

Knowledge Representation

Instructor: GP Saggese, PhD - gsaggese@umd.edu

References:

- Mostly papers and Internet
- AIMA 7: Logical agents
- AIMA 8, First-order logic
- AIMA 9: Inference in first-order logic
- AIMA 10, Knowledge representation

Knowledge Representation

- **Knowledge Representation**
 - Basics of Knowledge Representation
 - Examples of Logic
 - Logical Agents
 - Ontologies
 - Reasoning in Ontologies
- Propositional logic
- First-order Logic
- Non-classical Logics
- Description Logics

Basics of Knowledge Representation

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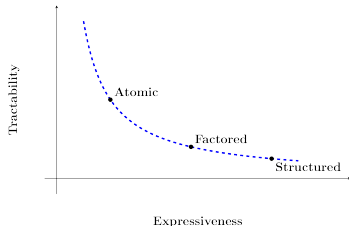
What is Knowledge Representation?

- **Knowledge Representation (KR)** is the study of how to formally encode information so that machines can reason with it
 - E.g., rules, logic, ontologies, semantic networks
 - It is at the heart of symbolic AI and complements learning-based approaches
- Defines:
 - **structure** (how knowledge is organized)
 - **semantics** (what it means)
- Serves as a bridge between perception (data) and reasoning (logic)
 - Essential for explainability and transparency in intelligent systems
- Enables machines to:
 - Draw conclusions
 - Perform planning
 - Answer queries
 - ...

Expressiveness vs. Tractability

- **Tradeoff in AI / ML**

- **Expressiveness:** richness of concepts that can be captured
- **Tractability:** whether reasoning can be performed efficiently
- More expressive languages lead to harder computation



- Choosing the right knowledge representation formalism depends on the application needs

- **Atomic**

- Treats each state as a single, indivisible entity
- E.g., depth-first search algorithms (e.g., E3 in Chess)
- Simple and fast but limited in capturing complex relationships

- **Factored**

- E.g., propositional logic
- E.g., $P_{1,1}$: "Pit in square (1,1)", $B_{1,2} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{1,3})$
- Captures relationships between variables but can't express complex structures

- **Structured**

- E.g., first-order logic
- $\forall x \forall y \text{ Father}(x, y) \Rightarrow \text{Parent}(x, y) = \text{"A father of a person is their parent"}$
- More expressive but undecidable in general

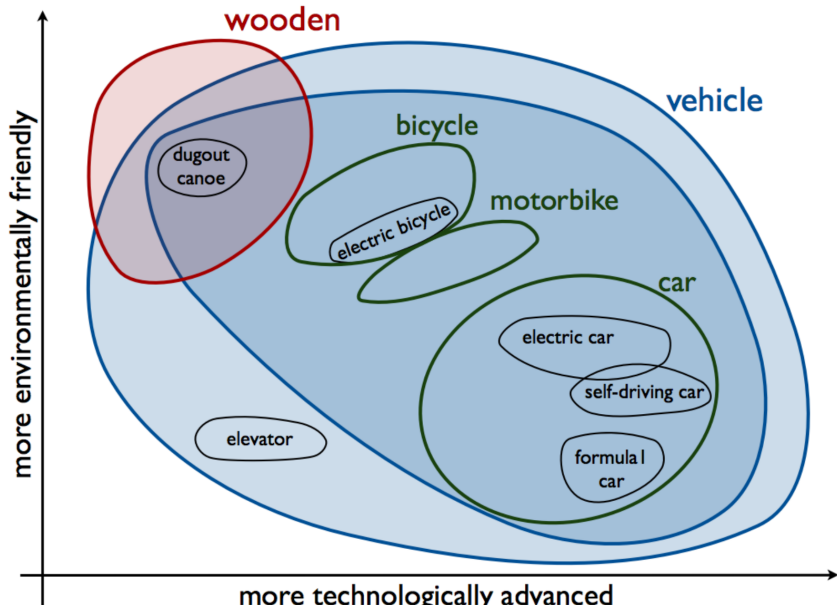
Symbolic vs. Sub-symbolic Representation

- **Symbolic knowledge** representation uses discrete, human-readable symbols
 - E.g., logic, knowledge graphs
 - Interpretable and suitable for rule-based reasoning
 - Struggle with ambiguity
- **Sub-symbolic knowledge** representation uses learned, distributed representations
 - E.g., vector embeddings
 - E.g., deep learning excels at perception and pattern recognition
 - Lack transparency
- **Neuro-symbolic approaches** blends the two approaches
 - Reason over learned concepts using structured logic

Symbolic
(explainable AI)

Sub-symbolic
(black-box AI)

Neuro-symbolic Approach: Conceptual Spaces



Procedural vs Declarative Approaches

- **Procedural approach**
 - Focuses on *how* a task is done
 - Encodes desired behavior directly into the program
 - E.g., a robot programmed with specific steps to navigate a maze
- **Declarative approach**
 - Specifies *what* the goal is, *not how* to achieve it
 - Describes relationships between actions and goals
 - Leaves solution search to the system
 - E.g., describing the goal “reach the exit” and letting the system find the path
- **Comparison**
 - Procedural: more control, less flexibility
 - Declarative: more abstraction, easier to modify or extend
- **Integration of approaches**
 - Many successful AI systems use a hybrid
 - Declarative knowledge can be compiled into procedural code
 - E.g., a planner generates procedures (plans) from declarative goals

Examples of Logic

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Propositional Logic

- Uses atomic statements (propositions) and logical connectives
 - **Syntax**
 - Atomic formulas: P, Q
 - Connectives: NOT (\neg), AND (\wedge), OR (\vee), IMPLIES (\implies)
 - **Semantics**
 - Based on truth tables
 - Each proposition has a binary truth value: true or false
 - **Inference mechanisms**
 - Modus ponens: from P and $P \implies Q$, infer Q
 - Resolution: derive contradictions to infer conclusions
- **Applications:** best used in closed and well-defined environments
 - Digital circuit design
 - Rule-based systems
 - Simplified AI models
- **Limitations**
 - Cannot represent objects, relations, or quantifiers
 - Not suitable for open or dynamic domains

First-Order Logic (FOL)

- **Extension of propositional logic**

- Introduces predicates, variables, and quantifiers
 - Variables x
 - Predicate $Human(x)$
 - Universal quantifier “for all” \forall
 - Existential quantifier “there exists” \exists
- E.g., $\forall x(Human(x) \implies Mortal(x)) = \text{“All humans are mortal”}$
- Represents more complex and structured knowledge than propositional logic
- Can model properties, relationships, and quantification over objects

- **Inference mechanisms**

- Unification: matches predicates with variables
- Resolution: deduces new facts from known statements
- Model checking: verifies truth of statements under specific interpretations

- **Computational properties**

- Inference is semi-decidable: valid conclusions may require infinite time
- More powerful but computationally more complex than propositional logic

- **Applications**

- Knowledge representation
- Automated theorem proving
- Semantic web and ontologies

Rule-Based Systems (1/2)

- A rule-based system uses “if-then” rules to derive conclusions or make decisions
 - It mimics human decision-making by applying logical rules to a set of facts
- **Key Components**
 - Knowledge base: stores facts and rules
 - Inference engine: applies rules to known facts to infer new facts or take actions
 - Working memory: holds current facts being considered
- **How It Works**
 - Match: find rules whose conditions match current facts
 - Conflict resolution: decide which rule to apply if multiple rules match
 - Act: apply the chosen rule to modify facts or trigger actions
 - Repeat: continue until no more rules can be applied
 - **E.g.,**
 - Rule: If a patient has a fever and a rash, then suggest measles
 - Fact: Patient has a fever and a rash
 - Conclusion: Suggest measles

Rule-Based Systems (2/2)

