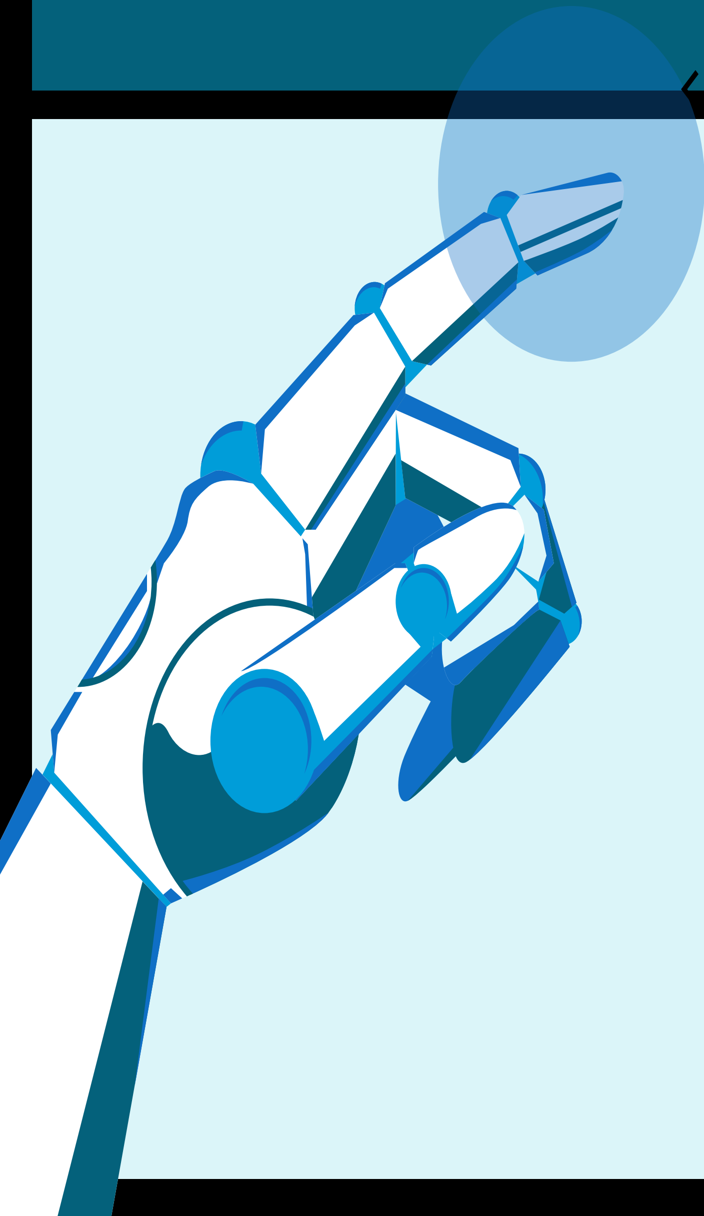

BIO-INSPIRED COMPUTING (INFOBIO)

Chapter 01

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CHAPTER 1: COMPUTER SCIENCE AND NATURE (10%)

- Inspiration from Nature
- Synthesis of Natural Phenomena through Computing; the Notion of Metaphor
- Natural Materials for Computing

