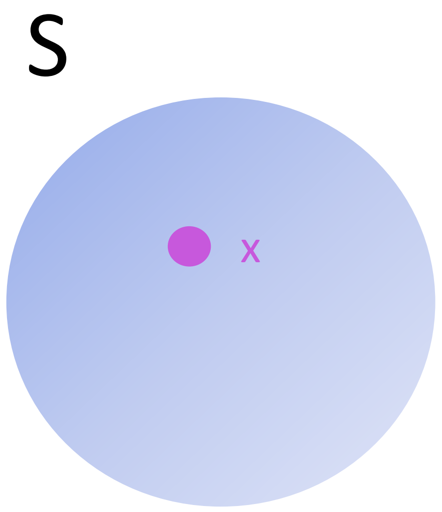
START RECORDING

Sets & Quantifiers

CMSC250

What is a set?

- A set is a collection of **distinct** objects.
- We use the notation $x \in S$ to say that S contains x.
- We'd like to know if $x \in S$ fast!
- Unless explicitly specified otherwise, **sets are unordered**.



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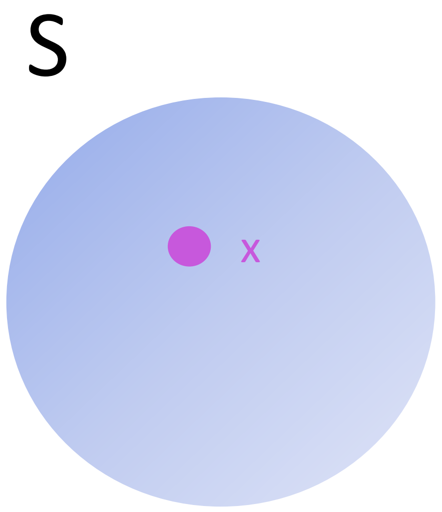
- Given the last two requirements, what's the best possible data structure to implement a set in memory?



Doubly Linked List

Binary Tree

Stack

Something else (what?)

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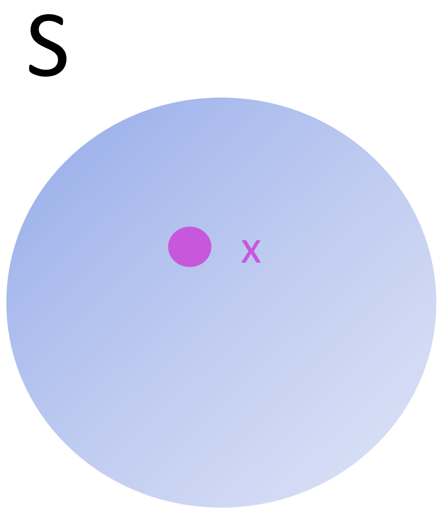

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Something else (what?)

Hash table!

Elementary number sets

- $\mathbb{N}$: the **natural** numbers
  - $\mathbb{N} = \{\mathbf{0}, 1,2,3, \dots .\}$. In our class, $0 \in \mathbb{N}$!
- $\mathbb{Z}$: the **integers**
  - $\mathbb{Z} = \{\dots -3, -2, -1, 0, 1, 2, 3, \dots\}$
- $\mathbb{Q}$: the **rationals**
  - $\mathbb{Q} = \{\frac{a}{b}, (a \in \mathbb{Z}) \wedge (b \in \mathbb{Z}) \wedge (b \neq 0)$
  - Any number that can be written as a ratio of integers!
- $\mathbb{R}$: the reals
  - This will typically be our “upper limit” in 250.
  - That is, we don’t usually care about $\mathbb{C}$, the set of **complex** numbers

Fill those in!

	$\mathbb{N}$	$\mathbb{Z}$	$\mathbb{Q}$	$\mathbb{R}$
0	☐	☐	☐	☐
-1	☐	☐	☐	☐
$1/2$	☐	☐	☐	☐
$-1/2$	☐	☐	☐	☐
$0.333333\ldots$	☐	☐	☐	☐
$0.333333.../0.11111111...$	☐	☐	☐	☐
π	☐	☐	☐	☐
i, such that $i^2 = -1$	☐	☐	☐	☐

Fill those in!

