MATH401: Lecture 1 (08/19/2025)

This is Introduction to Analysis I

I'm Bala Krishnamoorthy (Call me Bala).

Today: * syllabus, logistics → see the course web page for details
* proof techniques
  - contrapositive proof
  - proof by contradiction
  - proof by induction

Book: Lindstrøm: Spaces—An Intro to Real Analysis (LSIRA)

LSIRA 1.1

Logical statements and notation.

If A then B (or $A \Rightarrow B$) "implies"

$A \Rightarrow B$ typically does not mean $B \Rightarrow A$.

e.g., A: p a natural number, is divisible by 6

B: p is divisible by 3.

$A \Rightarrow B$ holds, but $B \not\Rightarrow A$ (B does not imply A),

e.g., $p = 9$.

But if $A \Rightarrow B$ and $B \Rightarrow A$ hold, we say A $\underbrace{\text{if and only if}}_{\text{iff}}$ B, or

$A \Leftrightarrow B$ (or A is equivalent to B).

To prove $A \Leftrightarrow B$, we often prove $A \Rightarrow B$ and $B \Rightarrow A$

$(A \Leftarrow B)$ separately.

We start by reviewing certain standard techniques to construct proofs of mathematical statements.

1. Contrapositive Proof

To show $A \Rightarrow B$, equivalently show not $B \Rightarrow$ not A ($\neg B \Rightarrow \neg A$).

$\neg$ "negation" or "not"

"If A happened then B happened" This statement is equivalent to "If B did not happen then A did not happen."

LSIRA 1.1 Prob 3. Prove the following Lemma.

Lemma 1 If n is a natural number such that n^2 is divisible by 3, then n is divisible by 3.

This is $A \Rightarrow B$ where A: $3 \mid n^2$ (n^2 is divisible by 3). → or 3 divides n^2

B: $3 \mid n$ (n is divisible by 3).

Let's try to prove $A \Rightarrow B$ directly: $n^2 = 3k$ (as $n^2|3$) $\Rightarrow$ $n = \sqrt{3}\sqrt{k}$ (taking square root on both sides)

Hard to conclude that $n|3$ ☹! → Would have to argue $k|3$, which is not obvious!

Let's try proving $\neg B \Rightarrow \neg A$.

$\neg B$: n is not divisible by 3.

$\Rightarrow$ $n = 3p+1$ or $n = 3q+2$, for $p, q \in \mathbb{N}$. (set of natural numbers)

Case 1. $n = 3p+1$

$$\Rightarrow n^2 = (3p+1)^2$$
$$= 9p^2 + 6p + 1$$
$$= 3(3p^2+2p)+1$$
$$= 3k+1 \text{ for } k = 3p^2+2p$$

$\Rightarrow n^2$ is not divisible by 3

Case 2. $n = 3q+2$

$$\Rightarrow n^2 = (3q+2)^2$$
$$= 9q^2 + 12q + 4$$
$$= 9q^2 + 12q + 3 + 1$$
$$= 3\underbrace{(3q^2+4q+1)}_{=k'}+1$$
$$= 3k'+1$$

$\Rightarrow n^2$ is not divisible by 3.

Hence we have proved that if n is not divisible by 3, then n^2 is not divisible by 3. Hence, by the contrapositive, we have $n^2|3 \Rightarrow n|3$. □

Should we always try to build a contrapositive proof?
Not necessarily! In cases where $A \Rightarrow B$ could be concluded directly, the contrapositive argument might make life harder! It is one of the different proof approaches that you should be aware of.

2. Proof by Contradiction

Assume opposite of what you want to prove, and end up with a contradiction (or an obviously wrong statement). Hence the original assumption must be wrong, i.e., you have proved the statement.

LSIRA 1.1 Prob 3 (continued) Prove the following Theorem.

Theorem 2 $\sqrt{3}$ is irrational.

Assume $\sqrt{3}$ is rational. → the opposite of what you want to prove

$\Rightarrow \sqrt{3} = \frac{p}{q}$, $p, q \in \mathbb{N}$ with no common factors. → by definition, any positive rational number can be written in the form p/q as specified.

Let's square both sides, and cross multiply.

$\Rightarrow 3q^2 = p^2 \Rightarrow 3 \mid p^2$ (p^2 is divisible by 3).

