

CS1231S

AY20/21 sem 1

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01. PROOFS

sets of numbers

\mathbb{N} : natural numbers ($\mathbb{Z}_{\geq 0}$)

\mathbb{Z} : integers

\mathbb{Q} : rational numbers

\mathbb{R} : real numbers

\mathbb{C} : complex numbers

basic properties of integers

closure (under addition and multiplication)

$$x + y \in \mathbb{Z} \wedge xy \in \mathbb{Z}$$

commutativity

$$a + b = b + a \wedge ab = ba$$

associativity

$$a + b + c = a + (b + c) = (a + b) + c$$

$$abc = a(bc) = (ab)c$$

distributivity

$$a(b + c) = ab + ac$$

trichotomy

$$(a < b) \vee (a > b) \vee (a = b)$$

transitive law

$$(a < b) \wedge (b < c) \implies (a < c)$$

definitions

even/odd

$$n \text{ is even} \leftrightarrow \exists k \in \mathbb{Z} \mid n = 2k$$

$$n \text{ is odd} \leftrightarrow \exists k \in \mathbb{Z} \mid n = 2k + 1$$

prime/composite

$$n \text{ is prime} \leftrightarrow n > 1 \text{ and } \forall r, s \in \mathbb{Z}^+, n = rs \rightarrow (r = n) \vee (s = n)$$

$$n \text{ is composite} \leftrightarrow n > 1 \text{ and } \exists r, s \in \mathbb{Z}^+ s.t. n =$$

$$rs \text{ and } 1 < r < n \text{ and } 1 < s < n$$

divisibility (d divides n)

$$d \mid n \leftrightarrow \exists k \in \mathbb{Z} \mid n = kd$$

rationality

$$r \text{ is rational} \leftrightarrow \exists a, b \in \mathbb{Z} \mid r = \frac{a}{b} \text{ and } b \neq 0$$

floor/ceiling

$$\lfloor x \rfloor : \text{largest integer } y \text{ such that } y \leq x$$

$$\lceil x \rceil : \text{smallest integer } y \text{ such that } y \geq x$$

rules of inference

generalisation

$$p, \therefore p \vee q$$

specialisation

$$p \wedge q, \therefore p$$

elimination

$$p \vee q; \sim q, \therefore p$$

transitivity

$$p \rightarrow q; q \rightarrow r; \therefore p \rightarrow r$$

04. METHODS OF PROOF

Proof by Exhaustion/Cases

1. list out possible cases

1.1. Case 1: n is odd OR If $n = 9$, ...

1.2. Case 2: n is even OR If $n = 16$, ...

2. therefore ...

Proof by Contradiction

1. Suppose that ...

1.1. <proof>

1.2. ...but this contradicts ...

2. Therefore the assumption that ... is false.

Hence

Proof by Contraposition

1. Contrapositive statement: $\sim q \rightarrow \sim p$

2. let $\sim q$

2.1. <proof>

2.2. hence $\sim p$

3. $\therefore p \rightarrow q$

Proof by Construction

1. Let $x = 3, y = 4, z = 5$.

2. Then $x, y, z \in \mathbb{Z}_{\geq 1}$ and $x^2 + y^2 = 3^2 + 4^2 = 9 + 16 = 25 = 5^2$.

3. Thus $\exists x, y, z \in \mathbb{Z}_{\geq 1}$ such that $x^2 + y^2 = z^2$.

Proof by Induction

1. For each $n \in \mathbb{Z}_{\geq 1}$, let $P(n)$ be the proposition "..."

2. (base step) $P(1)$ is true because <manual method>

3. (induction step)

3.1. let $k \in \mathbb{Z}_{\geq 1}$ s.t. $P(k)$ is true

3.2. Then ...

3.3. proof that $P(k + 1)$ is true - e.g.

$$P(k + 1) = P(k) + \text{term}_{k+1}$$

3.4. So $P(k + 1)$ is true.

4. Hence $\forall n \in \mathbb{Z}_{\geq 1} P(n)$ is true by MI.

Proofs for Sets

Equality of Sets (A=B)

1. (\Rightarrow)

1.1. Take any $z \in A$.

1.2. ...

1.3. $\therefore z \in B$.

2. (\Leftarrow)

2.1. Take any $z \in B$.

2.2. ...

2.3. $\therefore z \in A$.

Element Method

1. $A \cap (B \setminus C) = \{x : x \in A \wedge x \in (B \setminus C)\}$ (by def. of \cap)

2. $= \{x : x \in A \wedge (x \in B \wedge x \notin C)\}$ (by def. of \setminus)

3. ...

4. $= (A \cap B) \setminus C$ (by def. of \setminus)

Other Proofs

iff ($A \leftrightarrow B$)

1. (\Rightarrow) Suppose A .

1.1. ... <proof> ...

1.2. Hence $A \rightarrow B$

2. (\Leftarrow) Suppose B .

2.1. ... <proof> ...

