INF3580/4580 – Semantic Technologies – Spring 2017

Lecture 5: Mathematical Foundations

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Mandatory exercises

- Remember: Hand-in Oblig 3 by tomorrow.
- Oblig 4 published after next lecture.

Today's Plan

1. Basic Set Algebra
2. Pairs and Relations
3. Propositional Logic

Outline

Motivation

- The great thing about Semantic Technologies is. . .
- . . . Semantics!
- ~~“The study of meaning”~~
- RDF has a precisely defined semantics (=meaning)
- Mathematics is best at precise definitions
- RDF has a mathematically defined semantics

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Sets: Cantor's Definition

- From the inventor of Set Theory, Georg Cantor (1845–1918):

> Unter einer „Menge“ verstehen wir jede Zusammenfassung M von bestimmten wohlunterschiedenen Objekten m unserer Anschauung oder unseres Denkens (welche die „Elemente“ von M genannt werden) zu einem Ganzen.

- Translated:

> A 'set' is any collection M of definite, distinguishable objects m of our intuition or intellect (called the 'elements' of M) to be conceived as a whole.

- There are some problems with this, but it's good enough for us!

Sets

- A set is a mathematical object like a number, a function, etc.
- Knowing a set is
  - knowing what is in it
  - knowing what is not
- Need to know whether elements are equal or not!
- There is no order between elements
- Nothing can be in a set several times
- Two sets A and B are equal if they contain the same elements
  - everything that is in A is also in B
  - everything that is in B is also in A

Elements, Set Equality

$$\{\cdots\}$$

- Notation for finite sets:

$$\{\text{'a'}, 1, \triangle\}$$

- Contains 'a', 1, and $\triangle$, and nothing else.
- There is no order between elements

$$\{1, \triangle\} = \{\triangle, 1\}$$

- Nothing can be in a set several times

$$\{1, \triangle, \triangle\} = \{1, \triangle\}$$

- Sets with different elements are different:

$$\{1, 2\} \neq \{2, 3\}$$

Element of-relation

- We use $\in$ to say that something is element of a set:

$$1 \in \{\text{`a'}, 1, \triangle\}$$

$$\text{`b'} \notin \{\text{`a'}, 1, \triangle\}$$

$\in$

- $\{3, 7, 12\}$: a set of numbers
  - $3 \in \{3, 7, 12\}$, $0 \notin \{3, 7, 12\}$
- $\{\text{`a'}, \text{`b'}, \ldots, \text{`z'}\}$: a set of letters
  - $\text{`y'} \in \{\text{`a'}, \text{`b'}, \ldots, \text{`z'}\}$, $\text{`æ'} \notin \{\text{`a'}, \text{`b'}, \ldots, \text{`z'}\}$,
- $\mathbb{N} = \{1, 2, 3, \ldots\}$: the set of all natural numbers
  - $3580 \in \mathbb{N}$, $\pi \notin \mathbb{N}$.
- $\mathbb{P} = \{2, 3, 5, 7, 11, 13, 17, \ldots\}$: the set of all prime numbers
  - $257 \in \mathbb{P}$, $91 \notin \mathbb{P}$.
- The set P_{3580} of people in the lecture room right now
  - Martin Giese $\in P_{3580}$, Georg Cantor $\notin P_{3580}$.

Sets as Properties

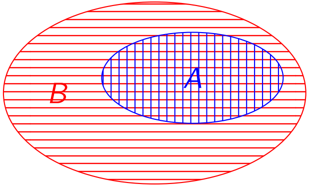
- Sets are used a lot in mathematical notation
- Often, just as a short way of writing things
- More specifically, that something has a property
- E.g. "n is a prime number."
- In mathematics: $n \in \mathbb{P}$
- E.g. "Martin is a human being."
- In mathematics, $m \in H$, where
  - H is the set of all human beings
  - m is Martin
- One *could* define $Prime(n)$, $Human(m)$, etc. but that is not usual
- Instead of writing "x has property XYZ" or "$XYZ(x)$",
  - let P be the set of all objects with property XYZ
  - write $x \in P$.

