

CHAPTER 10 Graphs

10.1 Graphs and Graph Models

10.2 Graph Terminology and Special Types of Graphs

10.3 Representing Graphs and Graph Isomorphism

10.4 Connectivity

10.5 Euler and Hamilton Paths

10.6 Shortest Path Problems

10.7 Planar Graphs

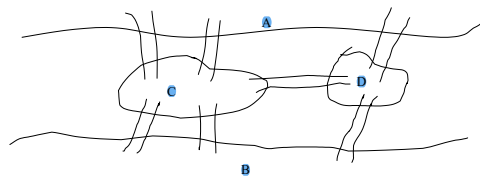
10.8 Graph Coloring



10.5.1 Euler Paths

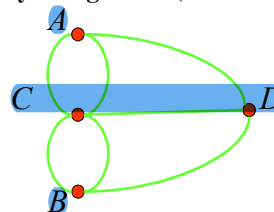
9.5.1 Euler Paths

1. Königsberg Seven Bridge Problem



Problem: Is it possible to start at some location in the town, travel across all the bridges without crossing any bridge twice, and return the starting point?

The question becomes: Is there a simple circuit in this multigraph that contains every edge?



Terminologies:■ **Euler Path**

An Euler path is a **simple path** containing every edge of G .

■ **Euler Circuit**

An Euler circuit is a **simple circuit** containing every edge of G .

■ **Euler Graph**

A graph contains an Euler circuit.

**2. Necessary and sufficient conditions for Euler circuit and paths**

【 Theorem 1 】 A connected multigraph has an Euler circuit if and only if each of its vertices has even degree.

Proof:**(1) Necessary condition**

G has an Euler circuit \Rightarrow Every vertex in V has even degree

Consider the Euler circuit.

- ◆ the vertex a which the Euler circuit begins with
- ◆ intermeidate vertices



(2) sufficient condition

We will **form a simple circuit** that begins at an arbitrary vertex a of G .

- Build a simple circuit $x_0=a, x_1, x_2, \dots, x_n=a$.
- An Euler circuit has been constructed if all the edges have been used. otherwise,
- Consider the **subgraph H** from G by deleting the edges already uses and vertices that are not incident with any remaining edges.

Let w be a vertex which is the common vertex of the circuit and H .

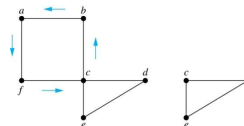
Beginning at w , construct a simple path in H .



Sufficient Conditions for Euler Circuits and Paths

Suppose that G is a connected multigraph with ≥ 2 vertices, all of even degree. Let $x_0 = a$ be a vertex of even degree. Choose an edge $\{x_0, x_1\}$ incident with a and proceed to build a simple path $\{x_0, x_1\}, \{x_1, x_2\}, \dots, \{x_{n-1}, x_n\}$ by adding edges one by one until another edge can not be added.

We illustrate this idea in the graph G here. We begin at a and choose the edges $\{a, f\}$, $\{f, c\}$, $\{c, b\}$, and $\{b, a\}$ in succession.



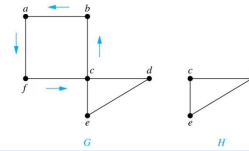
• The path begins at a with an edge of the form $\{a, x\}$; we show that it must terminate at a with an edge of the form $\{y, a\}$. Since each vertex has an even degree, there must be an even number of edges incident with this vertex. Hence, every time we enter a vertex other than a , we can leave it. Therefore, the path can only end at a .

• If all of the edges have been used, an Euler circuit has been constructed. Otherwise, consider the subgraph H obtained from G by deleting the edges already used.

➤ In the example H consists of the vertices c, d, e .



Sufficient Conditions for Euler Circuits and Paths (continued)



- Because G is connected, H must have at least one vertex in common with the circuit that has been deleted.

➤ In the example, the vertex is c .

- Every vertex in H must have even degree because all the vertices in G have even degree and for each vertex, pairs of edges incident with this vertex have been deleted. Beginning with the shared vertex construct a path ending in the same vertex (as was done before). Then splice this new circuit into the original circuit.

➤ In the example, we end up with the circuit a, f, c, d, e, c, b, a .

- Continue this process until all edges have been used. This produces an Euler circuit. Since every edge is included and no edge is included more than once.
- Similar reasoning can be used to show that a graph with exactly two vertices of odd degree must have an Euler path connecting these two vertices of odd degree.



Algorithm for Constructing an Euler Circuits

In our proof we developed this algorithms for constructing a Euler circuit in a graph with no vertices of odd degree.

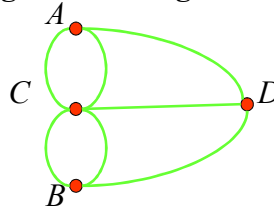
```

procedure Euler( $G$ : connected multigraph with all vertices of even degree)
  circuit := a circuit in  $G$  beginning at an arbitrarily chosen vertex
  with edges
    successively added to form a path that returns to this
    vertex.
   $H := G$  with the edges of this circuit removed
  while  $H$  has edges
    subcircuit := a circuit in  $H$  beginning at a vertex in  $H$  that also is
    an endpoint of an edge in circuit.
     $H := H$  with edges of subcircuit and all isolated vertices
    removed
    circuit := circuit with subcircuit inserted at the
    appropriate vertex.
  return circuit{circuit is an Euler circuit}
    
```



【 Theorem 2 】 A connected multigraph has an Euler path but not an Euler circuit if and only if it has exactly two vertices of odd degree.

【Example 1】 Königsberg Seven Bridge Problem

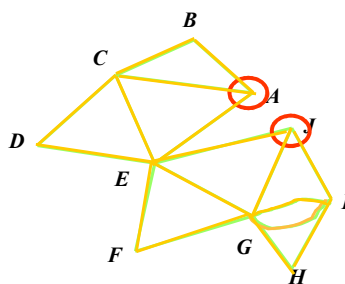


Solution:

1. The graph has four vertices of odd degree. Therefore, it does not have an Euler circuit.
2. It does not have an Euler path either.



【Example 2】 Determine whether the following graph has an Euler path. Construct such a path if it exists.



The Euler path:

$A, C, E, F, G, I, J, E, A, B,$
 C, D, E, G, H, I, G, J

Solution:

The graph has 2 vertices of odd degree, and all of other vertices have even degree. Therefore, this graph has an Euler path.



3. Euler circuit and paths in directed graphs

A directed multigraph having no isolated vertices has an Euler circuit if and only if

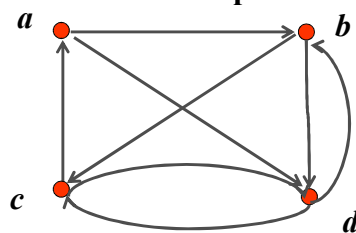
- the graph is weakly connected
- the in-degree and out-degree of each vertex are equal.

A directed multigraph having no isolated vertices has an Euler path but not an Euler circuit if and only if

- the graph is weakly connected
- the in-degree and out-degree of each vertex are equal for all but two vertices, one that has in-degree 1 larger than its out-degree and the other that has out-degree 1 larger than its in-degree.



[[Example 3]] Determine whether the directed graph has an Euler path. Construct an Euler path if it exists.



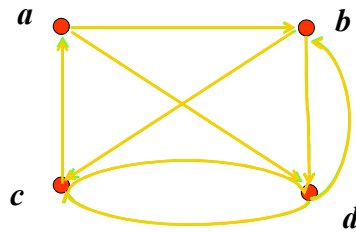
Solution:

	$\deg^-(v)$	$\deg^+(v)$
<i>a</i>	1	2
<i>b</i>	2	2
<i>c</i>	2	2
<i>d</i>	3	2

Hence, the directed graph has an Euler path.



[[Example 3]] Determine whether the directed graph has an Euler circuit. Construct an Euler circuit if it exists.



Solution:

	$\deg^-(v)$	$\deg^+(v)$
<i>a</i>	1	2
<i>b</i>	2	2
<i>c</i>	2	2
<i>d</i>	3	2

Hence, the directed graph has an Euler path.



4. Applications

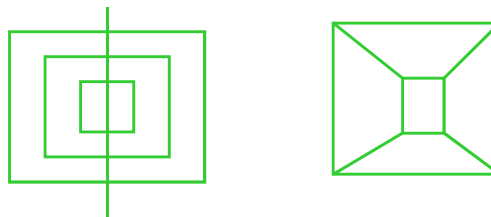
Euler path or circuit can be used to solve many practical problems.

1) A type of puzzle

Draw a picture in a continuous motion without lifting a pencil so that no part of the picture is retraced.

The equivalent problem: Whether the graph exist an Euler path or circuit.

For example,



4. Applications

Euler path or circuit can be used to solve many practical problems.

2) The Chinese postman problem

- The problem is named in honor of Guan Meigu (管梅谷), who posed it in 1962.

3) The other area, such as networking, molecular biology etc.



10.5.2 Hamilton paths and circuit

Hamilton's puzzle

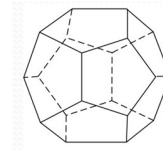
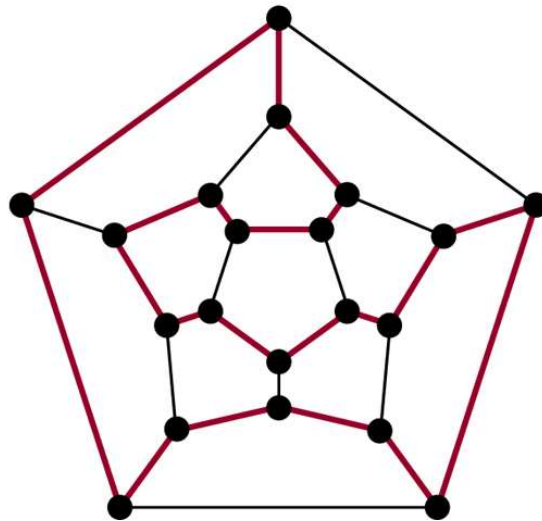


The object of the puzzle was to start at a city and travel along the edges of the dodecahedron, visiting each of the other 19 cities exactly once, and end back at the first city.