	$\mathbb{N}$	$\mathbb{Z}$	$\mathbb{Q}$	$\mathbb{R}$
0	■	■	■	■
-1	□	□	□	□
${}^{1}\!/_{2}$	□	□	□	□
$-{}^{1}\!/_{2}$	□	□	□	□
$0.333333\ldots$	□	□	□	□
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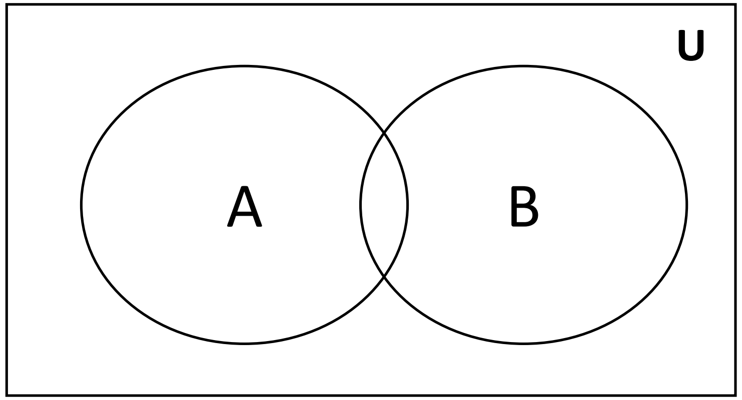
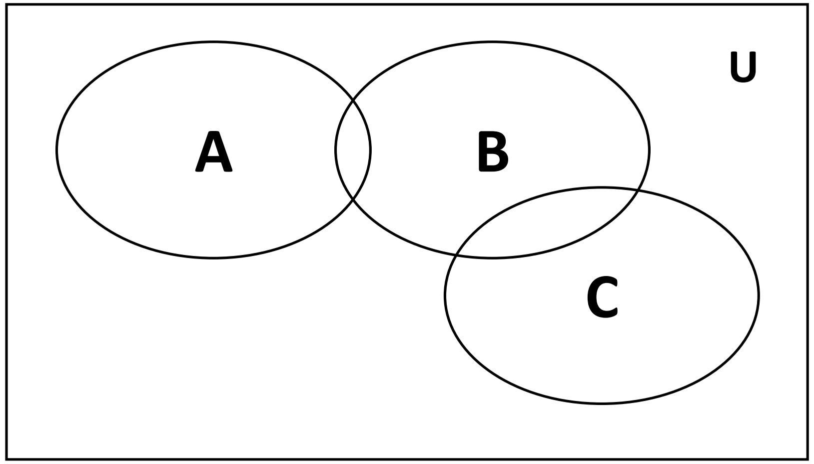
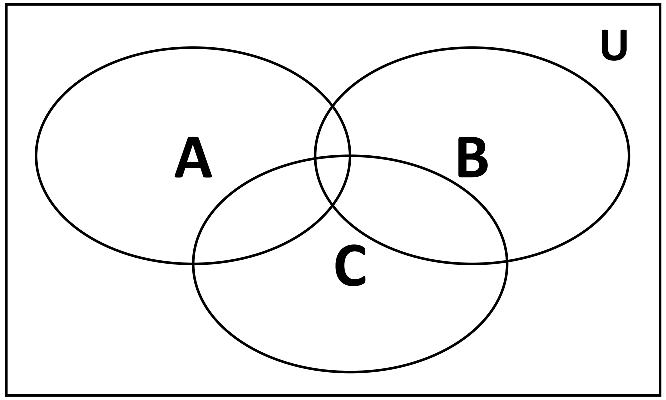
Not even a real number!

Venn Diagrams







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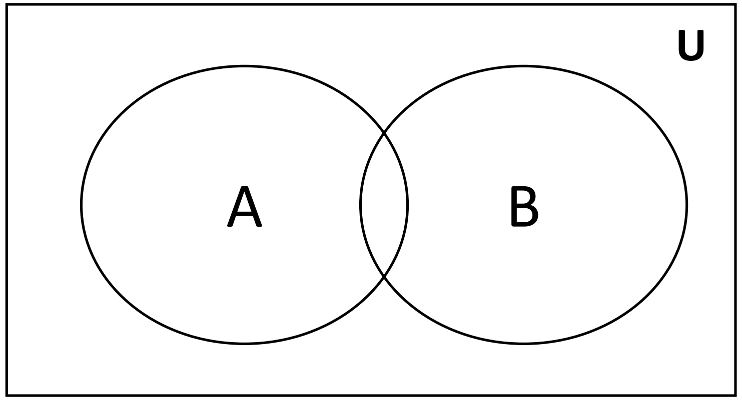

