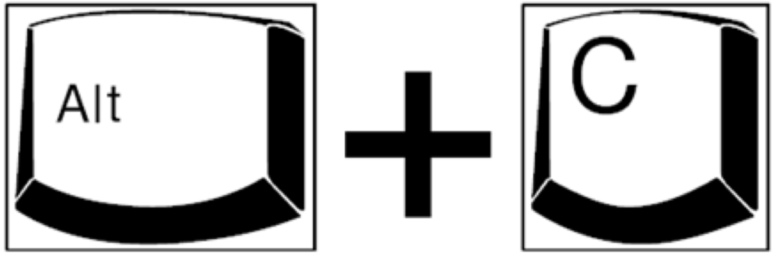

Alternative (Nano-) Computing

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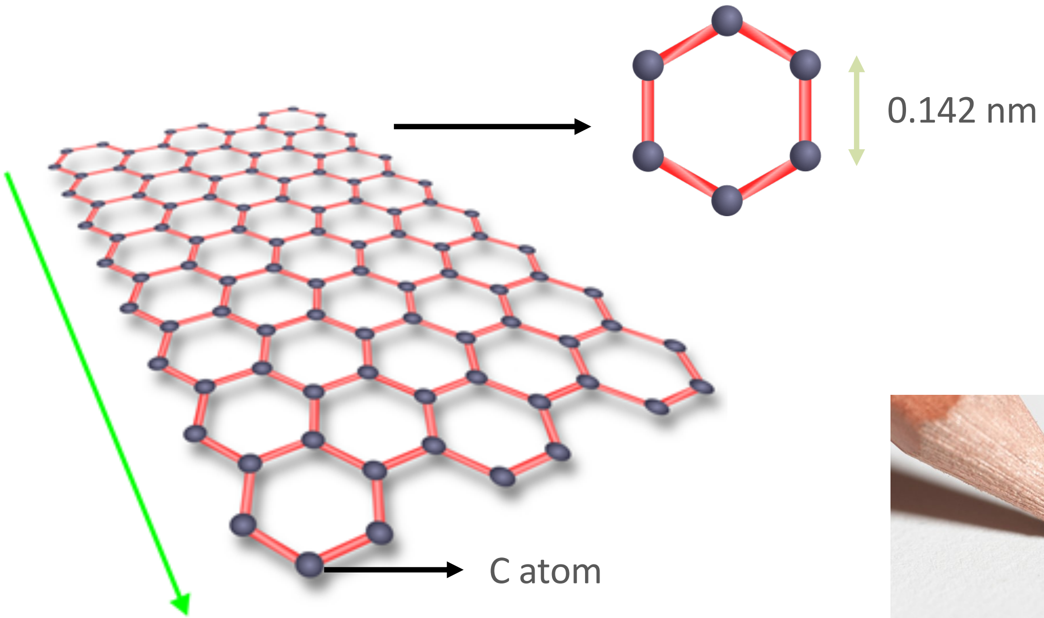
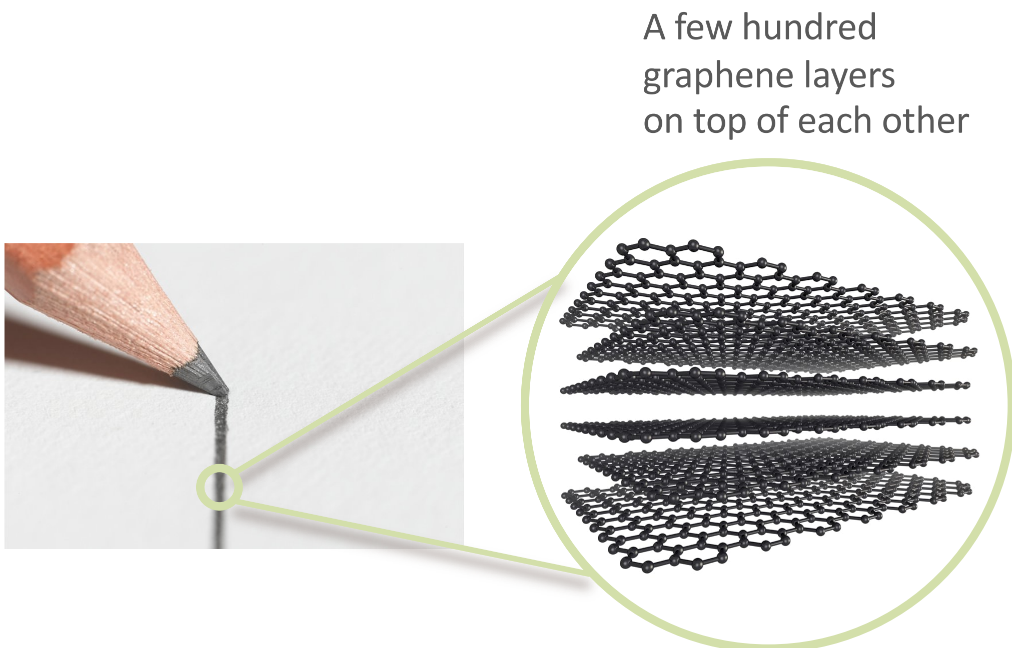
A-Computing Topics

