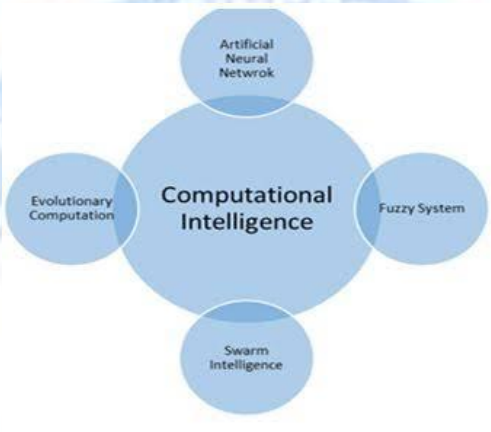
Neuro-Fuzzy Systems – AI Agents and Autonomous Systems – AIoT (Artificial Intelligence of Things) – Cyber-Physical Systems – Digital Twins – Neuromorphic Computing – Quantum-inspired Optimization – Swarm Robotics – Intelligent Robotics – Explainable Generative AI – Responsible AI Governance – AI Security – AI in Smart Cities – Healthcare 5.0 – Industry 5.0 – Future Trends in Evolutionary AI.1.2 Computational Intelligence

Computational Intelligence is a branch of Artificial Intelligence that uses Soft Computing techniques such as Fuzzy Logic, Neural Networks, Evolutionary Algorithms, and Swarm Intelligence to develop systems capable of learning, adaptation, and intelligent decision-making.



Core Techniques of Soft Computing:

Fuzzy Logic

Fuzzy Logic is a mathematical approach developed by Lotfi A. Zadeh in 1965 that allows computers to make decisions using degrees of truth Example: How hot is the temperature? The answer would be High (0.8), Very high (0.9), moderate (0.5), Low (0.3).

Neural Networks

Neural Networks is a computing model inspired by the structure and functioning of the human brain. It consists of interconnected artificial neurons that learn patterns from data through training.

For Example in Handwritten Numbers Recognition, for an input Image of digit 5, the initial prediction is 3(wrong prediction) and the Error is calculated. After Training with thousands of images a correct predicted answer of 5 is acquired

Evolutionary Computing

Evolutionary Computing is a problem-solving technique inspired by the process of biological evolution, particularly the principles explained by Charles Darwin. It searches for optimal or near-optimal solutions using mechanisms such as selection, crossover, mutation, and survival of the fittest.

Example: A delivery company needs to find the shortest route to deliver packages to 20 cities. Route A is 500 km, Route B is 430 km and Route C is 390 km.

The evolutionary algorithm selects the best routes, combines them, and makes small random changes (mutations) to create better routes. After several generations, it finds an improved Route D of 350 km.

Swarm Intelligence

Swarm Intelligence is a computing technique inspired by the collective behaviour of social organisms such as ants, bees, birds, fish, and termites. It consists of a group of simple agents that interact locally with one another and their environment without

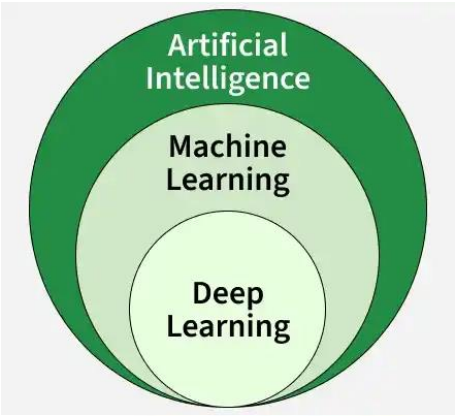
any central control. Through cooperation and self-organization, the swarm is able to find efficient solutions to complex problems.

Example: a food source is 100 meters away from an ant colony. Initially, ants explore different paths. Path A is 100 m, Path B is 80 m and Path C is 60 m. The ants traveling through the shortest path (Path C) return faster and leave stronger pheromone trails. More ants follow this path, reinforcing the pheromone. Over time, almost all ants choose Path C (60 m), enabling the colony to discover the shortest route without any central leader. Similarly group of robots cooperatively explores different paths shares information locally, collectively identifies the shortest and most efficient route to complete a task without requiring a central controller.

