http://www.n3cat.upc.edu

Graphene-enabled Wireless Communications for Networks on Chips

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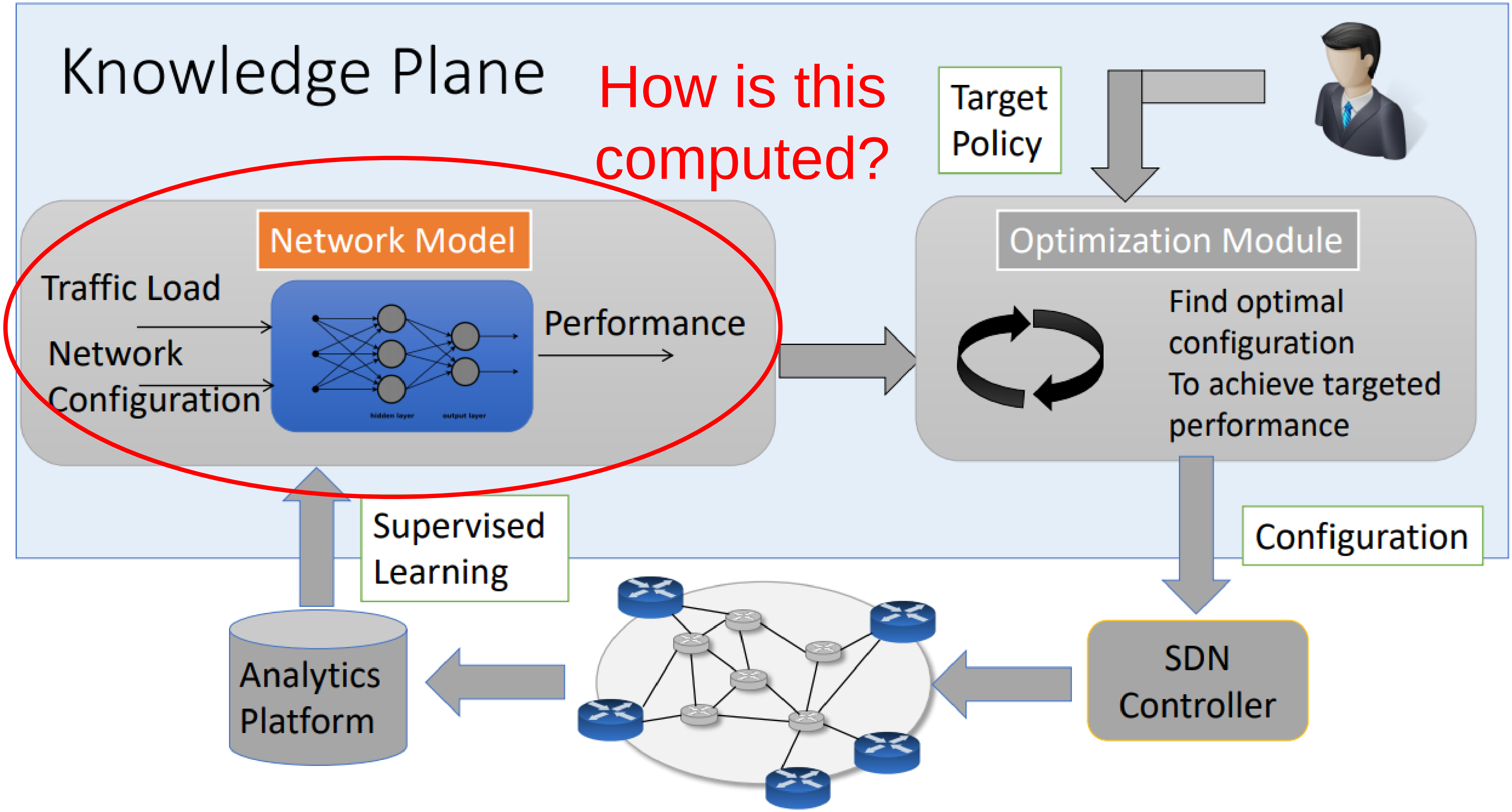
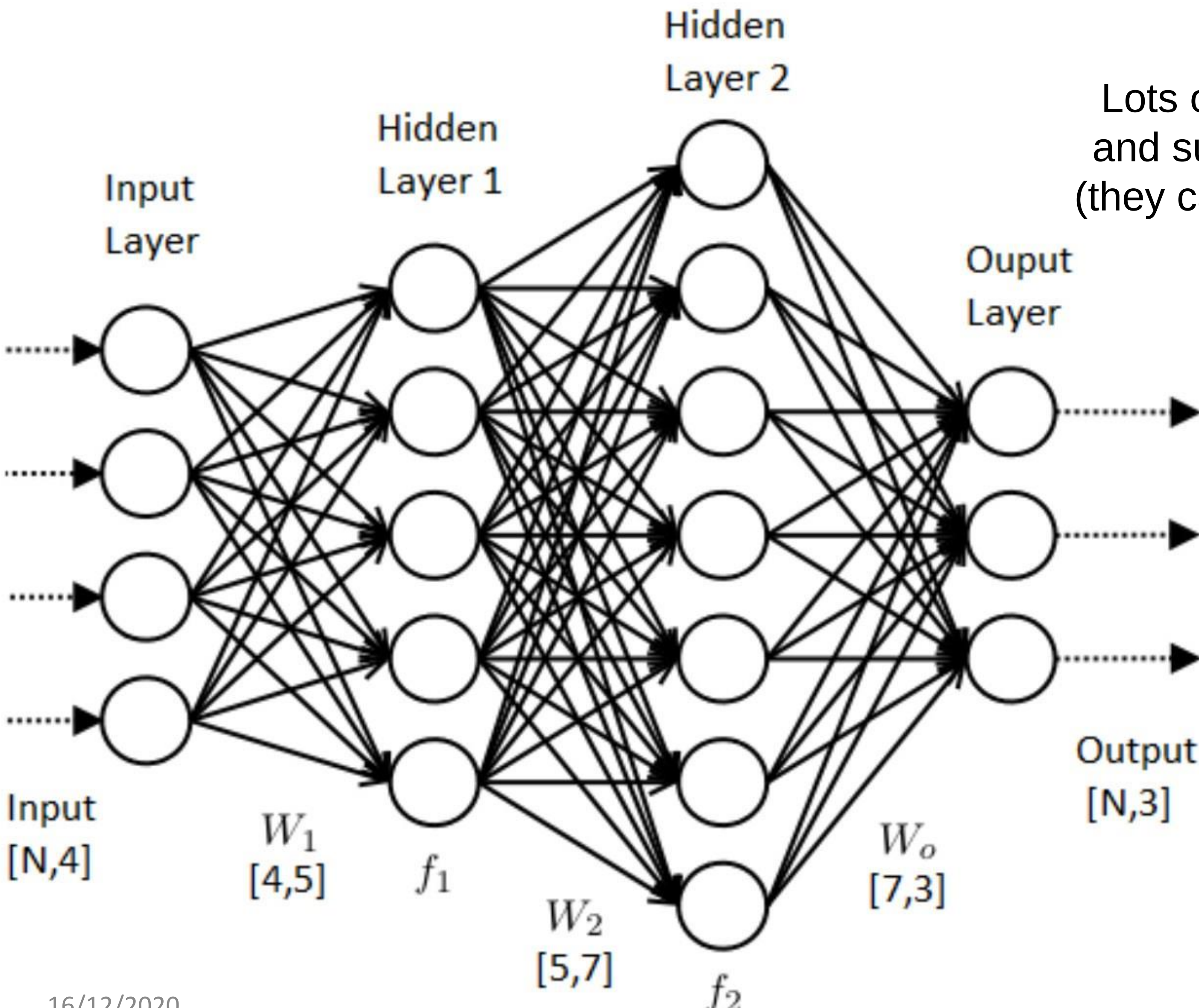
Prelude



Knowledge Plane
How is this computed?
Target Policy
Network Model
Traffic Load
Network Configuration
hidden layer
output layer
Performance
Optimization Module
Find optimal configuration
To achieve targeted performance
Supervised Learning
Configuration
Analytics Platform
SDN Controller

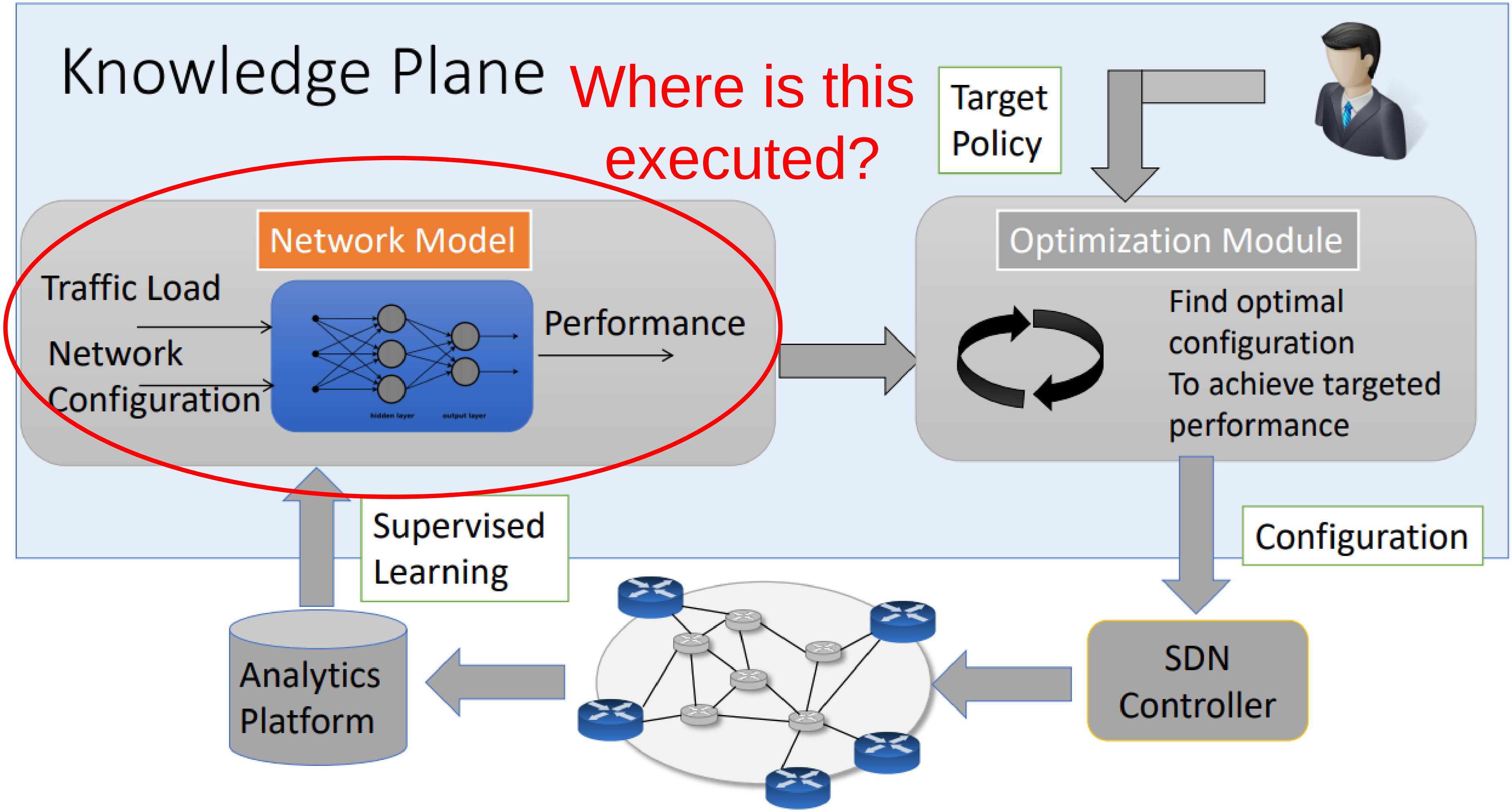
Computing a neural network

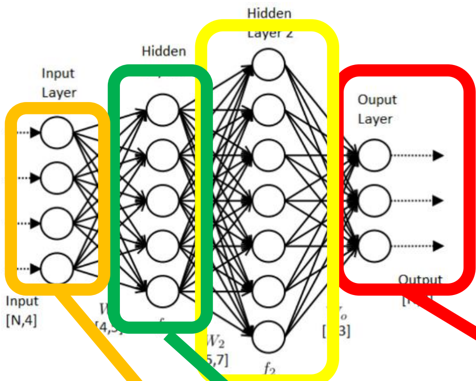


Lots of multiplications and sums in each layer (they can be parallelized)

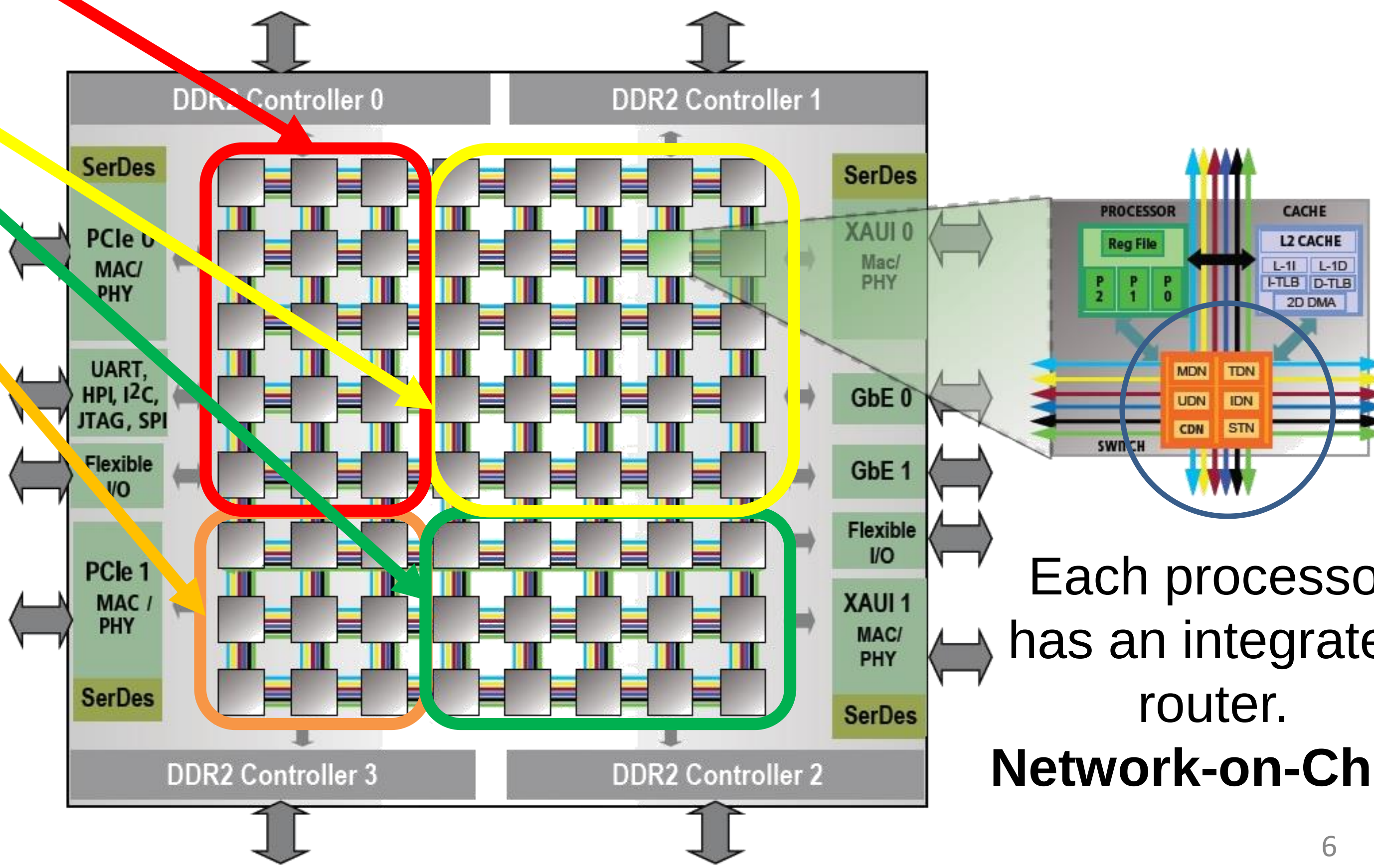
$$\sigma(f_2 W_o)$$

...from the last session



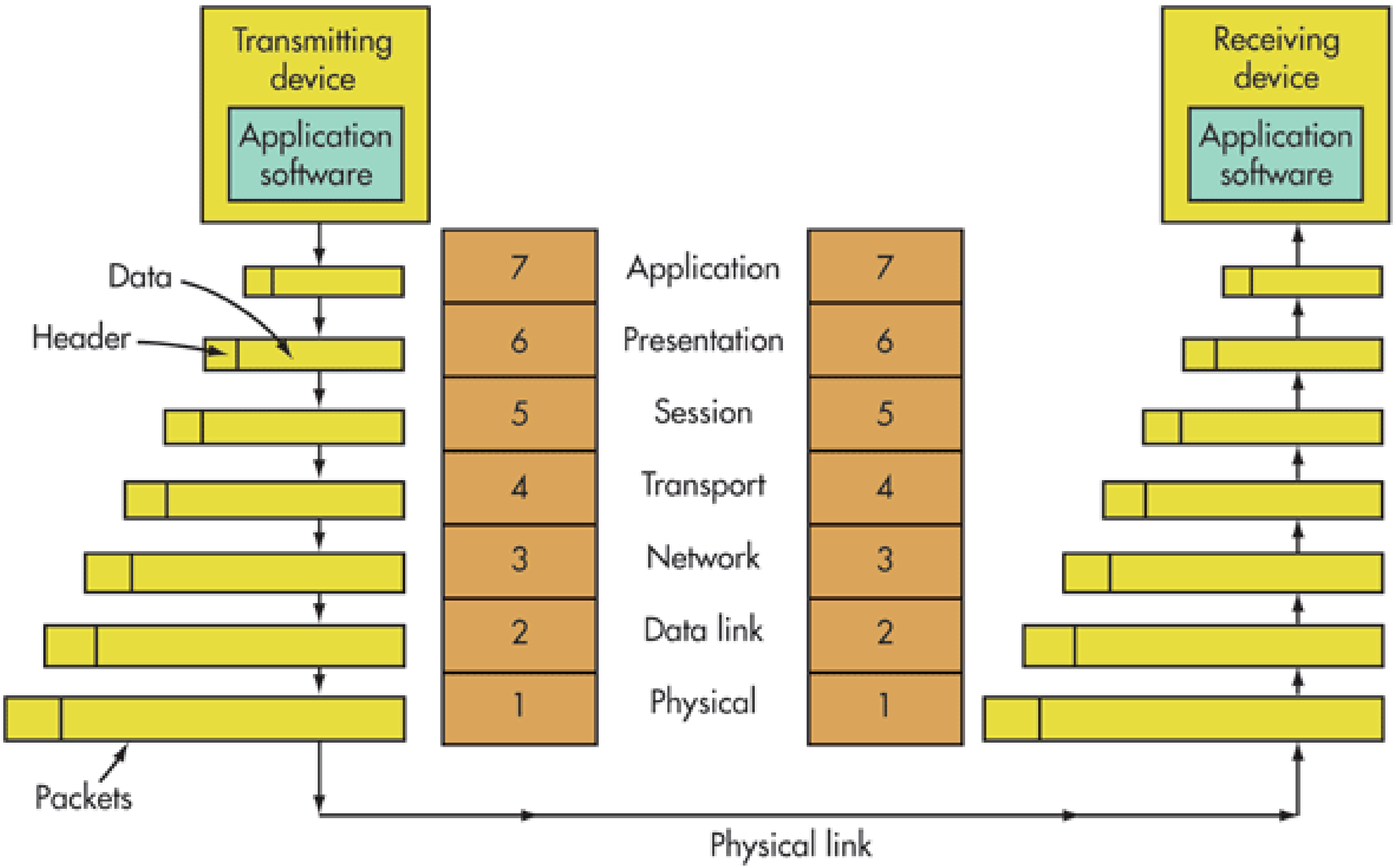


Communication among processors is a key determinant of performance



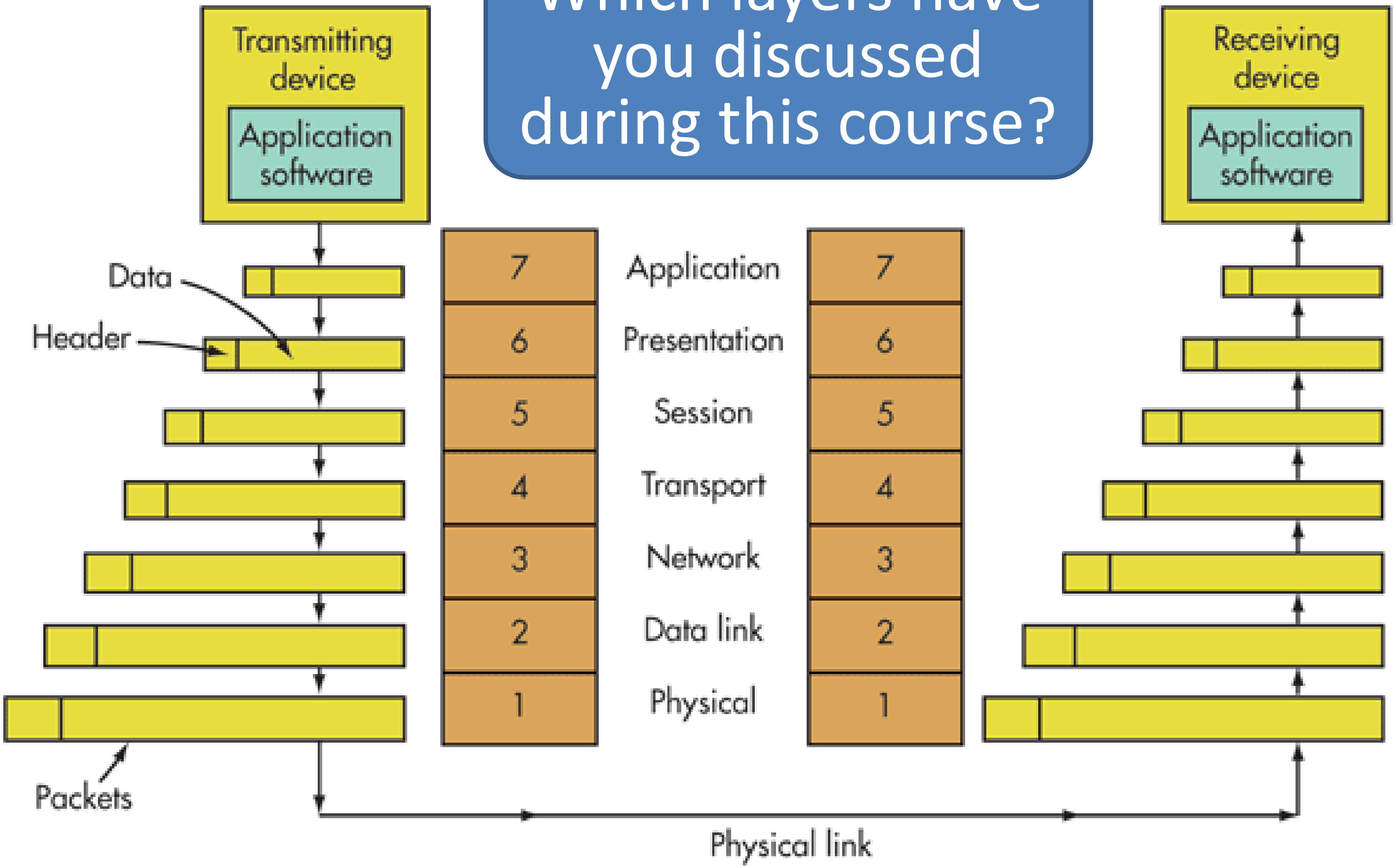
Each processor has an integrated router.
Network-on-Chip!

