

Logic

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Logic Revision

Prelude: A Basic Example of Boolean Logic i

Before diving into complex inference, let's recall the basics of **Boolean Logic** using a simple circuit metaphor.

- **Scenario:** A lamp (L) turns on only if *Switch A* (A) is ON **AND** *Switch B* (B) is ON.
- **Representation:**
 - 1 = True (On/High)
 - 0 = False (Off/Low)
- **Formula:** $L = A \wedge B$

Prelude: A Basic Example of Boolean Logic ii

Truth Table:

Switch A	Switch B	Lamp (L)
0	0	0
0	1	0
1	0	0
1	1	1

- **Key Concept:** Logic allows us to formalize the state of the world (A, B) and derive consequences (L) without physically checking the lamp every time.

Logic Systems Components

A logic system is defined by three main components:

1. **Syntax:** Describes the valid set of formulas that can be written.
 - *Note:* These are called **Well Formed Formulas (WFF)**.
2. **Semantics:** Connects the formulas to the facts or rules they represent in the real world.
 - *Example:* In Propositional Logic, semantics are defined via **Truth Tables**.
3. **Inference Rules:** Algorithms that allow deriving *new* formulas from *known* formulas.

Propositional Logic i

Based on **propositions** (elementary formulas that can be True or False).

- **Proposition:** An elementary formula (e.g., "Snow is white", "Sugar is a hydrocarbon").
- **Propositional Variable:** A variable (e.g., P , Q) that takes the truth value of a proposition.
- **Connectives:**
 - Negation (\neg)
 - Conjunction (\wedge)
 - Disjunction (\vee)
 - Implication (\Rightarrow)
 - Biconditional (\Leftrightarrow)

Example:

- P : "It is raining"
- Q : "The ground is wet"
- Formula: $P \Rightarrow Q$ ("If it is raining, then the ground is wet")

First-Order Logic (FOL)

Propositional logic is limited (it cannot handle objects or relations easily). FOL extends this by introducing:

- **Objects (Constants):** Specific entities.
 - *Examples:* 1215, Aveiro, Alice.
- **Functions:** Return an object.
 - *Examples:* `Power(4,3)`, `FatherOf(Paul)`.
 - *Note:* Constants can be seen as functions with arity 0.
- **Predicates (Relations):** Return True/False.
 - *Examples:* `Father(Rui, Paulo)`, `Brother(Paul, Rose)`.
- **Variables:** Placeholders for objects (x, y, z).

A well-formed formula in FOL is constructed recursively:

- **Terms:**
 - Constant | Variable | Function(Term, ...)
- **Atomic Formula:**
 - Predicate(Term, ...) | Term = Term
- **Complex Formula:**
 - \neg Formula
 - Formula \wedge Formula
 - Formula \vee Formula
 - Formula \Rightarrow Formula
 - Quantifier Variable Formula

Convention:

- **Predicates/Constants/Functions:** Start with Uppercase (e.g., Near, Alice).
- **Variables:** Start with lowercase (e.g., x, y).

Quantifiers: Universal (\forall)

"For all x , $P(x)$ is true."

Example: "All students in Oxford are smart."

- **Correct:** $\forall x(\text{Studies}(x, \text{Oxford}) \Rightarrow \text{Smart}(x))$
- **Common Mistake:** Using \wedge instead of \Rightarrow .
 - *Incorrect:* $\forall x(\text{Studies}(x, \text{Oxford}) \wedge \text{Smart}(x))$
 - *Why?* This means "Everyone in the universe studies at Oxford AND is smart."

Quantifiers: Existential (\exists)

“There exists an x such that $P(x)$ is true.”

Example: “Some student in Oxford is smart.”

- **Correct:** $\exists x(\text{Studies}(x, \text{Oxford}) \wedge \text{Smart}(x))$
- **Common Mistake:** Using \Rightarrow instead of \wedge .
 - *Incorrect:* $\exists x(\text{Studies}(x, \text{Oxford}) \Rightarrow \text{Smart}(x))$
 - *Why?* The implication $A \Rightarrow B$ is true if A is false. If there is *anyone* who does not study at Oxford, the statement becomes true vacuously, even if no smart students exist.

Interpretations and Models

- **Interpretation (Prop Logic):** An assignment of truth values to all variables.
- **Interpretation (FOL):** A mapping of constants to objects, predicates to relations, and functions to functional mappings in the domain.
- **Model:** An interpretation that satisfies a formula (evaluates to True).
- **Satisfiability:** A formula is satisfiable if there exists at least one model for it.
- **Tautology (Validity):** A formula is true in **all** possible interpretations.
- **Entailment (\models):** $KB \models \alpha$ means α is true in all models where KB is true.

Logic Rewrite Rules (Equivalences)

Useful for simplifying formulas and converting to Normal Forms.