Hence by Lemma 1, $3 \mid p$. Let $p = 3k$. ($k \in \mathbb{N}$). Plug $p=3k$ back in:

$\Rightarrow 3q^2 = (3k)^2 = 9k^2$ (divide both sides by 3)

$\Rightarrow q^2 = 3k^2$, i.e., $3 \mid q^2$ (q^2 is divisible by 3).

Again by Lemma 1, $3 \mid q$.

Since we started with the assumption that p and q have no common factors

Thus p and q have a common factor of 3, which is a contradiction.

Hence $\sqrt{3}$ is irrational. $\square$

3. Proof by Induction

To show a statement $P(n)$ holds for all $n \in \mathbb{N}$,

1. show $P(1)$ holds;
2. Assume $P(k)$ holds for some $k \in \mathbb{N}$.
3. Show $P(k+1)$ holds under Assumption 2.

"for all"

Example

Show that $P(n) = 3 + 5 + \cdots + 2n+1 = n(n+2)$ $\forall n \in \mathbb{N}$.

1. $P(1) = 3 = 1(1+2)$ (so $P(1)$ is true).
2. Assume $P(k) = k(k+2)$ for some $k \in \mathbb{N}$.
3. $P(k+1) = P(k) + 2(k+1)+1 = P(k) + 2k+3$

$$= k(k+2) + 2k+3 \quad \text{by induction assumption.}$$

$$= k(k+2) + k + k+3$$

$$= k(k+3) + k+3$$

$$= (k+1)(k+3) = n(n+2) \text{ for } n = k+1.$$

$$\Rightarrow P(n) = n(n+2) \quad \forall n \in \mathbb{N}.$$

$\square$

MATH 401: Lecture 2 (08/21/2025)

Today: * sets and operations

Sets and Operations (LS IRA 1.2)

Set: Collection of mathematical objects.

They can be finite, e.g., $\{2,5,9,1,6\}$, or infinite, e.g., $[0,1]$, the collection of all $x \in \mathbb{R}$ with $0 \leq x \leq 1$.

"element of" set of all real numbers

Given sets A, B we have

$A \subseteq B$: A is a subset of, or equal to, B.

$A \subset B$: A is a strict subset of B, i.e., there is at least one $x \in B$ such that $x \notin A$.

But $\forall x \in A$, $x \in B$ holds.

To prove $A = B$, we often prove $A \subseteq B$ and $A \supseteq B$ (or $B \subseteq A$).

Here are ~~some~~ standard sets we will use regularly.

ϕ: empty set.

$\mathbb{N} = \{1, 2, 3, \ldots\}$, set of all natural numbers

$\mathbb{R}$ = set of all real numbers

$\mathbb{Z} = \{\ldots, -2, -1, 0, 1, 2, \ldots\}$, set of all integers

$\mathbb{Q}$ = set of rational numbers, $\mathbb{C}$ = set of complex numbers.

$\mathbb{R}^n$: set of all real n-tuples, or n-vectors

Notation for sets: $[-2,1] = \{x \in \mathbb{R} \mid -2 \leq x \leq 1\}$.

closed interval from -2 to 1

"such that"
could also use ":" instead of "|".

More generally, $A = \{a \in B \mid P(a)\}$.

bigger set than A

property

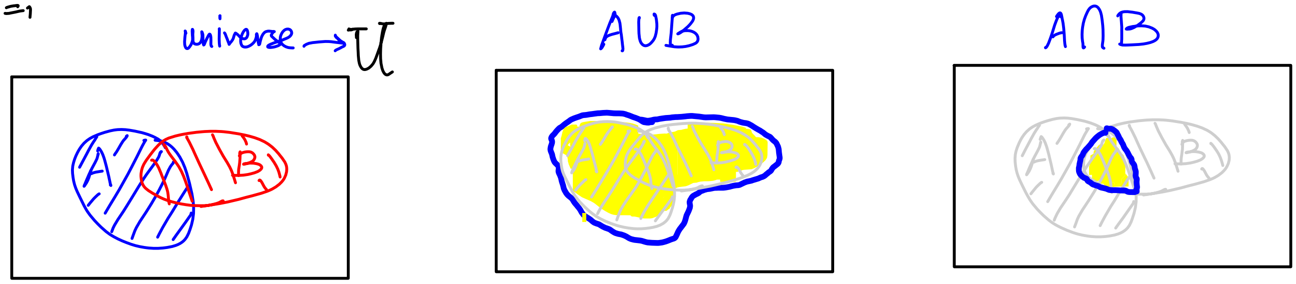
Union and Intersection

If A_i are sets for $i=1,\dots,n$, i.e., $A_1, A_2, \dots, A_n$ are sets, then

$$\bigcup_{i=1}^{n} A_i = A_1 \cup A_2 \cup \cdots \cup A_n = \{a \mid a \in A_i \text{ for at least one } i\}$$ is their union,

