

Mathematical Logic

Introduction to Reasoning and Automated Reasoning.
Hilbert-style Propositional Reasoning.

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Mathematical Logic

Complexity of deciding logical consequence in Propositional Logic

The truth table method is Exponential

The problem of determining if a formula A containing n primitive propositions, is a logical consequence of the empty set, i.e., the problem of determining if A is valid, ($\models A$), takes an n -exponential number of steps. To check if A is a tautology, we have to consider 2^n interpretations in the truth table, corresponding to 2^n lines.

More efficient algorithms?

Are there more efficient algorithms? I.e. Is it possible to define an algorithm which takes a polynomial number of steps in n , to determine the validity of A ? This is an unsolved problem

$P \stackrel{?}{=} NP$

The existence of a polynomial algorithm for checking validity is still an open problem, even if there are a lot of evidences in favor of non-existence

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Problem

Is there an algorithm to determine whether a formula ϕ is the logical consequence of a set of formulas Γ ?

Naïve solution

- Apply directly the definition of logical consequence i.e., for all possible interpretations \mathcal{I} determine if $\mathcal{I} \models \Gamma$, if this is the case then check if $\mathcal{I} \models A$ too.
- This solution can be used when Γ is finite, and there is a finite number of relevant interpretations.

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Deciding logical consequence is not always possible

Propositional Logics

The truth table method enumerates all the possible interpretations of a formula and, for each formula, it computes the relation \models .

Other logics

For first order logic and modal logics there is no general algorithm to compute the logical consequence. There are some algorithms computing the logical consequence for first order logic sub-languages and for sub-classes of structures (as we will see further on).

Alternative approach: decide logical consequence via reasoning.

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What the dictionaries say:

- **reasoning**: the process by which one judgement is deduced from another or others which are given (Oxford English Dictionary)
- **reasoning**: the drawing of inferences or conclusions through the use of *reason*
reason: the power of comprehending, inferring, or thinking, esp. in orderly rational ways (cf. *intelligence*) (Merriam-Webster)

- Reasoning is a process of deriving new statements (conclusions) from other statements (premises) by argument.
- For reasoning to be correct, this process should generally **preserve truth**. That is, the arguments should be **valid**.
- How can we be sure our arguments are valid?
- Reasoning takes place in many different ways in everyday life:
 - **Word of Authority**: we derive conclusions from a source that we trust; e.g. religion.
 - **Experimental science**: we formulate hypotheses and try to confirm them with experimental evidence.
 - **Sampling**: we analyse many pieces of evidence statistically and identify patterns.
 - **Mathematics**: we derive conclusions based on mathematical *proof*.
- Are any of the above methods **valid**?

- For centuries, mathematical proof has been the hallmark of logical validity.
- But there is still a **social aspect** as peers have to be convinced by argument.
- This process is open to **flaws**: e.g. Kempes proof of the Four Colour Theorem.
- To avoid this, we require that all proofs be broken down to their simplest steps and all hidden premises uncovered.

We can be sure there are no hidden premises by reasoning according to **logical form** alone.

Example

Suppose all men are mortal. Suppose Socrates is a man. Therefore, Socrates is mortal.

- The validity of this proof is independent of the meaning of "men", "mortal" and "Socrates".
- Indeed, even a nonsense substitution gives a valid sentence:
 - Suppose all borogroves are mimsy. Suppose a mome rath is a borogrove. Therefore, a mome rath is mimsy.
- General pattern:
 - Suppose all Ps are Q. Suppose x is a P. Therefore, x is a Q.

- The modern notion of **symbolic formal proof** was developed in the 20th century by logicians and mathematicians such as Russell, Frege and Hilbert.
- The benefit of formal logic is that it is based on a **pure syntax**: *a precisely defined symbolic language with procedures for transforming symbolic statements into other statements, based solely on their form.*
- No intuition or interpretation is needed**, merely applications of agreed upon rules to a set of agreed upon formulae.

Hilbert axioms for classical propositional logic

Axioms

- A1** $\phi \supset (\psi \supset \phi)$
A2 $(\phi \supset (\psi \supset \theta)) \supset ((\phi \supset \psi) \supset (\phi \supset \theta))$
A3 $(\neg\psi \supset \neg\phi) \supset ((\neg\psi \supset \phi) \supset \psi)$

Inference rule(s)

$$\text{MP} \quad \frac{\phi \quad \phi \supset \psi}{\psi}$$

Why there are no axioms for \wedge and \vee and \equiv ?

