Nature Inspired Computing

TY B.Tech Honours

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Unit	Description	Duration
1	Introduction to Natural Computing From nature to natural computing, sample idea, Philosophy of natural computing, Natural computing approaches, Natural Phenomena, Models, and Metaphors, From Nature to Computing and Back Again, General Concepts – Individuals, Entities, Agents; Parallelism and Distributivity; Interactivity; Adaptation; Feedback; Self-Organization; Bottom-Up Vs Top-Down	05
2	Artificial Neural Networks Biological Nervous Systems, Artificial Neural Networks, Neuron Models, Architectures, Supervised learning: Perceptron algorithm, Back Propagation Algorithm, Unsupervised learning: Self-organizing maps, ART, Reinforcement learning	06
3	Evolutionary Computing – Genetic Algorithms Basic Principles of Genetics, Fitness Function; Selection: Selective Pressure, Random Selection, Proportional Selection, Tournament Selection, Rank-Based Selection, Boltzmann Selection, Elitism; Reproduction Operators: Crossover operator, Mutation; Application: Pattern Recognition, Numerical Function Optimization.	08
4	Swarm Intelligence: Particle Swarm Optimization: Basic Particle Swarm Optimization: Global Best PSO, Local Best PSO, Velocity Components; Basic PSO parameters, Single Solution Particle Swarm Optimization: Guaranteed Convergence PSO, Social-Based Particle Swarm Optimization, Hybrid Algorithms, Sub-Swarm Based PSO, Multi-Start PSO Algorithms, Repelling Methods, Binary PSO; Application	08
5	Ant Algorithm: Simple Ant Colony Optimization, Ant Colony Optimization Meta-Heuristic, Cemetery Organization and Brood Care, Division of Labor, Application: Travelling Salesman Problem	06
6	Artificial Immune Models: Natural Immune System: Classical view, Antibodies and Antigens, White Cells, Immunity types, Network Theory, Danger Theory; Artificial Immune Models: Artificial Immune system algorithm, classical view models, Clonal Selection Theory: CLONALG; Network Theory Models; Danger Theory Models; Application: Intrusion Detection	06

Books Recommended:

- *Text Books:*

1. L. N. de Castro, "Fundamentals of Natural Computing: Basic Concepts, Algorithms and Applications", 2006, CRC Press, ISBN-13: 978-1584886433
2. Andries P. Engelbrecht, "Computational Intelligence an Introduction", Wiley, 2nd Edition
3. Tom Mitchell, Machine Learning, McGraw Hill, 1997, 0-07-042807-7

- *Reference Books:*

1. D. Floreano and C. Mattiussi, "Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies", 2008, MIT Press, ISBN-13: 978-0262062718
2. Russell C. Eberhart, Yuhui Shi, James Kennedy, "Swarm Intelligence: The Morgan Kaufmann Series in Evolutionary Computation", 1st Edition, ISBN-13: 978- 1558605954
3. Sam Jones (Editor), "Bio Inspired Computing-Recent Innovations and Applications", Clanrye International; 2nd edition (2 January 2015), ISBN-10: 1632400812
4. Yang Xiao (Editor), "Bio-Inspired Computing and Networking", CRC Press,