BIOLOGY AND COMPUTERS

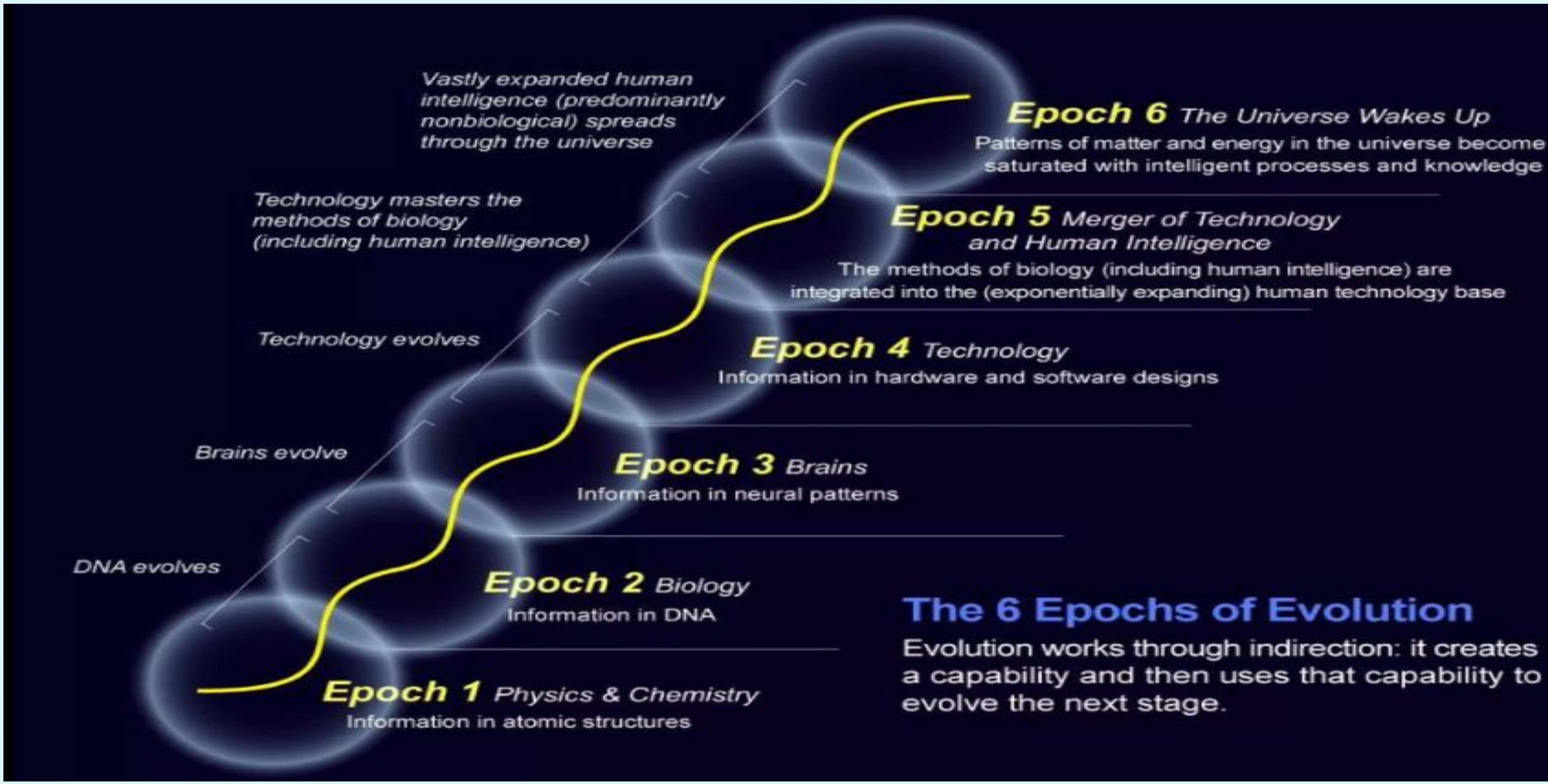
Important Distinctions that are often confused

- **Bioinformatics** Use of computers to improve biology
- **Biocomputer-based (biological) computing** Use of biology to improve computing
- **Biologically-inspired (bio-inspired) computing** Use of Biological concepts to improve our ability to program
- **DNA Computing (DNAC)** Use of biochemistry and molecular biology, instead of the traditional silicon-based computer systems
- **Bio-computing** "Catch all" can mean either bioinformatics or biocomputer-based
- **Biotechnology** Use of biological processes in industrial production
- **Convergence and Evolution of Informatics and Knowledge** All information and knowledge eventually converge

BIO-COMPUTING

- Biocomputing can mean two different things:
  - The construction and use of computers which function like living organisms or contain biological components, so-called biocomputers (in this meaning it is closely related to DNA computing)
  - The use of computers in biological research (in this meaning it is referred to as bioinformatics)
- Biological computing is often used for biocomputer-based computing
- Biocomputing is often used for bioinformatics
- Neither are considered Biologically-Inspired Computing (Bio-Inspired Computing)

EVOLUTION EPOCHS



WHY DO BIO-INSPIRED COMPUTATION?

