IIIT, HYDERABAD

NANONETWORKS:

A NEW FRONTIER IN COMMUNICATIONS

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INTRODUCTION

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- The concepts in nanotechnology was first pointed out by the 1965 nobel laureate physicist Richard Feynman in his famous speech entitled "There's Plenty of Room at the Bottom" in December 1959.
- The term "nanotechnology" was coined 15 years later.
- What is NanoTechnology?

FUTURE LOOK

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- **SILICON TECHNOLOGY ERA**
  - **IS COMING TO AN END (~ 2020-2030)**
- **MOLECULAR TECHNOLOGY ERA**
  - **IS STARTING AND WILL BE DOMINATING OUR LIVES FOR THE NEXT COMING YEARS ~(2020-onwards)**

DESIGN OF NANOMACHINES

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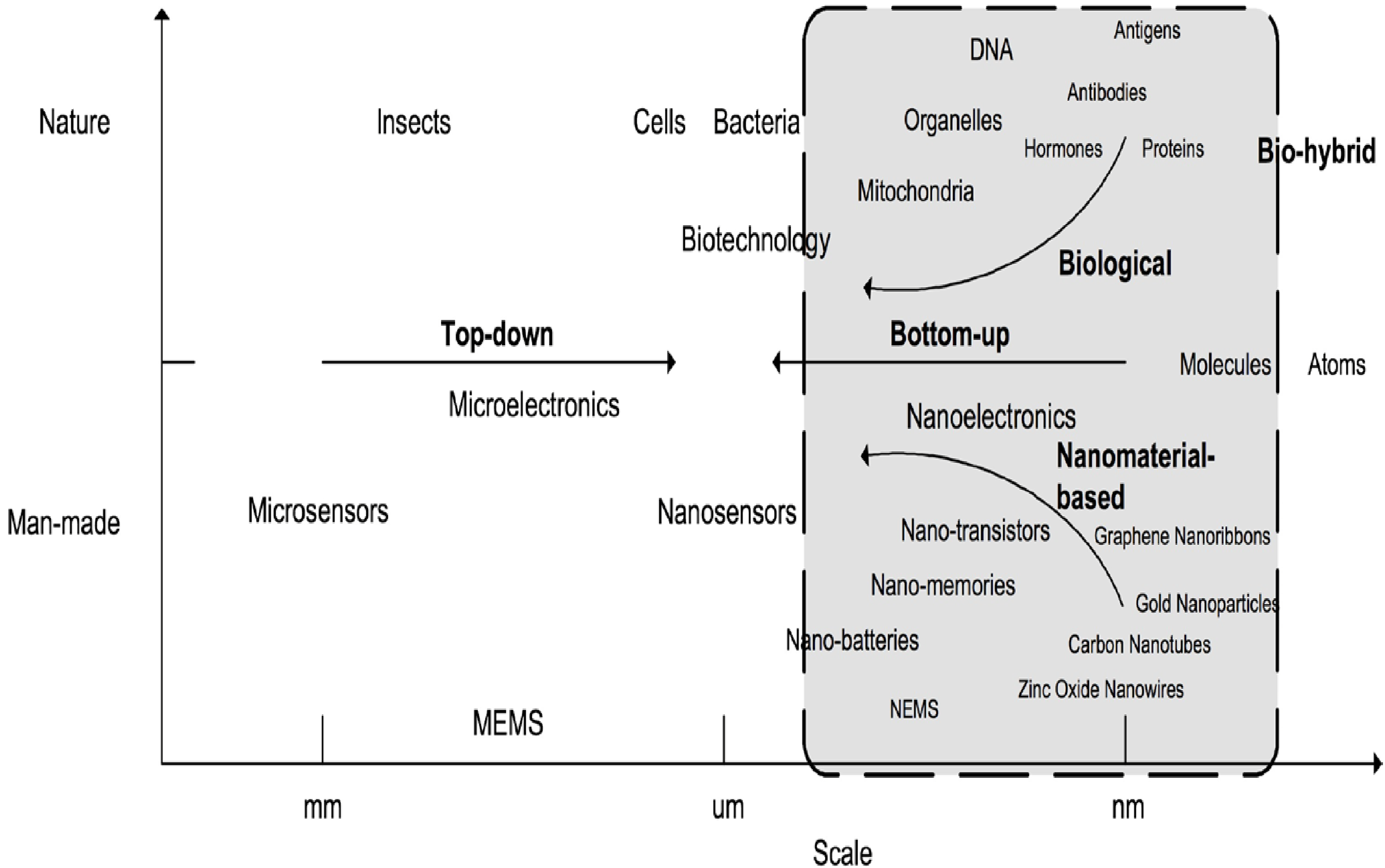

NANO MATERIALS

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- Graphene: A one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice
- Carbon Nanotubes (CNT): Rolled Graphene
- Graphene Nanoribbons (GNR): A thin strip of Graphene
- Bucky Balls: A Graphene sphere

GRAPHENE

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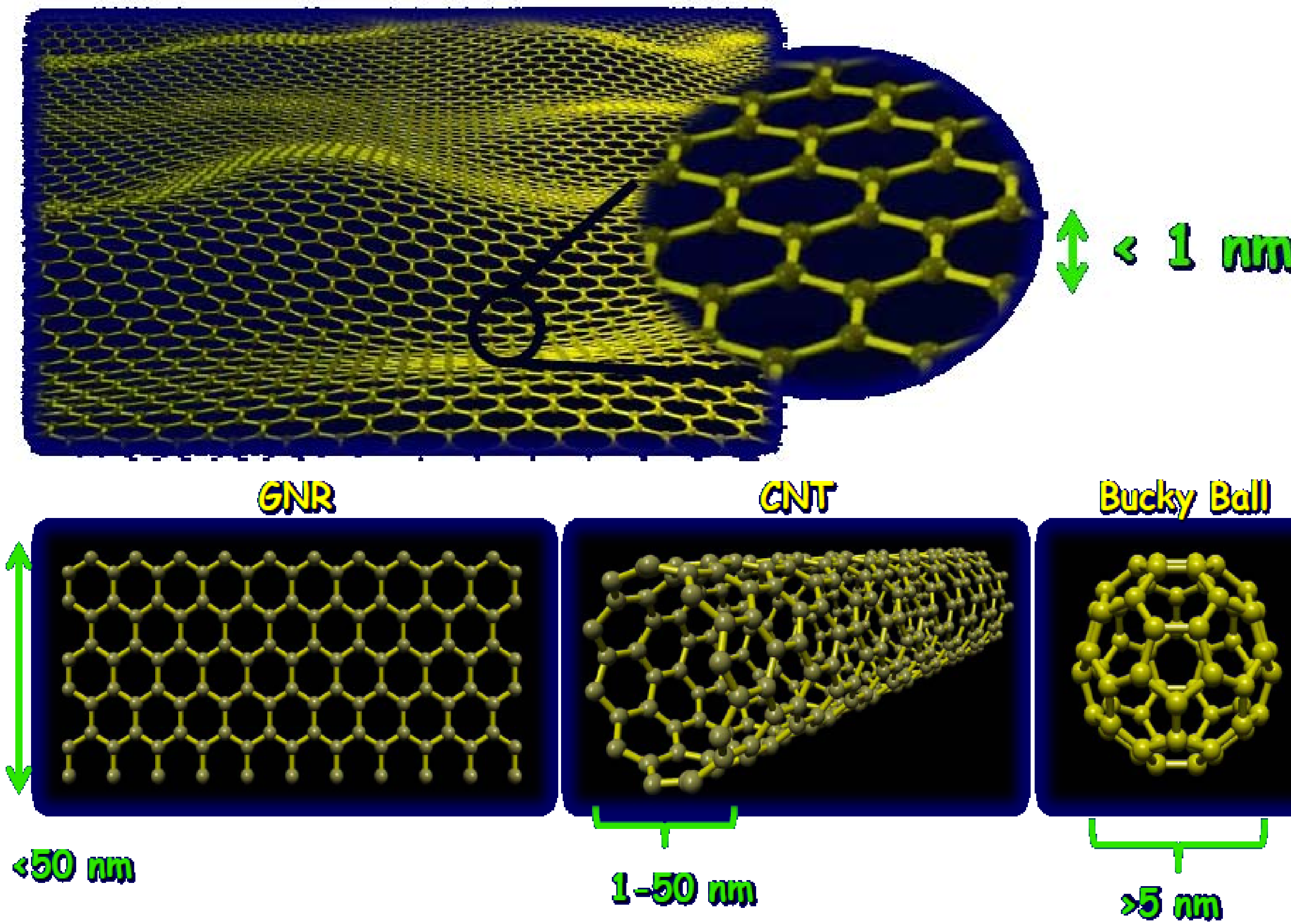

ABOUT GRAPHENE

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- **First 2D crystal ever known to us:**
  - **Only 1 atom thick!!!**
- **World's thinnest and lightest material**
- **World's strongest material**
  - **e.g., harder than diamond, 300 times stronger than steel**
- **Bendable, i.e., takes any form you want**
- **Conducts electricity much better than copper**
- **Transparent material**
- **Very good sensing capabilities**
- **Enable a plethora of new applications for device technology at the nanoscale and also at larger scales:**
  - **e.g., processors, memories, batteries, antennas, transceivers, sensors, cameras, etc.**

EXPECTED FEATURES OF NANOMACHINES

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- Intrinsically Self-Contained
- Self-Assembly
- Self-Replication
- Locomotion
- Communication

NANOMACHINES

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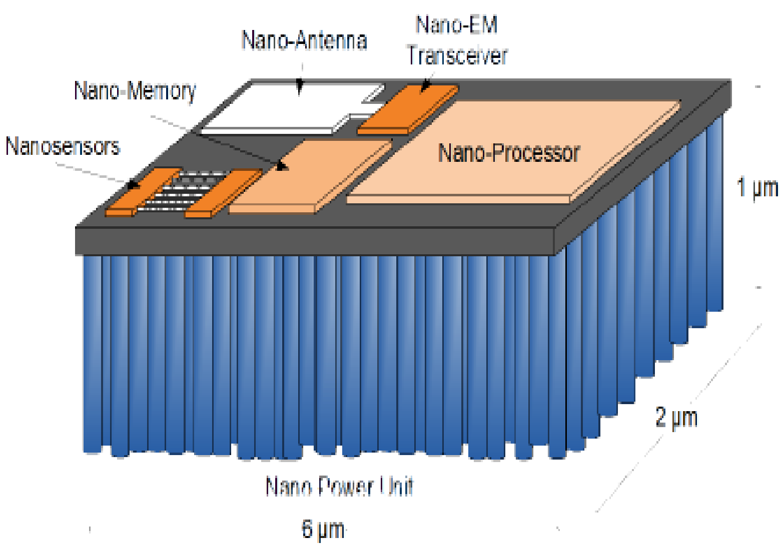
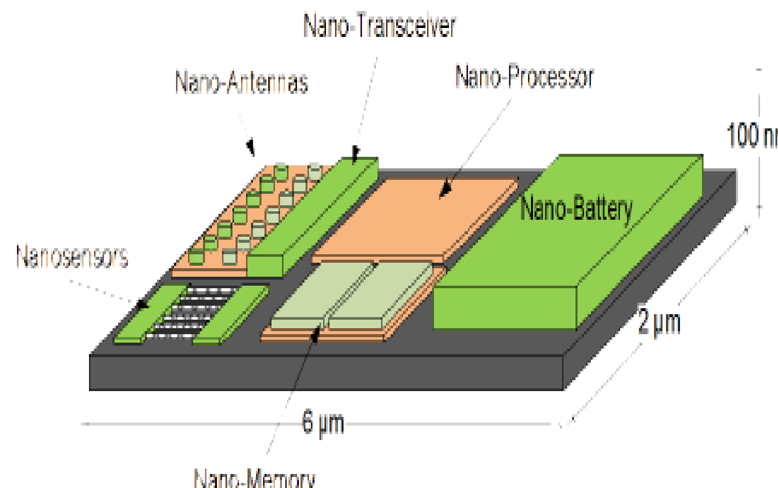
Nano-Material Based Design