The connectives \wedge and \vee are rewritten into equivalent formulas containing only \supset and \neg .

$$A \wedge B \equiv \neg(A \supset \neg B)$$

$$A \vee B \equiv \neg A \supset B$$

$$A \equiv B \equiv \neg((A \supset B) \supset \neg(B \supset A))$$

Proofs and deductions (or derivations)

proof

A **proof of a formula ϕ** is a sequence of formulas ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$, such that each ϕ_k is either

- an axiom or
- it is derived from previous formulas by **reasoning rules**

ϕ is **provable**, in symbols $\vdash \phi$, if there is a proof for ϕ .

Deduction of ϕ from Γ

A **deduction of a formula ϕ from a set of formulas Γ** is a sequence of formulas ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$, such that ϕ_k

- is an axiom or
- it is in Γ (an assumption)
- it is derived from previous formulas by **reasoning rules**

ϕ is **derivable from Γ** , in symbols $\Gamma \vdash \phi$, if there is a proof for ϕ from formulas in Γ .

Note: the sequence ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$ is finite!

Hilbert proofs and deductions

Hilbert proof

A **proof of a formula ϕ** is a sequence of formulas ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$, such that each ϕ_k is either

- an axiom or
- it is derived from previous formulas by **MP**

ϕ is **provable**, in symbols $\vdash \phi$, if there is a proof for ϕ .

Hilbert Deduction of ϕ from Γ

A **deduction of a formula ϕ from a set of formulas Γ** is a sequence of formulas ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$, such that ϕ_k

- is an axiom or
- it is in Γ (an assumption)
- it is derived from previous formulas by **MP**

ϕ is **derivable from Γ** in symbols $\Gamma \vdash \phi$ if there is a deduction for ϕ from Γ .

Note: the sequence ϕ_1, \dots, ϕ_n , with $\phi_n = \phi$ is finite!

Example (Proof of $A \supset A$)

1. A1 $A \supset ((A \supset A) \supset A)$
2. A2 $(A \supset ((A \supset A) \supset A)) \supset ((A \supset (A \supset A)) \supset (A \supset A))$
3. MP(1,2) $(A \supset (A \supset A)) \supset (A \supset A)$
4. A1 $(A \supset (A \supset A))$
5. MP(4,3) $A \supset A$

Example (proof of $\neg A \supset (A \supset B)$)

We prove that $A, \neg A \vdash B$ and by deduction theorem we have that $\neg A \vdash A \supset B$ and that $\vdash \neg A \supset (A \supset B)$

We label with **Hypothesis** the formula on the left of the \vdash sign.

1. *hypothesis* A
2. A1 $A \supset (\neg B \supset A)$
3. MP(1,2) $\neg B \supset A$
4. *hypothesis* $\neg A$
5. A1 $\neg A \supset (\neg B \supset \neg A)$
6. MP(4,5) $\neg B \supset \neg A$
7. A3 $(\neg B \supset \neg A) \supset ((\neg B \supset A) \supset B)$
8. MP(6,7) $(\neg B \supset A) \supset B$
9. MP(3,8) B

Logical consequence and derivability

A formula A is a **logical consequence** of a set of formulas Γ , in symbols

$$\Gamma \models A$$

if and only if for any interpretation \mathcal{I} that satisfies all the formulas in Γ , \mathcal{I} satisfies A ,

A formula A is **derivable** from a set of formulas Γ , in symbols

$$\Gamma \vdash A$$

if and only if there is a deduction of A with assumptions in Γ

How can we be sure that derivability exactly mimics logical consequence?

Soundness & Completeness of a proof system

Soundness

The proof system proves only logical consequences (or, analogously, does not enable us to prove non logical consequences).
Formally, if $\Gamma \vdash A$ then $\Gamma \models A$.

Completeness

The proof system enables us to prove all logical consequences.
Formally, if $\Gamma \models A$ then $\Gamma \vdash A$.

Theorem (Soundness of Hilbert axiomatization)

If $\Gamma \vdash A$ then $\Gamma \models A$.

Theorem (Completeness of Hilbert axiomatization)

If $\Gamma \models A$ then $\Gamma \vdash A$.

We will not prove the theorems.

Minimality

The main objective of Hilbert was to find the smallest set of axioms and inference rules from which it was possible to derive all the tautologies.