2.2. Hence $B \rightarrow A$

02. COMPOUND STATEMENTS

operations

1 \sim : negation (not)

2 \wedge : conjunction (and)

2 \vee : disjunction (or) - coequal to \wedge

3 \rightarrow : if-then

logical equivalence

• identical truth values in truth table

• definitions

• to show non-equivalence:

• truth table method (only needs 1 row)

• counter-example method

conditional statements

hypothesis \rightarrow conclusion

antecedent \rightarrow consequent

• **vacuously true** : hypothesis is false

• **implication law** : $p \rightarrow q \equiv \sim p \vee q$

• common if/then statements:

• if p then q: $p \rightarrow q$

• p if q: $q \rightarrow p$

• p only if q: $p \rightarrow q$

• p iff q: $p \leftrightarrow q$

• **contrapositive** : $\sim q \rightarrow \sim p$

• **inverse** : $\sim p \rightarrow \sim q$

• **converse** : $q \rightarrow p$

converse \equiv inverse
statement \equiv contra-
positive

• r is a **necessary** condition for s: $\sim r \rightarrow \sim s$ and $s \rightarrow r$

• r is a **sufficient** condition for s: $r \rightarrow s$

• **necessary & sufficient** : \leftrightarrow

valid arguments

• determining validity: construct truth table

• valid \leftrightarrow conclusion is true when premises are true

• **sylogism** : (argument form) 2 premises, 1 conclusion

• **modus ponens** : $p \rightarrow q; p; \therefore q$

• **modus tollens** : $p \rightarrow q; \sim q; \therefore \sim p$

• **sound argument** : is valid & all premises are true

fallacies

converse error

$$p \rightarrow q$$

$$q$$

$$\therefore p$$

inverse error

$$p \rightarrow q$$

$$\sim p$$

$$\therefore \sim q$$

03. QUANTIFIED STATEMENTS

• **truth set** of $P(x) = \{x \in D \mid P(x)\}$

• $P(x) \Rightarrow Q(x) : \forall x(P(x) \rightarrow Q(x))$

• $P(x) \Leftrightarrow Q(x) : \forall x(P(x) \leftrightarrow Q(x))$

relation between $\forall, \exists, \wedge, \vee$

• $\forall x \in D, Q(x) \equiv Q(x_1) \wedge Q(x_2) \wedge \dots \wedge Q(x_n)$

• $\exists x \in D \mid Q(x) \equiv Q(x_1) \vee Q(x_2) \vee \dots \vee Q(x_n)$

05. SETS

notation

• set roster notation [1]: $\{x_1, x_2, \dots, x_n\}$

• set roster notation [2]: $\{x_1, x_2, x_3, \dots\}$

• set-builder notation: $\{x \in \mathbb{U} : P(x)\}$

definitions

• **equal sets** : $A = B \leftrightarrow \forall x(x \in A \leftrightarrow x \in B)$

• $A = B \leftrightarrow (A \subseteq B) \wedge (A \supseteq B)$

• **empty set**, \emptyset : $\emptyset \subseteq$ all sets

• **subset** : $A \subseteq B \leftrightarrow \forall x(x \in A \rightarrow x \in B)$

• **proper subset** : $A \subsetneq B \leftrightarrow (A \subseteq B) \wedge (A \neq B)$

• **power set** of A : $\mathcal{P}(A) = \{X \mid X \subseteq A\}$

• $|\mathcal{P}(A)| = 2^{|A|}$, given that A is a finite set

• **cardinality** of a set, $|A|$: number of distinct elements

• **singleton** : sets of size 1

• **disjoint** : $A \cap B = \emptyset$

methods of proof for sets

• direct proof

• element method

• truth table

boolean operations

• **union**: $A \cup B = \{x : x \in A \vee x \in B\}$

• **intersection**: $A \cap B = \{x : x \in A \wedge x \in B\}$

• **complement** (of B in A): $A \setminus B = \{x : x \in A \wedge x \notin B\}$

• **complement** (of B): \bar{B} or $B^c = \mathbb{U} \setminus B$

• set difference law: $A \setminus B = A \cap \bar{B}$

ordered pairs and cartesian products

• **ordered pair** : (x, y)

• $(x, y) = (x', y') \leftrightarrow x = x' \text{ and } y = y'$

• **Cartesian product** :

$$A \times B = \{(x, y) : x \in A \text{ and } y \in B\}$$

• $|A \times B| = |A| \times |B|$

• **ordered tuples** : expression of the form (x_1, x_2, \dots, x_n)

06. FUNCTIONS

definitions

• **function/map** from A to B : assignment of each element of A to exactly one element of B.

• $f : A \rightarrow B$: " f is a function from A to B "

• $f : x \rightarrow y$: " f maps x to y "

• **domain** of $f = A$

• **codomain** of $f = B$

• **range/image** of $f = \{f(x) : x \in A\}$

$= \{y \in B \mid y = f(x) \text{ for some } x \in A\}$

• **identity function** on A, $\text{id}_A : A \rightarrow A$

• $\text{id}_A : x \rightarrow x$

• range = domain = codomain = A

• **well-defined function** : every element in the domain is assigned to exactly one element in the codomain

equality of functions

• same codomain and domain

• for all $x \in$ codomain, same output

function composition

- $(g \circ f)(x) = g(f(x))$
- for $(g \circ f)$ to be well defined, codomain of f must be equal to the domain of g
- \times commutative
- \checkmark associative

image & pre-image

for $f : A \rightarrow B$

- if $X \subseteq A$, **image** of X,
 $f(X) = \{y \in B : y = f(x) \text{ for some } x \in X\}$
- if $Y \subseteq B$, **pre-image** of Y,
 $f^{-1}(Y) = \{x \in A : y = f(x) \text{ for some } y \in Y\}$

injection & surjection

- surjective** (onto) : codomain = range
 - $\forall y \in B, \exists x \in A (y = f(x))$
 - surjective test: $\forall Y \subseteq B, Y \subseteq f(f^{-1}(Y))$
- injective** : one-to-one
 - $\forall x, x' \in A (f(x) = f(x') \Rightarrow x = x')$
 - injective test: $\forall X \subseteq A, X \subseteq f^{-1}(f(X))$
- bijective** : both surjective & injective
 - has an inverse