- Biological systems are:
- – efficient
- – robust
- – adaptive
- – flexible
- – parallel
- – decentralized
- – self-organizing
- – self-repairing
- – self-optimizing
- – self-protecting
- – self-*
- – etc.

FOUNDATION

- Computer Science is often viewed as a field of mathematics, logic, and engineering, something artificial, mechanical, and human-made. On the other hand, Nature represents the organic, spontaneous, and complex systems of life and the universe. Yet, these two worlds are deeply connected. The very foundation of computing problem-solving, pattern recognition, and adaptation mirrors how nature works.

- In recent decades, scientists have discovered that the **principles governing natural systems** can inspire more efficient and intelligent computational systems. Likewise, computer models help scientists understand and simulate **natural phenomena** from weather systems to cell growth. Moreover, recent research explores how **natural materials themselves**, such as DNA or neurons, can become the *medium* of computation.

- This chapter explores the powerful relationship between **Computer Science and Nature** through three main perspectives:

- **Inspiration from Nature** – how natural processes inspire computing ideas and algorithms.

- **Synthesis of Natural Phenomena through Computing** – how computers model, simulate, and recreate natural systems.

- **Natural Materials for Computing** – how living or organic materials are used as computing substrates.

- By understanding these relationships, we can see how computing is not just a human invention — it is a continuation of nature’s own ways of processing information.

OPTIMIZATION: NATURE'S WAY OF PROBLEM SOLVING

- **Optimization** means finding the *best possible solution* to a problem among many alternatives. It is the process of achieving the maximum benefit (such as profit, speed, or strength) or the minimum cost (such as waste, time, or energy).

- In simple terms:
- Optimization = "Doing something in the best possible way."
- In computing, optimization means improving the performance of an algorithm, minimizing memory usage, or finding the shortest path between two points.
  In nature, optimization happens *everywhere* often without conscious planning.

OPTIMIZATION IN EVERYDAY LIFE

We perform optimization constantly in daily life, often without realizing it:

Every decision we make involves a trade-off balancing multiple factors to achieve the best outcome.

This process mirrors the way **algorithms** and **biological systems** optimize performance.

Situation	What We Optimize	Example
Traveling	Shortest or fastest route	Using Google Maps to avoid traffic
Cooking	Time and resources	Preparing all dishes so they finish cooking together
Studying	Time vs. focus	Spending more time on harder subjects
Shopping	Cost vs. quality	Finding the best deal on groceries
Sports	Energy and strategy	Athletes pacing themselves to maximize endurance

OPTIMIZATION IN NATURE

- Nature is the original master of optimization. Over millions of years, biological systems have evolved to make the most efficient use of resources, energy, and structure.

- Let’s explore a few examples:

a. Honeybees and Foraging

Bees instinctively find the shortest path between flowers and their hive. By communicating through “waggle dances,” they share information about where to find the most nectar with the least effort.
This natural behavior inspired **Ant Colony Optimization** algorithms used in network routing and logistics.

b. Spider Webs and Material Efficiency

Spiders spin webs that balance **strength**, **flexibility**, and **minimum material use**. The design of their silk patterns minimizes energy while maximizing catch efficiency, a perfect optimization of geometry and function.

OPTIMIZATION IN NATURE

c. Trees and Light

- Trees grow branches and leaves in a way that maximizes light exposure for photosynthesis while minimizing shadow overlap. This process inspired **fractal algorithms** used in computer graphics to generate realistic trees and landscapes.

d. Human Body and Energy

- Our muscles, lungs, and heart adapt to minimize energy use during physical activity. For example, our walking stride automatically adjusts to use the least possible energy per step — a form of continuous, unconscious optimization.

e. Evolution Itself

- Evolution is the **ultimate optimization process**. Through natural selection, species that survive are those best optimized for their environment — in terms of reproduction, adaptation, and resource use.