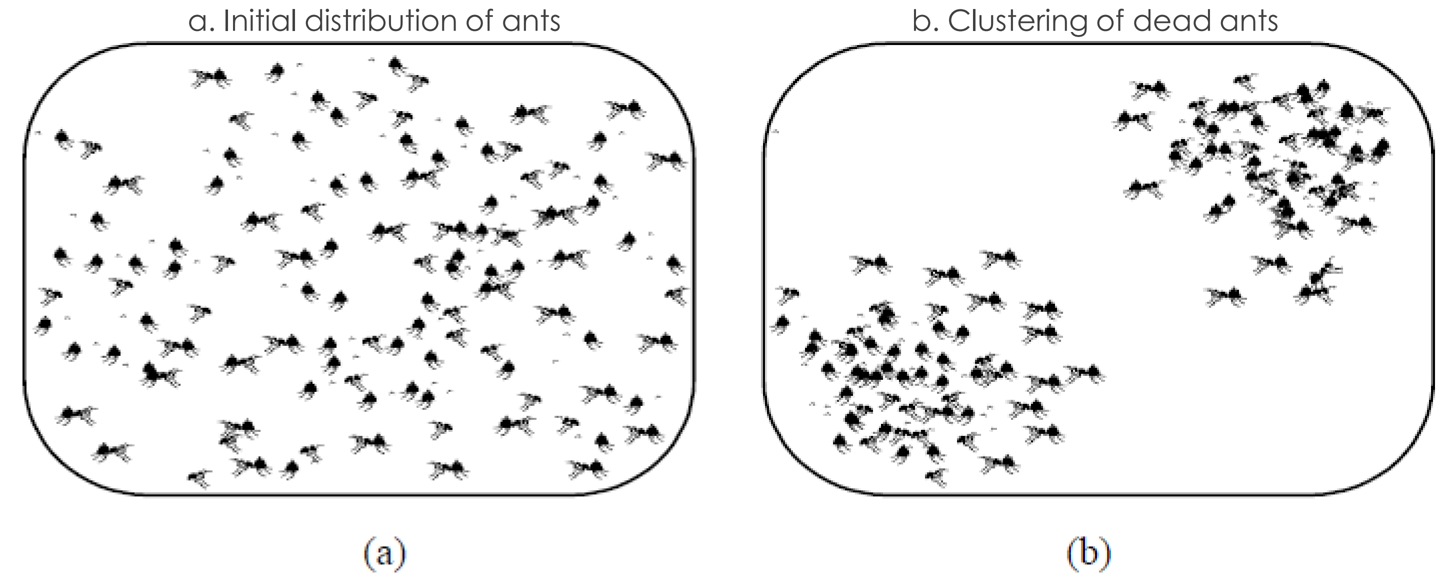
Unit 1: Introduction to Natural Computing

- Journey of Human – from using natural resources to learning from nature
  - Observing Physical, chemical and biological phenomena and patterns in nature
  - Laws of motion and gravity – designing aircrafts
  - Understanding basic principles of life – creating transgenic food and medicines to control diseases
  - Source of inspiration to imitate nature to create solutions in various domains ranging from engineering to biology
  - Simulate and emulate natural phenomenas

Unit 1: Introduction to Natural Computing

- Natural computing: is the computational version of this process of extracting ideas from nature to develop 'artificial' (computational) systems, or using natural media (e.g., molecules) to perform computation
- Branches of Natural Computing:
  - Computing inspired by nature:
    - makes use of nature as inspiration for the development of problem solving techniques
    - to develop computational tools (algorithms) by taking inspiration from nature for the solution of complex problems
  - The simulation and emulation of natural phenomena in computers:
    - a synthetic process aimed at creating patterns, forms, behaviors, and organisms that (do not necessarily) resemble 'life-as-we-know-it'.
    - Its products can be used to mimic various natural phenomena,
    - Increasing our understanding of nature and insights about computer models.
  - Computing with natural materials:
    - it corresponds to the use of natural materials to perform computation
    - constituting a true novel computing paradigm that comes to substitute or supplement the current silicon based computers.

Some Examples



Pick up rule: if an ant finds a dead body, it picks it up and wanders around the arena until it finds another dead body. The probability or likelihood that an ant picks up a dead body is inversely proportional to the number of items in that portion of the arena; that is, the more dead bodies around, the smaller the probability it is picked up, and vice-versa.

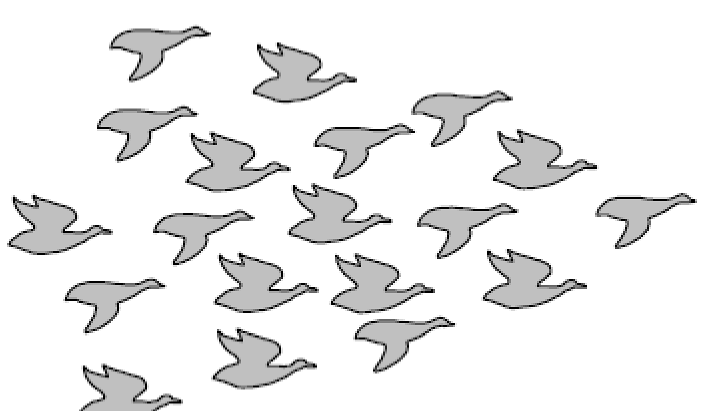
Dropping rule: while wandering around, the loaded ant eventually finds more dead bodies in its way. The more dead bodies are found in a given region of the arena, the higher the probability the ant drops the dead body it is carrying at that location of the arena, and vice-versa.