Bio-inspired Design



NANOMATERIAL-BASED NANOMACHINE ARCHITECTURE

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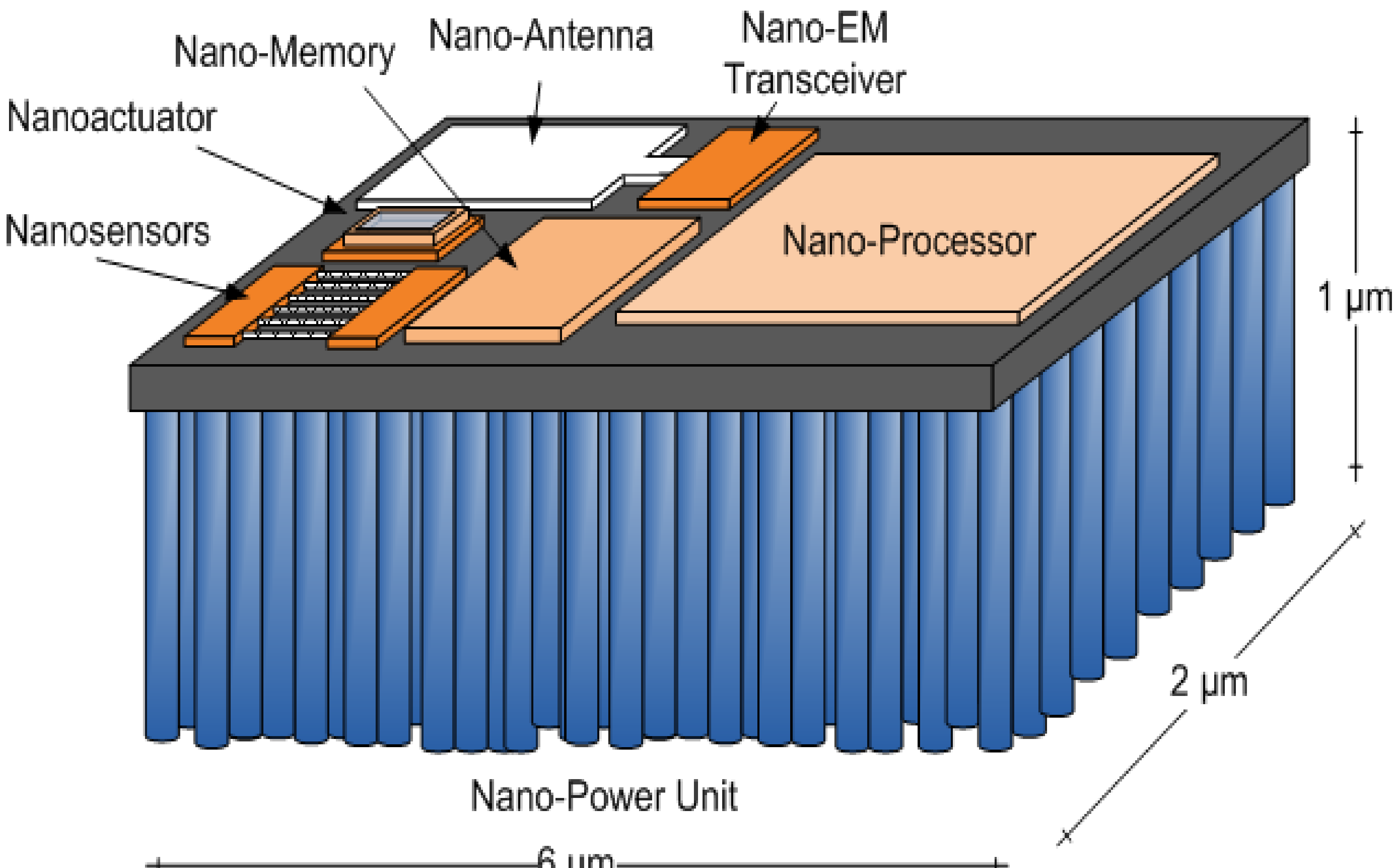

BIO-INSPIRED DESIGN

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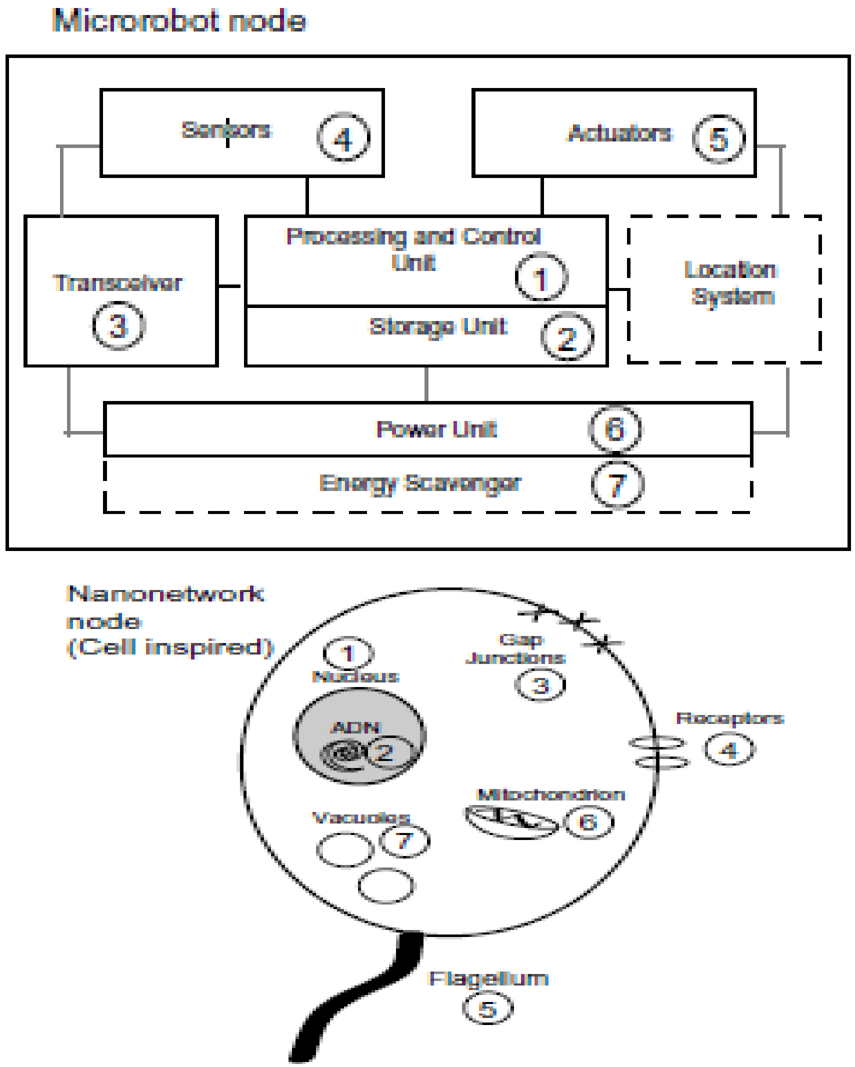

Functional architecture mapping between nano-machines of a micro or nano-robot, and nano-machines found in cells.

NANO-SENSING UNIT

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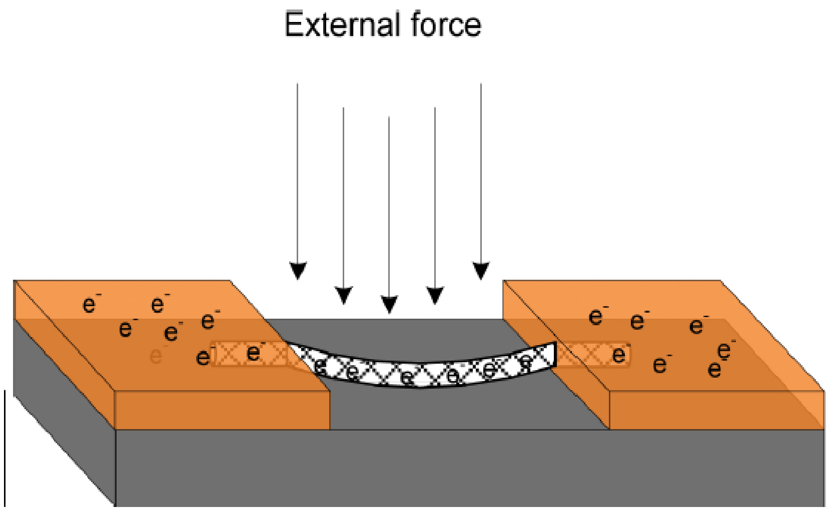
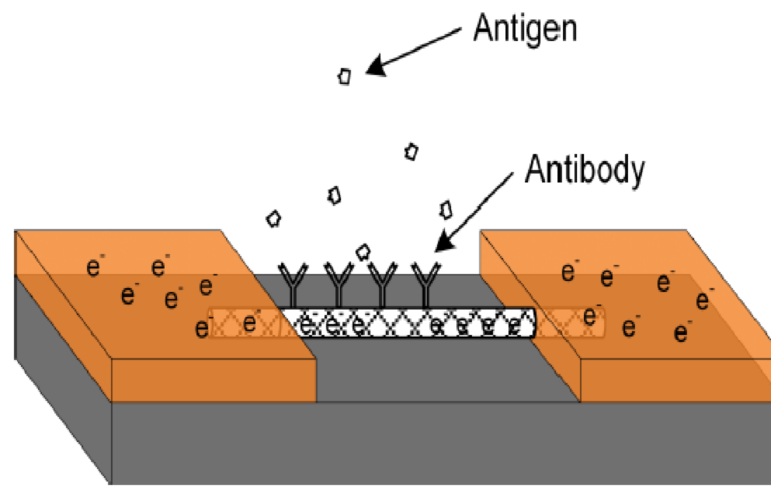
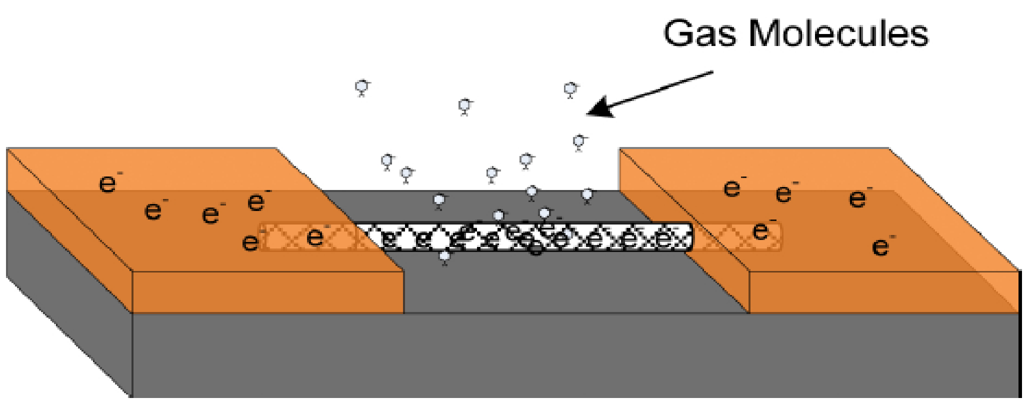


