

Discrete Mathematics Lecture Notes (WS18/19)

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Lecture 1 (10.10.2018)

Prelude: Motivation

What is the aim of the lecture?

Learn basic frameworks used in all areas of mathematics:

- Mathematicians deal with statements
- Usually the statements are about numbers
- The statements may be true or false
- To decide whether a statement is true or false requires a proof
- Use this framework to acquire some knowledge about principles of counting
- Graph theory has a direct application in real world problems
- The basic knowledge about algebraic methods will be used in coding theory

Example:

1. 15 is a multiple of 3
2. 20 is a multiple of 3

Theorem: 15 is a multiple of 3

Proof: $15 = 3 * 5$

Chapter 1: Principles of Counting

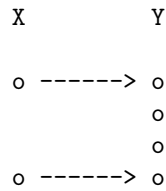
Basic Counting Problems

- Permutation: $\frac{n!}{(n-r)!}$
- Combinations: $\frac{n!}{(n-r)!r!}$

Definition 1.2.1

Remarks

Suppose that X and Y are sets. We say that we have a function/map from X to Y if for each $x \in X$ we can specify a unique element in Y , which we denote by $f(x)$.



- $f(x)$ is defined $\forall x \in X$
- these are just one such object $\forall x \in X$

Inverse Image Example

Given the function

$$f : \{1, 2, 3\}' \mapsto \{a, b, c, d\} \quad (1)$$

defined by

$$f(x) = \begin{cases} a, & \text{if } x = 1 \\ a, & \text{if } x = 2 \\ c, & \text{if } x = 3 \end{cases} \quad (2)$$

The produced map is:

$$\begin{array}{ccc}
 a & \rightarrow & 1 \\
 a & \rightarrow & 2 \\
 b & & \\
 c & \rightarrow & 3 \\
 d & &
 \end{array} \quad (3)$$

The image/inverse image of the following sets under f are:

1. set $\{2, 3\}$; image: $\{a, c\}$
2. set $\{a\}$; inverse image: $\{1, 2\}$
3. set $\{a, b\}$; inverse image: $\{1, 2\}$
4. set $\{b, d\}$; inverse image: \emptyset

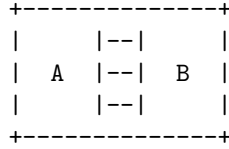
Definition 1.2.2 Cardinality

A set A is finite if a bijective mapping $A \mapsto \{1, \dots, n\}$ exists. (*This means that there is exactly n number of elements inside set A .*)

In this case n is called the **cardinality** of A and A has $|A| := n$ elements.

Two sets A, B are defined to have the same cardinality if a bijective mapping $A \mapsto B$ exists.

Not Disjoint Sets



1. $A = \{1, 2, 3, 4, 5\}, |A| = 5$
2. $B = \{3, 4, 5, 6, 7\}, |B| = 5$

$$|A \cup B| \tag{4}$$

$$= |1, 2, 3, 4, 5, 6, 7| \tag{5}$$

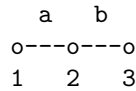
$$= 7 \tag{6}$$

$$\neq |A| + |B| \tag{7}$$

Counting Sets

1. $|X \cup Y| = |X| + |Y| - |X \cap Y|$
2. $|X \cup Y \cup Z| = |X| + |Y| + |Z| + (|X \cap Y| + |X \cap Z| + |Y \cap Z|) - |X \cap Y \cap Z|$

Double Counting Principle



1. $N = 1, 2, 3$, (nodes)
2. $E = a, b$ (edges)
3. R = incidence

$$|R| \text{ (over the nodes)} \tag{8}$$

$$= |x \in E|1 \text{ is incident to } x| + |x \in E|2 \text{ is incident to } x| + |x \in E|3 \text{ is incident to } x| \tag{9}$$

$$= |a| + |a, b| + |b| \tag{10}$$

$$= 4 \tag{11}$$

$$|R| \text{ (over the edges)} \tag{12}$$

$$= |x \in N|x \text{ is incident to } a| + |x \in N|x \text{ is incident to } b| \tag{13}$$

$$= |1, 2| + |2, 3| \tag{14}$$

$$= 4 \tag{15}$$

Lecture 2 (17.10.2018)

