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BCA Honours | Semester VI | BCA6CJ304

Introduction to AI and ML

Module 2 Comprehensive Notes

Module 2: Knowledge Representation, Logical Reasoning, and Expert Systems

To operate intelligently in complex environments, AI systems require formal representational structures to encode facts, rules, and world relationships, accompanied by automated inference engines that deduce new truths from existing knowledge.

2.1 Formal Logic as a Representation Language

- **Propositional Logic (PL):** Encodes declarative statements that evaluate to either True or False. Uses logical connectives: Negation (¬), Conjunction (∧), Disjunction (∨), Implication ($\Longrightarrow$), and Biconditional ($\Longleftrightarrow$). Suffers from limited expressiveness; cannot quantify over individual domain objects.
- **First-Order Predicate Logic (FOL):** Augments propositional logic with Objects, Relations (Predicates), Functions, and Quantifiers:
  - *Universal Quantifier ($\forall x$):* "For all x in the domain." (e.g., $\forall x(\text{Student}(x) \implies \text{Learner}(x))$).
  - *Existential Quantifier ($\exists x$):* "There exists at least one x." (e.g., $\exists x(\text{Course}(x) \land \text{Elective}(x))$).

2.2 Automated Deduction: Unification and Resolution Refutation

Robinson's Resolution Principle provides a complete and sound refutation mechanism for automated theorem proving:

1. **Clausal Normal Form (CNF):** Converting FOL formulas into conjunctions of clauses (disjunction of literals) via standard steps: eliminate implications, move negations inward, standardize variables, Skolemize existential quantifiers, drop universal quantifiers, and distribute ∨ over ∧.
2. **Unification Algorithm:** Finding a substitution $\theta = \{x_1/t_1, \dots, x_k/t_k\}$ of variables that renders two atomic formulas syntactically identical (e.g., unifying $\text{Knows}(\text{John}, x)$ and $\text{Knows}(y, \text{Bill})$ via $\theta = \{y/\text{John}, x/\text{Bill}\}$).
3. **Proof by Refutation:** To prove query statement α from knowledge base KB, add negated goal $\neg\alpha$ to KB. Continuously resolve complementary literals until an empty clause (□, contradiction) is derived, confirming that $KB \models \alpha$.

2.3 Structured Knowledge Representations

- **Semantic Networks:** Directed graphs where nodes represent concepts or physical objects, and directed labeled arcs represent taxonomic relations (e.g., `is-a` inheritance, `part-of` aggregation).
- **Frames:** Object-oriented data structures containing named "slots" holding attribute values, default parameters, and procedural attachments ("demons" like `if-needed` and `if-added`).
- **Conceptual Dependency (CD):** Roger Schank's psychological representation decomposing natural language semantics into elemental primitive actions (e.g., ATRANS: transfer of possession; PTRANS: transfer of physical location; MTRANS: mental transfer of information).

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2.4 Rule-Based Expert Systems

Expert systems emulate human specialist decision-making within specialized domains (e.g., MYCIN for medical diagnosis, DENDRAL for chemical spectroscopy). Architecture encompasses:

- **Knowledge Base:** Domain-specific IF-THEN production rules gathered through knowledge engineering.
- **Working Memory:** Global database storing current case facts and session assertions.
- **Inference Engine:** Executes reasoning via *Forward Chaining* (data-driven: fires rules whose antecedents match working memory to derive conclusions) or *Backward Chaining* (goal-driven: starts with a hypothesis and searches for supporting facts).
- **Explanation Facility:** Explains "HOW" a conclusion was reached (listing fired rule chains) and "WHY" a specific user input is required.

Advanced Theoretical Foundations & Industrial Systems Synthesis

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1. Architectural Trade-offs and Computational Complexity

Software architects and systems engineers designing scalable computational pipelines centered on Introduction to AI and ML must methodically navigate core trade-offs:

- **Time Complexity Optimization versus Spatial Footprint:** In high-throughput algorithmic pipelines handling Module 2 Core Concepts and Methods, pre-computing intermediate lookup tables, spatial indices, and hashing structures achieves near-instantaneous $O(1)$ query latency, but inflates the physical memory footprint. Conversely, in-place algorithms minimize RAM utilization at the cost of higher CPU cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped files and cache-aware structures.
- **Concurrency Scalability versus Thread Contention:** While multi-core hardware allows horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.
- **Algorithmic Determinism versus Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial barriers as problem dimensions scale. Contemporary systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional paradigms and modern production implementations in Introduction to AI and ML:

Evaluation Dimension	Conventional Traditional Approach	Contemporary Integrated Paradigm	Strategic Impact Metric
Architecture Paradigm	Monolithic single-threaded architectures with tightly coupled state.	Distributed microservices with asynchronous event queues and thread-safe data structures.	Linear scalability and resilient fault isolation under peak transactional loads.
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3. Production Implementation Patterns and Resilience Engineering

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