The protocol stack

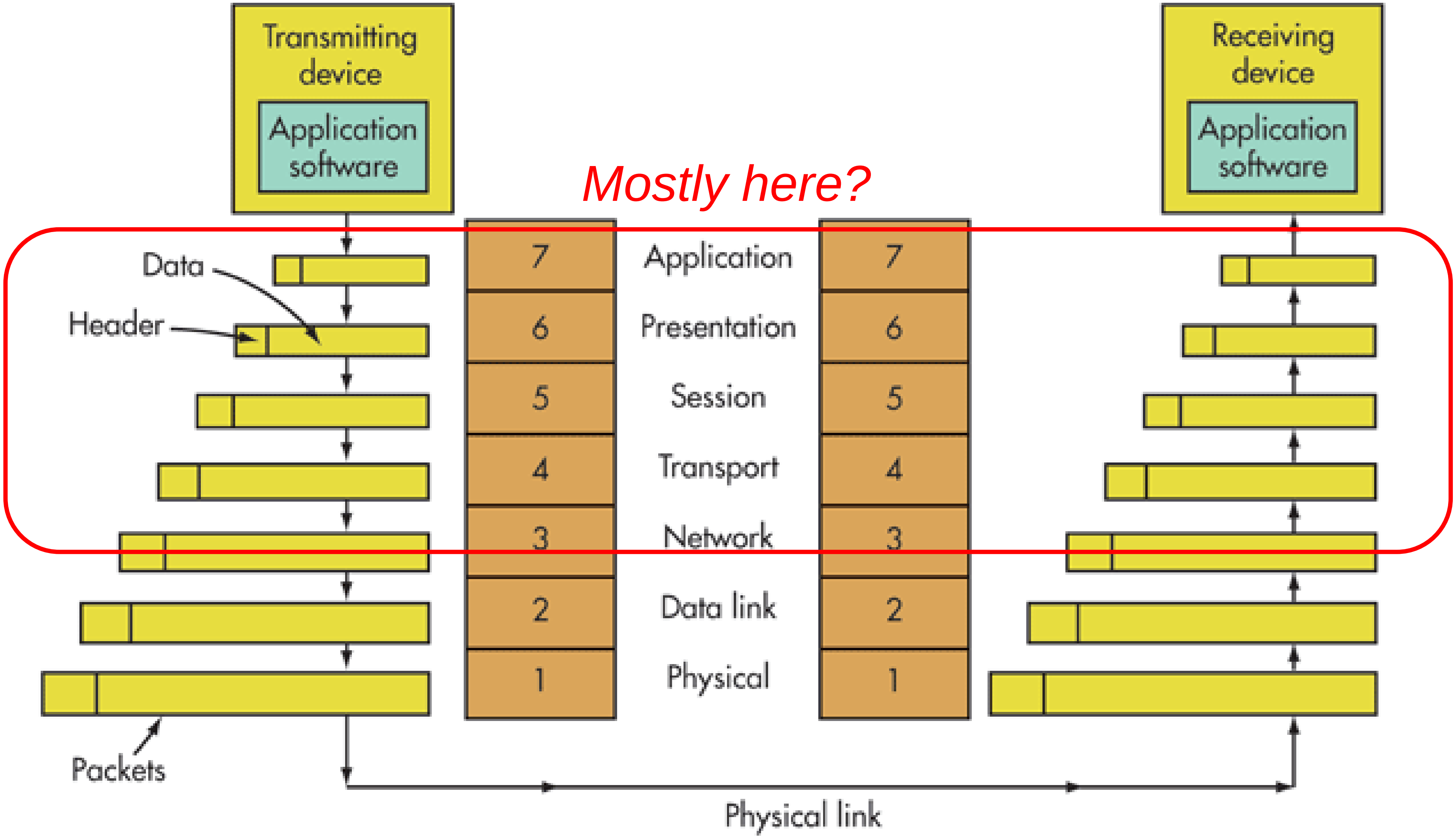


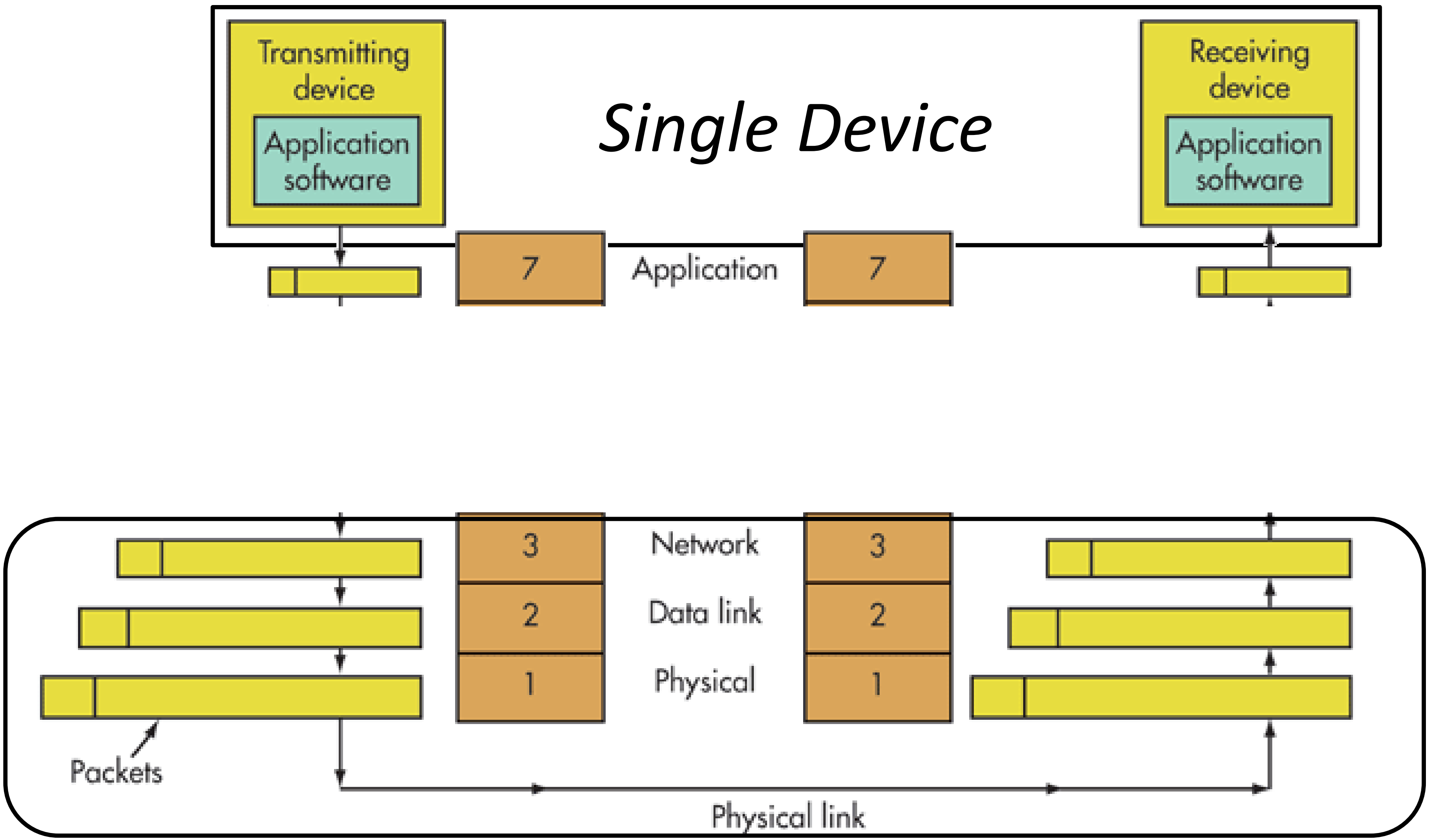
The protocol stack

Which layers have you discussed during this course?



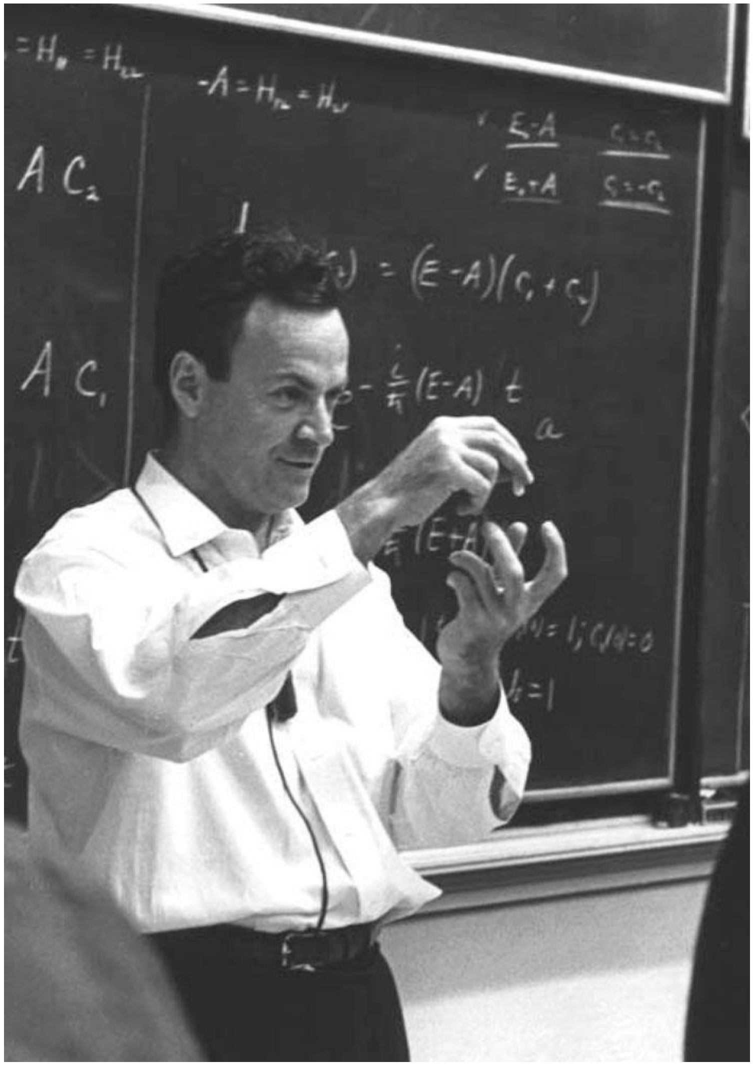
The protocol stack



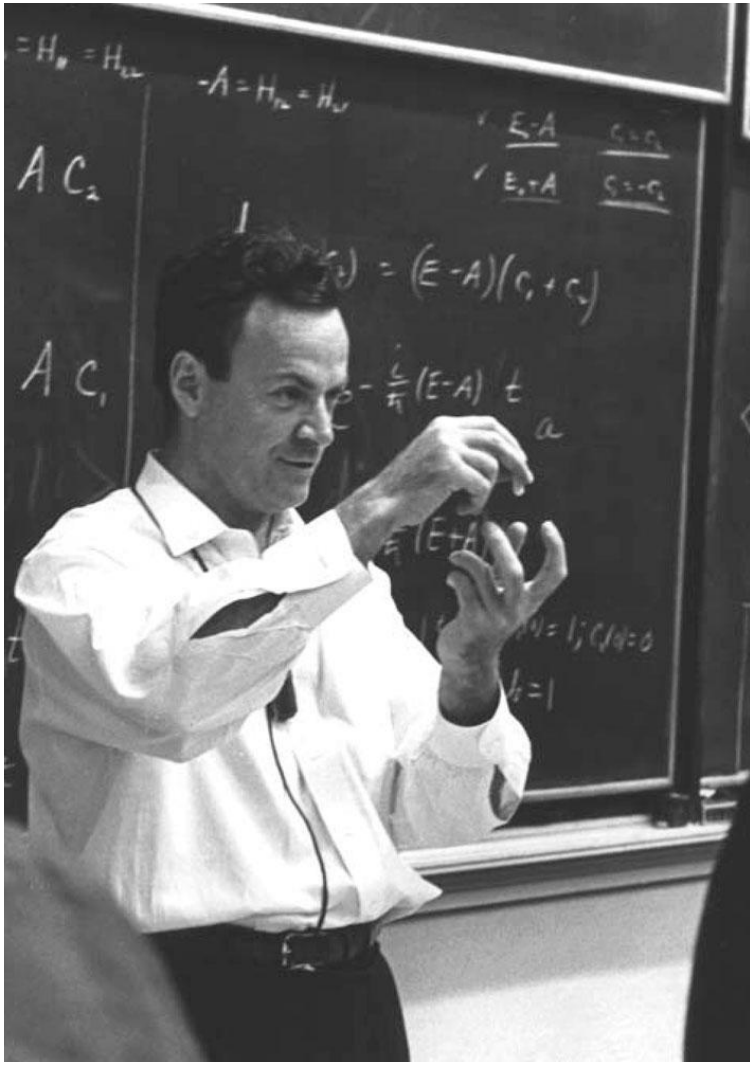

Transmitting device
Application software
Single Device
Receiving device
Application software
7
Application
7
3
Network
3
2
Data link
2
1
Physical
1
Packets
Physical link

Today

Towards nanonetworking



"There's plenty of room at the bottom"



<u>Nanotechnology:</u>

Manipulation of matter at an atomic, molecular, and supramolecular scale

(atom: 0.15 nm)
(DNA: ø2 nm)
(bacteria: 200 nm)

N3Cat

Nanonetworking Center in Catalunya

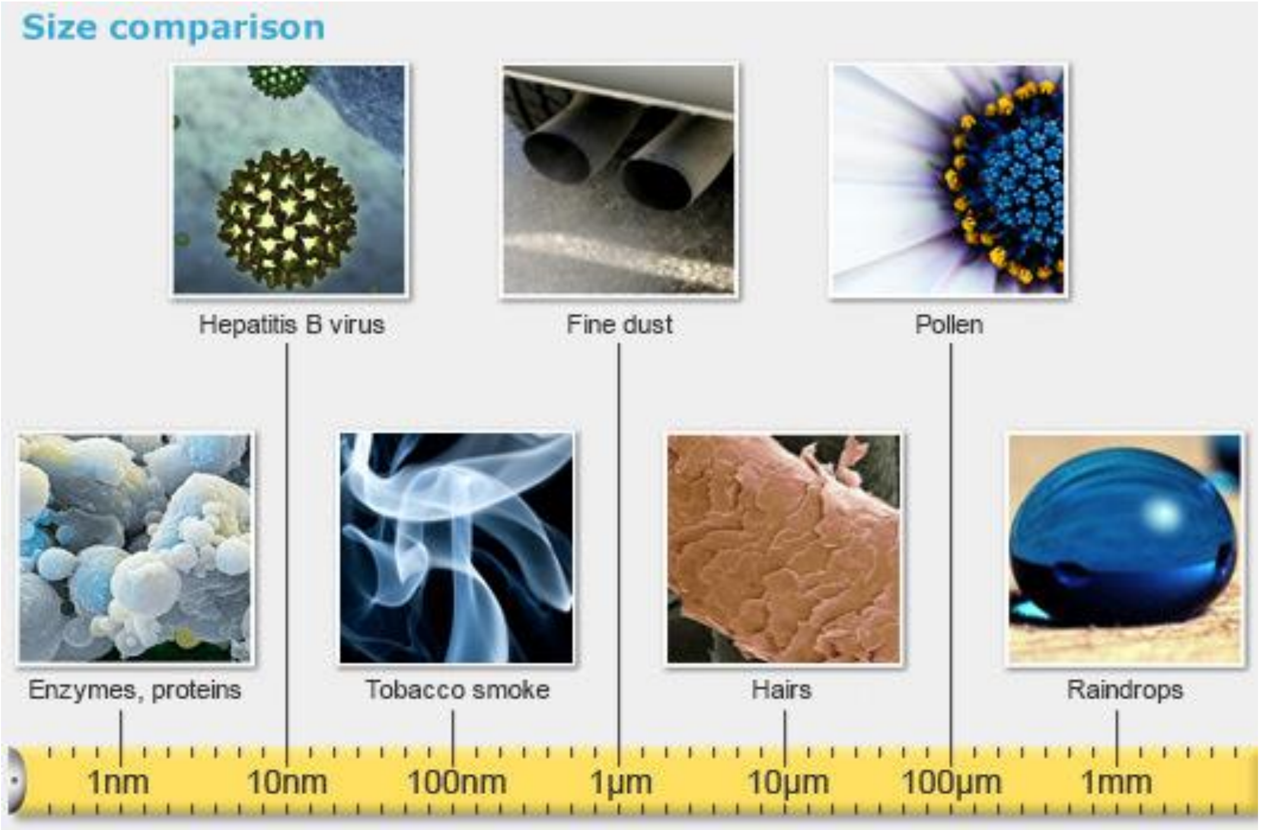
Research Center within UPC devoted to investigating how nanotechnology can be leveraged to improve current communications and networks

N3Cat

Nanonetworking Center
in Catalunya

NANO: working at very small sizes and making use of nanotechnology

- Nanodevices, nanocommunications, nanonetworks: composed by elements whose dimensions are on the nanometer scale
  - 1 meter = 10^9 = 1.000.000.000 nanometers



N3Cat

Nanonetworking Center
in Catalunya

MULTIDISCIPLINARY: we need experts in materials, telecom, computer science, biotechnology...

- Core members in <u>different departments</u> at UPC
  - Josep Solé i Pareta (AC)
  - Albert Cabellos (AC)
  - Eduard Alarcón (EE)
  - Sergi Abadal (AC)
- Members in <u>other institutions</u>
  - Northeastern University (USA)
  - Telefónica Research (Spain)
  - University of Antwerpen (Belgium)




N3Cat

Nanonetworking Center in Catalunya

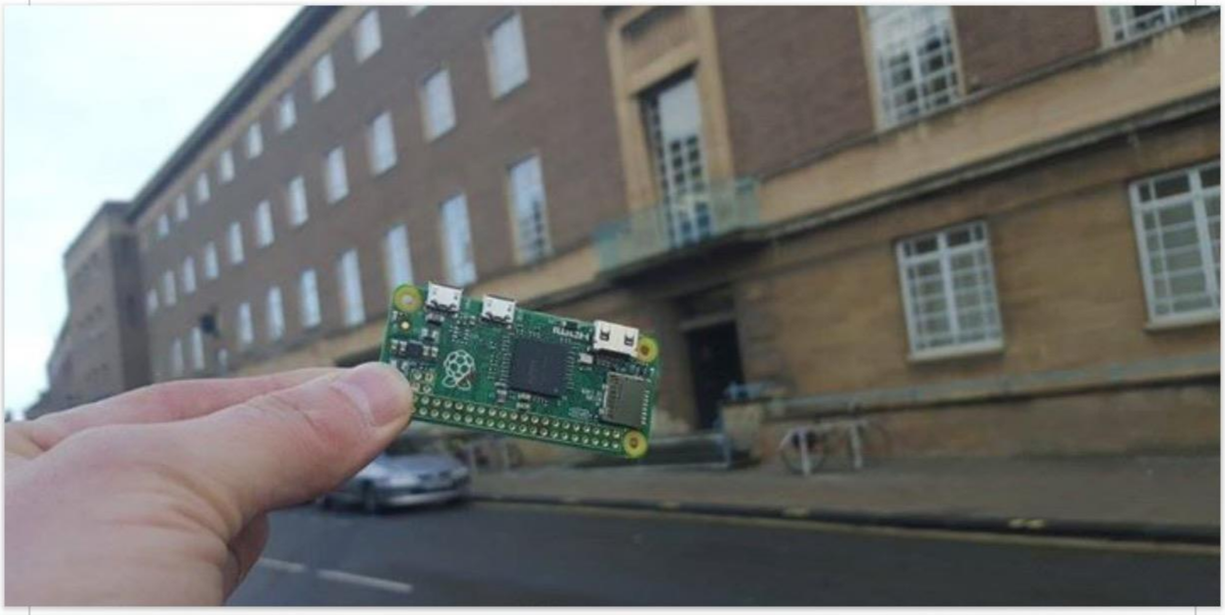
DISRUPTIVE: we do not seek incremental advances, our prospects are (at least) 10 years from now

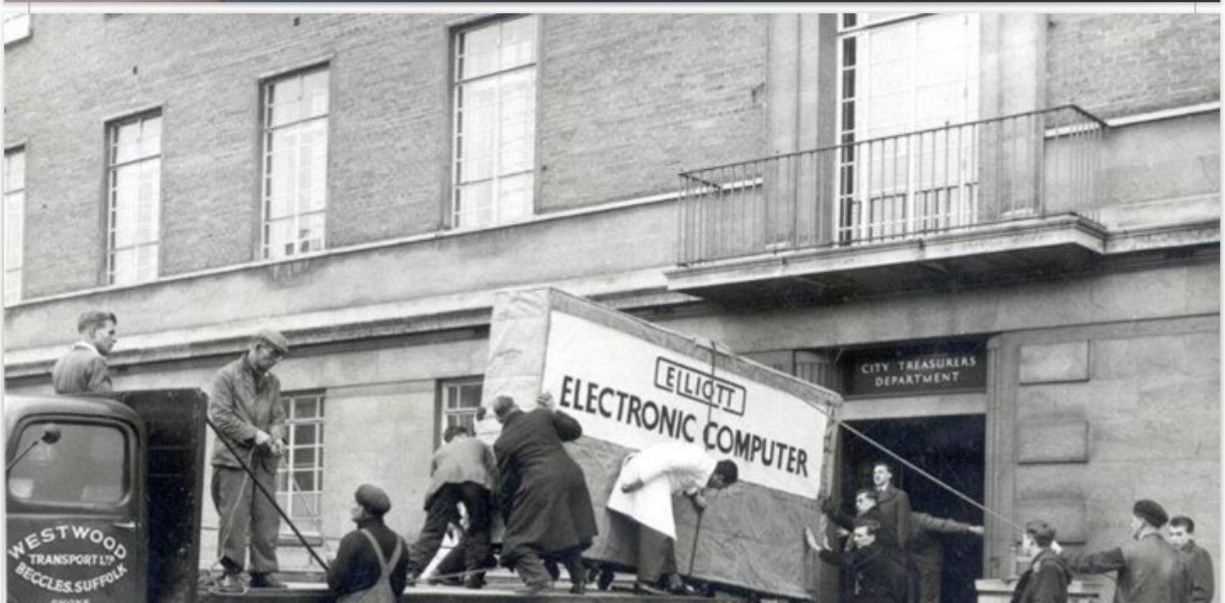
The research of N3Cat summarized in one question

- Which is the downscaling limit of communication devices and systems? Ten years ahead and beyond

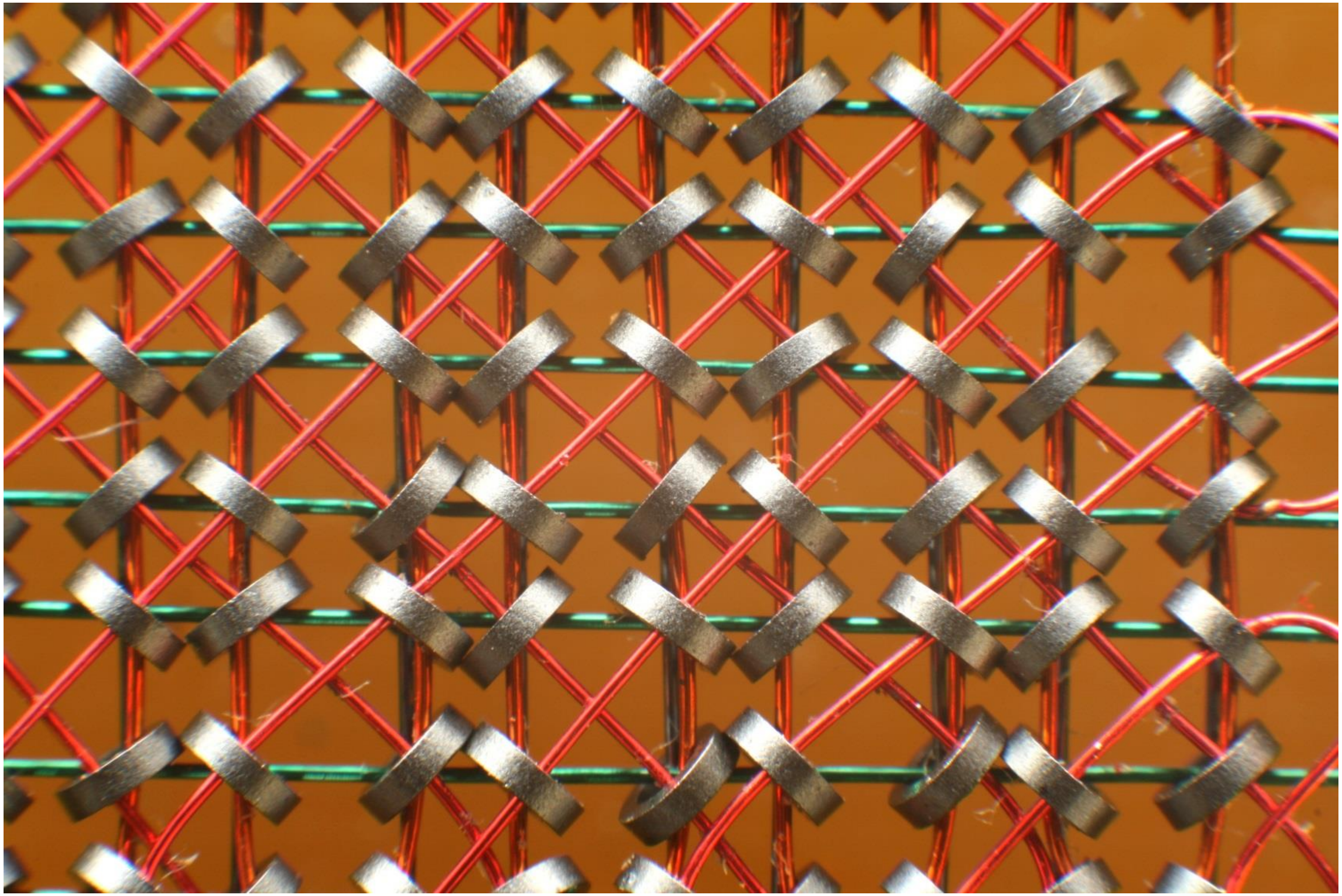
Same place, 60 years later

N3Cat





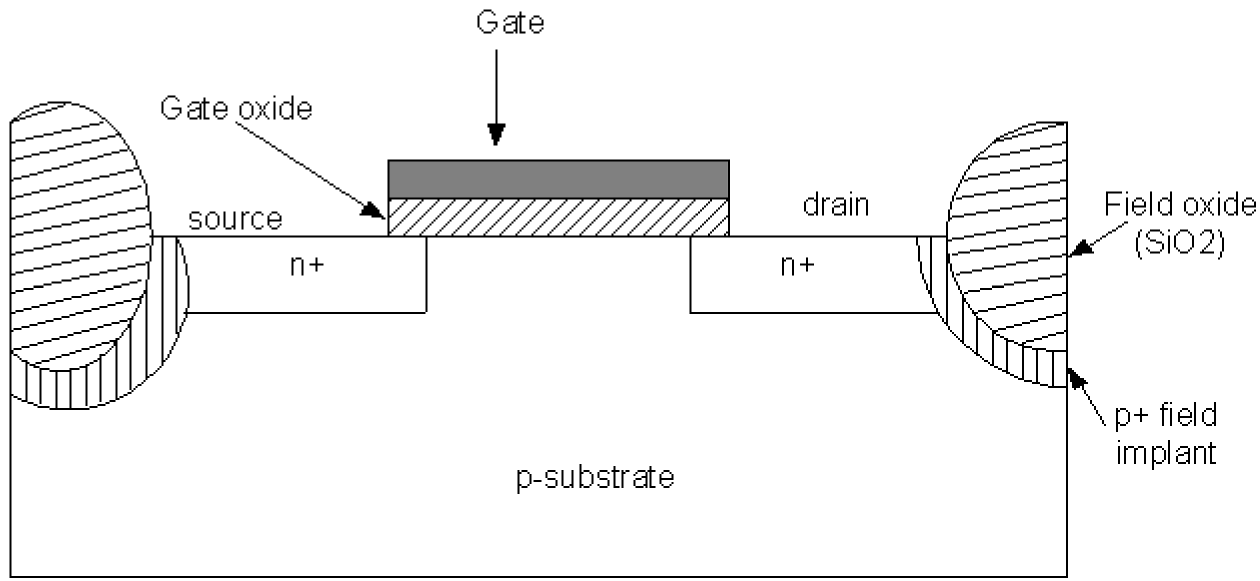
The beginning: Magnetic-core memories vs. pen drives