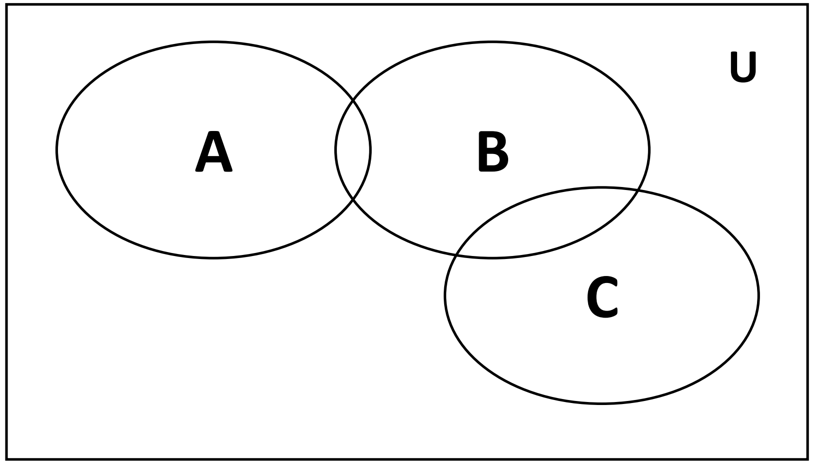

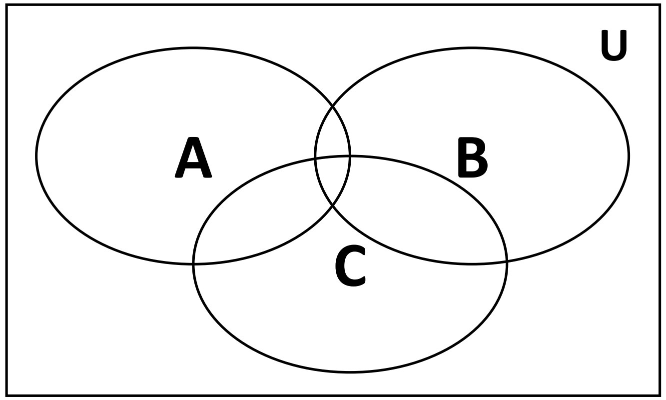

- *U* is the *Universal Domain:* a set that we imagine holds every *conceivable* element.
- When talking about sets of numbers, *U* is usually $\mathbb{R}$, the reals.

"There exists" (∃)

- The symbol ∃ *(LaTeX: \exists)* is read "There exists".
- Examples:
  - $(\exists x \in \mathbb{R})\ [8x = 1]$

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  - $(\exists x \in \mathbb{R})\ [8x = 1]$ True
  - $(\exists n \in \mathbb{Z})[n^2 = -1]$ False
- Is there a domain *D* where $(\exists n \in D)[n^2 = -1]$ is true?

Yes

No

Something else

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The complex numbers $\mathbb{C}$

Yes

No

Something else

"For all"

- The symbol ∀ *(LaTeX: \forall)* is read "for all".
- Examples:
  - $(\forall x \in \mathbb{N})\ [((x > 2) \wedge (x\ is\ prime)) \Rightarrow (x\ is\ odd)]$

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    True
  - $(\forall n \in \mathbb{Z})\ [n^2 \geq 0]$

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  - $(\forall x \in \mathbb{N})\ [((x > 2) \land (x\ is\ prime)) \Rightarrow (x\ is\ odd)]$ True
  - $(\forall n \in \mathbb{Z})\ [n^2 \geq 0]$ True

"For all"

- Let D be the set of all students in this class who are over 8 feet tall.
- $(\forall x \in D)[x\ has\ perfect\ attendance\ so\ far!]$

True

False

Something else

“For all”

- Let D be the set of all students in this class who are over 8 feet tall.
- $(\forall x \in D)[x \text{ has perfect attendance so far!}]$

True

False

Something else

- If disagree, need to find $x \in D$ who missed a class
- Called vacuously true!