- **De Morgan's Laws:**

- $\neg(A \wedge B) \equiv \neg A \vee \neg B$
- $\neg(A \vee B) \equiv \neg A \wedge \neg B$

- **Implication:**

- $A \Rightarrow B \equiv \neg A \vee B$

- **Double Negation:**

- $\neg\neg A \equiv A$

- **Quantifier Negation (Generalized De Morgan):**

- $\neg\forall x P(x) \equiv \exists x \neg P(x)$
- $\neg\exists x P(x) \equiv \forall x \neg P(x)$

Conjunctive Normal Form (CNF)

Standard format required for the **Resolution** algorithm.

1. **Literal:** An atomic formula (P) or its negation ($\neg P$).
2. **Clause:** A disjunction (\vee) of literals.
 - Example: $(A \vee B \vee \neg C)$
3. **CNF:** A conjunction (\wedge) of clauses.
 - Example: $(A \vee B) \wedge (\neg B \vee C \vee D) \wedge (\neg A)$

Clausal Form: Often represented as a set of sets:

$\{\{A, B\}, \{\neg B, C, D\}, \{\neg A\}\}$

Proofs and Logical Consequence

- **Logical Consequence:** $\Delta \models A$ (A follows from set Δ).
- **Deduction Theorem:** $\{A_1, \dots, A_n\} \models B$ iff $(A_1 \wedge \dots \wedge A_n) \Rightarrow B$ is a valid (tautology).

Proof by Refutation (Reductio ad Absurdum) To prove $\Delta \models A$:

1. Assume the negation of the goal: $\Delta \cup \{\neg A\}$.
2. Show that this set is **unsatisfiable** (leads to a contradiction/false).
3. If $\Delta \wedge \neg A$ is impossible, then $\Delta \Rightarrow A$ must be true.

Inference: The Resolution Rule

Resolution is a sound inference rule that generalizes “Modus Ponens”.

Propositional Resolution:

$$\frac{A \vee B, \quad \neg B \vee C}{\vdash} A \vee C$$

- **Logic:** If B is True, C must be True (from the second clause). If B is False, A must be True (from the first clause). Therefore, either A or C is True.
- **Step:** Resolving $(A \vee B)$ and $(\neg B \vee C)$ cancels out the complementary literals B and $\neg B$.

Completeness: Resolution is **refutation-complete**. It may not derive every true sentence directly, but it can always confirm a contradiction if the KB is unsatisfiable.

In FOL, clauses contain variables. To apply resolution, we must match predicates by finding a substitution θ that makes terms identical.

- **Substitution:** $\theta = \{x/\text{Alice}, y/\text{Bob}\}$
- **Unifiable:** Two terms T_1, T_2 are unifiable if there exists θ such that $T_1\theta = T_2\theta$.
- **MGU (Most General Unifier):** The simplest substitution that solves the unification.

Examples:

1. Unify $\text{Knows}(\text{John}, x)$ and $\text{Knows}(y, \text{Mother}(y))$?
 - $\theta = \{y/\text{John}, x/\text{Mother}(\text{John})\}$
 - Result: $\text{Knows}(\text{John}, \text{Mother}(\text{John}))$
2. Unify $\text{King}(x)$ and $\text{Greedy}(y)$?
 - **Fail:** Predicates differ.

Resolution in First-Order Logic i

Combines Propositional Resolution with Unification.

Rule: Given clauses C_1 and C_2 :

- $C_1 = l_1 \vee \dots \vee l_k$
- $C_2 = m_1 \vee \dots \vee m_n$
- If l_i and $\neg m_j$ unify with substitution θ :

$$\text{Resolvent} = \text{SUBST}(\theta, (C_1 - \{l_i\}) \cup (C_2 - \{m_j\}))$$

Example:

1. $C_1: \neg \text{Man}(x) \vee \text{Mortal}(x)$ (All men are mortal)
2. $C_2: \text{Man}(\text{Socrates})$
3. Unify $\neg \text{Man}(x)$ and $\text{Man}(\text{Socrates})$:
 $\theta = \{x/\text{Socrates}\}.$
4. Resolvent: $\text{Mortal}(\text{Socrates}).$

Horn Clauses

A restricted subset of logic used in **Logic Programming (Prolog)** allowing efficient linear-time inference.

- **Definition:** A clause with **at most one positive literal**.
- **Forms:**
 1. **Rule:** $\neg P_1 \vee \neg P_2 \vee H \equiv (P_1 \wedge P_2) \Rightarrow H$.
 - Prolog: `H :- P1, P2.`
 2. **Fact:** H (no negative literals).
 - Prolog: `H.`
 3. **Goal:** $\neg P_1 \vee \neg P_2$ (no positive literal).
 - Prolog: `:- P1, P2.`
- **Inference:** Supports **Forward Chaining** (Data-driven) and **Backward Chaining** (Goal-driven).