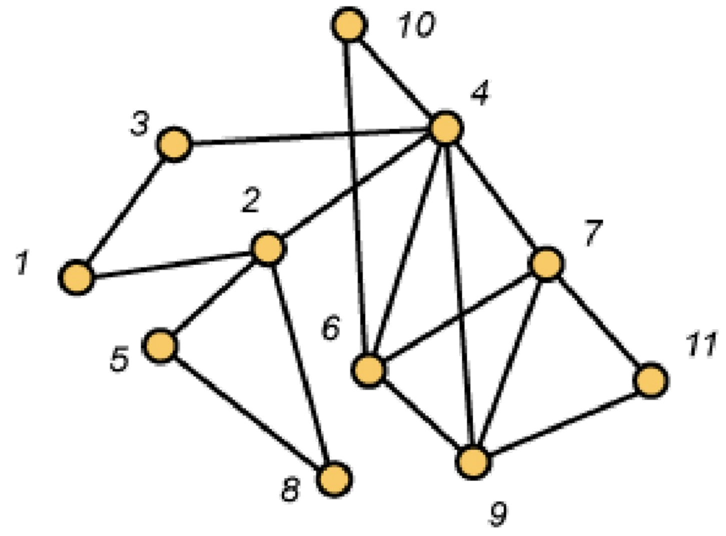
- Lemma (1.2.25, W) If every vertex of a graph G has degree at least 2, then G contains a cycle.

Proposition (1.3.1, D) Every graph G contains a path of length $\delta(G)$ and a cycle of length at least $\delta(G) + 1$, provided $\delta(G) \geq 2$.

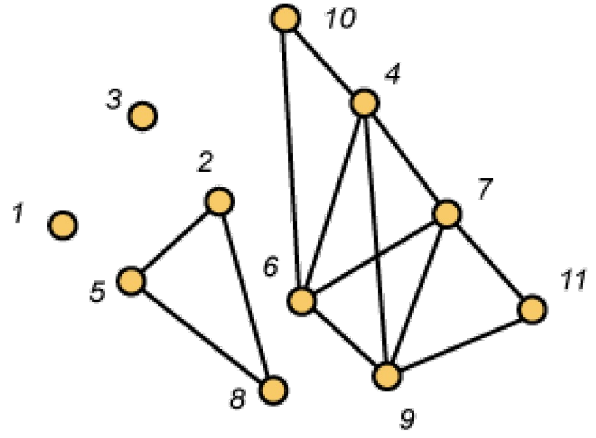
Hierholzer's Algorithm for Euler Circuits

1. Choose a root vertex r and start with the trivial partial circuit (r)
2. Given a partial circuit $(x_0, e_1, x_1, \ldots, x_{t-1}, e_t, x_t = x_0)$ that traverses not all edges of G, remove these edges from G
3. Let i be the least integer for which x_i is incident with one of the remaining edges
4. Form a greedy partial circuit among the remaining edges of the form $(x_i = y_0, e'_1, y_1, \ldots, y_{s-1}, e'_s, y_s = x_i)$
5. Expand the original circuit by setting $(x_0, e_1, \ldots, e_i, x_i = y_0, e'_1, y_1, \ldots, y_{s-1}, e'_s, y_s = x_i, e_{i+1}, \ldots, e_t, x_t = x_0)$
6. Repeat step 2-5