Physical Nanosensor



Biological Nanosensor



Chemical Nanosensor

NANO POWER GENERATOR

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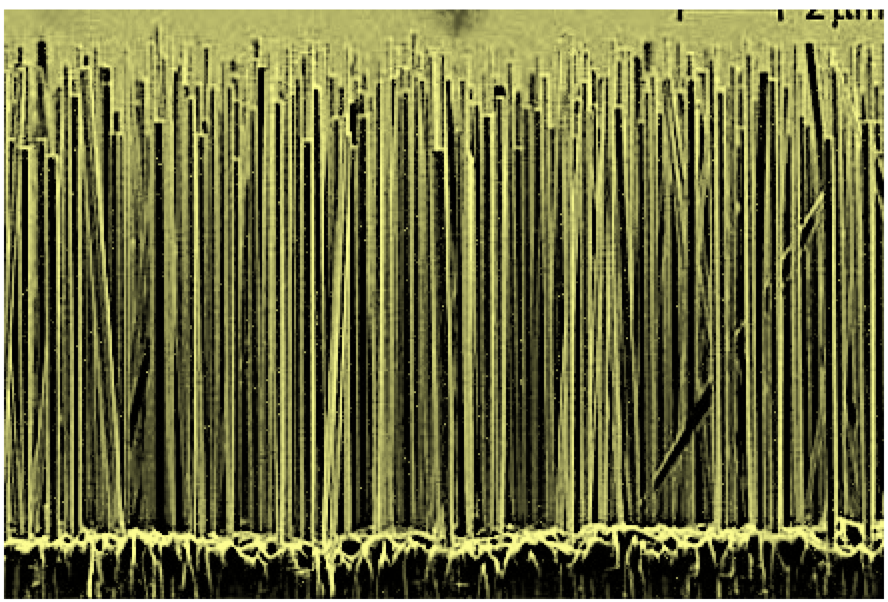
- Zinc Oxide nanowires can be used for vibrational energy harvesting systems in nano-devices



High density array of nanowires used in piezoelectric nano-generators

NANO POWER GENERATOR

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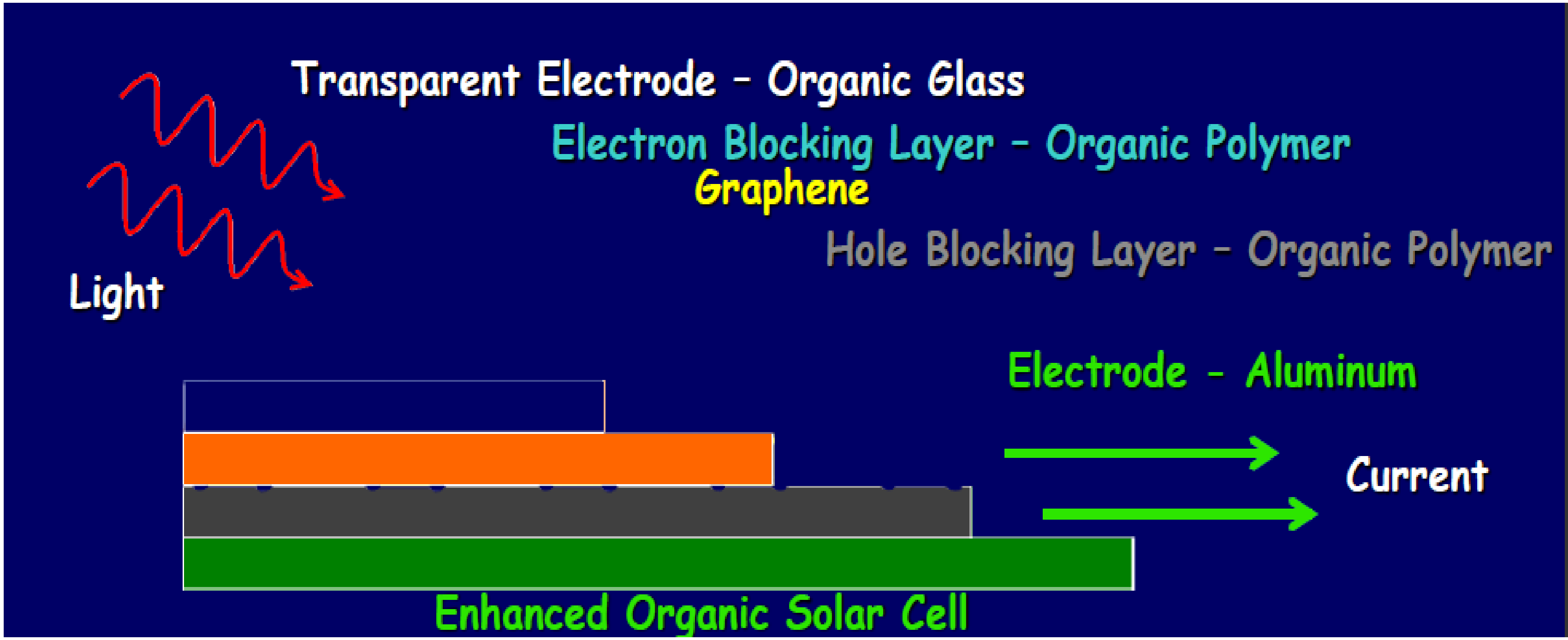
- **Graphene can be used to enhance the efficiency of organic solar cells (up to 300 times higher!!)**



NANO-PROCESSORS

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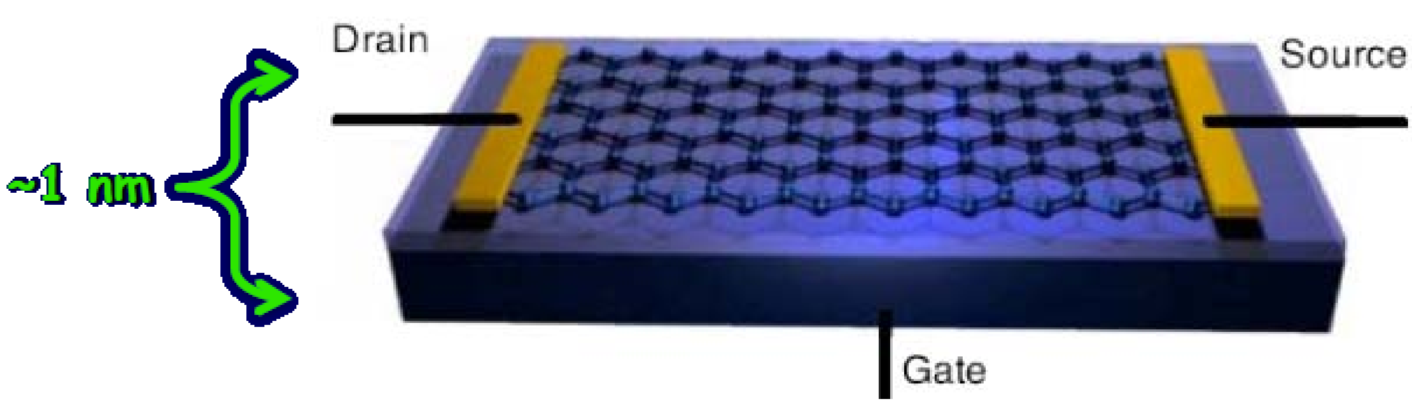
- **32 nm or 20 nm transistor technology (e.g., IBM, Qualcomm, Samsung)…**
- **World's smallest transistor (2008) is based on a graphene nanoribbon**
  - **just 1 atom x 10 atoms (1 nm transistor)**
- **Switching frequency close to 1 THz**
  - **(compare to few GHz in current silicon transistors).**

Graphene Transistor



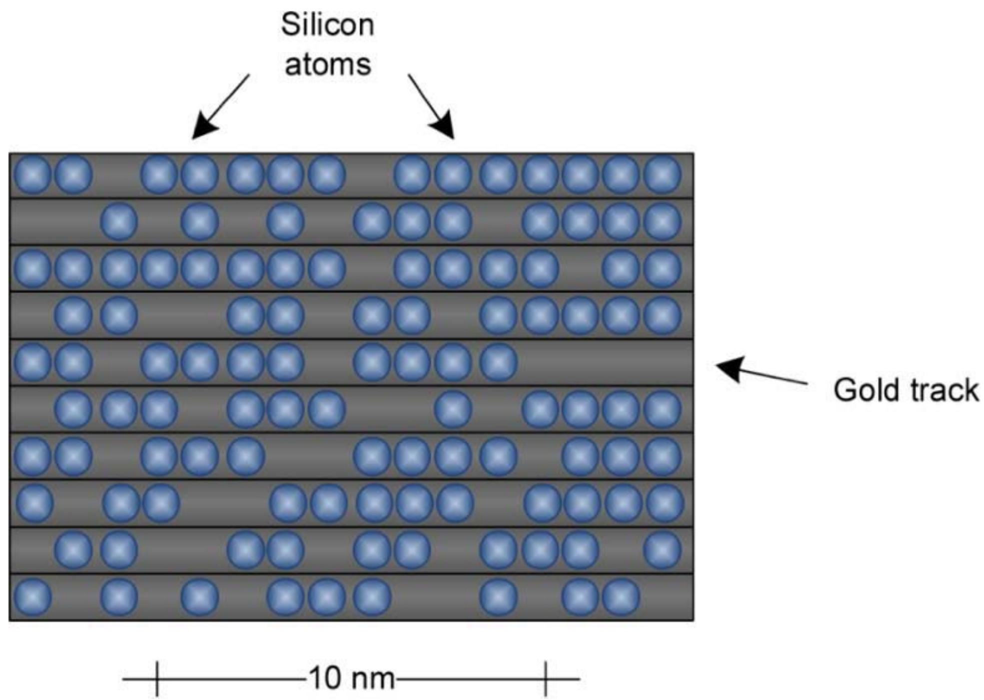
NANO-MEMORY

- Single atom memories: Store a bit in a single atom !
  - Richard Feynman defined them back in 1959!
    - In his example, 5x5x5 atoms were used to store a bit and to avoid inter-atom interference