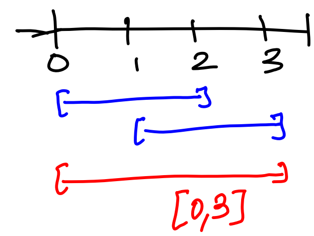
"for all"

$$\bigcap_{i=1}^{n} A_i = A_1 \cap A_2 \cap \cdots \cap A_n = \{a \mid a \in A_i \ \forall i\}$$ is their intersection.



LSIRA 1.2 Prob1

Show $[0,2] \cup [1,3] = [0,3]$.



We show $[0,2] \cup [1,3] \subseteq [0,3]$ and
$[0,2] \cup [1,3] \supseteq [0,3]$.

The result is an obvious one. But we go through the steps of a formal proof more for practice!

($\subseteq$) Let $x \in [0,2] \cup [1,3]$

$\Rightarrow x \in [0,2]$ or $x \in [1,3]$ (definition of $\cup$).

$x \in [0,2] \Rightarrow x \in [0,3]$ (as $[0,3]$ contains $[0,2]$)

$x \in [1,3] \Rightarrow x \in [0,3]$. In either case, $x \in [0,3]$.

Hence $[0,2] \cup [1,3] \subseteq [0,3]$.

($\supseteq$) Let $x \in [0,3]$. Hence $0 \le x \le 3$. Then we get that either $x \le 2$, and hence $x \in [0,2]$, or $x \in (2,3]$.

But if $x \in (2,3]$ then $x \in [1,3]$ (as $[1,3]$ includes $(2,3]$).

$\Rightarrow x \in [0,2] \cup [1,3]$.

Hence $[0,3] \subseteq [0,2] \cup [1,3]$. $\square$

Distributive Laws of Union and Intersection

For all sets $B, A_1, \ldots, A_n$, we have

LSIRA (1.2.1) $$B \cap (A_1 \cup A_2 \cup \cdots \cup A_n) = (B \cap A_1) \cup (B \cap A_2) \cup \cdots \cup (B \cap A_n).$$

Using more compact notation, we can write

$$B \cap \left(\bigcup_{i=1}^{n} A_i\right) = \bigcup_{i=1}^{n} (B \cap A_i)$$

Proof

We will prove

$$B \cap (A_1 \cup \cdots \cup A_n) \subseteq (B \cap A_1) \cup \cdots \cup (B \cap A_n), \text{ and}$$

$$B \cap (A_1 \cup \cdots \cup A_n) \supseteq (B \cap A_1) \cup \cdots \cup (B \cap A_n).$$

('$\subseteq$') Let $x \in B \cap (A_1 \cup \cdots \cup A_n)$.

$\Rightarrow x \in B$ and $x \in (A_1 \cup \cdots \cup A_n)$ (definition of $\cap$)

$\Rightarrow x \in B$ and $x \in A_i$ for at least one A_i. (defn. of $\cup$)

$\Rightarrow x \in B \cap A_i$ for at least one A_i.

$\Rightarrow x \in (B \cap A_1) \cup \cdots \cup (B \cap A_n)$.

('$\supseteq$') let $x \in (B \cap A_1) \cup \cdots \cup (B \cap A_n)$.

$\Rightarrow x \in (B \cap A_i)$ for at least one A_i.

$\Rightarrow x \in B$ and $\underbrace{x \in A_i \text{ for at least one } A_i}$

$\Rightarrow x \in B$ and $x \in (A_1 \cup \cdots \cup A_n)$

$\Rightarrow x \in B \cap (A_1 \cup \cdots \cup A_n)$. $\square$

LSIRA (1.2.2) is assigned in Homework 1.

Set Difference and Complement

We write $A \setminus B$ or $A - B$ "setminus"

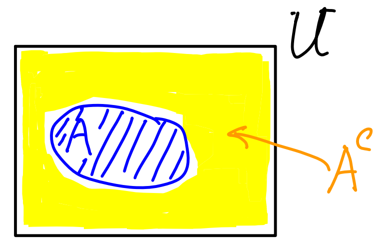
Caution! * $A \setminus B \neq B \setminus A$!