The equivalent question: Is there a circuit in the graph shown in b that passes through each vertex exactly once?



© The McGraw-Hill Companies, Inc. all rights reserved.



17



A **Hamilton path** in a graph G is a path which visits every vertex in G exactly once.

A **Hamilton circuit** (or **Hamilton cycle**) is a cycle which visits every vertex exactly once, *except for the first vertex*, which is also visited at the end of the cycle.

If a connected graph G has a Hamilton circuit, then G is called a **Hamilton graph**.

Question:

1) H path is a simple path?

18



1. The sufficient condition for the existence of Hamilton path and Hamilton circuit

【 Theorem 3】 DIRAC'THEOREM

If G is a simple graph with n vertices with $n \geq 3$ such that the degree of every vertex in G is at least $n/2$, then G has a Hamilton circuit.

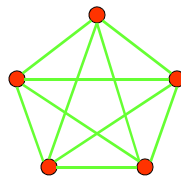
【 Theorem 4】 ORE'THEOREM

If G is a simple graph with n vertices with $n \geq 3$ such that $\deg(u) + \deg(v) \geq n$ for every pair of nonadjacent vertices u and v in G , then G has a Hamilton circuit.



【Example 4】 Show that K_n has a Hamilton circuit whenever $n \geq 3$?

For example,



Proof:

We can form a Hamilton circuit in K_n beginning at any vertex. Such a circuit can be built by visiting vertices in any order we choose, as long as the path begins and ends at the same vertex and visits each other vertex exactly once. This is possible since there are edges in K_n between any two vertices.



2. The necessary condition for Hamilton path and Hamilton circuit

For undirected graph:

The necessary condition for the existence of Hamilton path:

- G is connected;
- There are at most two vertices which degree are less than 2.



2. The necessary condition for Hamilton path and Hamilton circuit

The necessary condition for the existence of Hamilton circuit:

- The degree of each vertex is larger than 1.

Some properties:

- If a vertex in the graph has degree two, then both edges that are incident with this vertex must be part of any Hamilton circuit.
- When a Hamilton circuit is being constructed and this circuit has passed through a vertex, then all remaining edges incident with this vertex, other than the two used in the circuit, can be removed from consideration.

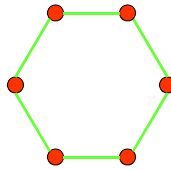


Another important necessary condition

- G is a Hamilton graph, for any nonempty subset S of set V , the number of connected components in $G-S \leq |S|$.

Note:

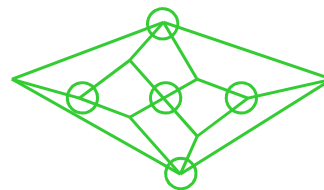
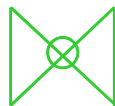
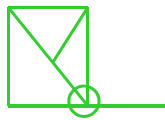
- (1) $G-S$ is a subgraph of G
- (2) Suppose that C is a H circuit of G . For any nonempty subset S of set V , the number of connected components in $C-S \leq |S|$.



- (3) the number of connected components in $G-S \leq$ the number of connected components in $C-S$



[[Example 5]] Does the following graphs have a Hamilton circuit?



3. Applications

Hamilton path or circuit can be used to solve many practical problems also.

For example,

- 1) Find a path or circuit that visits each road intersection in a city, or each node in a communication network exactly once.
- 2) The famous **traveling salesman problem (TSP)**
- 3)



【**Example 6**】 There are seven people denoted by A, B, C, D, E, F, G. Suppose that the following facts are known.

A--English (A can speak English.)

B--English, Chinese

C--English, Italian, Russian

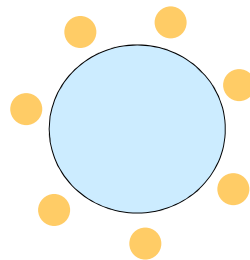
D--Japanese, Chinese

E--German, Italia

F--French, Japanese, Russian

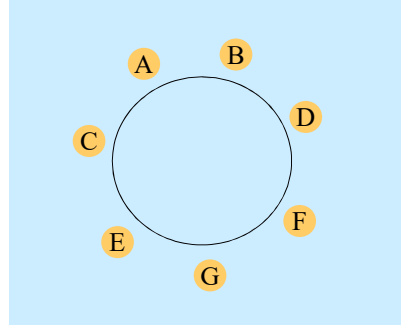
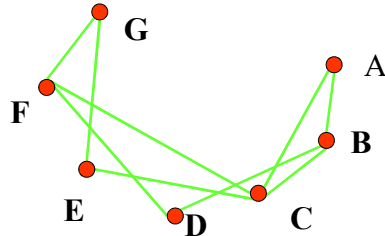
G--French, German

How to arrange seat for the round desk such that the seven people can talk each other?



Solution:**(1) Construct graph**

$V = \{A, B, C, D, E, F, G\}$, $E = \{(u, v) \mid u, v \text{ can speak at least one common language.}\}$



(2) If there is a H circuit, then we can arrange seat for the round desk such that the seven people can talk each other.

H circuit: A,B,D,F,G,E,C,A

**Homework:**

Sec. 10.5 4, 6, 31, 34, 38, 41



CHAPTER 10 Graphs

10.1 Graphs and Graph Models

10.2 Graph Terminology and Special Types of Graphs

10.3 Representing Graphs and Graph Isomorphism

10.4 Connectivity

10.5 Euler and Hamilton Paths

10.6 Shortest Path Problems

10.7 Planar Graphs

10.8 Graph Coloring

29



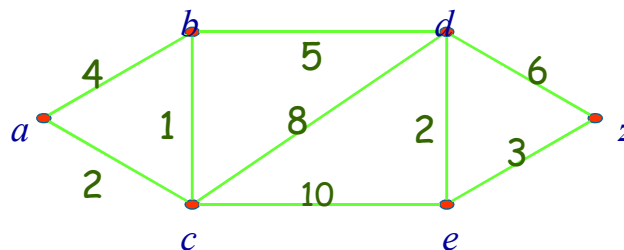
10.6 Shortest Path Problems

1. Introduction

■ **Weighted graph** $G = (V, E, W)$

We can assign weights to the edges of graphs.

For example,



30



1. Introduction

■ *Weighted graph* $G = (V, E, W)$

We can assign weights to the edges of graphs.

■ *The length of a path in a weighted graph*

-- the sum of the weights of the edges of this path.

■ *Shortest Path Problems*

$G = (V, E, W)$ is a weighted graph, where $w(x, y)$ is the weight of edge (x, y)

(if $(x, y) \notin E, w(x, y) = \infty$). $a, z \in V$, find the shortest path between a and z .



2. A shortest path algorithm

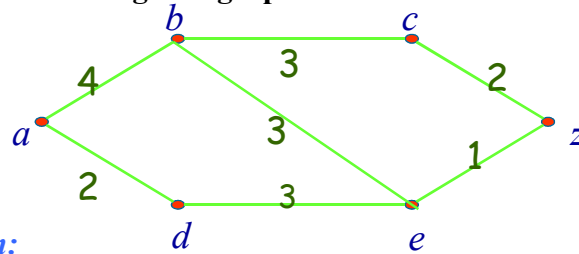
There are several different algorithms that find the shortest path between two vertices in a weighted graph.

Dijkstra's Algorithm (undirected graph with positive weights)

- An algorithm discovered by the Dutch mathematician E. Dijkstra in 1959.
- An iterative procedure.
- Proceed by finding the length of the shortest path from a to a first vertex, the length of the shortest path from a to a second vertex, and so on, until the length of the shortest path from a to z is found.



[[Example 1]] What is the length of the shortest path between a and z in the weighted graph.



Solution:

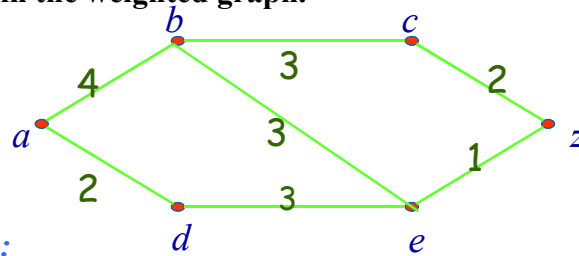
We will solve this problem by finding the length of a shortest path from a to successive vertices, until z is reached.

1) The first closest vertex: d

The only paths starting at a that contain no vertex other than a are a, b and a, d .



[[Example 1]] What is the length of the shortest path between a and z in the weighted graph.



Solution:

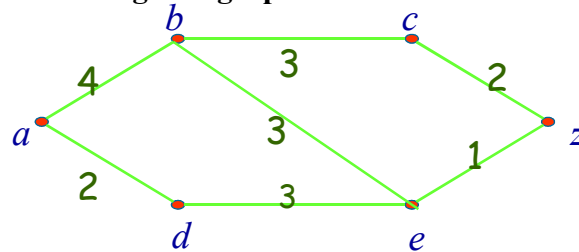
1) The first closest vertex: d

2) The second closest vertex: b

Looking at all paths that go through only a and d .