As a result of these very simple behavioral rules, all dead items will eventually be brought together into a single group, depending on the initial configuration of the arena and how the rules are set up.

Question 1: what kind of problem could be solved inspired by this simple model of a natural phenomenon?

Question 2: how would you use these ideas to develop a computing tool (e.g., an algorithm) for solving the problem you specified above?

Some Examples



Flock of Birds

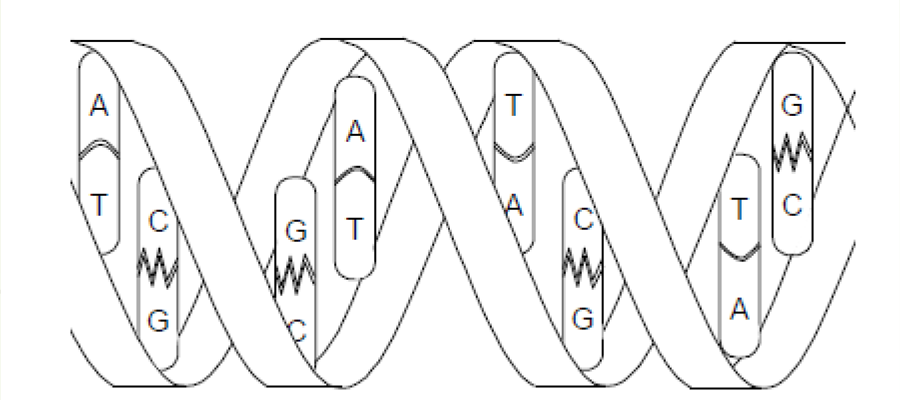
Follow the leader: When we see birds flocking in the sky, it is most natural to assume that the birds 'follow a leader'; in this picture, the one in front of the flock.

No Global rule: There is no 'global rule' that can be defined so as to simulate a bird flock. It is possible, however, to generate scripts for each bird in a simulated flock so as to create a more realistic group behavior (for example, in a computer simulation).

Question 1: describe (some of) these behavioral rules that, when applied to each bird in the flock, result in an emergent group behavior that is not specifically defined by the individual rules

Question 2: can you extend these rules to herds of land animals and schools of fish? That is, is there a significant qualitative difference between these various types of group behavior?

Some Examples



Double strand of DNA

Strands of DNA: The DNA molecules contain the genetic information of all living beings on earth. It is known that this genetic information, together with the environmental influences, determines the phenotype (expressed physical characteristics) of an individual.

Genetic engineering techniques can nowadays be used to artificially manipulate DNA so as to alter the genetic information encoded in these molecules. For instance, DNA molecules can be denatured (separated into single strands), annealed (single strands can be 'glued' together to form double strands of DNA), shortened (reduced in length), cut (separated in two), multiplied (copied), modified (e.g., new sequences inserted),

Question 1: Based on your knowledge of how standard computers (PCs) work, propose a new model of computer based on DNA strands and suggest a number of DNA manipulation techniques that can be used to compute with molecules

Question 2: what would be the advantages and disadvantages of your proposed DNA computer over the standard computers?

Natural computing could be used when:

• The problem to be **solved is complex**, i.e., involves a large number of variables or potential solutions, is highly dynamic, nonlinear, etc.

• It is not possible to guarantee that a **potential solution found is optimal** (in the sense that there is no better solution), but it is possible to find a quality measure that allows the comparison of solutions among themselves.

• The problem to be solved **cannot be (suitably) modeled**, such as pattern recognition and classification (e.g., vision) tasks. In some cases, although it is not possible to model the problem, there are examples (samples) available that can be used to 'teach' the system how to solve the problem, and the system is somehow capable of 'learning from examples'.