"A setminus B" is $A \setminus B = \{a \mid a \in A, a \notin B\}$.

If $\mathcal{U}$ is the universe, i.e., $A \subseteq \mathcal{U}$ for all sets A, then

$$A^c = \mathcal{U} \setminus A = \{a \in \mathcal{U} \mid a \notin A\}$$

is the complement of A (or A-complement).



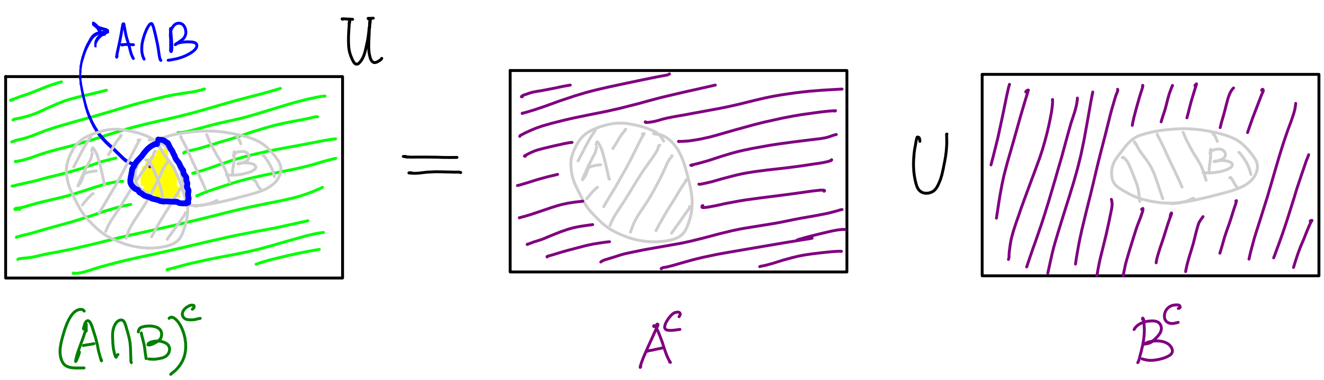
De Morgan's Laws

LSIRA (1.2.3) $(A_1 \cup \cdots \cup A_n)^c = A_1^c \cap \cdots \cap A_n^c$. "complement of union = intersection of complements"

LSIRA (1.2.4) $(A_1 \cap \cdots \cap A_n)^c = A_1^c \cup A_2^c \cup \cdots \cup A_n^c$. complement of intersection = union of complements.

See LSIRA for the proof.

Let's illustrate (1.2.4) for $n=2$, i.e., with A_1 and A_2 first.



We will prove subset inclusion in both directions.

($\subseteq$) Let $x \in (A_1 \cap \cdots \cap A_n)^c$.

$\Rightarrow x \notin A_1 \cap \cdots \cap A_n$ (definition of complement)

$\Rightarrow x \notin A_j$ for some j. (definition of $\cap$)

$\Rightarrow x \in A_j^c$ for some j

$\Rightarrow x \in A_1^c \cup \cdots \cup A_n^c$.

Hence $(A_1 \cap \cdots \cap A_n)^c \subseteq A_1^c \cup \cdots \cup A_n^c$.

($\supseteq$) Let $x \in A_1^c \cup \cdots \cup A_n^c$.

$\Rightarrow x \in A_j^c$ for some j

$\Rightarrow x \notin A_j$ for some j

$\Rightarrow x \notin A_1 \cap \cdots \cap A_n$. since $x \notin A_j$ for some j, it cannot be in the intersection of all A_i's.

$\Rightarrow x \in (A_1 \cap \cdots \cap A_n)^c$.

Hence $A_1^c \cup \cdots \cup A_n^c \subseteq (A_1 \cap \cdots \cap A_n)^c$. $\square$

Cartesian Products

For A, B : sets, we define

$$A \times B = \{(a,b) \mid a \in A, b \in B\}$$ cartesian product of A and B

given A_i, $i = 1, \dots, n$ $(A_1, \dots, A_n)$, we define

compact notation $\prod$: product

$$A_1 \times A_2 \times \cdots \times A_n = \prod_{i=1}^{n} A_i = \{(a_1, \dots, a_n) \mid \underbrace{a_i \in A_i \ \forall i}_{a_1 \in A_1, a_2 \in A_2, \dots, a_n \in A_n}\}.$$

e.g., $\mathbb{R}^n$: set of n-tuples of real numbers
(or set of real n-vectors)

LSIRA 1.2 Prob 9 (Pg 11) Prove that $(A \cup B) \times C = (A \times C) \cup (B \times C)$.