The typical amazing numbers

- A ferrite memory of 0.25 m^2 could hold 0.5 KB
  - PDP 11 had 128 ferrite boards for an amazing 64 KB
- Newest USB drives have surpassed the TB barrier
  - That means 12-15 orders of magnitude greater density
- **Where's the catch?**
  - The use of the right material: silicon
  - It allowed the creation of basic devices such as the transistor, the foundation of almost any elecronic device today
  - Technology advances have later allowed us to make smaller, fester, more efficiency transistors ➔ Moore's Law
- **Is this going to be forever?**

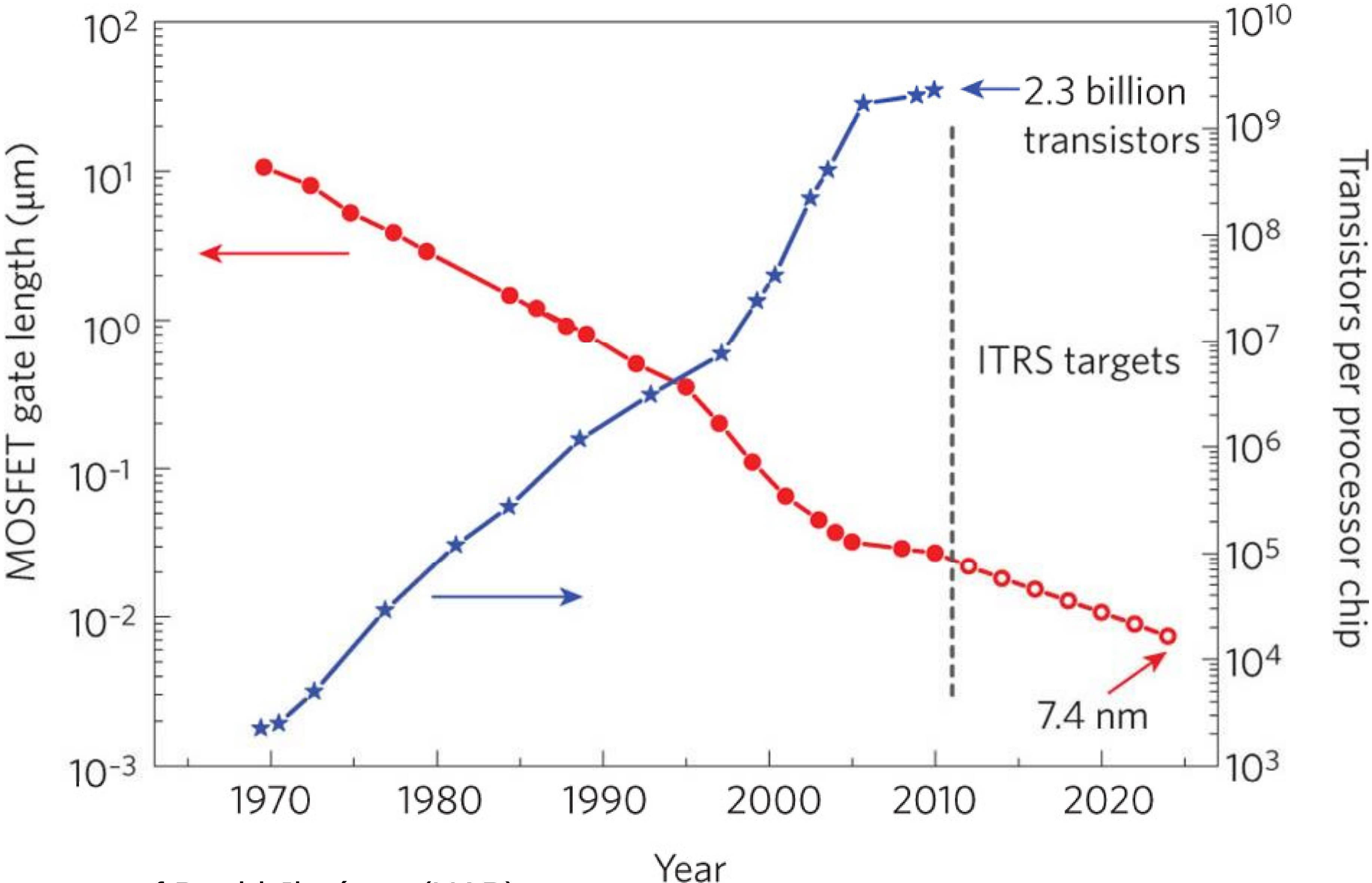
A transistor



Consequences of Dennard scaling

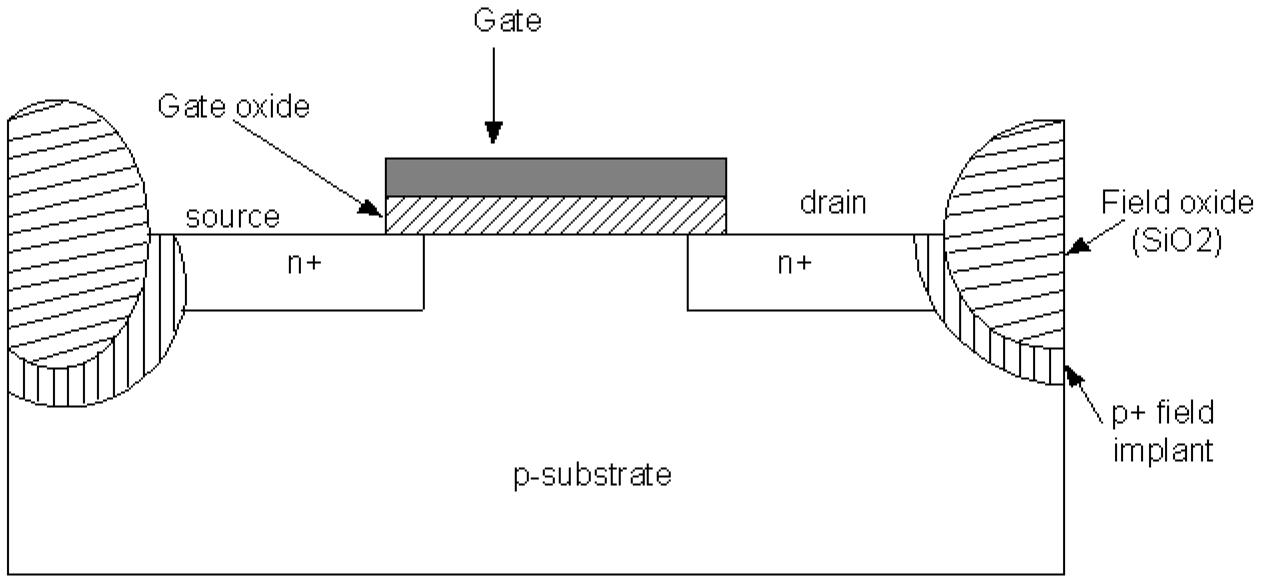
- Smaller means, of course, higher density
- Smaller means more efficient
- Smaller means faster

Evolution of silicon transistors



Courtesy of David Jiménez (UAB)

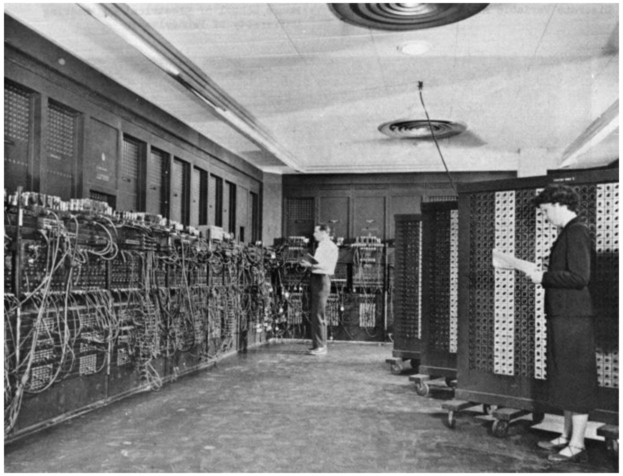
A transistor

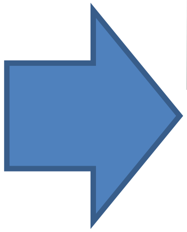


- Problem #1: it becomes increasingly difficult to avoid quantum tunneling
- Problem #2: the technology has a limit – transistors with a few atoms?

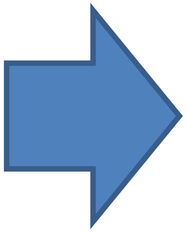
- So, is this going to be forever?
- No, we arrived pretty far with silicon, but the Moore's era will end soon
- We need a solution:
  - More Moore: desperately looking for ways to further scale down transistors
  - More than Moore: application-driven components with other architectures (accelerators), other functionalities (sensing) and, in the end, ***other materials***

First technologies





Mastering Silicon

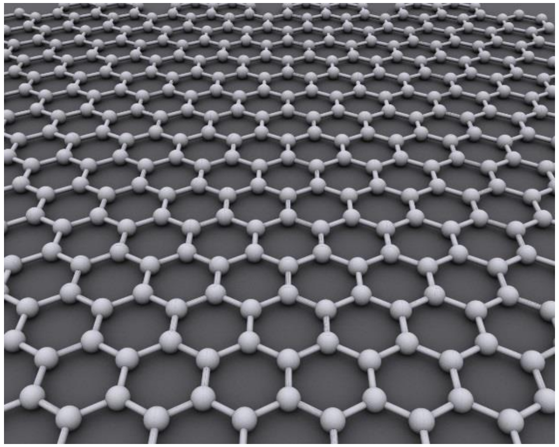


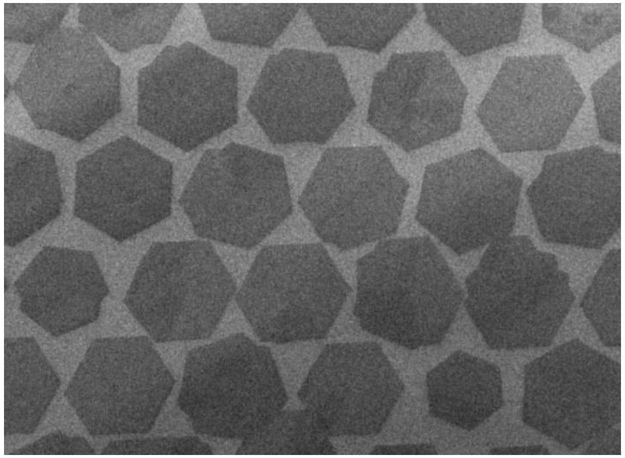
Graphene
Singular properties and applications

Graphene

Graphene

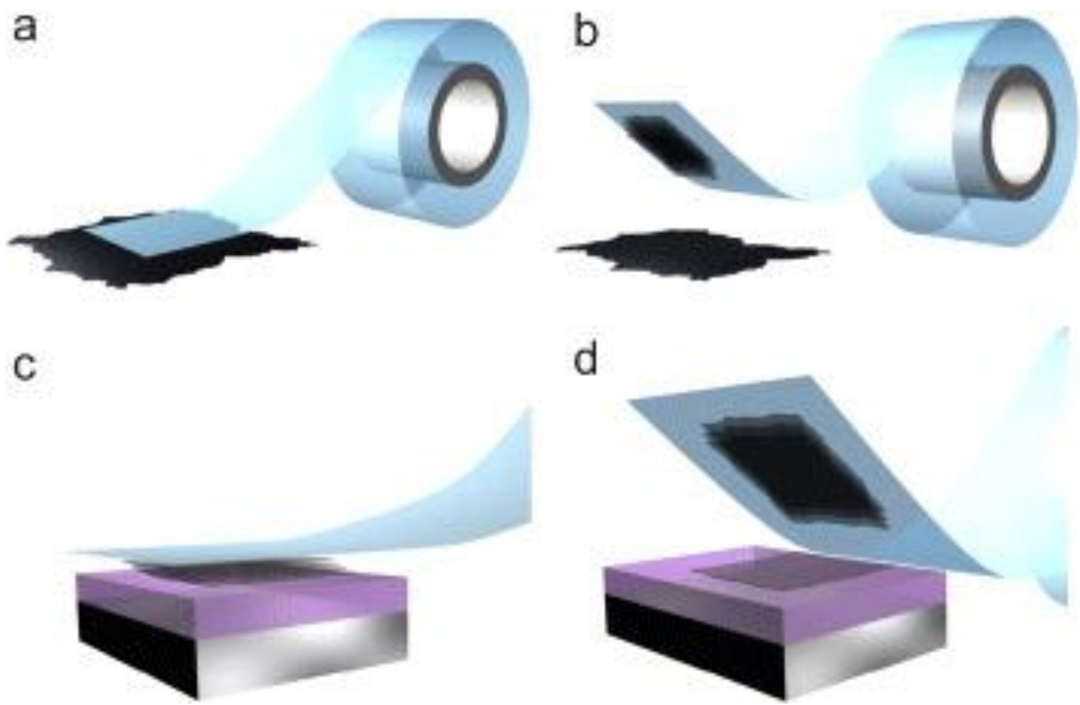
- One-atom-thick honeycomb lattice of carbon atoms (2D)
- First theorized by P. Wallace in 1947
- First isolated by A. K. Geim and K. S. Novoselov in 2004
- A. K. Geim and K. S. Novoselov are awarded with the nobel prize in physics in 2010





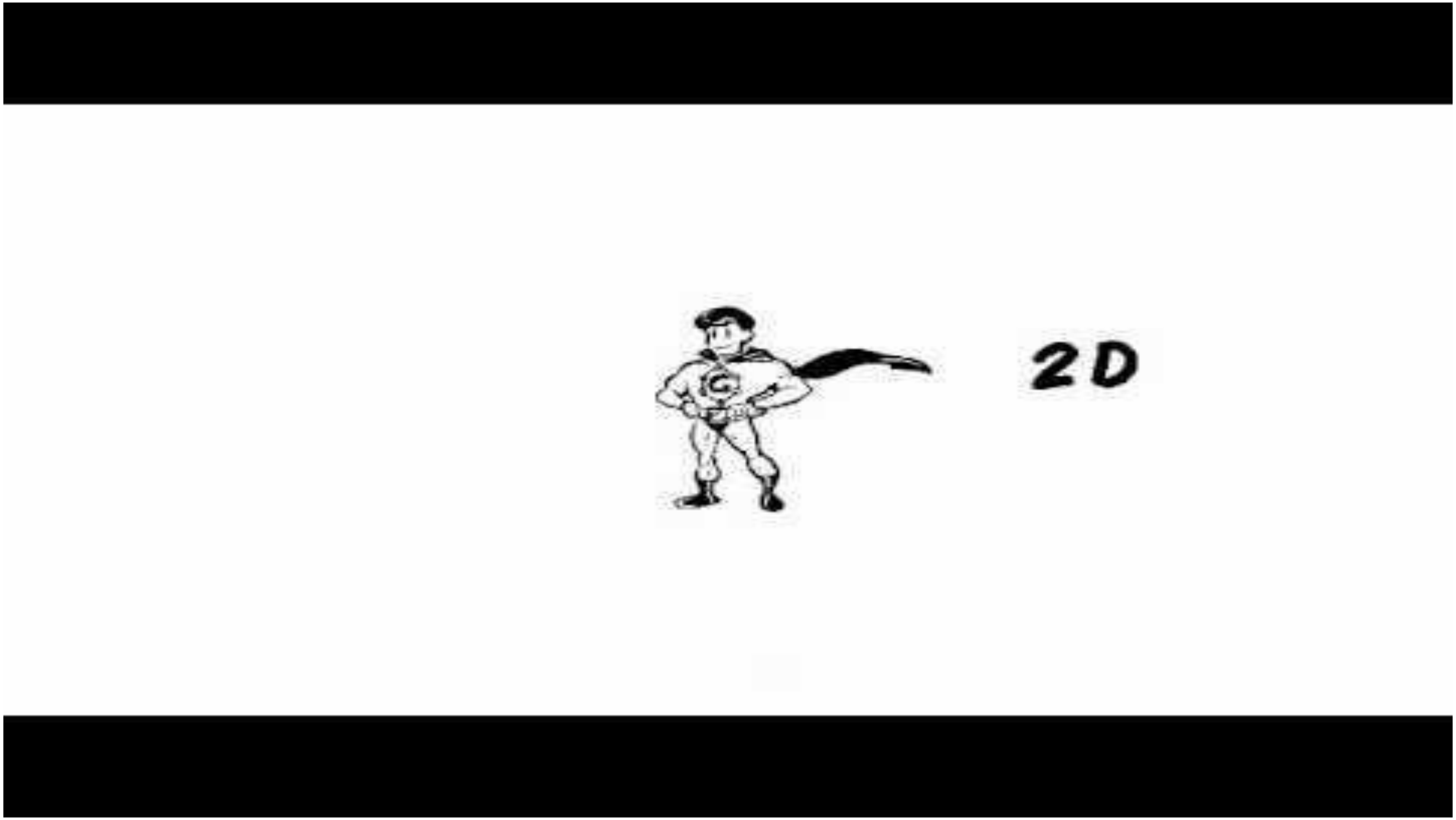
Graphene: How to isolate it

- Scotch tape method

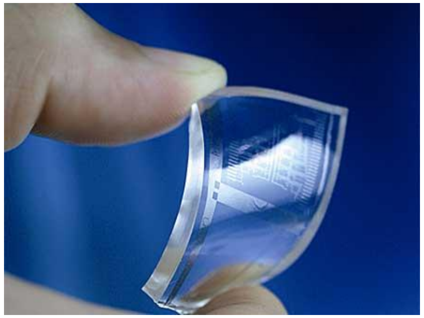


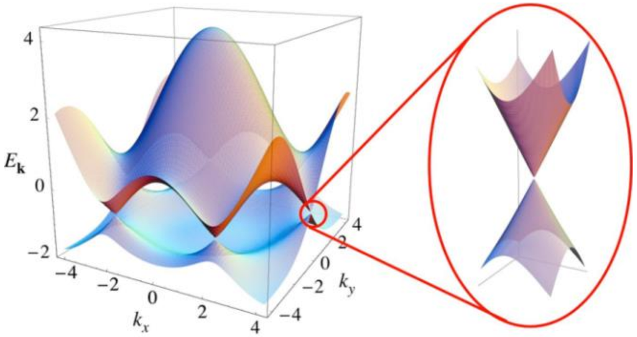
- Now the challenge is how to make this at massive scales and obtain graphene with good properties

The properties of graphene



- What are graphene’s extraordinary properties?
  - Thinnest and lightest material in nature
  - Tougher that diamons
  - More resistant than steel (300 times)
  - Impermeable
  - Transparent
  - Extremely flexible
  - Great thermal conductor
  - **Better electrical conductor than copper**





Applications of graphene

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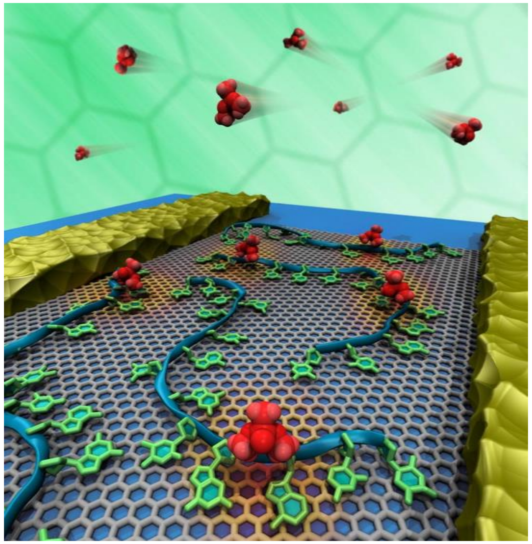
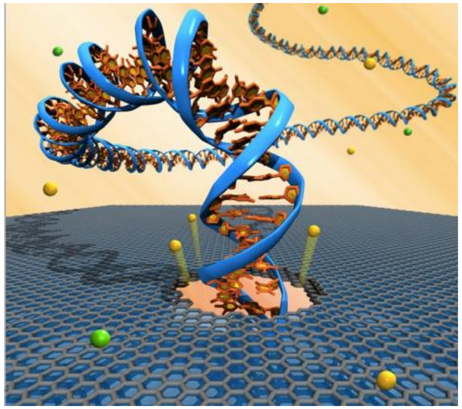
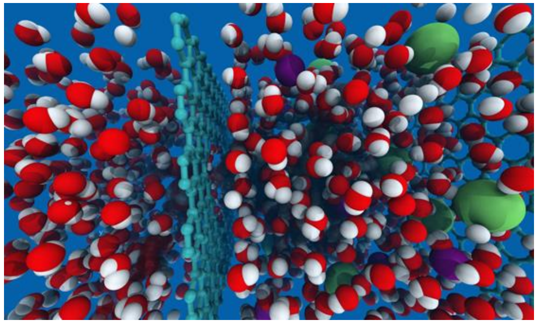
- These properties lead to a wide variety of potential applications
  - Materials
    - Next generation of touch screens: dirt-repellant
    - Light but strong structures for aeronautics
  - Chemistry
    - Ultra-precise gas sensors
    - Filters for polluted water (radioactive)
  - Bio-medicine
    - Bacterium detection
    - DNA sequencing

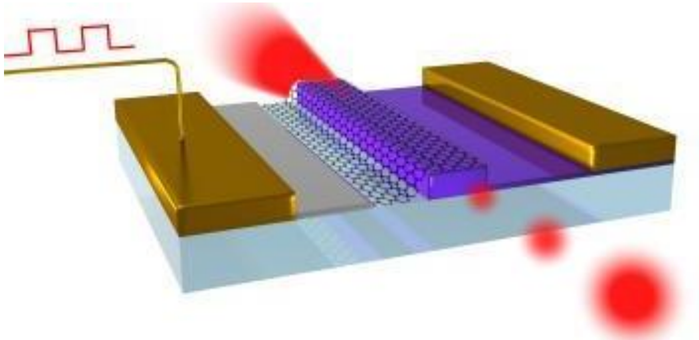


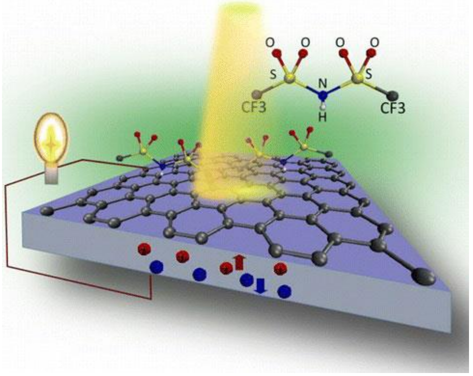


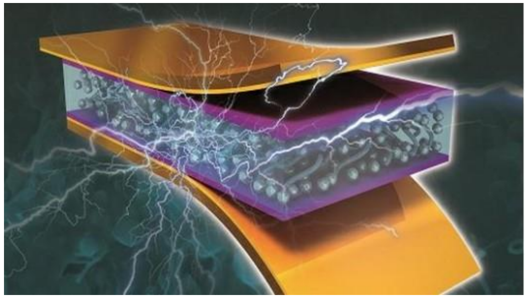


Graphene's applications relevant to N3Cat

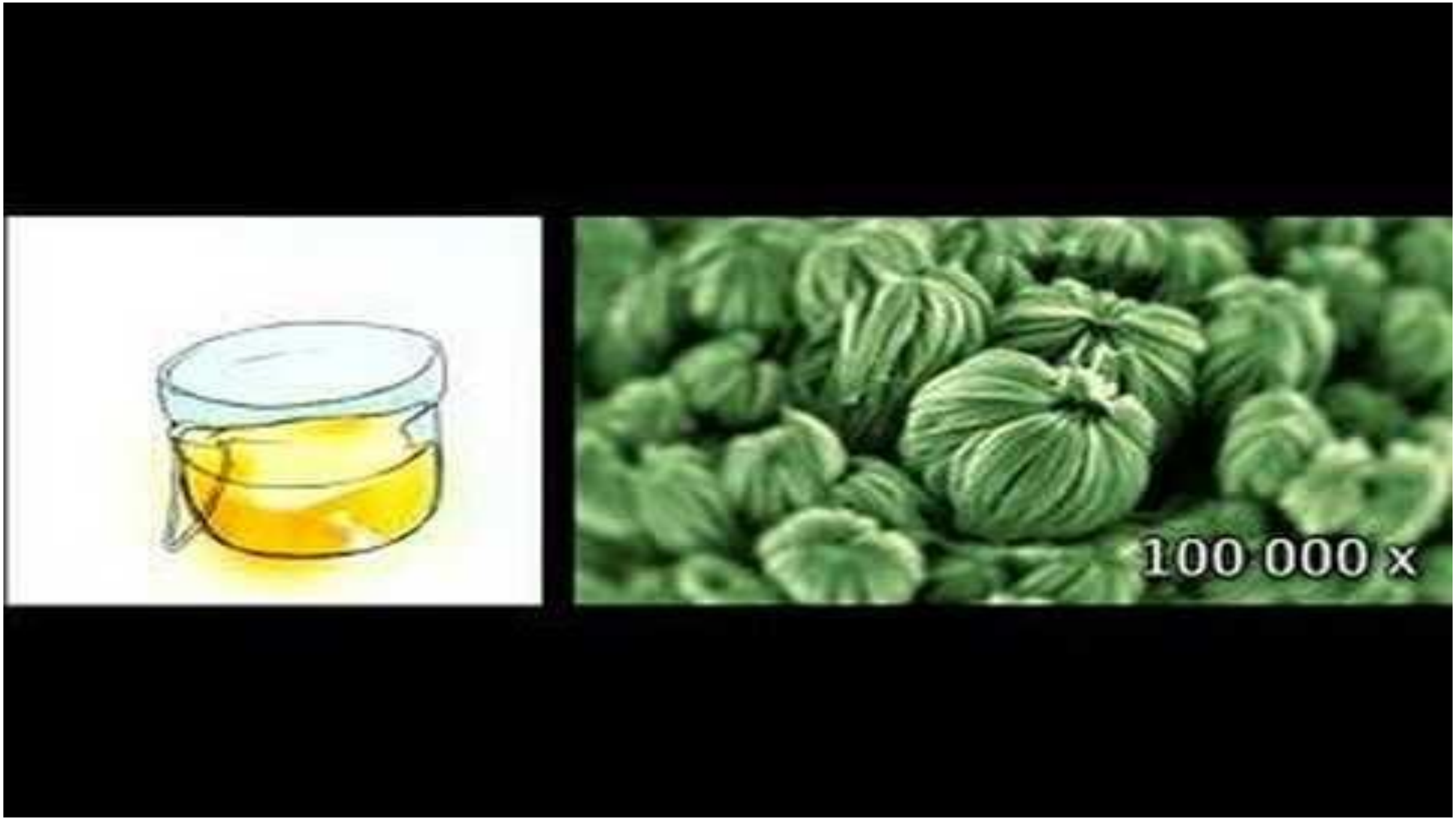
- **Nano-electronics**
  - Miniaturization of transistors and ultrafast integrated circuits
  - Supercapacitors for fast-charging and long-lasting new batteries
  - Piezoelectric effect at the nanoscale (nanogenerators)
- **Nano-optics**
  - Nano-lasers
  - Optical modulators
  - More efficient solar cells
- **Information and Communication Technologies**
  - Nanocommunication networks