- **Pros**
 - Easy to modify and update rules
 - Transparent and explainable reasoning
 - Good when expert knowledge can be clearly articulated
- **Cons**
 - Hard to scale to very large or complex domains
 - Cannot handle uncertainty without extensions (e.g., probabilistic reasoning)
 - Rule conflicts and maintenance can become challenging
- **Applications**
 - Expert systems (e.g., medical diagnosis, technical troubleshooting)
 - Business rule engines
 - Game AI
 - Legal reasoning tools

Reasoning and Inference in Logic

- **Logical inference** is the process of deriving new facts from known ones using formal rules
 - Used to make decisions and answer questions based on a Knowledge Base
- **Knowledge base (KB):**
 - A structured set of facts and rules used for logical reasoning
- **Inference engine:**
 - Mechanism that applies logical rules to a KB to derive conclusions or answer queries
 - **Forward chaining:**
 - Starts with known facts and applies inference rules to extract more data
 - E.g., given $A \rightarrow B$ and A , infer B
 - **Backward chaining:**
 - Begins with a goal and works backward to find supporting facts
 - E.g., to prove B , check if $A \rightarrow B$ and then prove A
 - **Resolution:**
 - A complete inference rule for propositional and first-order logic
 - Useful in automated theorem proving
 - **Entailment** ($KB \models \alpha$):
 - Sentence α is entailed by KB if it is true in all models where KB is true

Grounding and Symbol Anchoring

- **Grounding**

- Connecting abstract symbols to real-world entities or observations
- E.g., the symbol Apple must be linked to the fruit “apple” in the world
- Essential for making representations meaningful beyond pure syntax
 - Enables agents to act meaningfully in the real world
 - Avoids purely symbolic manipulation without real-world relevance

- **Symbol Anchoring**

- Specific instance of grounding where sensory data anchors symbols in an agent's memory
- E.g., a robot sees a round red object and anchors it to the symbol Apple

- **Challenges**

- Sensory data is noisy and incomplete
- Mapping from real-world inputs to abstract concepts can be complex and context-dependent

- **Applications**

- Robotics (object recognition, manipulation)
- Natural language understanding
- Autonomous agents and cognitive systems

Logical Agents

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Reflex Agents

- **Reflex agents** act based on the current percept, ignoring percept history
 - Operate using a condition-action rule: “if condition, then action”
 - Rely on predefined rules
 - Have no internal state or memory
 - E.g., a thermostat turns on the heater if $\text{temperature} < \text{threshold}$
- **Pros**
 - Fast and efficient in well-defined environments
- **Cons**
 - Struggle with complex or partially observable environments
 - Cannot plan ahead or learn from experience
- **Application**
 - Simple or fully observable environments where quick reactions are sufficient

Knowledge-based agents

- **Intelligence** is achieved by *reasoning* on an internal *representation of knowledge*
- **Knowledge-based agents:**
 - Form representations of a complex world
 - Use inference to derive new representations about the world
 - Use new representations to deduce actions
 - Accept tasks as goal descriptions
 - Achieve competence by learning new knowledge
 - Adapt to environmental changes by updating knowledge
 - Utilize a knowledge base to store information
 - Explain actions based on their knowledge
 - E.g., a medical diagnosis system using patient data to infer diseases and suggest treatments
 - E.g., a chess-playing program using a database of moves to plan strategy
 - Require mechanisms to update their knowledge base with new information
 - Handle incomplete or uncertain information through probabilistic reasoning

Logic / Knowledge Base (1/2)

- **Knowledge base (KB)** is a set of:
 - Sentences α expressing assertions (observed, assumed or derived) about the world
 - E.g., “it rains”, “the ground is dry”, “the ground is wet”
 - Rules
 - E.g., “If it rains, the ground gets wet”
- **Knowledge representation language** is a formal way of creating sentences about the world
- **Syntax** specifies all the sentences α that are well-formed in a logic / knowledge base
 - E.g., in arithmetic the sentence:
 - “ $x + y = 4$ ” is well-formed
 - “ $x4y+ =$ ” is not well-formed
- **Semantics** is the meaning of sentences (i.e., their truth) with respect to each possible world
 - E.g., the sentence $x + y = 4$
 - Is true in the world (model) in which $x = 2, y = 2$
 - Is false in the world $x = 1, y = 1$

Logic / Knowledge Base (2/2)

- **Axiom** is sentence taken as given without being derived from other sentences
- **Inference** is a process of deriving new sentences from old ones
 - It should be done in a “logical” way, i.e., the answer should “follow” from what is in the knowledge base
- Truth values of a sentence
 - In **most logics** every sentence is either true or false
 - **Fuzzy logic** allows sentences to have different degrees of truth
 - **Probabilistic logic** allows sentences to have different probability of being true

Model and possible worlds

- We want to represent worlds where there is rain and wet ground
 - In each possible world/model, values are assigned to all relevant variables
 - “Possible worlds” can be thought of as real environments
 - E.g., a world where *Rain* is true and *WetGround* is false
 - Model m is a mathematical abstraction of “possible world”
 - E.g., m is $(Rain = F, WetGround = T)$
 - Each possible world is a complete assignment of truth values to all relevant propositions
 - World 1: $(Rain = T, WetGround = T)$
 - World 2: $(Rain = T, WetGround = F)$
 - World 3: $(Rain = F, WetGround = T)$
 - World 4: $(Rain = F, WetGround = F)$
- E.g., we represent worlds with “men and women sitting at a table”
 - The model represents all possible worlds as $(x \text{ men}, y \text{ women})$
 - The sentence $x + y = 4$ is true in certain worlds and false in others
 - In worlds with $x = 2$ men and $y = 2$ women sitting at the table, $x + y = 4$ is true

Satisfaction of a sentence in a model

- Any model m fixes all the variables x_1, \dots, x_n used in sentences
 - E.g., $(Rain = T, WetGround = T)$
- If a sentence α is true in model m , we say “the model m satisfies the sentence α ”
 - E.g., the model $(Rain = T, WetGround = F)$ satisfies $\alpha : Rain = T$
 - Note: this seems backwards, since in our common way of reasoning, the model is fixed and sentences are evaluated as true or false
- $M(\alpha)$ is the set of all the models in which α is true
 - E.g., $M(Rain = T) = \{(Rain, WetGround), (Rain, \neg WetGround)\}$

Logical entailment

- **Logical entailment** between sentences is the relation representing the fact that a sentence follows logically from another sentence in a KB, e.g.,
- “ α entails β ” (written $\alpha \models \beta$) iff (by def) in every model in which α is true, β is also true, e.g.,
 - $\alpha : \text{“Rain} \implies \text{WetGround”}$ entails $\beta : \text{“}(Rain = T, WetGround = F)\text{”}$
 - Equivalent to $M(\alpha) \subseteq M(\beta)$
- E.g., in the table world
 - $\alpha : \text{“}x = 0\text{”}$, $\beta : \text{“}x \cdot y = 0\text{”}$
 - α entails β since in any model in which $x = 0$ is true, also $x \cdot y = 0$ is true, regardless of the value of y
- Intuition:
 - Entailment is not related to a proof, it just “preserves truth” across all models
 - *“If you believe your KB, you must believe the entailed sentences”*

Logical Entailment vs Implication

- Entailment and implication are related but distinct
 - **Logical entailment** is about truth following from known facts
 - **Implication** is about a relationship between two statements
- **Logical entailment** ($KB \models \alpha$):
 - Means α is always true in any world where KB is true
 - E.g.,
 - KB: "It is raining", "If it rains, the ground is wet"
 - Entailed: "The ground is wet"
- **Implication** ($A \implies B$):
 - A statement in logic that says: "If A is true, then B is true"
 - Doesn't guarantee A or B is true by itself
 - Implication is true unless A is true and B is false
 - E.g.,
 - A: "It is raining", B: "The ground is wet"
 - $A \implies B$ is the statement "If it is raining, then the ground is wet"
 - This statement can be true even if it's not raining