Nesting quantifiers

- $(\exists x \in \mathbb{N})(\exists y \in \mathbb{N})[x + 2y = 3x + y = 4]$

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- $(\exists x \in \mathbb{N})(\exists y \in \mathbb{N})[x + 2y = 3x + y = 4]$ False
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Nesting quantifiers

- $(\exists x \in \mathbb{N})(\exists y \in \mathbb{N})[x + 2y = 3x + y = 4]$ False
- $(\exists x \in \mathbb{Q})(\exists y \in \mathbb{Q})[x + 2y = 3x + y = 4]$

True, $x = \frac{4}{5}, y = \frac{8}{5}$

Nesting quantifiers

- $(\exists x \in \mathbb{N})(\exists y \in \mathbb{N})[x + 2y = 3x + y = 4]$ False
- $(\exists x \in \mathbb{Q})(\exists y \in \mathbb{Q})[x + 2y = 3x + y = 4]$

  True, $x = \frac{4}{5}, y = \frac{8}{5}$

- Common abbreviation: $(\exists x, y \in D)[\ldots]$
- Generally: $(\exists x_1, x_2, \ldots, x_n \in D)[\ldots]$

Alternating nested quantifiers

- Notice the differences between the following:
  - $(\forall x \in \mathbb{N})(\exists y \in \mathbb{N})[x < y]$
  - $(\exists x \in \mathbb{N})(\forall y \in \mathbb{N})[x < y]$

Alternating nested quantifiers

- Notice the differences between the following:
  - $(\forall x \in \mathbb{N})(\exists y \in \mathbb{N})[x < y]$ True ($\mathbb{N}$ unbounded from above)
  - $(\exists x \in \mathbb{N})(\forall y \in \mathbb{N})[x < y]$ False ($\mathbb{N}$ bounded from below)

- ***WHEN QUANTIFIERS ARE DIFFERENT, THEIR ORDER MATTERS!!!!!!!***

Fill this in!

Statement	**True**	**False**
$(\exists n \in \mathbb{N})[n + n = 0]$	◯	◯
$(\exists n \in \mathbb{N})[n + n = 1]$	◯	◯
$(\exists n \in \mathbb{Z})[n + n = 1]$	◯	◯
$(\exists x, y \in \mathbb{Z})[x + y = 1]$	◯	◯
$(\exists x \in \mathbb{R})[x(x + 1) = -1]$	◯	◯
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	◯	◯
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^3 < y^3 < z^3)]$	◯	◯
$(\forall x, y \in \mathbb{N})(\exists z \in \mathbb{Q})[(x < y) \Rightarrow (x < z < y)]$	◯	◯

Fill this in!

Statement	True	False
$(\exists n \in \mathbb{N})[n + n = 0]$	●	○
$(\exists n \in \mathbb{N})[n + n = 1]$	○	○
$(\exists n \in \mathbb{Z})[n + n = 1]$	○	○
$(\exists x, y \in \mathbb{Z})[x + y = 1]$	○	○
$(\exists x \in \mathbb{R})[x(x + 1) = -1]$	○	○
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	○	○
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^3 < y^3 < z^3)]$	○	○
$(\forall x, y \in \mathbb{N})(\exists z \in \mathbb{Q})[(x < y) \Rightarrow (x < z < y)]$	○	○

$n = 0$

Fill this in!

Statement	True	False	
$(\exists n \in \mathbb{N})[n + n = 0]$	●	○	$n = 0$
$(\exists n \in \mathbb{N})[n + n = 1]$	○	●	$2n = 1 \Rightarrow n = \frac{1}{2} \notin \mathbb{N}$
$(\exists n \in \mathbb{Z})[n + n = 1]$	○	○	
$(\exists x, y \in \mathbb{Z})[x + y = 1]$	○	○	
$(\exists x \in \mathbb{R})[x(x + 1) = -1]$	○	○	
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	○	○	
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^3 < y^3 < z^3)]$	○	○	
$(\forall x, y \in \mathbb{N})(\exists z \in \mathbb{Q})[(x < y) \Rightarrow (x < z < y)]$	○	○	