The graphene-enabled future: an example



- The ***smartphone*** in 2025
  - Foldable and bendable screen
  - Hydrophobic materials
  - Changing size and color
  - Multiple sensors
  - Higher autonomy
  - Energy harvesting
  - Haptic interface
  - ***Nanoantennas???***

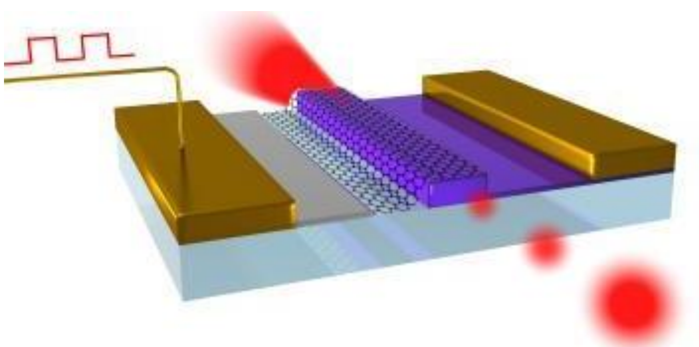
Graphene-based Nanoantennas

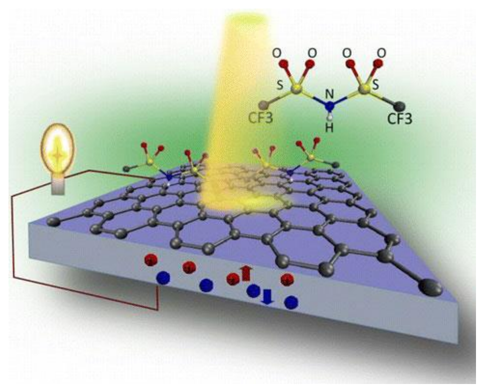
The importance of graphene in ICT

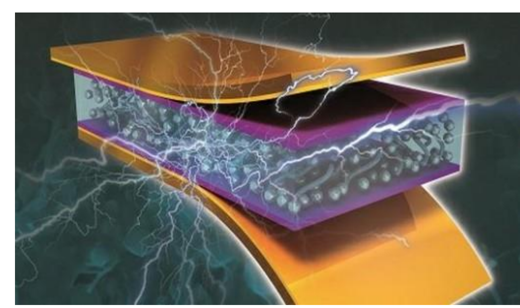
- We just described what is graphene, which are the most important properties, and the multiple applications that it could enable
- We have also seen that this material has a huge economic potential and has opened the door to lots of opportunities in Europe and around the world
- Now, we focus on the importance of graphene in the ICT context in general and, in particular, in the development of nanocommunication networks.

Graphene's applications relevant to N3Cat

- Nano-electronics
  - Miniaturization of transistors and ultrafast integrated circuits
  - Supercapacitors for fast-charging and long-lasting new batteries
  - Piezoelectric effect at the nanoscale (nanogenerators)
- Nano-optics
  - Nano-lasers
  - Optical modulators
  - More efficient solar cells
- Information and Communication Technologies
  - Nanocommunication networks







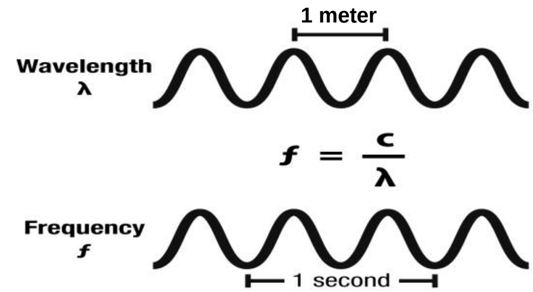
- What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm, nm)?
  - **How?**
    - Reducing the size of the communication system: the antennas first
  - **For what?**
    - Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
    - Place antennas in complex systems, but that are extremely constrained in area

- The resonance frequency
  - An RF antenna is a tuned circuit that has an inductance and a capacitance, which lead to a given resonant frequency (waves oscillate constructively inside the antenna)
  - This frequency is used as the transmission and reception frequency of the antenna
  - The main characteristic determining the resonant frequency is the size of the antenna. The longer are the antenna elements, the lower the resonant frequency

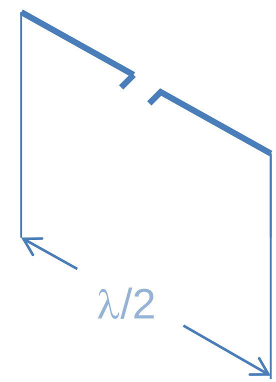
Designing antennas for nanocommunications

N3Cat

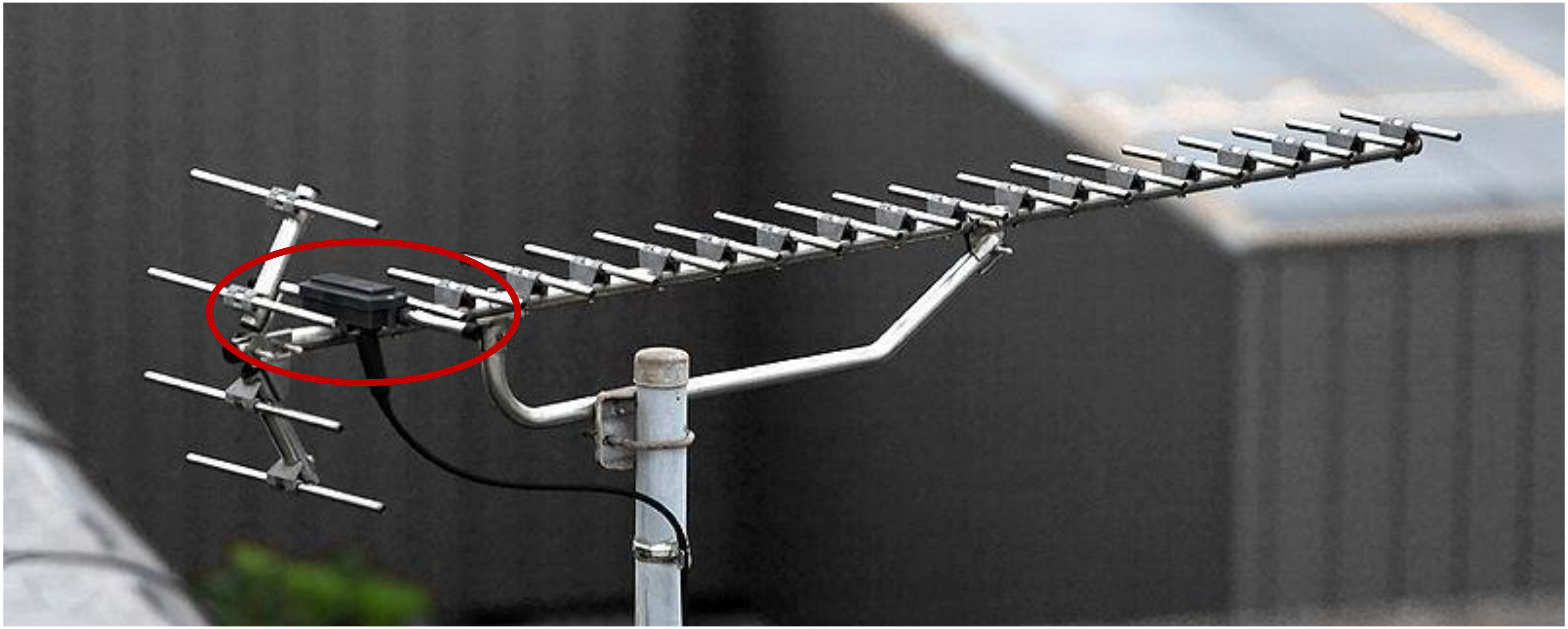
The relation between frequency *f* and wavelength λ in a metallic antenna is:



- Antenna dimensions
  - The length a metallic antenna use to receive signals from a given frequency needs to be $\lambda/2$

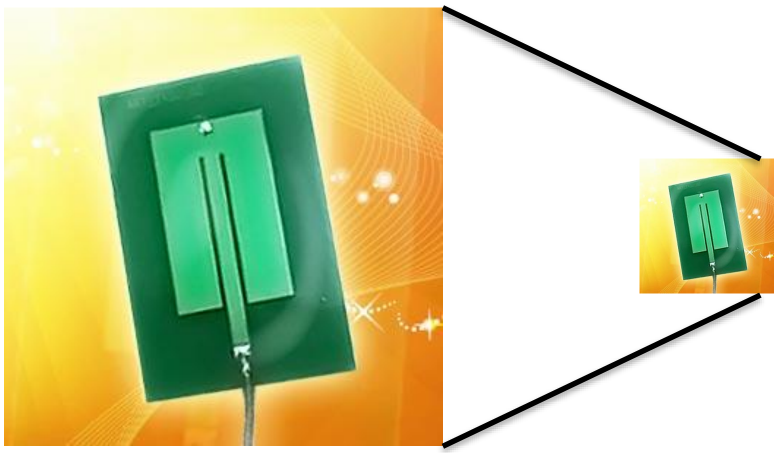


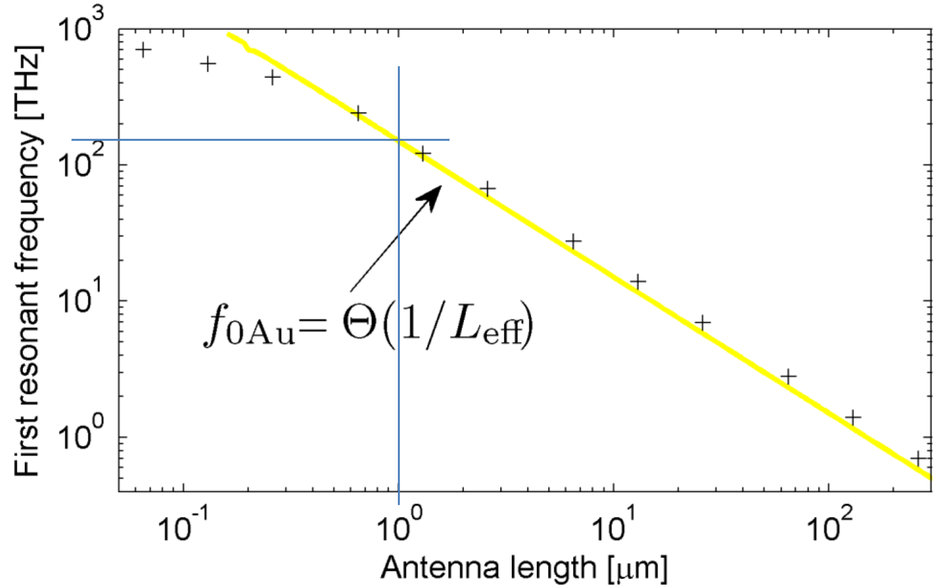
- Examples:
  - VHF (Very High Frequency): 30 – 300 MHz → λ: 10 - 1 m
  - UHF (Ultra High Frequency): 300 MHz – 3 GHz → λ: 1 – 0.1 m
    - $\lambda/2 \sim$ 0’30 m (2 x 0’15 m) → MOVIL? WIFI?



Designing antennas for nanocommunications

mm → **µm**



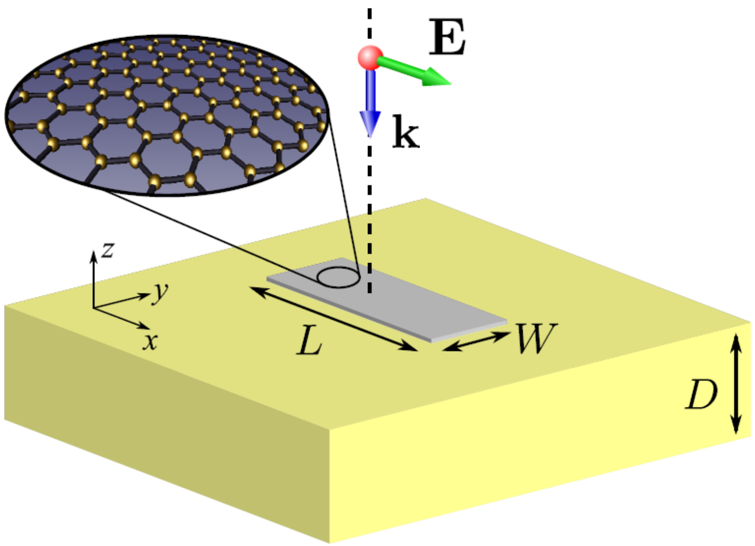


- Imagine now that we attempt to downscale our antenna to a few **µm** so that we can embed it in microdevices
- We just mentioned that the resonant frequency scales as Θ(1/L)
- At the microscale, our metallic antenna becomes optical, which means that we need a laser to excite it (among other problems)

I. Llatser, C. Kremers, A. Cabellos-Aparicio, E. Alarcón and D. N. Chigrin, ***"Comparison of the Resonant Frequency in Graphene and Metallic Nano-antennas"***, in AIP (American Institute of Physics) Conference Proceedings, 2012

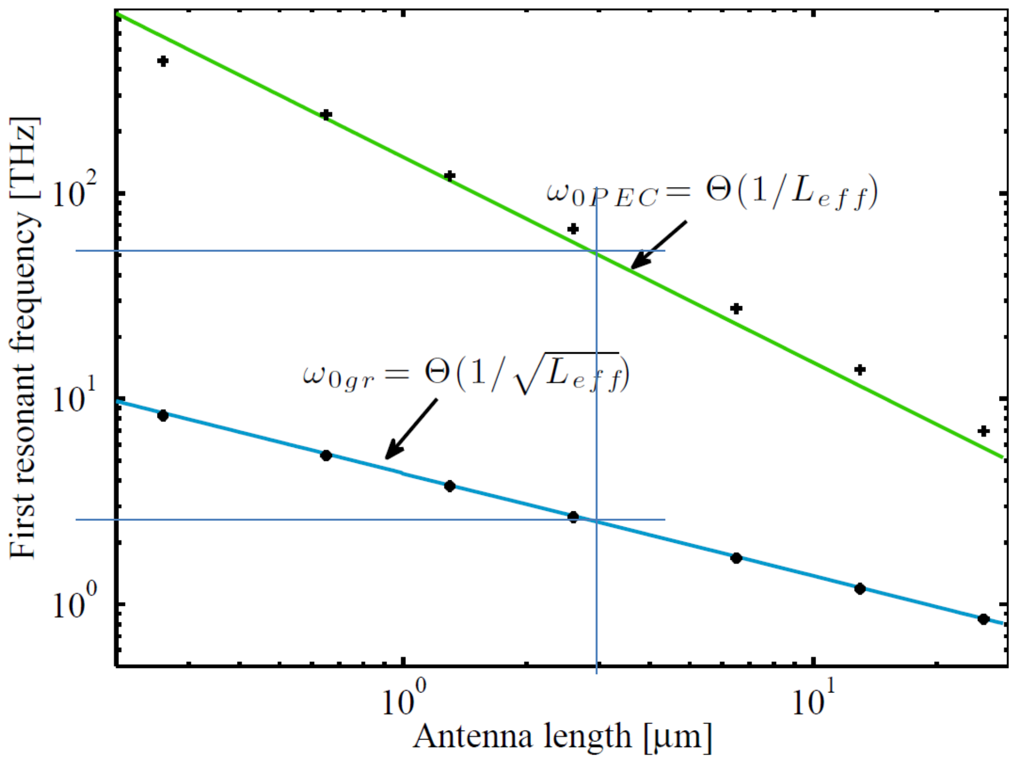
Graphene antennas (graphennas)

- This problem can be solved if instead of making our antenna out of metal, we use graphene (***graphenna***)
- Graphennas can be as simple as a high-quality graphene sheet laid over a dielectric
- The particularity of graphennas is that they are plasmonic, which causes their resonance frequency to be much lower than for conventional metallic antennas.
- Graphenna example:
  - L ~ a few µm
  - W ~ 1 µm
  - f ~ 1 THz



Comparing metallic antennas and graphennas

- This unique miniaturization characteristic of graphennas makes the communications system much more integrable
- We in fact discover that these antennas do scale different from the traditional 1/L relation of metallic antennas (blue line)



A 3-µm long *graphenna* resonates at around 2.5 THz, one order of magnitude lower than for a same-size metallic antenna

- We started with theory, we are now trying to experimentally prove that this works

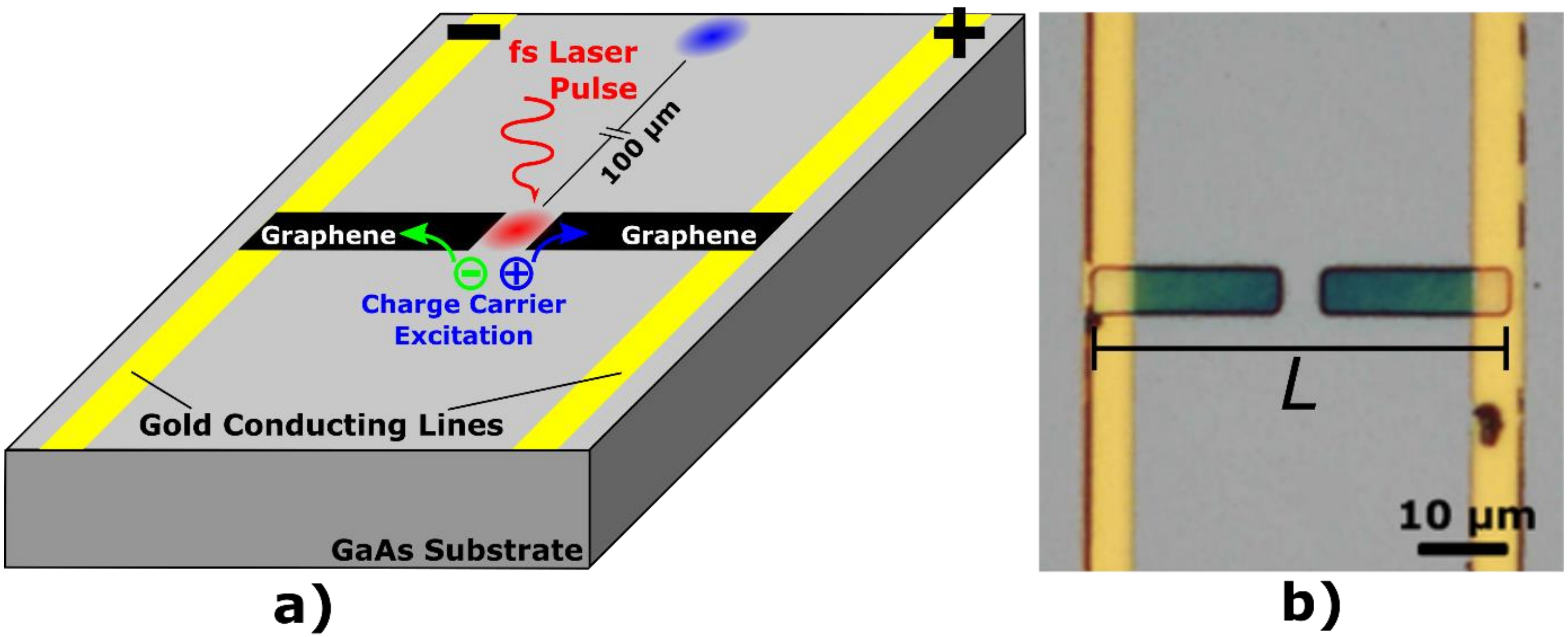
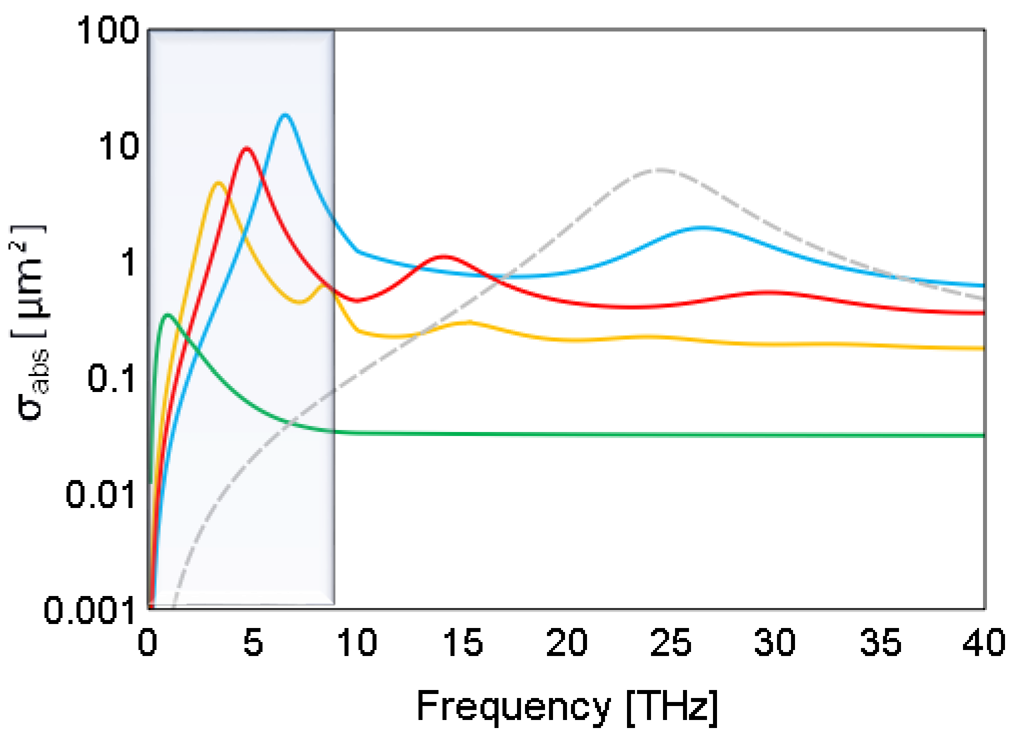
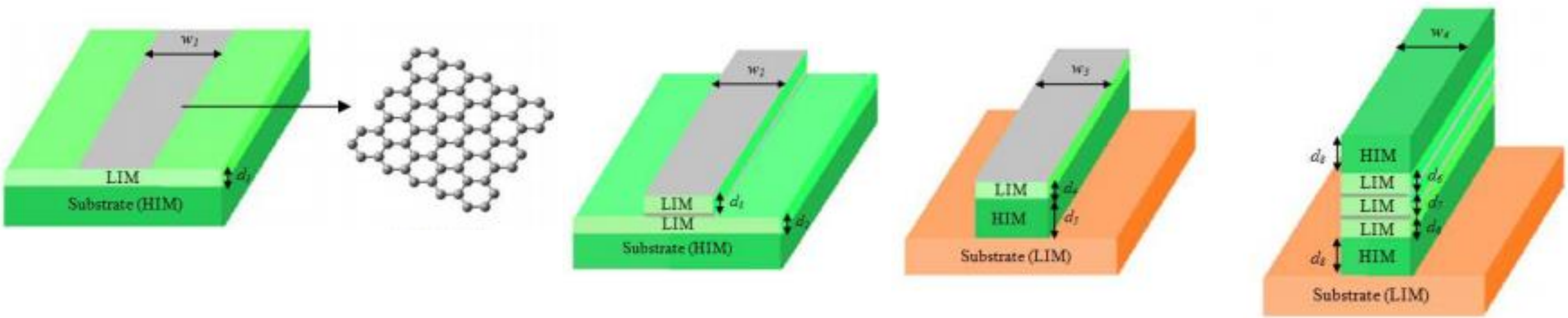


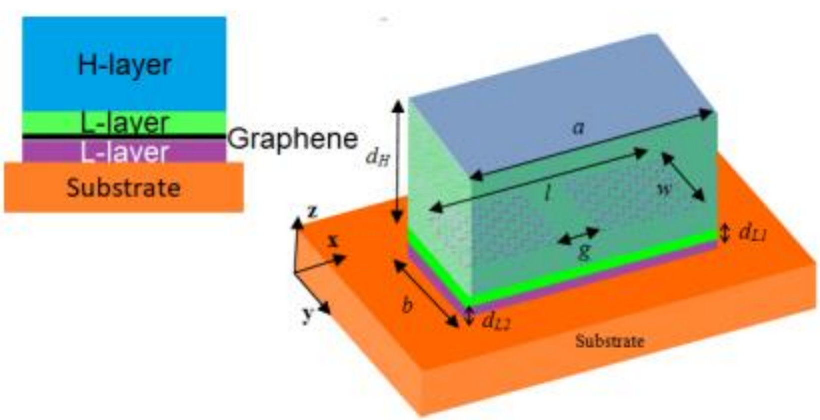
Fig. 1: a) Sample schematic. A fs-laser pulse excites charge carriers at the antenna gap. They are accelerated by the DC bias voltage applied to the gold biasing lines. The red and blue spot (not to scale) show the excitation spot at the antenna gap and 100 μm above respectively.
b) Microscopic image of the device with length L=47 μm and PMMA resist on top.