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Examples

- 1) The first person may choose among 100 seats, the second among 99 etc.
So we have $100 * 99 * \dots$

$$\frac{100!}{(100 - 95)!}, (n)_k \quad (16)$$

- 2) Let the pearls be enumerated by 1 to n . Then we cut the necklace at the part with number 1. So each assignment of pearls is bijectively mapped to an n -list, where the first element of the list always is the pearl with numbers 1. So there exists $(n - 1)!$ possibilities

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Example

A card game consists of 52 cards:

- Each card has a suit out of {I, II, III, IV}
- Each card has a value out of {2, 3, 4, 5, 6, 7, 8, 9, 10, J, Q, K, A}
- 2 cards form a pair, if they have the same value

How many possibilities exist so that we have among 5 arbitrary cards one pair and 3 cards with each the same value (but other than the pair)?

Solution

- 1) Choose the value of the pairs (13 possibilities)
- 2) Choose the value of the three cards (12 possibilities)
- 3) Choose the suit of the pair ($4C2 = 6$ possibilities)
- 4) Choose the suit of the other three cards ($4C3 = 4$ possibilities)

Therefore, we need the product rule:

$$p = 13 * 12 * C(4, 2) * C(4, 3) \quad (17)$$

$$= 3744 \quad (18)$$

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$$C(n, m_1) * C(n - m_1, m_2) * \dots * C(m_k, m_k) \quad (19)$$

$$= \frac{n!}{(n - m_1)!m_1!} * \frac{(n - m_1)!}{(n - m_1 - m_2)!m_2!} * \dots * \frac{m_k!}{m_k!(m_k - m_k!)} \quad (20)$$

$$= \frac{n!}{m_1! * \dots * m_k!} \quad (21)$$

Lecture 3 (24.10.2018)

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The Stirling numbers $s_{n,k}$ of first order is the number of permutation of a n -set with exactly k cycles

Theorem 1.8.4

$S(n, 1) = 1$, $S(n, n) = 1$ denotes from set n , choosing 1 partition or n partitions results in only one element

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Let f, g be the permutation

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 1 & 4 & 5 & 3 \end{pmatrix} \quad (22)$$

$$g = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 1 & 4 & 5 & 1 \end{pmatrix} \quad (23)$$

then

$$f \circ g = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 4 & 5 & 3 & 2 \end{pmatrix} \quad (24)$$

$$g \circ f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 3 & 2 & 5 & 1 & 4 \end{pmatrix} \quad (25)$$

This example shows that in general the composition of permutation is not commutative since a permutation is bijective, also the inverse function is a permutation.

Let f be

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 1 & 4 & 5 & 3 \end{pmatrix} \quad (26)$$

First we invert, then we order the first row

$$f^{-1} = \begin{pmatrix} 2 & 1 & 4 & 5 & 3 \\ 1 & 2 & 3 & 4 & 5 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 1 & 5 & 3 & 4 \end{pmatrix} \quad (27)$$

$$f \circ f^{-1} = id, f^{-1} \circ f = id \quad (28)$$

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Example

Let f be

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 2 & 4 & 8 & 1 & 5 & 9 & 3 & 7 & 6 \end{pmatrix} \quad (29)$$

We take the cycles without repetition:

- i. 1: $1 \mapsto 2 \mapsto 4 \mapsto 1$. The cycle is $(1, 2, 4)$
- ii. 3: $3 \mapsto 8 \mapsto 7 \mapsto 3$. The cycle is $(3, 8, 7)$
- iii. 5: $5 \mapsto 5$. The cycle is (5)
- iv. 6: $6 \mapsto 9 \mapsto 6$. The cycle is $(6, 9)$

The cycle representation of f is:

$$f = (1, 2, 4) \circ (3, 8, 7) \circ (5) \circ (6, 9) \quad (30)$$

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Let f be the permutation which describes the change of sorting:

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 1 & 5 & 9 & 2 & 6 & 10 & 3 & 7 & 11 & 4 & 8 & 12 \end{pmatrix} \quad (31)$$

$$= (2, 5, 6, 10, 4) \circ (3, 9, 11, 8, 7) \text{ (starting the cycle at 2)} \quad (32)$$

Since the two cycles have length 5, the cards are back to its original position after 5 procedures.