• A single **solution is not good enough**; that is, when diversity is important. Most standard problem-solving techniques are able to provide a single solution to a given problem, but are not capable of providing more than one solution. One reason for that is because most standard techniques are deterministic, i.e., always use the same sequence of steps to find the solution, and natural computing is, in its majority, composed of probabilistic methods.

• Biological, physical, and chemical systems and processes have to be **simulated or emulated with realism**. Euclidean geometry is very good and efficient to create man-made forms, but has difficulty in reproducing natural patterns. This is because nature is fractal, and only fractal geometry provides the appropriate tools with which to model nature.

• Life behaviors and phenomena **have to be synthesized in artificial media**. No matter the artificial media (e.g., a computer or a robot), the essence of a given natural behavior or pattern is extracted and synthesized in a, usually,
much simpler form in artificial life systems.

• **The limits of current technology are reached** or new computing materials have to be sought. Nature abounds with information storage and processing systems, and the scientific and engineering aspects of how to use these natural materials to compute are the main challenges of the third branch of natural computing: computing with natural materials

Natural Phenomena, Models, and Metaphors

Q1

- Natural phenomena:
  - Approaches are rooted on and enhanced by natural plausibility
  - Focus is on How nature has offered inspiration and motivation for the development of these approaches
  - Approaches also help us study and understand the world we inhabit,
  - Help us create new worlds, new forms of life, and new computing paradigms.
  - They hold out the hope of offering computationally sufficient accurate mechanistic accounts of the natural phenomena they model, mimic, or study, almost always with a view of computing, understanding, and problem solving.
  - They have also radically altered the way we think of and see nature; the computational beauty and usefulness of nature.

Natural Phenomena, Models, and Metaphors

- Models:
  - Models are defined abstractions of real world systems or implementations of a hypothesis in order to investigate particular questions or to demonstrate particular features of a system or a hypothesis - Trappenberg, 2002
  - It corresponds to a (schematic) description of a system, theory, or phenomenon, which accounts for its known or inferred properties and that may be used for further study of its characteristics
  - Models can be used to represent some aspect of the world, some aspect of theories about the world, or both simultaneously.
  - The representative usefulness of a model lies in its ability to teach us something about the phenomenon it represents.
  - Construction of model – requires selection of salient features and laws governing the phenomena under investigation.
  - Models are simple to understand, but provide (emergent) behaviors that are surprising, interesting, useful, and significant.
- Metaphors:
  - The steps to construct a model are guided by Metaphor.

Natural Phenomena, Models, and Metaphors

- Metaphors:
  - The steps to construct a model are guided by Metaphor.
  - Metaphor is used to assign one thing to designate another, Characterizes one thing in terms of another
  - E.g. Artificial neural network is characterized on human brain

Top-Down vs Bottom-Up Approach
Starting Point
Top-Down: Begin with an initial complete structure.
Bottom-Up: Start with minimal elements and expand.
Explanation
Top-Down: Like creating an oversized neural network - start with a large structure and refine it.
Bottom-Up: Like building a complex neural network: Begin with a single neuron and add more until it recognizes desired patterns.
Development
Top-Down: Planned and structured development.
Bottom-Up: Organic and evolving development.
Example
Top-Down: Designing an oversized neural network: You start with a large network and refine it over time.
Bottom-Up: Building a complex neural network: You begin with a single neuron and keep adding more until it recognizes the patterns you want.
Emergent Properties
Top-Down: May miss unexpected features or interactions.
Bottom-Up: More likely to discover new properties or behaviors as you study individual elements.

From Nature to Computing and Back Again

- the first step toward developing a natural computing system is to
  - To look at nature or theoretical models of natural phenomena in order to have some insights into how nature is, works, and how it behaves
- Mapping of problem to similar sort of natural phenomena
  - Extraction of metaphors and inspiration from nature is difficult to understand how the natural phenomena works e.g. human brain functions, immune system etc.
    - Though some basic signal transmission processes might be already known (and many other facts as well), it is still out of human reach to fully uncover its mysteries, mainly some cognitive abilities such as hate & love.
  - Can we simulate wetware with current hardware?
  - Why do airplanes not fly by flapping wings?

