ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ

Δίκτυα Καθοριζόμενα από Λογισμικό

Ενότητα 4.1 Προγραμματιζόμενα Υλικά

Ξενοφώντας Δημητρόπουλος
Τμήμα Επιστήμης Υπολογιστών

Programmable Materials

Extending the Software-Defined concept to the electromagnetic behavior of mater

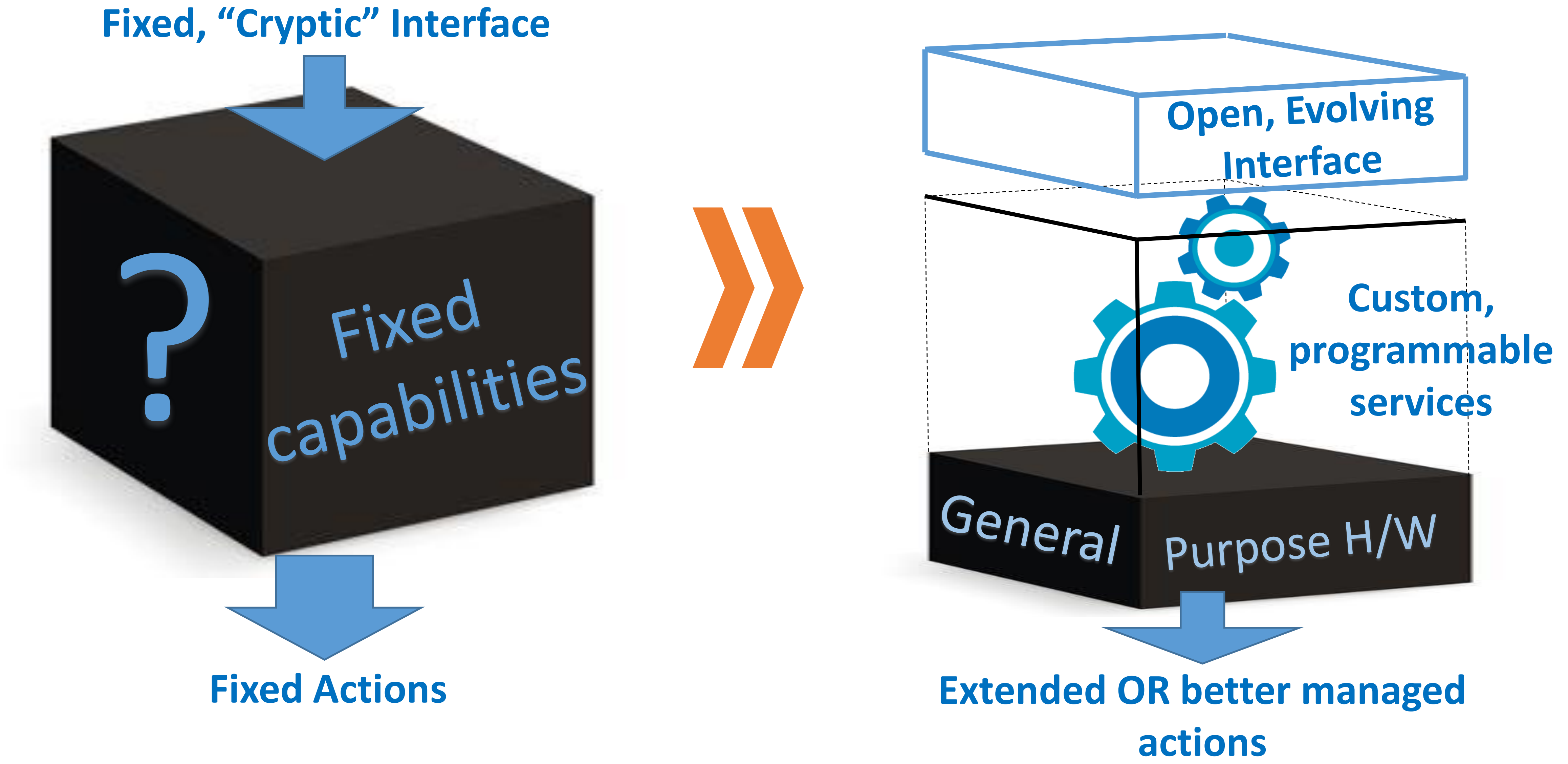
Outline

- **Overview of Software-Defined “X” technologies.**
  - Advantages
    - What lead us here?
- **Going one step further: Software-Defined Materials**
  - Building block 1: Meta-materials
  - Building block 2: Nanonetworks
  - Merge: SDM Conceptual operation
- **Applications: Invisibility & more**
- **Challenges**

Overview of Software-Defined “X” technologies

- Emerging Technologies
  - **Software-Defined Networking.**
    - Separate the Data plane from the Network control plane.
  - **Software-Defined Data Centers.**
    - Separate the DataCenter Physical Infrastructure from the offered services (virtualization).
  - **Software-Defined Storage.**
    - Separate the Storage Hardware from the Storage control software (logic).
  - **Software-Defined Radio.**
    - Separate Radio Hardware from the offered functions (modulation, encoding, multiplexing).

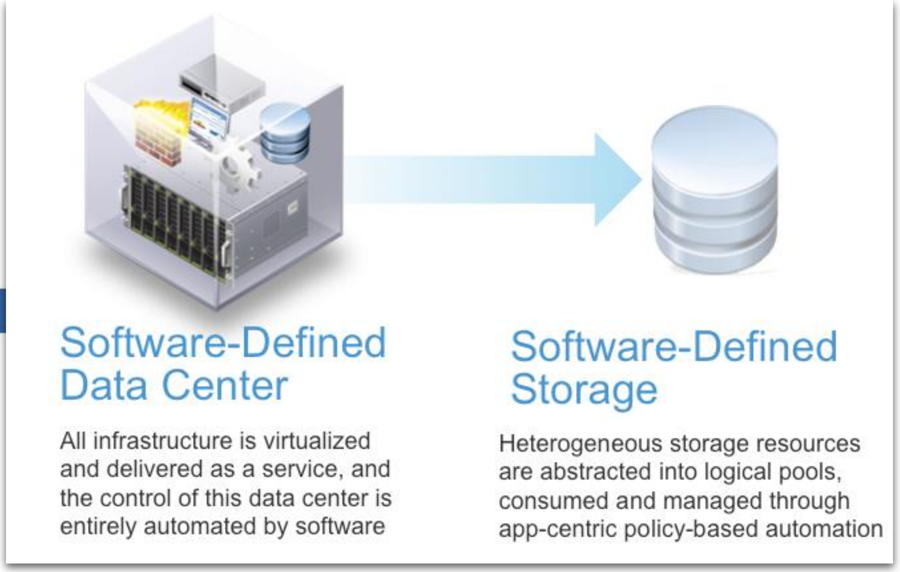
A forming trend → plasticity

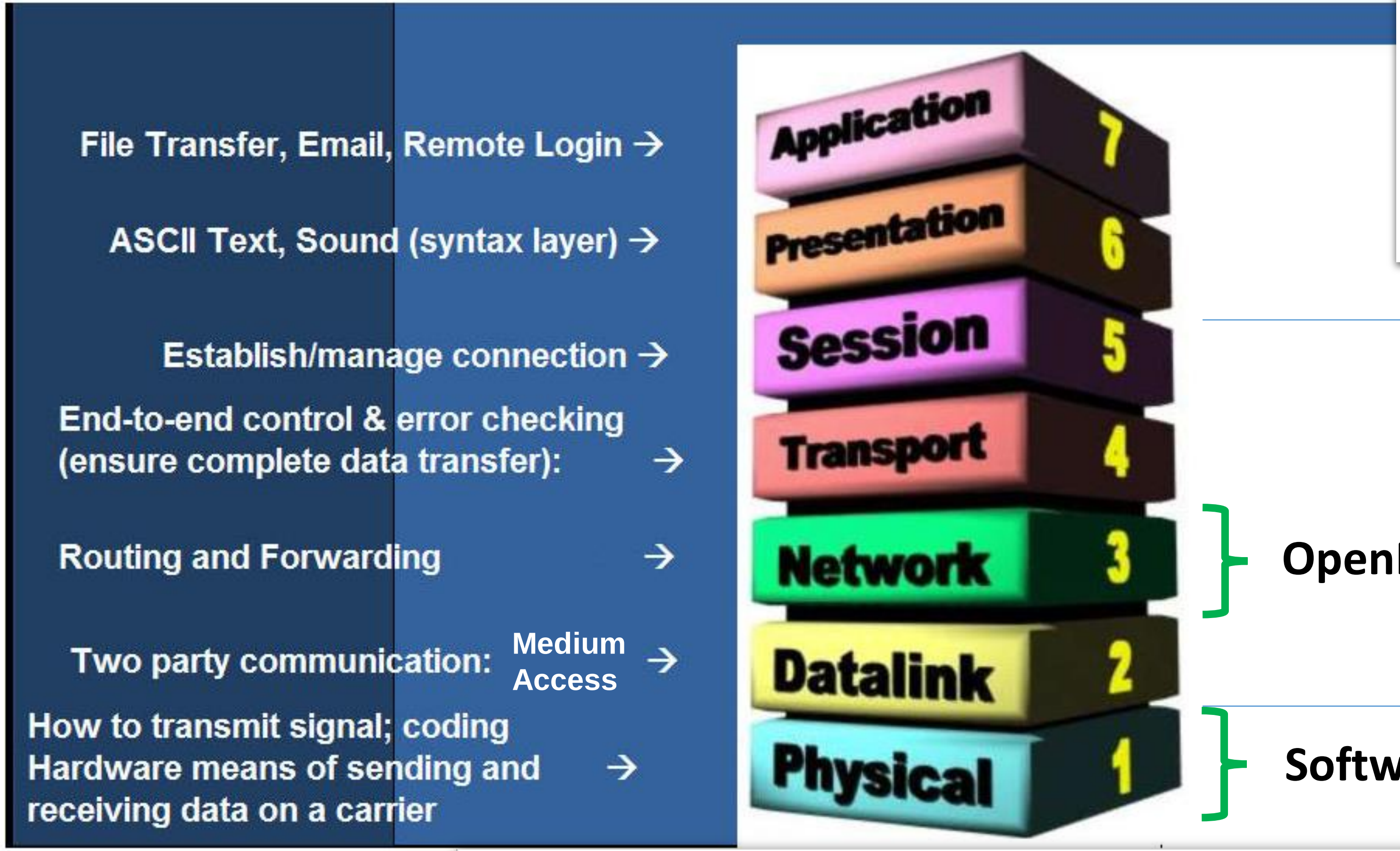


Advantages of plasticity

- **More value for money**
  - Same device, reconfigured, does more.
    - As opposed to "BUY a new one".
- **A catalyst for innovation**
  - Try out new ideas in SOFTWARE (0$), on the same physical device.
    - As opposed to "BUILD a new one".
- **Control better the internals of your owned devices**
  - Open API, programmable functionality.
    - As opposed to "Don't touch the internals of your device!".
- **Beautify and <u>unify</u> the programming interface!**
  - Constantly evolve towards a single, human-friendly API.
    - As opposed to multiple, ossified, case-specific or even unexposed API.

Plasticity at OSI layers thus far



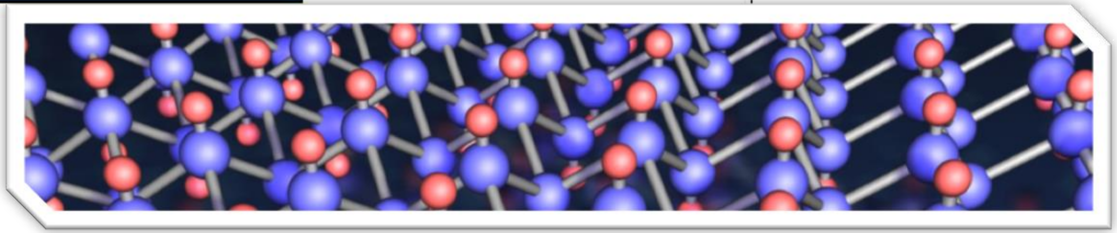


OpenFlow

Software Defined Networking Potential

Software-Defined Radio

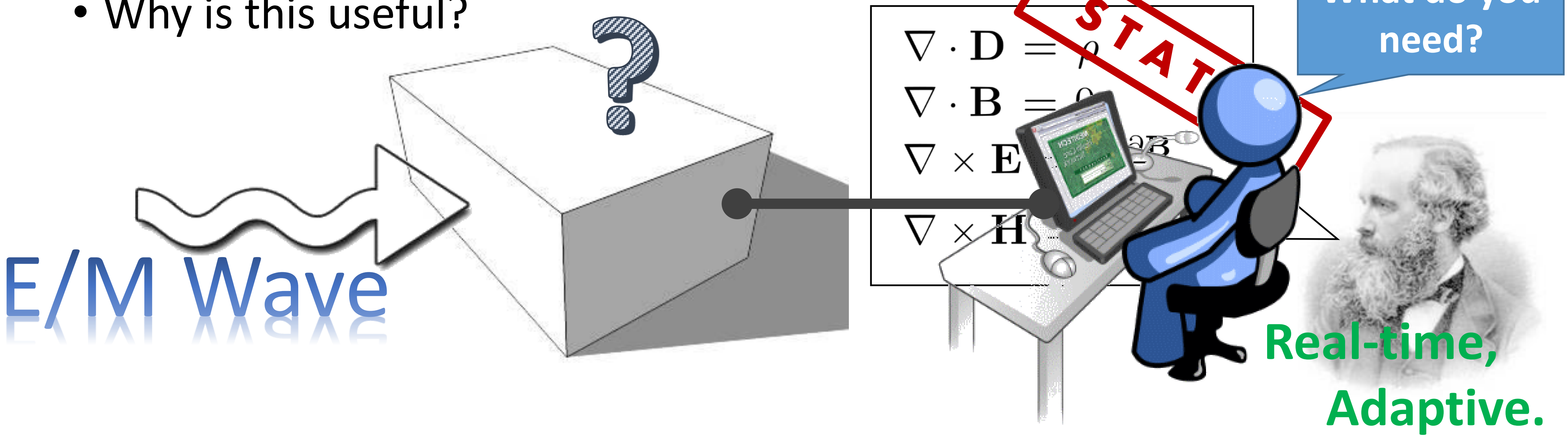
"OK.. So, where is the hardware?"



Common denominator:
The static laws of material physics!

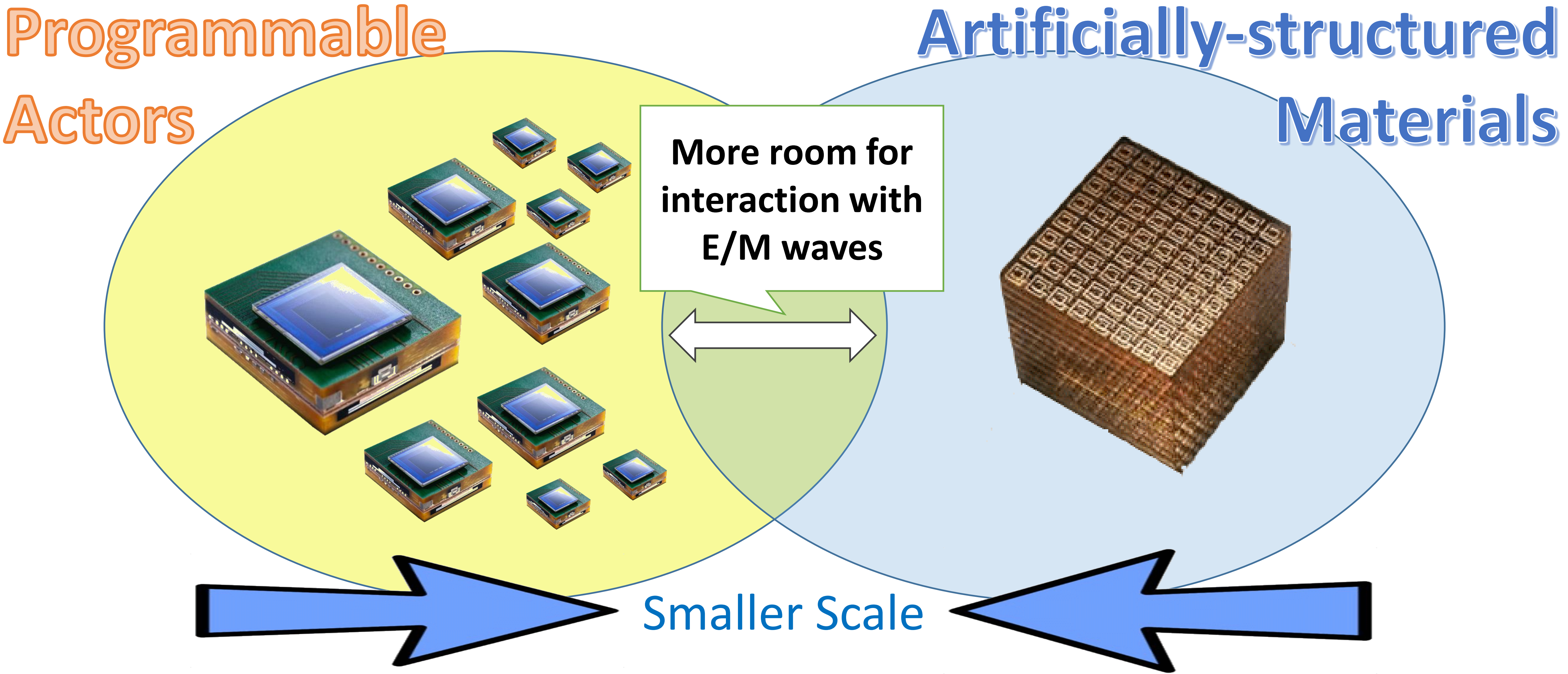
What could a plastic material offer?

- Define VIA SOFTWARE how it interacts with:
  - Light,
  - Electromagnetic waves in general.
  - *(Not focusing on **mechanical** properties → see "Claytronics" project for r/w)*
- Why is this useful?