Model Checking Procedure

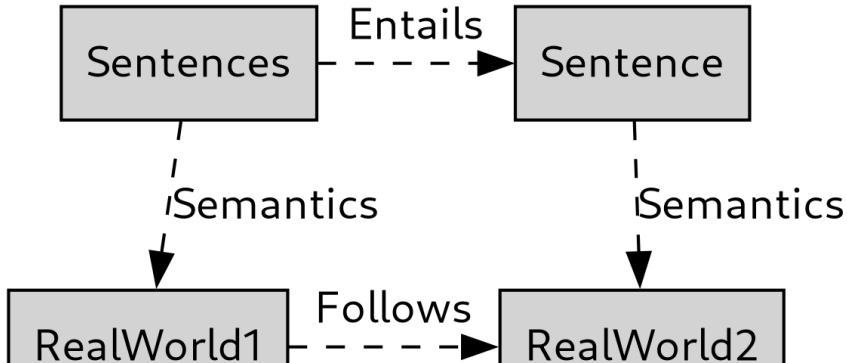
- $M(KB)$ represents all the models / possible worlds that are true given our KB
- **Problem:**
 - We want to verify whether “a sentence α is entailed by KB ” ($KB \models \alpha$)
- **Solution:**
 - According to the definition, we need to verify that α is true in all the models in which KB is true
 - I.e., $M(KB) \subseteq M(\alpha)$
 - Model checking procedure (brute force)
 1. Enumerate all the models / possible worlds
 2. Find which models are possible given the KB , i.e., $M(KB)$
 3. Check whether the sentence α is true in all the models that are compatible with the KB

Sound and Complete Inference Algorithm

- The ideal inference algorithm is both sound and complete
- **Sound** inference algorithm
 - Derives only sentences entailed from KB
 - “Whatever the inference algorithm finds, it's correct”, i.e., no false positives
 - E.g., model checking is sound
 - It works only when the space of models is finite
 - When it works, it is truth preserving
- **Complete** inference algorithm
 - Can derive any sentence entailed from KB
 - “The inference algorithm doesn't miss anything,” i.e., no false negatives

Isomorphism between Representation and World

- A sound and complete inference algorithm should yield conclusions guaranteed to be true in any world where the premises are true
- In other words, even if the inference operates on “syntax” (the internal representation):
 - “Sentences in the representation” correspond to “aspects of the real world”
 - “Entailment between sentences in the representation” corresponds to “implication between aspects of the real world”



Grounding

- Grounding is the operation of linking abstract symbols (e.g., words, logical variables, ..) to reality (e.g., objects, entities, or situations in the real world)
 - It is the bridge between representation in a KB and the world
- A philosophical question: how can we know that a KB accurately reflects the real world?
 - We can't be sure
 - Do we live in a simulation? What is reality?
- We assume that is correct
 - Agent's sensors create a sentence in the KB when something happens in the real world
IF smell = burning THEN food_is_burning
IF object = {red, round, small} THEN object_is_tomato
 - We assume that "learning" (generalizing particular cases to general cases) is possible and typically correct
IF food_is_burning THEN turn_off_stove
 - Learning is still fallible
 - E.g., maybe somebody is cooking on a grill

Ontologies

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Ontologies (in computer science)

- **An ontology:**
 - Is a formal, explicit representation of a domain
 - Describes the types of things that exist and how they relate to each other
 - E.g., some components are:
 - Classes: types of things
 - Individuals: specific objects
 - Properties: how things are related
- **Examples:**
 - A medical ontology defines relationships between diseases, symptoms, and treatments
 - A geographical ontology describes cities, states, and countries
 - Semantic web (an extension of the current web to give meaning to information)
- **Purpose**
 - Provide a common vocabulary for a domain of knowledge
 - Enable machines and humans to understand and share information consistently
 - Enable reasoning about entities and their relationships
- **Related Concepts**
 - Schema: database-oriented structure, often more rigid than ontologies
 - Taxonomy: simpler hierarchical classification (like a tree)
 - Knowledge base: a collection of facts and rules, sometimes built from an

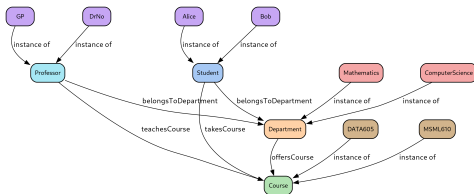
Ontologies: Main Components

- **Classes / Concepts:**
 - Represent general concepts in a domain
 - E.g., Person, City, Car
- **Individuals / Instances:**
 - Specific, concrete examples of classes
 - E.g., GP (an instance of Person), Rome, Ferrari 458
- **Properties / Relations:**
 - Describe interactions or associations between classes or instances
 - E.g., isMortal, locatedIn, hasAge
- **Attributes / Data values**
 - Specify data associated with instances
 - E.g., (GP, hasAge, <your_guess>)
- **Constraints**
 - Rules that restrict the kinds of values a property can take
 - E.g., (Ferrari 458, mustBe, red)
- **Axioms:**
 - Logical statements that define rules and constraints
 - Used to infer new knowledge
 - E.g., all humans are mortal: $\forall x (Person(x) \implies Mortal(x))$
- **Hierarchies:**
 - Organize classes and properties into parent-child relationships

Ontology: Example University

- Classes: general types of things

- Student
- Professor
- Course
- Department



- Properties: relationships between Classes
 - takesCourse (Student \rightarrow Course)
 - teachesCourse (Professor \rightarrow Course)
 - belongsToDepartment (Student, Professor \rightarrow Department)
 - offersCourse (Department \rightarrow Course)
- Individuals / Instances: examples of Classes
 - Student: Alice, Bob
 - Professor: GP, DrNo
 - Course: DATA605, MSML610
 - Department: ComputerScience, Mathematics
- Axioms: logical rules that must be true
 - Every Course must be taught by exactly one Professor
 - Every Student must belong to exactly one Department
 - A Department offers at least one Course

Reasoning in Ontologies

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Example of Reasoning Tasks (1/4)

- **Subsumption**

- “Is class A a subclass of B?”
- Check whether one concept is more general than another
- E.g., if Person subsumes Student, every Student is necessarily a Person
- Important for building taxonomies and ontologies

- **Satisfiability:**

- “Can an instance of a concept exist?”
- Test if a concept is logically consistent (i.e., without contradiction)
- E.g., if the concept FlyingPenguin requires flying but is also defined as a penguin (which cannot fly), it might be not satisfiable

- **Classification**

- Organize concepts into a hierarchy
- Automatically organize concepts into a hierarchy by checking subsumption relationships
- E.g., given definitions of Animal, Bird, and Penguin, classification places Penguin under Bird, and Bird under Animal

Example of reasoning tasks in KR (2/4)

- **Instance Checking**
 - “Is a specific individual an instance of a concept?”
 - E.g., is GP an instance of Student?
- **Consistency Checking**
 - “Is the entire knowledge base free of contradictions?”
 - E.g., no Person is both Alive and Dead at the same time
- **Realization**
 - “What is the most specific class an instance belongs to?”
 - E.g., discovering that GP is a Professor rather than just a Human
- **Retrieval**
 - Find all individuals that satisfy a certain condition
 - E.g., retrieve all instances classified as TeachingAssistant

Example of reasoning tasks in KR (3/4)

- **Query Answering**
 - Answer complex queries about the knowledge base
 - E.g., “Find all Person that study at the university and are not Student”
- **Abduction**
 - Given an observation, infer the best explanation
 - E.g., seeing a Person carrying a backpack and wearing flip-flops in the snow and infer that is likely a Student
- **Deduction**
 - Infer consequences that logically follow from facts and rules
 - E.g., if John is a Student in ComputerScience then he can attend MSML610

E.g., of reasoning tasks in KR (4/4)

- **Belief Revision**

- Update the knowledge base when new, possibly conflicting, information arrives
- E.g., learning that not every student in ComputerScience can take MSML610 and revise a previous rule

- **Temporal Reasoning**

- Reason about events over time
- E.g., If EventA happens before EventB, then EventB cannot Cause EventA

- **Causal Reasoning**

- Infer causes and effects among entities or events
- E.g., inferring that (Storm, Cause, Flooding) based on temporal and physical knowledge

