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BCA Honours | Semester VI | BCA6CJ304

Introduction to AI and ML

Module 3 Comprehensive Notes

Module 3: Machine Learning Paradigms and Supervised Classification

Machine Learning (ML) focuses on algorithms that iteratively learn from training experience E with respect to some class of tasks T and performance measure P, improving performance with increased empirical observations (Tom Mitchell's formal definition).

3.1 Taxonomy of Machine Learning Paradigms

Learning Paradigm	Supervision Signal & Training Data	Primary Algorithmic Tasks
Supervised Learning	Dataset consists of paired input features and explicit target ground-truth labels $\{(x_i, y_i)\}_{i=1}^{n}$.	Classification (discrete categorical target labels) and Regression (continuous numerical target variables).
Unsupervised Learning	Unlabeled input features $\{x_i\}_{i=1}^{n}$ without ground-truth targets. System uncovers hidden structure.	Clustering, Dimensionality Reduction, Density Estimation, Association Rule Mining.
Reinforcement Learning (RL)	Autonomous agent interacts with dynamic environment; receives scalar numerical rewards or penalties.	Policy optimization, robotic locomotion, autonomous navigation, algorithmic game play.

3.2 Linear and Logistic Regression

1. Linear Regression

Models continuous target $y \in \mathrm{R}$ as a linear combination of input features x: $\hat{y} = w^T x + b$. Optimized by minimizing the Mean Squared Error (MSE) loss via gradient descent:

$$J(w, b) = \frac{1}{2n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2$$

Where: *J(w, b)* represents the convex quadratic loss surface minimized by gradient descent.

2. Logistic Regression (Binary Classification)

Maps real-valued linear outputs into normalized class probability $P(y = 1|x) \in [0, 1]$ via the Sigmoid (logistic) activation function:

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$$P(y = 1|x) = sigma(z) = \frac{1}{1 + e^{-z}}, \quad z = w^T x + b$$

Where: $\sigma(z) = 1 / (1 + e^{-z})$ maps real numbers to the probability interval (0, 1).

Parameters are estimated by minimizing the **Binary Cross-Entropy Loss (Log-Loss)**:

$$L(w) = -\frac{1}{n} \sum_{i=1}^{n} [y_i \ln \hat{y}_i + (1 - y_i) \ln(1 - \hat{y}_i)]$$

Where: $L = -(1/n) \Sigma [y_i \ln \hat{y}_i + (1 - y_i) \ln (1 - \hat{y}_i)]$ quantifies divergence between true labels and predicted probabilities.

3.3 Decision Trees and Information Theory

Decision trees recursively partition feature space into homogeneous sub-regions. Splitting criteria rely on Information Theory metrics:

- **Shannon Entropy:** Measures sample impurity:

$$H(S) = -\sum_{i=1}^{C} p_i \log_2(p_i)$$

- **Information Gain (ID3 Algorithm):** Expected entropy reduction after splitting dataset S on attribute A:

$$\text{Gain}(S, A) = H(S) - \sum_{v \in \text{Values}(A)} \frac{|S_v|}{|S|} H(S_v)$$

- **Gini Impurity (CART Algorithm):** $I_G(S) = 1 - \sum_{i=1}^{C} p_i^2$. Measures the probability of misclassifying a randomly chosen element.

3.4 Instance-Based Learning: K-Nearest Neighbors (K-NN)

K-NN is a non-parametric, lazy learning algorithm that defers generalization until query time. To classify query point x_q:

1. Compute pairwise Euclidean distance $d(x_q, x_i) = \sqrt{\sum_{j=1}^{d} (x_{q_j} - x_{i_j})^2}$ to all training samples.
2. Identify the K closest training instances.
3. Assign the class label via majority voting (or distance-weighted voting). Choosing odd K avoids tie votes in binary classification.

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3.5 Support Vector Machines (SVM)

SVM identifies an optimal decision hyperplane that separates binary classes with **maximum geometric margin** $\frac{2}{\|w\|}$. Training instances lying precisely on the margin boundaries are the *Support Vectors*. For non-linearly separable distributions, the **Kernel Trick** implicitly maps input vectors into higher-dimensional feature spaces where linear separation becomes feasible (deploying Radial Basis Function RBF, Polynomial, or Sigmoid kernels).

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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 3 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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Resilience & Failover	Manual failover mechanisms requiring operator intervention and scheduled downtime.	Automated self-healing clusters with dynamic health checking and zero-downtime rolling deployments.	Continuous availability meeting strict 99.999% Service Level Agreements (SLAs).
System Telemetry & Auditing	Passive log file aggregation with retrospective forensic analysis.	Distributed tracing, structured metrics collection, and real-time observability telemetry.	Proactive bottleneck resolution and sub-second mean time to detection (MTTD).

3. Production Implementation Patterns and Resilience Engineering

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