We'll finish the proof in the next lecture...

MATH 401: Lecture 3 (08/26/2025)

Today: * families of sets, properties
* functions, images, pre images

We first do a problem on Cartesian products...

LSIRA 1.2 Prob 9 (Pg 11) Prove that $(A \cup B) \times C = (A \times C) \cup (B \times C)$.

'$\subseteq$' Let $(x,y) \in (A \cup B) \times C$.

$\Rightarrow$ $x \in A \cup B$, $y \in C$ (Definition of cartesian product)

$\Rightarrow$ $x \in A$ or $x \in B$, $y \in C$

If $x \in A$ then $(x,y) \in A \times C$, and

if $x \in B$ then $(x,y) \in B \times C$.

$\Rightarrow$ $(x,y) \in A \times C$ or $(x,y) \in B \times C$

$\Rightarrow$ $(x,y) \in (A \times C) \cup (B \times C)$.

'$\supseteq$' Let $(x,y) \in (A \times C) \cup (B \times C)$

$\Rightarrow$ $(x,y) \in A \times C$ or $(x,y) \in B \times C$

$\Rightarrow$ $x \in A, y \in C$ or $x \in B, y \in C$ $\Rightarrow$ $(x \in A$ or $x \in B)$, $y \in C$.

$\Rightarrow$ $x \in A \cup B, y \in C$ $\Rightarrow$ $(x,y) \in (A \cup B) \times C$.

$\square$

LSIRA 1.3 **Families of Sets**

Recall: $B\cap\left(\bigcup_{i=1}^{n} A_i\right)=\bigcup_{i=1}^{n}(B\cap A_i)$. compact notation for distributive law (from Lecture 2)

We could write, instead, $B\cap\left(\bigcup_{i\in\mathcal{I}} A_i\right)=\bigcup_{i\in\mathcal{I}}(B\cap A_i)$, where $\mathcal{I}=\{1,2,\dots,n\}$.

We now generalize $\mathcal{I}$ to be infinite in some cases, or indexing more general collections in general.

Def A collection of sets is a **family**.

e.g., $\mathcal{A}=\{[a,b]\mid a,b\in\mathbb{R}\}$ is the family of all closed intervals on $\mathbb{R}$.

Union and Intersection

We extend union, intersection, as well as their distribution to families.

$$\bigcup_{A\in\mathcal{A}} A=\{a\mid a\in A \text{ for some } A\in\mathcal{A}\}.$$

collection of elements that belong to at least one set in the family

$$\bigcap_{A\in\mathcal{A}} A=\{a\mid a\in A \text{ for all } A\in\mathcal{A}\}$$

collection of elements that belong to every set in the family.

We naturally extend distributive and De Morgan's laws to families..

$$B\cap\left(\bigcup_{A\in\mathcal{A}} A\right)=\bigcup_{A\in\mathcal{A}}(B\cap A),\quad \left(\bigcap_{A\in\mathcal{A}} A\right)^c=\bigcup_{A\in\mathcal{A}} A^c,\ \text{etc.}$$

We now work on some problems involving families of sets.

LSIRA 1.3 Prob 1 (Pg 12)

Show that $\bigcup_{n\in\mathbb{N}} [-n,n] = \mathbb{R}$.

('$\subseteq$') $\mathbb{R}$ is the universe here, so $\bigcup_{n\in\mathbb{N}} [-n,n] \subseteq \mathbb{R}$.

Or, observe that $[-n,n] \in \mathbb{R}$ for each $n \in \mathbb{N}$, hence $\bigcup_{n\in\mathbb{N}} [-n,n] \subseteq \mathbb{R}$.

('$\supseteq$') Let $x \in \mathbb{R}$. To be more careful, we could consider $x=0$ separately. Note that $x=0 \in [-n,n]$ $\forall n \in \mathbb{N}$.

Let $m = \lceil |x| \rceil$, ceiling of absolute value of x, i.e., the smallest natural number $\geq |x|$.

$\lceil x \rceil = \text{ceil}(x)$ = smallest integer $\geq x$.