INSPIRATION FROM NATURE

- **Learning from Nature's Intelligence**

- Nature has been solving complex problems for billions of years. Animals adapt to their environments, plants optimize energy use, and ecosystems maintain balance without any central control system. Humans have learned that by studying these natural processes, we can create **algorithms and machines** that exhibit similar intelligence and adaptability.

- This approach is called **bio-inspired computing** or **nature-inspired computation**.

Computer Science and Nature

- In parallel with the significant development that computer science has undergone since the 1940s, another trend has emerged: **the fusion of ideas between Nature and Computing.**
- This trend has accelerated over the **last three decades.**

- Researchers now commonly draw inspiration from **nature** to:

1. Develop **new problem-solving techniques**,
2. **Simulate natural phenomena** on computers,
3. And use **new materials** (in addition to silicon) to perform computational processes.

Computer Science and Nature

- We therefore consider that **Natural Computing** can be divided into **three branches**:

1. **Computing Inspired by Nature:**
   This involves developing computational tools inspired by **nature and its ways of solving complex problems.**

2. **Simulation and Emulation of Natural Phenomena:**
   This is mainly a **synthetic process** aimed at creating **patterns, forms, behaviors, or organisms** that more or less resemble living systems as we know them.

3. **Computation Using New Materials:**
   This refers to building **computational platforms** capable of processing information using a **substrate other than silicon** (Silicon + Oxygen).

Computer Science and Nature

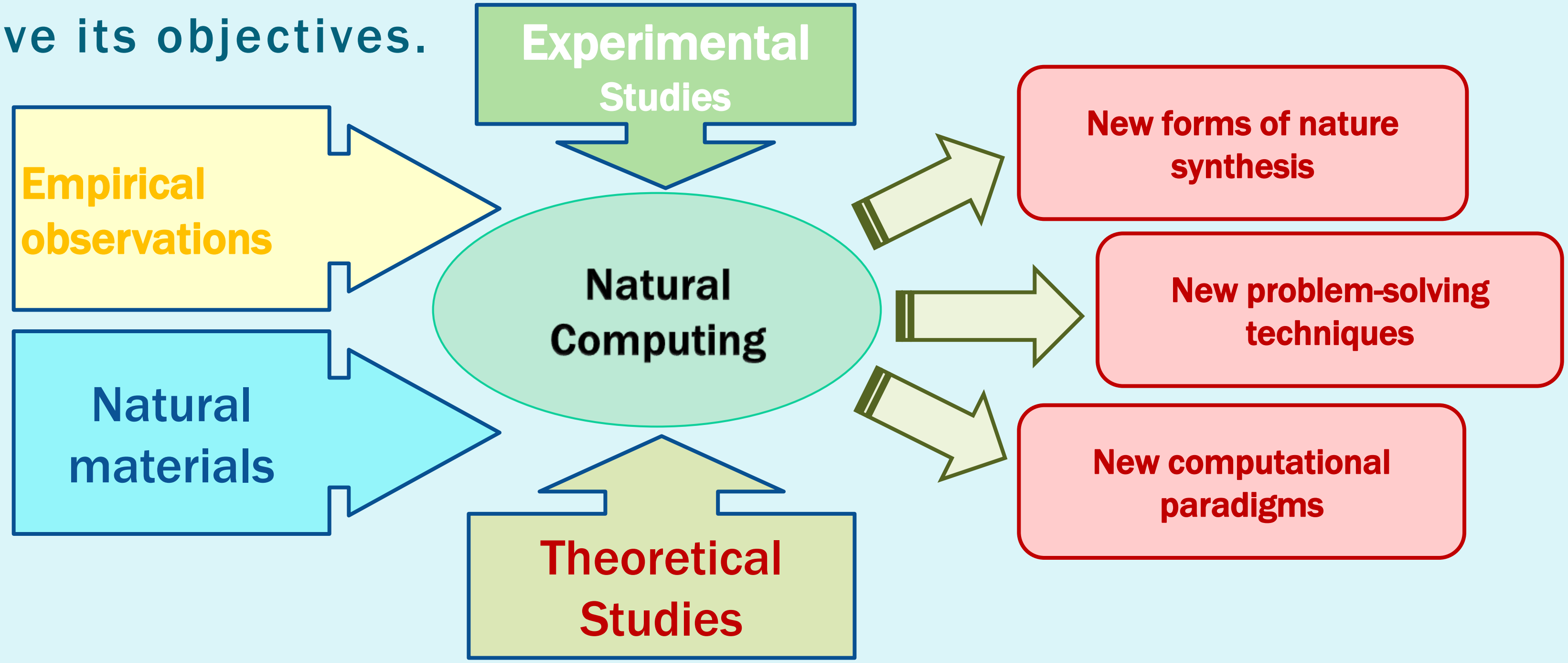
- **Natural Computing** is a research field that goes **against the traditional specialization** of scientific disciplines.