– 125 atoms per bit

– DNA uses 32 atoms per bit

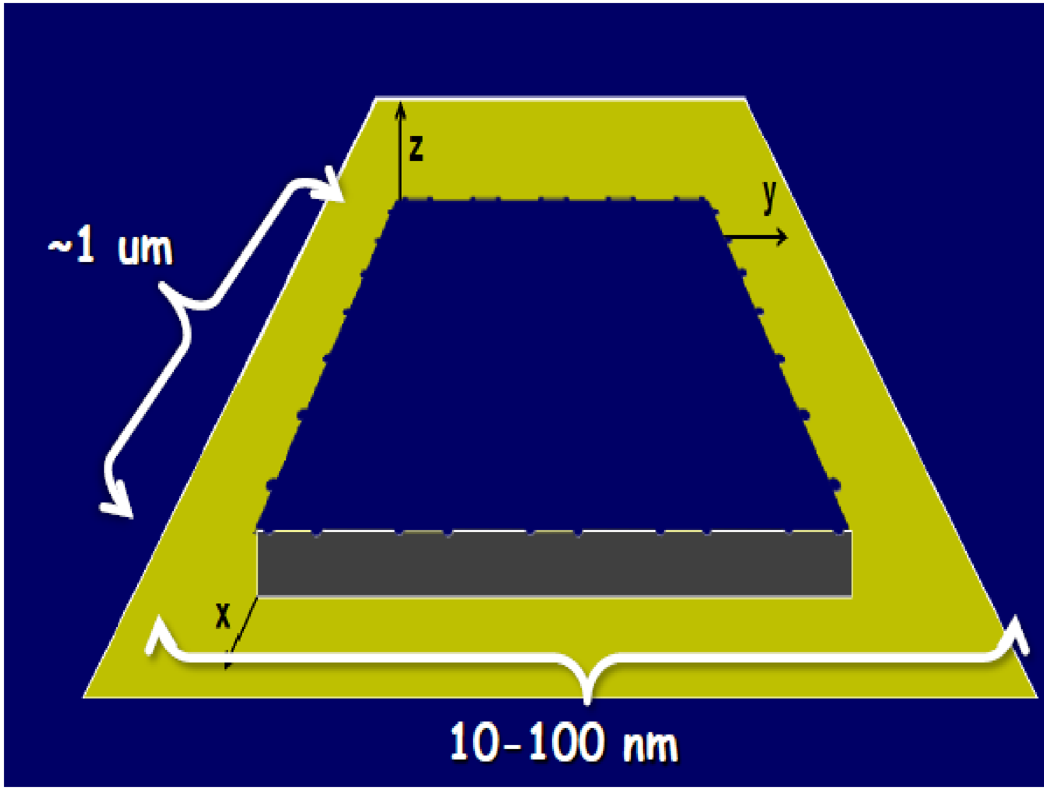
Example: Gold nano-memories



GRAPHENE-BASED NANO-ANTENNAS

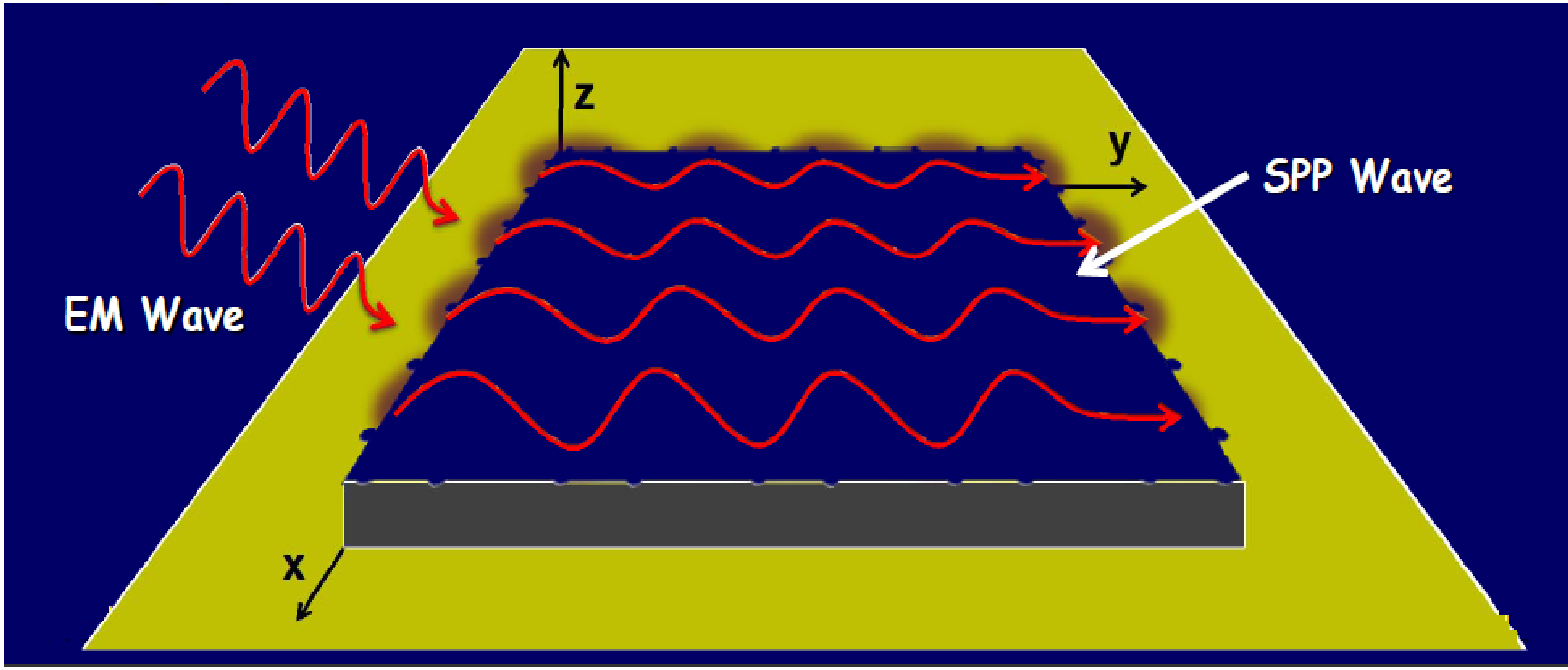
- Can radiate at lower frequencies than metallic nano- antennas…

- … by exploiting the behavior of plasmons in graphene



GRAPHENE PLASMONICS

- Graphene supports the propagation of Surface Plasmon Polariton (SPP) waves at frequencies in the THz Band (0.1-10 THz):
  - Global oscillations of electric charge at the interface between graphene and a dielectric material



COMMUNICATION AMONG NANOMACHINES

- Among all of the expected features of future nano-machines, the communication capabilities are also very important.
- This is the only feature that enables them to work in a synchronous, supervised and cooperative manner to pursuit a common objective.
- Nano-machines communication can include the two following bidirectional scenarios:

(1) Communication between a nano-machine and a larger system such as electronic micro-devices, and

(2) Communication between two or more nanomachines.

- Communication based on *electromagnetic* waves is the most common technique to interconnect microelectronic devices.
- At nano-level, *acoustic* communication is mainly based on the transmission of ultrasonic waves.
- In *nanomechanical* communication, the information is transmitted through hard junctions between linked devices at nano-level.

MOLECULAR COMMUNICATION

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Defined as the transmission and reception of information encoded in molecules

A new and interdisciplinary field that spans nano, ece, cs, bio, physics, chemistry, medicine, and information technologies

MOLECULAR COMMUNICATION

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- Molecular communication is defined as the transmission and reception of information encoded in molecules.
- Molecular communication is a new and interdisciplinary field that spans nano, bio and communication technologies.
- Molecular communication can be used to interconnect multiple nano-machines, resulting in nanonetworks.
- Nanonetworks expand the capabilities of single nano-machines in the following terms:
  - More complex objectives can be achieved if multiple nano-machines cooperate.
  - If a large number of nano-machines are interconnected, they can pursuit macro-scale objectives, and work over larger areas.
  - If multiple nano-machines are deployed over large areas, the interaction with a specific nano-machine is extremely difficult due to its small size.

MOLECULAR COMMUNICATION

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- Short Range (nm to μm)
  - Molecular Motors (e.g., Kinesin, Dynein)
  - Molecule Diffusion (e.g., Bacterial Auto-inducers, Calcium ions)
- Medium Range (μm to mm)
  - Chemotaxis (e.g., Bacterial Chemotaxis and Conjugation)
- Long Range (mm to m)
  - Molecule Advection + Diffusion (e.g., Pheromones and Pollen)

SHORT-RANGE COMMUNICATION USING MOLECULAR MOTORS

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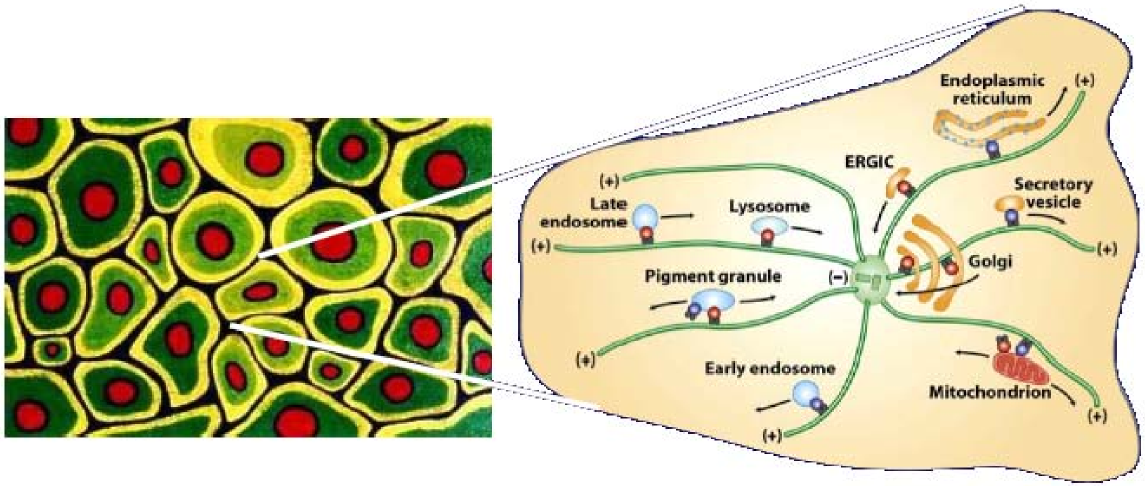