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$(\exists n \in \mathbb{N})[n + n = 1]$	○	●	$2n = 1 \Rightarrow n = \frac{1}{2} \notin \mathbb{N}$
$(\exists n \in \mathbb{Z})[n + n = 1]$	○	●	Similarly, $\frac{1}{2} \notin \mathbb{Z}$
$(\exists x, y \in \mathbb{Z})[x + y = 1]$	○	○	
$(\exists x \in \mathbb{R})[x(x + 1) = -1]$	○	○	
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	○	○	
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$n = 0$

$2n = 1 \Rightarrow n = \frac{1}{2} \notin \mathbb{N}$

Similarly, $\frac{1}{2} \notin \mathbb{Z}$

$\boldsymbol{x = 0, y = 1}$ or
$\boldsymbol{x = -1, y = 2}$, or...

Fill this in!

Statement	True	False	
$(\exists n \in \mathbb{N})[n + n = 0]$	●	○	$n = 0$
$(\exists n \in \mathbb{N})[n + n = 1]$	○	●	$2n = 1 \Rightarrow n = \frac{1}{2} \notin \mathbb{N}$
$(\exists n \in \mathbb{Z})[n + n = 1]$	○	●	Similarly, $\frac{1}{2} \notin \mathbb{Z}$
$(\exists x, y \in \mathbb{Z})[x + y = 1]$	●	○	$\boldsymbol{x = 0, y = 1}$ or $\boldsymbol{x = -1, y = 2}$, or…
$(\exists x \in \mathbb{R})[x(x + 1) = -1]$	○	●	$x^2 + x + 1 = 0$ has no real solutions
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	○	○	
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^3 < y^3 < z^3)]$	○	○	
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$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^2 < y^2 < z^2)]$	○	●	Think of graph of $f(x) = x^2$
$(\forall x, y, z \in \mathbb{R})[((x < y < z) \Rightarrow (x^3 < y^3 < z^3)]$	○	○	
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$(\forall x, y \in \mathbb{N})(\exists z \in \mathbb{Q})[(x < y) \Rightarrow (x < z < y)]$	●	○	E.g: arithmetic mean

Finding domains

- Give infinite sets D such that $(\forall x \in D)(\exists y \in D)[x < y]$
  1. Is true

Finding domains

- Give infinite sets D such that $(\forall x \in D)(\exists y \in D)[x < y]$
    1. Is true ($D = \mathbb{N}$, select $y = x + 1$)

Finding domains

- Give infinite sets D such that $(\forall x \in D)(\exists y \in D)[x < y]$
  1. Is true ($D = \mathbb{N}$, select $y = x + 1$)
  2. Is false

Finding domains

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  1. Is true ($D = \mathbb{N}$, select $y = x + 1$)
  2. Is false ($D = \mathbb{Z}^{\leq 0}$, counter-example is 0)

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1. True for $D = (-\infty, 1)$
2. False for $D = (-\infty, 1]$ (!)