Carnegie Mellon University, "Claytronics", http://www.cs.cmu.edu/~./claytronics/index.html

A sketch of a software-defined, programmable material



The SDM Components

- **The actors:**
  - Network of minified computers.
  - **Right now:** ASICs, same technology as modern CPUs (about 500μm).
  - **Under research:** **nanonetworks** (100nm-1μm expected).
- **The artificial "scaffold":**
  - **Meta-materials.**
  - A very well-known, hot topic in Physics research.
  - Very popular in recent research on E/M invisibility.
    - http://gulfnews.com/news/world/usa/scientists-racing-to-build-invisibility-devices-1.1270952
    - On The Quest To Invisibility - Metamaterials and Cloaking: Andrea Alu at TEDxAustin
      - http://www.youtube.com/watch?v=jseHPnqXlPY

Definition of Metamaterials

"Metamaterials are periodic or quasi-periodic, sub-wavelength metal structures. The electro-magnetic material properties are derived from its structure rather than inheriting them directly from its material composition."

empty glass

regular water, n = 1.3

"negative" water, n = -1.3

Based on definition of J.Pendry 2000

Some trivia:

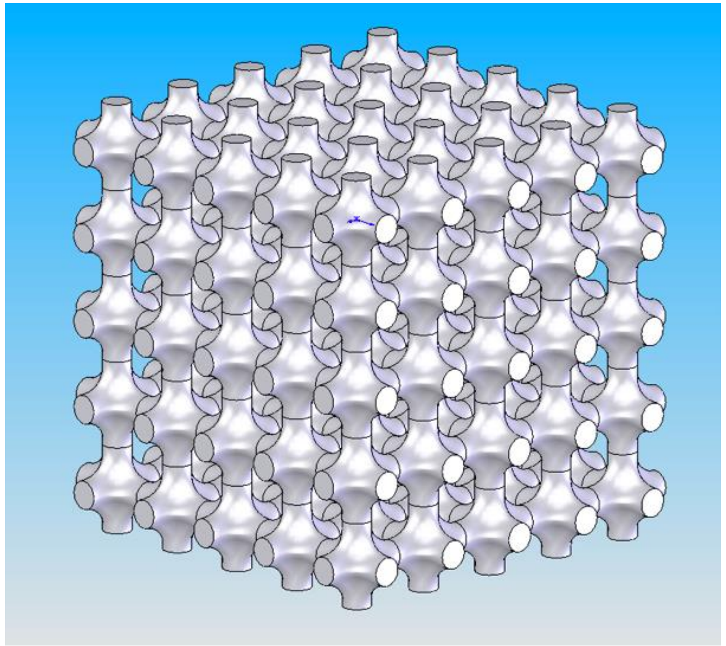
- Developing field of research

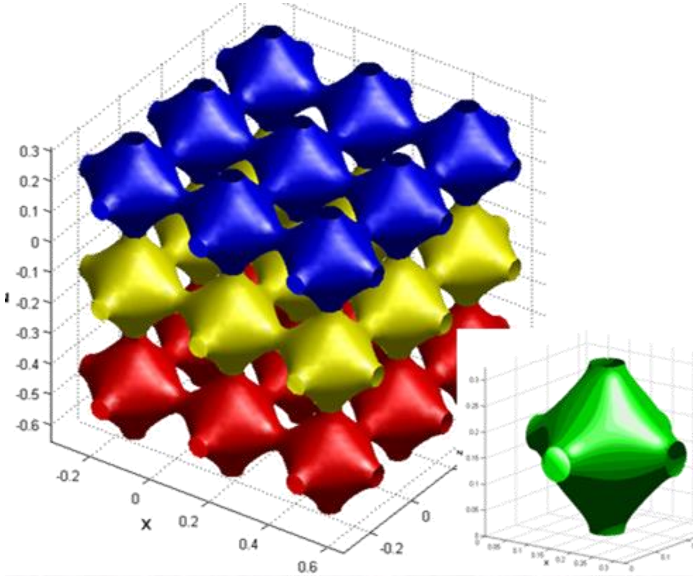
- Applications in wide range of sectors, such as communications, optics, energy

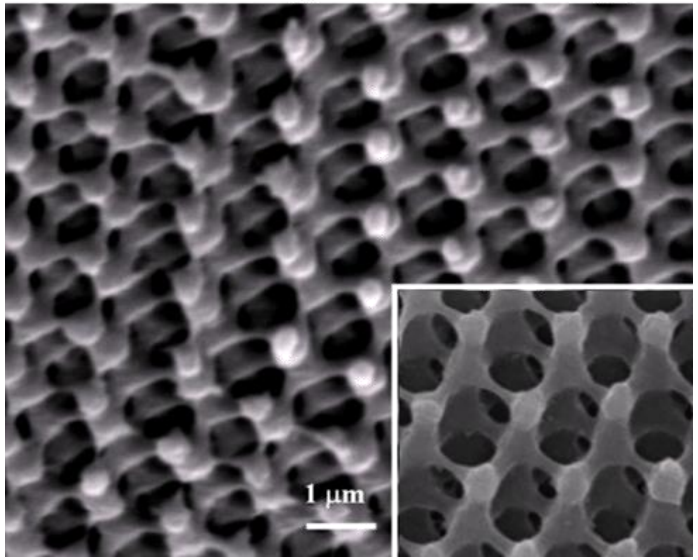
- Currently used for wave manipulation

How does a metamaterial look?

A periodic material that derives its properties from its structure rather than its components.



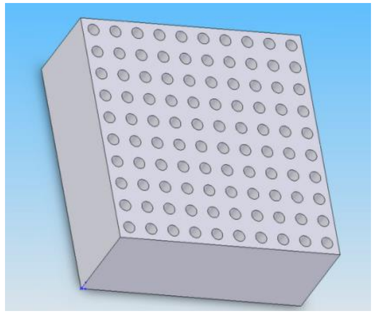


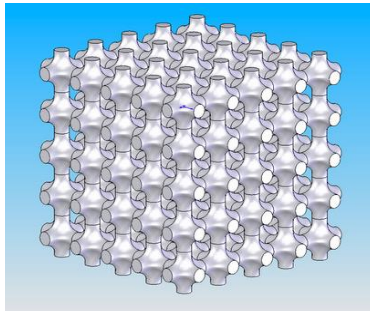


*Taken From 3.042 handout & Physics Worlds 2005 “Sound Ideas”

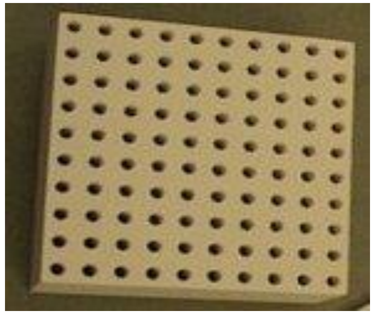
How do we build one?

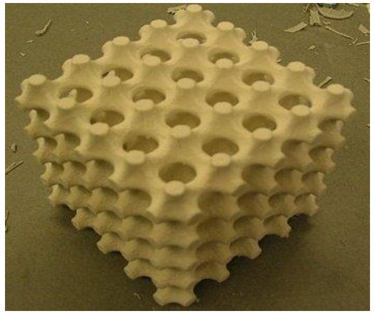
CAD Model





3-D Printing

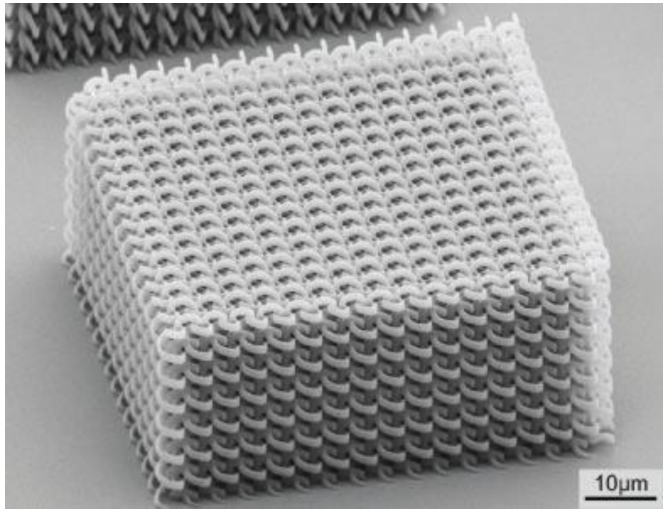


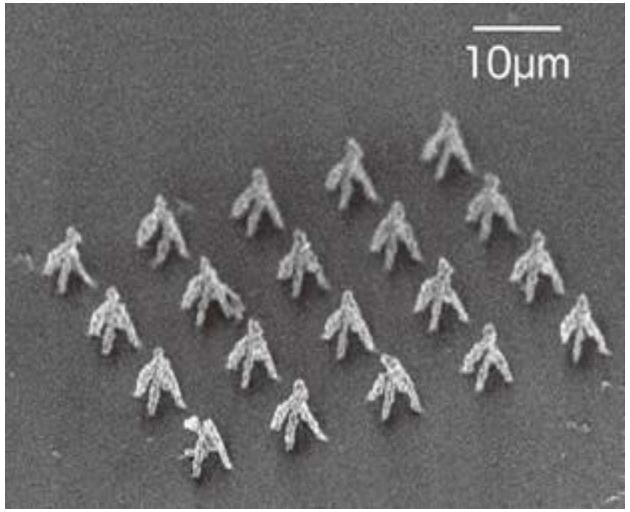


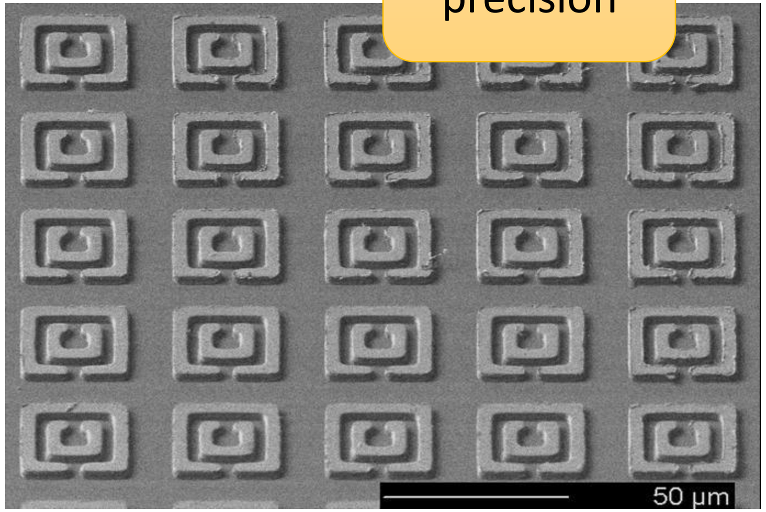
mm precision

VLSI-based techniques (same as chipset manufacturing)

Even **nm** precision







(Meta-)Material Properties By Design

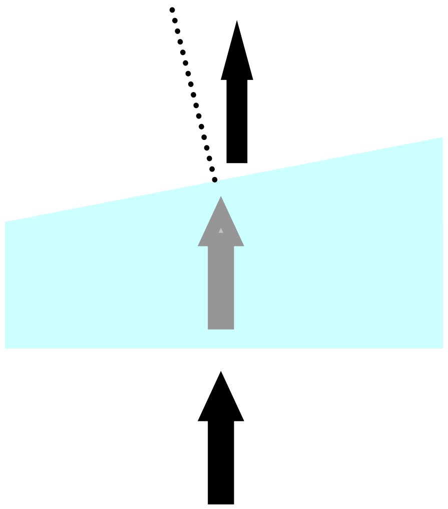
- Each elementary block yields different macroscopic attributes. I.e. **Customizable E/M behavior**.
- From
  - "Find a material with these properties"

To

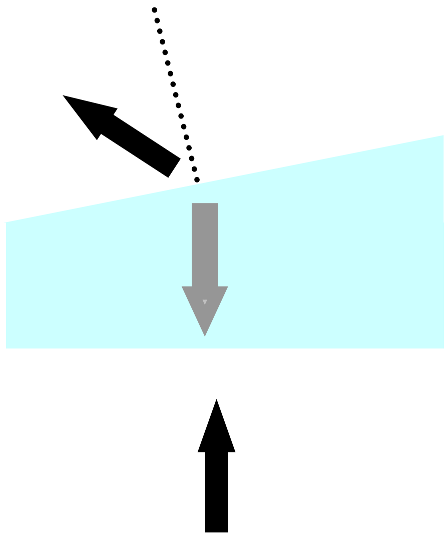
  - "**Design** a material with these properties"
- **BONUS:** Design materials with **unnatural** properties as well!

No. 1 Customizable E/M property

Custom ray steering (Light or E/M wave) within a metamaterial.



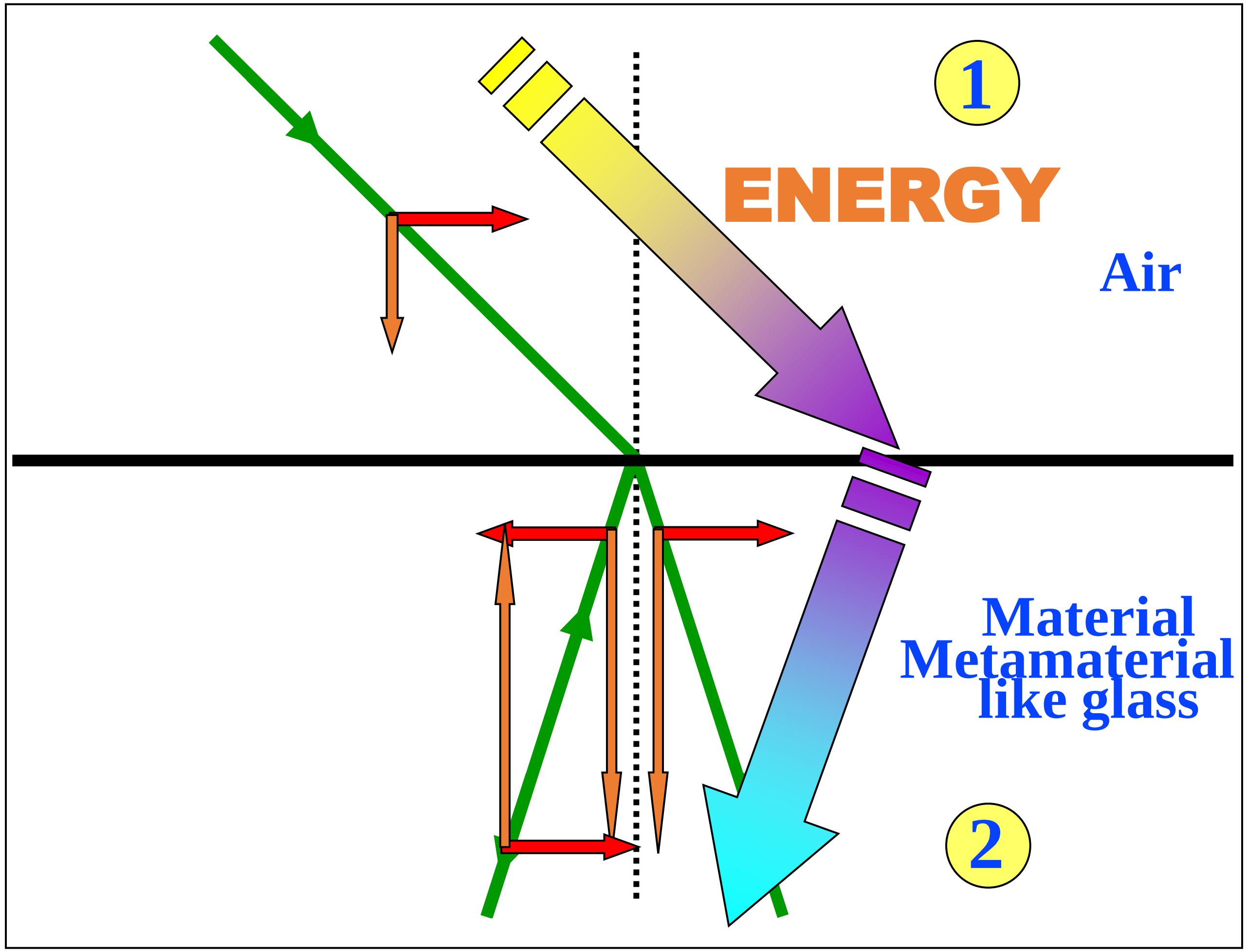
Positive refraction index



Negative refraction index

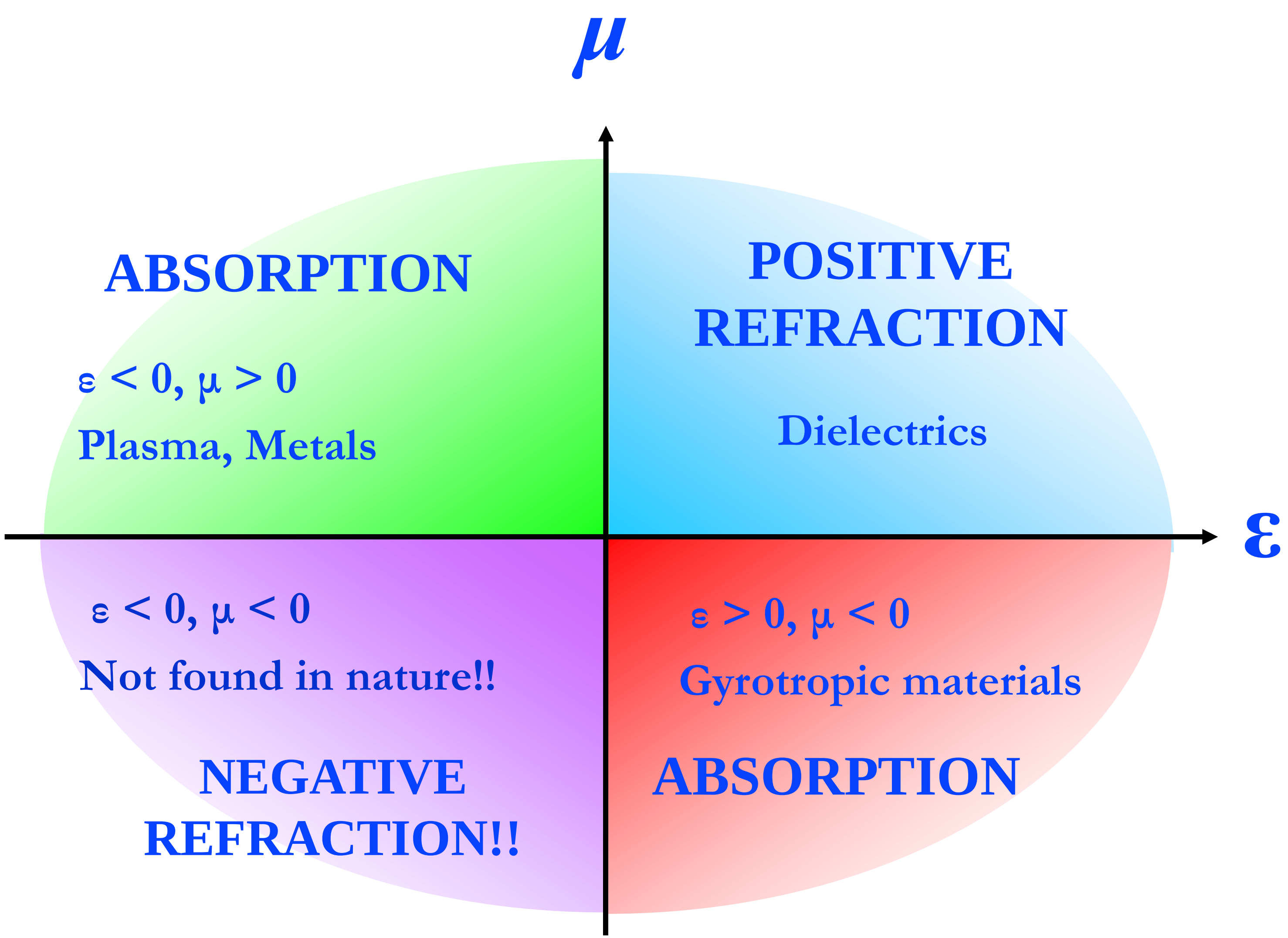
Expected refractions

Is This Refraction Possible?