- With the three areas of investigation mentioned above, **knowledge from multiple research domains** is required:

1. To **better understand living systems**,
2. To **study and simulate natural systems and processes**,
3. To **propose new computational paradigms**.
4. **Computer scientists, chemists, physicists, biologists, and engineers** must work together in close collaboration.

Computer Science and Nature

Natural Computing generally integrates **experimental and theoretical biology**, **physics**, and **chemistry**, as well as **empirical observations of nature** and various **scientific facts and processes** at different levels of investigation in the natural world, in order to achieve its objectives.



Computer Science and Nature
Computing with a natural substrate

- It concerns new computing methods based on natural materials other than silicon.
- Computing with natural materials is an approach that promises to bring a major change to current computer technology.
- Motivated by the need to identify alternative media for computation, researchers are now attempting to design new computers based on molecules such as DNA (Deoxyribonucleic Acid) and RNA (Ribonucleic Acid), or on quantum theory.
- These ideas have led to what is now called molecular computing or DNA computing, and quantum computing.

THE NOTION OF METAPHOR IN COMPUTING

- Many foundational ideas in Computer Science are actually **metaphors drawn from nature**. These metaphors are not just language, they shape how we think about and design computers.

Natural Concept	Computing Metaphor	Explanation
Brain	Neural network	Computers modeled after the brain's neurons
DNA	Genetic code	Data stored in sequences, replication through copying
Ecosystem	Internet	Distributed, adaptive system with feedback loops
Virus	Computer virus	Self-replicating code that spreads across systems
Evolution	Evolutionary algorithms	Programs that evolve over time to optimize performance

SYNTHESIS OF NATURAL PHENOMENA THROUGH COMPUTING

- While nature inspires computing, computing also helps us understand nature. Using models, simulations, and artificial life experiments, computers can recreate natural phenomena and allow scientists to explore the dynamics of life, physics, and ecosystems.
- **3.1 Simulation of Natural Systems**
- Computer simulations are essential tools for studying systems that are too vast, complex, or dangerous to observe directly. Through simulation, we can explore how natural phenomena behave under different conditions.

a. Weather and Climate Modeling

- Supercomputers model the Earth’s atmosphere using physics equations that describe wind, temperature, humidity, and ocean currents. These simulations predict hurricanes, droughts, and climate change

b. Biological and Chemical Processes

- Computers simulate protein folding, cell division, and molecular interactions. These simulations help biologists understand diseases and design new drugs.

c. Ecological and Evolutionary Systems

- Simulations can model predator-prey dynamics, population growth, and resource competition.
  For instance, the **Lotka-Volterra model** simulates interactions between predators (like foxes) and prey (like rabbits) to predict cycles in population sizes.