inverse

- $\forall x \in A, \forall y \in B (f(x) = y \Leftrightarrow g(y) = x)$

07. INDUCTION

mathematical induction

to prove that $\forall n \in \mathbb{Z}_{\geq m} (P(n))$ is true,

- base step: show that $P(m)$ is true
- induction step: show that $\forall k \in \mathbb{Z}_{\geq m} (P(k) \Rightarrow P(k+1))$ is true.
 - induction hypothesis: assumption that $P(k)$ is true

strong MI

to prove that $\forall n \in \mathbb{Z}_{\geq 0} (P(n))$ is true,

- base step: show that $P(0), P(1)$ are true
- induction step: show that $\forall k \in \mathbb{Z}_{\geq 0} (P(0) \cdots \wedge P(k+1) \Rightarrow P(k+2))$ is true.

justification:

- $P(0) \wedge P(1)$ by base case
- $P(0) \wedge P(1) \rightarrow P(2)$ by induction with $k = 0$
- $P(0) \wedge P(1) \wedge P(2) \rightarrow P(3)$ by induction with $k = 1$
- \dots
- we deduce that $P(0), P(1), \dots$ are all true by a series of **modus ponens**

well-ordering principle

- every nonempty subset of $\mathbb{Z}_{\geq 0}$ has a smallest element.
- application: recursion has a base case

RECURSION

a sequence is **recursively defined** if the definition of a_n involves a_0, a_1, \dots, a_{n-1} for all but finitely many $n \in \mathbb{Z}_{\geq 0}$.

recursive definitions

e.g. recursive definition for \mathbb{Z}

- (base clause)** $0 \in \mathbb{Z}_{\geq 0}$
- (recursion clause)** If $x \in \mathbb{Z}_{\geq 0}$, then $x + 1 \in \mathbb{Z}_{\geq 0}$
- (minimality clause)** Membership for $\mathbb{Z}_{\geq 0}$ can be demonstrated by (finitely many) successive applications of the clauses above

recursion vs induction

- recursion** - to define the set
- induction** - to show things about the set

well-formed formulas (WFF)

in propositional logic

define the set of WFF(Σ) as follows

- (base clause) every element ρ of Σ is in WFF(Σ)
- (recursion clause) if x, y are in WFF(Σ), then $\sim x$ and $(x \wedge y)$ and $(x \vee y)$ are in WFF(Σ)
- (minimality clause) Membership for WFF(Σ) can be demonstrated by (finitely many) successive applications of the clauses above

08. NUMBER THEORY

divisibility

- $n \bmod d$ is always non-negative.

	transitivity of divisibility
	If $a \mid b$ and $b \mid c$, then $a \mid c$.
	closure lemma (non-standard name)
Let $a, b, d, m, n \in \mathbb{Z}$. If $d \mid m$ and $d \mid n$, then $d \mid am + bn$.	division theorem
$\forall n \in \mathbb{Z}$ and $d \in \mathbb{Z}^+, \exists!q, r \in \mathbb{Z}$ s.t.	
$n = dq + r$ and $0 \leq r < d$	
$q = n \operatorname{div} d = \lfloor n/d \rfloor$	
$r = n \operatorname{mod} d = n - dq$	

base-b representation

of positive integer n is $(a_\ell a_{\ell-1} \dots a_0)_b$
where $\ell \in \mathbb{Z}_{\geq 0}$ and $a_0, a_1, \dots, a_\ell \in \{0, 1, \dots, b-1\}$
s.t. $n = a_\ell b^\ell + a_{\ell-1} b^{\ell-1} + \dots + a_0 b^0$ and $a_\ell \neq 0$

greatest common divisor

- $m \operatorname{mod} n$
- if $m \neq 0$ and $n \neq 0$, then gcd(m, n) exists and is positive.
- Euclidean Algorithm** for finding gcd

Bezout's Lemma:
For all $m, n \in \mathbb{Z}$ with $n \neq 0$, there exist $s, t \in \mathbb{Z}$ such that $\operatorname{gcd}(m, n) = ms + nt$.
Euclid's Lemma:

Let $m, n \in \mathbb{Z}^+$. If p is prime and $p \mid mn$, then $p \mid m$ or $p \mid n$.

prime factorization

- Fundamental Theorem of Arithmetic:** Every integer $n \geq 2$ has a unique prime factorization in which the prime factors are arranged in nondecreasing order.
 - aka Prime Factorisation Theorem

modular arithmetic

Let $a, b, c \in \mathbb{Z}$ and $n \in \mathbb{Z}^+$.
congruence
$a \equiv b \pmod n \Leftrightarrow a \bmod n = b \bmod n$
Then $\exists k \in \mathbb{Z} \mid a = nk + b$ and $n \mid (a - b)$
reflexivity
$a \equiv a \pmod n$
symmetry
$a \equiv b \pmod n \rightarrow b \equiv a \pmod n$
transitivity
$a \equiv b \pmod n \wedge b \equiv c \pmod n \rightarrow a \equiv c \pmod n$

additive inverse

b is an *additive inverse* of $a \bmod n \Leftrightarrow a + b \equiv 0 \pmod n$.
 b is an *additive inverse* of $a \bmod n \Leftrightarrow b \equiv -a \pmod n$.