Ontologies tools: Protege Example

- Protégé is a free, open-source platform for building ontologies
 - Developed at Stanford
- Provides tools to construct and visualize ontologies
 - Users can define classes, properties, individuals, and relationships
- Enable reasoning over ontologies using plugins
 - E.g., checking consistency, inferring new knowledge
- Supports:
 - Major ontology languages
 - OWL (Web Ontology Language)
 - RDF (Resource Description Framework)
 - Multiple serialization formats
 - RDF/XML, Turtle, OWL Functional Syntax
- Use cases:
 - Domain-specific knowledge modeling (e.g., biomedicine, law)
 - Semantic Web applications
 - AI systems that require structured knowledge

Propositional logic

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Propositional Logic

- Propositional logic is a formal system for reasoning about statements that can be true or false
 - Syntax defines the allowable sentences
 - Consists of proposition symbol and logical connectives
 - E.g., $P \wedge Q$
 - Semantics is the way in which the truth of sentences is determined
 - Truth tables or deduction rules evaluate the truth value of complex sentences
 - E.g., if P is true and Q is false then $P \wedge Q$ is false
- Atomic representation
 - No internal structure within atomic propositions
- **Uses:**
 - SAT solvers
 - Tools for determining if a propositional logic formula can be satisfied
 - E.g., used in hardware verification and scheduling problems
 - Expert systems
 - Systems that use logic rules to mimic human decision-making
 - E.g., medical diagnosis systems
 - Rule-based agents
 - Agents that operate based on a set of predefined rules
 - E.g., automated customer service chatbots

Proposition symbol

- Proposition symbol
 - Is an atomic sentence consisting of a single symbol
 - E.g., P , Q , $North$
 - Doesn't have truth value, it is just a symbol for a real-world statement
 - Stands for a proposition that can be true or false
 - E.g., $K_{E,5} = \text{"the Knight is in E5"}$
 - $K_{E,5}$ is not composed of any other symbol, it is an atomic symbol
 - *True* and *False* are proposition symbols with inherent truth values

Sentences

- Atomic sentence:
 - Is a sentence composed of a single proposition symbol
- Complex sentence:
 - Is constructed from simpler (sentences) using parentheses and logical connectives
 - Note: it is a recursive definition that allow to build more complex sentences
- Each sentence (atomic or complex) can be only true or false
- Common logical connectives
 - Not: \neg
 - And: \wedge (looks like an “A” for “and”)
 - Or: \vee (comes from Latin “vel” which means “or”)
 - Implies: \implies
 - If and only if: \iff

Proposition Logic: Weather Example

- Proposition symbols are
 - $Rain$ = "it's raining"
 - $Cold$ = "it's cold"
 - $Sunny$ = "it's sunny"
 - $Snow$ = "it's snowing"
 - $Cloudy$ = "it's cloudy"
- Atomic sentence can be positive (e.g., $Rain$) or negated (e.g., $\neg Rain$ = "it's not raining")
- Negation
 - E.g., $\neg(Rain \vee Cloudy)$ = "it's not the case that it's raining or cloudy"
- Conjunction
 - E.g., $Rain \wedge Cold$ = "it's raining and it's cold"
- Disjunction
 - E.g., $Rain \vee Snow$ = "it's either raining or snowing"
- Implication is a sentence containing a premise (aka antecedent), the connective \implies , and a conclusion (aka consequent)

Grammar in BNF form

- Use BNF to formally represent the grammar of propositional logic
- Ambiguous, i.e., the same sentence can be parsed in multiple ways
 - E.g.,
 $\neg A \vee B = (\neg A) \vee B$ or $\neg(A \vee B)$?
- To eliminate ambiguity define the precedence for each operator
 - E.g., \neg has higher precedence than \wedge, \vee so:
 $\neg A \vee B$ means $(\neg A) \vee B$

```
Sentence → AtomicSentence | ComplexSentence
AtomicSentence → True | False | P | Q | R | ...
ComplexSentence → ( Sentence )
                  | ¬ Sentence
                  | Sentence ∧ Sentence
                  | Sentence ∨ Sentence
                  | Sentence ⇒ Sentence
                  | Sentence ⇔ Sentence
```

OPERATOR PRECEDENCE : $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$

Semantics of propositional logic

- Semantics are rules for determining the truth of a sentence α with respect to a model m
 - We want to determine if a sentence is true or false, given a possible world
- In propositional logic, a model m fixes the truth value (true or false) for every proposition symbol/atomic sentence, e.g.,
- The models are abstractions of the real world and have no a-priori connection to a specific world, e.g.,
 - $P_{1,2}$ is just a symbol and can mean:
 - “There is a pit in $[1, 2]$ ” or
 - “I’m in Paris today and tomorrow”

Computing the truth value of a sentence

- The truth value of a sentence can be derived from the truth of the proposition symbols (recursively from the model m), e.g.,
- If the KB is based on proposition symbols $P_{1,2}, P_{2,2}, P_{3,1}$:

$$m = \{P_{1,2} = F, P_{2,2} = F, P_{3,1} = T\}$$

- All sentences α are constructed from atomic sentences (assigned by the model m) and the five connectives:
 - $\neg P$ is T iff P is F in m
 - $P \wedge Q$ is T iff P and Q are both true in m
 - $P \vee Q$ is T iff P or Q are true in m
 - $P \implies Q$ is true unless P is true and Q is false in m
 - $P \iff Q$ is true iff P and Q are both true or both false in m
- Truth table contains the truth value of a sentence (no matter how complex) for each possible assignment of truth values to its components
 - E.g., $X = A \wedge B \vee C$

A	B	C	X
F	F	F	F
F	F	F	T

Interpretation of Implication

- In a logical implication $P \implies Q$ there is no causation between P and Q
 - E.g., “5 is odd implies that Tokyo is the capital of Japan” is a true sentence in propositional logic (although very odd)
- Pathological cases for implication
 - An implication is true whenever the antecedent is false
 - E.g., “5 is even implies pigs fly” is true
 - E.g., “5 is even implies Sam is smart” is true, even if Sam is not smart
 - The reason is that $P \implies Q$ is saying “If P is true, I claim that Q is true. Otherwise I am making no claim”

Model Checking is Sound and Complete

- **Model checking algorithm:**
 - Enumerate all models (truth tables)
 - Check if α is true for every model where KB is true
- The model checking algorithm is:
 - **Sound**
 - “Any inference made by the algorithm is correct”
 - Implements the definition of entailment
 - **Complete**
 - “Any true sentence is inferred correctly by the algorithm”
 - Works for any KB and α
 - Always terminates (finite number of models)
- Complexity of model checking with n variables
 - Time complexity is $O(2^n)$ (NP-complete)
 - Worst case is exponential
 - Average case is better than exponential
 - Space complexity is $O(n)$ since enumeration is depth-first

Propositional Theorem Proving

- To prove a desired sentence α under a knowledge base KB
 - Apply rules of inference to construct a proof of α
 - Any sentence can have only one of the following truth values:
 1. True
 2. False
 3. Undecidable under the KB
- Theorem proving vs. model checking:
 - Model checking involves enumerating all models to show the sentence is true/false in all models where KB is true
 - If the proof is short, theorem proving can be more efficient than model checking

Logical equivalence of sentences

- Two sentences α and β are logically equivalent $\alpha \equiv \beta$
 - Iff they are true in the same set of models:

$$M(\alpha) = M(\beta)$$

- Iff they entail each other:

$$\alpha \models \beta \wedge \beta \models \alpha$$

- E.g., $P \vee Q \equiv Q \vee P$

Logical equivalences (1/2)

- Commutativity of \wedge and \vee

$$(\alpha \wedge \beta) \equiv (\beta \wedge \alpha)$$

$$(\alpha \vee \beta) \equiv (\beta \vee \alpha)$$

- Associativity of \wedge and \vee

$$(\alpha \wedge \beta) \wedge \gamma \equiv \alpha \wedge (\beta \wedge \gamma) \equiv \alpha \wedge \beta \wedge \gamma$$

$$(\alpha \vee \beta) \vee \gamma \equiv \alpha \vee (\beta \vee \gamma) \equiv \alpha \vee \beta \vee \gamma$$