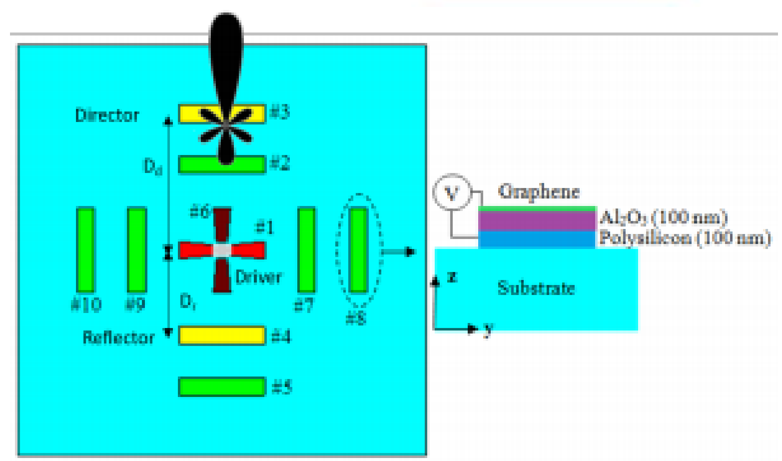
- Another compelling property of *graphennas*, compared to metallic antennas, is that its resonant frequency can be changed just changing its chemical potential (voltage, basically)



- This property offers a great flexibility when designing
    1) New antennas

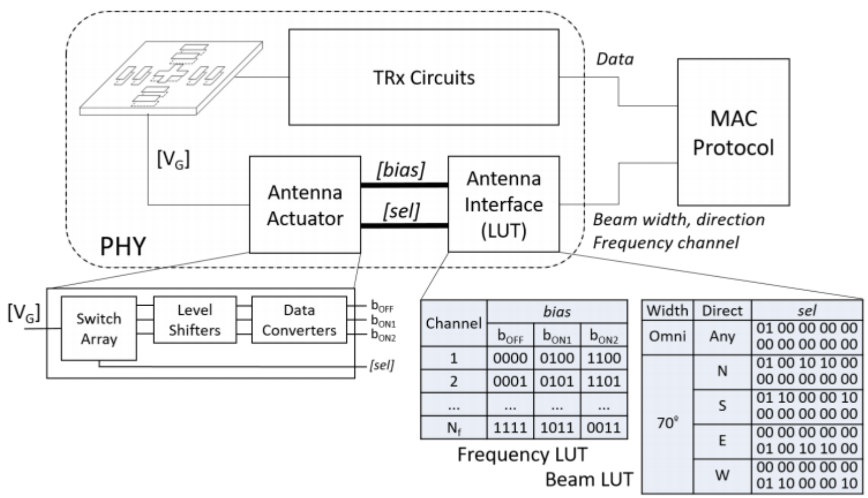






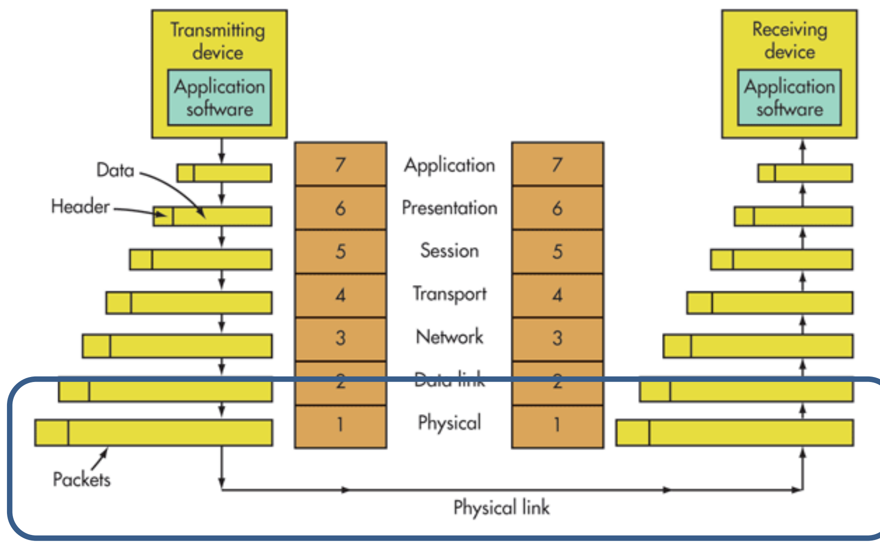
Comparing metallic antennas and graphennas

- This property offers a great flexibility when designing
  1) New antennas
  2) The communication protocols based on these antennas



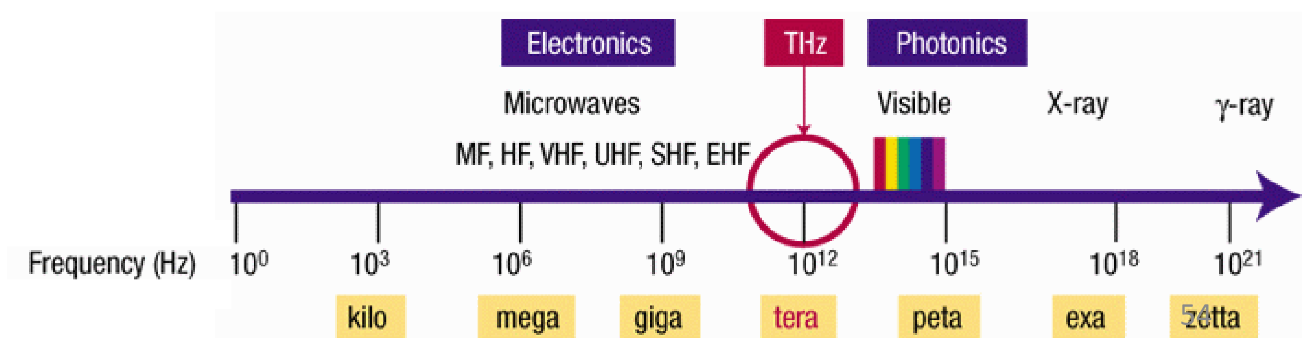
Algorithm 1 Simplified multichannel MAC protocol using the antenna controller (controller instructions in bold).

> **set(omni, any_dir, control_ch)**
> send(RTS, addrRX, control_ch)
> {data_ch, direction} ← receive(CTS, addrRX, control_ch)
> **set(70°, direction, data_ch)**
> send(data, addrRX, data_ch)



Graphene-enabled Wireless Communications

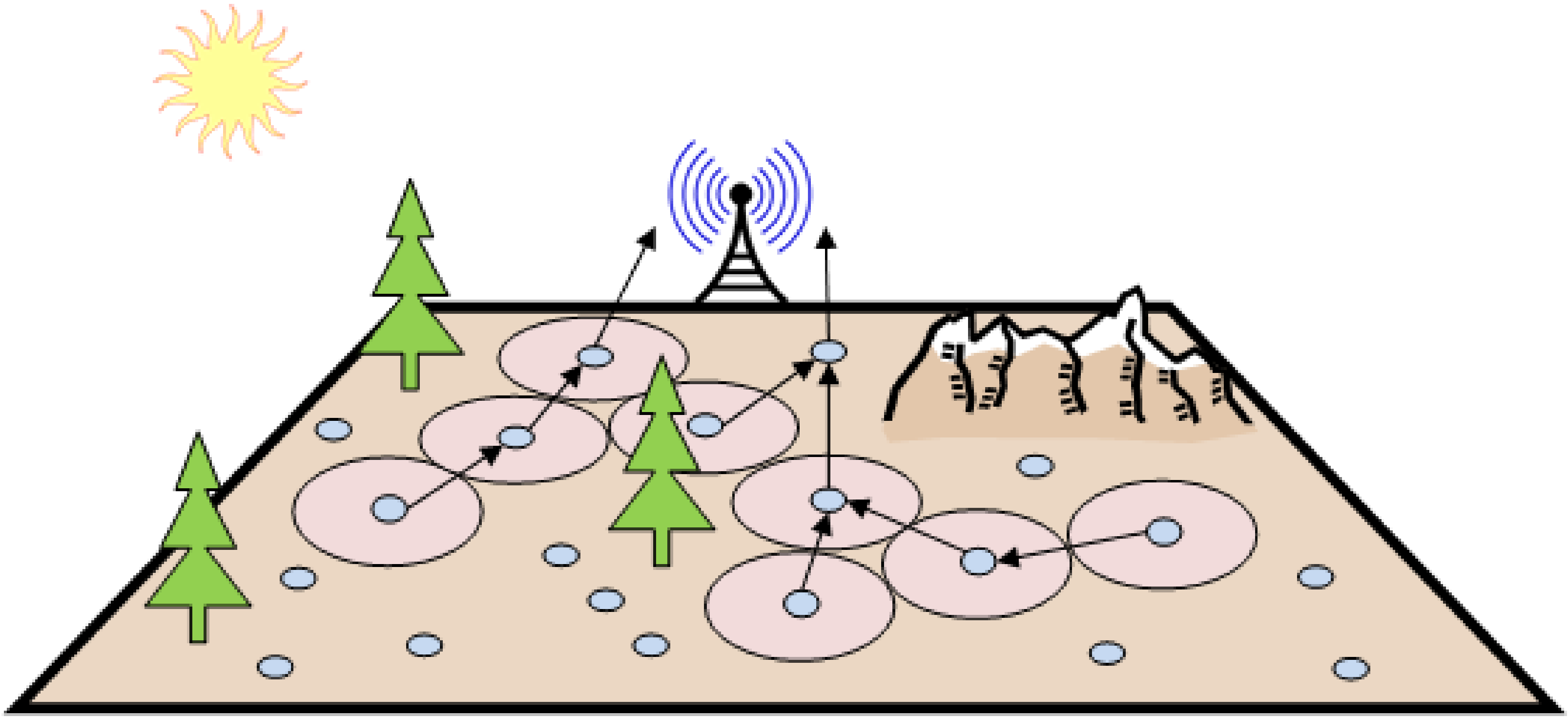
- Graphennas represent a technology that allows miniaturizing wireless RF communications down to the micro and nano scales
  - **2 order of magnitude** smaller than metallic antennas
  - Radiates in the **Terahertz band** (0.1 – 10 THz)
    → The gap between the millimeter-waves (60 GHz) and the infrared-optics (100 THz) with potential for extreme speeds (~Tbps)
  - **Tunable resonant frequency by just changing the voltage**
    → An unprecedented design flexibility
  - **Transmission range**: from 1mm to 1m (depending on the transmission medium, the modulation, etc...)



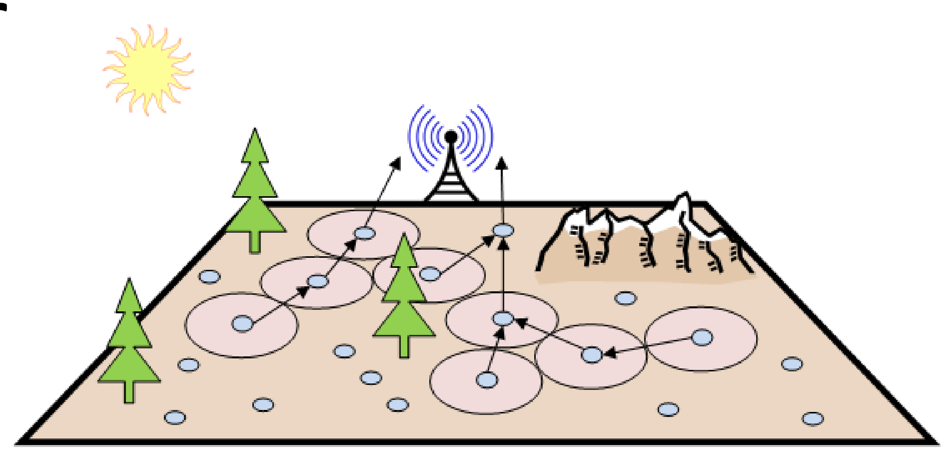
Nanonetworks and their applications

- What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm, nm)?
  - **How?**
    - Reducing the size of the communication system: the antennas first
  - **For what?**
    - Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
    - Place antennas in complex systems, but that are extremely constrained in area

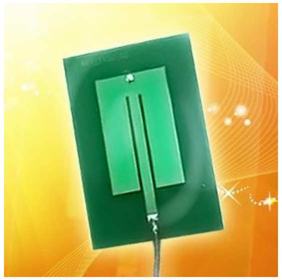
Wireless Sensor Networks and Internet of Things

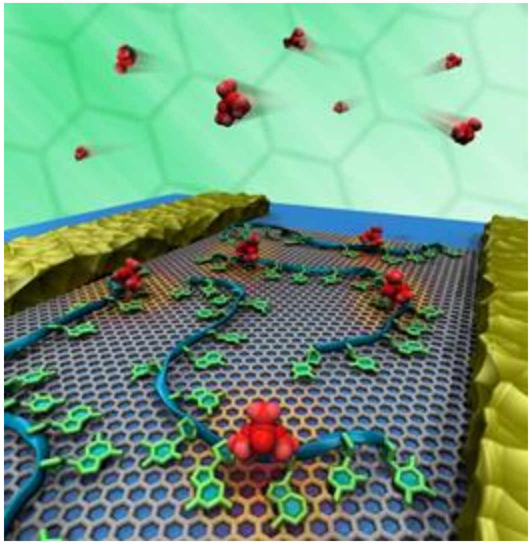


- Applications
  - Industrial IoT
  - Smart home / city / farm
  - Smart grid
  - Connected car
  - Wearables
  - …

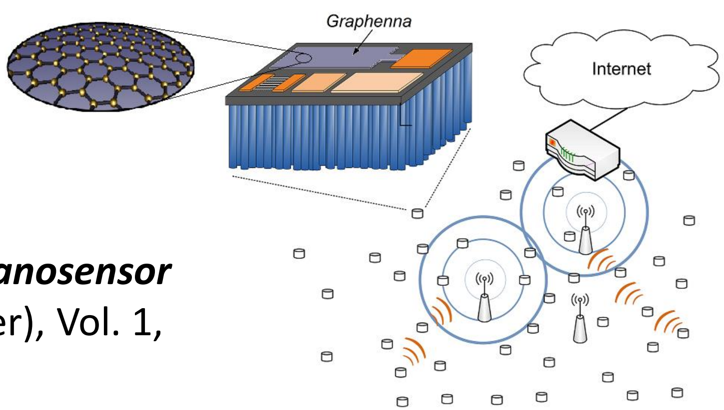


- **What if?** Nanosensors
  - Physical, chemical, or biological
  - Ultra-precise (single molecule)
  - Ultra-small (nano)
- **What if?** Nanoantennas



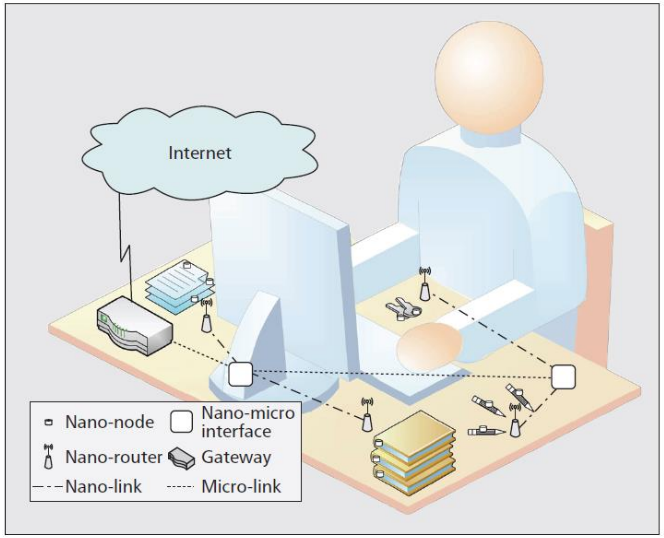


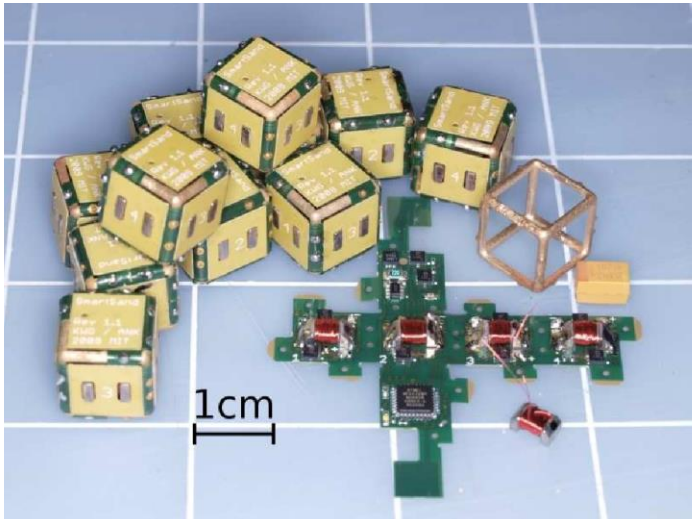
- Extension of IoT with nanosensors functionalities
  - To reach unprecedented locations
    - Concealed, implanted, scattered
  - To have unprecedented precision
  - Equipped, of course, with communication systems to reach the macroworld



Akyildiz, I. F. and Jornet, J. M. ***"Electromagnetic Wireless Nanosensor Networks",*** Nano Communication Networks Journal (Elsevier), Vol. 1, No. 1, pp. 3-19, March 2010

- Interconnected office
- Smart fabrics, materials
- Programmable matter
- Haptic interfaces
- Bio-chemical defense
- Plague defeating systems
- More?

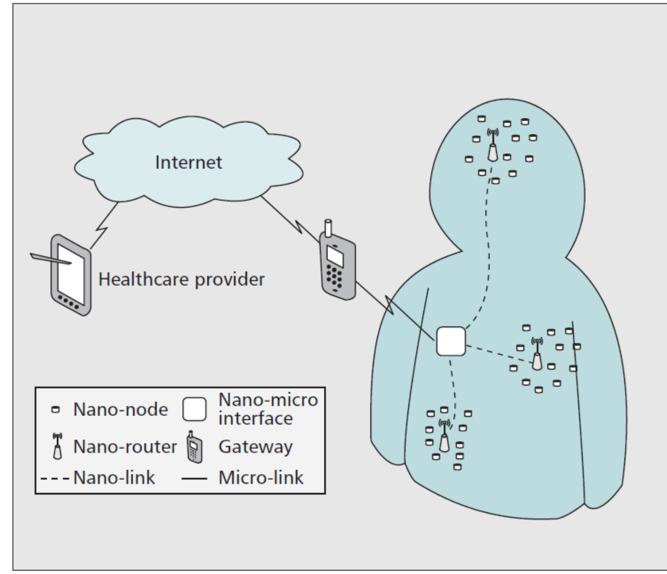


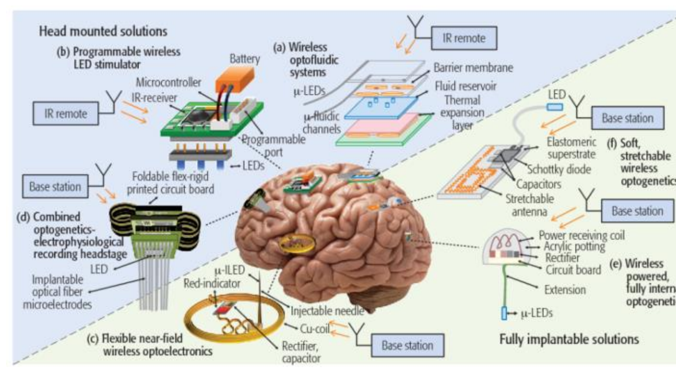


Applications of the Internet of BioNanoThings

N3Cat

- Localized sensing
- Drug delivery (insulin)
- Ultra-precise tumor destruction
- Brain interfacing
- Functionality recovery
  - Paralysis, alzheimer



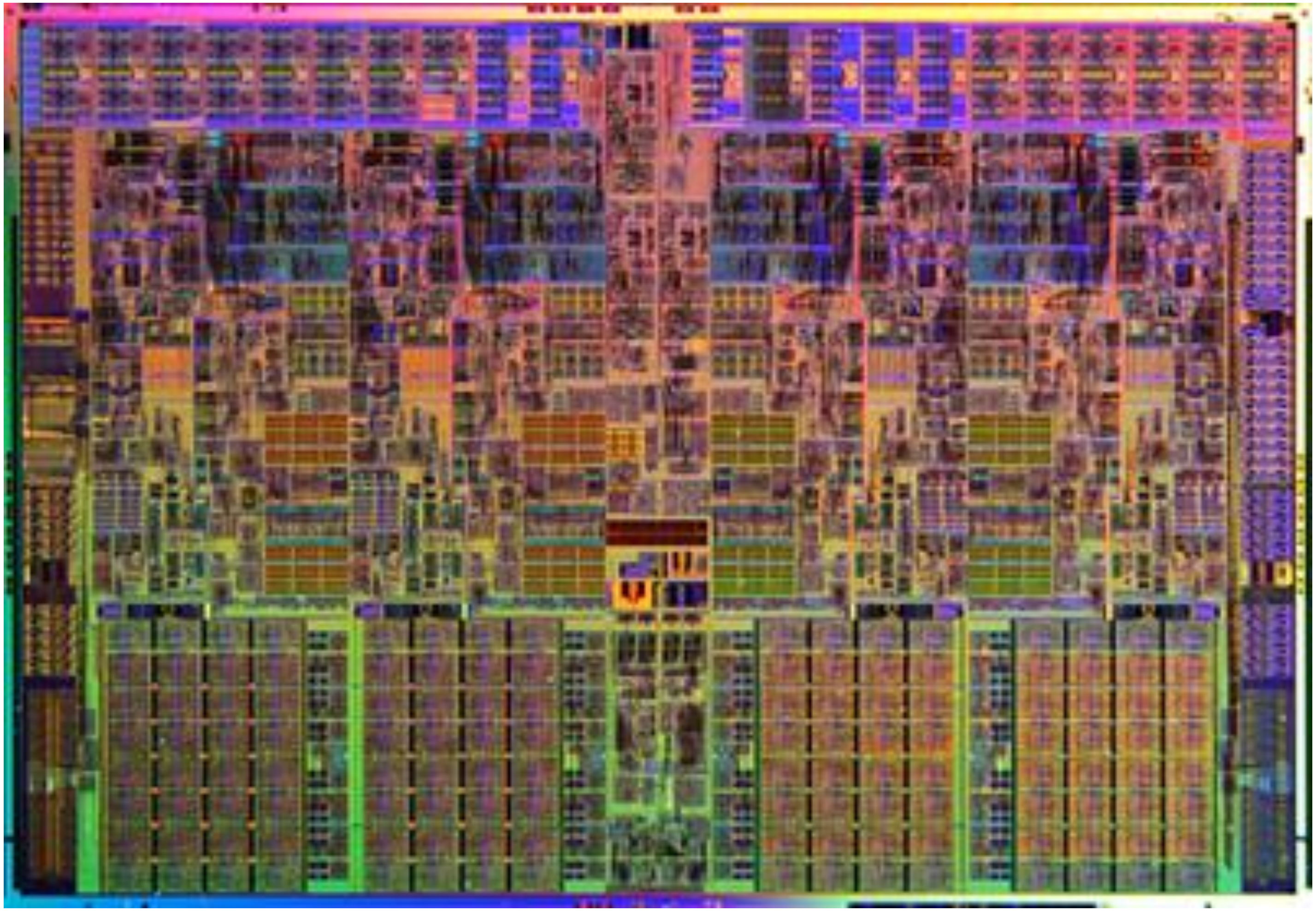


Neuralink++

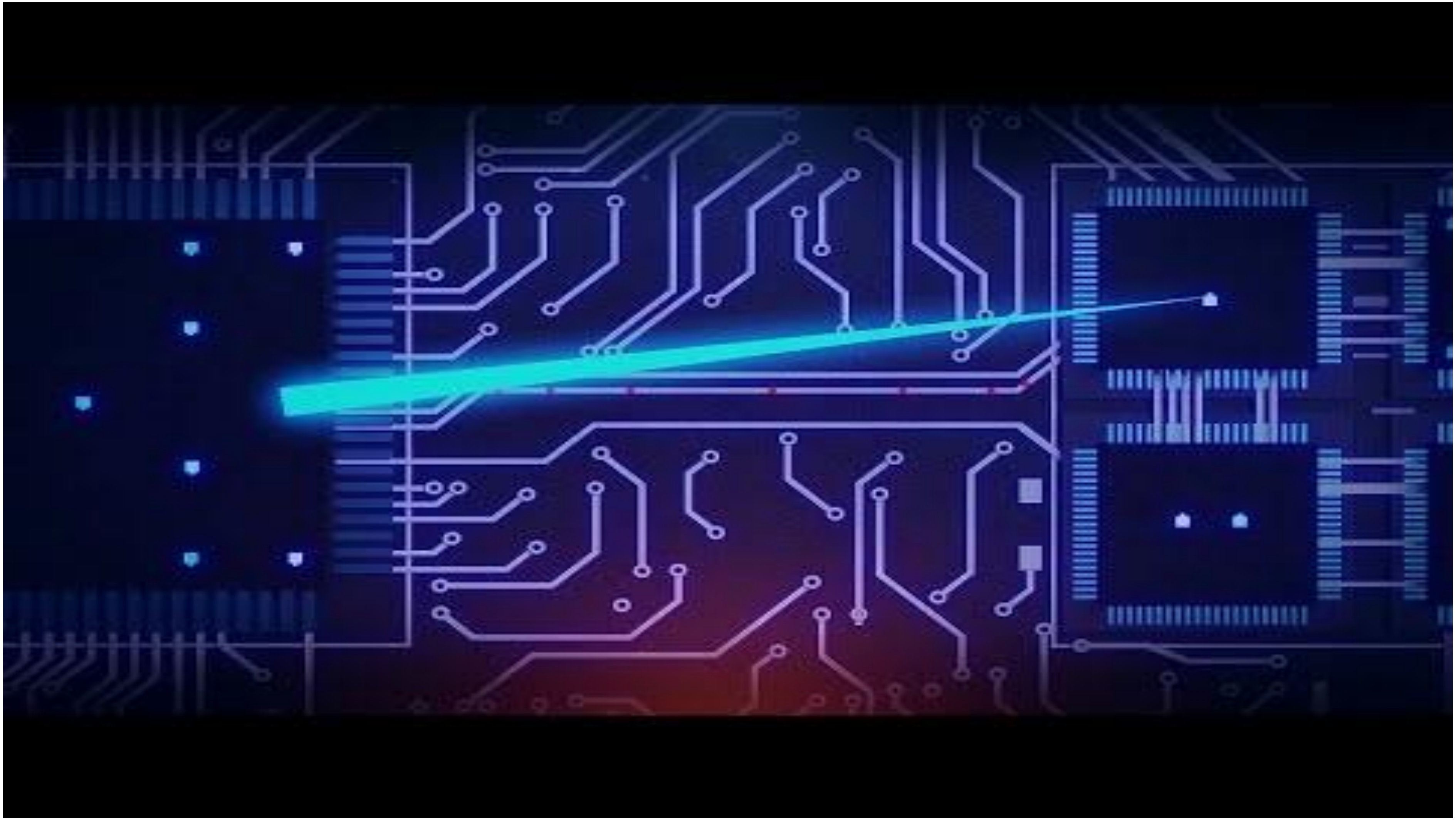
- Interesting challenges
  - How do we schedule transmissions to avoid interferences when we have thousands of nodes?
  - How do we cope with nano-batteries, intermittent connectivity?
  - How do we collectively send information to a single end-receiver?