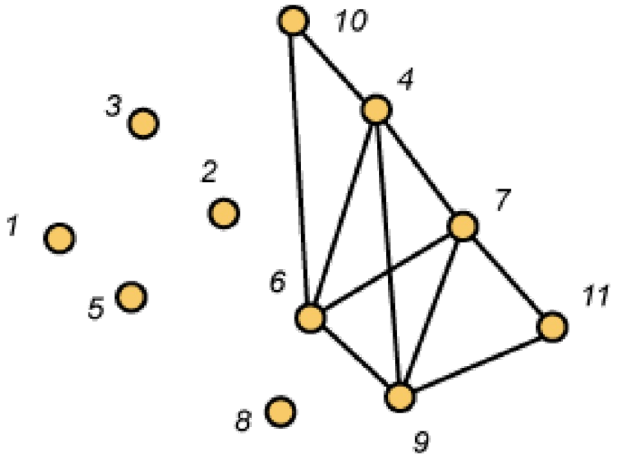
Example



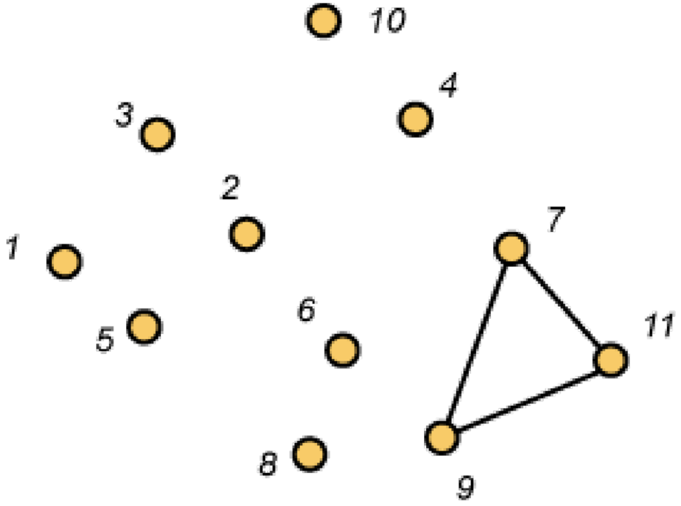
1. Start with the trivial circuit (1)
2. Greedy algorithm yields the partial circuit
   (1,2,4,3,1)
3. Remove these edges
4. The first vertex incident with remaining edges is 2
5. Greedy algorithms yields (2,5,8,2)
6. Expanding (1,2,5,8,2,4,3,1)
7. Remove these edges



Example (cont.)