The Empty Set

- Sometimes, you need a set that has no elements.
- This is called the *empty set*
- Notation: $\emptyset$ or $\{\}$
- $x \notin \emptyset$, whatever x is!

$$\emptyset$$

Subsets



- Let A and B be sets
- *if* every element of A is also in B
- *then* A is called a *subset* of B
- This is written

$$A \subseteq B$$

$$\subseteq$$

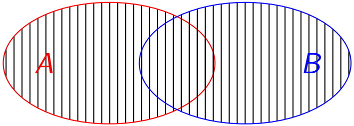
- Examples
  - $\{1\} \subseteq \{1, \text{‘a’}, \triangle\}$
  - $\{1, 3\} \not\subseteq \{1, 2\}$
  - $\mathbb{P} \subseteq \mathbb{N}$
  - $\emptyset \subseteq A$ for any set A
- $A = B$ if and only if $A \subseteq B$ and $B \subseteq A$

Set Union

- The *union* of A and B contains
  - all elements of A
  - all elements of B
  - also those in both A and B
  - and nothing more.
- It is written

$$A \cup B$$

- (A cup which you pour everything into)
- Examples
  - $\{1,2\} \cup \{2,3\} = \{1,2,3\}$
  - $\{1,3,5,7,9,\ldots\} \cup \{2,4,6,8,10,\ldots\} = \mathbb{N}$
  - $\emptyset \cup \{1,2\} = \{1,2\}$



$A \cup B$

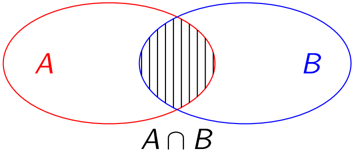
$$\bigcup$$

Set Intersection

- The *intersection* of A and B contains
  - those elements of A
  - that are also in B
  - and nothing more.
- It is written

$$A \cap B$$

- Examples
  - $\{1, 2\} \cap \{2, 3\} = \{2\}$
  - $\mathbb{P} \cap \{2, 4, 6, 8, 10, \ldots\} = \{2\}$
  - $\emptyset \cap \{1, 2\} = \emptyset$



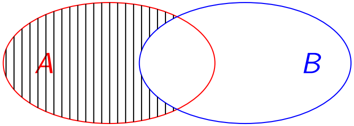
$$\bigcap$$

Set Difference

- The *set difference* of A and B contains
  - those elements of A
  - that are *not* in B
  - and nothing more.
- It is written

$$A \setminus B$$

- Examples
  - $\{1,2\} \setminus \{2,3\} = \{1\}$
  - $\mathbb{N} \setminus \mathbb{P} = \{1,4,6,8,9,10,12,\ldots\}$
  - $\emptyset \setminus \{1,2\} = \emptyset$
  - $\{1,2\} \setminus \emptyset = \{1,2\}$



$A \setminus B$

$\setminus$

Set Comprehensions

- Sometimes enumerating all elements is not good enough
- E.g. there are infinitely many, and "..." is too vague
- Special notation:

$$\{x \in A \mid x \text{ has some property}\}$$

$$\{\ldots \mid \ldots\}$$

- The set of those elements of A which have the property.
- Examples:
  - $\{n \in \mathbb{N} \mid n = 2k \text{ for some } k \in \mathbb{N}\}$: the even numbers
  - $\{n \in \mathbb{N} \mid n < 5\} = \{1, 2, 3, 4\}$
  - $\{x \in A \mid x \notin B\} = A \setminus B$

Question

The *symmetric difference* $A \triangle B$ of two sets contains

- All elements that are in A or B...
- ...but not in both.