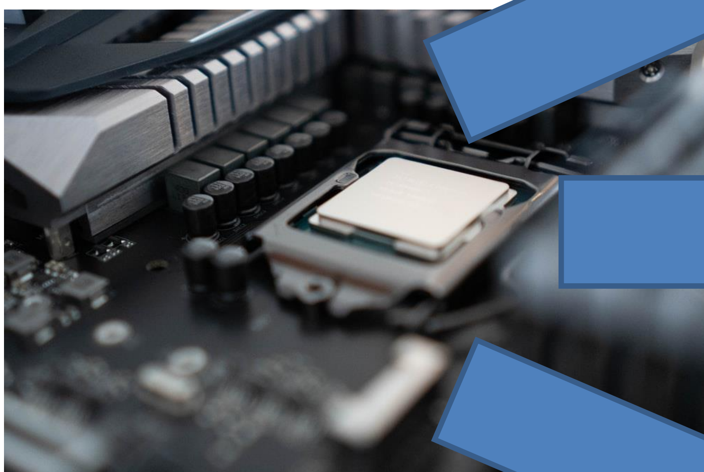
- What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm, nm)?
  - **How?**
    - Reducing the size of the communication system: the antennas first
  - **For what?**
    - Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
    - Place antennas in complex systems, but that are extremely constrained in area

Wireless Network-on-Chip



Wireless Network-on-Chip



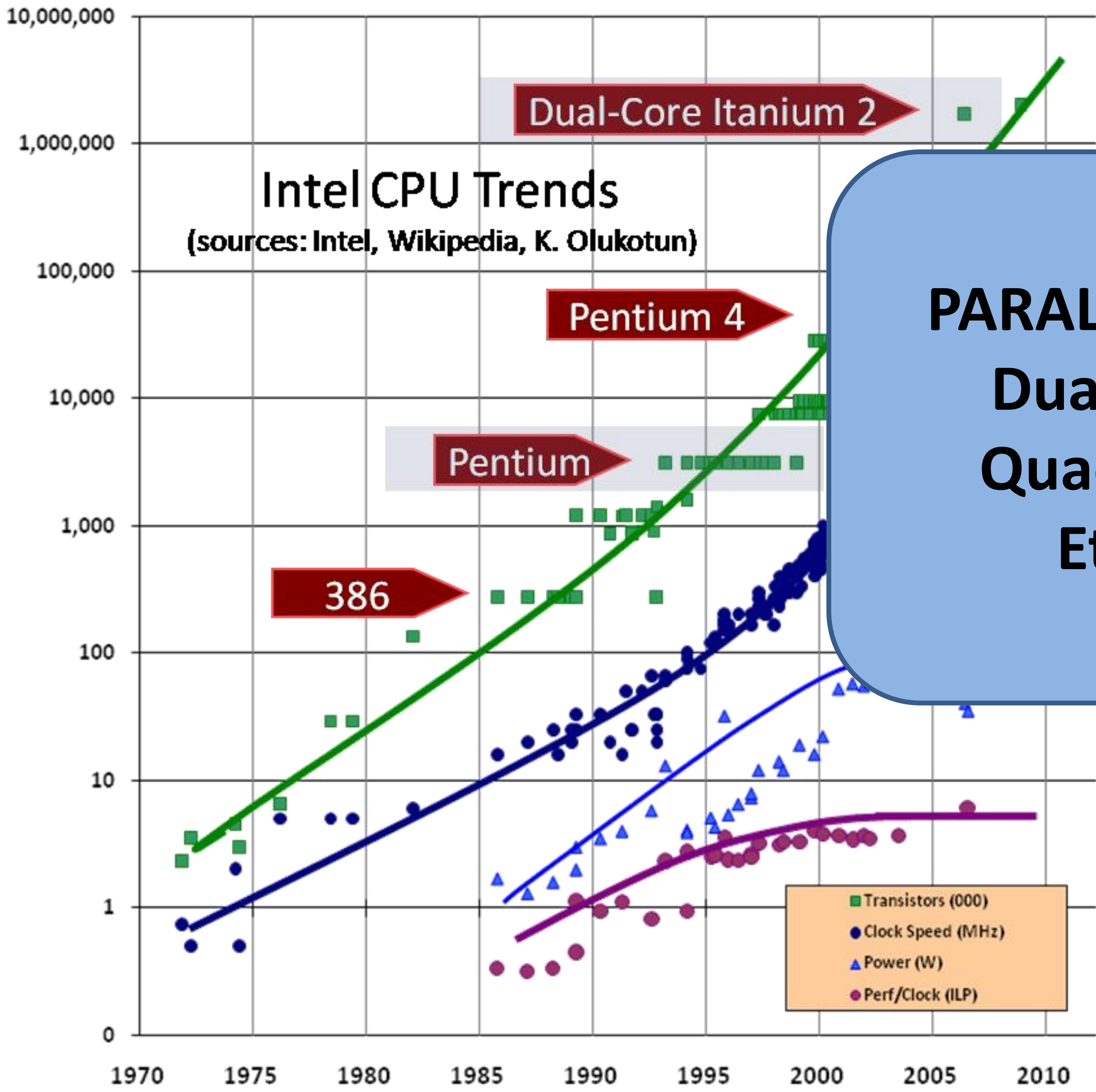


We want them faster

We want them more efficient

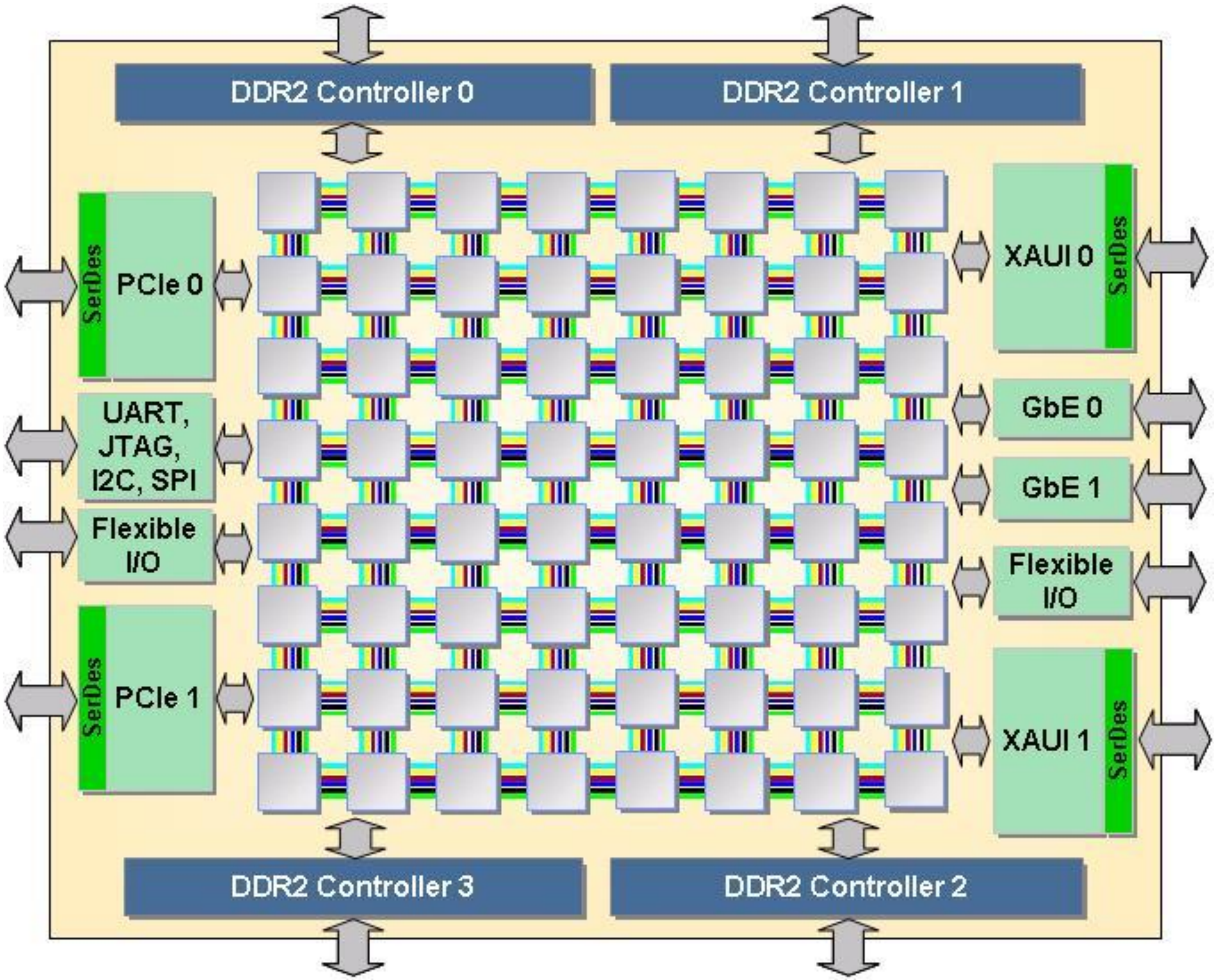
Anywhere, always

Why do we need a network on a chip?

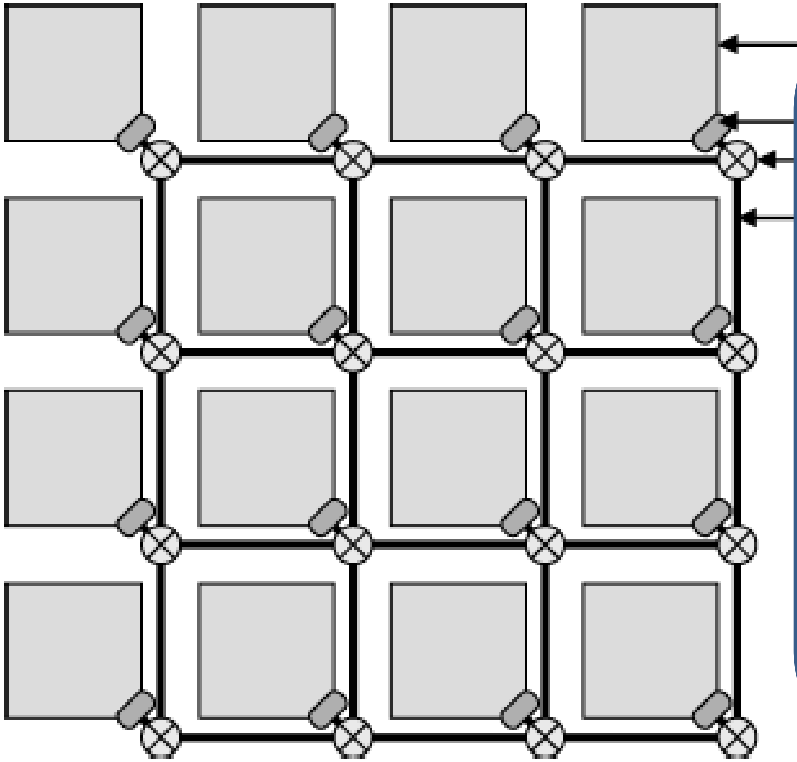


PARALLELISM!
Dual-core
Quad-core
Etc...

Multiprocessors that need an internal network

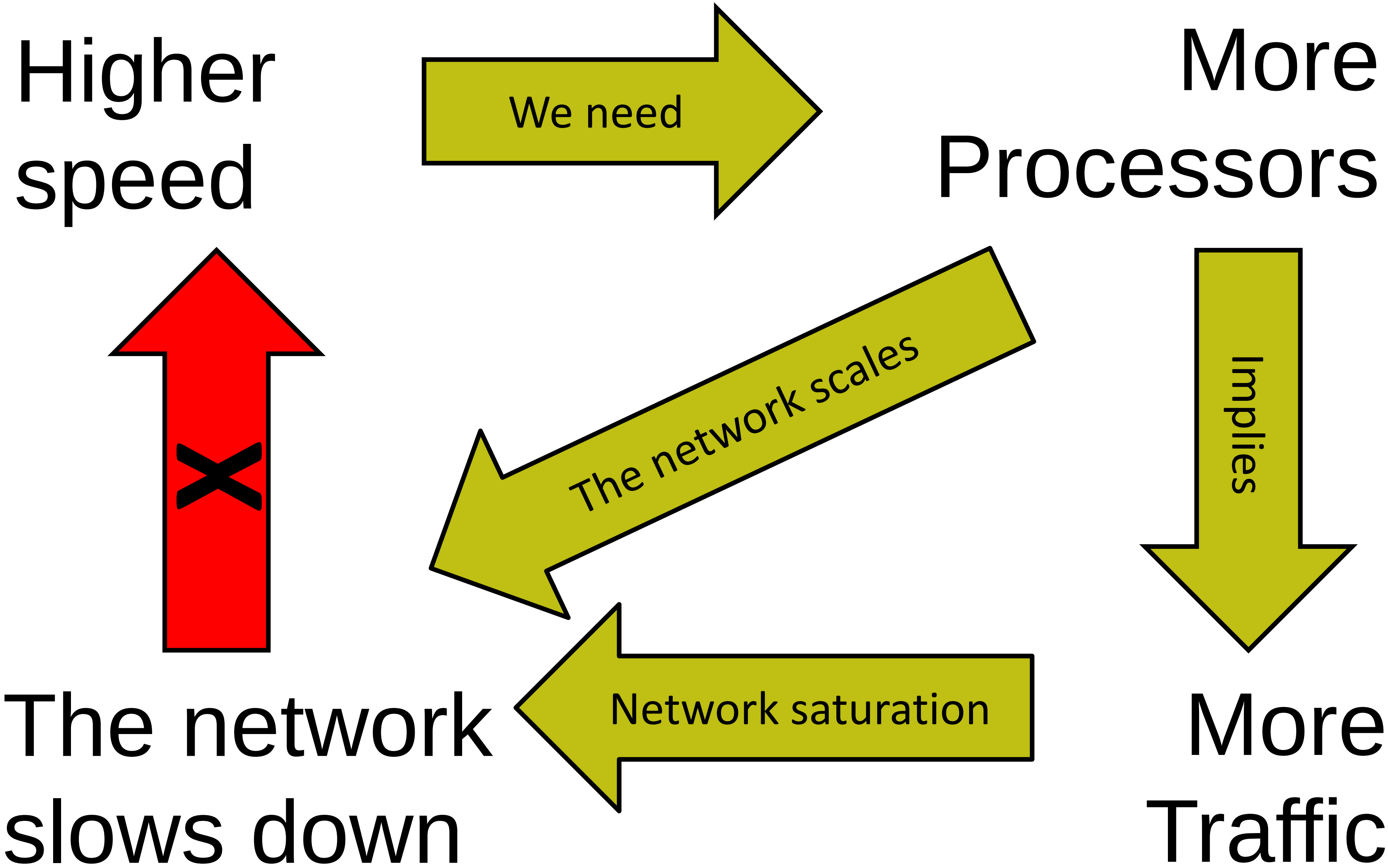


- There's literally a packet-switched network in the chip
- The cores of the processor are the clients
  - Need to communicate to share information, coordinate execution, etc...

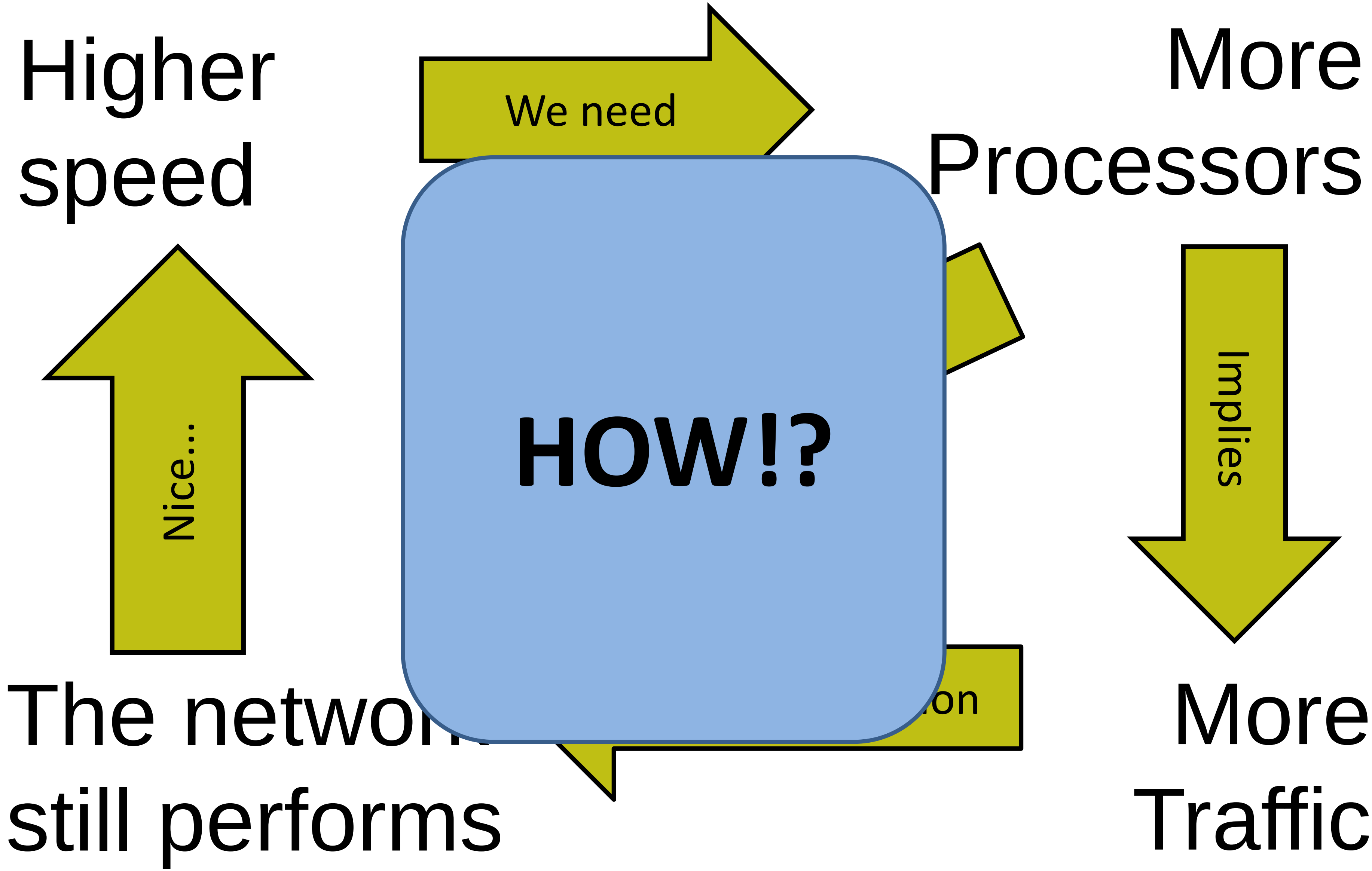


QUESTION: What happens if, instead of 16, we have 256 processors?

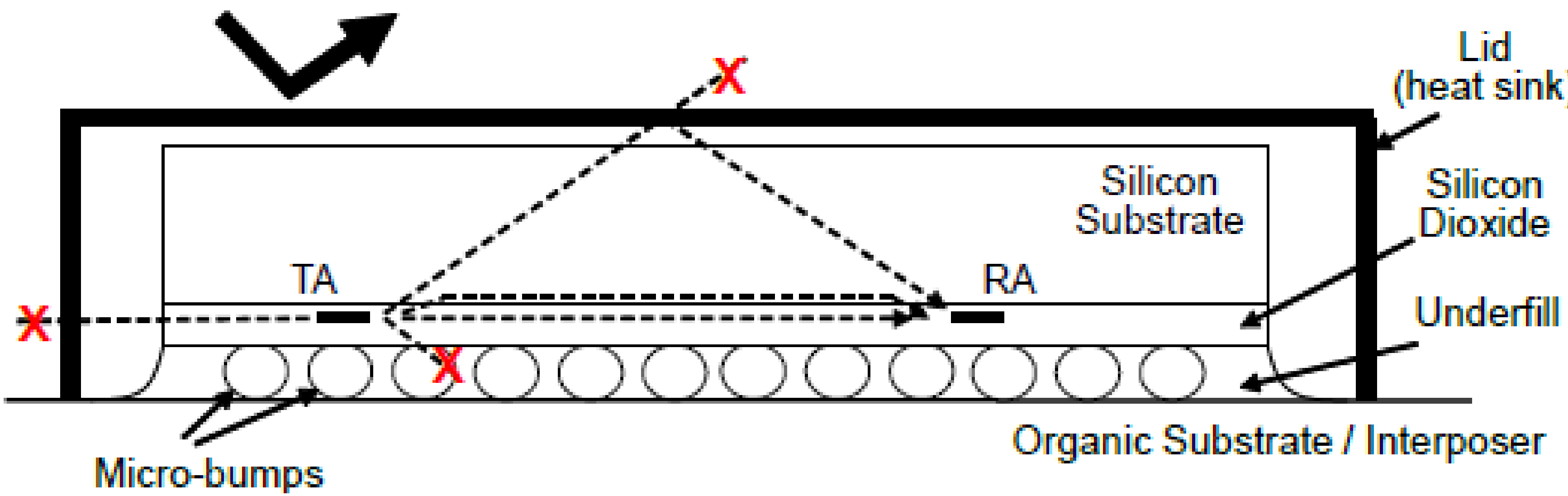
We broke the circle of scaling (tick-tock)



Fixing the cycle

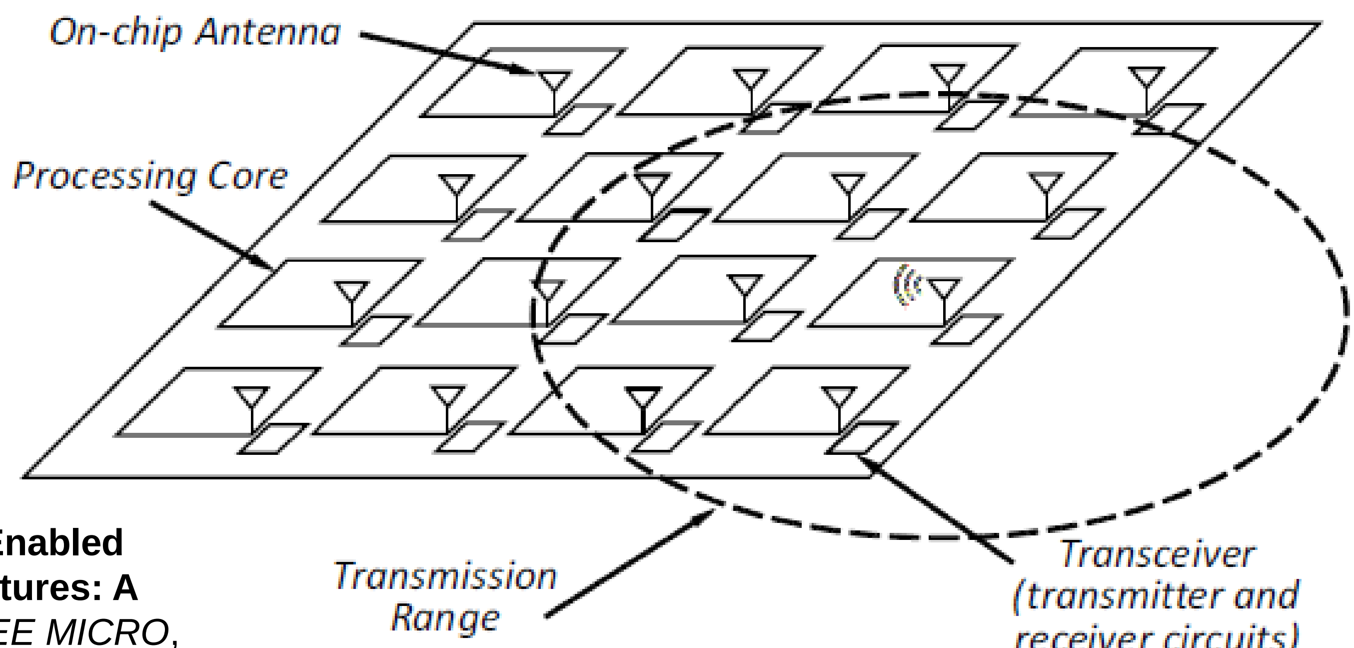


- We have small antennas, let's use them
- Several antennas within the same chip



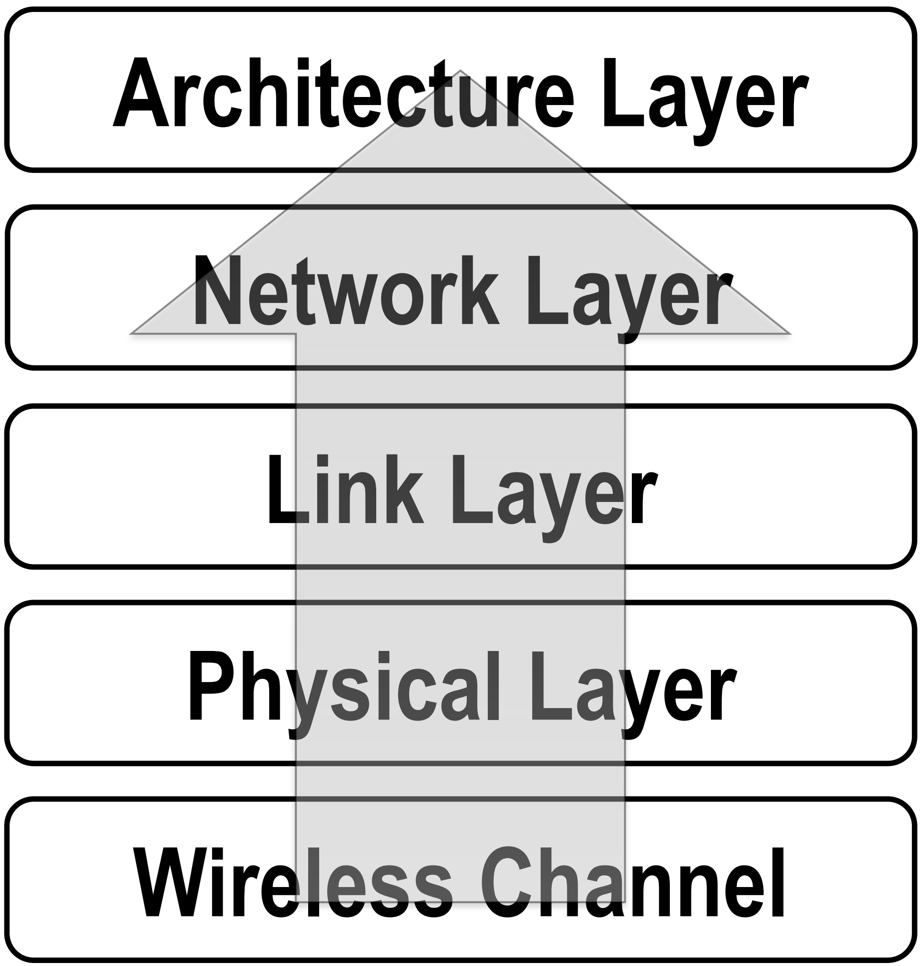
S. Abadal, B. Sheinman, O. Katz, O. Markish, D. Elad, Y. Fournier, D. Roca, M. Hanzich, G. Houzeaux, M. Nemirovsky, E. Alarcón, and A. Cabellos-Aparicio, "**Broadcast-Enabled Massive Multicore Architectures: A Wireless RF Approach,**" *IEEE MICRO*, vol. 35, no. 5, pp. 52–61, 2015.