[[Example 1]] What is the length of the shortest path between a and z in the weighted graph.



Solution:

- 1) The first closest vertex: d
- 2) The second closest vertex: b
- 3) The third closest vertex: e

Examine only paths go through only a , d and b .

- 4) The fourth closest vertex: z



The details of Dijkstra's algorithm

Dijkstra's algorithm proceeds by forming a distinguished set of vertices iteratively. Let S_k denote this set of vertices after k iterations of **labeling procedure**.

Step 1 Label a with 0 and other with ∞ , i.e. $L_0(a)=0$, and $L_0(v)=\infty$ and $S_0=\emptyset$.

Step 2 The set S_k is formed from S_{k-1} by adding a vertex u not in S_{k-1} with the smallest label. Once u is added to S_k , we update the labels **of all vertices not in S_k** , so that **$L_k(v)$** , the label of the vertex v at the k th stage, is the length of the shortest **path from a to v that containing vertices only in S_k** .



Let v be a vertex not in S_k . To **update the label of v** , note that $L_k(v)$ is the shortest path from a to v containing only vertices in S_k ,

1. the shortest path from a to v containing only elements of S_{k-1}

Or

2. it is the shortest path from a to u at the $(k-1)$ st stage with the edge (u,v) added.

In other words,

$$L_k(v) = \min\{L_{k-1}(v), L_{k-1}(u) + w(u,v)\}$$



Algorithm 1 Dijkstra's Algorithm.

Procedure Dijkstra(G : weighted connected simple graph, with all weights positive)

{ G has vertices $a = v_0, v_1, \dots, v_n = z$ and weights $w(v_i, v_j)$ }

where $w(v_i, v_j) = \infty$ if $\{v_i, v_j\}$ is not an edge in G }

For $i := 1$ to n

$L(v_i) := \infty$

$L(a) := 0$

$S := \emptyset$

{the labels are now initialized so that the label of a is zero and all other labels are ∞ , and S is the empty set }



While $z \notin S$

Begin

$u :=$ a vertex not in S with $L(u)$ minimal

$S := S \cup \{u\}$

for all vertices v not in S

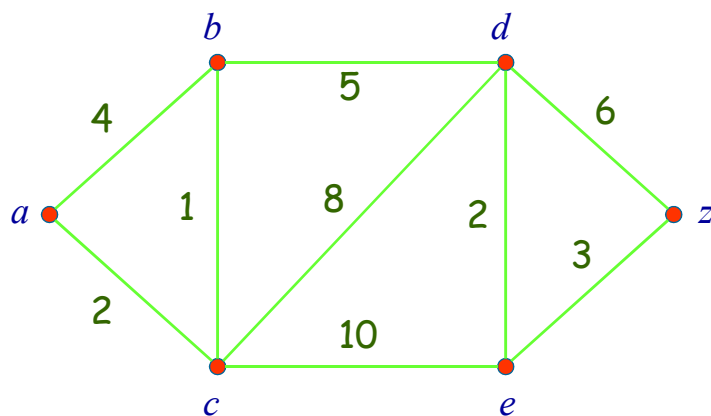
if $L(u) + w(u,v) < L(v)$ $L(v) := L(u) + w(u,v)$

{this adds a vertex to S with minimal label and updates the labels of vertices not in S }

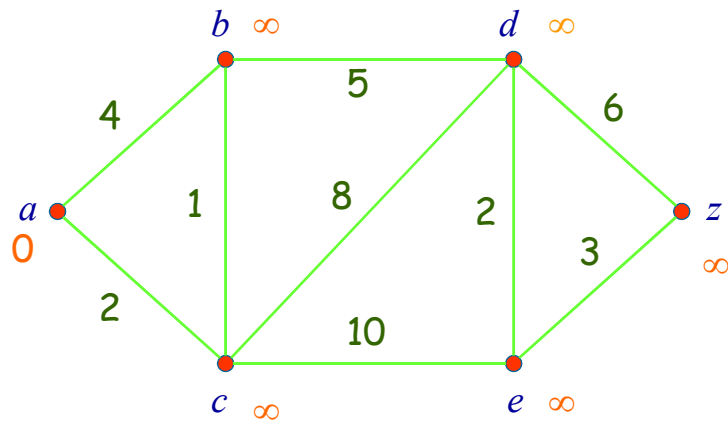
End { $L(z)$ = length of shortest path from a to z }



[[Example 1]] Find the length of the shortest path between a and z in the given weighted graph.