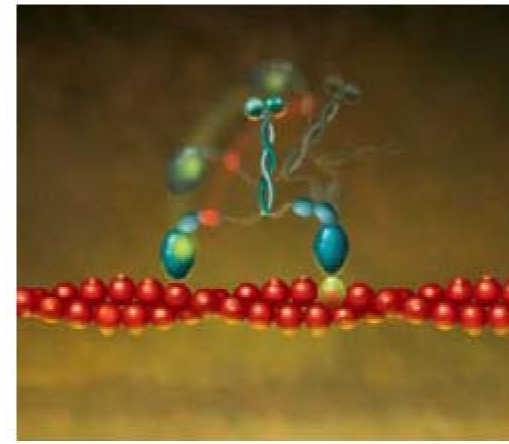

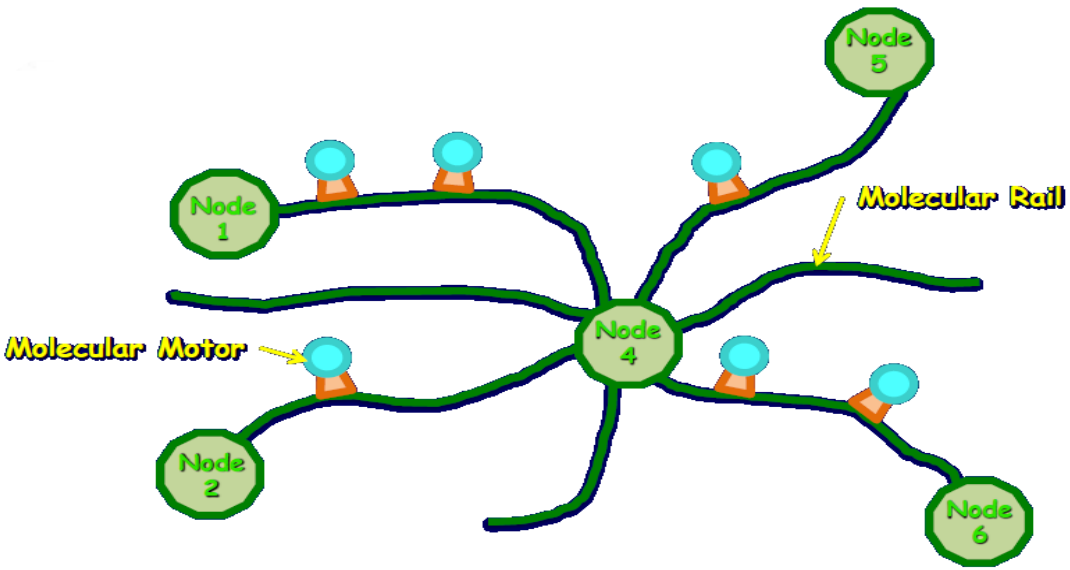

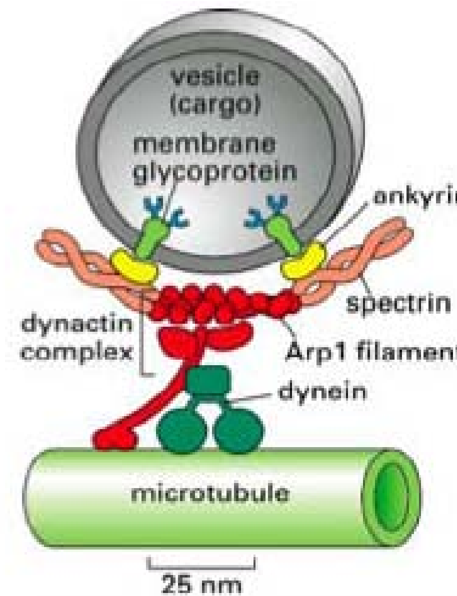

MOLECULAR COMMUNICATION BLOCKS USING MOLECULAR MOTORS

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Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Molecular Motors

- Select Molecules to represent information
- Encapsulate molecules into vesicles

  attach them to molecular motors
- Molecular motors

  travel along

  molecular rails
- Detach vesicles from Molecular motors

  Extract molecules from vesicles
- Interpret received information

  from molecules characteristics

SHORT-RANGE COMMUNICATION USING MOLECULE DIFFUSION

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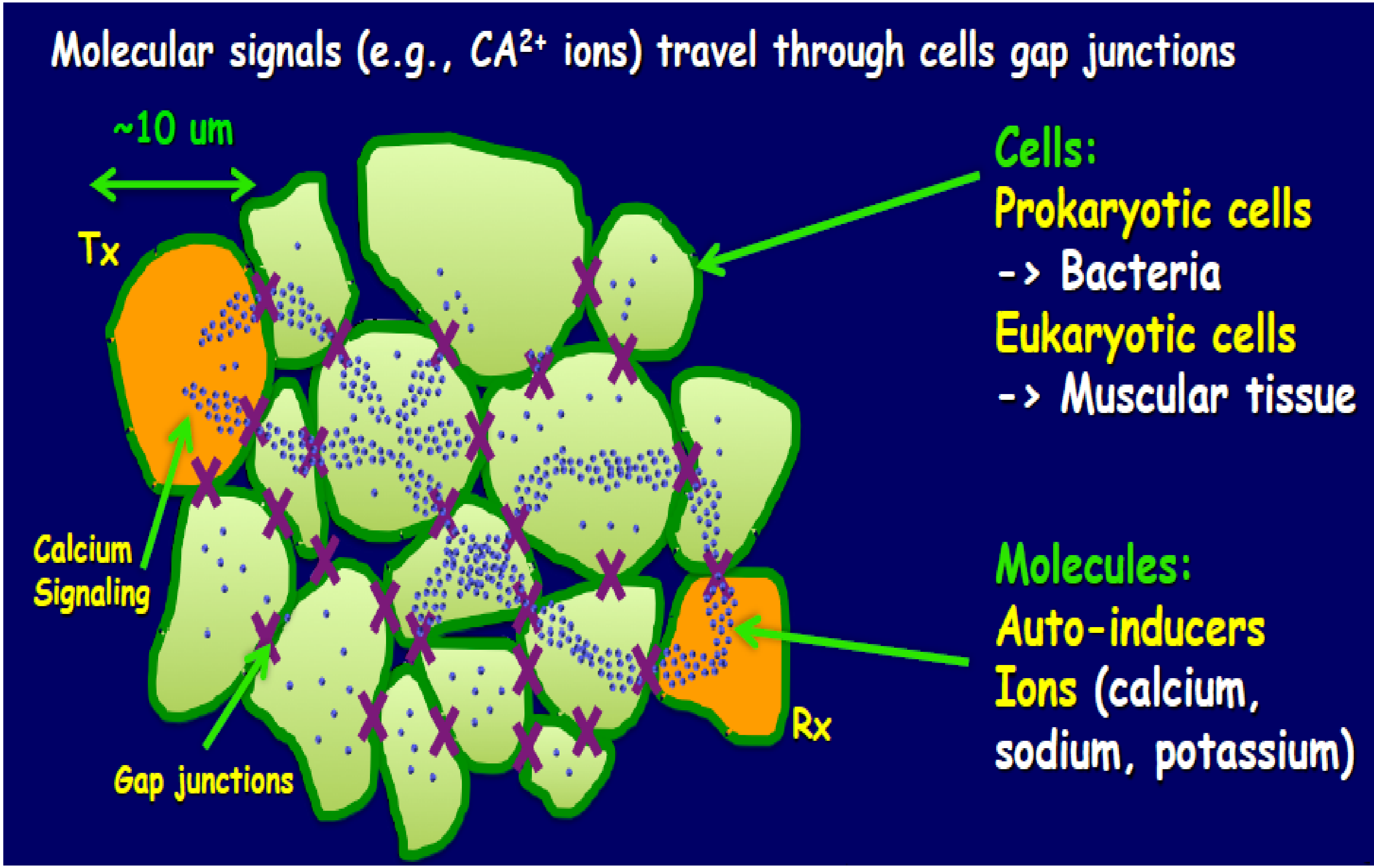

MOLECULAR COMMUNICATION BLOCKS USING MOLECULE DIFFUSION

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Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Molecule Diffusion-based Communication

Encoding	Transmission	Propagation	Reception	Decoding
Modulate molecule concentration according to the information	Emit modulated concentration from gap junctions on the nanomachine	Modulated concentration propagates via molecule diffusion	Absorb incoming molecules in the nanomachine Sense their concentration through chemical receptors	Interpret received information from variations in concentration

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

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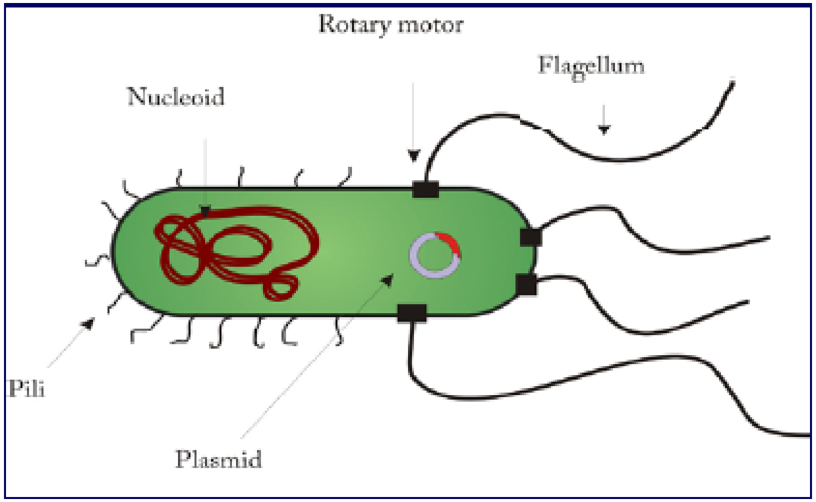

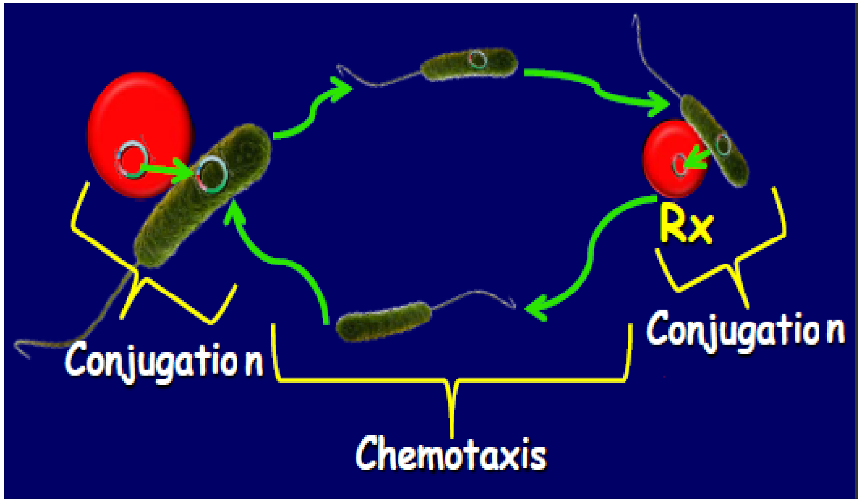

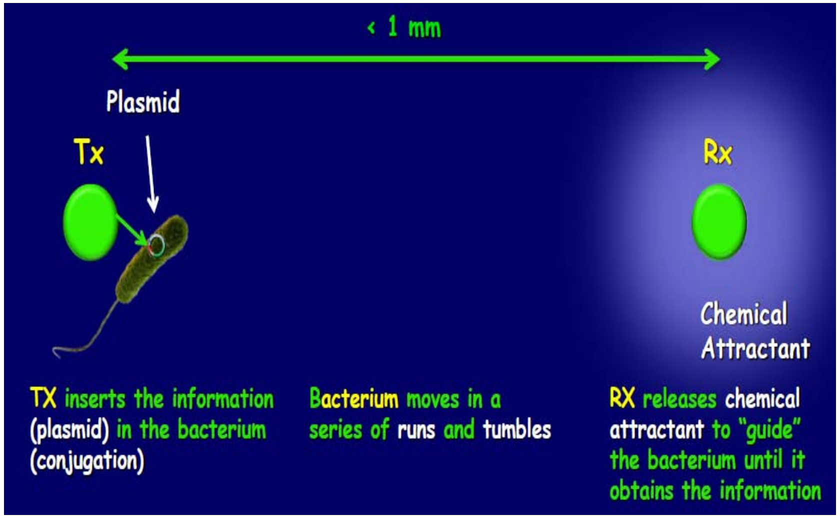

- Bacteria are microorganisms composed only by one prokaryotic cell
- Flagellum allows them to convert chemical energy into motion
- 4 and 10 flagella (moved by rotary motors, fuelled by chemical compounds)
- Approximately 2 μm long and 1 μm in diameter.