- sometimes looking at nature or theoretical studies may not be sufficie necessary insight into what could be done in computing and engineering with these phenomena
  - Clustering of dead bodies in ants resulted in computer algorithms for solving problems
  - Behavior of ants foraging for food resulted in powerful algorithms for solving combinatorial optimization problems

General Concepts

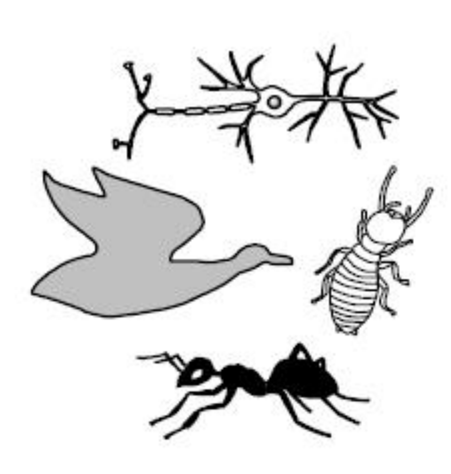
Q3

- **Individuals, Entities, and Agents**
  - Examples - populations of individuals, insect societies, flocks of bird, schools of fish, herds of land animals, repertoires of immune cells and molecules, networks of neurons, and DNA strands
- agent is currently used to mean anything between a mere subroutine of a computer program and an intelligent organism, such as a human being
  - Agent must present some kind of autonomy or identity
  - It must be distinguishable from its environment by some spatial, temporal or functional boundary
- agent-based models are drawn on examples of biological phenomena and processes, such as social insects and immune systems.
  - These systems are formed by distributed collections of interacting elements (agents) that work under no central control. From simple agents, who interact locally following simple rules of behavior and responding to environmental stimuli, it is possible to observe a synergistic behavior that leads to higher-level behaviors that are much more intricate than those of individuals.

- **Different definitions of agent**:

1. "An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors." (Russell and Norvig, 1995)
2. "Perhaps the most general way in which the term agent is used is to denote a hardware or (more usually) software-based computer system that enjoys the following properties: autonomy, social ability, reactivity, and proactiveness." (Wooldridge and Jennings, 1995) [Summarized definition, for the full version please consult the cited reference]
3. "An autonomous agent is a system situated within and part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and also so as to effect what it senses in the future." (Franklin and Graesser, 1997)

- an agent can be understood as an entity endowed with a (partial) representation of the environment, capable of acting upon itself and the environment, and also capable of communicating with other agents.
- Its behavior is a consequence of its observations, knowledge, and its interactions with other agents and the environment.
- Agents can be of many types, including biological (e.g., ants, termites, neurons, immune cells, birds, etc.), physical (e.g., robots), and virtual agents (e.g., a computer algorithm, Tamagotchi, etc.),



General Concepts

Q5

- **Parallelism and Distributivity**
  - All the individuals in the population play important roles in exploring the environment and sometimes exchanging (genetic) information, producing progenies more adapted to the life in a spatial location.
  - Evident in insect societies, brain processing, immune functioning, the evolution of species
    - In Insect societies tasks are distributed.
      - A colony of ants (termites, wasps, bees) has individuals assigned to various tasks, such as harvesting food, cleaning the nest, and caring for the queen.
    - All insects in a colony work in parallel in a given task, but they may switch tasks when needed. For e.g. worker ants may be recruited for battle when the nest is attacked
    - In the human nervous system, a huge number of neurons are involved in processing information at each time instant.
      - Talking while driving, watching TV while studying, hearing a name while having a conversation with someone
    - In immune systems, a large variety and number of cells are involved in an immune response.
      - When a virus infects a cell, some specialized immune cells, named T-cells, recognize fragments of this virus presented by a molecular complex of another specialized antigen presenting cell. This recognition triggers the action of many other immune cells to the site of infection.
    - Several other cells are performing the same and other processes, all at once in a distributed and parallel form.