Can you write $A \triangle B$ using $\cap$, $\cup$, $\setminus$?

$$A \triangle B = (A \cup B) \setminus (A \cap B)$$

Or:

$$A \triangle B = (A \setminus B) \cup (B \setminus A)$$

Outline

Motivation

- RDF is all about
  - Resources (objects)
  - Their properties (`rdf:type`)
  - Their relations amongst each other
- Sets are good to group objects with some properties!
- How do we talk about relations between objects?

Pairs

- A pair is an *ordered* collection of two objects
- Written

$$\langle x, y \rangle \qquad\qquad \Big\langle \cdot \; \cdot \; \cdot \Big\rangle$$

- Equal if components are equal:

$$\langle a, b \rangle = \langle x, y \rangle \quad \text{if and only if} \quad a = x \quad \text{and} \quad b = y$$

- Order matters:

$$\langle 1, \text{`a'} \rangle \neq \langle \text{`a'}, 1 \rangle$$

- An object can be twice in a pair:

$$\langle 1, 1 \rangle$$

- $\langle x, y \rangle$ is a pair, no matter if $x = y$ or not.

The Cross Product

- Let A and B be sets.
- Construct the set of all pairs $\langle a, b \rangle$ with $a \in A$ and $b \in B$.
- This is called the *cross product* of A and B, written

$$A \times B \qquad\qquad \times$$

- Example:
  - $A = \{1, 2, 3\}$, $B = \{\text{`a'}, \text{`b'}\}$.
  - $A \times B = \{ \langle 1, \text{`a'} \rangle, \langle 2, \text{`a'} \rangle, \langle 3, \text{`a'} \rangle, \langle 1, \text{`b'} \rangle, \langle 2, \text{`b'} \rangle, \langle 3, \text{`b'} \rangle \}$
- Why bother?
- Instead of "$\langle a, b \rangle$ is a pair of a natural number and a person in this room"...
- ... $\langle a, b \rangle \in \mathbb{N} \times P_{3580}$
- But most of all, there are subsets of cross products...

Relations

- A *relation* R between two sets A and B is...
- ...a set of pairs $\langle a, b \rangle \in A \times B$

$$R \subseteq A \times B$$

- We often write aRb to say that $\langle a, b \rangle \in R$
- Example:
  - Let $L = \{\text{'a'}, \text{'b'}, \ldots, \text{'z'}\}$
  - Let $\triangleright$ relate each number between 1 and 26 to the corresponding letter in the alphabet:

$$1 \triangleright \text{'a'} \qquad 2 \triangleright \text{'b'} \quad \ldots \quad 26 \triangleright \text{'z'}$$

  - Then $\triangleright \subseteq \mathbb{N} \times L$:

$$\triangleright = \{\langle 1, \text{'a'} \rangle, \langle 2, \text{'b'} \rangle, \ldots, \langle 26, \text{'z'} \rangle\}$$

  - And we can write:

$$\langle 1, \text{'a'} \rangle \in \triangleright \qquad \langle 2, \text{'b'} \rangle \in \triangleright \quad \ldots \quad \langle 26, \text{'z'} \rangle \in \triangleright$$

More Relations

- A relation R *on* some set A is a relation between A and A:

$$R \subseteq A \times A = A^2$$

- Example: $<$
  - Consider the $<$ order on natural numbers:

$$1 < 2 \qquad 1 < 3 \qquad 1 < 4 \quad \ldots \quad 2 < 3 \qquad 2 < 4 \quad \ldots$$

  - $< \subseteq \mathbb{N} \times \mathbb{N}$:

$$\begin{array}{lllllll} < & = & \{ & \langle 1,2 \rangle\,, & \langle 1,3 \rangle\,, & \langle 1,4 \rangle\,, & \ldots \\ & & & & \langle 2,3 \rangle\,, & \langle 2,4 \rangle\,, & \ldots \\ & & & & & \langle 3,4 \rangle\,, & \ldots \\ & & & \ldots & & & \quad \} \end{array}$$