Then $x \in [-m,m] = [-\lceil |x| \rceil, \lceil |x| \rceil]$, as

$x \leq |x| \leq \lceil |x| \rceil = m$, and $x \geq -|x| \geq -\lceil |x| \rceil$.

e.g., $x = -3.3 \Rightarrow x \geq -|-3.3| = -3.3 \geq -4$.

$\Rightarrow x \in \bigcup_{n\in\mathbb{N}} [-n,n]$.

□

LSIRA 1.3 Prob 4

Show $\bigcap_{n\in\mathbb{N}} (0,\frac{1}{n}] = \emptyset$ (empty set).

('$\supseteq$') $\emptyset \subseteq A$ for any set A (trivially).

('$\subseteq$') We show $\bigcap_{n\in\mathbb{N}} (0,\frac{1}{n}] \subseteq \emptyset$.

$\emptyset^c = \mathbb{R}$. Hence we show $x \in \mathbb{R}$ is not in $\bigcap_{n\in\mathbb{N}} (0,\frac{1}{n}]$.

For $x \in \mathbb{R}$, we show $x \notin \bigcap_{n\in\mathbb{N}} (0,\frac{1}{n}]$.

If $x \leq 0$, then clearly, $x \notin (0,\frac{1}{n}]$ $\forall n \in \mathbb{N}$.

If $x \geq 1$, then $x \notin (0,\frac{1}{2}]$ for $n=2$, for instance.

Let $0<x<1$. Consider $m=\lceil \frac{1}{x} \rceil+1$.

Then $x \notin (0, \frac{1}{m}]$ as $x > \frac{1}{m} = \frac{1}{\lceil \frac{1}{x} \rceil+1}$. $\left(\lceil \frac{1}{x} \rceil +1 > \frac{1}{x} \right)$

$\Rightarrow \quad x \notin \bigcap_{n \in \mathbb{N}} (0, \frac{1}{n}]$.

Q. Why take $\lceil \frac{1}{x} \rceil+1$?

Consider $x=\frac{1}{5}$, for instance.
Then $\lceil \frac{1}{x} \rceil = \lceil 5 \rceil = 5$.
Hence $x \in (0, \frac{1}{m}]$ here!

$\square$

<u>LSIRA 1.3 Prob 5 (Pg 12)</u>

Prove that $B \cup \left(\bigcap_{A \in \mathcal{A}} A \right) = \bigcap_{A \in \mathcal{A}} (B \cup A)$.

($\subseteq$) Let $x \in B \cup \left(\bigcap_{A \in \mathcal{A}} A \right)$

$\Rightarrow x \in B$ or $x \in \bigcap_{A \in \mathcal{A}} A$

$\Rightarrow x \in B$ or $x \in A$ for each $A \in \mathcal{A}$.

$\Rightarrow x \in B \cup A$ for each $A \in \mathcal{A}$.

$\Rightarrow x \in \bigcap_{A \in \mathcal{A}} (B \cup A)$.

($\supseteq$) Let $x \in \bigcap_{A \in \mathcal{A}} (B \cup A)$

$\Rightarrow x \in B \cup A$ for every $A \in \mathcal{A}$.

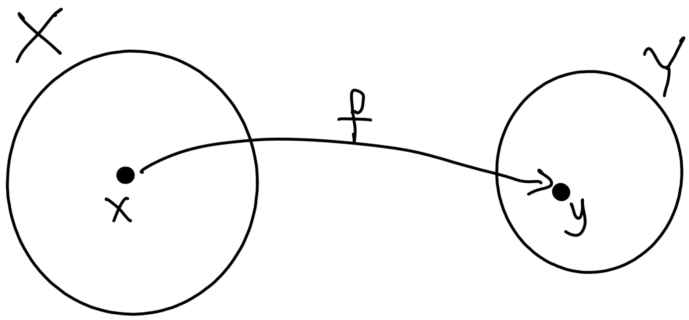
$\Rightarrow x \in B$ or $\underbrace{x \in A \text{ for every } A \in \mathcal{A}}$.

$\Rightarrow x \in B$ or $x \in \bigcap_{A \in \mathcal{A}} A \Rightarrow x \in B \cup \left(\bigcap_{A \in \mathcal{A}} A \right)$.