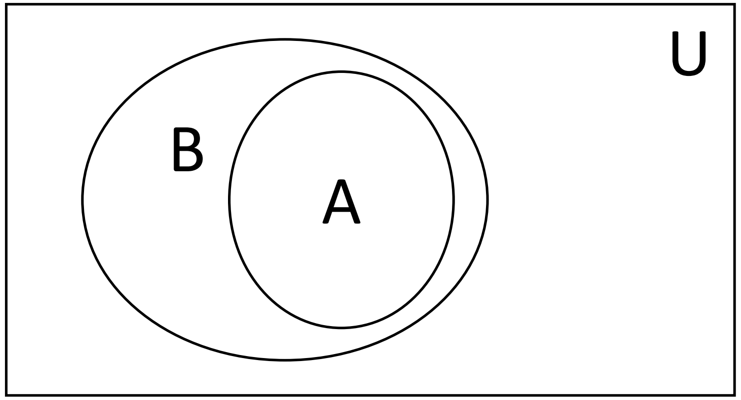
Subset

- We say that A is a subset of B ($A \subseteq B$) iff

$$(\forall x \in A)[x \in B]$$

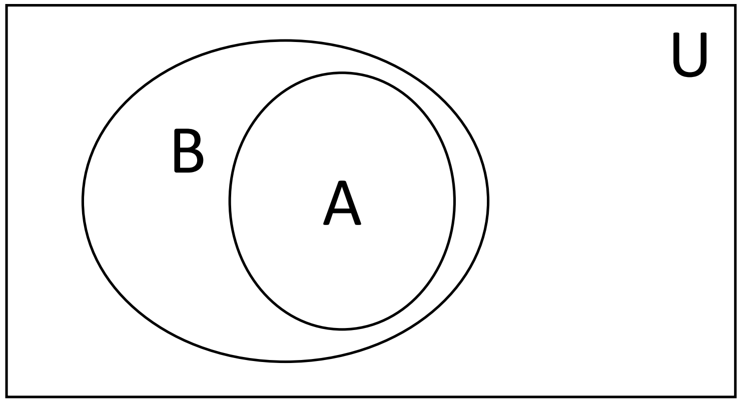
$$\Leftrightarrow$$

$$(\forall x \in U)[(x \in A) \Rightarrow (x \in B)]$$



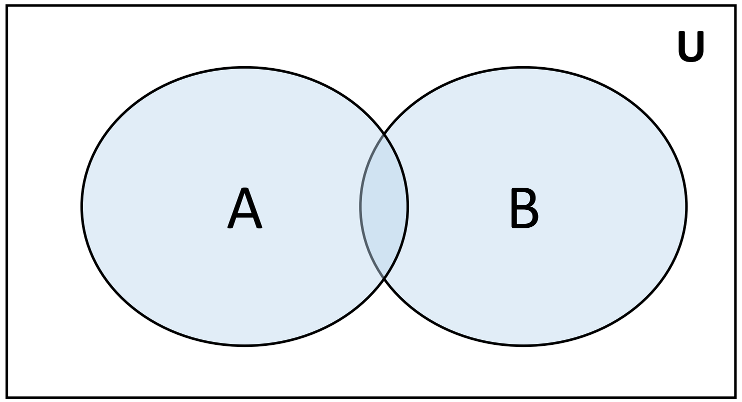
Superset and proper subset/superset

- We say that B is a **superset** of A ($B \supseteq A$) iff $A \subseteq B$.
- We say that A is a **proper subset** of B ($A \subset B$) iff $(A \subseteq B) \wedge (A \neq B)$.
- We say that B is a **proper superset** of A ($B \supset A$) iff $A \subset B$



Union

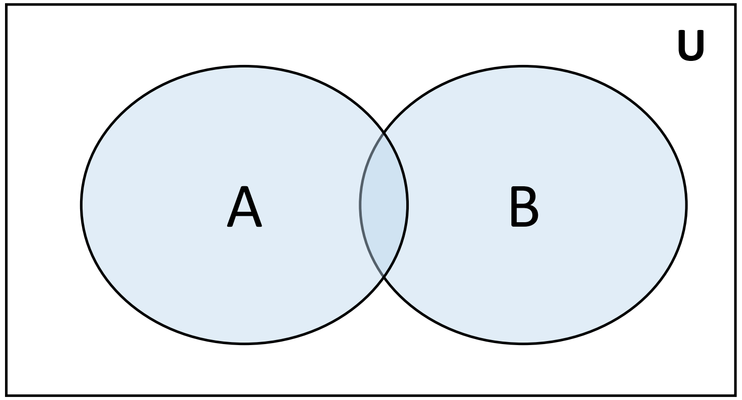
$$A \cup B = \{(x \in A) \vee (x \in B)\}$$



Union

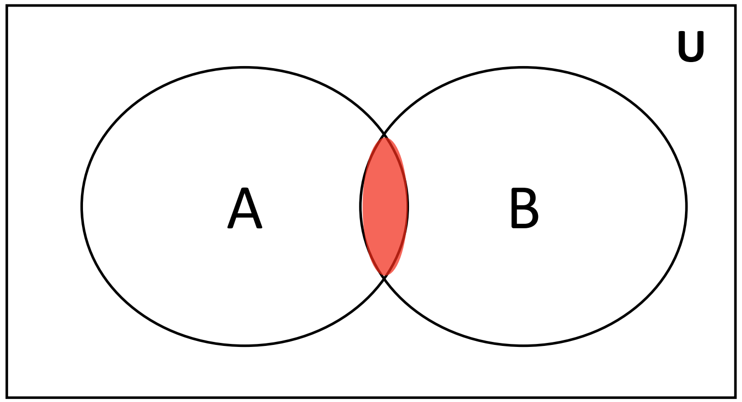
$$A \cup B = \{(x \in A) \vee (x \in B)\}$$

Connection between union and logical disjunction!