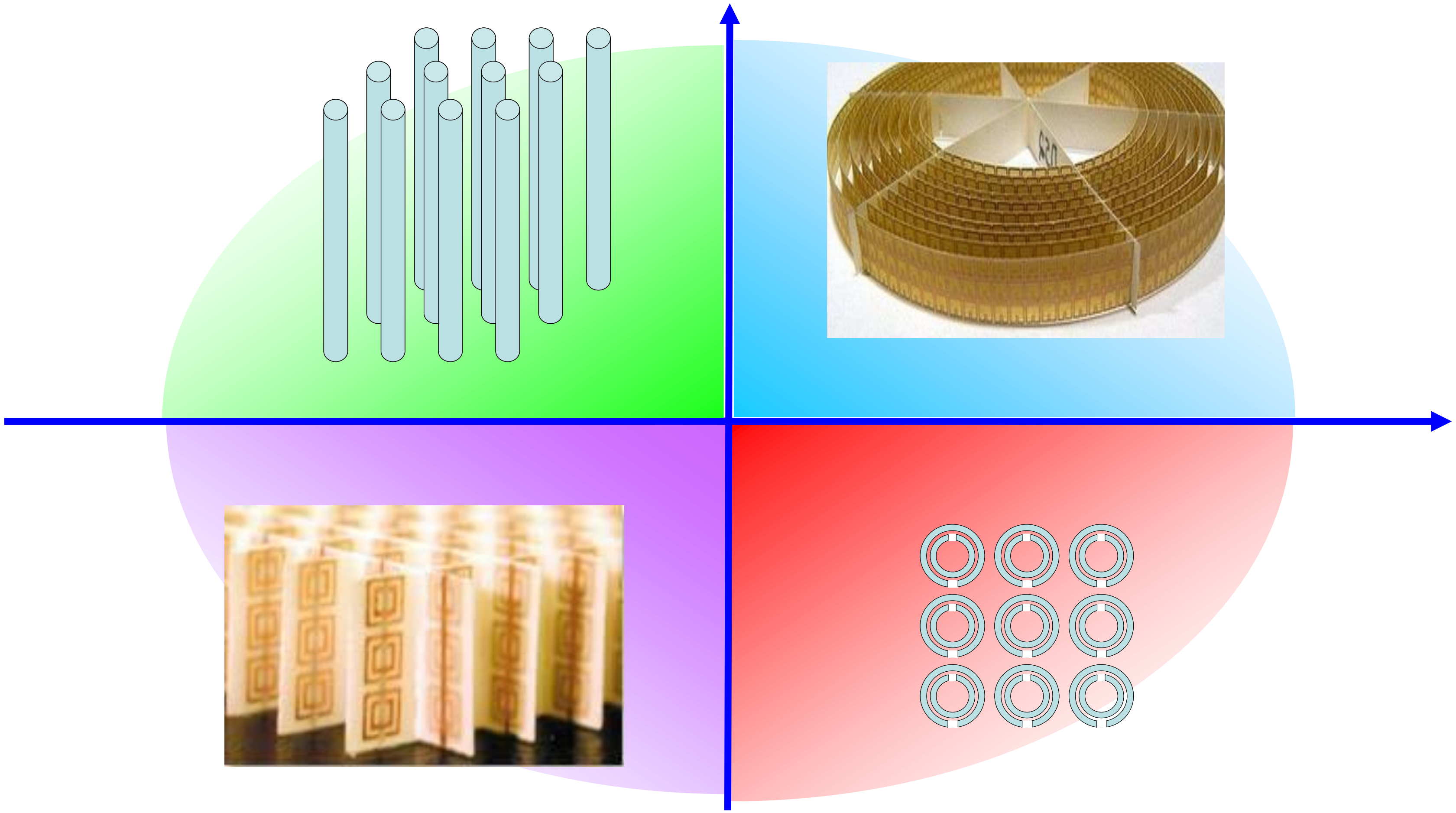


Classification of materials

$$n = \pm\sqrt{\varepsilon\mu}$$



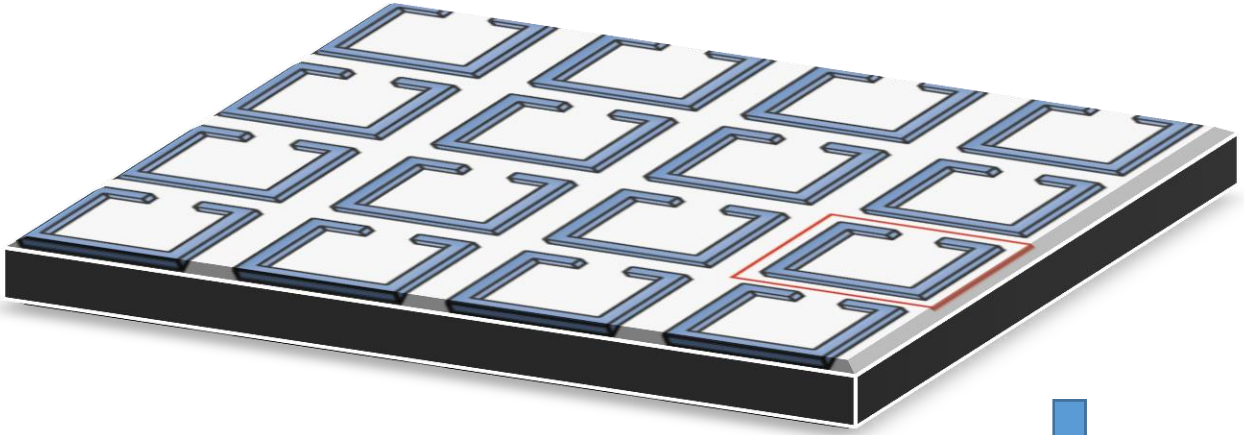
Classification of materials

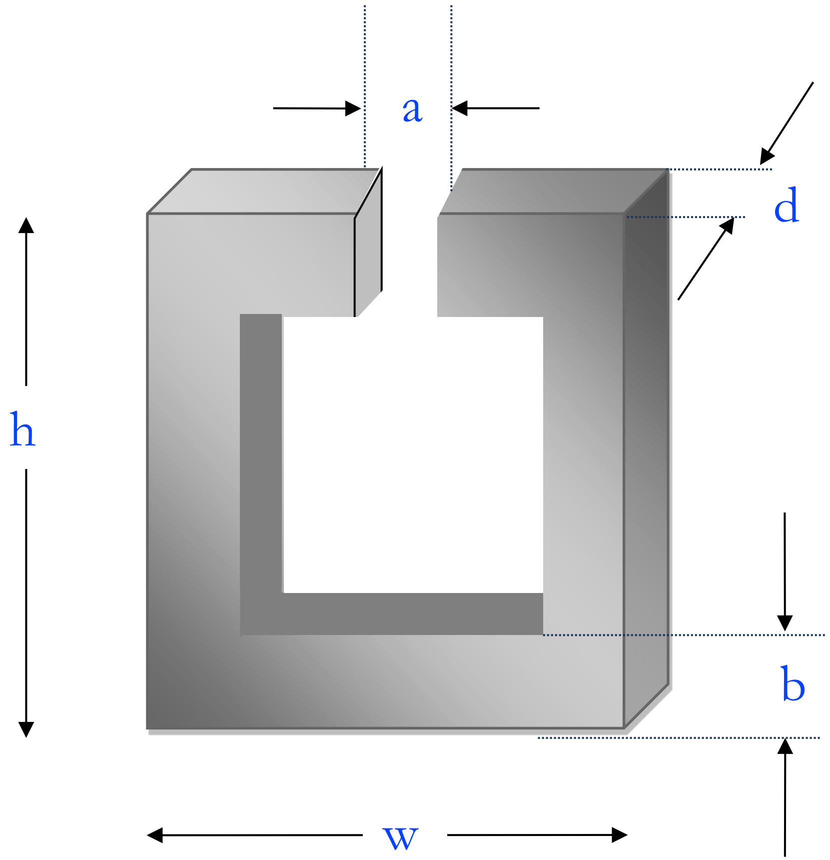


With the right pattern, metamaterials can achieve any combination!

- Natural or Unnatural!
- Steering or Absorbing at any angle!

Tuning a Metamaterial Pattern

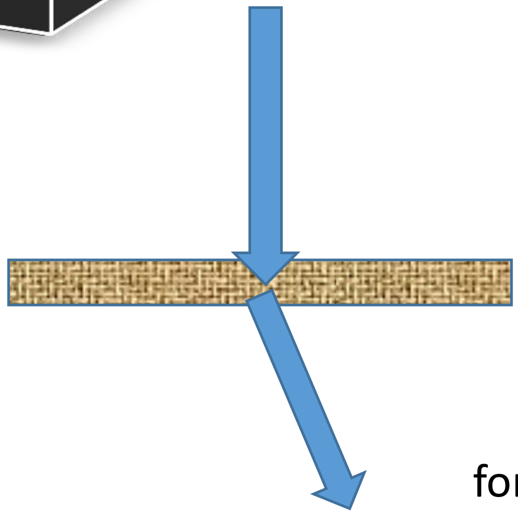




schematics of the elementary cell.

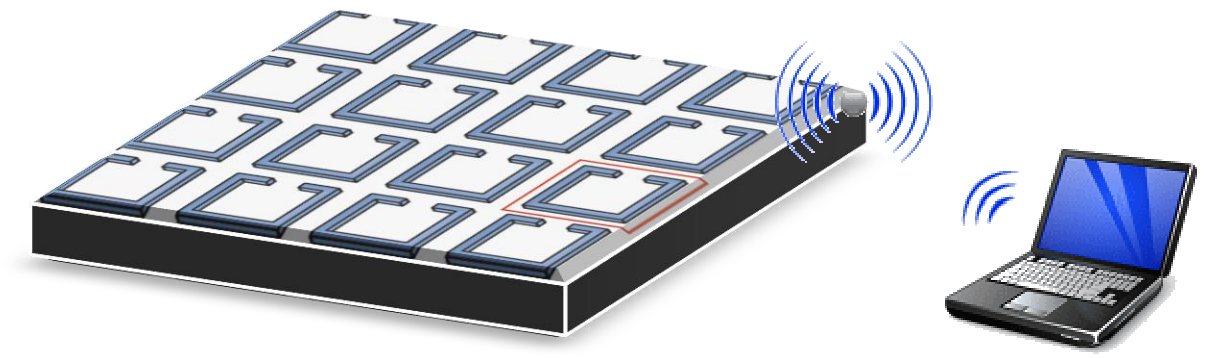
STEER

ABSORB

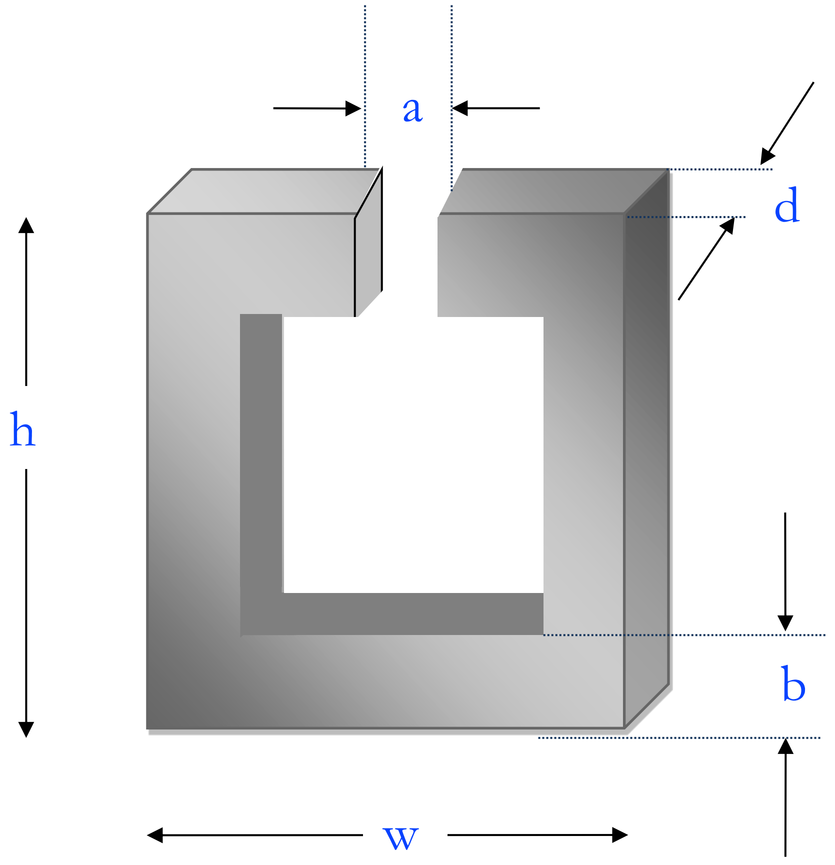


STEER at variable angle,
for variable operating frequency

What if we had a software-defined Pattern?

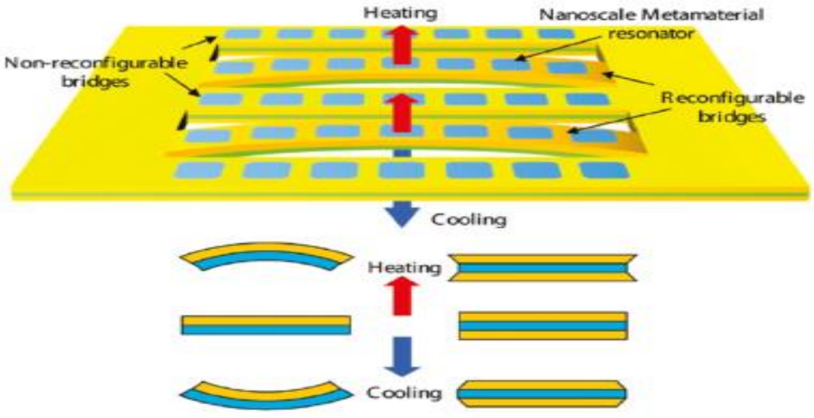


```
> SET h=3nm w=3nm a=1nm;
  Material now absorbing energy at (e.g.) F=10GHz.
> SET h=… w=… a=… b=… d=…;
  Material now refracting waves at angle Θ=45º.
> IF environmental_radiation>10Watt THEN ABSORB.
  Absorber mode activated..
```

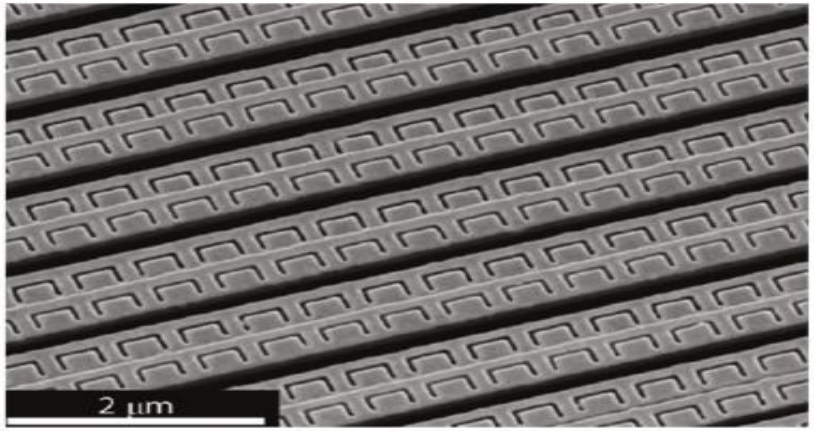


schematics of the elementary cell.