- Distributivity of \wedge over \vee

$$\alpha \wedge (\beta \vee \gamma) \equiv (\alpha \wedge \beta) \vee (\alpha \wedge \gamma)$$

- Distributivity of \vee over \wedge

$$\alpha \vee (\beta \wedge \gamma) \equiv (\alpha \vee \beta) \wedge (\alpha \vee \gamma)$$

- Double negation elimination:

$$\neg(\neg\alpha) \equiv \alpha$$

Logical equivalences (2/2)

- Contraposition:

$$(\alpha \implies \beta) \equiv (\neg\beta \implies \neg\alpha)$$

- Implication elimination:

$$(\alpha \implies \beta) \equiv (\neg\alpha \vee \beta)$$

- Biconditional elimination:

$$(\alpha \iff \beta) \equiv (\alpha \implies \beta) \wedge (\beta \implies \alpha)$$

- De Morgan:

$$\neg(\alpha \wedge \beta) \equiv (\neg\alpha \vee \neg\beta)$$

$$\neg(\alpha \vee \beta) \equiv (\neg\alpha \wedge \neg\beta)$$

Valid sentence

- A valid sentence α is true for all the models
 - E.g., $P \vee \neg P$
 - Aka “tautology”
 - Every tautology is equivalent to the sentence *True*
- Contradiction is a sentence α that is false for all the models
 - E.g., $P \wedge \neg P$
 - Every contraction is equivalent to the sentence *False*

Deduction theorem

- The sentence α entails β (written $\alpha \models \beta$) iff the sentence $\alpha \implies \beta$ is a tautology, i.e., is equivalent to *True*

Satisfiability

- A sentence α is satisfiable iff α is true for some model
- SAT problem is about determining satisfiability of sentence in propositional logic
 - One can enumerate all the possible models until one is found to satisfy the sentence α
 - It is NP-complete
- A sentence α is un-satisfiable iff α is never true (i.e., a contradiction)
- Validity and satisfiability
 - α is valid (i.e., a tautology) iff $\neg\alpha$ is un-satisfiable
 - By contrapositive α is satisfiable iff $\neg\alpha$ is not valid ($\neg\alpha$ is not a tautology)

Proof by contraction

- The sentence $\alpha \models \beta$ is true iff the sentence $(\alpha \vee \neg\beta)$ is un-satisfiable (i.e., a contradiction)
- In other words in a proof by contradiction:
 - Assume α
 - Assume that the sentence β is false and
 - Prove that this leads to a contradiction
 - Thus β must be true

First-order Logic

- Knowledge Representation
- Propositional logic
- **First-order Logic**
- Non-classical Logics
- Description Logics

Natural languages

- Natural languages (e.g., English, Italian) are:
 - Expressive
 - Medium for communication rather than representation
 - Ambiguous
 - E.g., “spring” is both a “season” and “something that goes boing”
 - Context-dependent
 - Meaning depends on the sentence and context
 - E.g., “Look!”
- **Sapir-Whorf hypothesis**
 - Understanding of the world is influenced by language
 - Language influences thought (even through arbitrary grammatical features, e.g., gender of nouns)
 - Some languages lack words for certain concepts (e.g., direction)

Programming languages

- A programming language (e.g., C++, Python) is a formal language
 - Data structures represent facts
 - Code updates data structures in a domain-specific way
- **Cons:**
 - Programming is procedural (vs declarative)
 - Programming languages lack:
 1. A general mechanism for deriving facts from other facts
 - Code updates data structures based on programmer's domain knowledge
 2. Expressiveness to handle partial information
 - A variable represents a single value or unknown
 - Can't easily handle partial information or quantify uncertainty
 - E.g., "A white knight is in b1 or in f6"
- Declarative language (e.g., propositional logic, first order logic)
 - Knowledge and inference are separate:
 1. Knowledge represents the domain-specific problem
 2. Inference is domain independent
 - Compositional semantics
 - The meaning of a sentence is a function of the meaning of its parts

Propositional logic

- E.g., $P \wedge Q$
- **Pros**
 - Declarative
 - Semantics is based on relation between sentences and possible worlds
 - Can deal with partial information
 - E.g., “A white knight is in b1 or in f6” is represented with $WK1_{b1} \vee WK2_{f6}$
 - Compositional semantics
 - The meaning of a sentence is a function of the meaning of its parts
 - Context independent
 - Unambiguous
- **Cons**
 - Can't concisely describe environment with many objects, e.g.,
 - In English “The pawn is in a cell around b6” requires all the possible states to be enumerated

First-Order Logic (FOL): Intro

- First-order logic (FOL) extends propositional logic by:
 - Introducing quantifiers (\forall , \exists)
 - Using predicates to represent properties and relations
- Combines pros of propositional logic with pros of natural language
 - Built around objects and relations
 - Allows to express facts about some or all objects, e.g.,
 - “Some humans have blue eyes”
 - “Squares neighboring the Wumpus are smelly”
- FOL provides expressive power to represent structured, relational knowledge

First-Order Logic: Syntax

- **Constants:** represent specific objects (e.g., Socrates)
- **Predicates:** describe properties or relations (e.g., *Human*(*x*))
- **Functions:** map tuples of objects to objects (e.g., *Mother*(*x*))
- **Variables:** placeholders (e.g., *x*, *y*)
- **Quantifiers:** $\forall x$ (for all *x*), $\exists x$ (there exists an *x*)
-

<i>Sentence</i>	→	<i>AtomicSentence</i> <i>ComplexSentence</i>
<i>AtomicSentence</i>	→	<i>Predicate</i> <i>Predicate</i> (<i>Term</i> ,...) <i>Term</i> = <i>Term</i>
<i>ComplexSentence</i>	→	(<i>Sentence</i>)
		\neg <i>Sentence</i>
		<i>Sentence</i> \wedge <i>Sentence</i>
		<i>Sentence</i> \vee <i>Sentence</i>
		<i>Sentence</i> \Rightarrow <i>Sentence</i>
		<i>Sentence</i> \Leftrightarrow <i>Sentence</i>
		<i>Quantifier</i> <i>Variable</i> ,... <i>Sentence</i>
<i>Term</i>	→	<i>Function</i> (<i>Term</i> ,...)
		<i>Constant</i>
		<i>Variable</i>
<i>Quantifier</i>	→	\forall \exists
<i>Constant</i>	→	<i>A</i> <i>x</i> ₁ <i>John</i> ...
<i>Variable</i>	→	<i>a</i> <i>x</i> <i>s</i> ...
<i>Predicate</i>	→	<i>True</i> <i>False</i> <i>After</i> <i>Loves</i> <i>Raining</i> ...
<i>Function</i>	→	<i>Mother</i> <i>LeftLeg</i> ...