Unnatural

Proofs and deductions in Hilbert axiomatization are awkward and unnatural. Other proof styles, such as Natural Deductions, are more intuitive. As a matter of facts, nobody is practically using Hilbert calculus for deduction.

Why it is so important

Providing an Hilbert style axiomatization of a logic describes with simple axioms the entire properties of the logic. Hilbert axiomatization is the "identity card" of the logic.

The deduction theorem

Theorem

$\Gamma, A \vdash B$ if and only if $\Gamma \vdash A \supset B$

Proof.

\implies direction (\impliedby is easy)

If A and B are equal, then we know that $\vdash A \supset B$ (see previous example), and by monotonicity $\Gamma \vdash A \supset B$.

Suppose that A and B are distinct formulas. Let $\pi = (A_1, \dots, A_n = B)$ be a deduction of $\Gamma, A \vdash B$, we proceed by induction on the length of π .

Base case $n = 1$ If $\pi = (B)$, then either $B \in \Gamma$ or B is an axiom. Then

| | |
|-----------------------------------|---------------------------|
| Axiom A1 | $B \supset (A \supset B)$ |
| $B \in \Gamma$ or B is an axiom | B |
| by MP | $A \supset B$ |

is a deduction of $A \supset B$ from Γ or from the empty set, and therefore $\Gamma \vdash A \supset B$.



The deduction theorem

Proof.

Step case If $A_n = B$ is either an axiom or an element of Γ , then we can reason as the previous case.

If B is derived by **MP** form A_i and $A_j = A_i \supset B$. Then, A_i and $A_j = A_i \supset B$, are provable in less than n steps and, by induction hypothesis, $\Gamma \vdash A \supset A_i$ and $\Gamma \vdash A \supset (A_i \supset B)$. Starting from the deductions of these two formulas from Γ , we can build a deduction of $A \supset B$ form Γ as follows:

| | | |
|--------------|-----------|---|
| By induction | ⋮ | deduction of $A \supset (A_i \supset B)$ form Γ |
| | | $A \supset (A_i \supset B)$ |
| By induction | ⋮ | deduction of $A \supset A_i$ form Γ |
| | | $A \supset A_i$ |
| | A2 | $(A \supset (A_i \supset B)) \supset ((A \supset A_i) \supset (A \supset B))$ |
| | MP | $(A \supset A_i) \supset (A \supset B)$ |
| | MP | $A \supset B$ |



But... Formal proofs are bloated and over expanded!

I find nothing in [formal logic] but shackles. It does not help us at all in the direction of conciseness, far from it; and if it requires 27 equations to establish that 1 is a number, how many will it require to demonstrate a real theorem? (Poincaré)

Can automation help?

- **Automated Reasoning (AR)** refers to reasoning in a computer using **logic**.
- AR has been an active area of research since the 1950s.
- It uses deductive reasoning to tackle problems such as:
 - constructing formal mathematical proofs;
 - verifying programs meet their specifications;
 - modelling human reasoning.

Different Forms of Reasoning

- **Deduction:** Given a set of premises Γ and a conclusion ϕ show that indeed $\Gamma \models \phi$ (this includes Validity: $\Gamma = \emptyset$)
- **Abduction/Induction:** given a theory T and an observation ϕ , find an explanation Γ such that $T \cup \Gamma \models \phi$
- **Satisfiability Checking:** given a set of formulae Γ , check whether there exists a model \mathcal{I} such that $\mathcal{I} \models \phi$ for all $\phi \in \Gamma$?
- **Model Checking:** given a model \mathcal{I} and a formula ϕ , check whether $\mathcal{I} \models \phi$

Automated reasoning attempts to mechanise all of these forms of reasoning for different *logics*: propositional or first-order, classical, intuitionistic, modal, temporal, non-monotonic, ...

More efficient reasoning systems?

Automate Hilbert style reasoning

Checking if $\Gamma \models \phi$ by searching for a Hilbert-style deduction of ϕ from Γ is not an easy task for computers. Indeed, in trying to generate a deduction of ϕ from Γ , there are too many possible actions a computer could take:

- adding an instance of one of the three axioms (infinite number of possibilities)
- applying **MP** to already deduced formulas,
- adding a formula in Γ

More efficient methods

Resolution to check if a formula is *not* satisfiable

SAT DP, DPLL to search for an interpretation that satisfies a formula

Tableaux search for a model of a formula guided by its structure