Some work on tunable metamaterials already

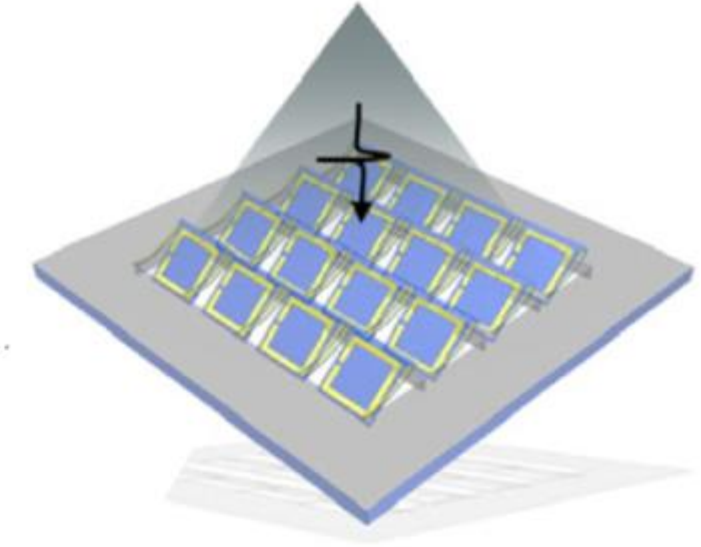


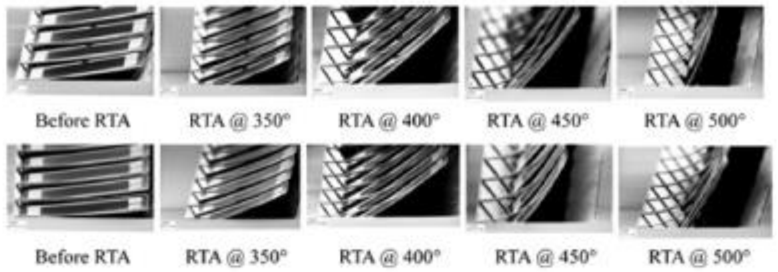
(a)



(b)

Modifiability is there, but programmability is missing.





- *N. I. Zheludev and Y. S. Kivshar, "From metamaterials to metadevices," Nature Materials, vol. 11, no. 11, pp. 917–924, 2012.*
- *A. Q. Liu, W. M. Zhu, D. P. Tsai, and N. I. Zheludev, "Micromachined tunable metamaterials: a review," J. Opt, vol. 14, no. 11, p. 114009, 2012.*

The actors

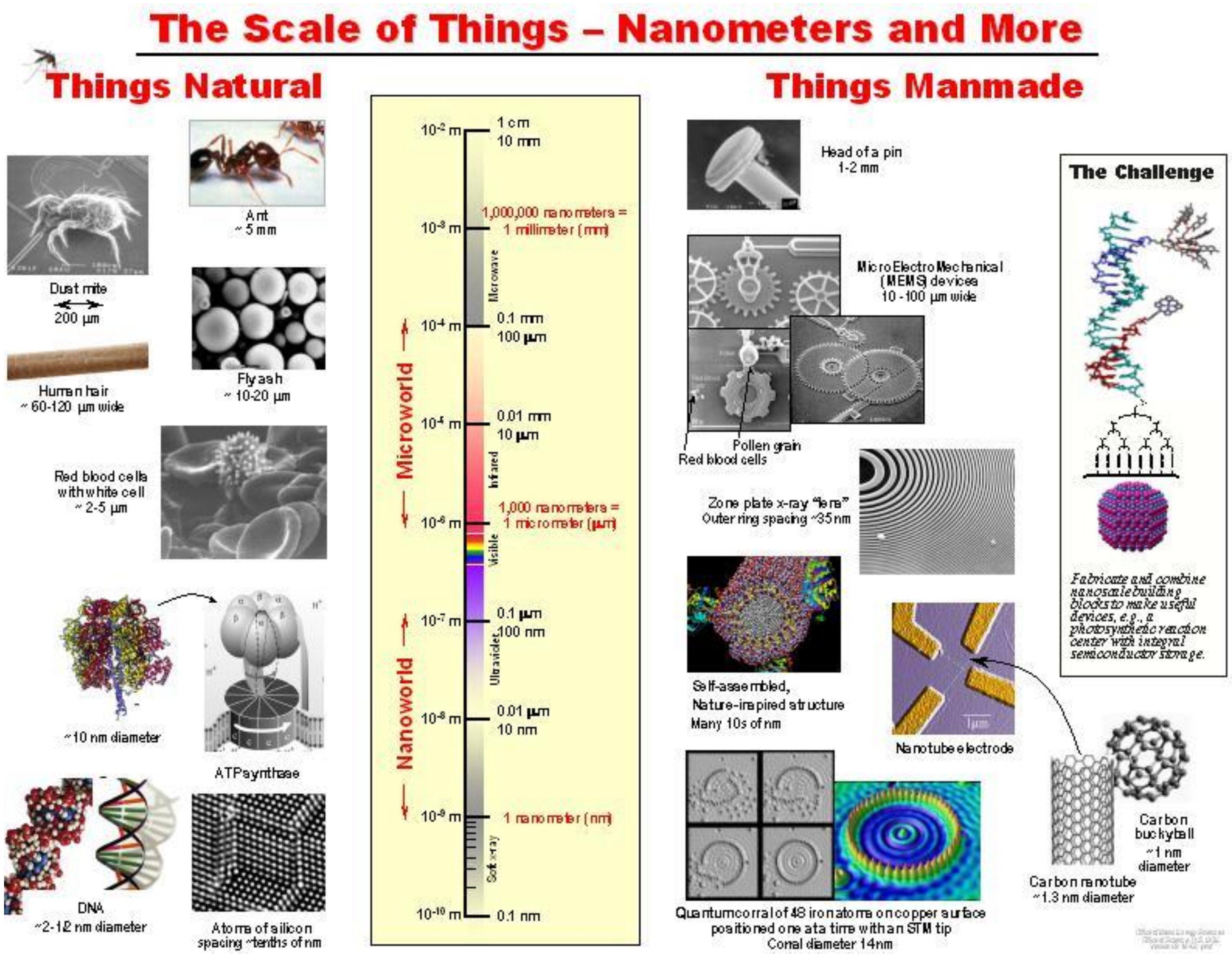
- We need “smart” elements, hidden inside a metamaterial, that:
  - Receive programmatic commands,
  - Execute pattern-altering actions,
  - WITHOUT messing with the metamaterial function.

HENCE

  - A network of miniaturized, electronic controllers,
  - Ideally, equipped with a wireless communications interface,
    - (But wired can also be good enough for some cases)
  - Ideally, overall size at Nanoscale,
    - (But bigger ones could work in some cases as well)

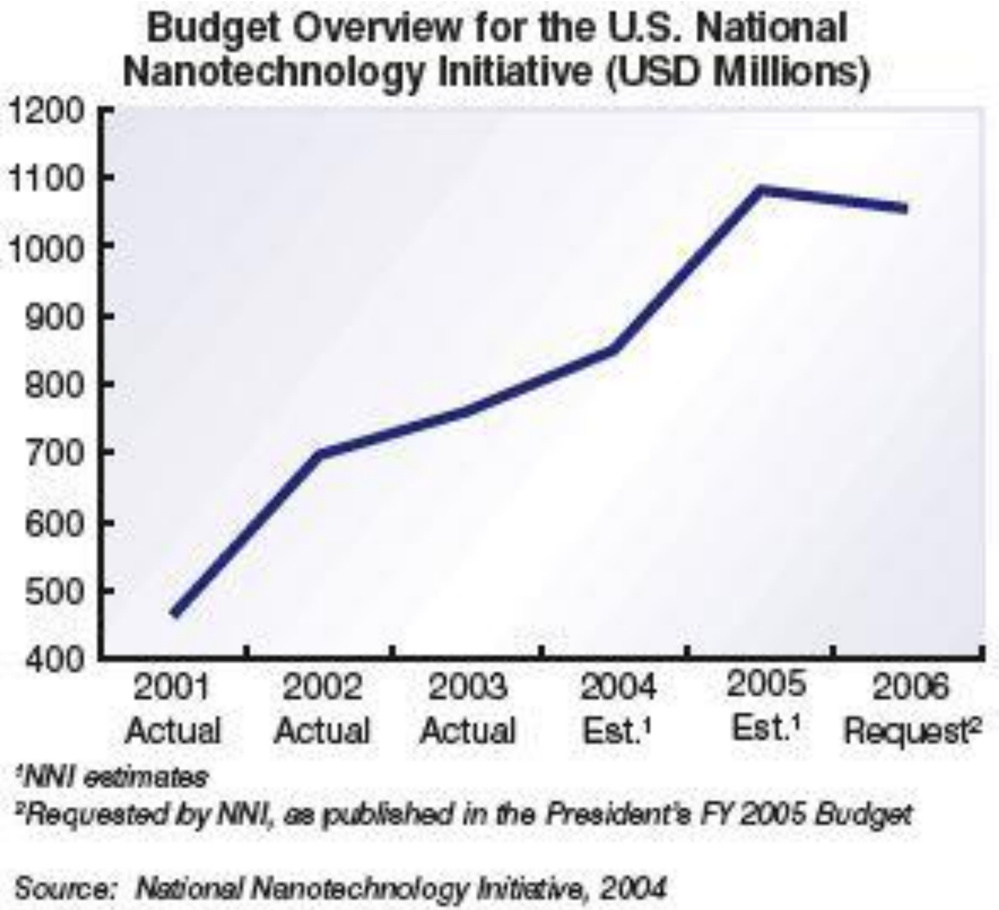
Nanotechnology

- Understanding and control of matter at dimensions of 1 to 100 nanometers
- Ultimate aim: design and assemble any structure atom by atom - molecular manufacturing

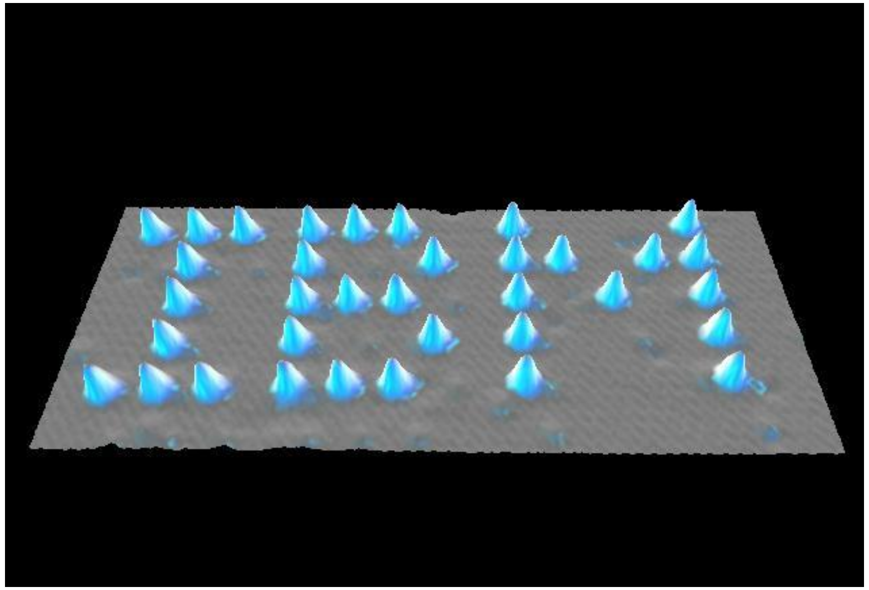


Courtesy Office of Basic Energy Sciences,
Office of Science, U.S. Department of Energy

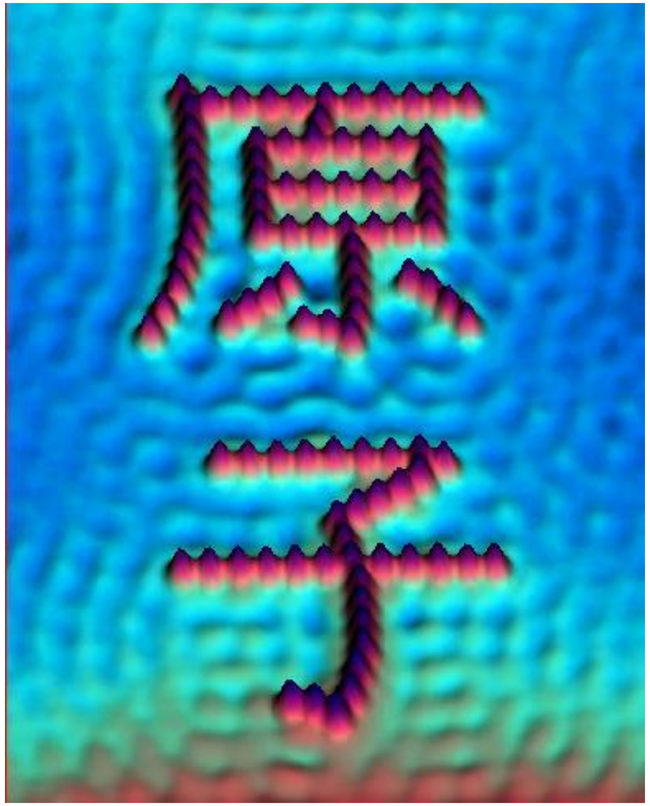
How much are we investing in Nanotechnology today?



STM allows manipulation of individual atoms (1989)



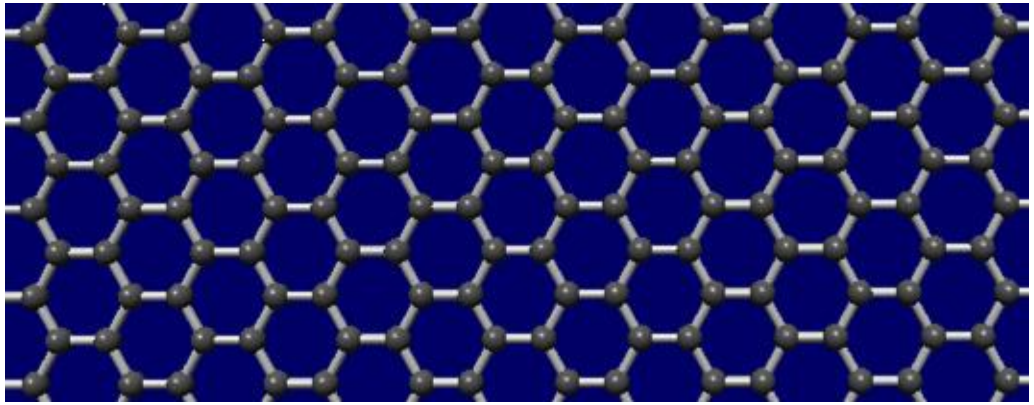
Xenon atoms spell IBM on a nickel plate
(IBM)



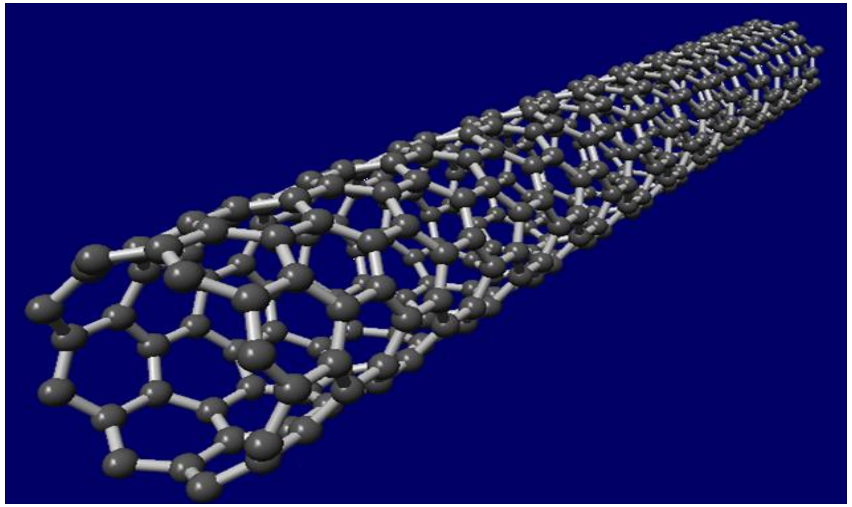
Iron atoms spell “Atom” on copper
in Kanji characters.
(IBM)

Nanomaterials:
Graphene, Nanotubes & Nanoribbons

Graphene: A one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice.

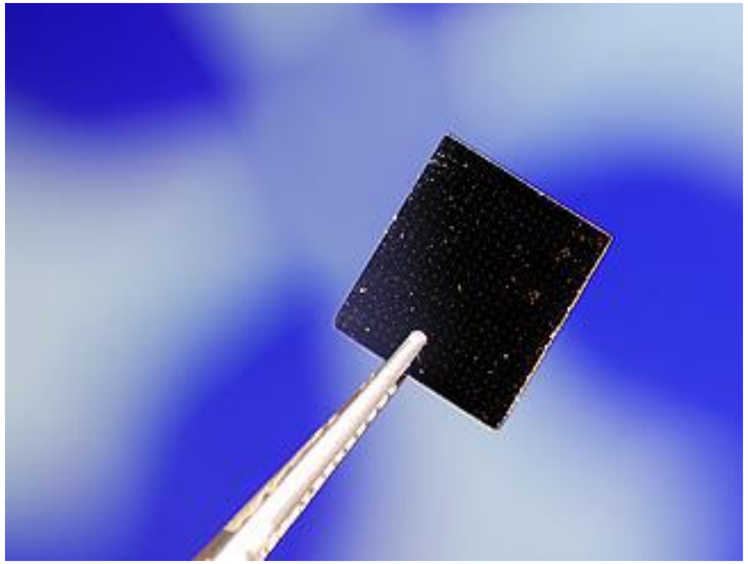


* Graphene Nanoribbons (GNR): A thin strip of graphene (2004)

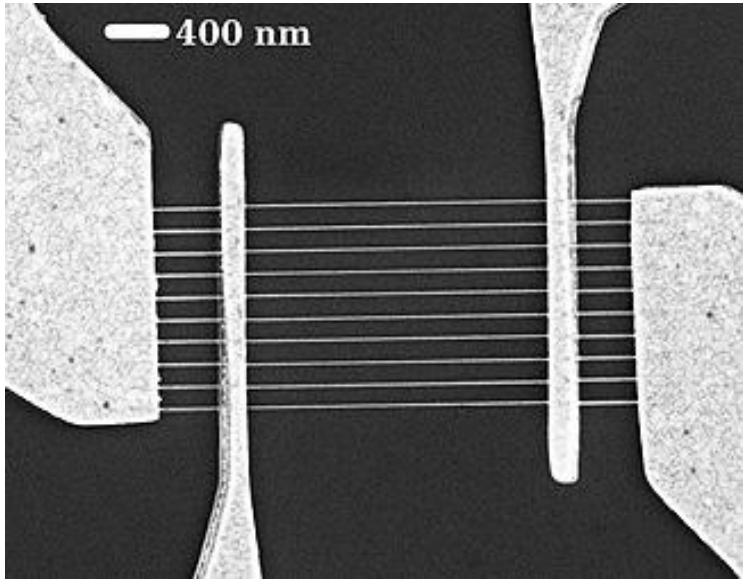


* Carbon Nanotubes (CNT): A folded nano-ribbon (1991)

Nanomaterials: Graphene, Nanotubes & Nanoribbons



A graphene material sample used for testing its properties.