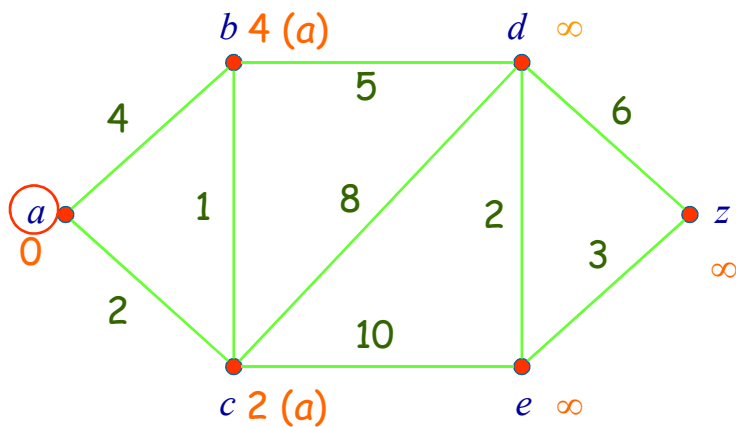
Step 0



41



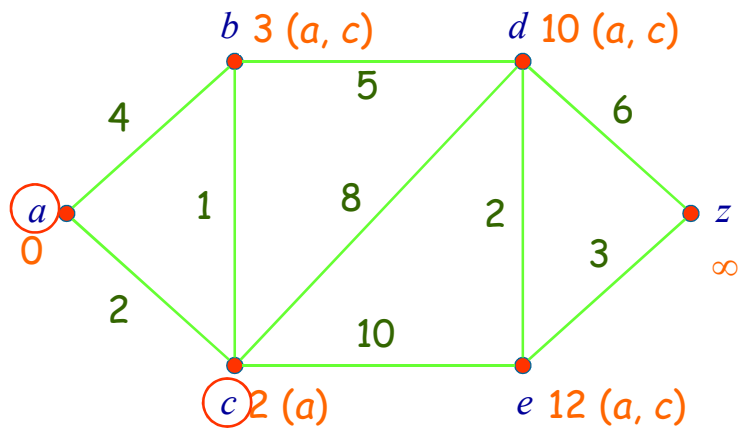
Step 1



42



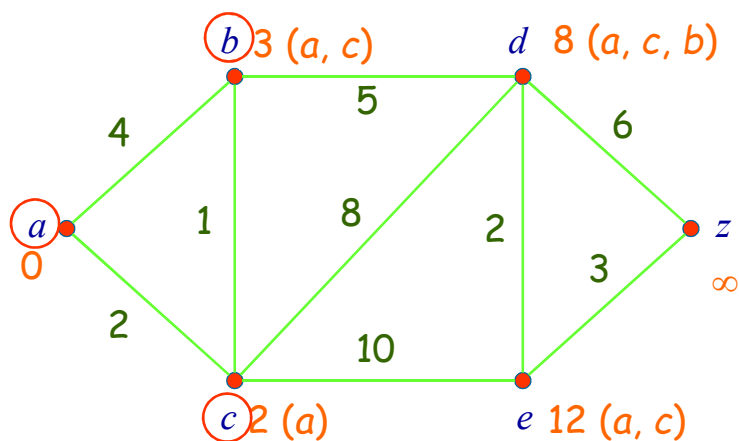
Step 2



43



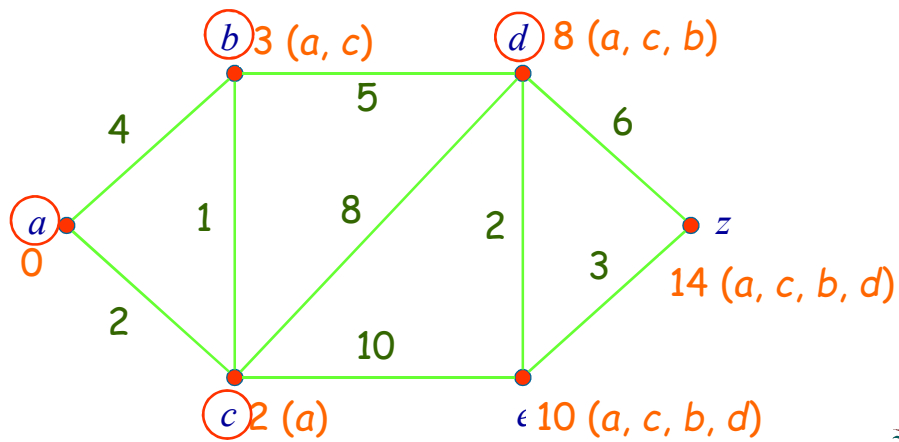
Step 3



44



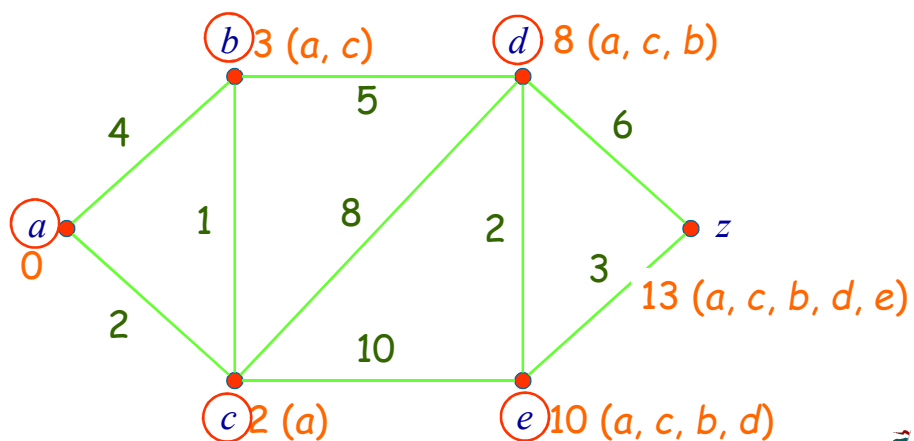
Step 4



45



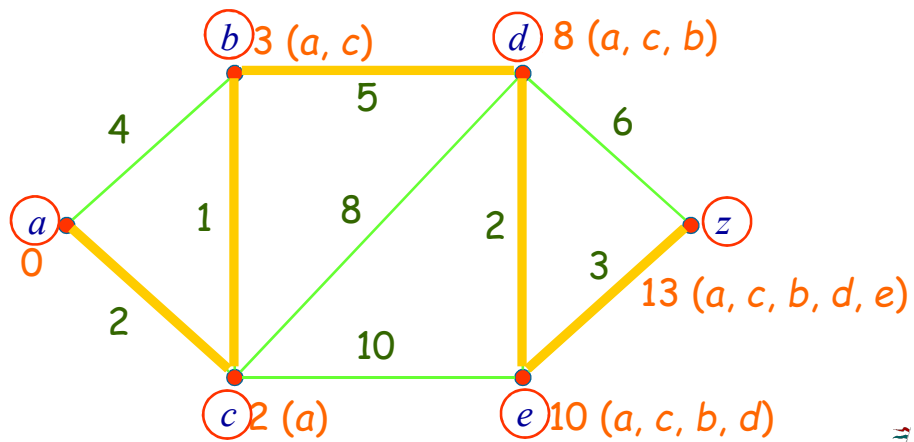
Step 5



46



Step 6



47

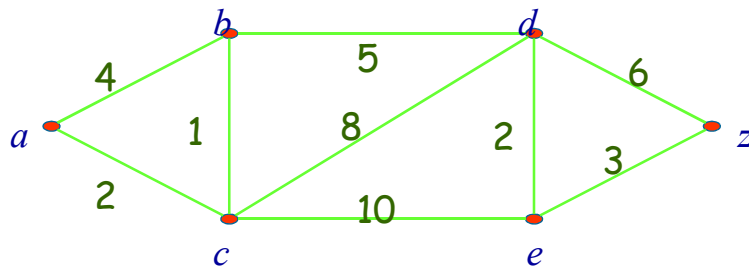
**Remark:**

In performing Dijkstra's algorithm it is sometimes more convenient to keep track of labels of vertices in each step using a table.

48



10.6 Shortest Path Problems

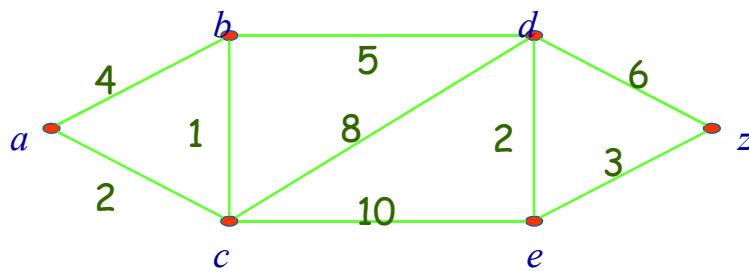


Vertex	S	Link						
a								
b								
c								
d								
e								
z								

49



10.6 Shortest Path Problems

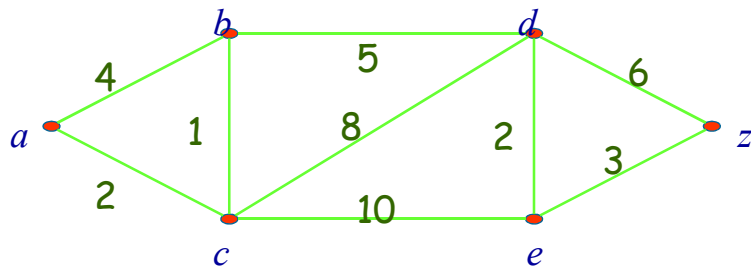


Vertex	S	Link	L_0					
a			0					
b			∞					
c			∞					
d			∞					
e			∞					
z			∞					

50



10.6 Shortest Path Problems

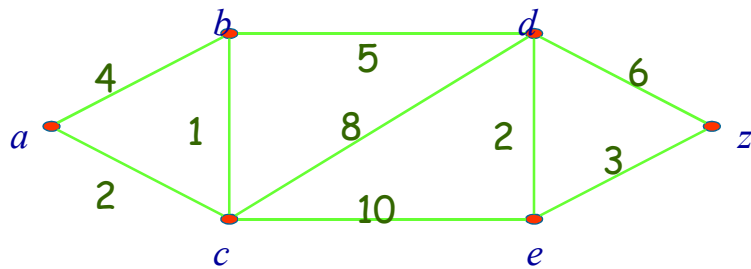


Vertex	S	Link	L_0	L_1				
a	1		0					
b		a	∞	4				
c		a	∞	2				
d			∞	∞				
e			∞	∞				
z			∞	∞				

51



10.6 Shortest Path Problems

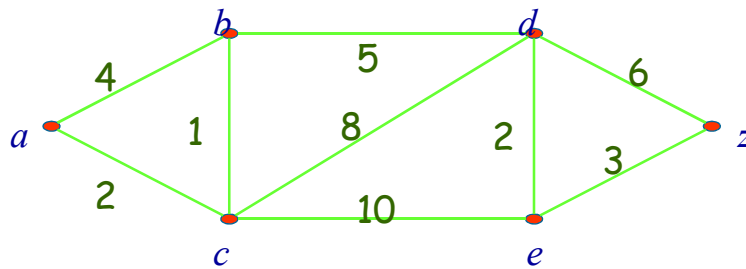


Vertex	S	Link	L_0	L_1	L_2			
a	1		0					
b		a→c	∞	4	3			
c	1	a	∞	2				
d		a→c	∞	∞	10			
e		a→c	∞	∞	12			
z			∞	∞	∞			

52



10.6 Shortest Path Problems

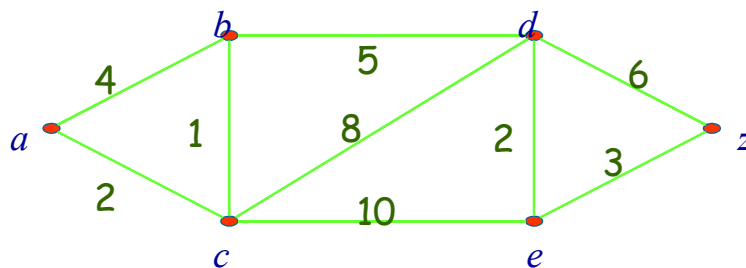


Vertex	S	Link	L ₀	L ₁	L ₂	L ₃		
a	1		0					
b	1	a→c	∞	4	3			
c	1	a	∞	2				
d		a→c→b	∞	∞	10	8		
e		a→c	∞	∞	12	12		
z			∞	∞	∞	∞		

53



10.6 Shortest Path Problems

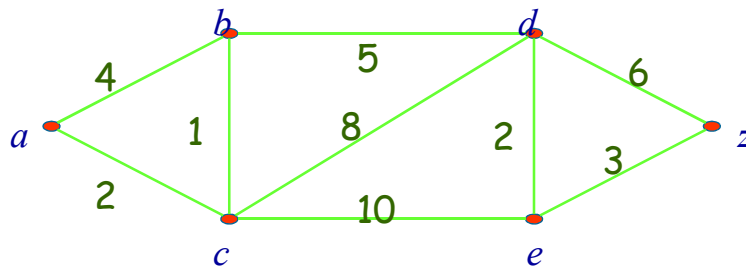


Vertex	S	Link	L ₀	L ₁	L ₂	L ₃	L ₄	
a	1		0					
b	1	a→c	∞	4	3			
c	1	a	∞	2				
d	1	a→c→b	∞	∞	10	8		
e		a→c→b→d	∞	∞	12	12	10	
z		a→c→b→d	∞	∞	∞	∞	14	

54



10.6 Shortest Path Problems

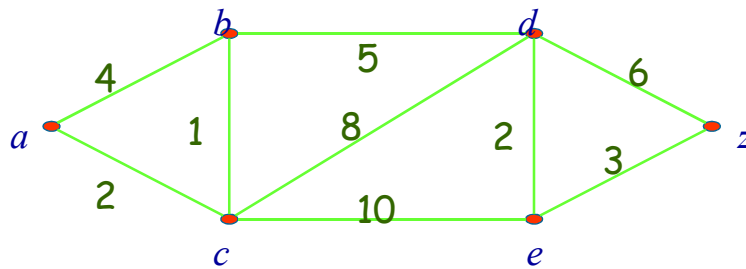


Vertex	S	Link	L ₀	L ₁	L ₂	L ₃	L ₄	L ₅
a	1		0					
b	1	a→c	∞	4	3			
c	1	a	∞	2				
d	1	a→c→b	∞	∞	10	8		
e	1	a→c→b→d	∞	∞	12	12	10	
z		a→c→b→d→e	∞	∞	∞	∞	14	13

55



10.6 Shortest Path Problems



Vertex	S	Link	L ₀	L ₁	L ₂	L ₃	L ₄	L ₅
a	1		0					
b	1	a→c	∞	4	3			
c	1	a	∞	2				
d	1	a→c→b	∞	∞	10	8		
e	1	a→c→b→d	∞	∞	12	12	10	
z	1	a→c→b→d→e	∞	∞	∞	∞	14	13

56



【 Theorem 1 】 Dijkstra's algorithm finds the length of a shortest path between two vertices in a **connected simple undirected weighted graph**.