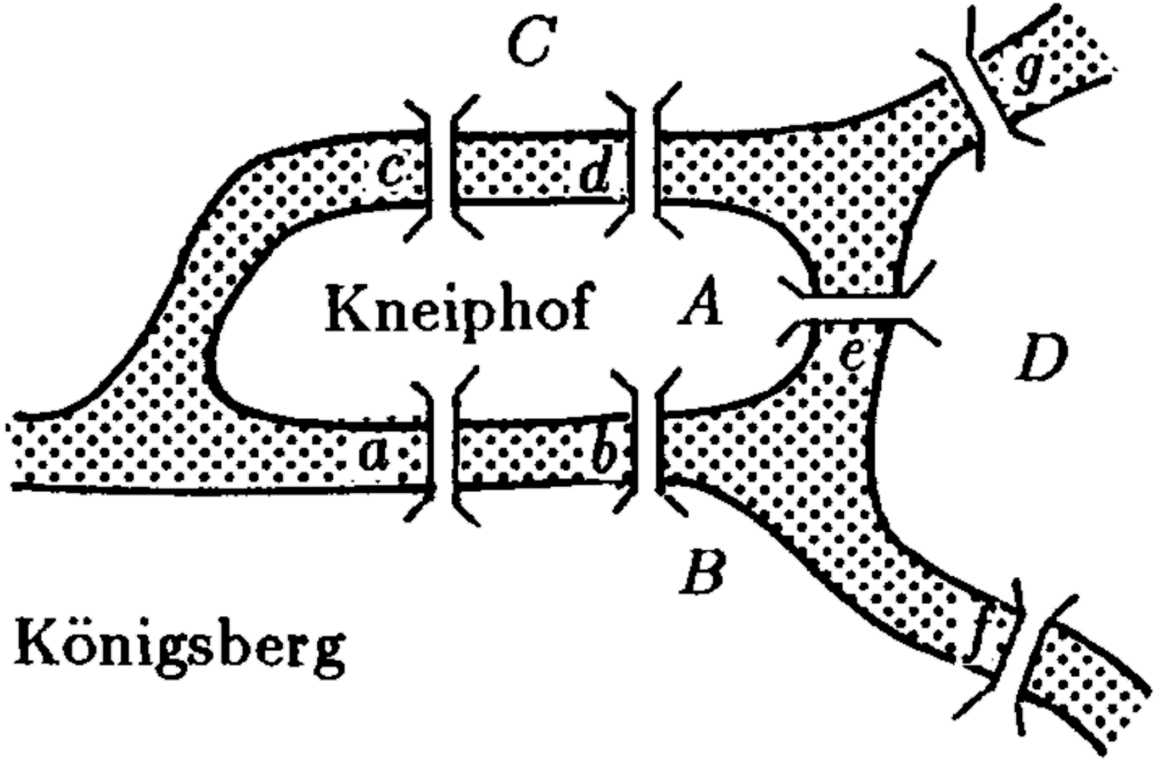


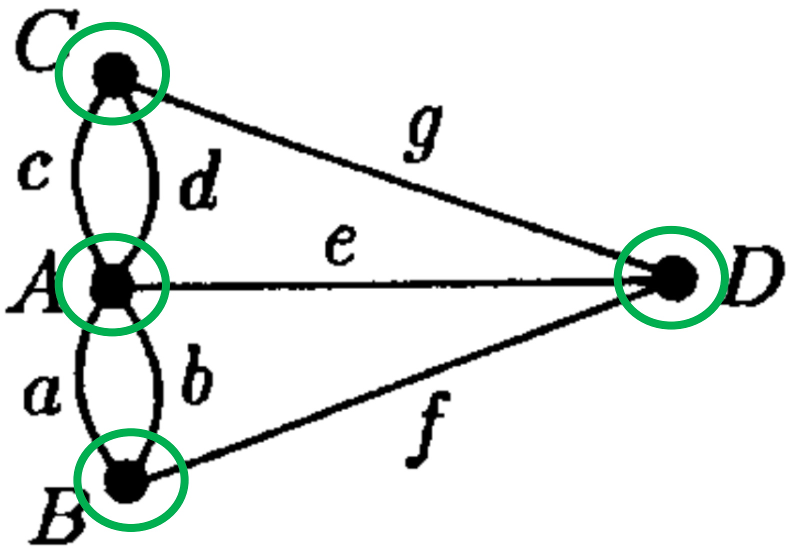
6. Expanding (1,2,5,8,2,4,3,1)
7. Remove these edges
8. First vertex incident with remaining edges is 4
9. Greedy algorithm yields (4,6,7,4,9,6,10,4)
10. Expanding (1,2,5,8,2,4,6,7,4,9,6,10,4,3,1)
11. Remove these edges
12. First vertex incident with remaining edges is 7
13. Greedy algorithm yields (7,9,11,7)
14. Expanding (1,2,5,8,2,4,6,7,9,11,7,4,9,6,10,4,3,1)



Eulerian circuit

- Theorem (1.2.26, W) A graph G is Eulerian $\Leftrightarrow$ it has at most one nontrivial component and its vertices all have even degree





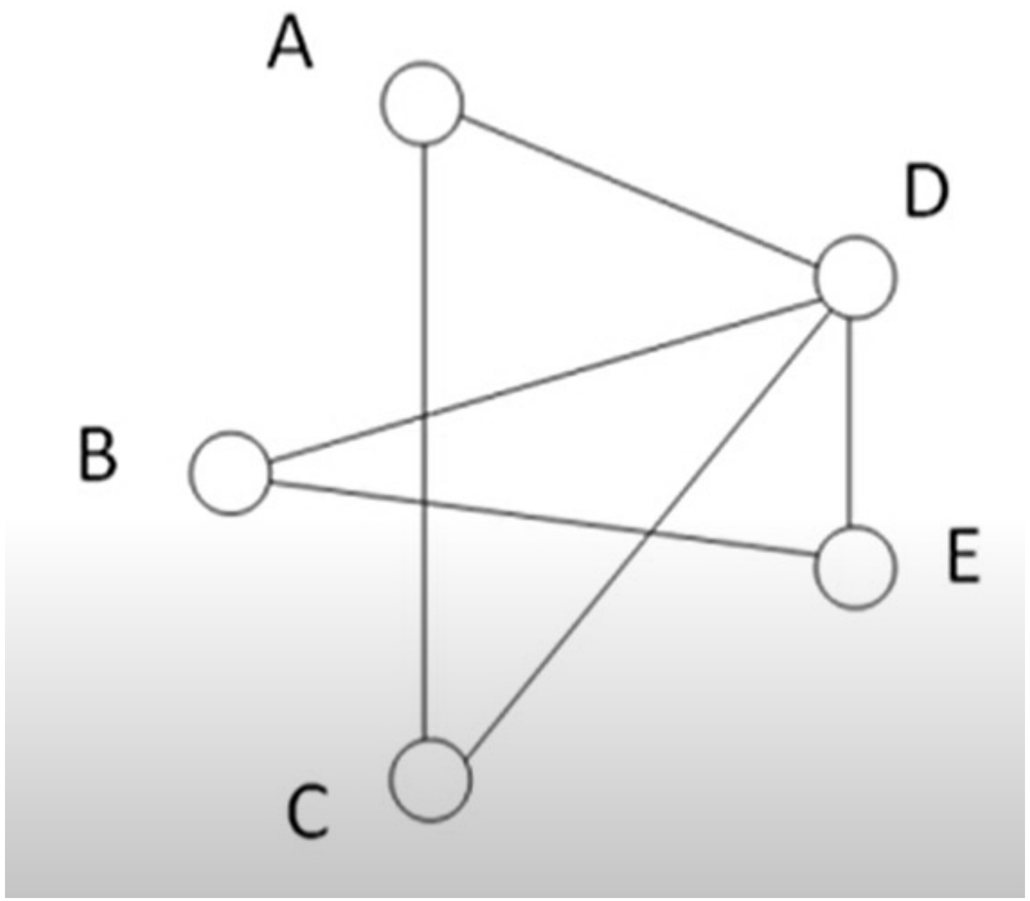
Fleury’s Algorithm for Identifying Eulerian Circuits