$\square$

LSIRA 1.4 Functions

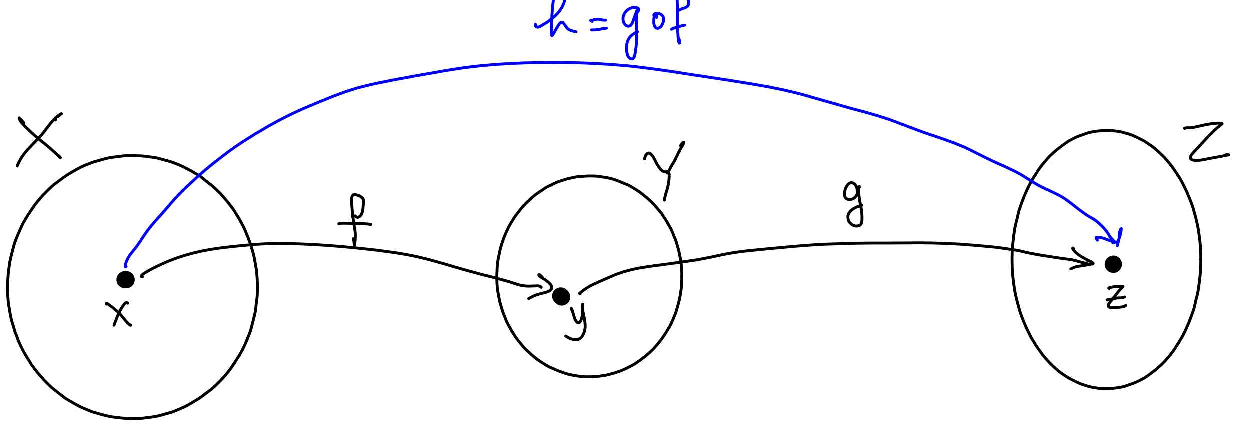
A function $f: X \to Y$ for sets X, Y is a rule that assigns for each $x \in X$ a **unique** $y \in Y$. We write $f(x) = y$, or $x \mapsto y$ "maps to".



Rather than the graphs of functions you may have seen previously, we think of such visualizations for functions now.

X is the domain and Y the codomain of f.

Compositions



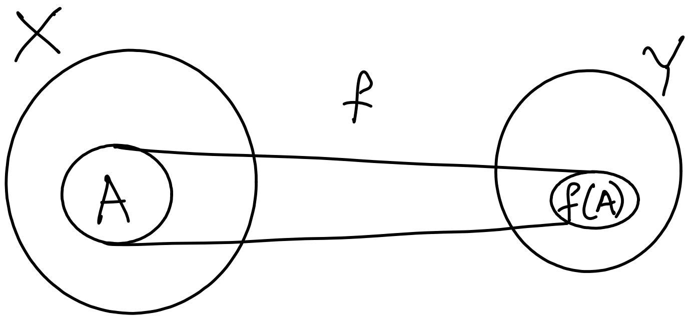
Let $f: X \to Y$ and $g: Y \to Z$ be functions. Then their composition is specified as $h: X \to Z$ defined as $h(x) = g(f(x))$.

The composition is written as $g \circ f$, with $g \circ f(x) = g(f(x))$.

"composition of f and g"

$f_1(f_2(\cdots f_n(x)))\cdots)$ → composition of n functions $f_1, f_2, \ldots, f_n$

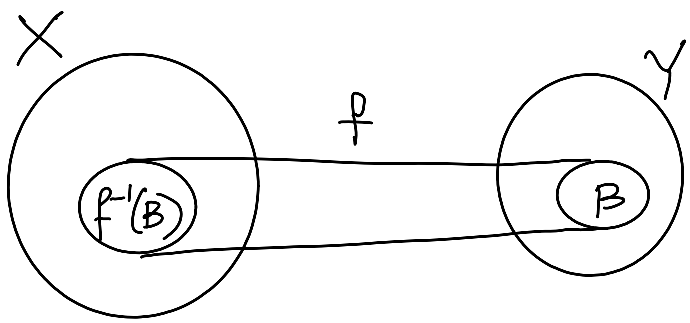
Function: $f: X \to Y$. We now define images and preimages under f.



For $A \subseteq X$, $f(A) \subseteq Y$ is defined as

$$f(A) = \{f(a) \mid a \in A\},$$

and is called the **image** of A under f.



For $B \subseteq Y$, the set $f^{-1}(B) \subseteq X$ defined as

$$f^{-1}(B) = \{x \in X \mid f(x) \in B\}$$

is the **inverse image** or **preimage** of B under f.

In the next lecture, we consider how preimages and images commute with unions and intersections, or not...