Proof:

Take as the induction hypothesis the following assertion:
At the k th iteration

- I. the label of every vertex v in S is the length of the shortest path from a to this vertex, and
- II. the label of every vertex not in S is the length of the shortest path from a to this vertex that contains only (besides the vertex itself) vertices in S .

(I) $k=0$

$$S = \emptyset, L_0(a) = 0, L_0(v) = \infty$$



(2) Assume that the inductive hypothesis holds for the k th iteration.

Let v be the vertex added to S at the $(k+1)$ st iteration so that v is a vertex not in S at the end of the k th iteration with the smallest label.

■ (I) holds at the end of the $(k+1)$ st iteration

- ✓ The vertices in S before the $(k+1)$ st iteration are labeled with the length of the shortest path from a .
- ✓ v must be labeled with the length of the shortest path to it from a .

If this were not the case, at the end of the k th iteration there would be a path of length less than $L_k(v)$ containing a vertex not in S .



Let u be *the first* vertex not in S in such a path. There is a path with length less than $L_k(v)$ from a to u containing only vertices of S . This contradicts the choice of v .

■ (II) is true.

Let u be a vertex not in S after $k+1$ iteration.

A shortest path from a to u containing only elements of S either contains v or it does not.

- If it does not contain v , then by the inductive hypothesis its length is $L_k(u)$.
- If it does contain v , then it must be made up of a path from a to v of the shortest possible length containing elements of S other than v , followed by the edge from v to u . In this case its length would be $L_k(v) + w(v, u)$.



【 Theorem 2 】 Dijkstra's algorithm uses $O(n^2)$ operations (additions and comparisons) to find the length of the shortest path between two vertices in a connected simple undirected weighted graph.

Analysis:

- Use no more than $n-1$ iteration
- Each iteration,
 - using no more than $n-1$ comparisons to determine the vertex not in S_k with the smallest label
 - no more than $2(n-1)$ operations are used to update no more than $n-1$ labels



Floyd's Algorithm (find the distance $d(a, b) \forall a, b$)

Procedure *Floyd*(G : weighted simple graph)

$\{G$ has vertices v_1, \dots, v_n and weights $w(v_i, v_j)$ with
 $w(v_i, v_j) = \infty$ if $\{v_i, v_j\}$ is not an edge $\}$

for $i := 1$ **to** n

for $j := 1$ **to** n

$d(v_i, v_j) := w(v_i, v_j)$

for $i := 1$ **to** n

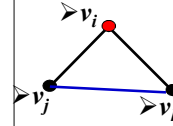
for $j := 1$ **to** n

for $k := 1$ **to** n

if $d(v_j, v_i) + d(v_i, v_k) < d(v_j, v_k)$

then $d(v_j, v_k) := d(v_j, v_i) + d(v_i, v_k)$

$\{d(v_i, v_j)$ is the length of a shortest path between v_i and $v_j\}$



➤对每个 v_i ，检查任何一对点目前的距离会不会因为改走 v_i 而变小。

➤This algorithm cannot be used to construct shortest paths.



10.6 Shortest Path Problems

3. The Traveling Salesman Problem

* The traveling salesman problem

The traveling salesman problem asks for the circuit of minimum total weight in a weighted, complete, undirected graph that visits each vertex exactly once and returns to its starting point.

The equivalent problem:

Find a Hamilton circuit with minimum total weight in the complete graph.



✳ **Solution of the traveling salesman problem**

(1) A straightforward method

Examine all possible Hamilton circuits and select one of minimum total length.

The number of Hamilton circuits: $(n-1)!$

Since a Hamilton circuits can be traveled in reverse order, we need only examine $(n-1)!/2$ circuits to find the answer.

The time complexity: $n!$



(2) Approximation algorithm

These are algorithms that do not necessary produce the exact solution to the problem but instead are guaranteed to produce a solution that is close to an exact solution.

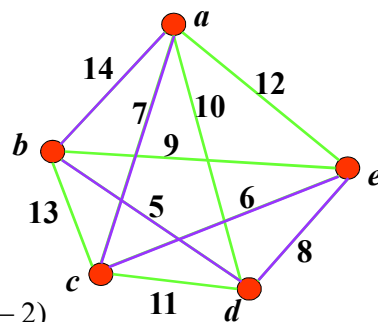
For example,

The length of this path: 40

The exact solution (the length is 37): a, c, e, b, d, a

The time complexity:

$$1 + 2 + 3 + \dots + (n-2) = \frac{1}{2}(n-1)(n-2)$$



Homework:

Sec. 10.6 3, 17a), 26



CHAPTER 10 Graphs

10.1 Graphs and Graph Models

10.2 Graph Terminology and Special Types of Graphs

10.3 Representing Graphs and Graph Isomorphism

10.4 Connectivity

10.5 Euler and Hamilton Paths

10.6 Shortest Path Problems

10.7 Planar Graphs

10.8 Graph Coloring



【Definition】 A graph is called *planar* if it can be drawn in the plane without any edges crossing.

Such a drawing is called a *planar representation* of the graph.

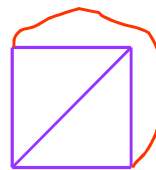
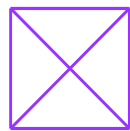
Understanding planar graph is important:

- Any graph representation of maps is planar.
- Electronic circuits usually represented by planar graphs.

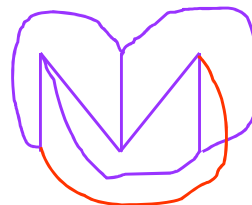
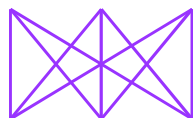


【Example 1】 Are the following graphs planar?

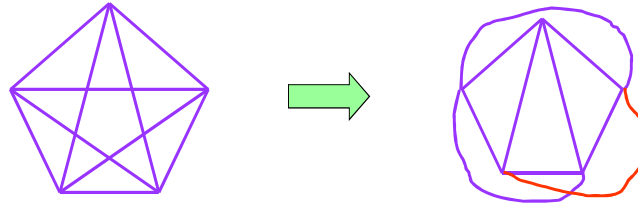
(1)



(2)



(3)

**Note:**

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.

**1. Euler's Formula****Region**

-- A region is a part of the plane completely disconnected off from other parts of the plane by the edges of the graph.

- Bounded region**
- Unbounded region**

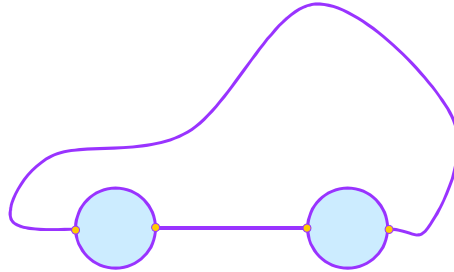
Note:

There is one unbounded region in a planar graph.



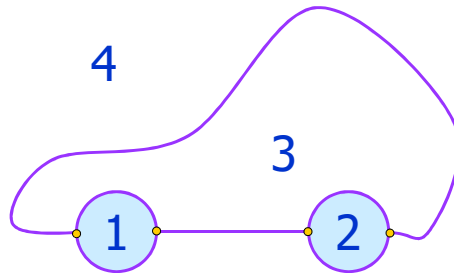
[[Example 2]] How many regions does the following graph have?

(1)

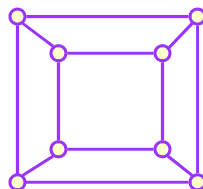


[[Example 2]] How many regions does the following graph have?

(1)

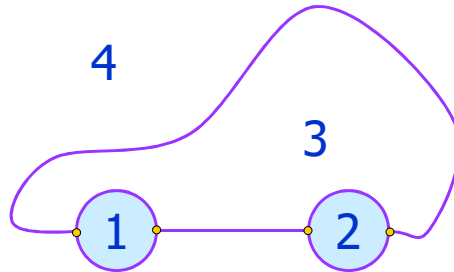


(2)

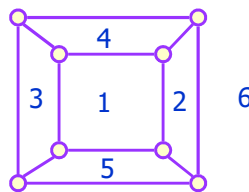


【Example 2】 How many regions does the following graph have?

(1)



(2)



【 Theorem 1 】 Euler's formula

Let G be a **connected planar simple** graph with e edges and v vertices. Let r be the number of regions in a planar representation of G . Then $r=e-v+2$.

Proof:

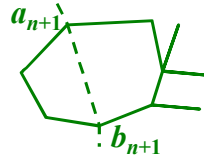
First, we specify a planar representation of G . We will prove the theorem by constructing a sequence of subgraphs $G_1, G_2, \dots, G_e = G$, successively adding an edge at each stage.

The constructing method: Arbitrarily pick one edge of G to obtain G_1 . Obtain G_n from G_{n-1} by arbitrarily adding an edge that is incident with a vertex already in G_{n-1} , adding the other vertex incident with this edge if it is not already in G_{n-1} .

Let r_n, e_n , and v_n represent the number of regions, edges, and vertices of the planar representation of G_n induced by the planar representation of G , respectively.