  - $< = \{\langle x, y \rangle \in \mathbb{N}^2 \mid x \text{ is less than } y\}$

Family Relations

- Consider the set $S = \{\text{Homer}, \text{Marge}, \text{Bart}, \text{Lisa}, \text{Maggie}\}$.
- Define a relation P on S such that

$$x \, P \, y \quad \text{iff} \quad x \text{ is parent of } y$$

- For instance:

$$\text{Homer } P \text{ Bart} \qquad \text{Marge } P \text{ Maggie}$$

- As a set of pairs:

$$P = \{ \langle \text{Homer}, \text{Bart} \rangle , \langle \text{Homer}, \text{Lisa} \rangle , \langle \text{Homer}, \text{Maggie} \rangle , \langle \text{Marge}, \text{Bart} \rangle , \langle \text{Marge}, \text{Lisa} \rangle , \langle \text{Marge}, \text{Maggie} \rangle \} \subseteq S^2$$

- For instance:

$$\langle \text{Homer}, \text{Bart} \rangle \in P \qquad \langle \text{Marge}, \text{Maggie} \rangle \in P$$

Set operatrions on relations

- Since relations are just sets of pairs, we can use set operations and relations on them.
- We say that R is a subrelation P if $R \subseteq P$.
- E.g.: if F is the father-of-relation,

  $$F = \{\langle \text{Homer}, \text{Bart} \rangle, \langle \text{Homer}, \text{Lisa} \rangle, \langle \text{Homer}, \text{Maggie} \rangle\}$$

  then $F \subseteq P$.
- If M is the mother-of-relation,

  $$M = \{\langle \text{Marge}, \text{Bart} \rangle, \langle \text{Marge}, \text{Lisa} \rangle, \langle \text{Marge}, \text{Maggie} \rangle\}$$

  then $F \cup M = P$.

Special Kinds of Relations

- Certain properties of relations occur in many applications
- Therefore, they are given names
- $R \subseteq A^2$ is *reflexive*
  - $x \, R \, x$ for all $x \in A$.
  - E.g. "$=$", "$\leq$" in mathematics, "has same color as", etc.

- $R \subseteq A^2$ is *symmetric*
  - If $x \, R \, y$ then $y \, R \, x$.
  - E.g. "$=$" in mathematics, friendship in facebook, connected by rail, etc.

- $R \subseteq A^2$ is *transitive*
  - If $x \, R \, y$ and $y \, R \, z$, then $x \, R \, z$
  - E.g. "$=$", "$\leq$", "$<$" in mathematics, "is ancestor of", etc.

Question

Let $A = \{1, 2\}$, a set of two elements.
How many different relations on A are there?

$$A \times A = \{\langle 1, 1\rangle, \langle 1, 2\rangle, \langle 2, 1\rangle, \langle 2, 2\rangle\}$$

A relation on A is a subset of $A \times A$. So how many subsets are there?

$$\{\}, \quad \{\langle 1, 1\rangle\}, \quad \{\langle 1, 2\rangle\}, \quad \{\langle 1, 1\rangle, \langle 1, 2\rangle\}, \ldots$$

16 relations on A. Generally: $2^{(|A|^2)}$

Outline

Many Kinds of Logic

- In mathematical logic, many kinds of logic are considered
  - propositional logic (and, or, not)
  - description logic (a mother is a person who is female and has a child)
  - modal logic (Alice knows that Bob didn't know yesterday that. . .)
  - first-order logic (For all. . . , for some. . .)
- All of them formalizing different aspects of reasoning
- All of them defined mathematically
  - Syntax ($\approx$ grammar. What is a formula?)
  - Semantics (What is the meaning?)
    - proof theory: what is legal reasoning?
    - model semantics: declarative using set theory.
- For semantic technologies, description logic (DL) is most interesting
  - talks about sets and relations
- Basic concepts can be explained using predicate logic

Propositional Logic: Formulas

- Formulas are defined "by induction" or "recursively":