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Let f be a composition of transpositions:

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix} \quad (33)$$

$$= (1, 2, 3, 4) \quad (34)$$

$$= (1, 4) \circ (1, 3) \circ (1, 2) \quad (35)$$

But also adding $(3, 4)$ and $(4, 3)$ doesn't change the identity:

$$f = (1, 4) \circ (4, 3) \circ (3, 4) \circ (1, 3) \circ (1, 2) \quad (36)$$

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Further Remarks

Generalization of polynomials, where the number of terms is allowed to be infinite. The solution of a combinatorial problem can often be expressed as a sequence u_n . In such cases it is often appropriate to use methods based on the representation of u_n as a power series:

$$U(x) = u_0 + u_1x + u_2x^2 + \dots \quad (37)$$

where $U(x)$ is called the generating function for the sequence u_n

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Taylor Series

The n-th Taylor polynomial is defined as:

$$T_n f(x, a) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x - a)^k \quad (38)$$

$$= f(a) + f'(a)(x - a) + \frac{f''(a)}{2}(x - a)^2 + \dots \quad (39)$$

In the special case where $a = 0$, then the Taylor series is called McLaurin series.

$$f(x) = (1 + x)^n \quad (40)$$

$$\Rightarrow f^{(k)}(x) \quad (41)$$

$$= (n(1 + x)^{n-1})^{(k-1)} \quad (42)$$

$$= (n(n-1)(1 + x)^{n-2})^{(k-2)} * \dots \quad (43)$$

$$= n(n-1) * (n(1 + x)^{n-1})^{(k-1)} * \dots \quad (44)$$

$$\Rightarrow f^{(k)}(0) = n(n-1)(n-2) * \dots * (n - (k-1)) \quad (45)$$

This is to compute the sequence of coefficients from the generating function. The other way round, given a sequence and then compute the function is easy: sequence

$$\langle f_0, f_1, \dots \rangle = F(x) = f_0x^0 + f_1x^1 + f_2x^2 + \dots \quad (46)$$

$$F(x) = (1 + x)^n = \binom{n}{0} + (n, 1)x + (n, 2)x^2 + \dots \quad (47)$$

can be regarded as saying the the generating function for the sequence defined by $u_n = (n, k)$ for any given integer n is $F(x) = (1 + x)^n$

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Convolution definition

$$c_k = a_0b_k + a_1b_{k-1} + \dots + a_kb_0 \quad (48)$$

Example

Given

$$f(x) = 2 + 3x - 4x^2 \quad (49)$$

$$g(x) = 5 - x + x^3 \quad (50)$$

$$c_0 = a_0b_0 = 2 * 5 = 10 \quad (51)$$

$$c_1 = a_0b_1 + a_1b_0 = (2 * -1) + (3 * 5) = 13 \quad (52)$$

$$c_2 = a_0b_2 + a_1b_1 + a_2b_0 = (2 * 0) + (3 * -1) + (-4 * 5) = -23 \quad (53)$$

$$f(x) * g(x) = c_0 + c_1x^1 + c_2x^2 + \dots \quad (54)$$

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Example

Geometrical Series

$$(1 - x) \sum_{k=0}^{\infty} x^k \quad (55)$$

$$= \sum_{k=0}^{\infty} x^k - \sum_{k=0}^{\infty} x^{k+1} \quad (56)$$

$$= 1 + \sum_{k=1}^{\infty} x^k - \sum_{k=1}^{\infty} x^k = 1 \quad (57)$$

So $(1 - x)$ is inverse to the geometrical series and we get $\sum_{k=0}^{\infty} x^k = \frac{1}{1-x}$

Here are some more generating functions:

$$\sum_{k=0}^{\infty} (-1)^k x^k \quad (58)$$

$$= 1 - x + x^2 - x^3 + \dots \quad (59)$$

$$\hat{=}(1, -1, 1, -1, \dots) \quad (60)$$

$$\sum_{k=0}^{\infty} x^2 k \quad (61)$$

$$= 1 + x^2 + x^4 + x^6 + \dots \quad (62)$$

$$\hat{=}(1, 0, 1, 0, 1, \dots) \quad (63)$$

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$$F_n = F_{n-1} + F_{n-2} \quad (64)$$

The above equation is a homogeneous (no constants) linear recursion equation of second order (going back 2 steps)