Artificial Intelligence, Machine Learning, and Deep Learning (DL) Relationship

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are closely related technologies that enable machines to perform intelligent tasks. AI is the broader concept of creating intelligent systems, ML is a subset of AI that learns from data, and DL is a specialized subset of ML that uses neural networks to learn complex patterns.

- **Artificial Intelligence (AI):** The field of creating systems that can mimic human intelligence and decision-making.
- **Machine Learning (ML):** A subset of AI that enables systems to learn from data without explicit programming.
- **Deep Learning (DL):** A subset of ML that uses neural networks to learn complex patterns from data.



How ML and DL are structured?

The primary algorithms used to power ML and DL are Artificial Neural Networks (ANN)

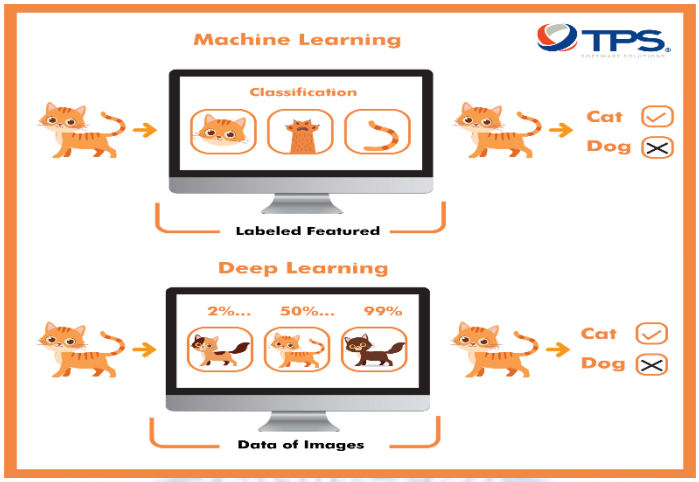
The most common ANN used by DL is which consists of an input, an output layer, and multiple hidden layers. The hidden layers apply an operation to the inputs and then pass the result to the next layer. Each layer builds upon the one before to increase its ability to categorize information.

Training a model is the process of providing known inputs and outputs to the ANN so the model can learn. Providing more data to a model during this phase increases its accuracy. Most of the time, the data collected would not be in a suitable format for a machine learning model. Therefore, they must be manipulated as required by the model and application. Once a model is trained with sufficient data and required accuracy, you can test it with previously unknown samples to benchmark and compare it. After additional improvements (if required) you may finally deploy it in a real-world application.



How different are Deep Learning and Machine Learning models

A key difference between the Machine Learning model and the Deep Learning model is how they learn.



Machine Learning Model

To help the ML algorithm categorize the images in the collection according to the two categories of dogs and cats, we will need to present these images collectively. But how does the algorithm know which one is which?

The answer to this question, as in the above definition of machine learning, is structured data. We can label the pictures of dogs and cats in a way that will define specific features of both the animals. This data should be enough for the machine learning algorithm to learn. Afterward, the algorithm will continue working based on the labels that it learns, and classify millions of other pictures of both animals at each feature it learned through the said labels.