multiplicative inverse

- b is a multiplicative inverse of $a \bmod n \Leftrightarrow ab \equiv 1 \pmod n$.
- If b, b' are multiplicative inverses of a , then $b \equiv b' \pmod n$.
 - exists $\Leftrightarrow \operatorname{gcd}(a, n) = 1$.
 - a, n are coprime
 - to find multiplicative inverse: **Euclidean Algorithm**

09. EQUIVALENCE RELATIONS

relations

Let R be a relation from A to B and $(x, y) \in A \times B$. Then:
 xRy for $(x, y) \in R$ and \cancel{xRy} for $(x, y) \notin R$

- A relation from A to B is a subset of $A \times B$.
- A **(binary) relation** on set A is a relation from A to A.
 - subset of A^2

reflexivity, symmetry, transitivity

Let A be a set and R be a relation on A .

reflexive
$\forall x \in A (xRx)$
symmetric
$\forall x, y \in A (xRy \Rightarrow yRx)$
transitive
$\forall x, y, z \in A (xRy \wedge yRz \Rightarrow xRz)$

- equivalence relation:** a relation that is reflexive, symmetric and transitive
- equivalence class:** the set of all things equivalent to x

equivalence classes

Let A be a set and R be an equivalence relation on A .

- $[x]_R$: **equivalence class** of x with respect to R
 $\forall x \in A, [x]_R = \{y \in A : xRy\}$
- A/R : The set of all equivalent classes
 $A/R = \{[x]_R : x \in A\}$

$xRy \Rightarrow [x] = [y] \Rightarrow [x] \cap [y] \neq \emptyset$

partitions

- a **partition** of a set A is a set \mathcal{C} of *non-empty subsets* of A such that
 - $(\geq 1) \forall x \in A, \exists S \in \mathcal{C} (x \in S)$
 - $(\leq 1) \forall x \in A, \forall S, S' \in \mathcal{C} (x \in S \wedge x \in S' \Rightarrow S = S')$
- components** : elements of a partition
- every partition comes from an equivalence relation

partial orders

Let A be a set and R be a relation on A .

- R is **antisymmetric** if $\forall x, y \in A (xRy \wedge yRx \rightarrow x = y)$
 - includes vacuously true cases (e.g. $xRy \Leftrightarrow x < y$)
- x and y are **comparable** if $\forall x, y \in A (xRy \vee yRx)$
- R is a **(non-strict) partial order** if R is reflexive, antisymmetric and transitive.
 - \preceq - partial order
 - $x \prec y \Leftrightarrow x \preceq y \wedge x \neq y$ (NOT a partial order)
 - Hasse diagram
- R is a **(non-strict) total order** if R is a partial order and x and y are comparable

min and max

Let \preceq be a partial order on a set A , and $c \in A$.

- c is a **minimal element** if $\forall x \in A (x \preceq c \Rightarrow c = x)$
 - nothing is strictly below it
- c is a **maximal element** if $\forall x \in A (c \preceq x \Rightarrow c = x)$
 - nothing is strictly above it
- c is the **smallest element** or **minimum element** if $\forall x \in A (c \preceq x)$.
- c is the **largest element** or **maximum element** if $\forall x \in A (x \preceq c)$.

linearization

Let A be a set and \preceq be a partial order on A .
Then there exists a total order \preceq^* on A such that $\forall x, y \in A (x \preceq y \Rightarrow x \preceq^* y)$

10A. COUNTING

permutations

$$P(n, r) = \frac{n!}{(n-r)!} \quad (\text{also } {}_n P_r, P_r^n)$$

- multiplication/product rule:** An operation of k steps can be performed in $n_1 \times n_2 \times \dots \times n_k$ ways.
- addition/sum rule:** Suppose a finite set A equals the union of k distinct mutually disjoint subsets A_1, A_2, \dots, A_k . Then $|A| = |A_1| + |A_2| + \dots + |A_k|$
- difference rule:** if A is a finite set and $B \subseteq A$, then $|A \setminus B| = |A| - |B|$
- complement:** $P(\bar{A}) = 1 - P(A)$
- inclusion/exclusion rule:** $|A \cup B \cup C| = |A| + |B| + |C| - |A \cap B| - |B \cap C| - |C \cap A| + |A \cap B \cap C|$

permutations with indistinguishable objects

For n objects with n_k of type k indistinguishable from each other, the total number of distinguishable permutations $= \frac{n!}{n_1!n_2! \dots n_k!}$

pigeonhole principle

For any function f from a finite set X with n elements to a finite set Y with m elements and for any positive integer k , if $k < \frac{n}{m}$, then there is some $y \in Y$ such that y is the image of at least $k + 1$ distinct elements of X .

- A function from a finite set to a smaller finite set cannot be injective.

combinations

$$\binom{n}{r} = \frac{n!}{r!(n-r)!}$$
 (also $C(n, r)$, ${}_nC_r$, $C_{n,r}$, nC_r)
 r -combinations from n elements with **repetition**
$$= \binom{r+n-1}{r}$$

pascal's formula

Suppose $n, r \in \mathbb{Z}^+$ with $r \leq n$. Then
$$\binom{n+1}{r} = \binom{n}{r-1} + \binom{n}{r}$$

binomial theorem

$$(a + b)^n = \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k$$

binomial coefficient: $\binom{n}{k}$

10B. PROBABILITY

probability

Let S be a sample space. For all events A and B in S , a *probability function* P satisfies the following axioms:

- 1. $0 \leq P(A) \leq 1$
- 2. $P(\emptyset) = 0$ and $P(S) = 1$
- 3. $(A \cap B = \emptyset) \Rightarrow [P(A \cup B) = P(A) + P(B)]$
- 4. $P(\bar{A}) = 1 - P(A)$
- 5. $P(A \cup B) = P(A) + P(B) - P(A \cap B)$

expected value

For possible outcomes a_1, a_2, \dots, a_n which occur with probabilities p_1, p_2, \dots, p_n , the **expected value** is

$$\sum_{k=1}^n a_k p_k$$

linearity of expectation

- $E[X + Y] = E[X] + E[Y]$
- $E\left[\sum_{i=1}^n c_i \cdot X_i\right] = \sum_{i=1}^n (c_i \cdot E[X_i])$

conditional probability

The conditional probability of A given B ,
$$P(A \mid B) = \frac{P(A \cap B)}{P(B)}$$

probability tree:



bayes' theorem

Suppose a sample space S is a union of mutually disjoint events B_1, B_2, \dots, B_n and A is an event in S . For $k \in \mathbb{Z}$ and $1 \leq k \leq n$,

$$P(B_k \mid A) = \frac{P(A \mid B_k) \cdot P(B_k)}{\sum_{i=1}^n (P(A \mid B_i) \cdot P(B_i))}$$

independent events

A and B are **independent** iff
$$P(A \cap B) = P(A) \cdot P(B)$$

A, B and C are **pairwise independent** iff

- 1. $P(A \cap B) = P(A) \cdot P(B)$
- 2. $P(B \cap C) = P(B) \cdot P(C)$
- 3. $P(A \cap C) = P(A) \cdot P(C)$

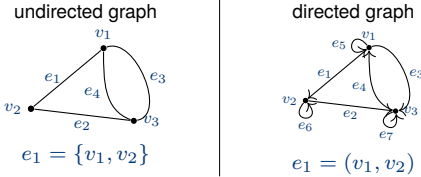
A, B and C are **mutually independent** iff

- 1. A, B and C are pairwise independent
- 2. $P(A \cap B \cap C) = P(A) \cdot P(B) \cdot P(C)$

11. GRAPHS

• mathematical structures used to model pairwise relations between objects

types of graphs

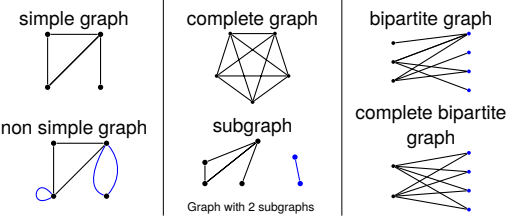


undirected graph

- denoted by $G = (V, E)$, comprising
 - nonempty set of *vertices/nodes*, $V = \{v_1, v_2, \dots, v_n\}$
 - a set of *edges*, $E = \{e_1, e_2, \dots, e_k\}$
- $e = \{v, w\}$ for an undirected edge E incident on vertices v and w

directed graph

- denoted by $G = (V, E)$, comprising
 - nonempty set V of *vertices*
 - a set E of *directed edges* (ordered pair of vertices)
- $e = (v, w)$ for an directed edge E from vertex v to vertex w



simple graph

- **undirected graph** with no loops or parallel edges

complete graph

- a complete graph on n vertices, $n > 0$, denoted K_n , is a simple graph with n vertices and exactly one edge connecting each pair of distinct vertices

bipartite graph

- a simple graph whose vertices can be divided into two disjoint sets U and V such that every edge connects a vertex in U to one in V
- **complete bipartite graph**: $K_{m,n}$
 - bipartite graph on two disjoint sets U and V such that every vertex in U connects to every vertex in V
 - denoted $K_{m,n}$ where $|U| = m, |V| = n$

subgraph of a graph

H is a subgraph of $G \Leftrightarrow$

- every vertex in H is also a vertex in G
- every edge in H is also an edge in G
- every edge in H has the same endpoints as it has in G

degree

- **degree** of v , $deg(v)$ = number of edges incident on v
- **total degree** of G = sum of the degrees of all vertices of G
total degree of $G = 2 \times$ (number of edges of G)
- C10.1.2 - the total degree of a graph is even
- P10.1.3 - in any graph there are an even number of vertices of odd degree

trails, paths and circuits

Let G be a graph; let v and w be vertices of G .

- **walk** (from v to w): a finite alternating sequence of adjacent vertices and edges of G .
 - e.g. $v_0 e_1 v_1 e_2 \dots v_{n-1} e_n v_n$
 - **length** of walk: the number of edges, n
- a **trivial walk** from v to v consists of the single vertex v
- **trail** (from v to w): a walk from v to w that does not contain a repeated edge
- **path** (from v to w): a trail that does not contain a repeated vertex
- **closed walk**: walk that starts and ends at the same vertex
- **circuit/cycle**: an undirected graph $G(V, E)$ where
 - $V = \{x_1, x_2, \dots, x_n\}$
 - $E = \{\{x_1, x_2\}, \{x_2, x_3\}, \dots, \{x_{n-1}, x_n\}, \{x_n, x_1\}\}$
 - $n \in \mathbb{Z}_{\geq 3}$
 - aka a closed walk that does not contain a repeated edge
- **simple circuit/cycle**: does not have any other repeated vertex except the first and last
- (an undirected graph is) **cyclic** if it contains a loop/cycle

connectedness

- vertices v and w are connected $\Leftrightarrow \exists$ a walk from v to w
- graph G is connected $\Leftrightarrow \forall$ vertices $v, w \in V, \exists$ a walk from v to w

connected component

- a connected subgraph of the largest possible size
- graph H is a connected component of graph $G \Leftrightarrow$
 - 1. H is a subgraph of G
 - 2. H is connected
 - 3. no connected subgraph of G has H as a subgraph and contains vertices or edges that are not in H

Euler circuit

- **Euler circuit**: a circuit that contains every vertex and traverses every edge of G exactly once
- **Eulerian graph**: graph that contains an Euler circuit

T10.2.3

Euler circuit \Leftrightarrow connected and every vertex has positive even degree

T10.2.4

Eulerian graph \Leftrightarrow every vertex has positive even degree

- **Euler trail** (from v to w): a sequence of adjacent edges and vertices that starts at v , ends at w , and passes through every vertex of G at least once, and traverses every edge of G exactly once.