OPERATOR PRECEDENCE : $\neg, =, \wedge, \vee, \Rightarrow, \Leftrightarrow$

- Term is a logical expression that refers to an object in a FOL model
- Atomic sentence = predicate symbol (i.e., which corresponds to relations) followed by a list of terms in parenthesis (i.e., constant or function symbol) *Predicate*(*Term*₁, *Term*₂, ...)
- E.g., *Brother*(*Richard*, *John*), under the model / interpretation, Richard is the brother of John
- E.g., *Married*(*Father*(*Richard*), *Mother*(*John*))
- Complex sentences = sentences using logical connectives complex, with

Quantifiers and Scope

- Quantifiers express properties of entire collections of objects, instead of enumerating objects by name (like in propositional logic)
- **Universal quantifier:** $\forall x P(x)$
 - Universal quantifier makes a statement about *every* object
 - Statement is true if $P(x)$ is true for all x
- **Existential quantifier:** $\exists x P(x)$
 - Existential quantifier makes a statement about *some* object (without naming it)
 - True if $P(x)$ is true for at least one x
- Scope determines the portion of a formula a quantifier applies to
- Variables are **bound** by quantifiers or **free** (unbound)
- Sentences with no free variables are called **closed formulas**
- Example:
 - $\forall x (Cat(x) \rightarrow Mammal(x))$

Nested quantifiers

- = express more complex sentences using multiple quantifiers
- The order of quantifiers is important, so one can use parentheses to clarify
- Example:
 - “Brothers are siblings”: $\forall x, y \text{Brother}(x, y) \implies \text{Sibling}(x, y)$
 - $\forall x, y \text{Sibling}(x, y) \iff \text{Sibling}(y, x)$ (symmetric relationship)
 - “Everybody loves somebody”: $\forall x \exists y \text{Loves}(x, y)$
 - “There is someone loved by everyone”: $\exists y \forall x \text{Loves}(x, y)$

Connection between \forall and \exists

- The two quantifiers are connected through negation and De Morgan rules

$$(\forall x \neg P) \iff (\neg \exists x P)$$

$$\neg(\forall x P) \iff (\exists x \neg P)$$

$$(\forall x P) \iff (\neg \exists x \neg P)$$

$$(\exists x P) \iff (\neg \forall x \neg P)$$

First-order logic: Semantics

- Semantics define how sentences are interpreted in a domain
- Symbols represent entities, relationships, and functions in the domain
 - **Constant symbols** represent specific objects
 - E.g., *Alice*, *GP*, *CS101*
 - **Predicate symbols** represent relationships among objects
 - E.g., *EnrolledIn(Student, Class)*, *Teaches(Professor, Class)*, *IsStudent(x)*, *IsProfessor(x)*
 - **Function symbols** represent mappings between objects
 - E.g., *AdvisorOf(Student)*, *DepartmentOf(Professor)*
- An interpretation maps the world to its mathematical description, and vice versa
 - There are many possible interpretations
 - The intended interpretation is the one that is the most natural
 - E.g., map the symbol *GP* \rightarrow me
- Example:
 - Sentence: $\forall x (Human(x) \rightarrow Mortal(x))$
 - True if for every x in the domain, *Human(x)* implies *Mortal(x)*

Inference in First-Order Logic

- Goal: derive new sentences from existing ones using sound rules
- **Universal Instantiation:**
 - From $\forall x P(x)$ infer $P(c)$ for any constant c
- **Existential Instantiation:**
 - From $\exists x P(x)$ infer $P(c)$ with a new constant c
- **Modus Ponens** and other propositional rules apply
- FOL inference is semi-decidable:
 - If a sentence is entailed, a proof can be found
 - If not entailed, proof search may not terminate

Representing Knowledge in FOL

- FOL enables representation of:
 - General rules: $\forall x (Bird(x) \rightarrow CanFly(x))$
 - Specific facts: $Bird(Tweety)$
- Complex relations captured through predicates:
 - $Loves(Romeo, Juliet)$, $GreaterThan(3, 2)$
- Functions express object construction:
 - $FatherOf(John)$
- Knowledge base built from axioms and facts
- Enables reasoning about objects, properties, and their relationships

Non-classical Logics

- Knowledge Representation
- Propositional logic
- First-order Logic
- **Non-classical Logics**
- Description Logics

Ontological commitment

- Ontological commitments are assumptions about reality made by a language
- Different formal models make different assumptions on how the truth of sentences is defined:
 - Propositional logic:
 - The world consists of facts that are either true or false
 - First-order logic:
 - The world consists of objects with relations among them that hold or do not hold
 - Temporal logic:
 - Facts about objects and relations hold at particular times or intervals
 - Higher-order logic:
 - Relations of first-order logic are objects themselves
 - E.g., can make assertions about relations (e.g., “all relations are transitive”)

Epistemological commitment

- Epistemological commitment is a possible states of knowledge by an agent with respect to each fact
 - Ontological commitment = what exists in the world
 - Epistemological commitment = what an agent believes about facts
- E.g.,
 - Propositional logic, first-order logic
 - 3 possible states of belief regarding any sentence: true, false, or unknown
 - Probability theory
 - There is a degree of belief in $[0, 1]$ about each sentence

Non-monotonic Logic

- Non-monotonic logic is a type of logic where adding new information can invalidate previous conclusions
- Contrast with Classical (Monotonic) Logic
 - In classical logic, once something is proven, it stays proven even if more information is added
 - In non-monotonic logic, conclusions can change as new facts are learned
- **E.g.,**
 - Initial knowledge: “Birds typically fly”
 - Conclusion: “Tweety is a bird, so Tweety can fly”
 - New information: “Tweety is a penguin”
 - Revised conclusion: “Tweety cannot fly”
- **Why it Matters**
 - Real-world situations often involve incomplete or evolving knowledge
 - Non-monotonic logic allows systems to reason flexibly and adapt to new circumstances

Default reasoning

- **Default reasoning** is reasoning where assumptions are made by default in the absence of contrary evidence
 - It allows conclusions based on typical situations unless exceptions are found
- **Key Idea**
 - Assume the most likely case unless specified otherwise
 - If new information contradicts the assumption, revise the conclusion
- **E.g.,**
 - Default rule: “Typically, birds can fly”
 - Fact: “Tweety is a bird”
 - Conclusion: “Tweety can fly”
 - New fact: “Tweety is a penguin”
 - Revised conclusion: “Tweety cannot fly”
- **Why It Is Useful**
 - In real life, information is often incomplete or uncertain
 - Default reasoning allows systems to function reasonably without knowing everything

Non-Monotonic Logic: University Example

- **Initial Facts**

- *Alice* is a *Student*
- *Alice* belongs to the *ComputerScience* department
- CS101 is a *Course* offered by the *ComputerScience* department
- Default rule: *Students* in the *ComputerScience* department take classes in their department

- **Initial Reasoning**

- Since *Alice* is a *Student* in *ComputerScience*, by default *Students* take CS101
- Conclusion: *Alice takesCourse CS101*

- **New Information**

- *Alice* is an exchange student who does not meet the prerequisites for CS101

- **Revised Reasoning**

- New conclusion: *Alice* does not *takeCourse CS101*

Common Sense Reasoning

- **Common sense reasoning** is the ability to make assumptions, draw conclusions based on everyday knowledge about the world
 - Involves typical, unstated knowledge that humans take for granted, e.g.,
 - “If you drop a glass, it will likely break”
 - Knowing that “people eat food when they are hungry” without being explicitly told
- **Characteristics**
 - Deals with incomplete, uncertain, or ambiguous information
 - Relies on defaults, heuristics, and typical patterns rather than strict logical proofs
 - Often flexible and tolerant of exceptions
- **Challenges**
 - Common sense knowledge is vast, informal, and often not precisely defined
 - Difficult to encode all of it explicitly in a machine-readable form
 - Handling exceptions and contradictions is complex
- **Techniques**
 - Knowledge graphs
 - Non-monotonic logic
 - Probabilistic reasoning
 - Machine learning models trained on large, diverse data

Common Sense Reasoning: University Example

- **Initial facts**
 - *Alice* is a *Student*
 - *Bob* is a *Student*
 - CS101 is a *Course* offered by the *ComputerScience* department
- **Common sense knowledge**
 - Students typically enroll in courses offered by their department
 - Students usually attend classes they are enrolled in
 - Professors usually teach the courses they are assigned
- **Reasoning steps**
 - *Alice* belongs to the *ComputerScience* department
 - CS101 is offered by the *ComputerScience* department
 - Common sense suggests *Alice* is likely enrolled in CS101, even if enrollment is not explicitly stated
 - Therefore, it is reasonable to assume: *Alice takesCourse* CS101
- **New information**
 - *Alice* is pursuing research only and not taking courses
 - The assumption that *Alice takesCourse* CS101 must be revised

Open World vs Closed World Assumptions

- **Closed World Assumption (CWA)**

- Missing information is false, e.g.,
 - Fact: “Alice takes CS101” is known
 - Nothing is said about Bob
 - Under CWA: Conclude Bob does not take CS101
- Common in databases and logic programming