- (1) The relationship $r_1 = e_1 - v_1 + 2$ is true for G_1 , since $e_1 = 1$, $v_1 = 2$, and $r_1 = 1$.
- (2) Now assume that $r_n = e_n - v_n + 2$. Let $\{a_{n+1}, b_{n+1}\}$ be the edge that is added to G_n to obtain G_{n+1} .
- ◆ Both a_{n+1} and b_{n+1} are already in G_n .



These two vertices must be on the boundary of a common region R , or else it would be impossible to add the edge $\{a_{n+1}, b_{n+1}\}$ to G_n without two edges crossing (and G_{n+1} is planar).

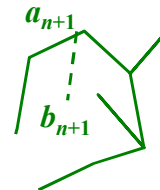
The addition of this new edge splits R into two regions.

Consequently, $r_{n+1} = r_n + 1$, $e_{n+1} = e_n + 1$, and $v_{n+1} = v_n$. Thus, $r_{n+1} = e_{n+1} - v_{n+1} + 2$.



- ◆ One of the two vertices of the new edge is not already in G_n .

Suppose that a_{n+1} is in G_n but that b_{n+1} is not.



Adding this new edge does not produce any new regions, since b_{n+1} must be in a region that has a_{n+1} on its boundary.

Consequently, $r_{n+1} = r_n$. Moreover, $e_{n+1} = e_n + 1$ and $v_{n+1} = v_n + 1$.

Hence, $r_{n+1} = e_{n+1} + 1 - v_{n+1} - 1 + 2$.

Note:

- 1) The Euler's formula is a **necessary condition**.
- 2) How about **unconnected simple planar graph**?

不成立



【Example 3】 Suppose that a connected planar simple graph has 20 vertices, each of degree 3. How many regions does this planar graph have?

Solution:

By handshaking theorem,

$$3v = 2e \Rightarrow e = 30$$

From Euler's formula, the number of regions is

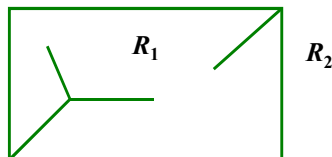
$$r = e - v + 2 = 30 - 20 + 2 = 12$$



【Definition】 Suppose R is a region of a connected planar simple graph, **the number of the edges on the boundary of R is called the *Degree of R* .**

Notation: $\text{Deg}(R)$

For example,



$$\text{Deg}(R_1) = 12$$

$$\text{Deg}(R_2) = 4$$



【 Corollary 1 】 If G is a connected planar simple graph with e edges and v vertices where $v \geq 3$, then $e \leq 3v - 6$

Proof:

Suppose that a connected planar simple graph divides the plane into r regions, the degree of each region is at least 3.

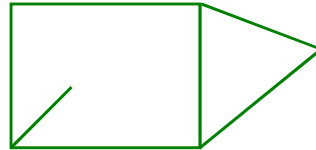
Since $2e = \sum \deg(R_i) \geq 3r$,

it imply $r \leq (2/3)e$

Using Euler's formula $e - v + 2 = r$, we obtain

$e - v + 2 \leq (2/3)e$, this shows that

$e \leq 3v - 6$



Note:

- ◆ The equality holds if and only if every region has exactly three edges.
- ◆ For unconnected planar simple graph, $e \leq 3v - 6$ also holds.

Since for a component, $e_i \leq 3v_i - 6$

$$e = \sum e_i \leq \sum (3v_i - 6) < 3 \sum v_i - 6 = 3v - 6$$



【 Corollary 2 】 If G is a connected planar simple graph, then G has a vertex of degree not exceeding five.

Proof:

- (1) G has one or two vertices
- (2) G has at least three vertices

By Corollary 1, we know that $e \leq 3v - 6$, so $2e \leq 6v - 12$

If the degree of every vertex were at least six, then

$$2e \geq 6v$$



【 Corollary 3 】 If a connected planar simple graph has e edges and v vertices with $v \geq 3$ and no circuits of length 3, then $e \leq 2v - 4$.

Generally, if every region of a connected planar simple graph has at least k edges, then

$$e \leq \frac{(v-2)k}{k-2}$$

$$r = e - v + 2$$

$$kr \leq 2e$$

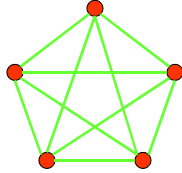
$$r \leq 2e/k$$



[[Example 4]] Show that k_5 , $k_{3,3}$ are nonplanar.

Proof:

(1)



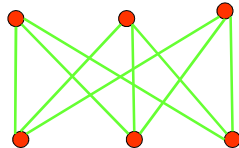
The graph k_5 has 5 vertices and 10 edges.

However, the inequality $e \leq 3v-6$ is not satisfied for this graph since $e=10$ and $3v-6=9$.

Therefore, k_5 is not planar.



(2)



$k_{3,3}$ has 6 vertices and 9 edges.

Since $k_{3,3}$ has no circuits of length 3 (this is easy to see since it is bipartite), Corollary 3 can be used .

Since $e=9$ and $2v-4=8$, corollary 3 shows that $k_{3,3}$ is nonplanar.

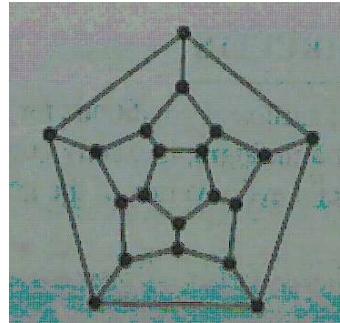


[[Example 5]] The construction of Dodecahedron .

Solution:

Since the degree of every vertex is 3 and the degree of every region is 5. Then

$$\begin{cases} 2e = 3v \\ 2e = 5r \\ r = e - v + 2 \end{cases}$$

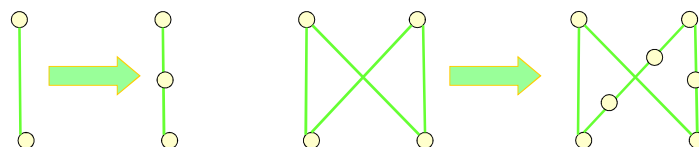


It follows that $v=20$, $e=30$ and $r=12$.



2. KURATOWSKI'S THEOREM

Elementary subdivision

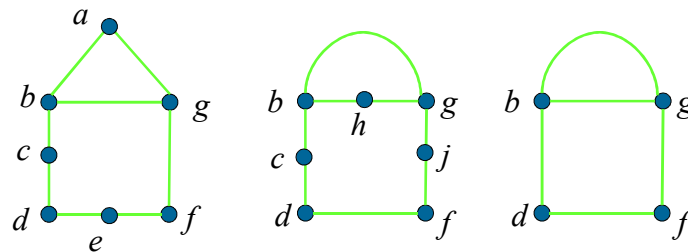


Homeomorphic

-- The graph $G_1=(V_1,E_1)$ and $G_2=(V_2,E_2)$ are called homeomorphic if they can be obtained from the same graph by a sequence of elementary subdivision.



For example,

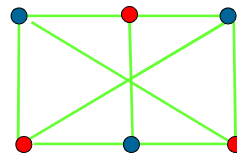
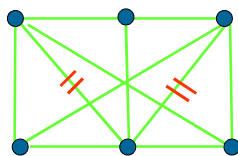


【 Theorem 2 】 A graph is nonplanar if and only if it contains a subgraph homeomorphic to $K_{3,3}$ or K_5 .

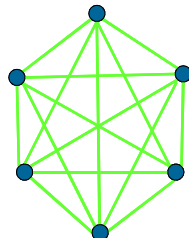


【Example 6】 Determine whether the following graphs are planar.

(1)

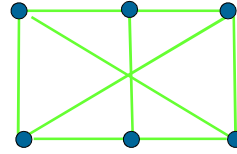
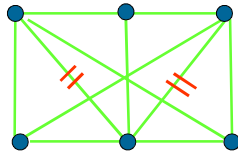


(2)

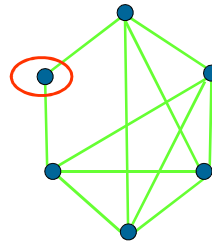
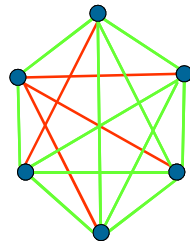


[[Example 6]] Determine whether the following graphs are planar.

(1)

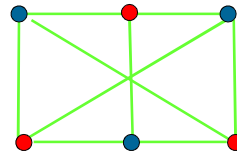
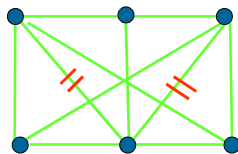


(2)

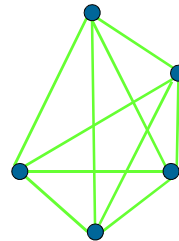
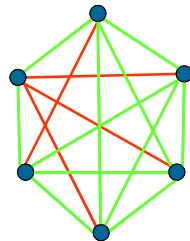


[[Example 6]] Determine whether the following graphs are planar.