- We have small antennas, let's use them
- We can reach all cores with one wireless hop, regardless of the number of cores
- Higher execution speed!



S. Abadal, et al"**Broadcast-Enabled Massive Multicore Architectures: A Wireless RF Approach,**" *IEEE MICRO*, vol. 35, no. 5, pp. 52–61, 2015.

Wireless Network-on-Chip



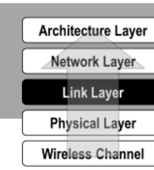
Unique points

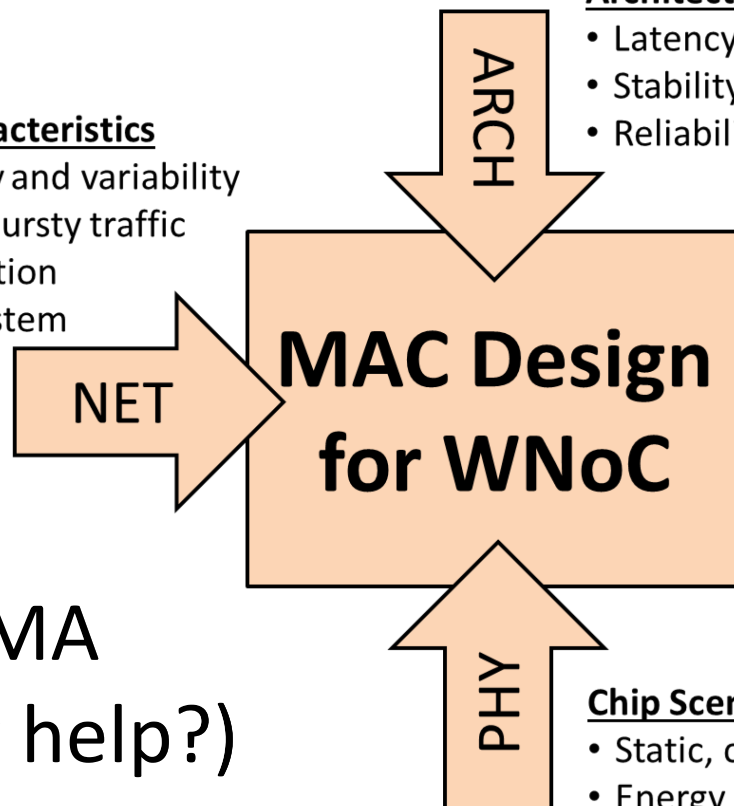
- Monolithic system with co-design opportunities
- Prior knowledge of traffic/architecture
- Static environment, known beforehand
- Global clock...

Interesting challenges

- How can we maximize the benefit of introducing a wireless network?
  - Which types of processors will benefit most from the addition of a wireless network?
- How do we leverage knowledge on the application at the MAC layer?
- Routing is trivial, but how do we orchestrate the wired and wireless networks?

MAC – Context Analysis

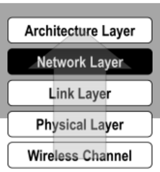




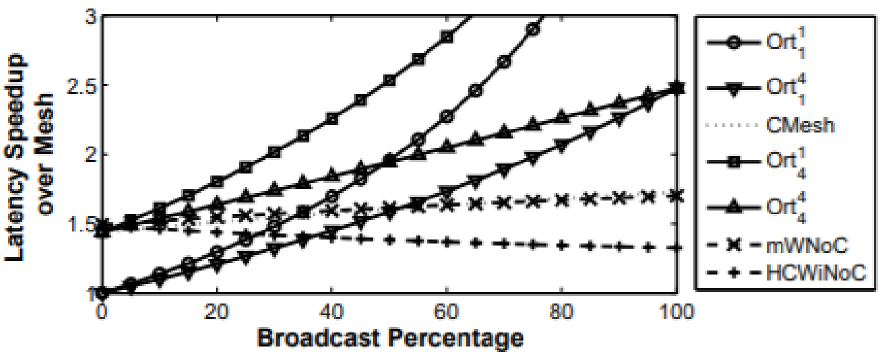
- Fairness of token
- Promptness of CSMA
- Intelligent (AI may help?)
- Exploit opportunities
  - Architecture, static environment

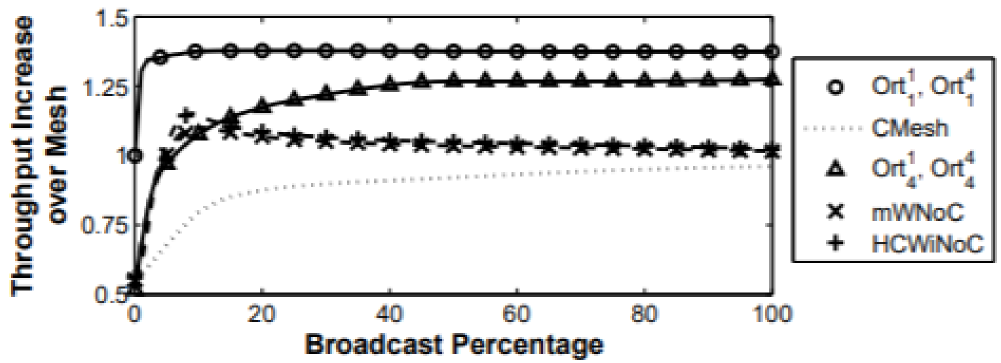
S. Abadal, A. Mestres, J. Torrellas, E. Alarcón, and A. Cabellos-Aparicio, **“Medium Access Control in Wireless Network-on-Chip: A Context Analysis,”** IEEE Communications Magazine, vol. 56, no. 6, pp. 172-178, 2018

NET – Load balancing

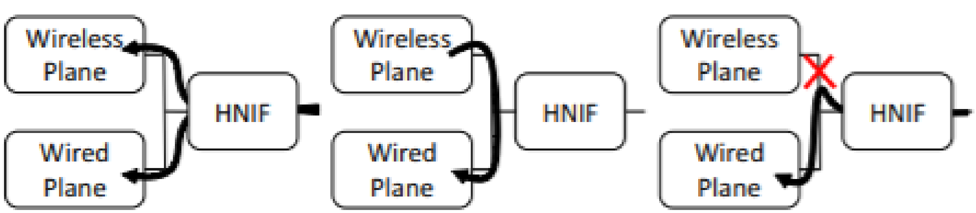


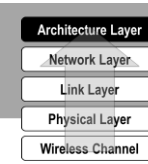
- We proposed a complete network architecture
  - Separate wired and wireless planes
  - Load balancing with plane select/switch/block
  - Clustering to control area/power overheads





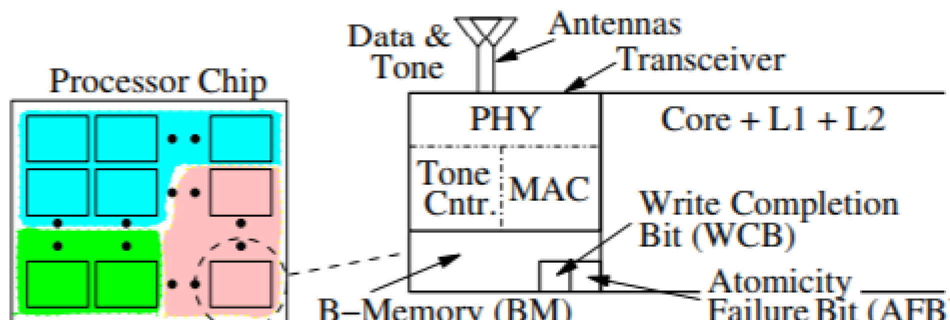
S. Abadal, J. Torrellas, E. Alarcón, and A. Cabellos-Aparicio, ***"OrthoNoC: A Broadcast-Oriented Dual-Plane Wireless Network-on-Chip Architecture,"*** *in IEEE Transactions on Parallel and Distributed Systems, vol. 29, no. 3, pp. 628-641, March 2018.*





- WiSync: use wireless for synchronization
  - Small broadcast memory to store locks and barriers
  - Kept coherent through the wireless network, separate from the cache coherence protocol
  - Every write is broadcasted – same value is seen across all the broadcat memories. Reads are local.
  - Wireless network is the ordering point

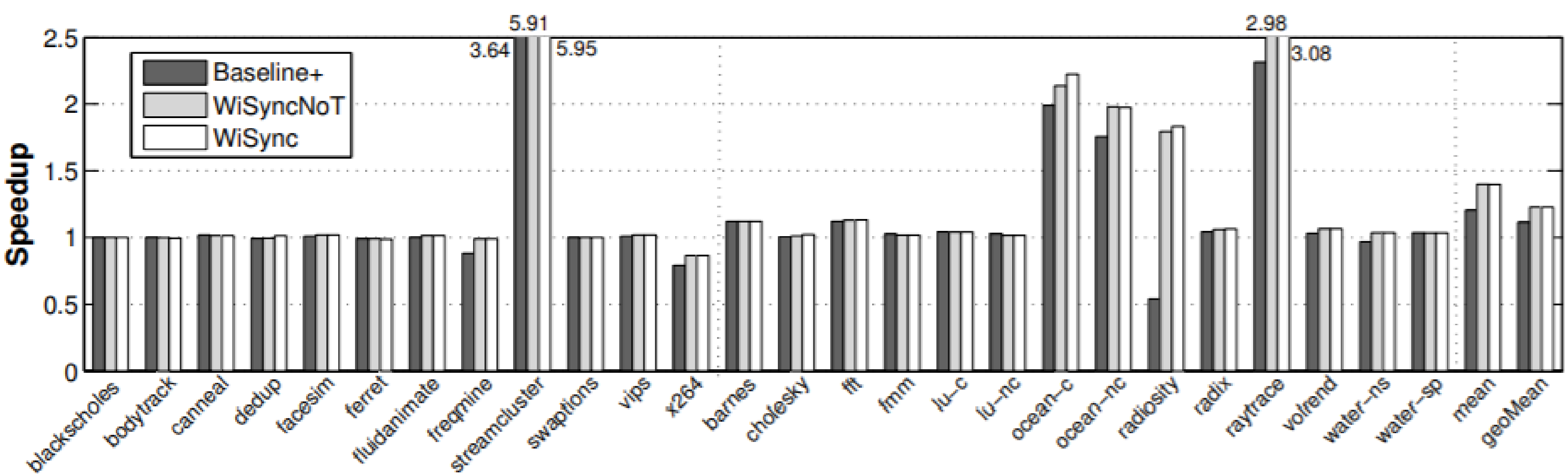
S. Abadal, E. Alarcón, A. Cabellos-Aparicio, and J. Torrellas, "**WiSync: An Architecture for Fast Synchronization through On-Chip Wireless Communication,**" in *ASPLOS '16*, 2016.



ARCH – WiSync

- Architecture Layer
- Network Layer
- Link Layer
- Physical Layer
- Wireless Channel

- Applications are really sped up!
  - One antenna per core
  - Wireless channel at 20 Gb/s
  - Small part of code, big impact: average of 1.41X



S. Abadal, E. Alarcón, A. Cabellos-Aparicio, and J. Torrellas, “**WiSync: An Architecture for Fast Synchronization through On-Chip Wireless Communication,**” in *ASPLOS ’16*, 2016.

Conclusions

Conclusions

- Graphennas may be a key enabler of miniaturized wireless communications
  - Miniaturization of up to two orders of magnitude
  - Wide tunability → Novel communication protocols
  - Efficiency issues exist → need to explore tradeoffs
- New area-constrained applications are possible thanks to this new technology
  - They have different performance/cost requirements
  - New communication challenges arise

We gratefully acknowledge support from the European Commission through grants:

- WIPLASH: Wireless Plasticity for Massive Heterogeneous Computer Architectures (H2020-863337)
- VISORSURF: A Hardware Platform for Software-driven Functional Metasurfaces (H2020-736876)

www.wiplash.eu

www.visorsurf.eu

MSc thesis at N3Cat

- Contact Prof. Pareta or myself if you would like to do your MSc thesis on:
  - Wireless Communications for Manycore Processor Systems and Big Data
  - Communication Analysis and Design of AI Accelerators (including GNNs)
  - Communication in quantum computers
  - Collision detection and protocol design for applications beyond 5G
  - Programmable Metamaterials

http://www.n3cat.upc.edu

Graphene-enabled Wireless Communications for Networks on Chips

Sergi Abadal

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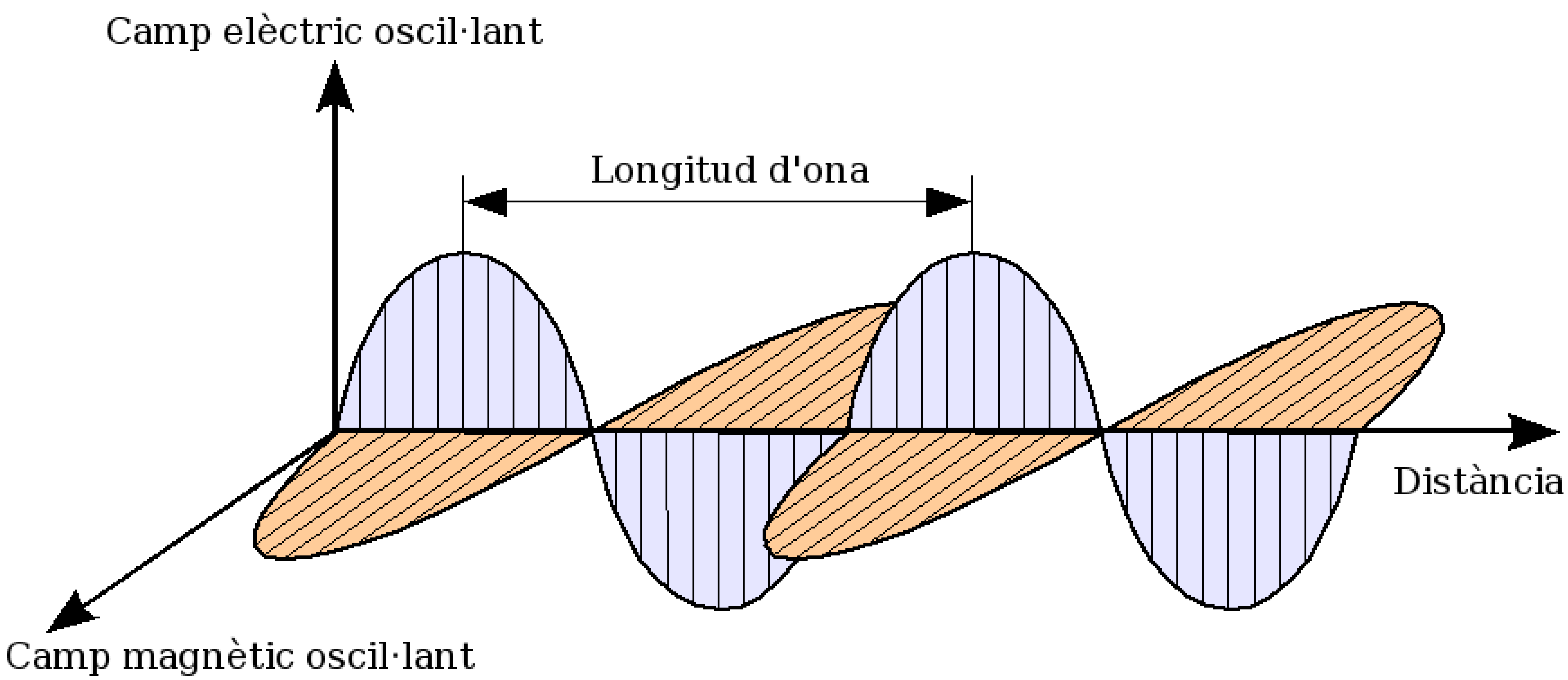
www.sergiabadal.com

Referències

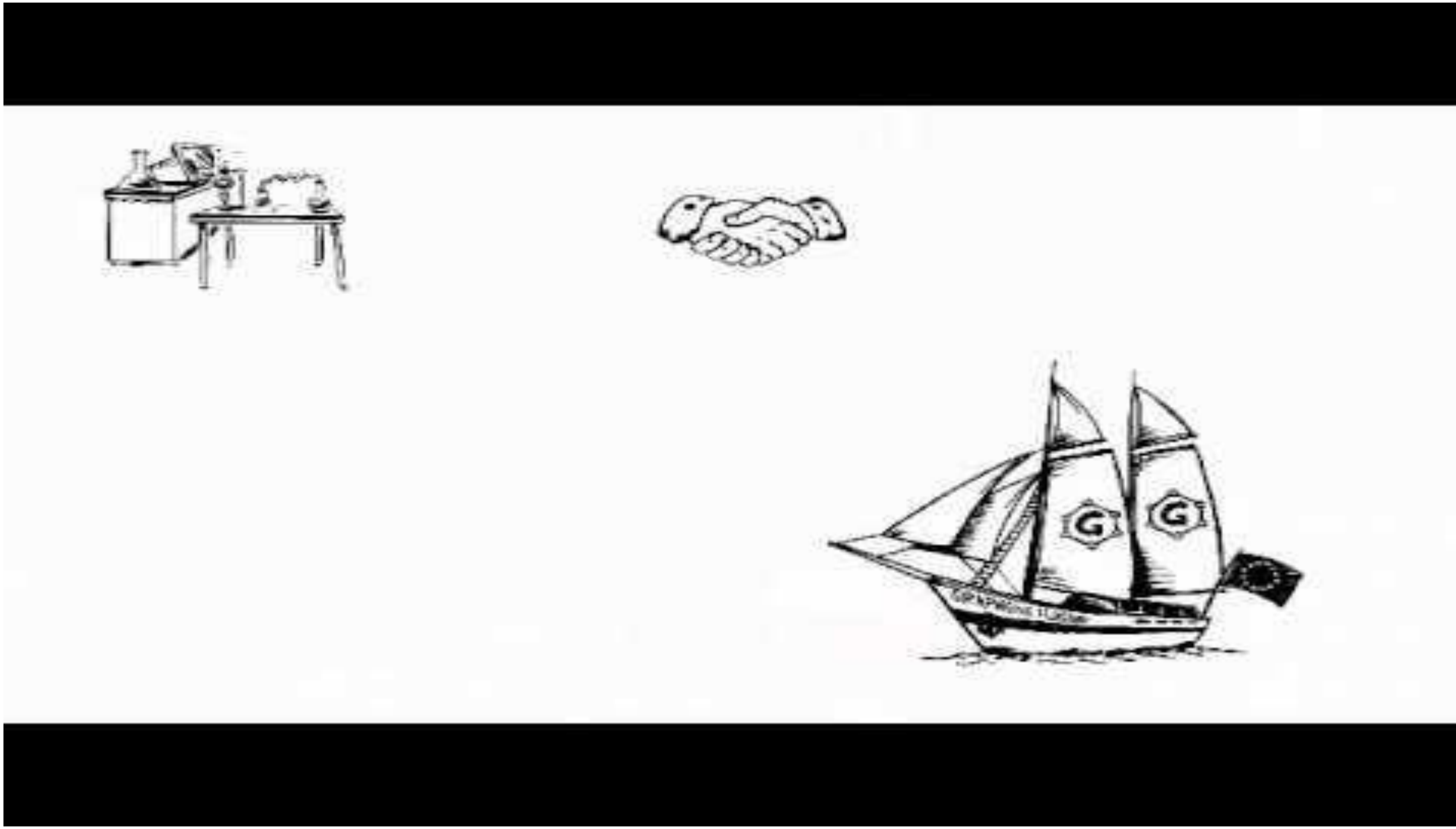
- What is Graphene : http://www.graphene-flagship.eu http://www.youtube.com/watch?feature=player_embedded&v=dTSnnlITsVg
- The Graphene Flagship project: http://www.graphene-flagship.eu http://www.youtube.com/watch?feature=player_embedded&v=3CoPVmWKraI
- Nokia Morph Project: http://research.nokia.com/morph http://www.youtube.com/watch?feature=player_detailpage&v=Zto6aTZM9t0
- Guardian Angels Flagship: www.ga-project.eu
- Six ways graphene could make the world a greener place , "The Guardian", January 28, 2015 http://www.theguardian.com/sustainable-business/2015/jan/28/graphene-six-ways-wonder-material-improve-world-sustainability?CMP=new_1194
- I. Llatser, A. Cabellos-Aparicio, E. Alarcón, J. M. Jornet, H. Lee and J. Solé-Pareta, ***"Scalability of the Channel Capacity of Graphene-enabled Wireless Communications to the Nanoscale"***, IEEE Transactions on Communications (to be published).
- I. Llatser, C. Kremers, D. N. Chigrin, J. M. Jornet, M. C. Lemme, A. Cabellos-Aparicio and E. Alarcón, **"*Radiation Characteristics of Tunable Graphennas in the Terahertz Band*"**, Radioengineering Journal, December 2012.
- J. M. Jornet and I. F. Akyildiz, **"Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band",** *IEEE Transactions on Wireless Communications*, 2011.