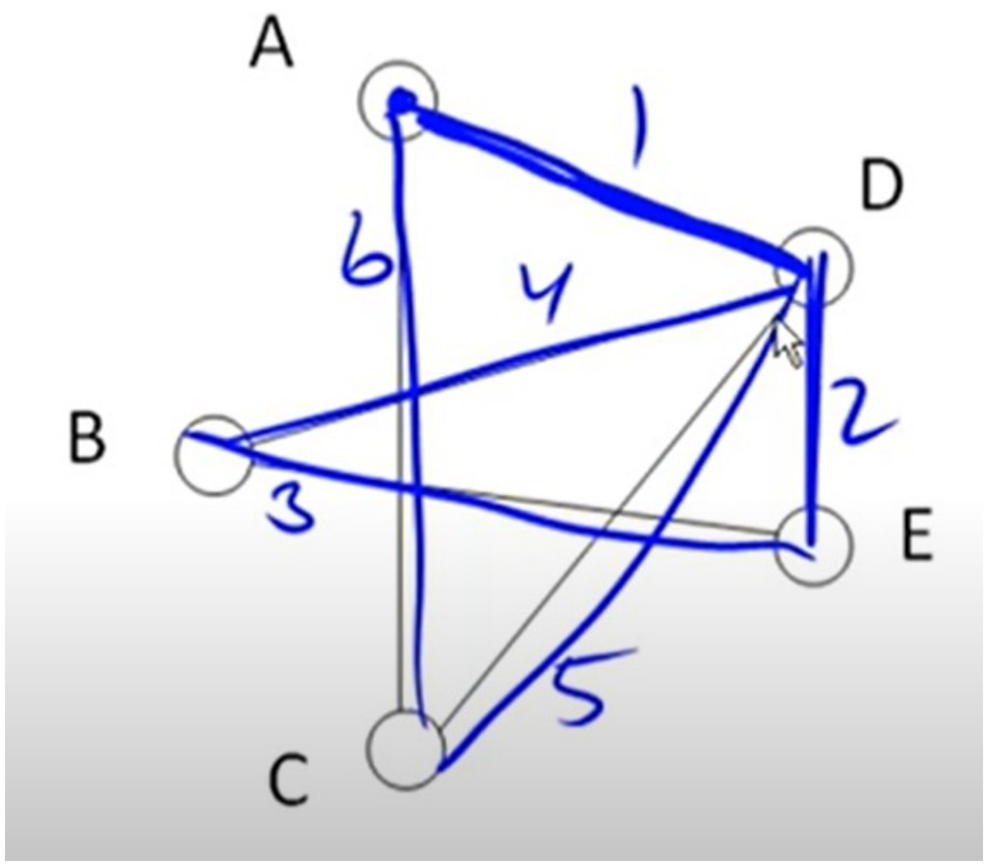
- (Ex3, S1.4.2, H)
- Given: An Eulerian graph G, with all of its edges *unmarked*

1. Choose a vertex v, and call it the “lead vertex”
2. If all edges of G have been marked, then stop. Otherwise continue to step 3
3. Among all edges incident with the lead vertex, choose, if possible, one that is not a bridge of the subgraph formed by the unmarked edges. If this is not possible, choose any edge incident with the lead. Mark this edge and let its other end vertex be the new lead vertex
4. Go to step 2