(1)

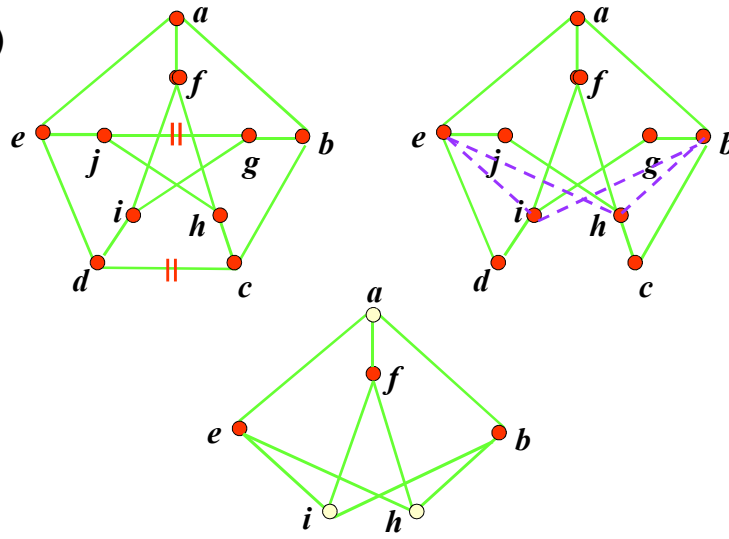


(2)



[[Example 6]] Determine whether the following graphs are planar.

(3)



91



Homework:

Sec. 10.7 7, 20, 22, 23, 25



CHAPTER 10 Graphs

- 10.1 Graphs and Graph Models
- 10.2 Graph Terminology and Special Types of Graphs
- 10.3 Representing Graphs and Graph Isomorphism
- 10.4 Connectivity
- 10.5 Euler and Hamilton Paths
- 10.6 Shortest Path Problems
- 10.7 Planar Graphs
- 10.8 Graph Coloring**

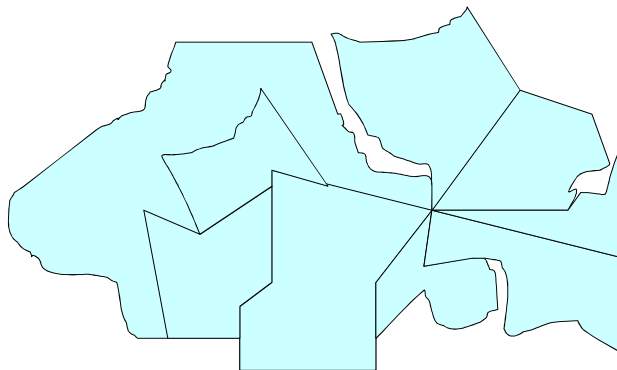
93



10.8 Graph Coloring

The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

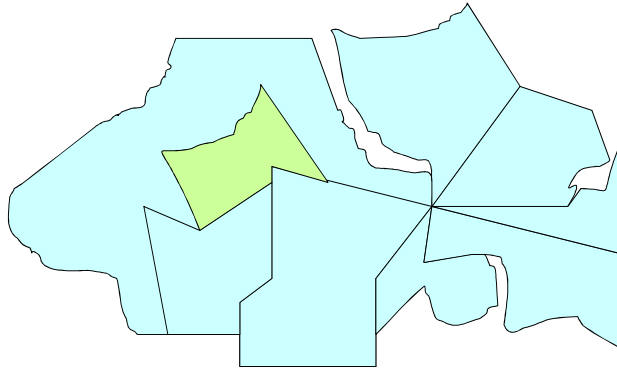


94



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

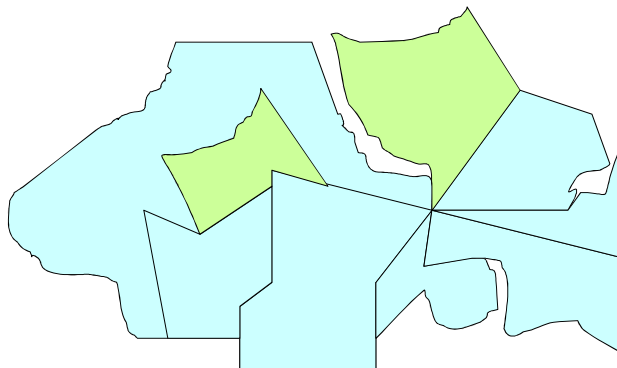


95



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

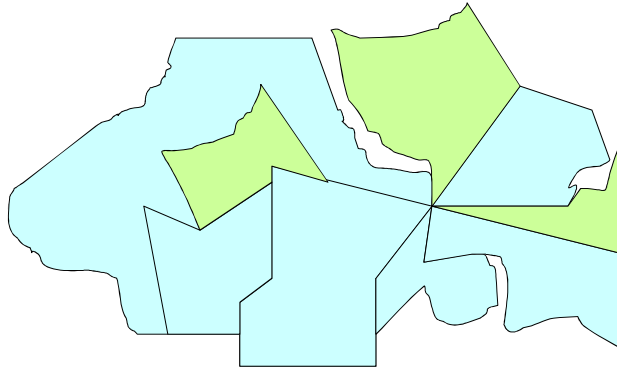


96



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

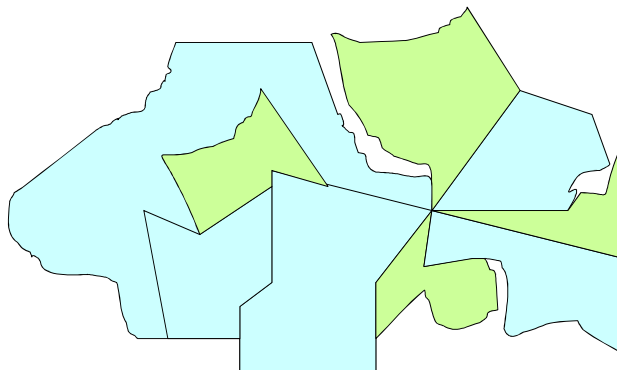


97



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

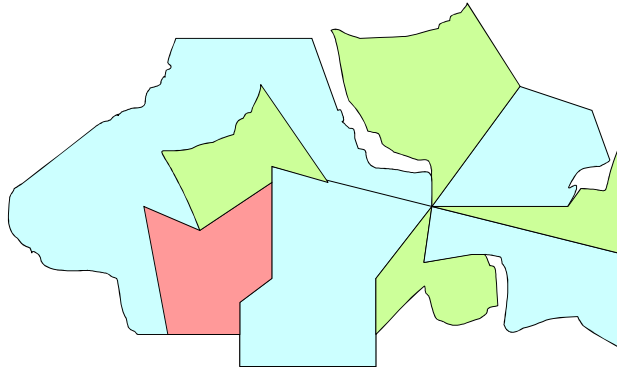


98



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.

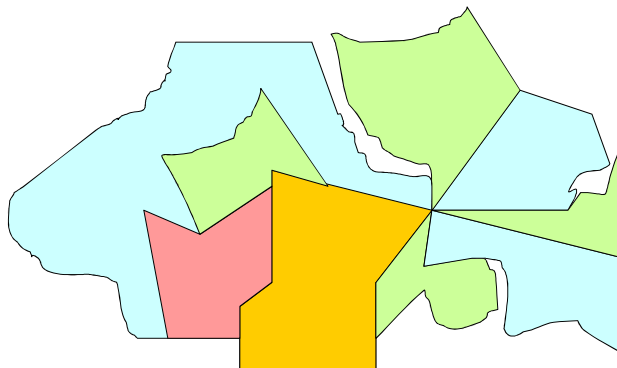


99



The problem related to the coloring of maps:

Determining the least number of colors that can be used to color a map so that adjacent regions never have the same color.



100

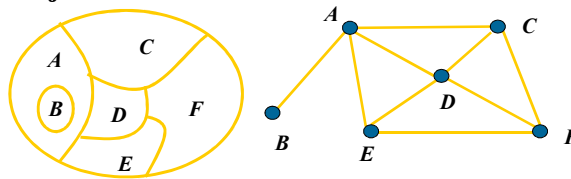


The problem of coloring a map, can be reduced to a graph-theoretic problem.

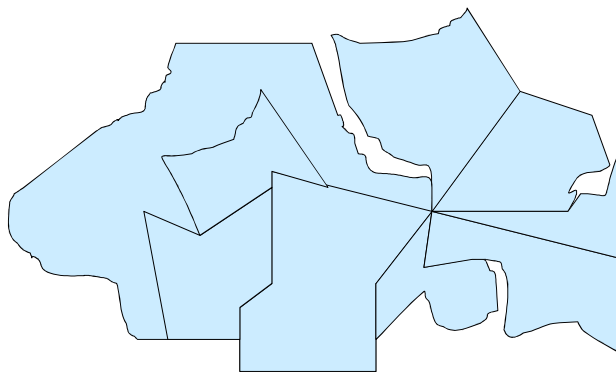
Each map in the plane can be represented by a graph, namely *the dual graph of the map*.

- Each region of the map is represented by a vertex.
- An edge connect two vertices if the regions represented by these vertices have a common border.
- Two regions that touch at only one point are not considered adjacent.

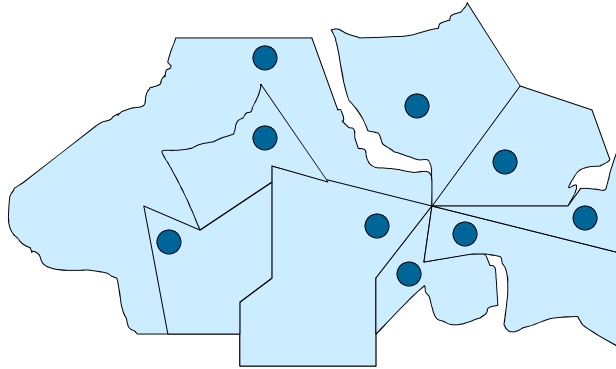
For example,



Coloring a map is equivalent to coloring the vertices of its dual graph so that no two adjacent vertices in this graph have the same color.