C10.2.5

\exists Euler trail $\Leftrightarrow G$ is connected; v, w have odd degree; all other vertices of G have positive even degree

Hamiltonian circuit

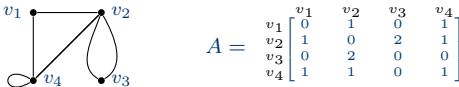
- **Hamiltonian circuit** (for G): a *simple circuit* that includes every vertex of G .
 - does not need to include all the edges of G (unlike Euler circuit)
- **Hamilton(ian) graph**: contains a Hamiltonian circuit
- If G is a Hamiltonian circuit, then G has subgraph H where:
 - 1. H contains every vertex of G
 - 2. H is connected
 - 3. H has the same number of edges as vertices
 - 4. every vertex of H has degree 2

matrix representations of graphs

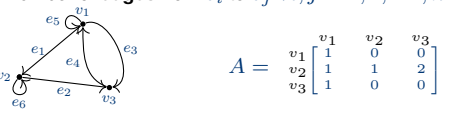
- **equal matrices** $\Leftrightarrow A$ and B are the same size and $a_{ij} = b_{ij}$ for all $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$
- **square matrix**: equal number of rows and columns
- **main diagonal**: all entries $a_{11}, a_{22}, \dots, a_{nn}$
- **symmetric matrix** $\Leftrightarrow \forall i, j \in \mathbb{Z}_{\leq n} (a_{ij} = a_{ji})$

adjacency matrix

The adjacency matrix of a **directed graph** G is the $n \times n$ matrix $A = (a_{ij})$ over the set of non-negative integers such that
 a_{ij} = number of **arrows** from v_i to $v_j \ \forall i, j = 1, 2, \dots, n$



The adjacency matrix of an **undirected graph** G is the $n \times n$ matrix $A = (a_{ij})$ over the set of non-negative integers such that
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identity matrix

The $n \times n$ identity matrix,

$$I_n = (\delta_{ij}) = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases} \quad \text{for all } i, j = 1, 2, \dots, n$$

matrix multiplication

scalar product

$$\begin{bmatrix} a_{i1} & a_{i2} & \dots & a_{in} \end{bmatrix} \begin{bmatrix} b_{1j} \\ b_{2j} \\ \vdots \\ b_{nj} \end{bmatrix} = a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{in}b_{nj}$$

matrix product

Let $A = (a_{ij})$ be an $m \times k$ matrix and $B = (b_{ij})$ be a $k \times n$ matrix with real entries.

$$AB = (c_{ij}) = \sum_{r=1}^k a_{ir}b_{rj}$$

\times commutative \checkmark associative

nth power of a matrix

For any $n \times n$ matrix A , the powers of A are defined as follows:

$$A^0 = I \text{ where } I \text{ is the } n \times n \text{ identity matrix}$$
$$A^n = AA^{n-1} \quad \forall n \in \mathbb{Z}_{\geq 1}$$

counting walks of length N

number of walks of length n from v_i to v_j
= the ij -th entry of A^n

isomorphism

• graph isomorphism (\cong) is an equivalence relation.
Let $G = (V_G, E_G)$ and $G' = (V_{G'}, E_{G'})$ be two graphs.

$$G \cong G' \Leftrightarrow \text{there exists a permutation } \pi : V_G \rightarrow V_{G'} \text{ such that } \{u, v\} \in E_G \Leftrightarrow \{\pi(u), \pi(v)\} \in E_{G'}$$

planar graph

- a graph that can be drawn on a two-dimensional plane without edges crossing.
 - divides a plane into *regions/faces* (includes 'outside' the graph)
- **Euler's formula:** For a connected planar simple graph $G = (V, E)$ with $e = |E|$ and $v = |V|$ and f faces,
 $f = e - v + 2$

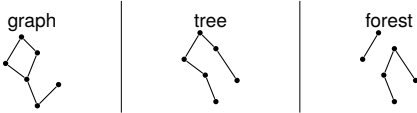
trees

- **tree** \Leftrightarrow graph that is circuit-free and connected

L10.5.4

If G is a connected graph with n vertices and $n - 1$ edges, then G is a tree.

- **trivial tree:** graph that comprises a single vertex
- **forest** \Leftrightarrow graph is circuit-free and connected
 - a group of trees
- **terminal vertex:** a vertex of degree 1
- **internal vertex:** a vertex of degree greater than 1



rooted trees

- **rooted tree:** a tree in which there is one vertex that is distinguished from the others and is called the root.
- **level** (of a vertex): the number of edges along the unique path between it and the root
- **height** (of a rooted tree): the maximum level of any vertex of the tree
- children, parent, siblings, ancestor, decendant

binary tree

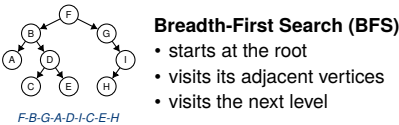
- **binary tree:** a rooted tree in which every parent has at most 2 children
 - at most one left child and at most one right child

- **full binary tree:** a binary tree in which every parent has exactly 2 children
- (left/right) **subtree:** Given any parent v in a binary tree T , the binary tree whose root is the (left/right) child of v , whose vertices consist of the left child of v and all its descendants, and whose edges consist of all those edges of T that connect the vertices of the left subtree.