Exercise Read the proof for Fleury’s Theorem that guarantees the effectiveness of Fleury’s algorithm

Example





Other properties

- Proposition (1.2.27, W) Every even graph decomposes into cycles

- The necessary and sufficient condition for a directed Eulerian circuit is that the graph is connected and that each vertex has the same ‘in-degree’ as ‘out-degree’

TONCAS

- TONCAS: The obvious necessary condition is also sufficient
- Theorem (1.2.26, W) A graph G is Eulerian $\Leftrightarrow$ it has at most one nontrivial component and its vertices all have even degree

- Proposition (1.3.28, W) The nonnegative integers $d_1, \ldots, d_n$ are the vertex degrees of some graph $\Leftrightarrow \sum_{i=1}^{n} d_i$ is even
  - (Possibly with loops)
  - Otherwise $(2,0,0)$ is not realizable

- **1.3.63.** (!) Let $d_1, \ldots, d_n$ be integers such that $d_1 \geq \cdots \geq d_n \geq 0$. Prove that there is a loopless graph (multiple edges allowed) with degree sequence $d_1, \ldots, d_n$ if and only if $\sum d_i$ is even and $d_1 \leq d_2 + \cdots + d_n$. (Hakimi [1962])

Hamiltonian path/circuits

- A path P is Hamiltonian if $V(P) = V(G)$
  - Any graph contains a Hamiltonian path is called traceable
- A cycle C is called Hamiltonian if it spans all vertices of G
  - A graph is called Hamiltonian if it contains a Hamiltonian circuit
- In the mid-19th century, Sir William Rowan Hamilton tried to popularize the exercise of finding such a closed path in the graph of the dodecahedron (正十二面体)

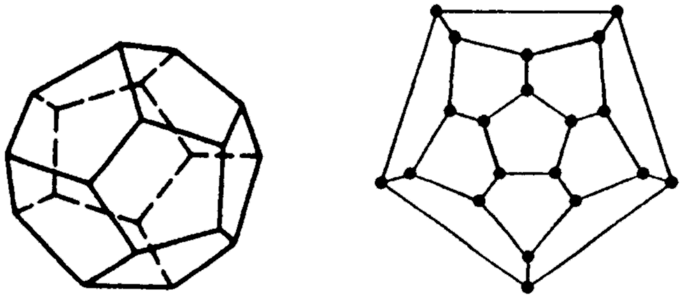
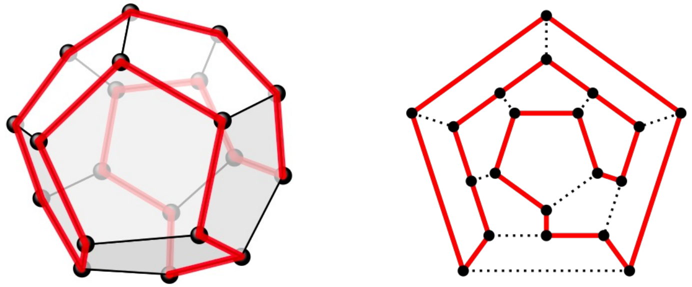


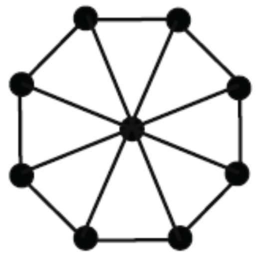
Figure 1.9



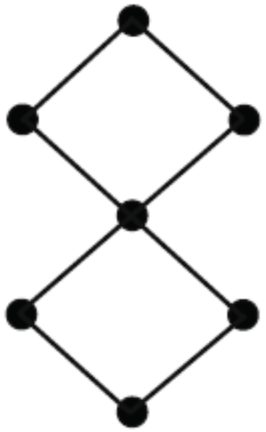
Degree parity is not a criterion

Theorem (1.2.26, W) A graph G is Eulerian $\Leftrightarrow$ it has at most one nontrivial component and its vertices all have even degree

- Hamiltonian graphs
  - all even degrees C_{10}
  - all odd degrees K_{10}
  - a mixture G_1
- non-Hamiltonian graphs
  - all even G_2
  - all odd $K_{5,7}$
  - mixed P_9