Deep Learning Model

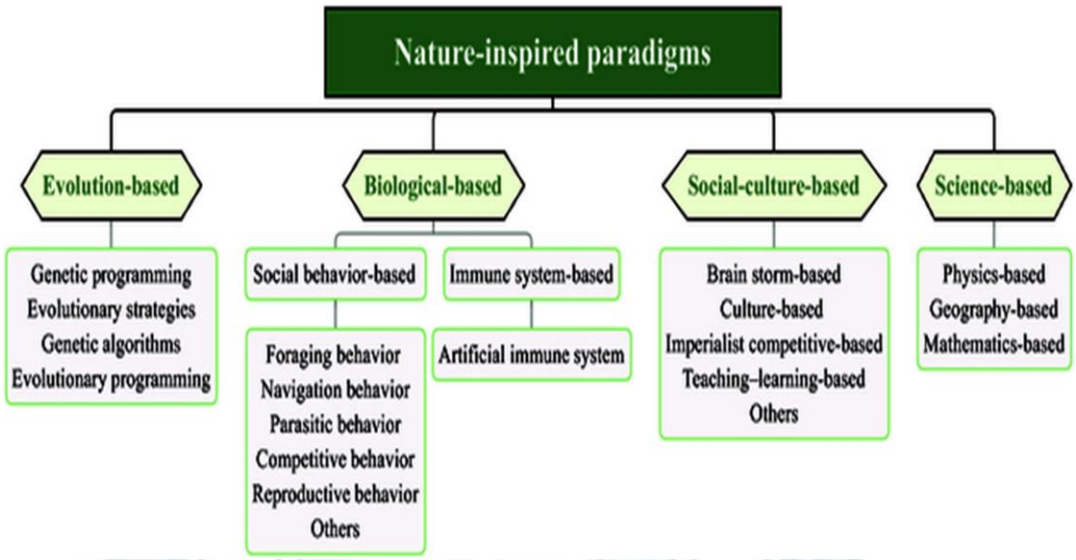
Deep learning networks would take a different approach to solve this problem. The main advantage of deep learning networks is that they do not necessarily need structured/labeled data of the pictures to classify the two animals. The artificial neural networks using deep learning send the input (the data of images) through different layers of the network, each of which hierarchically defines specific features of images. It is similar to how our human brain works to solve problems- by passing queries through various hierarchies of concepts and related questions to find an answer.

After the data is processed through layers within deep neural networks, the system finds the appropriate identifiers for classifying both animals from their images.

Deep learning models are loosely related to information processing and communication patterns in a biological nervous system, such as neural coding that attempts to define a relationship between various stimuli and associated neuronal responses in the brain. Deep learning architectures such as deep neural networks, deep belief networks, and recurrent neural networks have been applied to fields including computer vision, speech recognition, natural language processing, audio recognition, social network filtering, machine translation, bioinformatics, and drug design, where they have produced results comparable to and in some cases superior to human experts.

Nature-Inspired Computing

Nature-Inspired Computing (NIC) is a branch of computational intelligence in which algorithms and problem-solving techniques are developed by observing and imitating the processes, behaviours, and principles found in nature. These algorithms are used to solve complex optimization, search, learning, and decision-making problems that are difficult to solve using traditional computing methods.



Nature	Computing
Ants find shortest path to food	Network routing optimization
Birds fly together	Scheduling and optimization
Natural evolution	Optimization algorithms
Human immune system	Computer security
Bees search flowers	Resource allocation

Evolution-Based Computing

Evolution-Based Computing is inspired by Charles Darwin's Theory of Natural Evolution, where the strongest individuals survive and reproduce. The algorithm repeatedly improves solutions through evolution.

Examples of Evolution-Based Computing

- Genetic Algorithm (GA)
- Evolution Strategies (ES)

Biology-Based Computing

Biology-Based Computing imitates the behaviour of living organisms rather than evolution itself. These algorithms model the intelligence observed in animals, insects, cells, and the human brain.
Examples of Biology-Based Computing

- Artificial Neural Network (ANN)
- Ant Colony Optimization (ACO)
- Particle Swarm Optimization (PSO)

Social/Cultural – Based Computing

Social/Cultural-Based Computing is inspired by human society, cultural evolution, learning, cooperation, and communication. Instead of biological evolution, these algorithms imitate how humans solve problems using culture, cooperation, learning, communication collectively.

Science-Based Computing

Science-Based Computing develops algorithms inspired by physical, chemical, and mathematical laws of nature rather than living organisms. This computing involves Engineering optimization, parameter tuning, resource allocation