1 Any letter p, q, r,... is a formula

2 *if* A and B are formulas, *then*

  - $(A \wedge B)$ is also a formula (read: "A and B")
  - $(A \vee B)$ is also a formula (read: "A or B")
  - $(A \rightarrow B)$ is also a formula (read "A implies B")
  - $\neg A$ is also a formula (read: "not A")

$\wedge \vee \rightarrow \neg$

- Nothing else is. Only what rules [1] and [2] say is a formula.
- Examples of formulae:

$$p \quad (p \wedge \neg r) \quad (q \wedge q) \quad (q \wedge \neg q) \quad ((p \vee \neg q) \wedge (\neg p \rightarrow q))$$

- Examples of non-formulas:

$$pqr \quad p\neg q \quad \wedge(p$$

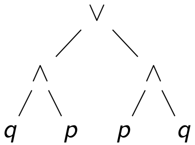
Propositional Formulas, Using Sets

- The set of all formulas Φ is the least set such that

1 All letters $p, q, r, \ldots \in \Phi$

2 *if* $A, B \in \Phi$, then
  - $(A \land B) \in \Phi$
  - $(A \lor B) \in \Phi$
  - $(A \rightarrow B) \in \Phi$
  - $\neg A \in \Phi$
- Formulas are just a kind of strings until now:
  - no meaning
  - but every formula can be "parsed" uniquely.

$$((q \land p) \lor (p \land q))$$



Terminology

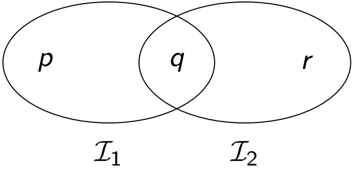
- $\neg, \wedge, \vee, \rightarrow$ are called *connectives*.
- A formula $(A \wedge B)$ is called a *conjunction*.
- A formula $(A \vee B)$ is called a *disjunction*.
- A formula $(A \rightarrow B)$ is calles an *implication*.
- A formula $\neg A$ is called a *negation*.

Truth

- Logic is about things being true or false, right?
- Is $(p \wedge q)$ true?
- That depends on whether p and q are true!
- *If* p is true, and q is true, then $(p \wedge q)$ is true
- *Otherwise,* $(p \wedge q)$ is false.
- So truth of a formula depends on the truth of the letters
- We also say the "interpretation" of the letters
- In other words, in general, truth depends on the context
- Let's formalize this context, a.k.a. interpretation, a.k.a. model

Interpretations

- Idea: put all letters that are "true" into a set!
- Define: An *interpretation* $\mathcal{I}$ is a set of letters.
- Letter p is true in interpretation $\mathcal{I}$ if $p \in \mathcal{I}$.
- E.g., in $\mathcal{I}_1 = \{p, q\}$, p is true, but r is false.
- But in $\mathcal{I}_2 = \{q, r\}$, p is false, but r is true.



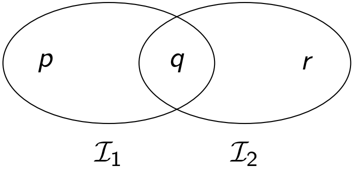
Semantic Validity $\models$

- To say that p is true in $\mathcal{I}$, write

$$\mathcal{I} \models p$$

$\models$

- For instance



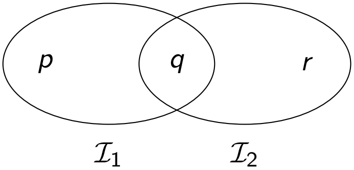
$$\mathcal{I}_1 \models p \qquad \mathcal{I}_2 \not\models p$$

- In other words, for all letters p:

$$\mathcal{I} \models p \qquad \text{if and only if} \qquad p \in \mathcal{I}$$

Validity of Compound Formulas

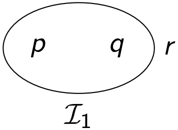
- So, is $(p \wedge q)$ true?
- That depends on whether p and q are true!
- And that depends on the interpretation.
- All right then, *given some* $\mathcal{I}$, is $(p \wedge q)$ true?
- Yes, if $\mathcal{I} \models p$ *and* $\mathcal{I} \models q$
- No, otherwise
- For instance