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

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Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Bacteria Chemotaxis and Conjugation

Introduce DNA plasmid inside the bacteria's cytoplasm (conjugation)

→ Receiver releases attractants so the bacteria can reach it

Bacteria sense the gradient of attractant particles

They move towards the gradient direction (chemotaxis)

→ DNA plasmids extracted from incoming bacteria (conjugation)

Plasmids are read and information is interpreted

LONG-RANGE COMMUNICATION USING PHEROMONES

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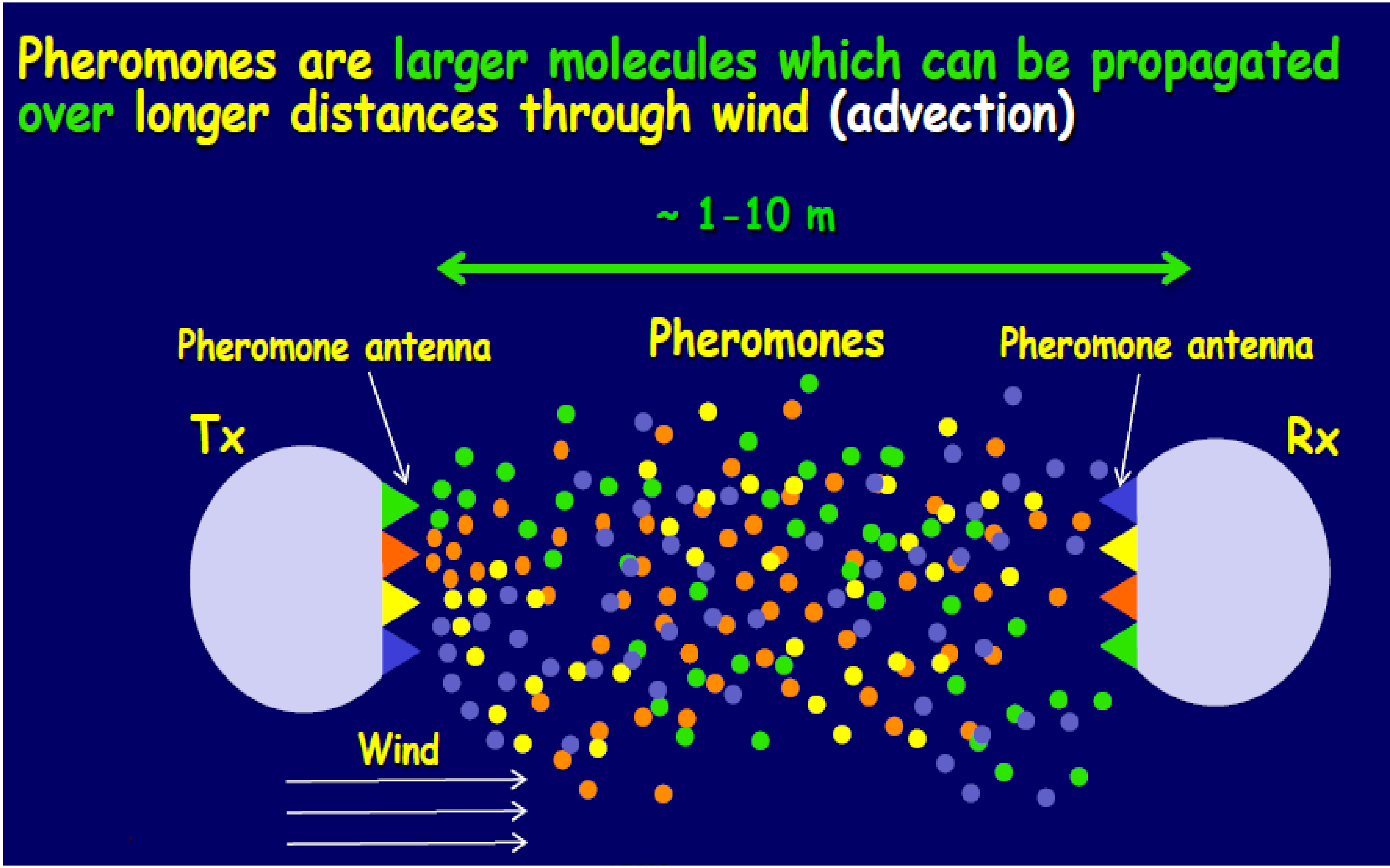

LONG-RANGE COMMUNICATION USING PHEROMONES

IIIT, HYDERABAD

Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Molecule Advection and Diffusion

- Modulate production of molecules with certain Chemical character.
- Release these molecules In the air
- Molecules propagate thanks to the **advection** of air turbulence (wind) and **diffusion**
- Sense incoming molecules with chemical receptors
- Interpret Received information from chemical charact.. of sensed molecules

COMPARISON OF MOLECULAR TO CURRENT COMMUNICATIONS

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- Compared to current communication network technologies, nanonetworks have the following advantages:
  - The reduced size of nano-machines and the nanonetwork components can be an advantage in many applications where the dimension of the involved systems is critic.
  - Nanotechnologies can be used to enhance the compatibility between nano-machines and natural organs or tissues by means of more friendly materials and interfaces.
  - Chemical reactions are highly efficient in terms of energy consumption and these reactions will power the nanonetworks nodes and processes. Chemical reactions can also represent complex computation and decision processes, which in traditional communication could mean multiple operations.

NANONETWORKS VERSUS TRADITIONAL COMMUNICATION NETWORKS

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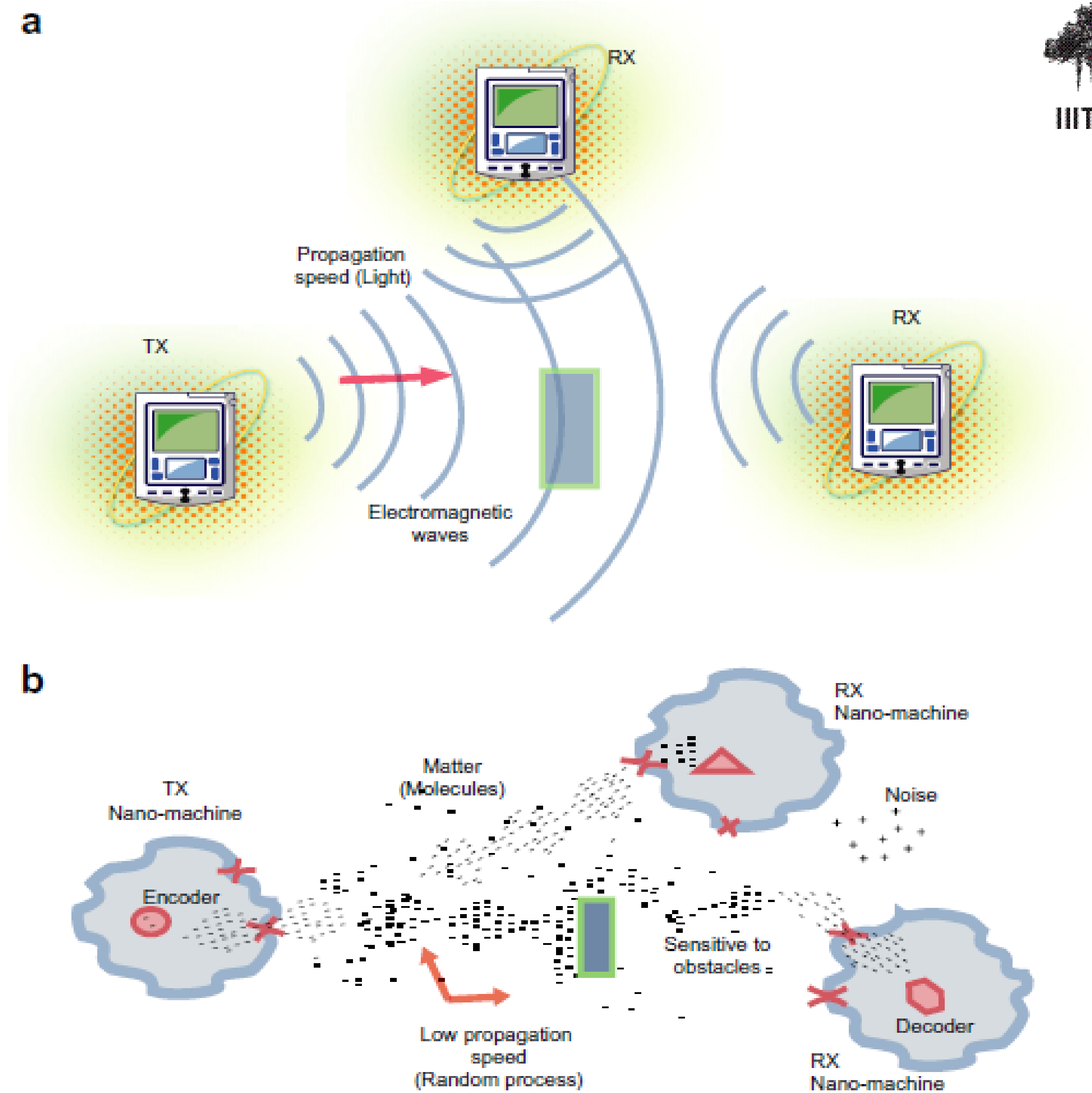
Communication	Traditional	Molecular
Communication carrier	Electromagnetic waves	Molecules
Signal type	Electronic and optical (Electromagnetic)	Chemical
Propagation speed	Light (3×10^8 m/s)	Extremely low
Medium conditions	Wired: Almost immune Wireless: Affect communication	Affect communication
Noise	Electromagnetic fields and signals	Particles and molecules in medium
Encoded information	Voice, text and video	Phenomena, chemical states or processes
Other features	High energy consumption	Low energy consumption



. Overview of (a) traditional communication systems and (b) nanonetworks: energy transmission vs. molecular transmission.

TERAHERTZ CHANNEL

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- Developed path loss and noise models for EM communications in the THz band (0.1-10 THz) by means of radiative transfer theory.
- Proposed different power allocation schemes and computed the channel capacity as a function of distance and channel composition.
- Losses:
  - TOTAL PATH-LOSS
    - Spreading Loss (A_{spread}): Attenuation due to the expansion of the wave as it propagates through the medium
    - Absorption Loss (A_{abs}): Attenuation due to molecular absorption
  - SPREADING LOSS: Depends on the frequency of the wave and the transmission distance.
  - ABSORPTION LOSS: Depends on the frequency of the wave, the total path length and the molecular composition of the channel .
  - MOLECULAR ABSORPTION NOISE: Depends on the frequency of the wave, the total path length and the molecular composition of the channel.