T10.6.1: Full Binary Tree Theorem

If T is a full binary tree with k internal vertices, then T has a total of $2k + 1$ vertices and has $k + 1$ terminal vertices.

binary tree traversal



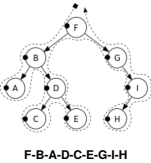
Breadth-First Search (BFS)

- starts at the root
- visits its adjacent vertices
- visits the next level

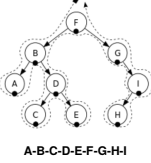
Depth-First Search (DFS)

- **pre-order**
 - process the root (or current vertex)
 - traverse the left subtree recursively
 - traverse the right subtree recursively
- **in-order**
 - traverse the left subtree recursively
 - process the root (or current vertex)
 - traverse the right subtree recursively
- **post-order**
 - traverse the left subtree recursively
 - traverse the right subtree recursively
 - process the root (or current vertex)

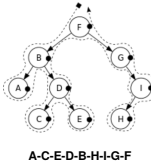
pre-order DFS



in-order DFS



post-order DFS



spanning trees

- **spanning tree** (for a graph G): a subgraph of G that contains every vertex of G and is a tree.
 - $w(e)$ - weight of edge e
 - $w(G)$ - total weight of G
- **weighted graph:** each edge has an associated positive real number weight
 - **total weight:** sum of the weights of all edges
- **minimum spanning tree:** least possible total weight compared to all other spanning trees

Kruskal's algorithm

- For a connected weighted graph G with n vertices
1. initialise T to have all the vertices of G and no edges.
 2. let E be the set of all edges in G ; let $m = 0$
 3. while ($m < n - 1$)
 - 3.1. find and remove the edge e in E of least weight
 - 3.2. if adding e to the edge set of T does not produce a circuit:
 - i. add e to the edge set of T
 - ii. set $m = m + 1$

Prim's algorithm

1. pick any vertex v of G and let T be the graph with this vertex only
2. let V be the set of all vertices of G except v
3. for ($i = 0$ to $n - 1$)
 - 3.1. find the edge e in G with the least weight of all the edges connected to T . let w be the endpoint of e .
 - 3.2. add e and w to the edge and vertex sets of T
 - 3.3. delete w from v

LOGICAL EQUIVALENCES			SET IDENTITIES		
commutative laws	$p \wedge q \equiv q \wedge p$	$p \vee q \equiv q \vee p$	commutative laws	$A \cap B = B \cap A$	$A \cup B = B \cup A$
associative laws	$(p \wedge q) \wedge r \equiv p \wedge (q \wedge r)$	$(p \vee q) \vee r \equiv p \vee (q \vee r)$	associative laws	$(A \cap B) \cap C = A \cap (B \cap C)$	$(A \cup B) \cup C = A \cup (B \cup C)$
distributive laws	$p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r)$	$p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$	distributive laws	$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$	$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$
identity laws	$p \wedge \text{true} \equiv p$	$p \vee \text{false} \equiv p$	identity laws	$A \cap U = A$	$A \cup \emptyset = A$
idempotent laws	$p \wedge p \equiv p$	$p \vee p \equiv p$	idempotent laws	$A \cap A = A$	$A \cup A = A$
universal bound laws	$p \vee \text{true} \equiv \text{true}$	$p \wedge \text{false} \equiv \text{false}$	universal bound laws	$A \cap \emptyset = \emptyset$	$A \cup U = U$
negation laws	$p \vee \sim p \equiv \text{true}$	$p \wedge \sim p \equiv \text{false}$	complement laws	$A \cap \overline{A} = \emptyset$	$A \cup \overline{A} = U$
double negation law	$\sim(\sim p) \equiv p$	—	double complement law	$\overline{(\overline{A})} = A$	—
absorption laws	$p \vee (p \wedge q) \equiv p$	$p \wedge (p \vee q) \equiv p$	absorption laws	$A \cup (A \cap B) = A$	$A \cap (A \cup B) = A$
De Morgan's Laws	$\sim(p \vee q) \equiv \sim p \wedge \sim q$	$\sim(p \wedge q) \equiv \sim p \vee \sim q$	De Morgan's Laws	$\overline{A \cup B} = \overline{A} \cap \overline{B}$	$\overline{A \cap B} = \overline{A} \cup \overline{B}$

proven:

- L1E1 - the product of 2 consecutive odd numbers is always odd.
- L1E5 - the difference between 2 consecutive squares is always odd
- L4E4 - the sum of any 2 even integers is even
- L4T4.6.1 - there is no greatest integer
- L4T4.3.1 - for all positive integers a and b , if $a|b$, then $a \leq b$.
- L1P4.6.4 - for all integers n , if n^2 is even then n is even
- L4T4.2.1 - all integers are rational numbers
- L4T4.2.2 - the sum of any 2 rational numbers is rational
- L1E7 - there exist irrational numbers p and q such that p^q is rational
- L4T4.7.1 - $\sqrt{2}$ is irrational.
- L4T4.3.2 - the only divisors of 1 are 1 and -1 .
- L4T4.3.3 - **transitivity of divisibility**
 - if $a|b$ and $b|c$, then $a|c$.
- L3T3.2.1 - **negation of a universal statement:**
 - $\sim(\forall x \in D, P(x)) \equiv \exists x \in D \mid \sim P(x)$
- L3T3.2.2 - **negation of an existential statement:**
 - $\sim(\exists x \in D \mid P(x)) \equiv \forall x \in D, \sim P(x)$
- L5T5.1.14 - there exists a unique set with no element. It is denoted by \emptyset .
- L5E5.3.7 - for all A, B : $(A \cap B) \cup (A \setminus B) = A$
- L5T5.3.11(1) - let A, B be disjoint finite sets. Then $|A \cup B| = |A| + |B|$
- L5T5.3.11(2) - let A_1, A_2, \dots, A_n be pairwise disjoint finite sets. Then $|A_1 \cup A_2 \cup \dots \cup A_n| = |A_1| + |A_2| + \dots + |A_n|$
- L5T5.3.12 - **Inclusion-Exclusion Principle:**
 - for all finite sets A and B , $|A \cup B| = |A| + |B| - |A \cap B|$
- L6T6.1.26 - **associativity of function composition:**
 - $f \circ (g \circ h) = (f \circ g) \circ h$
- L6P2.6.16 - **uniqueness of inverses:**
 - If g, g' are inverses of $f : A \rightarrow B$, then $g = g'$.
- E6.1.24 - $f \circ \text{id}_A = f$ and $\text{id}_A \circ f = f$
- T6.2.18 - bijective \Leftrightarrow has an inverse
- L7.3.19 - If $x \in \text{WFF}^+(\Sigma)$, then assigning false to all elements of Σ makes x evaluate to false.
- T7.3.20 - $\sim(\forall x \in \text{WFF}(\Sigma), \exists y \in \text{WFF}^+(\Sigma) \ y \equiv x) \equiv \exists x \in \text{WFF}(\Sigma) \ \forall y \in \text{WFF}^+(\Sigma) \ y \not\equiv x$ aka \sim (not) must be included in the definition of WFF.
- L8.1.5 - Let $d, n \in \mathbb{Z}$ with $d \neq 0$. Then $d \mid n \Leftrightarrow n/d \in \mathbb{Z}$
- L8.1.9 - Let $d, n \in \mathbb{Z}$. If $d \mid n$, then $-d \mid n$ and $d \mid -n$ and $-d \mid -n$
- L8.1.10 - Let $d, n \in \mathbb{Z}$. If $d \mid n$ and $d \neq 0$, then $|d| \leq |n|$
- L8.2.5 - **Prime Divisor Lemma** (non-standard name):
 - Let $n \in \mathbb{Z}_{\geq 2}$. Then n has a prime divisor.
- P8.2.6 - **sizes of prime divisors:**
 - Let n be a composite positive integer. Then n has a prime divisor $p \leq \sqrt{n}$.
- T8.2.8 - there are infinitely many prime numbers
- T8.3.13 - $\forall n \in \mathbb{Z}^+, \exists! \ell \in \mathbb{Z}_{\geq 0}$ and $a_0, a_1, \dots, a_\ell \in \{0, 1, \dots, b-1\}$ such that \langle the definition of base- b representation \rangle holds.

- L8.4.11 - If $x, y, r \in \mathbb{Z}$ such that $x \bmod y = r$, then $\gcd(x, y) = \gcd(y, r)$.
- Let $a, b, c, d \in \mathbb{Z}$ and $n \in \mathbb{Z}^+$ s.t. $a \equiv b \pmod{n}$ and $c \equiv d \pmod{n}$.
 - P8.6.6 - **addition:** Then $a + c \equiv b + d \pmod{n}$
 - P8.6.13 - **multiplication:** Then $ac \equiv bd \pmod{n}$
- T9.3.4 - Let R be an equivalence relation on a set A . Then A/R is a partition of A .
- T9.3.5 - If \mathcal{C} is a partition of A , then there is an equivalence relation of R on A such that $A/R = \mathcal{C}$.
- L9.5.5 - Consider a partial order \preceq on set A .
 - A smallest element is minimal.
 - There is at most one smallest element.
- L10.2.1 - Let G be a graph.
 - L10.2.1a - If G is connected, then any two distinct vertices of G can be connected by a path
 - L10.2.1b - If vertices v and w are part of a circuit in G and one edge is removed from the circuit, then there still exists a trail from v to w in G .
 - L10.2.1c - If G is connected and G contains a circuit, then an edge of the circuit can be removed without disconnecting G .
- L10.5.1 - Any non-trivial tree has at least one vertex of degree 1.
- T10.5.2 - Any tree with n vertices ($n > 0$) has $n - 1$ edges.
- L10.5.3 - If G is any connected graph, C is any circuit in G , and one of the edges of C is removed from G , then the graph that remains is still connected.
- L10.5.4 - If G is a connected graph with n vertices and $n - 1$ edges, then G is a tree.
- T10.6.1 - If T is a full binary tree wiht k internal vertices, then T has a total of $2k + 1$ vertices and has $k + 1$ terminal vertices.
- T10.6.2 - For non-negative integers h , if T is any binary tree with height h and t terminal vertices, then $t \leq 2^h$.
- P10.7.1 -
 - Every connected graph has a spanning tree.
 - Any two spanning trees for a graph have the same number of edges
-

abbreviations

- L - lemma
- E - example
- P - proposition
- T - theorem