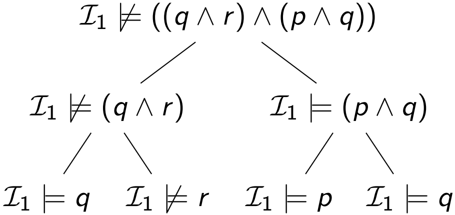


$\mathcal{I}_1 \models p \wedge q$ $\qquad$ $\mathcal{I}_2 \not\models p \wedge q$

Validity of Compound Formulas, cont.

- That was easy, p and q are only letters...
- ...so, is $((q \wedge r) \wedge (p \wedge q))$ true in $\mathcal{I}$?
- Idea: apply our rule recursively
- For any formulas A and B,...
- ...and any interpretation $\mathcal{I}$,...
- ...$\mathcal{I} \models A \wedge B$ if and only if $\mathcal{I} \models A$ and $\mathcal{I} \models B$
- For instance, if $\mathcal{I}_1 = \{p, q\}$:





Semantics for $\neg$, $\rightarrow$ and $\vee$

- The complete definition of $\models$ is as follows:
- For any interpretation $\mathcal{I}$, letter p, formulas A, B:
  - $\mathcal{I} \models p$ iff $p \in \mathcal{I}$
  - $\mathcal{I} \models \neg A$ iff $\mathcal{I} \not\models A$
  - $\mathcal{I} \models (A \wedge B)$ iff $\mathcal{I} \models A$ and $\mathcal{I} \models B$
  - $\mathcal{I} \models (A \vee B)$ iff $\mathcal{I} \models A$ or $\mathcal{I} \models B$ (or both)
  - $\mathcal{I} \models (A \rightarrow B)$ iff $\mathcal{I} \models A$ implies $\mathcal{I} \models B$
- Semantics of $\neg$, $\wedge$, $\vee$, $\rightarrow$ often given as *truth table*:

A	B	$\neg A$	$A \wedge B$	$A \vee B$	$A \rightarrow B$
f	f	t	f	f	t
f	t	t	f	t	t
t	f	f	f	t	f
t	t	f	t	t	t

Some Formulas Are Truer Than Others

- Is $(p \lor \neg p)$ true?
- Only two interesting interpretations:

$$\mathcal{I}_1 = \emptyset \qquad\qquad \mathcal{I}_2 = \{p\}$$

- Recursive Evaluation:

$$\mathcal{I}_1 \models (p \lor \neg p)$$
$$\mathcal{I}_1 \not\models p \qquad \mathcal{I}_1 \models \neg p$$
$$\mathcal{I}_1 \not\models p$$

$$\mathcal{I}_2 \models (p \lor \neg p)$$
$$\mathcal{I}_2 \models p \qquad \mathcal{I}_2 \not\models \neg p$$
$$\mathcal{I}_2 \models p$$

- $(p \lor \neg p)$ is true in *all* interpretations!

Tautologies

- A formula A that is true in *all* interpretations is called a *tautology*
- also *logically valid*
- also a *theorem* (of propositional logic)
- written:

$$\models A$$

- $(p \lor \neg p)$ is a tautology
- True whatever p means:
  - The sky is blue or the sky is not blue.
  - Marit B. will win the race or Marit B. will not win the race.
  - The slithy toves gyre or the slithy toves do not gyre.
- Possible to derive true statements mechanically. . .
- . . . without understanding their meaning!