TOTAL PATH LOSS

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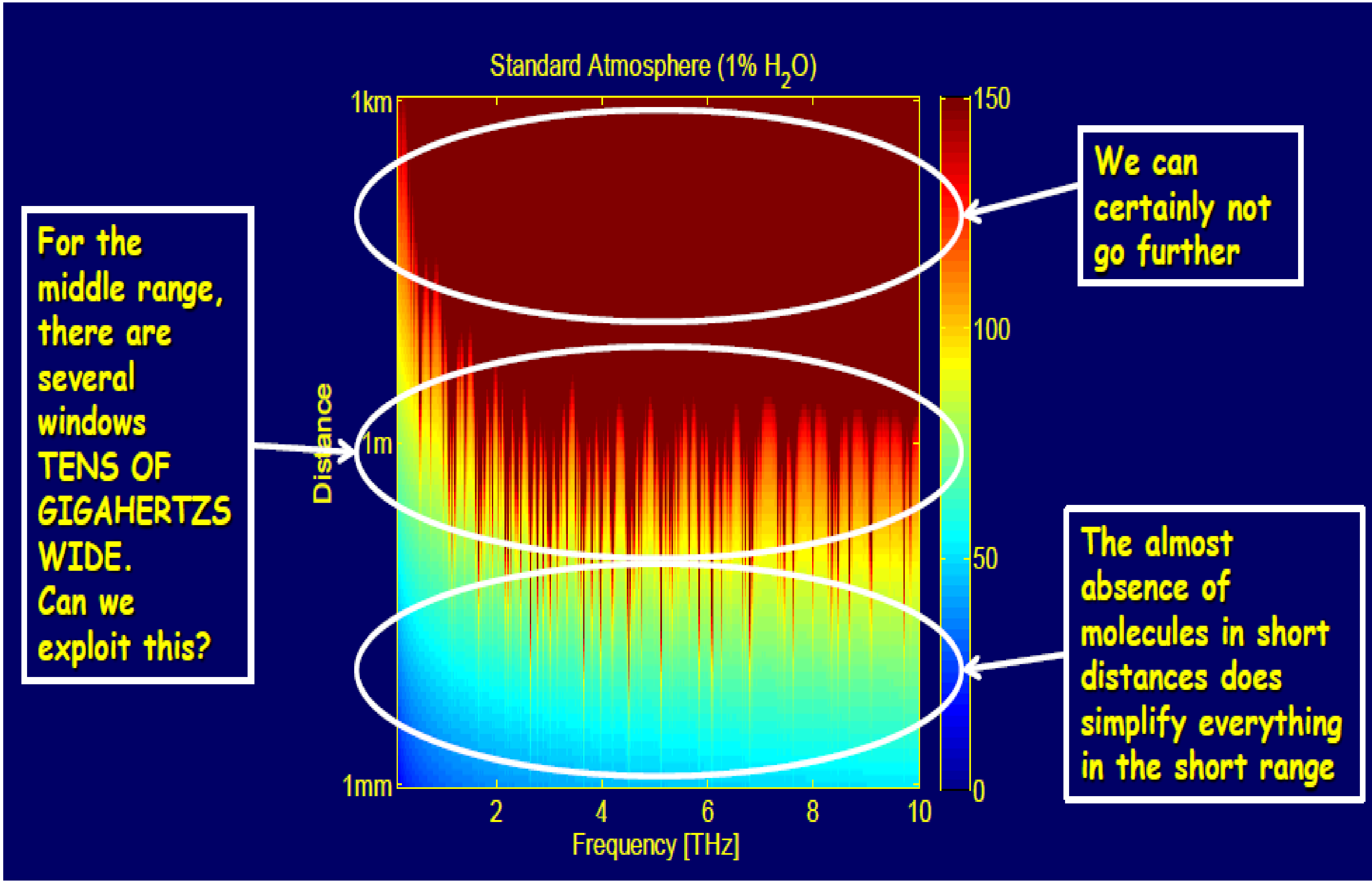

FACTORS AFFECTING TERAHERTZ CHANNEL

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- Terahertz channel has a strong dependence on
  - Transmission distance
  - Medium molecular composition

- Main factor affecting the performance
  - Presence of water vapor molecules

- Incredibly huge BWs for short ranges (< 1m):
  - 100 Tbps rates are feasible

NEW MODULATION TECHNIQUE & CAPACITY ANALYSIS

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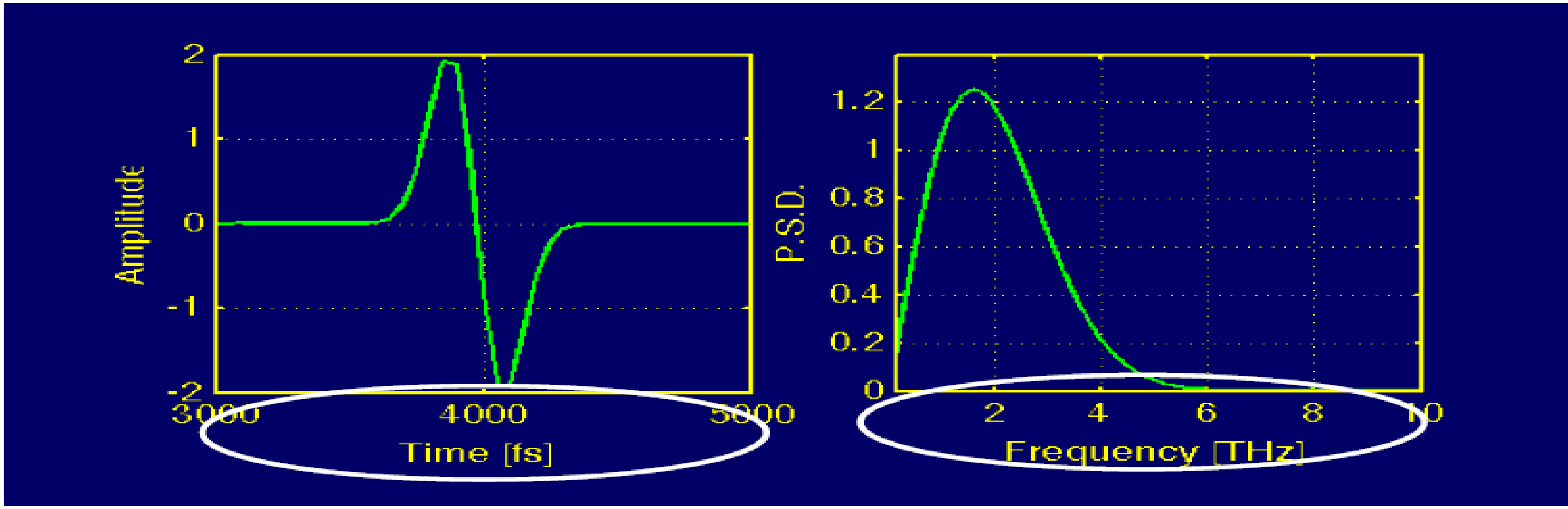
- A new modulation scheme based on the exchange of femtosecond long pulses spread in time:
  - TS-OOK (Time Spread On/Off Keying Mechanism)
- Performance analysis in terms of individual user achievable information rate and network capacity
  - New statistical model of interference in THz band is developed
- WHY FEMTOSECOND LONG GAUSSIAN PULSES?



TIME SPREAD ON-OFF KEYING

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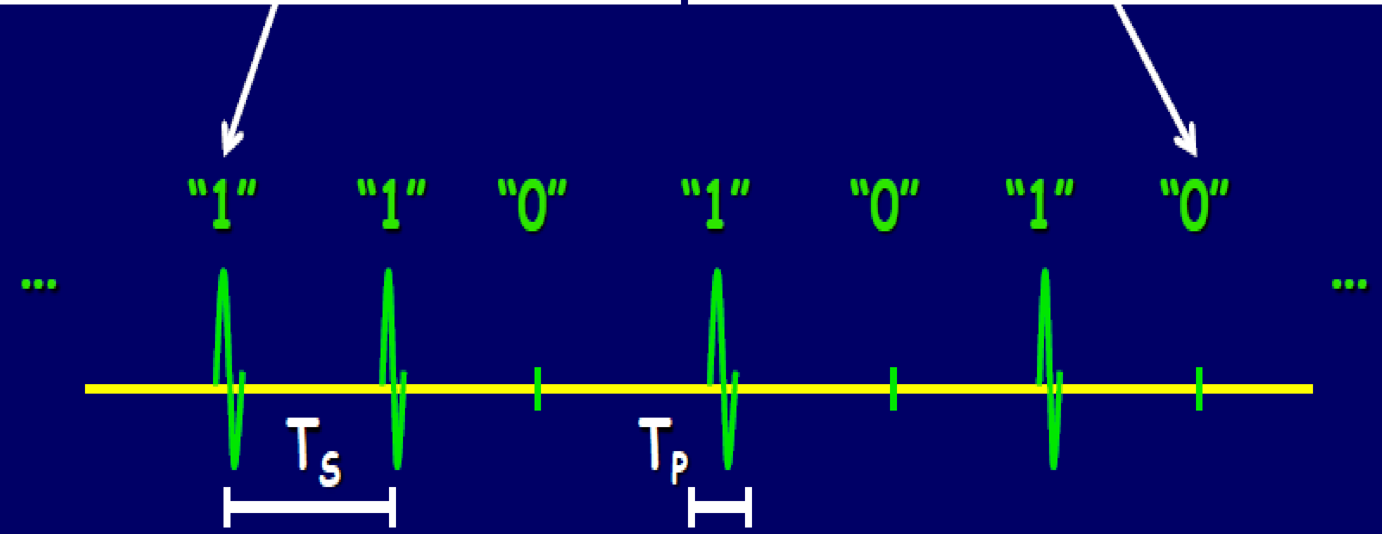
A logical "1" is encoded with a pulse:

- Pulse length: T_p = 100 fs
- Pulse energy: < 1 pJ !!!

A logical "0" is encoded with silence:

- Ideally no energy is consumed!!!
- After an initialization preamble, silence is interpreted as 0s



Pulses are spread in time to simplify the transceiver architecture...

CAPACITY

- Capacity is maximized when "more 0s than 1s" are transmitted:
  - By being silent, absorption noise and interference are reduced
  - New coding schemes that exploit this result should be developed!

NEW CODING SCHEMES FOR EM NANO-NETWORKS IN THZ BAND

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- Classical error correction codes in nano-networks:
  - Too complex for the limited capabilities of nano-devices
  - Coding takes too much time (more than the actual transmission)
- OUR IDEA:
  - Simple low-weight codes to minimize the number of tx errors
  - Analyzed the impact of the coding weight on the individual user information rate

OPTIMAL CODING WEIGHT

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- There is an optimal coding weight that maximizes the individual user information rate.
- This depends on:
  - Molecular composition of the channel
  - Nano-node density
  - Transmission power of the nano-nodes
  - Time between symbols in TS-OOK

NANONETWORK APPLICATIONS

- Biomedical Applications
  - Immune System Support
  - Bio-Hybrid Implants
  - Drug Delivery Systems
  - Health Monitoring
  - Genetic Engineering
- Industrial and Consumer Good Application
  - Food and Water Quality Control
  - Functionalized Materials and Fabrics
- Military Applications
  - Nuclear, biological and chemical (NBC) defenses.
  - Nano-functionalized equipments.
- Environmental applications
  - Biodegradation
  - Animals and biodiversity control
  - Air pollution control