Ten graphene nanoribbons between a pair of electrodes

Courtesy of the Exploratory Nanoelectronics and Technology (ENT) Group, School of ECE, GaTech.

Nanomaterials:
Graphene, Nanotubes & Nanoribbons

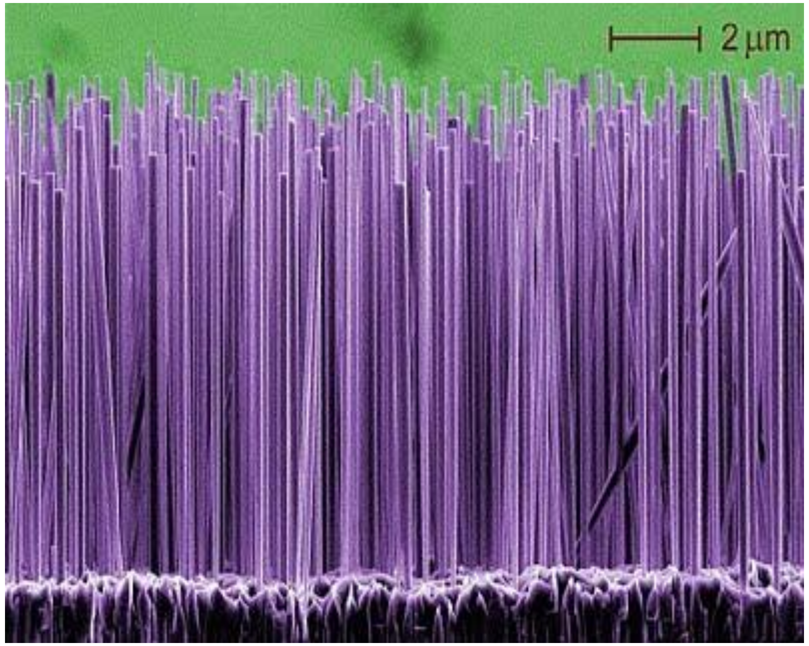
Their electrical and optical properties offer:

* High current capacity + High thermal conductivity → **Energy efficiency**
* Extremely high mechanical strength → **Robustness**
* Very high sensitivity (all atoms are exposed) → **Sensing capabilities**

New opportunities for device-technology:
Nano-batteries, nano-memories, nano-processors, nano-antennas, nano-tx, nano-rx.

POWER UNIT (NANO-BATTERIES)

- Zinc Oxide Nano Wires



High density nano-wires used for nano-batteries.

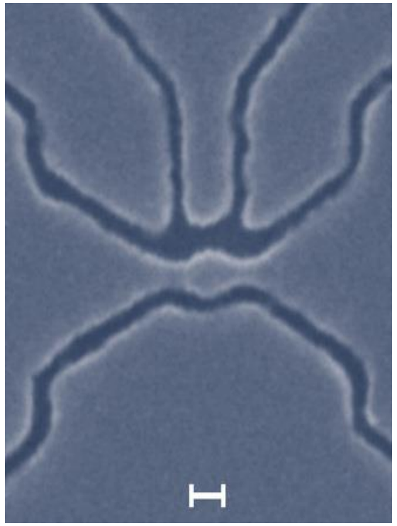
- Improved power density, lifetime, and charge/discharge rates.

NANO-PROCESSOR

* 45 nm transistor technology is already on the market

* 32 nm technology is around the corner

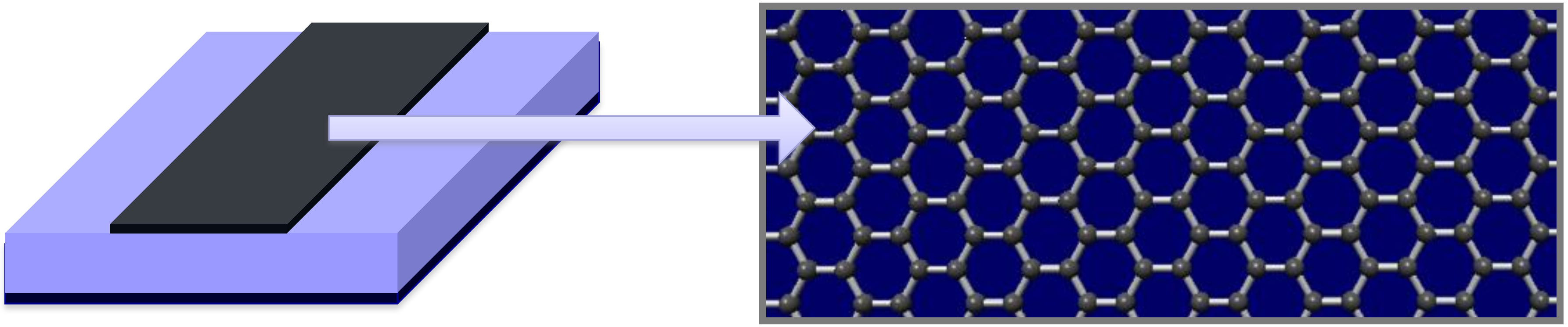
* World's smallest transistor (2008) is based on a thin strip of graphene just 1 atom x 10 atoms (1 nm transistor)



World smallest transistor
Courtesy of Mesoscopic Physics group at the University of Manchester.

NANO-ANTENNA

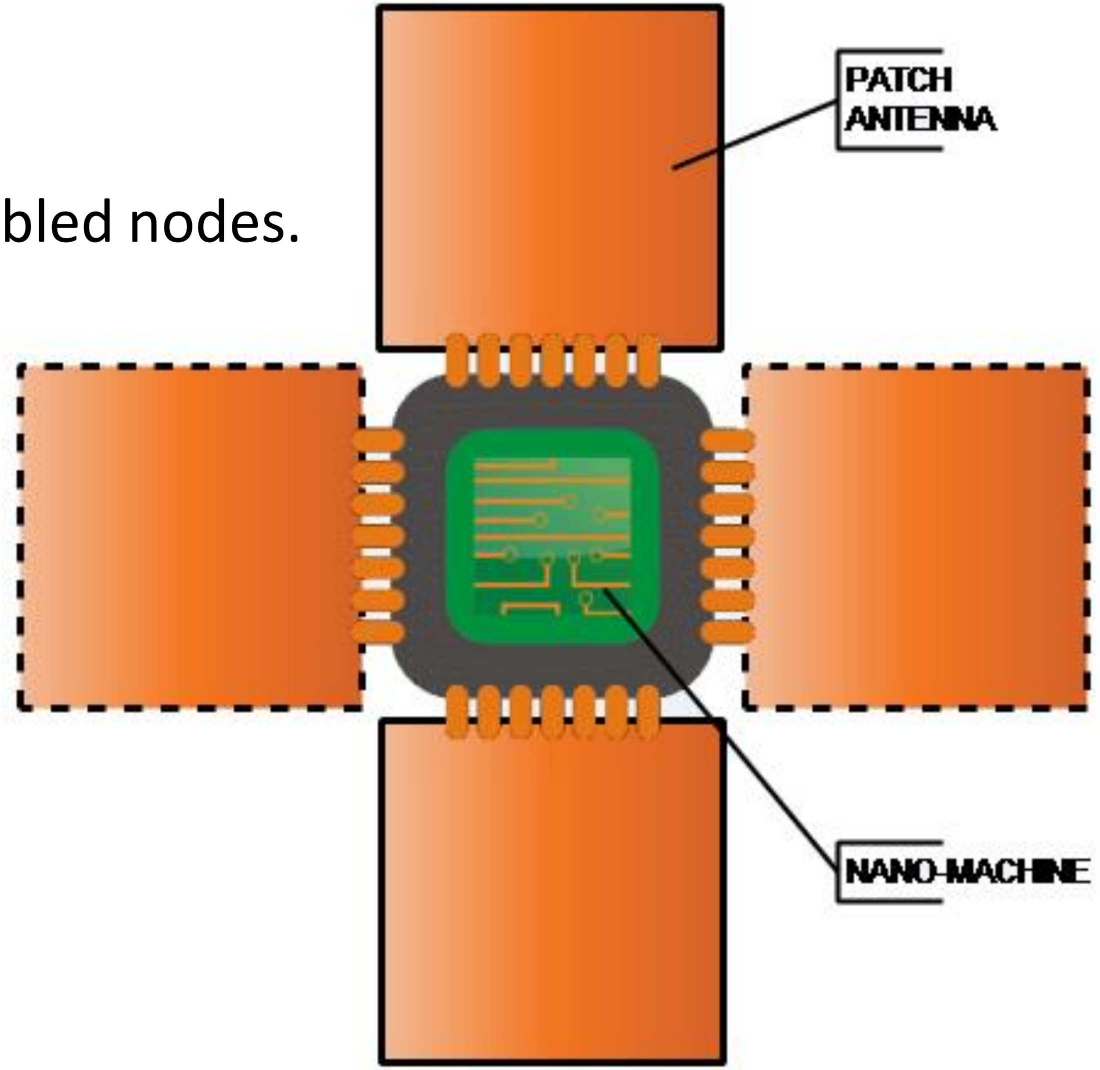
A nano-sized graphene strip can operate effectively as an antenna at THz.



M. Jornet and I.F. Akyildiz,
"**Graphene-based Nano-antennas for Electromagnetic Nanocommunications in the Terahertz Band**",
in Proc. of 4th European Conference on Antennas and Propagation, (EUCAP), April 2010.

Definition

- **Nano-network**
  - A set of minified, wireless comm.-enabled nodes.
  - Node components:
    - CPU
    - MEM
    - Wireless module (antenna & modem)
    - Power supply (internal or external)
  - Each COMPONENT:
    - A few nanometers
  - Final assembly:
    - A few µmeters



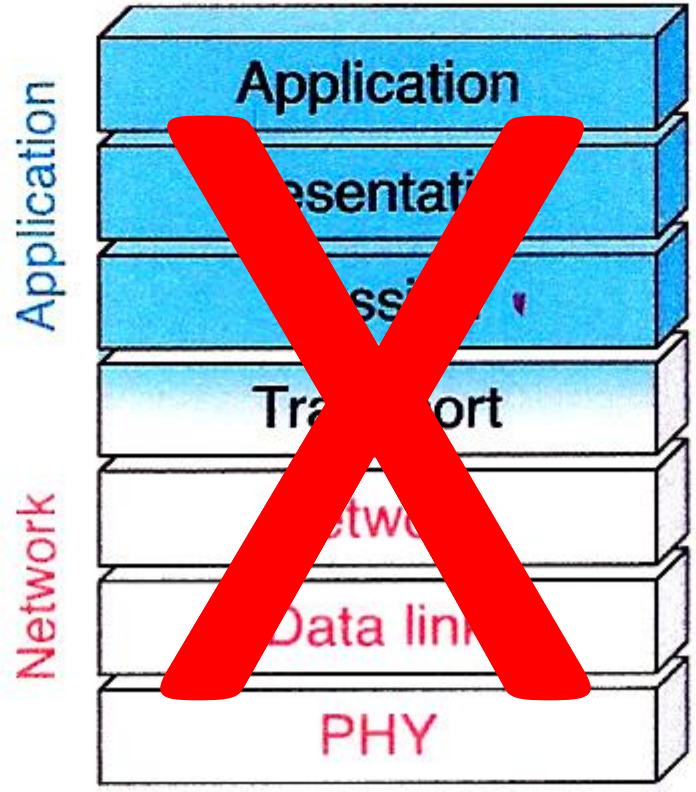
Applications beyond SD-Metamaterials

- **Nano-Sensing**
  - Industrial quality control
    - Find “flaws” (e.g.) nano-cracks at the manufacturing stage
  - Structural monitoring of materials
    - Material lifecycle monitoring → Detect alterations after deployment.
      - E.g. Nuclear reactors
- **Nano-acting**
  - 4D materials → e.g. able to sense/react to touch, heat events.

Challenges

- **Scalability**
  - Millions of nano-nodes.
    - Cost?
    - Networking?
    - Addressing?
- **VERY limited**:
  - CPU
  - RAM
  - Power
  - Tx throughput.

Out of the question!

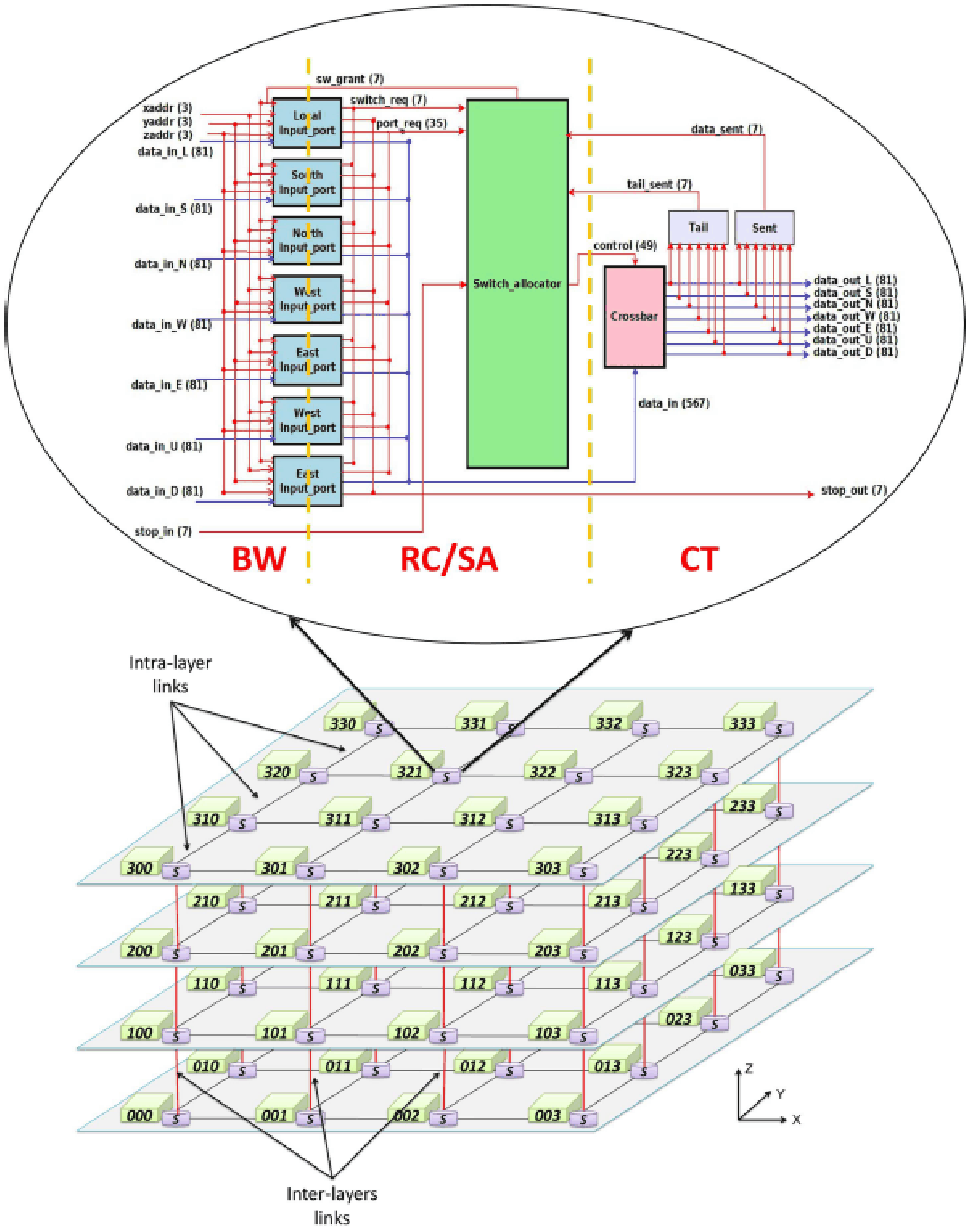


√

One-layer-does-it-all!

Implementations

- Presently, as
  - **“Networks on Chips”**
- Wired/wireless node communication.
- <u>External</u> power supply
  - Wired, or
  - Inductive
- Commercial providers:
  - NetSpeed, http://www.netspeedsystems.com/
  - Arteris, http://www.arteris.com/
  - Sonics, http://sonicsinc.com/



Wireless Implementations?