Checking Tautologies

- Checking whether $\models A$ is the task of SAT-solving
- (co-)NP-complete in general (i.e. in practice exponential time)
- Small instances can be checked with a truth table:

$$\models (\neg p \vee (\neg q \vee (p \wedge q))) \quad ?$$

p	q	$\neg p$	$\neg q$	$(p \wedge q)$	$(\neg q \vee (p \wedge q))$	$(\neg p \vee (\neg q \vee (p \wedge q)))$
f	f	t	t	f	t	t
f	t	t	f	f	f	t
t	f	f	t	f	t	t
t	t	f	f	t	t	t

- Therefore: $(\neg p \vee (\neg q \vee (p \wedge q)))$ is a tautology!

Entailment

- Tautologies are true in all interpretations
- Some Formulas are true only under certain assumptions
- *A entails B*, written $A \models B$ if

  $\mathcal{I} \models B$

  for all interpretations $\mathcal{I}$ with $\mathcal{I} \models A$
- Also: "B is a logical consequence of A"
- Whenever A holds, also B holds
- For instance:

$$p \wedge q \models p$$

- Independent of meaning of p and q:
  - If it rains and the sky is blue, then it rains
  - If M.B. wins the race and the world ends, then M.B. wins the race
  - If 'tis brillig and the slythy toves do gyre, then 'tis brillig

Checking Entailment

- SAT solvers can be used to check entailment:

$$A \models B \qquad \text{if and only if} \qquad \models (A \rightarrow B)$$

- We can check simple cases with a truth table:

$$(p \wedge \neg q) \models \neg(\neg p \vee q) \quad ?$$

p	q	$\neg p$	$\neg q$	$(p \wedge \neg q)$	$(\neg p \vee q)$	$\neg(\neg p \vee q)$
f	f	t	t	f	t	f
f	t	t	f	f	t	f
t	f	f	t	t	f	t
t	t	f	f	f	t	f

- So $(p \wedge \neg q) \models \neg(\neg p \vee q)$
- And $\neg(\neg p \vee q) \models (p \wedge \neg q)$

Equivalent formulas and redundant connectives

- In other words, $(p \wedge \neg q)$ and $\neg(\neg p \vee q)$ always have the same truth value, no matter the interpretation.
- We say that A and B are *equivalent* if A and B always have the same truth value.
- For this we often introduce another connective, $\leftrightarrow$.
- $\mathcal{I} \models (A \leftrightarrow B)$ iff $\mathcal{I} \models A$ if and only if $\mathcal{I} \models B$.
- To express that two formulas A, B are equivalent, we can write $\models (A \leftrightarrow B)$.

- We actually only need a subset of the connectives:
- E.g.:
  - $\models ((A \vee B) \leftrightarrow \neg(\neg A \wedge \neg B))$.
  - $\models ((A \rightarrow B) \leftrightarrow (\neg A \vee B))$.
  - $\models ((A \leftrightarrow B) \leftrightarrow ((A \rightarrow B) \wedge (B \rightarrow A)))$.
- So we actually only need $\neg$ and $\wedge$ to express any formula!
- Any formula is equivalent to a formula containing only the connectives $\neg$ and $\wedge$.

Recap

- Sets
  - are collections of objects without order or multiplicity
  - often used to gather objects which have some property
  - can be combined using $\cap, \cup, \setminus$
- Relations
  - are sets of pairs (subset of cross product $A \times B$)
  - $x \, R \, y$ is the same as $\langle x, y \rangle \in R$
  - can use set operations on relations, e.g. $F \subseteq P$.
- Predicate Logic
  - has formulas built from letters, $\wedge$, $\vee$, $\rightarrow$, $\neg$ *(syntax)*
  - which can be evaluated in an *interpretation (semantics)*
  - interpretations are sets of letters
  - recursive definition for semantics of $\wedge$, $\vee$, $\rightarrow$, $\neg$
  - $\models A$ if $\mathcal{I} \models A$ for all $\mathcal{I}$ *(tautology)*
  - $A \models B$ if $\mathcal{I} \models B$ for all $\mathcal{I}$ with $\mathcal{I} \models A$ *(entailment)*
  - truth tables can be used for checking validity and etailment.