APPLICATION: ADVANCED HEALTH MONITORING

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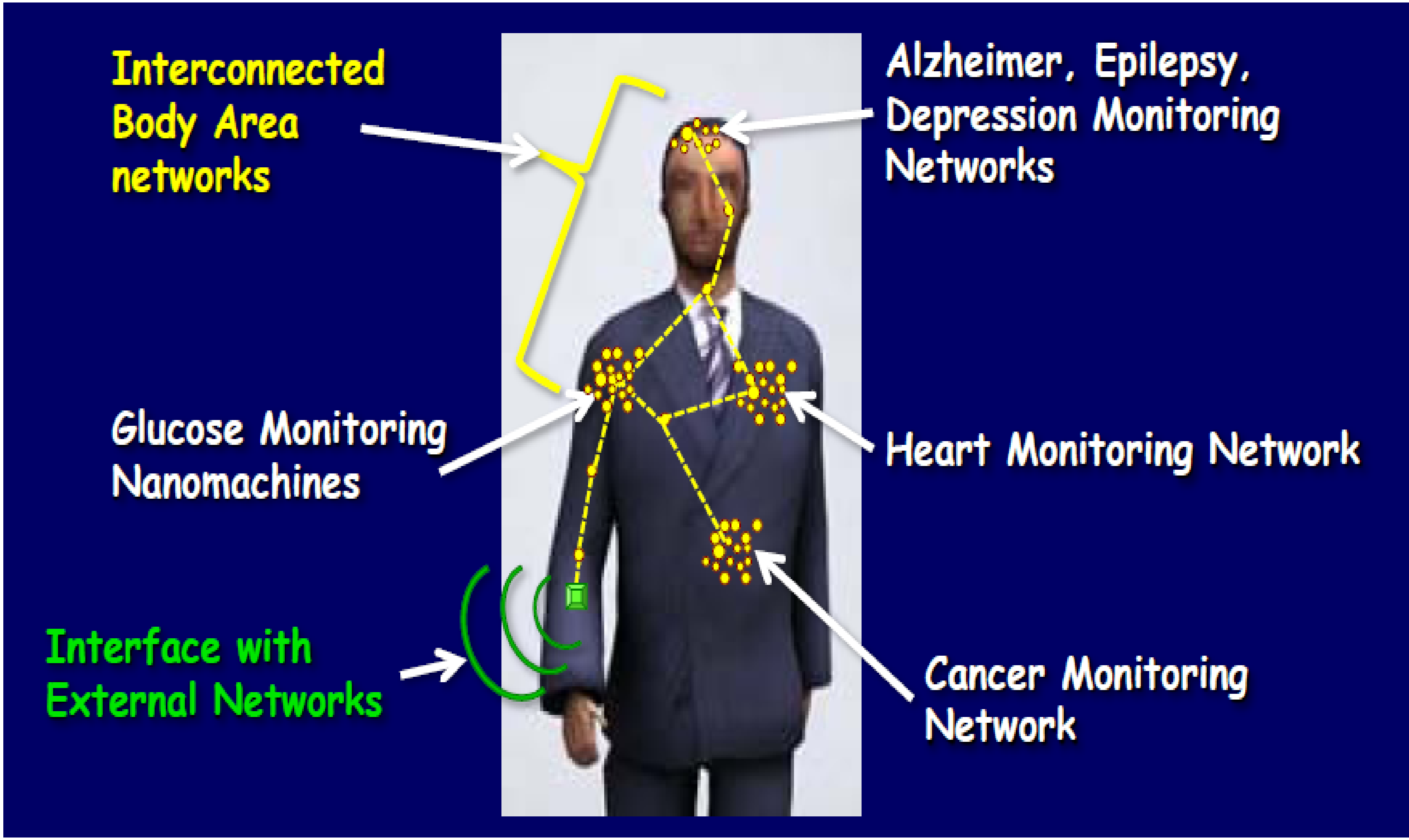
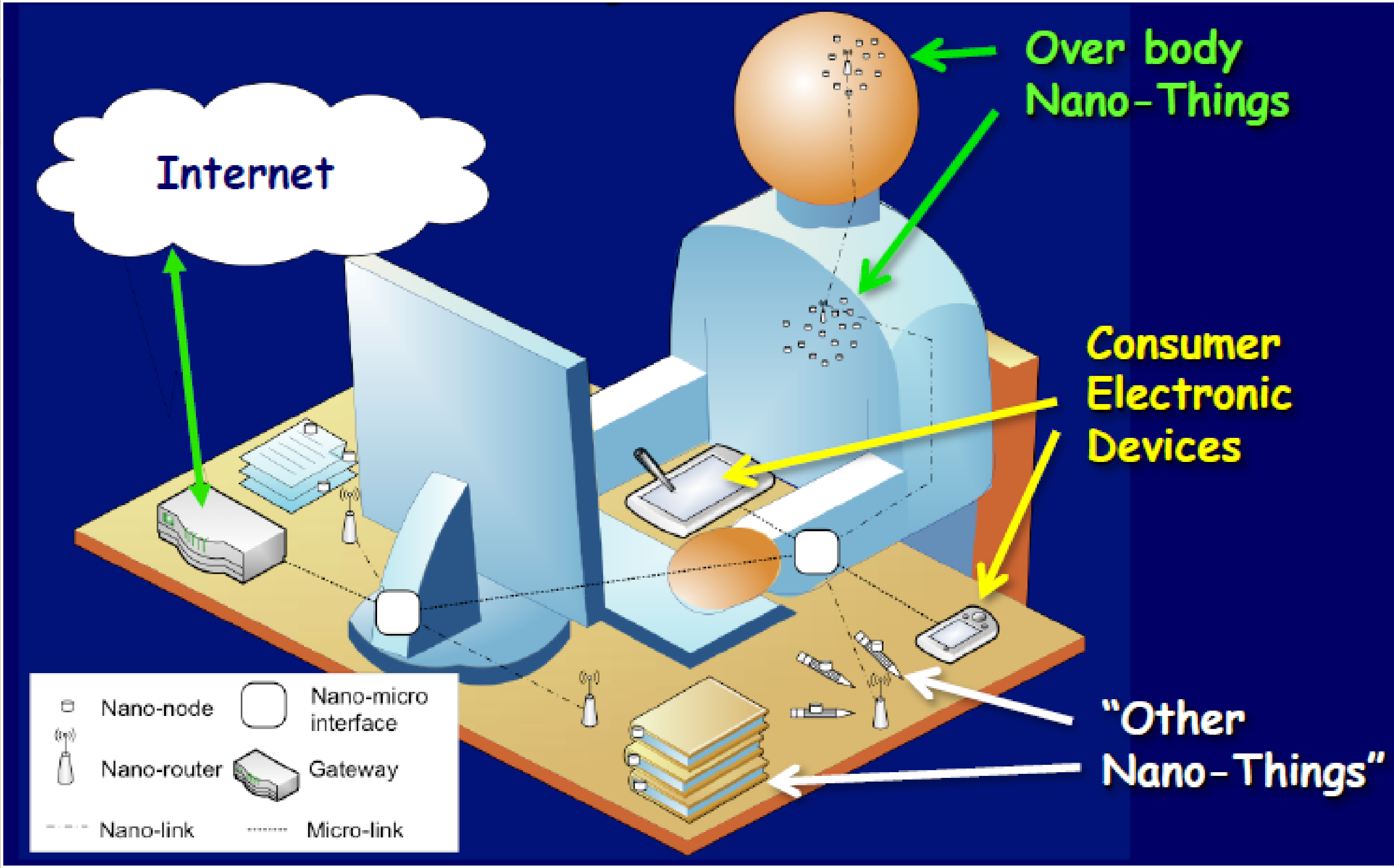


APPLICATION: INTERNET OF NANO-THINGS



APPLICATION: WIRELESS HIGH-VOLUME STORAGE TRANSFERS

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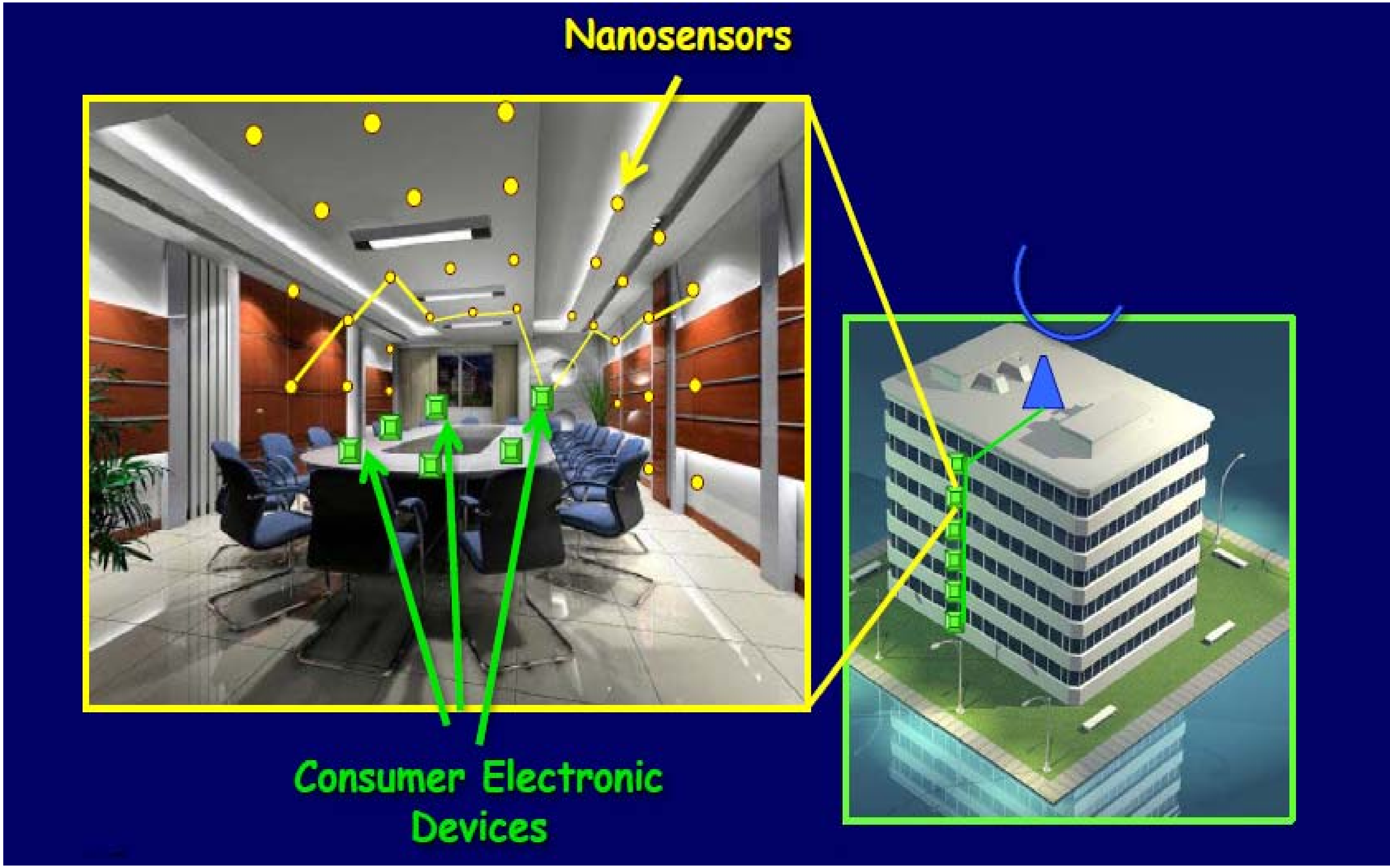
- Instantaneous transfer of high-volume storage data between consumer devices
- Multimedia kiosks

APPLICATION: CHEMICAL ATTACK PREVENTION



CONCLUSIONS

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- The development of nanotechnologies will continue and will have a great impact in almost every field.
- The use and control of these technologies will be a major advantage in economics, homeland security, sustainable growth and healthcare.
- Intrinsic technological burdens will limit the use of more advanced and smart materials, sensors actuators and devices at nano-scale, if they are not able to communicate to cooperate to perform more complex tasks.
- This need for a communication network will be more plausible with the increased complexity of developed nano-devices.
- Molecular communication seems to provide efficient mechanisms for networking of nano-machines.
- It represents a complete new communication paradigm in which the information is encoded into molecules.
- Nanonetworks demand innovative solutions to create reliable molecular communication channels among nano-machines.
- First developments are bio-inspired by existing biological nanonetworks.
- At nano-level, many components and communication process has been studied from a biological or chemical point of view.
- Despite being a novel communication paradigm that requires an interdisciplinary approach, information and communication technologies (ICT) are called to be a key contributor for the evolution of the nanonetworks.
- Network architectures, channel models, nano-machines and transceivers architectures, medium access control and routing protocols are some of the contributions that are expected from the ICT field.

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GOT
QUESTIONS?
...WE HEAR YOU


Thank You!