➢**Ultra low-energy radio**
- mW-level active power for a 2.4GHz radio
- 20x – 50x better than PAN SotA

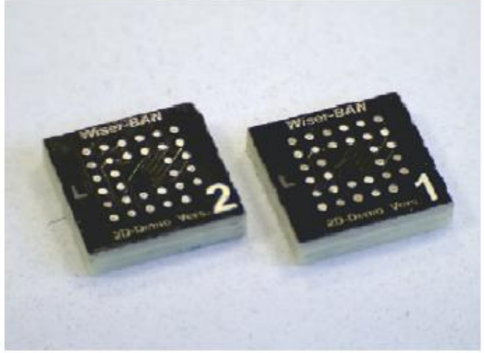
➢**Radio+DSP SoC**
- Signal processing + transmitting on single chip

➢**Miniature antenna**
- 10x smaller size than existing 2.4GHz solutions

➢**Miniaturization**
- MEMS-based radio using RF, IF and LF MEMS
- 4x4x1mm3 SiP, 50x improvement vs. PAN SotA

➢**Flexible protocol**
- proprietary & compliance with selected MAC/protocols

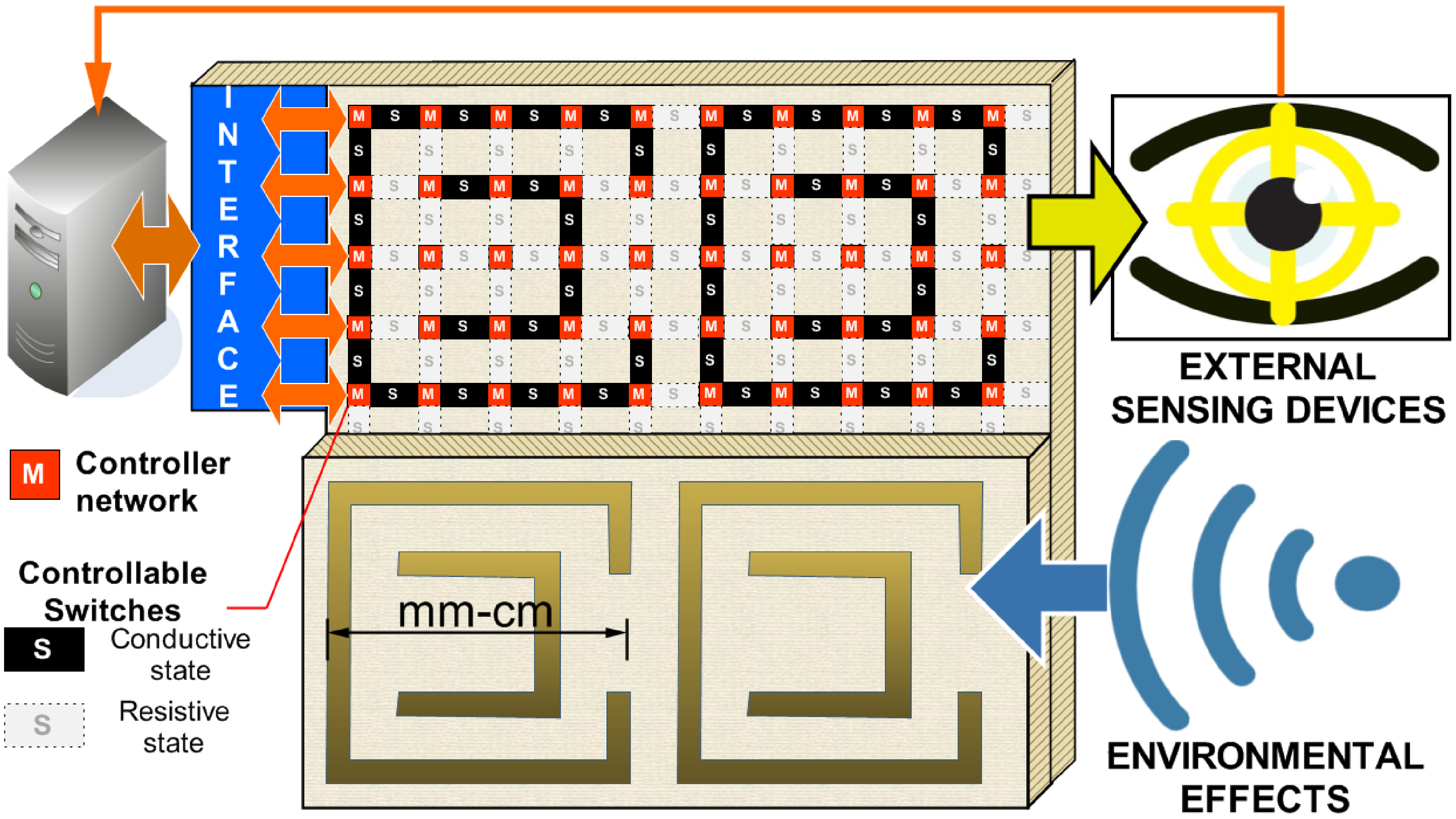
EU FP7 project:
➢ ICT 2009.3.9 Microsystems and Smart Min. Systems
➢ IP project ; Budget: 10 M€, EC grant 7 M€



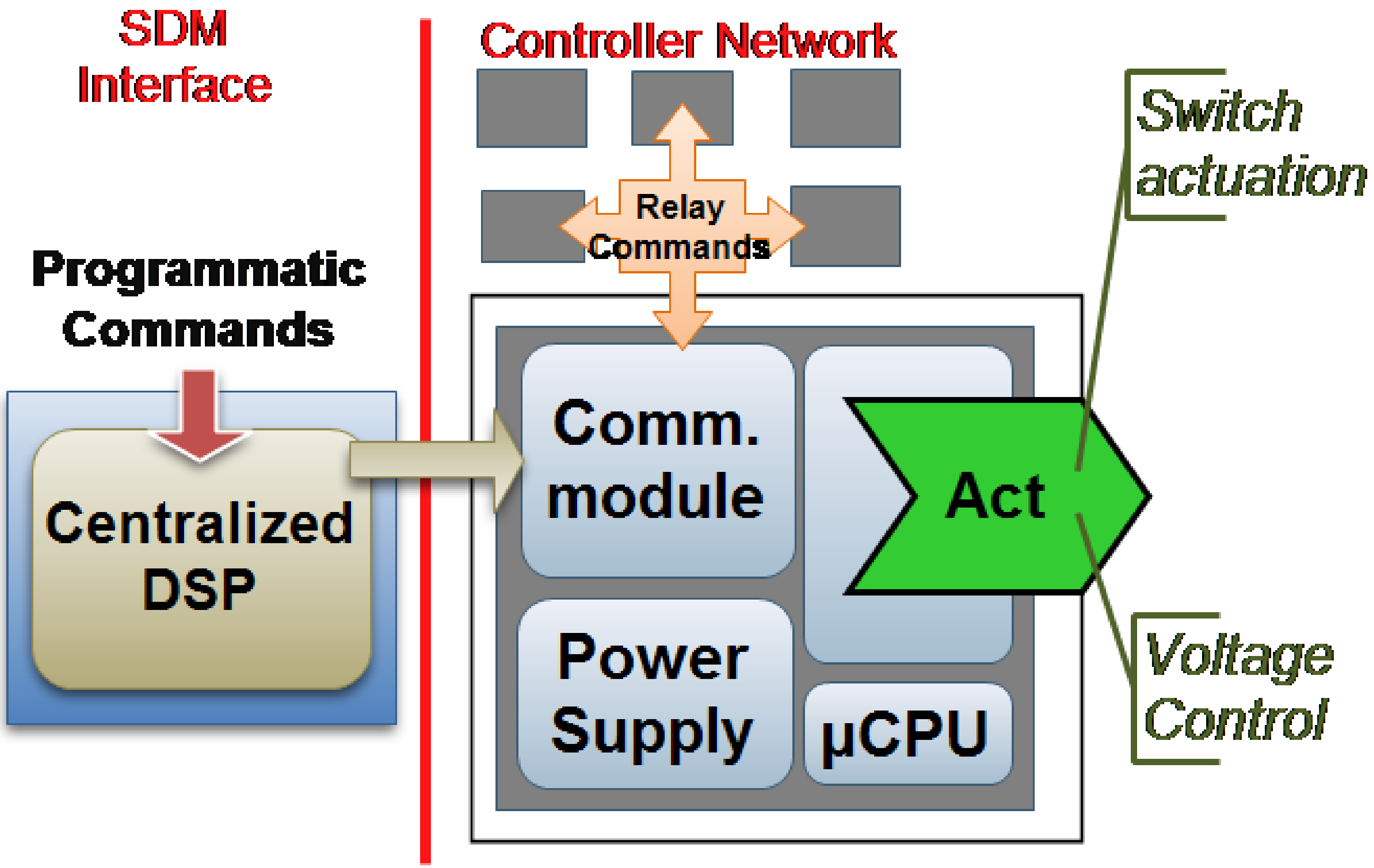
2D-SiP
4.2mmx4.3mmx0.770mm

1mm^2 at the end of the project

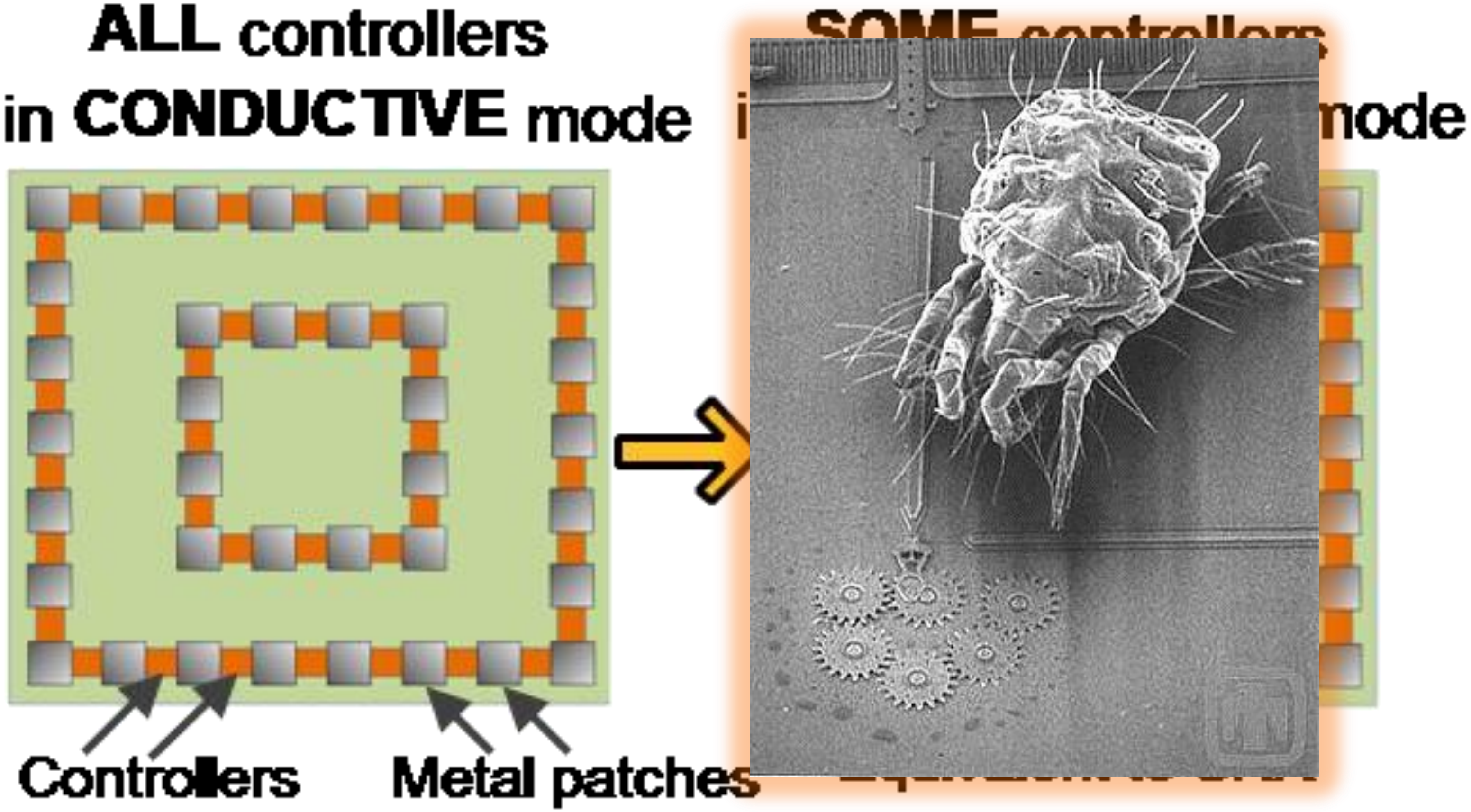
The merge: The schematics of a Software-Defined Material

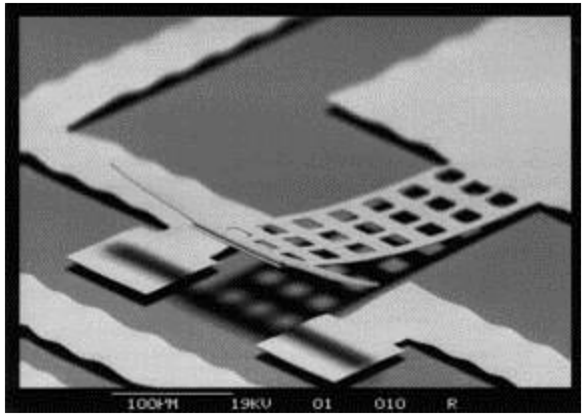


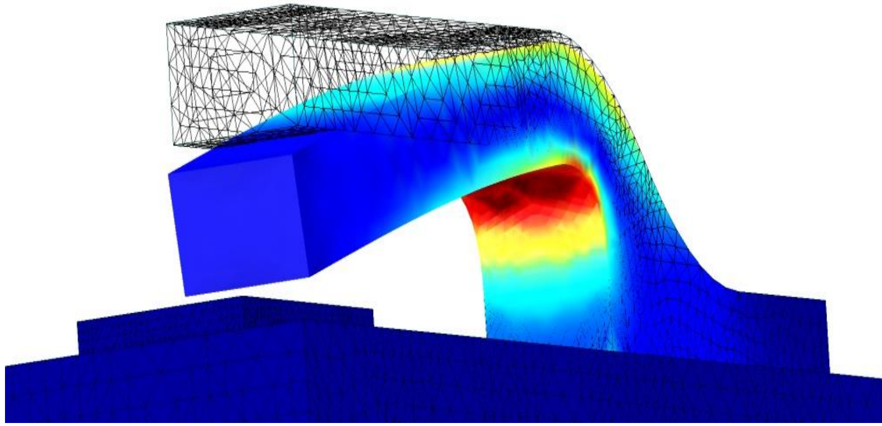
Actor (“nanonode”) architecture



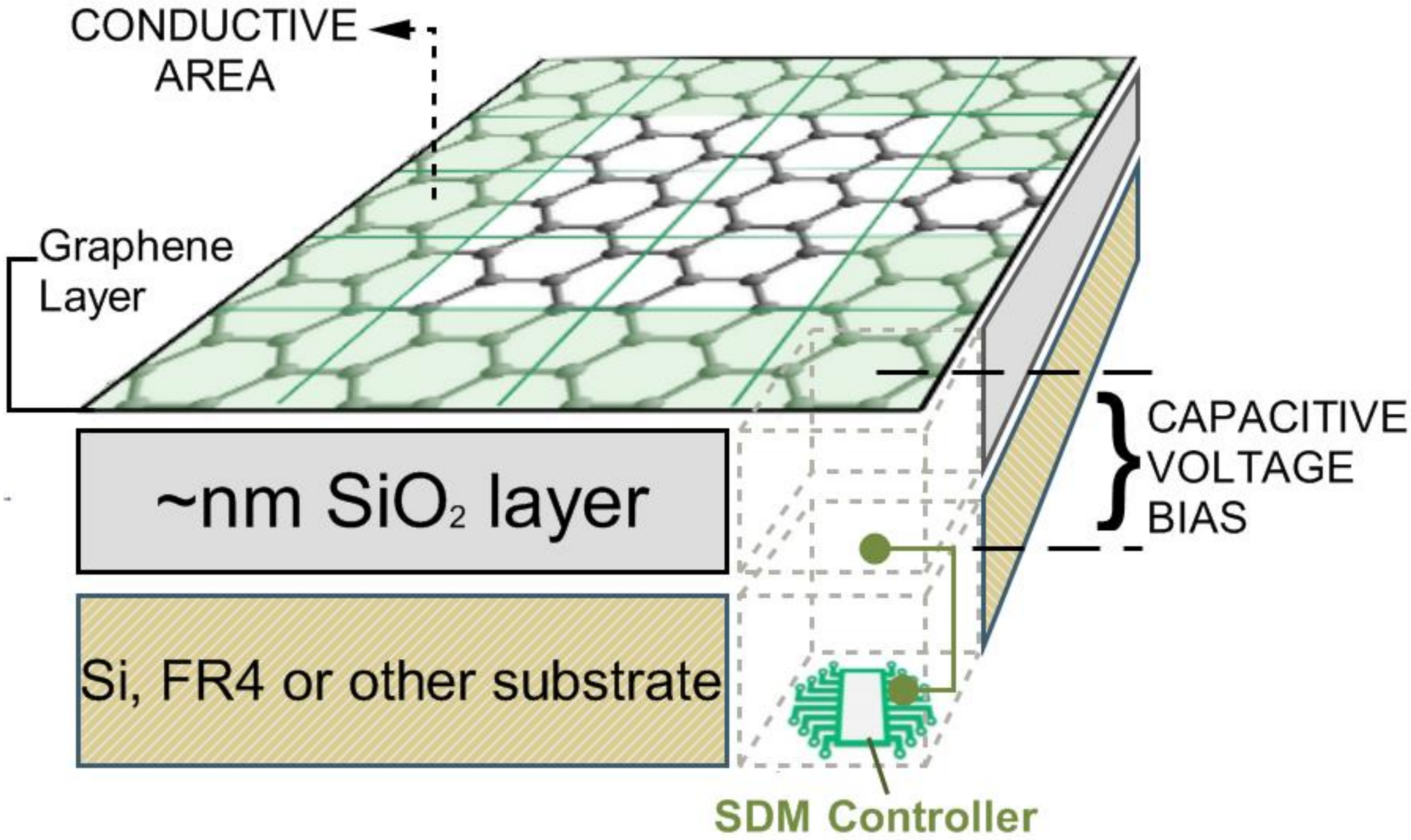
An SDM scaffold based on physical switches