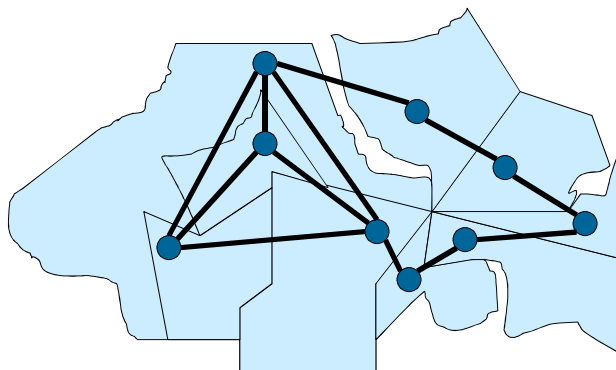
For each region introduce a vertex.



103



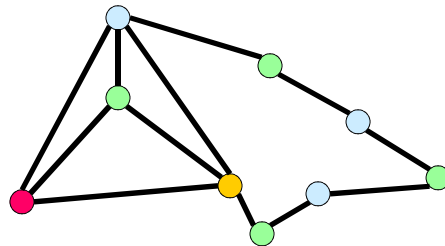
For each pair of regions with a positive-length common border introduce an edge.



104



Coloring regions of a map is equivalent to coloring vertices of its dual graph.



105



Terminologies:

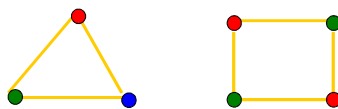
coloring

- A *coloring* of a simple graph is the assignment of a color to each vertex of the graph so that no two adjacent vertices are assigned the same color.

The *chromatic number* of a graph

- is the least number of colors needed for a coloring of this graph, denoted by $\chi(G)$

For example,



106



【 Theorem 1 】 The Four Color Theorem

The chromatic number of **a planar graph** is no greater than four.

- ◆ Any planar map of regions can be depicted using 4 colors so that no two regions with a common border have the same color.
- ◆ The four color theorem was originally proposed as a conjecture in 1850s.
- ◆ Proof by Haken and Appel used exhaustive computer search in 1976.
- ◆ The four color theorem applies only to planar graphs. Nonplanar graphs can have arbitrarily large chromatic numbers.

**1. The chromatic numbers of some simple graphs**

Show that the chromatic numbers of a graph is n .

- Show that the graph can be colored with n colors.
Method: constructing such a coloring.
- Show that the graph cannot be colored using fewer than n colors.

The chromatic numbers of some simple graphs:

- (1) The graph G contains only some isolated vertices.

$$x(G) = 1$$

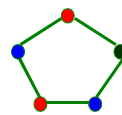
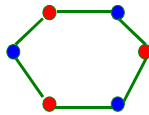


(2) The graph G is a path containing no circuit.

$$x(G) = 2$$



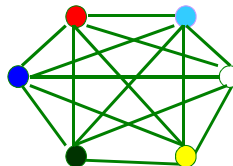
(3) C_n



$$\begin{cases} x(G) = 2 & \text{if } n \text{ is even} \\ x(G) = 3 & \text{if } n \text{ is odd} \end{cases}$$



(4) K_n



$$x(G) = n$$

- (5) A simple graph with a chromatic number of 2 is bipartite.
A connected bipartite graph has a chromatic number of 2.



2. Applications of graph colorings

(1) Scheduling Exams

How can the exams at a university be scheduled so that no student has two exams at the same time?

Solution:

This scheduling problem can be solved using a graph model, with vertices representing courses and with an edge between two vertices if there is a common student in the courses they represent.

Each time slot for a final exam is represented by a different color.

A scheduling of the exams corresponds to a coloring of the associated graph.



For example, Suppose we want to schedule some final exams for CS courses with following code numbers:

1007, 3137, 3157, 3203, 3261, 4115, 4118, 4156

Suppose also that there are no common students in the following pairs of courses because of prerequisites:

1007-3137

1007-3157, 3137-3157

1007-3203

1007-3261, 3137-3261, 3203-3261

1007-4115, 3137-4115, 3203-4115, 3261-4115

1007-4118, 3137-4118

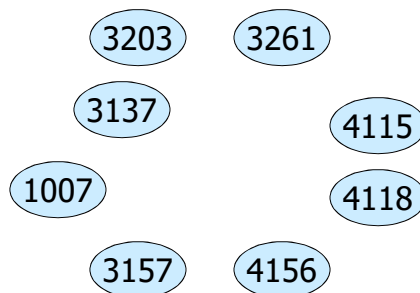
1007-4156, 3137-4156, 3157-4156

How many exam slots are necessary to schedule exams?



Turn this into a graph coloring problem.

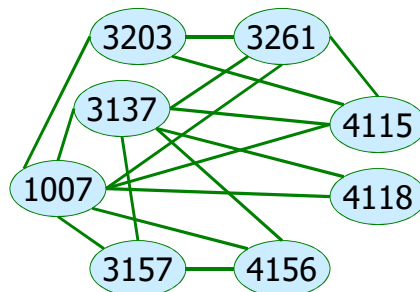
-- Vertices are courses, and edges connect courses which *cannot* be scheduled simultaneously because of possible common students in both courses



113



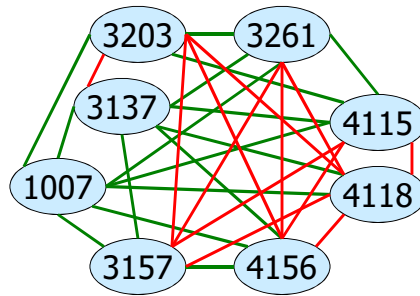
One way to do this is to put edges down where students mutually excluded...



114



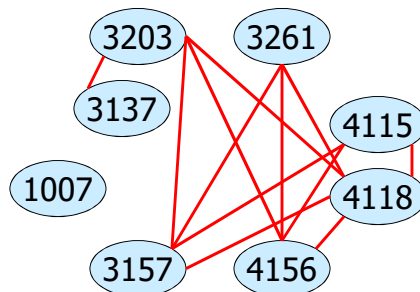
...and then compute the complementary graph:



115



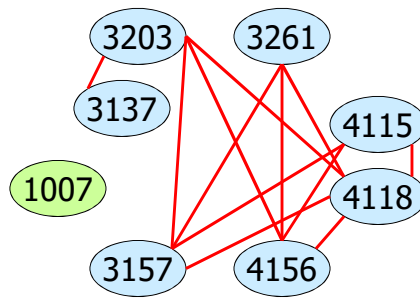
...and then compute the complementary graph:



116



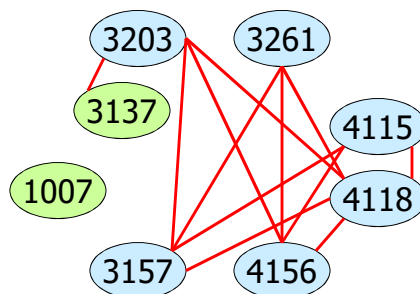
Coloring ...



117



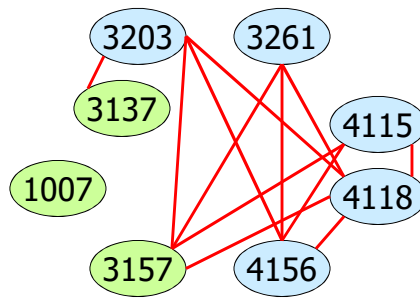
Coloring ...



118



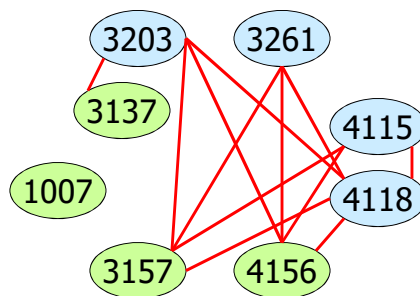
Coloring ...



119



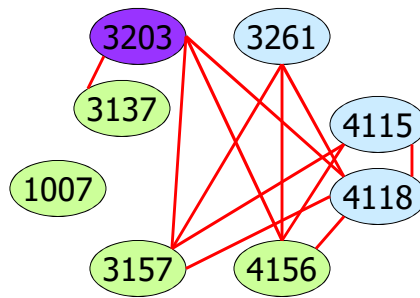
Coloring ...



120



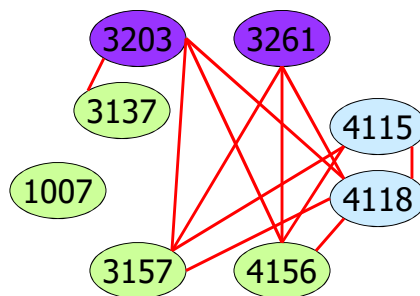
Coloring ...



121



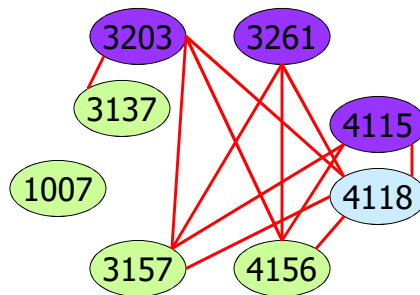
Coloring ...



122



Coloring ...



123



2. Applications of graph colorings

(2) Set up natural habitats of animals in a zoo

Solution:

Let the vertices of a graph represent the animals.

Draw an edge between two vertices if the animals they represent cannot be in the same habitat because of their eating habits.

A coloring of this graph gives an assignment of habitats.

124



Homework:

Sec. 10.8 3, 8, 9, 10, 17