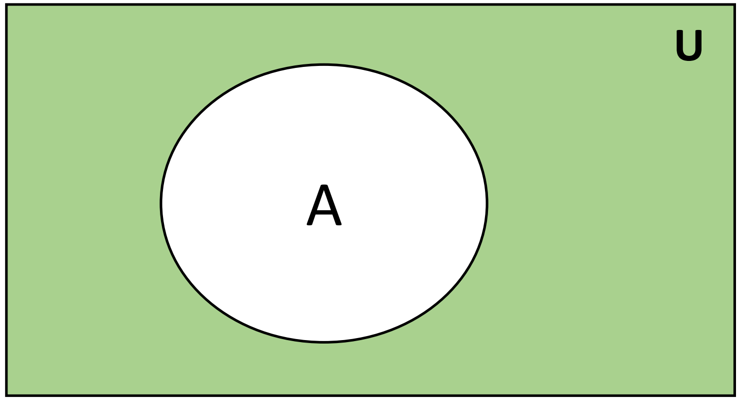
Intersection

$$A \cap B = \{(x \in A) \land (x \in B)\}$$



Absolute complement

$$A^c = \{(x \notin A)\} = \{(x \in U) \wedge (\sim(x \in A))\}$$



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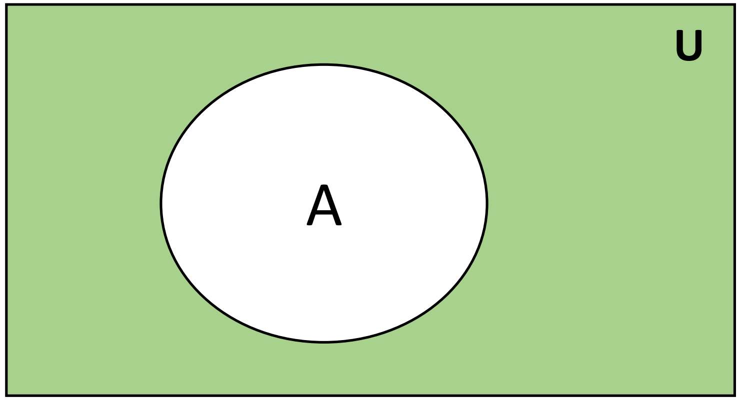

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Some use A' or $\overline{A}$. They are Wrong, we are right.

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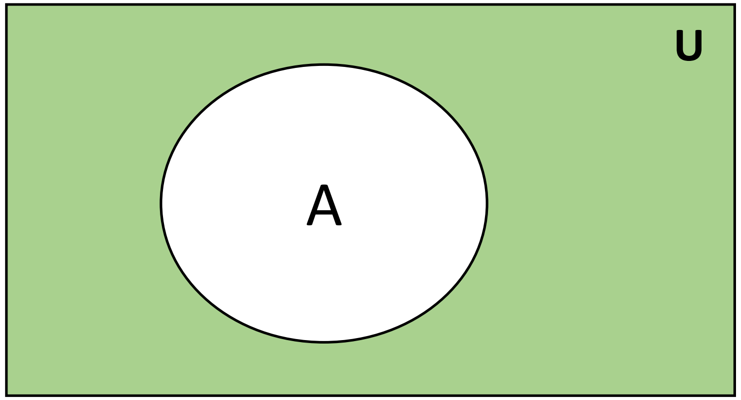
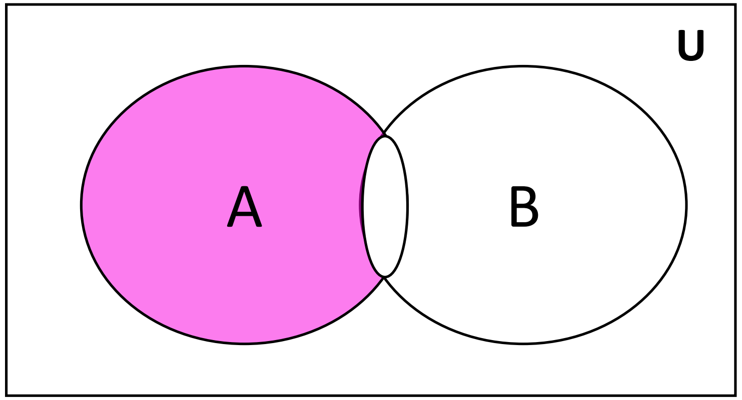