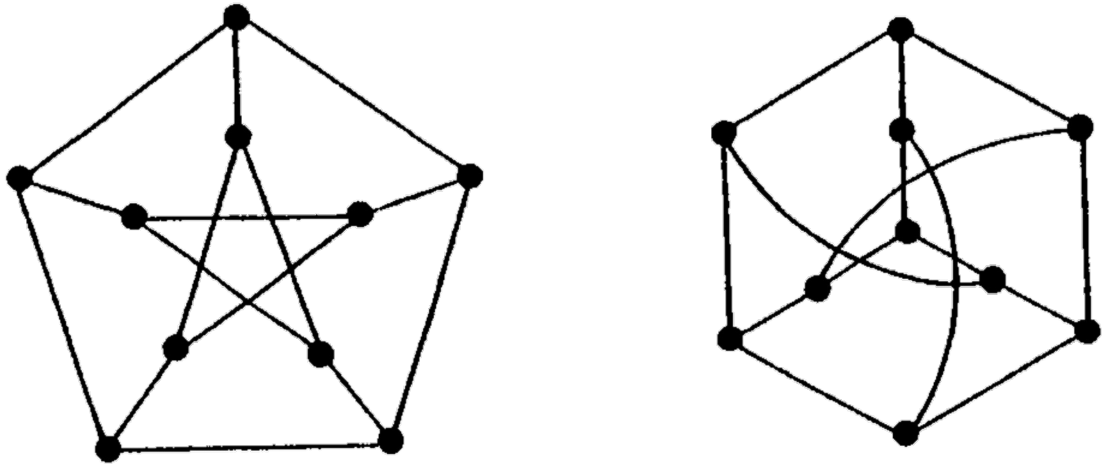
G_1



G_2

Example

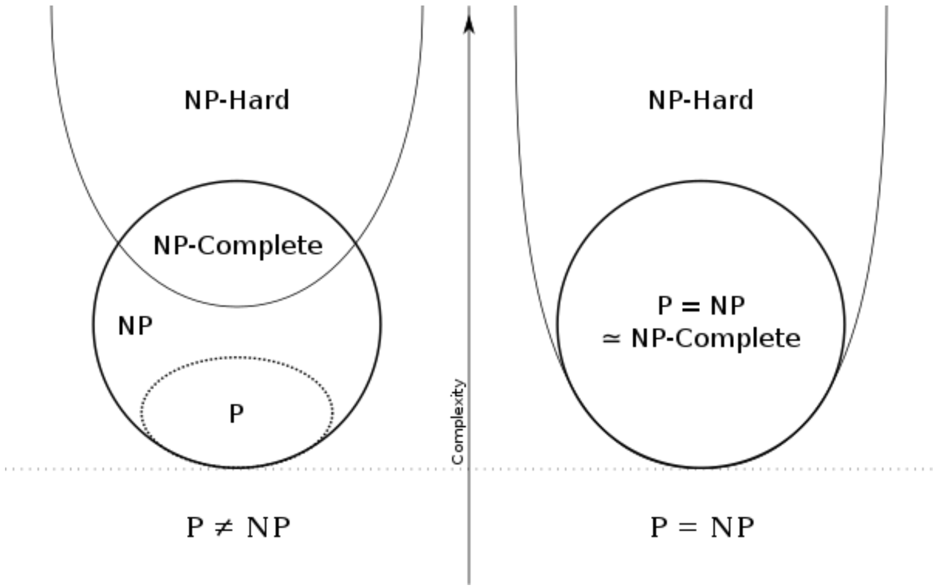
- The Petersen graph has a Hamiltonian path but no Hamiltonian cycle



- Determining whether such paths and cycles exist in graphs is the Hamiltonian path problem, which is NP-complete

P, NP, NPC, NP-hard

- P The general class of questions for which some algorithm can provide an answer in polynomial time
- NP (nondeterministic polynomial time) The class of questions for which an answer can be *verified* in polynomial time
- NP-Complete
    1. c is in NP
    2. Every problem in NP is reducible to c in polynomial time
- NP-hard
    - ~~c is in NP~~
    - Every problem in NP is reducible to c in polynomial time



Large minimal degree implies Hamiltonian

- Theorem (1.22, H, Dirac) Let G be a graph of order $n \geq 3$. If $\delta(G) \geq n/2$, then G is Hamiltonian

> Proposition (1.3.15, W) If $\delta(G) \geq \frac{n-1}{2}$, then G is connected
>
> (Ex16, S1.1.2, H) (1.3.16, W)
> If $\delta(G) \geq \frac{n-2}{2}$, then G need not be connected