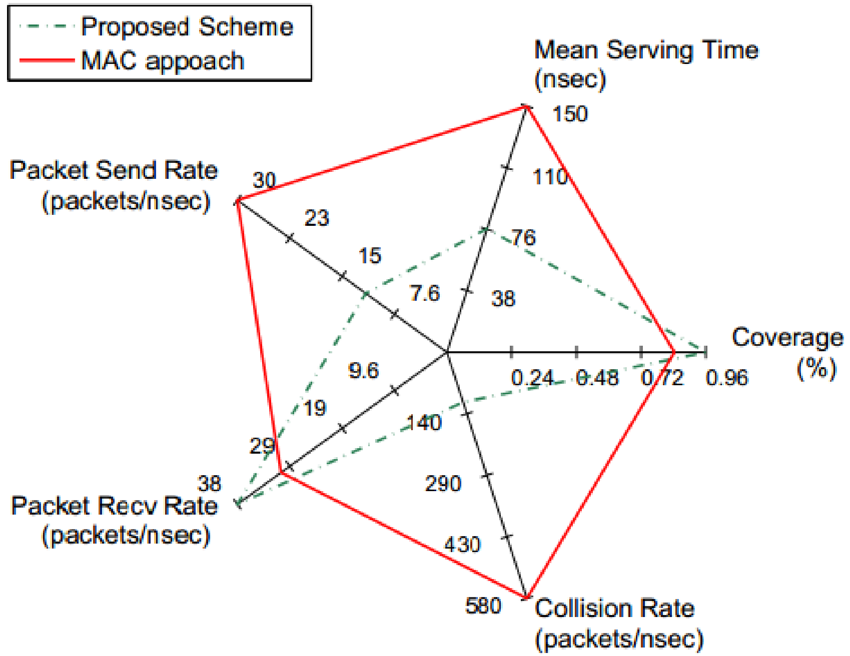


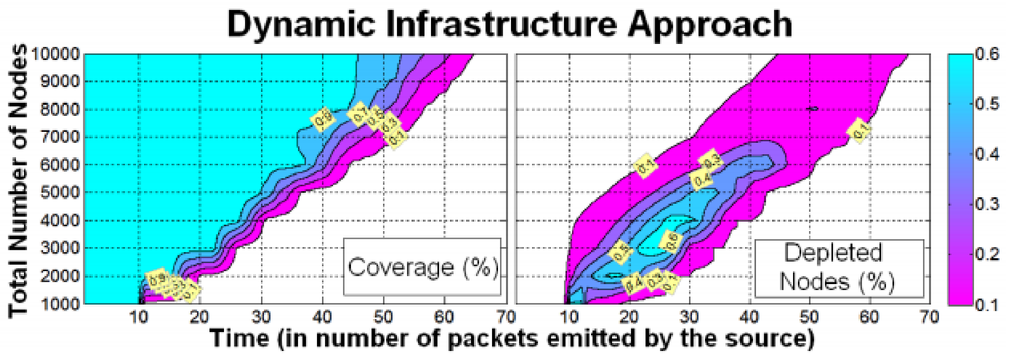
A scaffold based on Graphene.

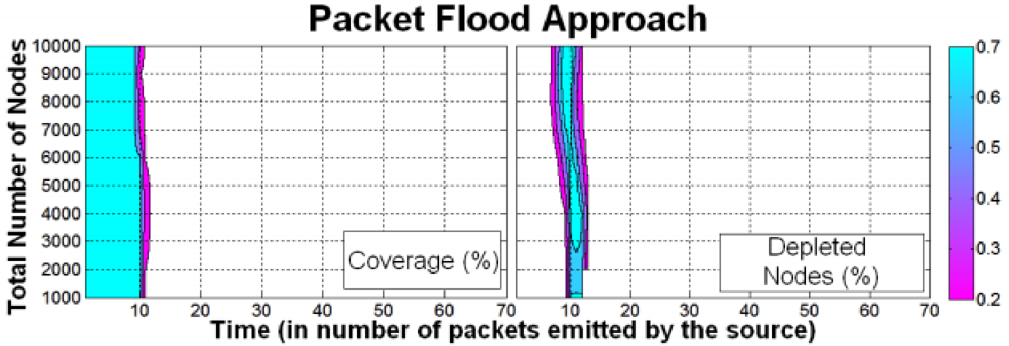


A novel nano-networking approach [1]

- **Wireless nodes**
- No addressing!
- No “neighborhood” info required!
- No packet queuing required!
- Infinitely scalable
- Beats queue-enabled:
  - CSMA MAC protocols
  - Optimal probabilistic flood approaches
- Plus, offers:
  - Packet source location discovery!
  - Geo-routing!
- Works with arranged **AND** random topologies



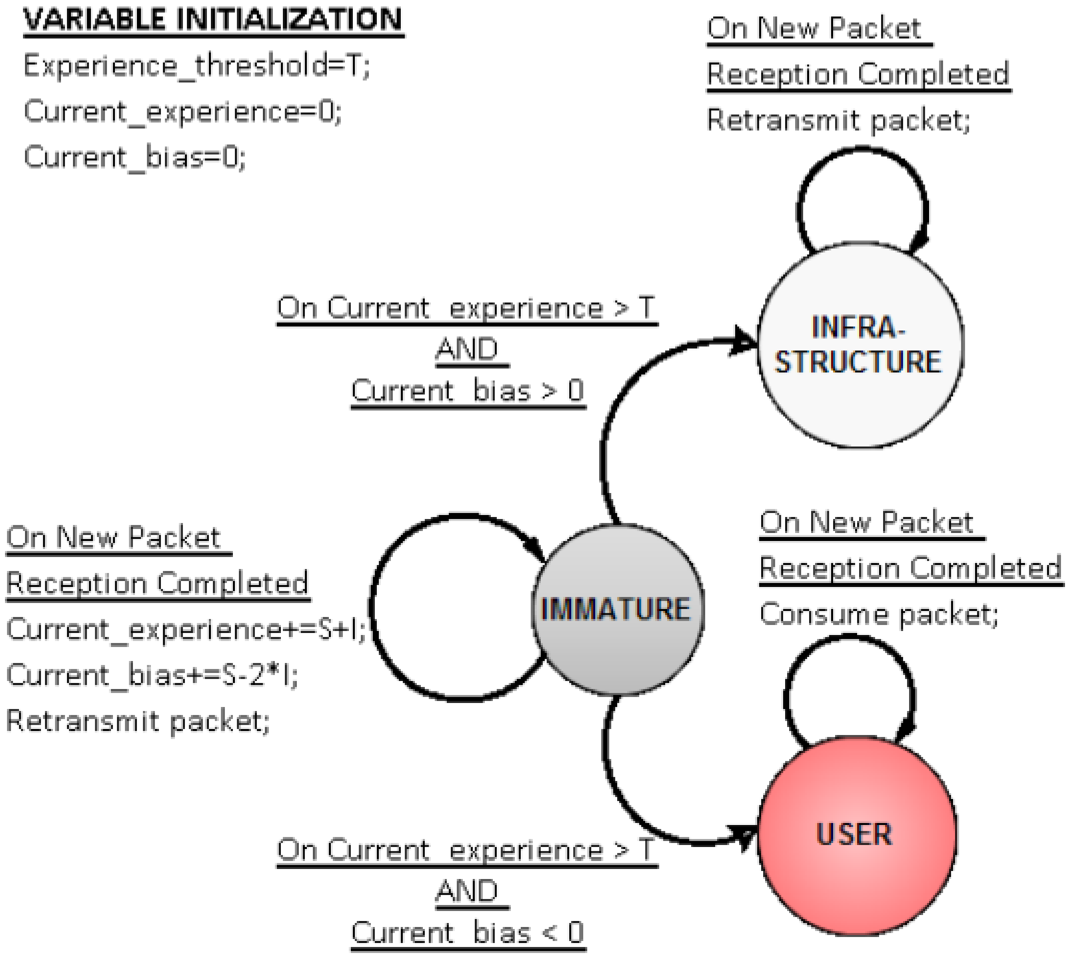




[1] C. Liaskos & A. Tsioliaridou, “A Promise of Realizable, Ultra-Scalable Communications at nano-Scale: A multi-Modal nano-Machine Architecture”, IEEE Transactions on Computers, Accepted, May, 2014.

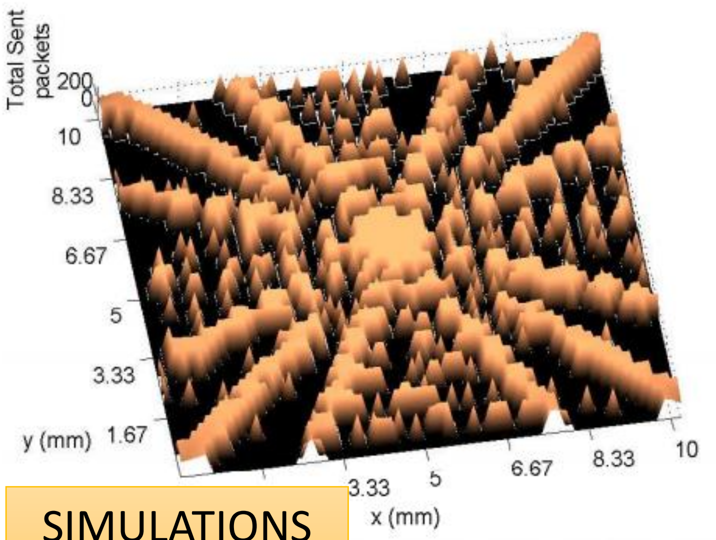
Dynamic Infrastructure Deployment

- Bi-modal operation.
- Nodes that "hear well" mature into <u>infrastructure.</u>
- Nodes with impaired Rx capacity become <u>users.</u>

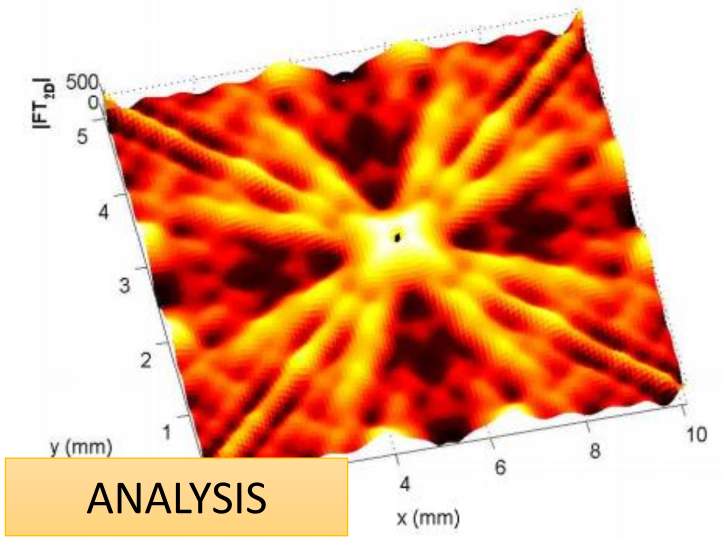


The end result

Infrastructure deployment

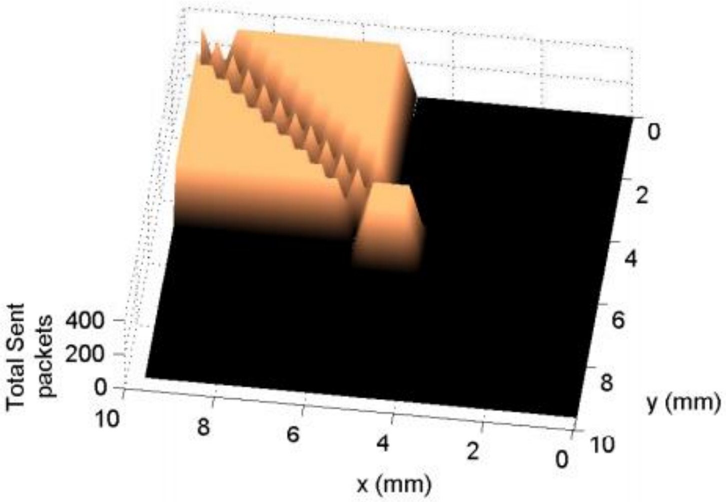


SIMULATIONS



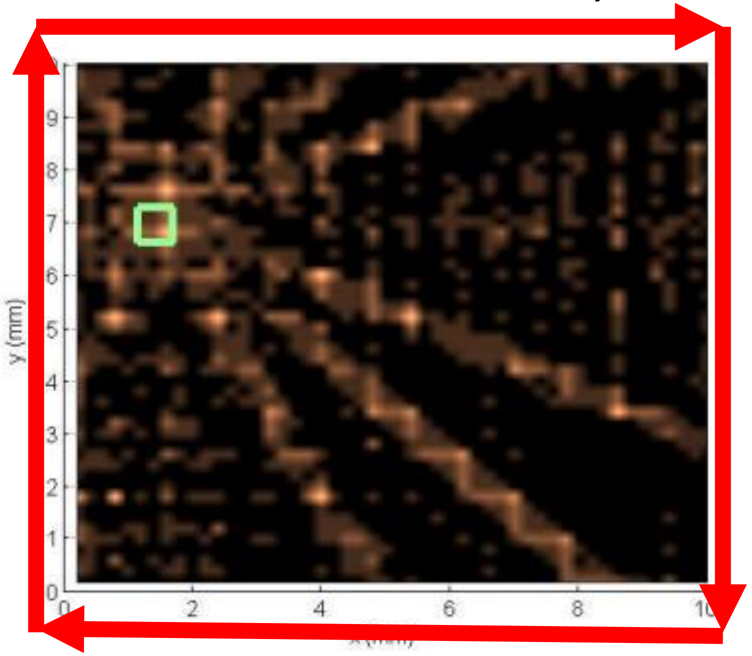
ANALYSIS

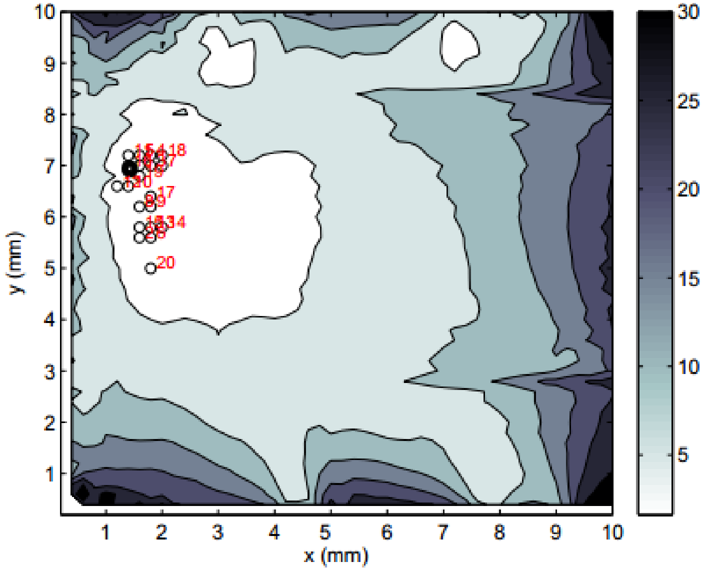
Geo-routing



Event location discovery

Using peripheral power measurements only





SDM Applications

Applications of Plain MetaMaterials:

- **Cloaking devices**
  - Making objects invisible to E/M.
- **Perfect Energy Absorbers**
  - Highly Efficient Antennas
  - E/M Isolators
  - Photovoltaics
- **Light and Sound Filtering**
  - Object masking (disguising)
  - High-resolution medical imaging
- **Macroscale:**
  - Seismic protection
    - Absorption or redirection of seismic waves

Presently limited to:

- A single angle,
- A single frequency,
- A single geometry,
- Uncontrollable operation.

- **No sense of**:
  - Adaptivity,
  - Reusability,
  - Programmatic control.

Attributes offered by Software-Defined Materials.

Example: SDM-Augmented Cloaking

Cloaking device

Is it real? How?

Cloaking device

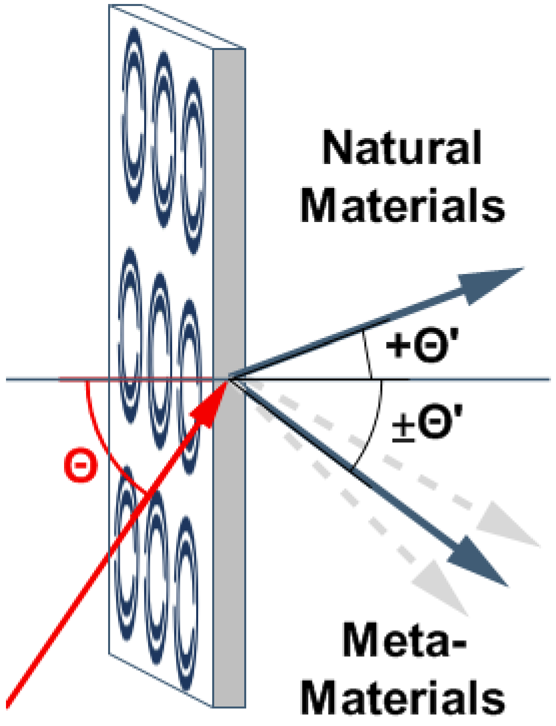
Not referring to optical-camo (virtual invisibility)

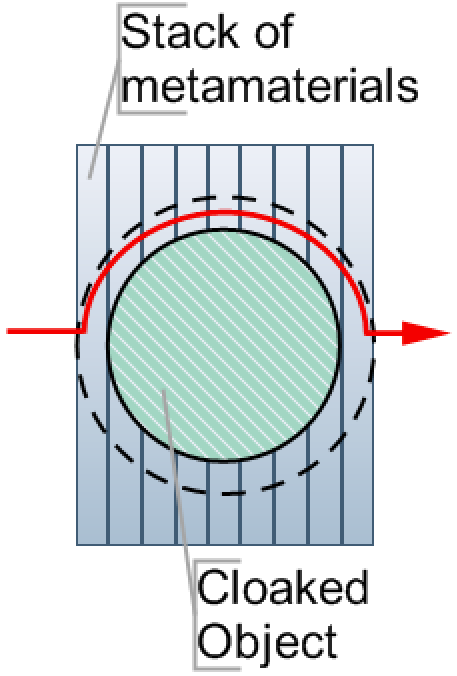
True Invisibility

To be realised by creating a new material

The idea is to create a region that is inaccessible to E/M waves.