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Example: Fibonacci Numbers

The main idea now is to expand the right series as a formal power series. To do this we factorize the denominator. We put:

$$1 - x - x^2 = (1 - ax)(1 - bx) \quad (65)$$

If we substitute $x = \frac{1}{y}$, equation (2) is equivalent to

$$1 - \frac{1}{y} - \frac{1}{y^2} = (1 - \frac{a}{y})(1 - \frac{b}{y}) \quad (66)$$

$$\Leftrightarrow y^2 - y - 1 \quad (67)$$

$$= (y - a)(y - b) \quad (68)$$

$$y_{1,2} = \frac{1}{2} + \sqrt{\frac{1}{4} + 1} \quad (69)$$

$$= \frac{1}{2} + \frac{\sqrt{5}}{2} \quad (70)$$

The zeroes of $y^2 - y - 1$ are:

$$a = \frac{1}{2} + \frac{\sqrt{5}}{2}, \quad b = \frac{1}{2} - \frac{\sqrt{5}}{2} \quad (71)$$

Now we decompose into partial fractions

$$\frac{1+x}{1-x-x^2} = \frac{\alpha}{(1-ax)} + \frac{\beta}{(1-bx)} \quad (72)$$

$$1+x = \alpha(1-bx) + \beta(1-ax) \quad (73)$$

$$1+x = \alpha + \beta + (-\alpha b - \beta a)x \quad (74)$$

$$\Rightarrow \alpha + \beta = 1, \quad -\alpha b - \beta a = 1 \quad (75)$$

$$\Rightarrow \alpha = \frac{1+a}{-b+a} = \frac{1+a}{\sqrt{5}}, \quad \beta = 1 - \frac{1+a}{\sqrt{5}} = -\frac{1+b}{\sqrt{5}} \quad (76)$$

Each summand from the right hand side is now expanded by the sum rule for the geometrical series:

$$\Rightarrow \frac{1+x}{1-x-x^2} = \frac{1+a}{\sqrt{5}(1-ax)} - \frac{1+b}{\sqrt{5}(1-bx)} \quad (77)$$

$$= \frac{1+a}{\sqrt{5}} \sum_{k=0}^{\infty} a^k x^k - \frac{1+b}{\sqrt{5}} \sum_{k=0}^{\infty} b^k x^k \quad (78)$$

$$= \sum_{k=0}^{\infty} \left[\frac{1+a}{\sqrt{5}} a^k - \frac{1+b}{\sqrt{5}} b^k \right] x^k \quad (79)$$

$$\Rightarrow F_k = \frac{a^{k+2}}{\sqrt{5}} - \frac{b^{k+2}}{\sqrt{5}} \quad (1+a = a^2, 1+b = b^2) \quad (80)$$

We can then compute the specific numbers k in F_k :

$$F_2 = \frac{(\frac{1}{2} + \frac{\sqrt{5}}{2})^4}{\sqrt{5}} - \frac{(\frac{1}{2} + \frac{\sqrt{5}}{2})^4}{\sqrt{5}} \quad (81)$$

$$= 3 \quad (82)$$

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Special case: Fibonacci numbers

$$F_n = F_{n-1} + F_{n-2} \quad (83)$$

So we have $k = 0, h_k = 0, \beta_1 = -1, \beta_2 = -1, \beta_j = 0$ for $3 \leq j \leq n$

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Remark on the proof 1.10.5

$$p_{n+k} = \sum_{j=0}^n a_{n+k-j} \beta_j = 0, \quad \forall k \geq 0 \quad (84)$$

$$A(x) = a_0 + a_1 x + a_2 x^2 + \dots \quad (85)$$

$$A(x) = \sum_{j=0}^n \beta_j x^j \quad (86)$$

$$= a_0 \beta_0 x^0 + (a_0 \beta_1 + a_1 \beta_0) x^1 + (a_0 \beta_2 + a_1 \beta_1 + a_2 \beta_0) x^2 + \dots \quad (87)$$

$$= \underbrace{(a_0 \beta_n + a_1 \beta_{n-1} + \dots + a_n \beta_0)}_{= 0 \text{ due to recursion formula}} x^n \quad (88)$$