- **Open World Assumption (OWA)**

- Missing information is unknown, not false, e.g.,
 - Fact: “Alice takes CS101” is known
 - Nothing is said about Bob
 - Under OWA: Cannot conclude if Bob takes CS101: it is unknown
- Common in Semantic Web, RDF, ontologies

- **Applications**

- OWA
 - Semantic Web (RDF, OWL)
 - Knowledge representation with incomplete or growing data
- CWA
 - Traditional relational databases (SQL)
 - Business rules and systems requiring complete data

Inductive Logic Programming

- **Inductive Logic Programming**

- Learns logical rules from examples and common sense knowledge
- Given positive and negative examples, and background facts, infer logical rules that explain the examples

- **Example**

- Background: “Birds have wings”
- Positive example: “Tweety can fly”
- Negative example: “Penguin cannot fly”
- Learned rule: “Birds can fly unless they are penguins”

- **Features**

- Produces human-readable logical rules
- Integrates learning with symbolic reasoning
- Supports background knowledge integration

- **Challenges**

- Computational complexity with large datasets
- Handling noisy, incomplete, or ambiguous data

Description Logics

- Knowledge Representation
- Propositional logic
- First-order Logic
- Non-classical Logics
- **Description Logics**
 - Semantic Web

Description Logic

- **Description Logic**
 - Represents structured knowledge about a domain
 - Balances expressivity and computational efficiency
 - More expressive than propositional logic, less than first-order logic
- **Core building blocks:**
 - Concepts / classes: abstract groups
 - E.g., *Person*, *Animal*
 - Roles / properties: binary relations between individuals
 - E.g., *hasChild*, *ownsPet*
 - Individuals / instances: specific objects
 - E.g., *GP*, *Nuvolo*
- Supports reasoning tasks such as:
 - Concept subsumption: “is *A* a subset of *B*?”
 - Instance checking: “does *a* belong to *A*?”
- **Syntax often combines:**
 - Atomic concepts and roles
 - Logical constructors (\sqcap , \sqcup , \neg , \forall , \exists)
 - E.g.,
 - $Father \equiv Man \sqcap \exists hasChild. Person$
- Widely used in ontologies, e.g., OWL (Web Ontology Language)

- Attributive Concept Language with Complements (ALC) is a basic but expressive description logic
 - Concepts can be combined using logical operators, e.g.,
 - \sqcap means “and”
 - \sqcup means “or”
 - \neg means “not”
 - Allows for existential and universal quantification, e.g., $\exists R.C$, $\forall R.C$
- Interpretation is set-theoretic
 - Concepts as sets, roles as binary relations
- Example:
 - “All students take some course”: $\text{Student} \sqsubseteq \exists \text{takes.Course}$
 - “A mother is a woman who has at least one child”
 $\text{Mother} \equiv \text{Woman} \sqcap \exists \text{hasChild.T}$
- ALC:
 - Is decidable
 - balances expressiveness and computational complexity
 - Is basis for more complex logics used in OWL
 - Practical for moderate-sized ontologies

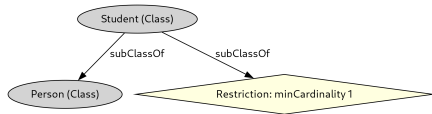
SHOIN

- SHOIN is a description logic more expressive than ALC
- Components:
 - \mathcal{S} : Allows transitive properties
 - E.g., `ancestorOf` is transitive
 - \mathcal{H} : Supports role hierarchies
 - E.g., `hasSon` \sqsubseteq `hasChild`
 - \mathcal{O} : Introduces specific individuals
 - E.g., `John` is a nominal class
 - \mathcal{I} : Enables roles to be navigated backward
 - E.g., `isChildOf` is inverse of `hasChild`
 - \mathcal{N} : Sets cardinality constraints
 - E.g., “has exactly 1 passport”
- E.g.,:
 - “Exactly two children” `Person` \sqsubseteq $(= 2 \text{ hasChild.}\top)$
- Characteristics
 - More powerful but reasoning is harder (exponential complexity)
 - Model richer real-world scenarios
 - Foundation for OWL DL reasoning capabilities

- OWL = Web Ontology Language
 - Semantic web language designed to represent complex knowledge about things and their relationships
 - Enables rich knowledge representation on the web (based on SHOIN)
 - “OWL” easier to pronounce than “WOL”
 - Supports formal semantics for machine reasoning
 - Key constructs:
 - Classes, properties, individuals, axioms
- Example:
 - “Every cat is a mammal” $\text{Cat} \sqsubseteq \text{Mammal}$
- OWL variants:
 - OWL Lite: simpler, for classification hierarchies
 - OWL DL: full expressiveness with decidable reasoning
 - OWL Full: maximum expressiveness, but undecidable
- Applications
 - Semantic search
 - Biomedical data

Example of OWL in RDF

```
1.  ```\n2.  <rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"\n3.      xmlns:owl="http://www.w3.org/2002/07/owl#"\n4.      xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"\n5.      xmlns:ex="http://example.org/">\n6.    <owl:Class rdf:about="http://example.org/Person"/>\n7.    <owl:Class rdf:about="http://example.org/Student">\n8.      <rdfs:subClassOf rdf:resource="http://example.org/Person"/>\n9.      <rdfs:subClassOf>\n10.        <owl:Restriction>\n11.          <owl:onProperty rdf:resource="http://example.org/hasAdvisor"/>\n12.          <owl:minCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#nonNegat\n13.            1\n14.          </owl:minCardinality>\n15.        </owl:Restriction>\n16.      </rdfs:subClassOf>\n17.    </owl:Class>\n18.    <owl:ObjectProperty rdf:about="http://example.org/hasAdvisor"/>\n19.  </rdf:RDF>\n20.  ```\n
```



RDF (Resource Description Framework)

- **RDF** is a standard model for data interchange on the web
 - Represent structured information in a machine-readable way
- **Basic building block** is a triple (*Subject, Predicate, Object*)
 - **Subject**: the entity being described, e.g., NuvoIo
 - **Predicate**: the property or relationship, e.g., isA
 - **Object**: the value or another entity, e.g., Dog
- **Key Features**:
 - Statements are directed graphs of nodes and edges
 - Components of the triple are URIs (Uniform Resource Identifiers) to ensure global uniqueness or literals (e.g., strings, numbers), e.g., `http://example.org/NuvoIo`
- **Use Cases**:
 - Building knowledge graphs
 - Enabling semantic search
 - Supporting ontologies (e.g., OWL)

Subject	Predicate	Object
Book123	hasTitle	"The Great Gatsby"
Book123	hasAuthor	Author456
Author456	hasName	"F. Scott Fitzgerald"
Book123	publishedYear	"1925"
Book123	belongsToGenre	"Fiction"

SPARQL

- SPARQL is the query language for RDF data
 - Allows users to retrieve and manipulate data stored in RDF format
- **Key Concepts:**
 - **Triple Patterns:** Query fragments that match triples in an RDF graph
 - **Basic Graph Pattern:** A set of triple patterns combined
 - **Variables:** Stand in for unknown parts of the triples (e.g., ?person, ?animal)
- **Main Query Types:**
 - **SELECT:** Retrieve specific variables from the data
 - **CONSTRUCT:** Create new RDF triples based on query results
 - **ASK:** Return a boolean indicating whether a pattern exists
 - **DESCRIBE:** Return an RDF graph describing resources
- **Example:**
 - "Find all resources that are of type Bird"
`SELECT ?animal WHERE { ?animal rdf:type ex:Bird }`

Semantic Web

- Knowledge Representation
- Propositional logic
- First-order Logic
- Non-classical Logics
- Description Logics
 - **Semantic Web**