Realisation with plain metamaterials





A change in:

- Object dimensions,
- Viewing angle,
- Wave frequency,

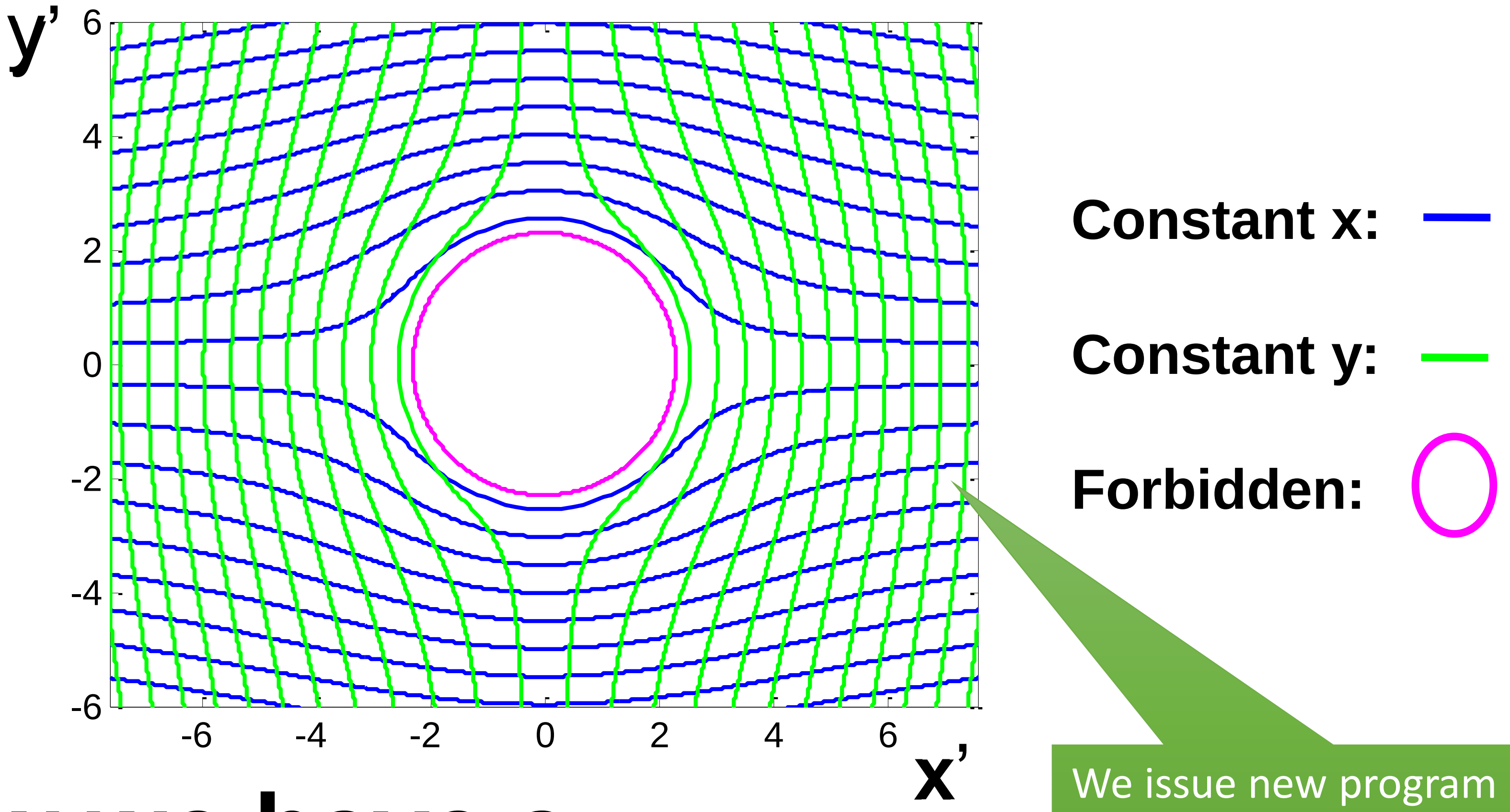
Will break the cloaking.

No resolution but:

- Discard the stacks,
- Make new ones.

Impossible for true, adaptive, real-time cloaking.

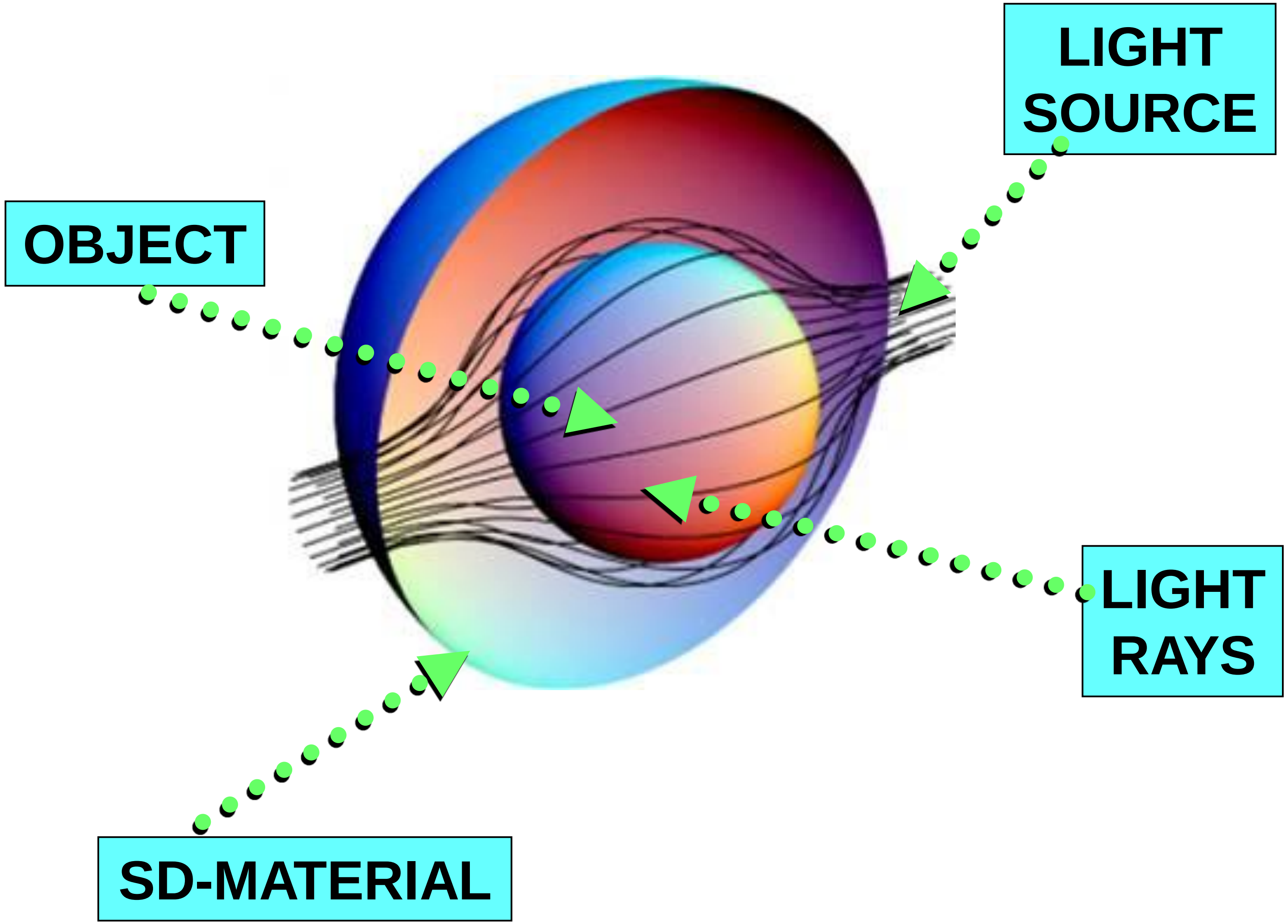
What if we used SD-Materials?



We issue new program directives at every time step.
The cloak adapts to the changes.

Now we have a cloaking device

A 3D Possibility



Key-Challenge #1

- **The theoretical foundation of SDM.**
  - ➢How do we design an SDM?
    - ➢ Make sure that the actors and the scaffold do not interact in unwanted ways.
      - ➢ Computational Simulation of Electromagnetic Propagation
  - ➢How do we optimize:
    - ➢ The nanonetwork topology?
      - ➢ Nano-nodes are cheap, but numerous means $$.
      - ➢ How do we control an SDM effectively with very few nanonodes?
    - ➢ The nanonetworks protocol?
      - ➢ It should be fast, simple, robust against (frequent) hardware and Tx/Rx errors.
      - ➢ .. And secure. **Hacking materials?**

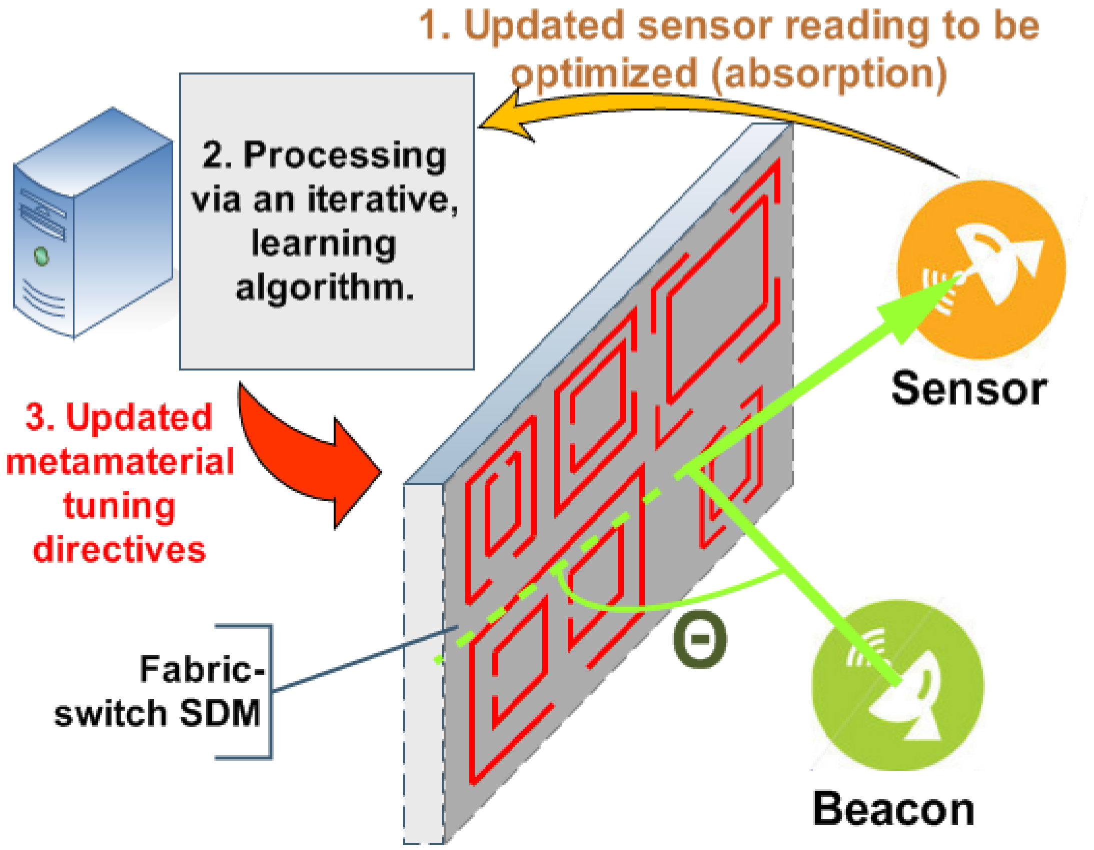
Key-Challenge #2

- **Manufacturing and testing.**
  - Essential to take into account the state-of-the-art manufacturing capabilities.
    - Metamaterial scaffold aspect,
    - Nanonetworking aspect.
  - The metric of success:
    - **The Duck test :)**

    "If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck."
    - **I.e. formal validation process (metamaterial characterization).**

Key-Challenge #3

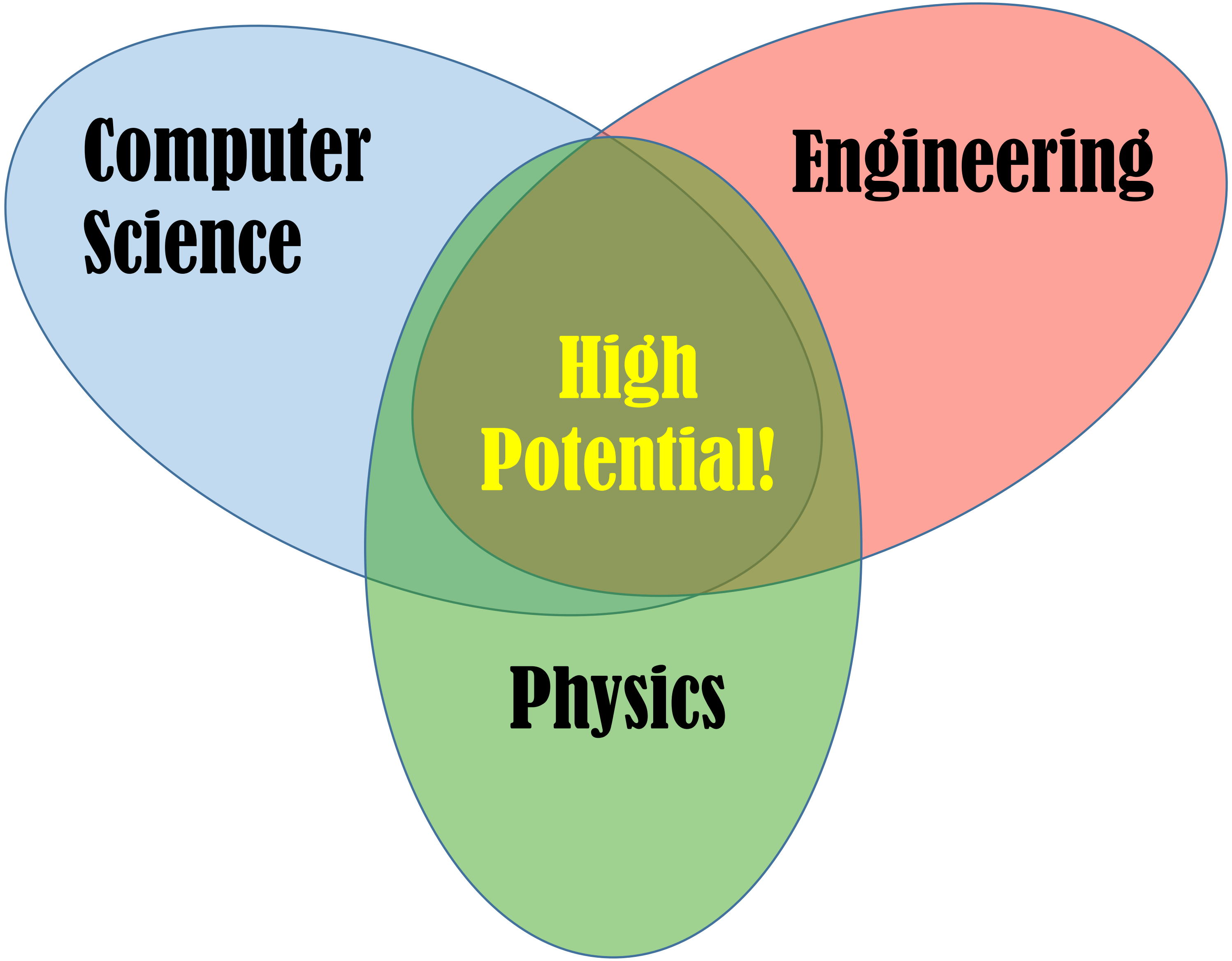
- **Demonstrate the SDM potential.**
  - ➢Apps to show:
    - ➢programmability,
    - ➢Interconnectivity,
    - ➢adaptivity potential



Conclusion

- **Software-Defined Materials** are a novel class of systems which allow for programmatic control over the electromagnetic behavior of matter.
- SDMs are an innovative **combination of nanonetworks and metamaterials** (MMs).
- MMs are artificially designed materials, with unnatural, geometry-dependent electromagnetic properties.
- A network of nanomachines receives external, programmatic commands and performs geometry-altering actions, yielding tunable or adaptive electromagnetic behavior.
- Very new field, lots of work to do (theory and experiments).

Conclusion



Extended Material

C. Liaskos, A. Tsioliaridou, A. Pitsillides, N. Kantartzis, A. Lalas, X. Dimitropoulos, S. Ioannidis, M. Kafesaki, C. Soukoulis, "**Building Software Defined Materials with Nanonetworks**", FORTH-ICS Technical Report 2014.TR447, http://www.ics.forth.gr/tech-reports/2014/2014.TR447_Software_Defined_Materials_Nanonetworks.pdf

Τέλος Ενότητας

Ευρωπαϊκή Ένωση
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ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
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ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης
ΕΣΠΑ 2007-2013
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

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- Το παρόν εκπαιδευτικό υλικό έχει αναπτυχθεί στα πλαίσια του εκπαιδευτικού έργου του διδάσκοντα.
- Το έργο «**Ανοικτά Ακαδημαϊκά Μαθήματα στο Πανεπιστήμιο Κρήτης**» έχει χρηματοδοτήσει μόνο τη αναδιαμόρφωση του εκπαιδευτικού υλικού.
- Το έργο υλοποιείται στο πλαίσιο του Επιχειρησιακού Προγράμματος «Εκπαίδευση και Δια Βίου Μάθηση» και συγχρηματοδοτείται από την Ευρωπαϊκή Ένωση (Ευρωπαϊκό Κοινωνικό Ταμείο) και από εθνικούς πόρους.

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Σημειώματα

Σημείωμα αδειοδότησης

Σημείωμα Αναφοράς

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