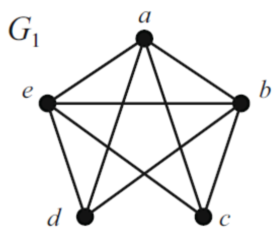
- The bound is tight
  (Ex12b, S1.4.3, H) $G = K_{r,r+1}$ is not Hamiltonian
  Exercise The condition when $K_{r,s}$ is Hamiltonian
- The condition is not necessary
  - C_n is Hamiltonian but with small minimum (and maximum) degree

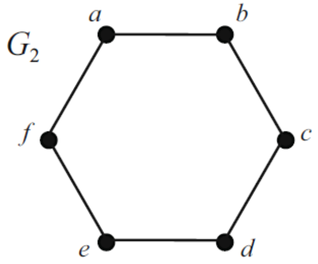
Generalized version

- Exercise (Theorem 1.23, H, Ore; Ex3, S1.4.3, H) Let G be a graph of order $n \geq 3$. If $\deg(x) + \deg(y) \geq n$ for all pairs of nonadjacent vertices x, y, then G is Hamiltonian

> Theorem (1.22, H, Dirac) Let G be a graph of order $n \geq 3$. If $\delta(G) \geq n/2$, then G is Hamiltonian

Independence number & Hamiltonian





- A set of vertices in a graph is called independent if they are pairwise nonadjacent
- The independence number of a graph G, denoted as $\alpha(G)$, is the largest size of an independent set
- Example: $\alpha(G_1) = 2, \alpha(G_2) = 3$
- Theorem (1.24, H) Let G be a connected graph of order $n \geq 3$. If $\kappa(G) \geq \alpha(G)$, then G is Hamiltonian

(Ex14, S1.1.2, H) $\kappa(G) \geq 2$ implies G has at least one cycle

Independence number & Hamiltonian 2

Theorem (1.24, H) Let G be a connected graph of order $n \geq 3$. If $\kappa(G) \geq \alpha(G)$, then G is Hamiltonian

- The result is tight: $\kappa(G) \geq \alpha(G)-1$ is not enough
  - $K_{r,r+1}$: $\kappa = \mathrm{r}, \alpha = r+1$
  - Exercise (Ex4, S1.4.3, H) Peterson graph: $\kappa = 3, \alpha = 4$

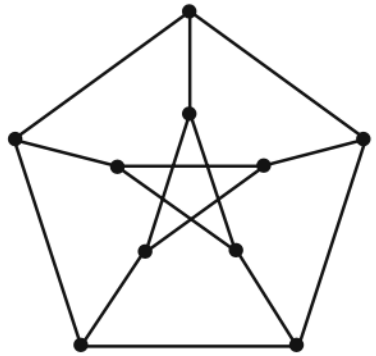
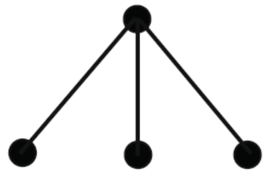
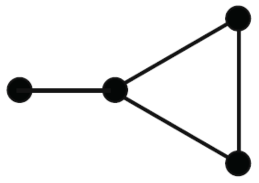


FIGURE 1.63. The Petersen Graph.

Pattern-free & Hamiltonian



$K_{1,3}$



Z_1

- G is H-free if G doesn't contain a copy of H as induced subgraph
- Theorem (1.25, H) If G is 2-connected and $\{K_{1,3}, Z_1\}$-free, then G is Hamiltonian

(Ex14, S1.1.2, H) $\kappa(G) \geq 2$ implies G has at least one cycle

- The condition 2-connectivity is necessary
- (Ex2, S1.4.3, H) If G is Hamiltonian, then G is 2-connected

Summary

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- Eulerian circuit
  - TONCAS, $\Leftrightarrow$ connected, and all vertices have even degree
  - Hierholzer's Algorithm, Fleury's Algorithm
- Hamiltonian path/circuits
  - NP-Complete
  - Degree parity is not a criterion
  - Large minimal degree implies Hamiltonian
  - Connected, $\kappa(G) \geq \alpha(G) \Rightarrow$ Hamiltonian
  - 2-connected, $\{K_{1,3}, Z_1\}$-free $\Rightarrow$ Hamiltonian

Questions?