At first we substitute in the equation $1 + \beta_1 x + \beta_2 x^2 + \dots = 0$

After multiplication by y^n we get the auxiliary equation:

$$y^n + \beta_1 y^{n-1} + \dots + \beta_n = 0 \quad (89)$$

According to the fundamental theorem of algebra, there exists numbers:

$$y_1, \dots, y_5 \in \mathbb{C} \quad (90)$$

such that:

$$y^n + \beta_1 y^{n-1} + \dots + \beta_n = (y - y_1)^{m_1} (y - y_2)^{m_2} \dots (y - y_5)^{m_5} \quad (91)$$

and

$$\sum_{j=0}^5 m_j = n \quad (92)$$

By back substituting, we have:

$$1 + \beta_1 x + \beta_2 x^2 + \dots + \beta_n x^n = x^n (y^n + \beta_1 y^{n-1} + \dots + \beta_n) \quad (93)$$

$$= x^n (y - y_1)^{m_1} (y - y_2)^{m_2} \dots (y - y_5)^{m_5} \quad (94)$$

$$= x^n \left(\frac{1}{x} - y_1\right)^{m_1} \left(\frac{1}{x} - y_2\right)^{m_2} \dots \left(\frac{1}{x} - y_5\right)^{m_5} \quad (95)$$

$$= (1 - y_1 x)^{m_1} (1 - y_2 x)^{m_2} \dots (1 - y_5 x)^{m_5} \quad (96)$$

So:

$$A(x) = \frac{P(x)}{(1 - y_1x)^{m_1}(1 - y_2x)^{m_2} \dots (1 - y_5)^{m_5}} \quad (97)$$

According to the theorem of partial fraction decomposition, it holds:

$$A(x) = \sum_{k=1}^5 \frac{H_k(x)}{(1 - y_kx)^{m_k}} \quad (98)$$

with polynomial H_k and $\deg(H_k) < m_k$.

Futhermore for each summand holds (omitting index k) due to partial fraction decomposition:

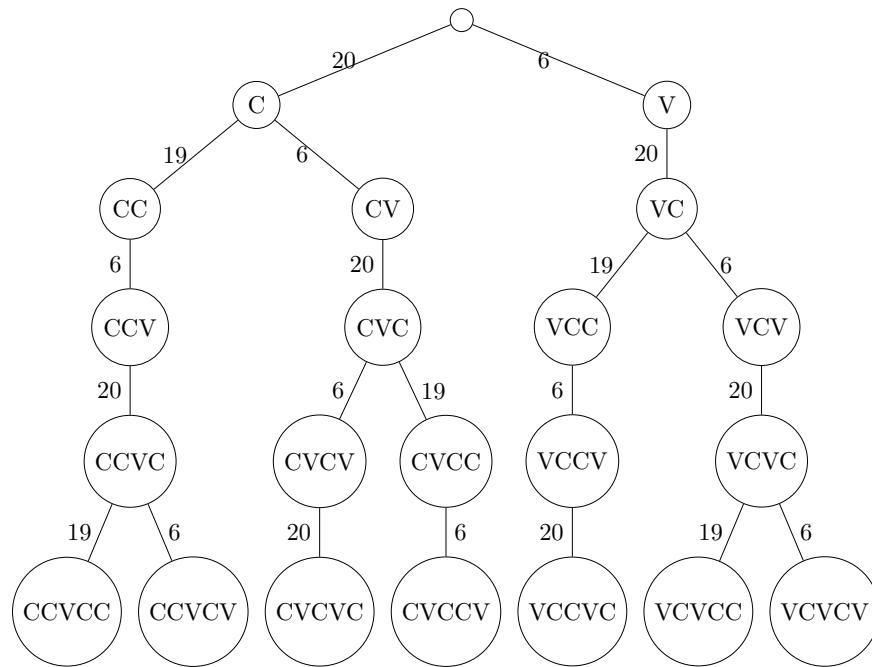
$$\frac{H(x)}{(1 - \beta x)^m} = \sum_{j=1}^m \frac{\gamma_j}{(1 - \beta x)^j}, \quad \gamma_j \in \mathbb{R} \quad (99)$$

Each summand on the right hand sind can now be expanded by means of the geometrical series into a power series.