General Concepts

- **Interactivity**
  - Interactivity is an important mean nature has to generate and maintain life.
  - Individual organisms interact with one another in variety of forms: reproductively, symbiotically, competitively, in a predator-prey situation, parasitically, via channels of communication.
  - At a macro level, an important outcome of these interactions is a struggle for limited resources and life. Individuals more adapted to the (local) environment tend to survive and mate thus producing more progenies and propagating their genetic material.
  - Interactivity allows for the emergence of self-organized patterns.
  - Complex systems, organisms, and behaviors emerge from interacting components.
    - e.g. Knockout, damaged brain functionalities revived
  - Examples of interactions:
    - immune cells and molecules communicate with one another and foreign agents through chemical messengers and physical contact
    - insects may also communicate with one another via chemical cues, dancing (e.g., bees dance to indicate where there is food to the other bees in the nest) or physical contact (e.g., antennation)
    - neurons are known to be connected with one another via small portions of its axons known as synapses
  - Two types of interactions:
    - Connectivity
    - Stigmergy

General Concepts

- **Adaptation**
  - Adaptation can be defined as the ability of a system to adjust its response to stimuli depending upon the environment.
  - **Learning**
  - **Evolution**

Adaptation can be defined as the ability of a system to adjust its response to stimuli depending upon the environment. Something, such as an organism, a device, or a mechanism, that is changed (or changes) so as to become more suitable to a new or a special application or situation, becomes more adapted to the new application or situation

Learning : it may be viewed as corresponding to the act, process, or experience of gaining knowledge, comprehension, skill, or mastery, through experience, study, or interactions

Evolution : In its simplest form, the theory of evolution is just the idea that life has changed over time, with younger forms descending from older ones, In contrast to learning, evolution requires some specific processes to occur.

General Concepts

- **Feedback**
  - **Positive feedback**
  - **Negative feedback**

feedback occurs when the response to a stimulus has an effect of some kind on the original stimulus. It can be understood as the return of a portion of the output of a process or system to the input, especially when used to maintain performance or to control a system or process. The nature of the response determines how the feedback is labeled: negative feedback is when the response diminishes the original stimulus (they go in the opposite direction); and positive feedback is when the response enhances the original stimulus (they go in the same direction).

positive: Positive feedback is a sort of self-reinforcing (growth) process in which the more an event occurs, the more it tends to occur.
eg more termites more pheranome

Negative feedback by contrast, plays the role of regulating positive feedback so as to maintain a(n) (dynamic) equilibrium of the medium. It refers to change in the opposite direction to the original stimulus. The thermostat is one of the most classic examples of negative feedback. It takes the reading of a room's temperature, measures that reading according to a desired setting, and then adjusts its state accordingly. If the room's temperature is too low, more hot air is allowed to flow into the room; else if the temperature is too high, then more cold air flows into the room

General Concepts

- **Self Organization**
  - **What is self-organization and what is not a self-organization**
  - **Characteristics of self-organization**

Self-organization refers to spontaneous ordering tendencies sometimes observed
in certain classes of complex systems, both natural and artificial. Most selforganized systems present a number of features:
• Collectivity and interactivity: self-organizing systems (SOS) are usually
composed of a large number of elements that interact with one another
and the environment.
• Dynamics: the multiplicity of interactions that characterize selforganizing systems emphasize that they are dynamic and require contin
ual interactions of lower-level components to produce and maintain structure.
• Emergent patterns: SOS usually exhibit what appears to be spontaneous
order; the overall state of a self-organized system is an emergent property.
• Nonlinearities: an underlying concept in self-organization is nonlinearity.
The interactions of components result in qualitatively new properties that
cannot be understood as the simple addition of the individual contributions.
• Complexity: most self-organizing systems are complex. The very concepts of complexity and emergence are embodied in SOS.
However, it is
more accurate to say that complex systems can be self-organizing systems.
• Rule-based: most SOS are rule-based, mainly biological self-organizing
systems. Examples of rules governing natural self-organized systems
were already reviewed, such as the ones that result in dead body clustering in ant colonies. Further examples will be given in the
following chapters.
• Feedback loops: positive and negative feedback contribute to the formation of self-organized processes by amplifying and regulating
fluctuations
in the system.