Relative Complement

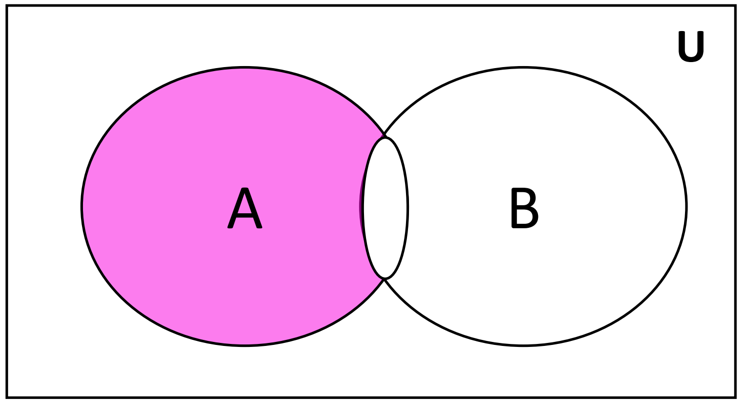
$$A - B = \{(x \in A) \land (x \notin B)\}$$



Relative Complement

$$A - B = \{(x \ \in A) \wedge (x \notin B)\}$$

Some use $A \setminus B$. They are wrong, we are right.



Careful about membership and subset!

- Be careful to distinguish between **members** of a set and **subsets** of a set…

True

False

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1. $1 \in \{-2, 0, 1, 3\}$

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1. $1 \in \{-2, 0, 1, 3\}$ T
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3. $1 \subseteq \{-2, 0, \{1\}, 3\}$

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2. $1 \in \{-2, 0, \{1\}, 3\}$ F
3. $1 \subseteq \{-2, 0, \{1\}, 3\}$ F, in fact, not even mathematically correct syntax
4. $\{1\} \subseteq \{-2, 0, \{1\}, 3\}$

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The empty set (∅, { })

- The empty set, denoted either ∅ or { }, is the **unique** set with **no elements.**
  - Uniqueness can be proven, through a proof by contradiction!

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1. $\emptyset \subseteq \mathbb{N}$ T
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The powerset

- Given a set A, the powerset $\mathcal{P}(A)$ is **the set of all subsets of A.**
  - $\mathcal{P}(\{0,1\}) = \{\emptyset, \{0\}, \{1\}, \{0,1\}\}$
  - $\mathcal{P}(\{0,1,2\}) = \{\emptyset, \{0\}, \{1\}, \{2\}, \{0,1\}, \{1,2\}, \{0,2\}, \{0,1,2\}\}$
  - $\mathbb{N}^{2k}, \mathbb{N}^{2k+1}, \mathbf{P}, \ \mathbf{SQUARES} \in \mathcal{P}(\mathbb{N})$
    - And lots more…

Facts about the powerset

- The following are **facts** about the powerset:
  - Since $\emptyset \subseteq A$ for all sets A, $\emptyset \in \mathcal{P}$(A) for all sets A
  - Since $A \subseteq A$ for all sets A, $A \in \mathcal{P}$(A) for all sets A

Powerset quizzing

- Let $A = \{1, 2, \ldots, n\}$
- Then, $|P(A)|$

$\approx n \cdot logn$	$= n^2$	$= 2^n$	$= n!$

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$= n^2$

$= 2^n$

$= n!$

Powerset quizzing

- $P(\{1\}) =$

Powerset quizzing

- $P(\{1\}) = \{\emptyset, \{1\}\}$
- $P(P(\{1\})) =$

Powerset quizzing

- $P(\{1\}) = \{\emptyset, \{1\}\}$
- $P(P(\{1\})) = \{\emptyset, \{\emptyset\}, \{\{1\}\}, \{\emptyset, \{1\}\}\}$
- $P(\emptyset) =$

Powerset quizzing

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- $P(\{\emptyset\}) =$

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STOP RECORDING