Lecture 4 (7.11.2018)

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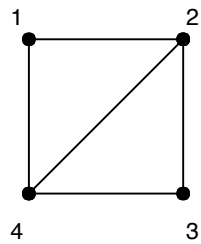
The number of possibilities for the leaves are:



For example: $CCVCC : 19 * 20 * 6 * 19 * 20$

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Example double counting principle



$v \backslash E$	$\{1, 2\}$	$\{1, 4\}$	$\{4, 3\}$	$\{3, 2\}$	$\{4, 2\}$	countSum
1	x	x				2
2	x			x	x	3
3			x	x		2
4		x	x		x	3
	2	2	2	2	2	10

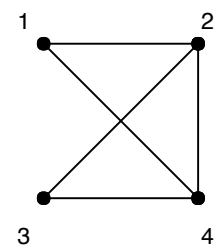
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Remark to proof 2.1.4

$|V_0|$ has to be even because:

t	even	odd
even	even	odd
odd	odd	even

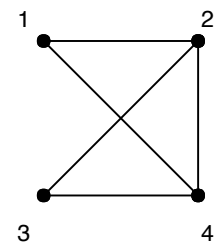
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1	2	3	4
2	1	2	1
4	3	4	2
	4		3

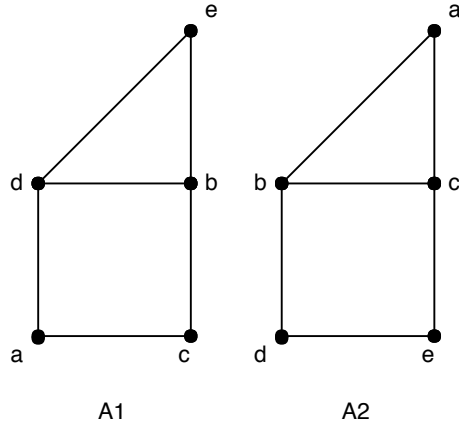
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Example adjacency matrix



$$\begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \quad (100)$$

Another adjacency matrix



$$A_1 = \begin{pmatrix} 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \end{pmatrix} \quad (101)$$

$$A_2 = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 \end{pmatrix} \quad (102)$$

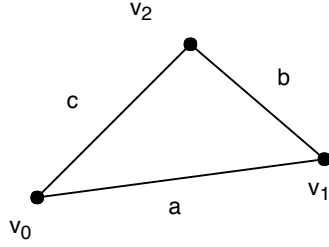
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Remarks to the Proof 2.3.3 (No. 2)

- Here we have the case $\{u, v\} \in E$. So $\{3, 2\} \in E$, $G' = (V', E')$, $V' = V \cup \{a\}$, $E' = E \cup \{\{2, a\}, \{3, a\}\}$ and a closed Euler line is $(1, 2, a, 3, 4, 2, 3, 1)$
- Here we have the case $\{u, v\} \notin E$. So $\{1, 3\} \notin E$, $G' = (V, E')$, $E' = E \cup \{\{1, 3\}\}$ and a closed Euler line is $(1, 3, 5, 4, 3, 2, 1)$

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Example



- a. $w = v_0, \quad F = E = \{a, b, c\}$
- b. $\deg(v_0, F) = 2 \Rightarrow v_1$ with $\{v_0, v_1\} \in F, W = (v_0, v_1), F = \{b, c\}$
- c. $\deg(v_1, F) = 1 \Rightarrow v_2$ with $\{v_2, v_1\} \in F, W = (v_0, v_1, v_2), F = \{c\}$
- d. $\deg(v_2, F) = 1 \Rightarrow v_0$ with $\{v_2, v_0\} \in F, W = (v_0, v_1, v_2, v_0), F = \emptyset$
- e. $\deg(v_0, F) = 0 \Rightarrow \text{STOP}$

Lecture 5 (14.11.2018)

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The principle of induction

Suppose that $P(n)$ is a statement with the following properties:

- a. $P(1)$ is true (induction basis)
- b. if $P(k)$ is true (induction hypothesis), then $P(k + 1)$ is true (induction step) $\forall k \in \mathbb{N}$, then $P(n)$ is true $\forall n \in \mathbb{N}$

Example

Prove that $\forall n \in \mathbb{N}, n^3 + 5n$ is a multiple of 6:

- a. $P(1)$ is true: $1^3 + 5 \cdot 1 = 6$ is a multiple of 6
- b. Suppose that $P(k)$ is true, that is $k^3 + 5k = 6m, m \in \mathbb{N}$. We have to deduce that $P(k + 1)$ is true.