Semantic Web

- The **Semantic Web** extends the current Web by enabling machines to understand and interpret data
 - HTML is human-readable but lacks semantic structure for computers
 - The Semantic Web adds meaning / semantics to data
 - Allow better data integration, automation, and discovery across sites
- **Key Technologies**
 - RDF (Resource Description Framework): base data model
 - SPARQL: query language for RDF data
 - OWL (Web Ontology Language): define rich ontologies
- **Current Status**
 - Some core ideas (e.g., structured data and ontologies) are widely adopted
 - Full vision remains only partially realized
- **Challenges**
 - Complexity of widespread adoption
 - Issues around privacy, data ownership, and feasibility
 - Need for standardization and tools
- **Criticism**
 - Skepticism about practicality and scalability
 - Concerns about centralization and censorship

WikiData

- **WikiData** is a free, open, collaborative knowledge base
 - Stores structured data for Wikipedia
 - Accessible via APIs using SPARQL queries
- **Graph-based data model**
 - Item: represents an entity or concept, e.g.,
 - Q42 → Douglas Adams
 - Property: describes a relationship or attribute, e.g.,
 - P31 (instance of), P27 (country of citizenship)
 - Value: specific data linked to an item via a property, e.g.,
 - Q42 (Douglas Adams) → P31 (instance of) → Q5 (human)
 - Q42 → P106 (occupation) → Q36180 (science fiction writer)
 - Reference: supports a claim by citing a source, e.g.,
 - Stating Douglas Adams's citizenship with a reference to a biography
 - Qualifier: adds context or additional information to a statement
 - Q90 (Paris) → P1082 (population) → "2,165,423"
 - With qualifier: P585 (point in time) → "2021"
 - Meaning: "The population of Paris was 2,165,423 in the year 2021"
- **Applications:**
 - Knowledge graph
 - Semantic search
 - AI reasoning
 - Data enrichment
 - AI and machine learning training datasets

- **DBpedia** extracts structured content from Wikipedia
 - Creates a large-scale, multilingual knowledge graph for querying
 - Data is extracted as RDF triples (subject-predicate-object), e.g.,
 - “Berlin” entity linked with properties like `dbo:country` Germany, `dbo:populationTotal` 3.7M
 - Enables semantic queries over Wikipedia data via SPARQL endpoints
- **Applications**
 - Semantic Web research
 - Enhancing AI models with real-world knowledge

Semantic Networks

- Semantic Networks represent knowledge as graphs of concepts and relations
 - Nodes represent concepts
 - Edges represent relations (e.g., “is-a”, “part-of”)
 - E.g., if a Dog is an Animal, it inherits Animal traits
 - Examples: WordNet, ConceptNet
- **Pros**
 - Easy to visualize and traverse
 - Support reasoning
 - Common in early AI systems and current KG applications

WordNet

- **WordNet** is a large lexical database of English words
 - Designed to model the semantic relationships between words
 - Groups words into sets of synonyms
 - Manually curated, ensuring high-quality semantic relations
 - Can be incomplete for domain-specific language
- Key Components:
 - Synsets: Sets of synonyms expressing a distinct concepts
 - E.g., {car, automobile} share the same synset
 - Relations between synsets:
 - Is-a relationships (e.g., Dog is a type of Animal)
 - Part-whole relationships (e.g., Wheel is a part of Car)
 - Opposite meanings
- Structure:
 - Semantic network where nodes are synsets and edges are relations
 - Organized hierarchically, especially for nouns and verbs
- Applications:
 - Word sense disambiguation: choose the correct meaning of a word in context
 - Semantic similarity measures: how close two concepts are
 - Information retrieval and question answering systems

ConceptNet

- **ConceptNet** is a large knowledge graph
 - Connects words and phrases with labeled semantic relationships
 - Represents commonsense knowledge about the world
- Key Characteristics:
 - Designed to capture knowledge that people generally assume but often leave unstated
 - Focuses on making AI systems more human-like in their understanding
- Structure:
 - Nodes: concepts (words or phrases)
 - Edges: semantic relationships between concepts, e.g.,
 - IsA: (dog, animal)
 - PartOf: (wheel, car)
 - UsedFor: (knife, cutting)
 - CapableOf: (bird, fly)
 - Causes: (fire, smoke)
- Example Triple:
 - (bicycle, UsedFor, transportation)
- Applications:
 - Natural language understanding
 - Question answering and chatbots
 - Commonsense reasoning in AI
 - Semantic search and recommendation systems

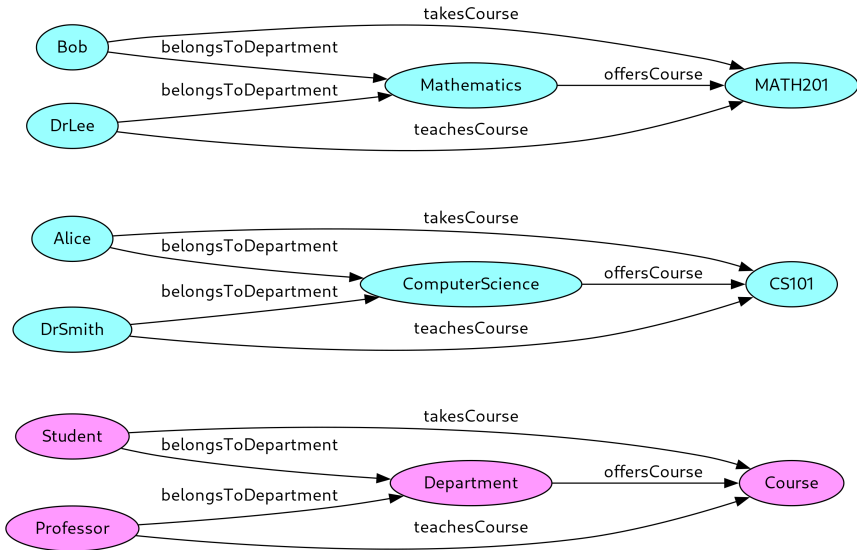
Frame-Based Representations

- Frame-based systems represent structured knowledge about objects, events, or situations
- Key Concepts:
 - Frame: A data structure for a concept or entity
 - E.g., a frame for Dog might include properties like `hasLegs`, `hasFur`, `barks`
 - Slots: attributes or relationships associated with the frame
 - E.g., slot `hasLegs` with value 4
 - Slot fillers: values or links to other frames that fill the slots
 - E.g., slot `eats` might link to another frame `Meat`
- Example:
 - Frame: Dog
 - Slots:
 - `isA: Animal`
 - `hasLegs: 4`
 - `sound: Bark`
 - `canDo: [Run, Fetch]`
- Features:
 - Inheritance: frames can inherit slots and slot values from more general frames, e.g.,

Knowledge Graphs (KGs)

- KGs represent entities and their relationships as a graph structure
 - Nodes = entities
 - Edges = relations
 - E.g., “Paris \rightarrow isCapitalOf \rightarrow France”
- Query languages like SPARQL allow expressive information retrieval
- KGs support reasoning via path traversal and schema inference
- Applications:
 - Question answering
 - Recommendation
 - Semantic search
- Widely used by Google, Facebook, and academic search engines

Knowledge Graph: University Example



Technologies

- **TransE (Translation Embedding)**
 - Embedding model for knowledge graph completion
 - Represents relationships as translations in vector space: $h + r \approx t$
 - Good for 1-to-1 relations, less effective with complex patterns
- **RotatE**
 - Embeds entities in complex space
 - Models relations as rotations: $t = h \circ r$ where \circ is complex multiplication
 - Captures symmetry, antisymmetry, inversion, and composition
- **DeepProbLog**
 - Combines ProbLog (probabilistic logic) with deep learning
 - Supports neural predicates in logic programs
 - Learns probabilistic facts and neural components jointly
- **PyMLN**
 - Python-based Markov Logic Network (MLN) system
 - MLNs combine first-order logic with probabilistic graphical models
 - Allows reasoning with weighted logical rules
- **ProbLog**
 - Probabilistic logic programming language
 - Extends Prolog by attaching probabilities to facts
 - Computes success probabilities of queries
- **Tuffy**