Artificial Life (A-Life)

- **Artificial Life** is a field dedicated to creating systems that behave like living organisms. Instead of studying life as it exists, A-Life tries to **synthesize life-like behaviors** in computers.

a. Conway's Game of Life

- One of the simplest examples of A-Life is **Conway's Game of Life**, created by mathematician John Conway in 1970. It's a grid of cells that live, die, or reproduce based on simple rules:
- A cell survives if it has 2 or 3 neighbors.
- A cell is born if it has exactly 3 neighbors.
- Otherwise, it dies.
- Even with these basic rules, the system creates **complex patterns** that seem alive — some move, some grow, and some even "self-replicate." It demonstrates how complexity can **emerge from simplicity**, just like in real biology.

b. Boids and Flocking Behavior

- Craig Reynolds' **Boids model (1986)** simulated bird flocking using only three rules:
- Move toward the average position of nearby boids (cohesion).
- Avoid crowding others (separation).
- Align with the average direction of nearby boids (alignment).
- From these simple rules, lifelike flocking behaviors emerge — showing how local interactions can produce global order.

c. Virtual Ecosystems

- Some computer games and research simulations create entire ecosystems — with digital creatures that eat, reproduce, and evolve. Over time, these creatures adapt to their environments, illustrating Darwinian evolution in a virtual world.

NATURE AS COMPUTATION

- Some scientists propose that **nature itself performs computation**. Every physical, chemical, or biological process involves the processing and transmission of information.
- DNA stores and replicates information — much like a hard drive.
- Neurons process signals — like processors.
- Evolution optimizes species — like an algorithm refining solutions.
- From this view, the **universe is a computer**, and physical laws are the “programs” running it. This philosophical idea, sometimes called **digital physics**, suggests that computation is a fundamental aspect of reality.

NATURAL MATERIALS FOR COMPUTING

- The final dimension of the connection between nature and computing is **material**. Instead of using silicon chips, researchers are exploring how **natural or biological materials** can perform computation.
- **4.1 DNA Computing**
- DNA, the molecule of life, stores enormous amounts of information in sequences of four bases: A, T, C, and G. Leonard Adleman (1994) demonstrated that DNA can also perform **mathematical computation**.
- **How it works:**
- Each strand of DNA represents a possible solution to a problem.
- Chemical reactions (like DNA hybridization) combine and eliminate strands based on biological rules.
- The final mixture contains the correct solution, which can be read out using biochemical techniques.

BIOCOMPUTING AND LIVING SYSTEMS

- In **biocomputing**, living organisms or cells are used to perform computation.
- **Examples:**
- Bacteria engineered to detect toxins and produce light if a dangerous chemical is present.
- Plant-based sensors that change color in response to environmental changes.
- Neurons grown in a lab to control robotic movement (so-called *hybrid bio-robots*).
- These systems blur the line between living and non-living machines, leading to new possibilities in medicine, environmental monitoring, and synthetic biology.

NEUROMORPHIC COMPUTING

- Neuromorphic computing aims to design hardware that mimics the **structure and dynamics of the brain**. Instead of traditional binary circuits, neuromorphic chips use *memristors* — components that remember previous electrical states, like biological synapses.

- **Example:**
  IBM's **TrueNorth** and Intel's **Loihi** are neuromorphic processors that simulate millions of neurons and synapses. They are energy-efficient and capable of real-time pattern recognition, much like human brains.

ORGANIC AND SUSTAINABLE COMPUTING

- Traditional computers use metals, plastics, and silicon — materials that require intensive manufacturing and create waste. Inspired by natural materials, scientists are developing **organic electronics** that are biodegradable and environmentally friendly.
- **Example:**
- **Protein-based transistors** that use natural molecules to conduct electricity.
- **Paper-based circuits** that decompose safely.
- **Fungal networks (mycelium)** being explored as a potential computing substrate due to their self-growing and self-repairing properties.
- This reflects a shift toward **sustainable computing**, where technology coexists with nature rather than damaging it.

QUANTUM COMPUTING: NATURE AT THE SMALLEST SCALE

- Quantum computing uses the **laws of quantum mechanics** — the behavior of particles at atomic and subatomic levels — to perform computations that classical computers cannot handle efficiently.

natural principles:

- **Superposition:** A quantum bit (qubit) can be both 0 and 1 simultaneously.
- **Entanglement:** Qubits can be connected in ways that make their states dependent on each other, no matter how far apart they are.
- **Example:**
  Quantum computers can simulate complex molecular interactions — something that even supercomputers struggle with. This could revolutionize drug discovery, material design, and cryptography.
- Here, **nature's own quantum behavior** becomes the computational engine — not just the inspiration.