Inserting

$$n = k + 1 : (k + 1)^3 + 5(k + 1) \quad (103)$$

$$= k^3 + 3k^2 + 3k + 1 + 5k + 5 \quad (104)$$

In order to use the assumption, we rewrite this as follows:

$$(k^3 + 5k) + 3(k^2 + k + 2) = 6m + 3k(k + 1) + 6 \quad (105)$$

Now $k(k + 1)$ is an even number, say:

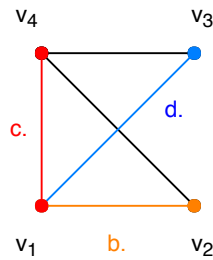
$$2r \Rightarrow 4m + 3k(k + 1) + 6 = 6m + 6r + 6 \quad (106)$$

$$= 6(m + r + 1) \quad (107)$$

We have shown that $P(1)$ is true, and that if $P(k)$ is true, then $P(k+1)$ is true. Applying the principle of induction, it follows that $P(n)$ is true $\forall n \in \mathbb{N}$

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Example: Generic Algorithm



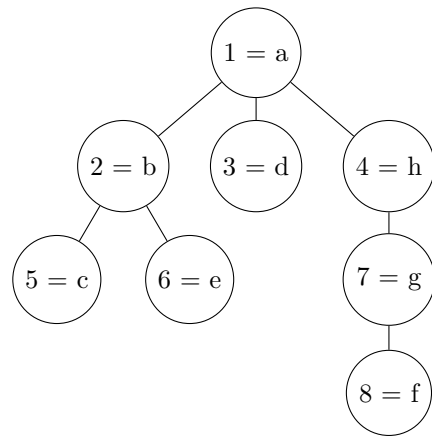
- $W = \{v_1\}, \quad F = \emptyset, \quad L = \{(v_1, v_2), (v_1, v_4), (v_1, v_3)\}$ (Choose (v_1, v_2))
- $W = \{v_1, v_2\}, \quad F = \{\{v_1, v_2\}\}, \quad L = \{(v_2, v_4), (v_1, v_4), (v_1, v_3)\}$ (Choose (v_1, v_4))
- $W = \{v_1, v_2, v_4\}, \quad F = \{\{v_1, v_2\}, \{v_1, v_4\}\}, \quad L = \{(v_1, v_3), (v_4, v_3)\}$ (Choose (v_1, v_3))
- $W = \{v_1, v_2, v_4, v_3\}, \quad F = \{\{v_1, v_2\}, \{v_1, v_4\}, \{v_1, v_3\}\}, \quad L = \emptyset$

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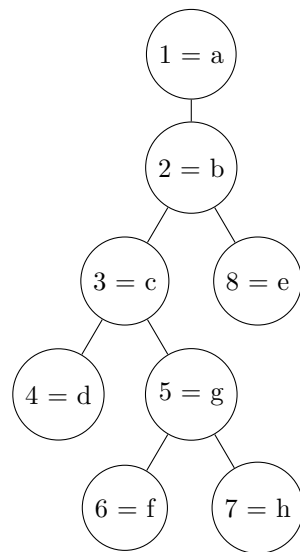
Edge table:

a	b	c	d	e	f	g	h
bdh	acde	bdg	abc	b	g	cfh	ag

Example: BFS

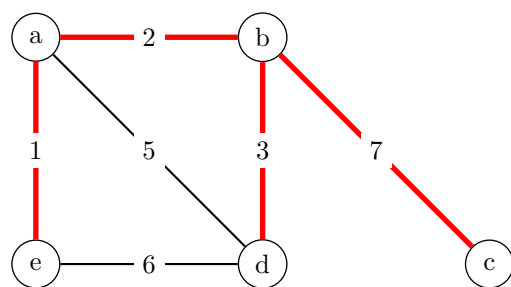


Example: DFS



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Example: Prim's Algorithm



Start with node $z = a$

- add $\{a, e\}$ with cost 1
- add $\{a, b\}$ with cost 2
- add $\{b, d\}$ with cost 3
- add $\{b, c\}$ with cost 7