Documentació addicional

La **ràdio** és la transmissió de senyals mitjançant la modulació d'ones electromagnètiques amb freqüències per sota de les de la llum visible.
La radiació electromagnètica es propaga per mitjà de camps electromagnètics oscil·lants que travessen l'aire i el buit de l'espai. [Viquipèdia]



Cap al futur de la mà del grafè



- What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm, nm)?
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    - Reducing the size of the communication system: the antennas first
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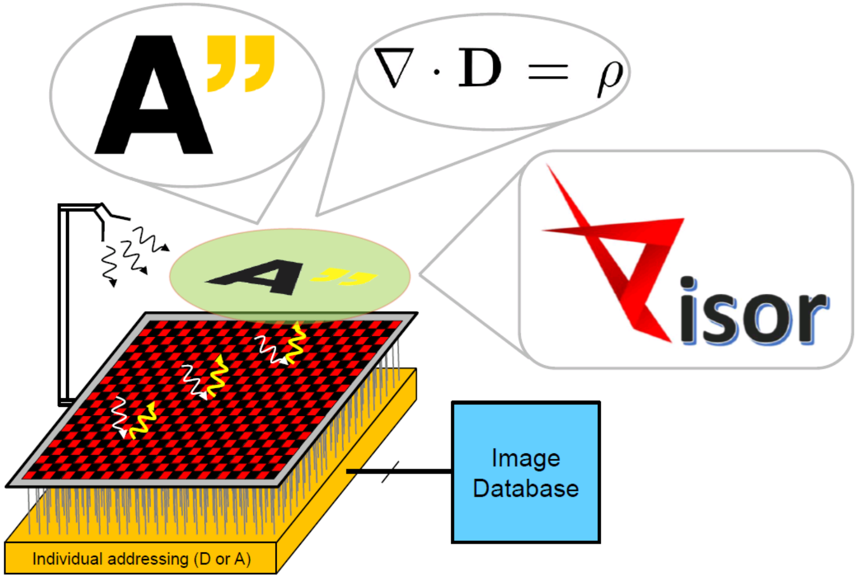
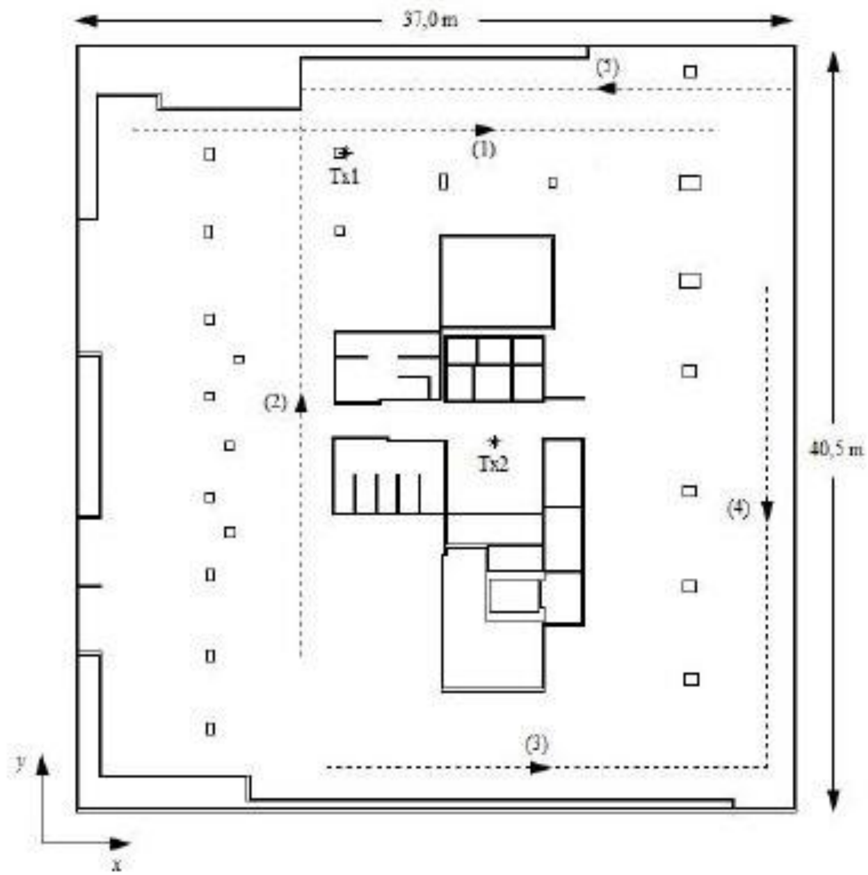
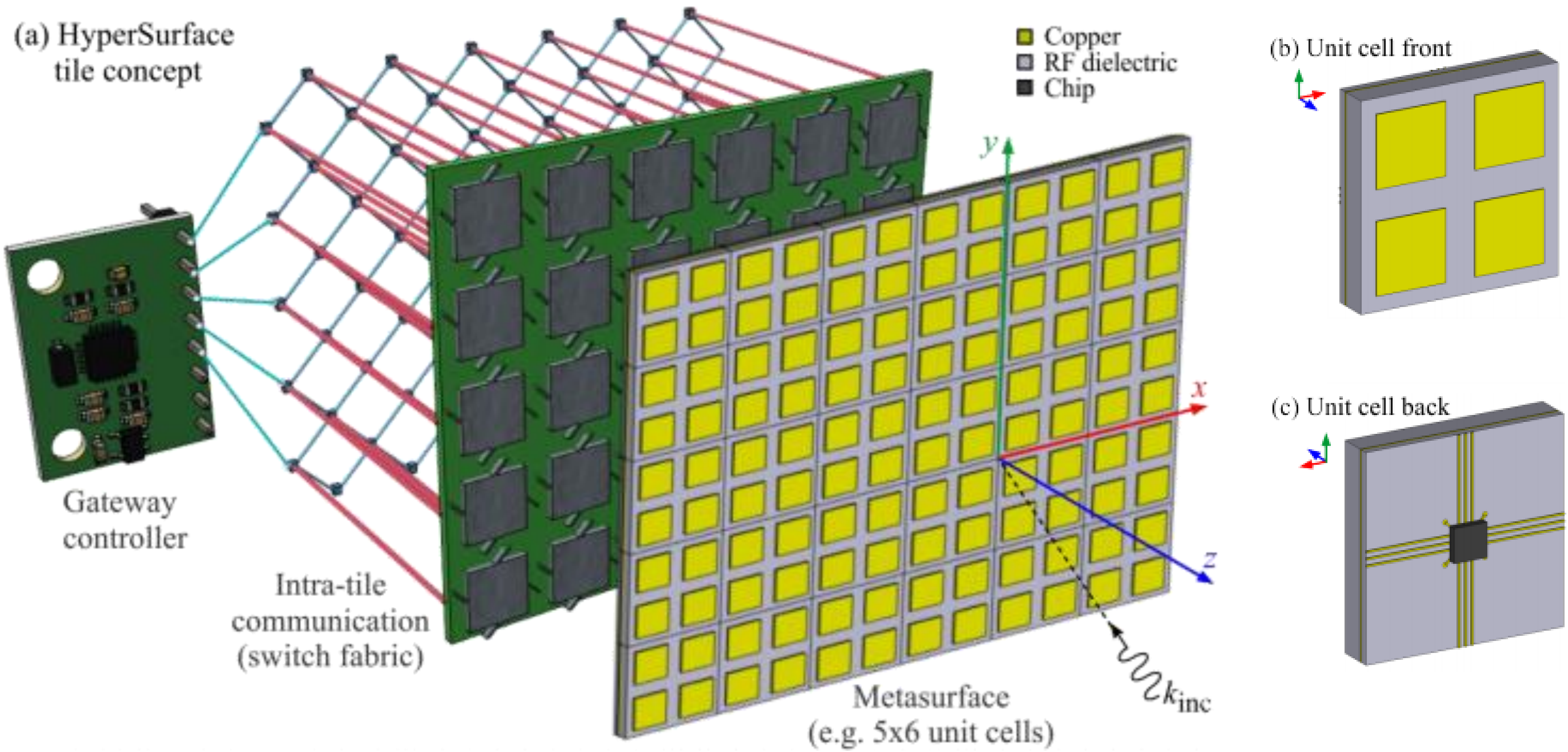
    - Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
    - Place antennas in complex systems, but that are extremely constrained in area

A wide variety of applications





Reconfigurable Metamaterials



S. Abadal, C. Liaskos, A. Tsioliaridou, S. Ioannidis, A. Pitsillides, J. Solé-Pareta, E. Alarcón, and A. Cabellos-Aparicio, **"Computing and Communications for the Software-Defined Metamaterial Paradigm: A Context Analysis,"** *IEEE Access*, vol. 5, 2017.

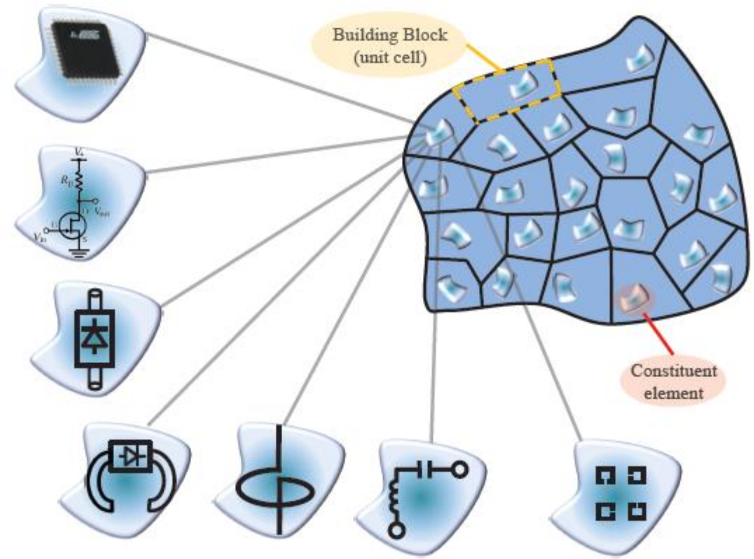
Reconfigurable **Metamaterials**

What does meta- mean?

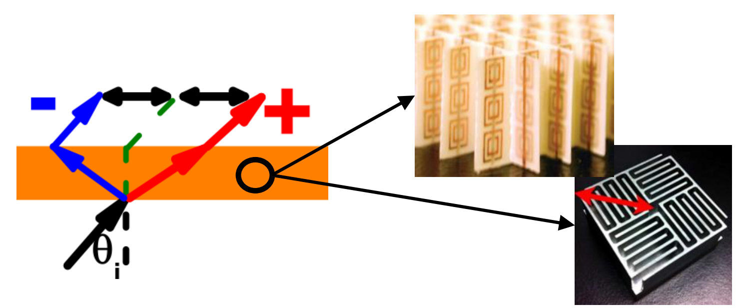
Metasurfaces: a loose definition

Ordinary materials

Metamaterials and metasurfaces

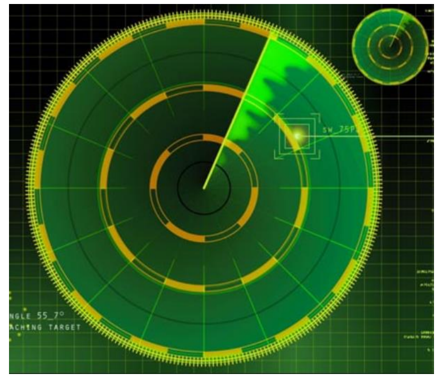


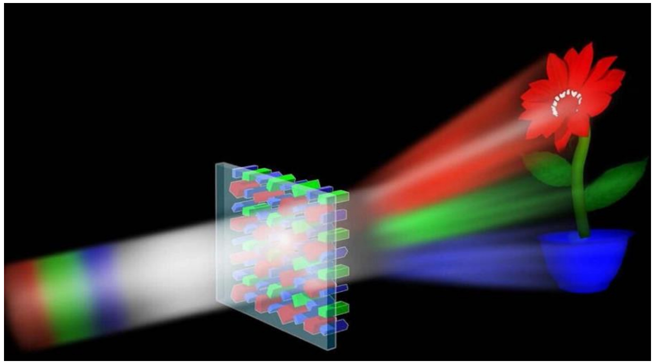
- Artificially structured materials
  - Elements, structures, devices …
- Subwavelength size and spacing
- Unusual properties for wave control
  - e.g., negative refraction

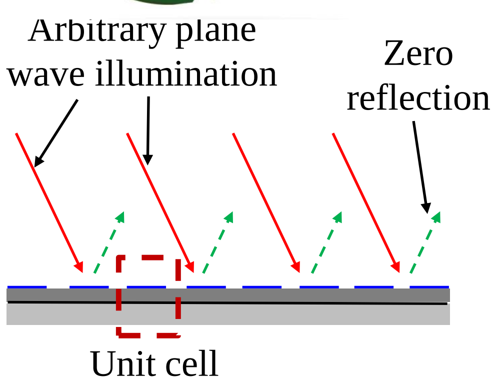


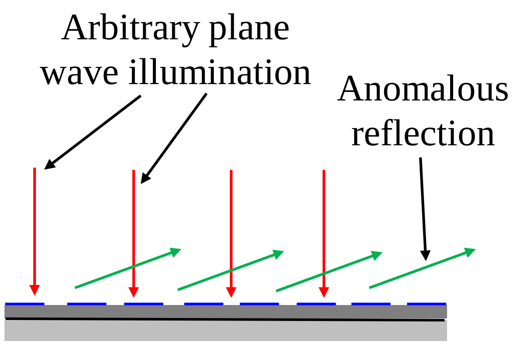
R. A. Shelby, *et al.*, *Science* **292**, 77 (2001)
Sci. Rep. **3**, 1614 (2013)

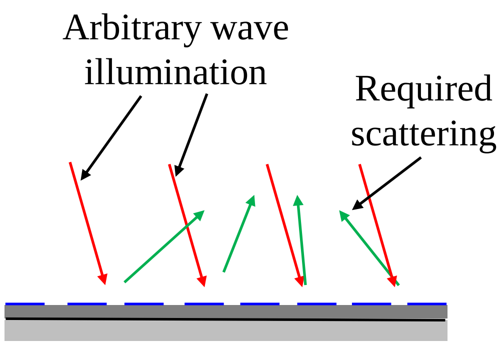
Applications of metamaterials

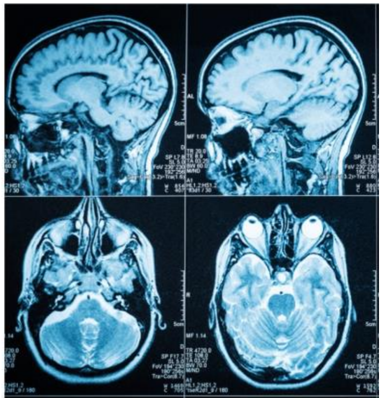


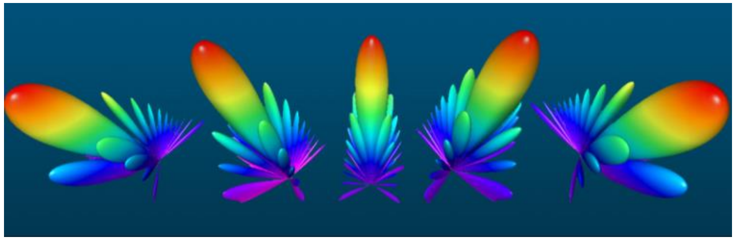


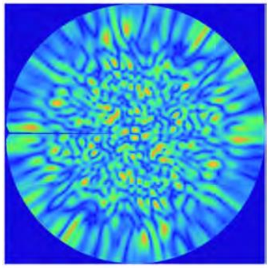


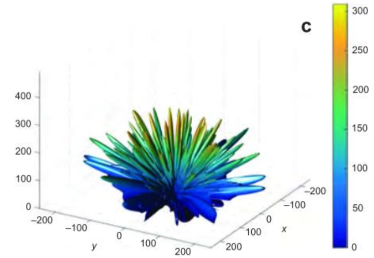








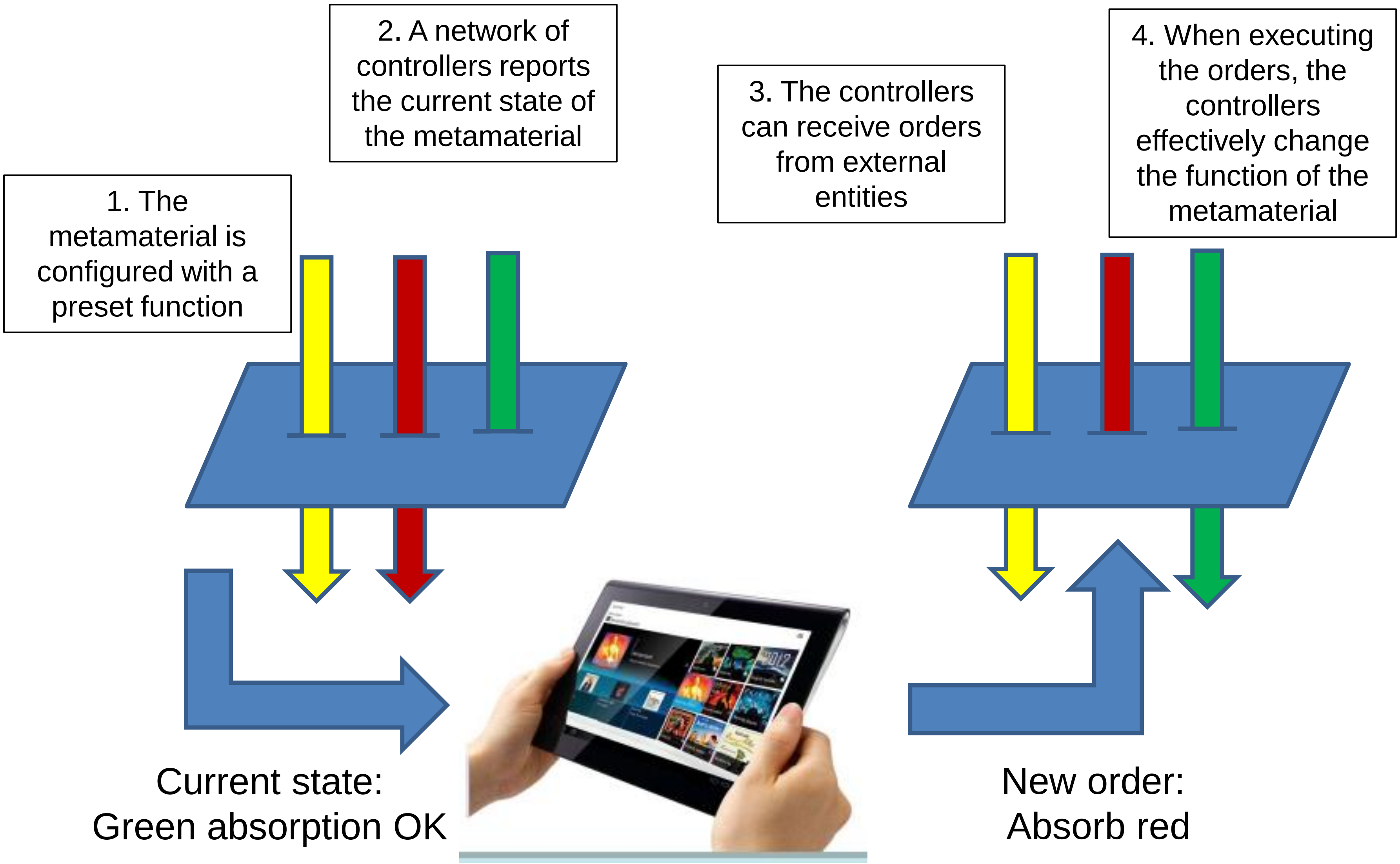




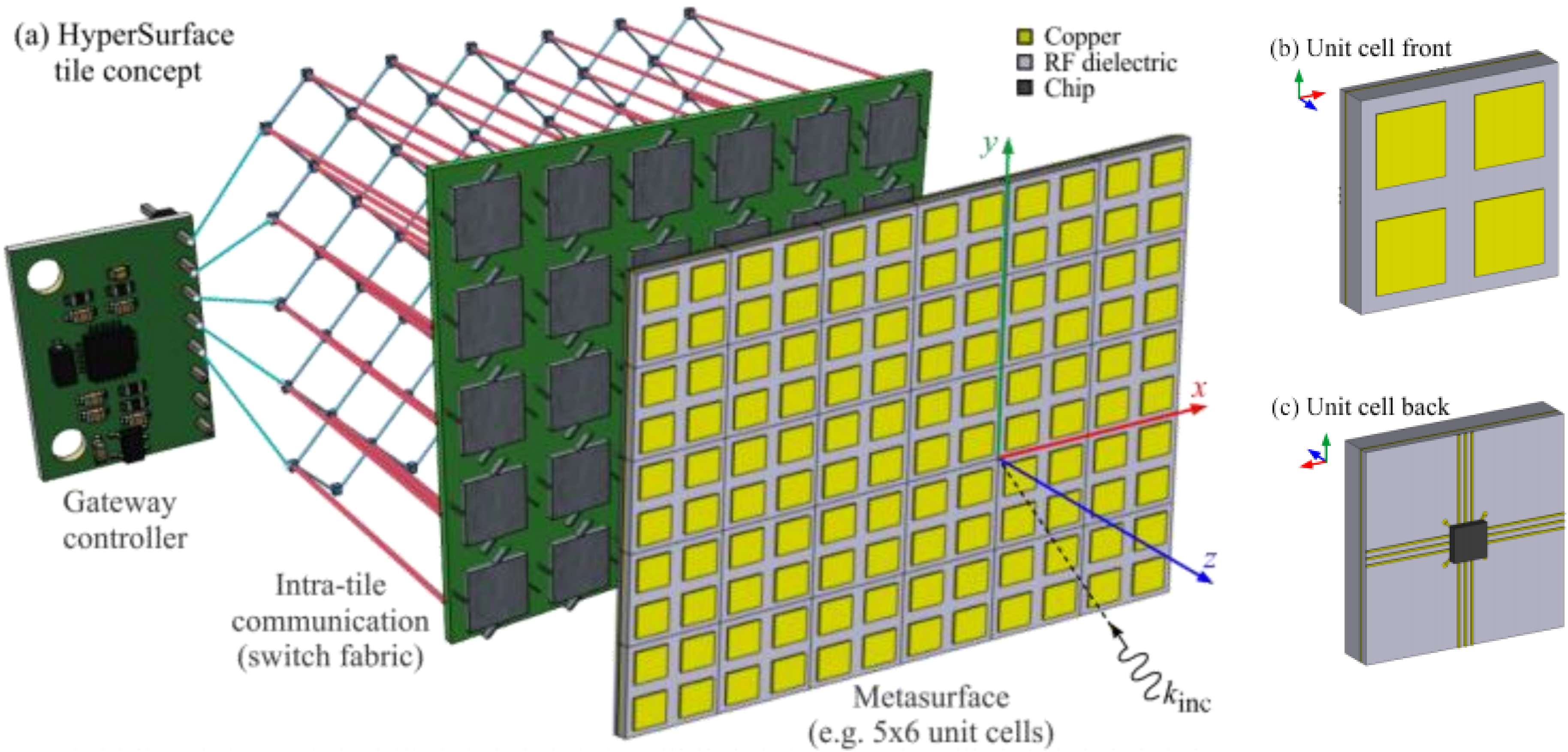
- Issues of metamaterials
  - They can only be designed by experts
  - They are expensive due to their complexity
  - They are bound to a single functionality once designed
  - It is near-to-imposible to modify certain parameters within the function for which it has been designed
  - They are completely isolated

- Objectives for reconfigurable metamaterials
  - Carrying out different functions
  - Being able to change their parameters at will or depending on the state of the surroundings
  - Being able to easily coordinate different metamaterials
  - Exposing reconfigurability to the non-expert (API)

Reconfigurable Metamaterials

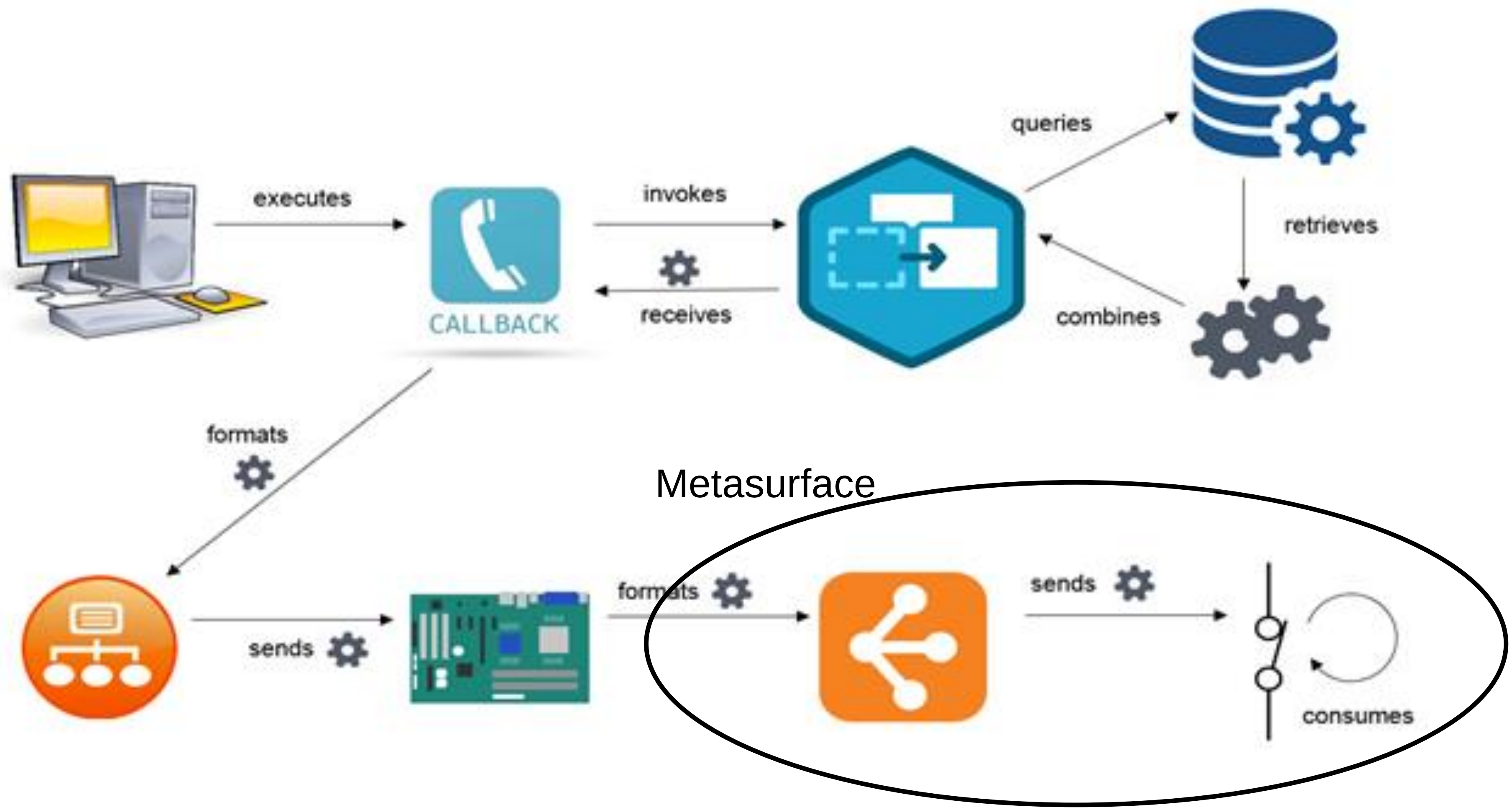


Why do we need antennas here?



S. Abadal, C. Liaskos, A. Tsioliaridou, S. Ioannidis, A. Pitsillides, J. Solé-Pareta, E. Alarcón, and A. Cabellos-Aparicio, **"Computing and Communications for the Software-Defined Metamaterial Paradigm: A Context Analysis,"** *IEEE Access*, vol. 5, 2017.

Why do we need antennas?



Interesting challenges

- How many bits of memory do we need at each controller?
- How do we, given a target EM behavior, know the state of each metallic patch?
- Should we design the network to be slow and low-power, or fast and intermittent?
- How much traffic should it support?

- A Hardware Platform for Software-driven Functional Metasurfaces
  - Multifunctional prototype at 5 GHz