- Graphene Based Circuits & Computing
- Brain Simulation & Neuro-Computing
- Computation with Emerging Devices, e.g., Single Electron Tunneling Junctions, NEMS, Magnetic Junction, Spintronic, …
- Predictable Computation with Unpredictable Devices (Boole-Shannon Logic)
- Noise Driven Computing (Liveness from Noise!)
- Adequate (Imprecise) Computing
- Aging Assessment, Life-Time Reliability Management, & Variability and Reliability Aware Architectures
- 3D Architectures and Circuits

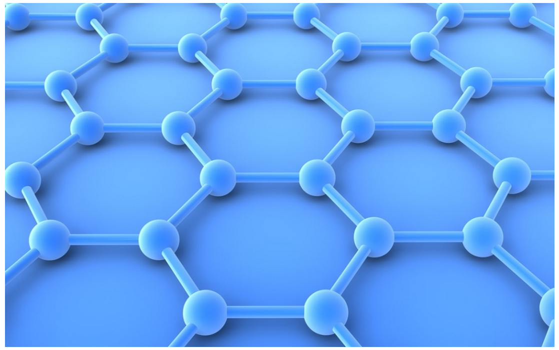
Graphene

- 2D single layer of Carbon atoms

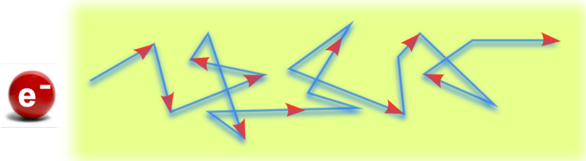




Graphene's Basic Properties

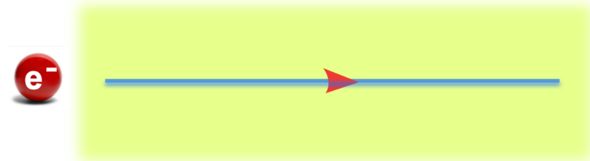


- Ultimate one-atom thinness ↦ 0.345 nm
- Conducts electricity extremely well
  - ↦ ballistic transport



Diffusive transport

vs.

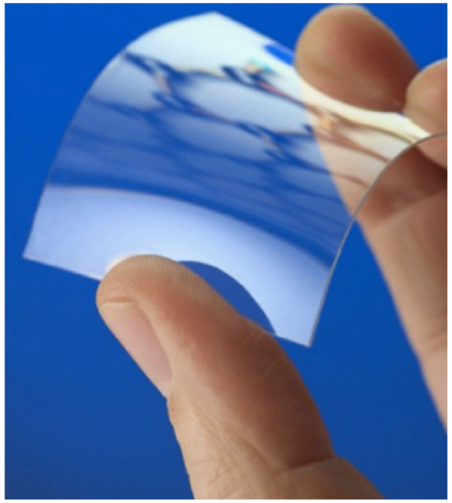


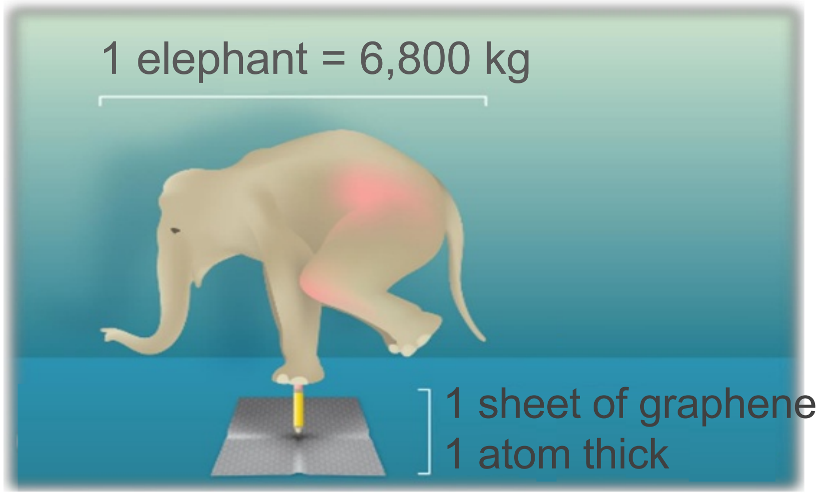
Ballistic transport

  - ↦ better conductor than copper (10x) and Si (100x)
- High thermal conductivity – heat can be quickly spread from a heat source
- Biocompatibility

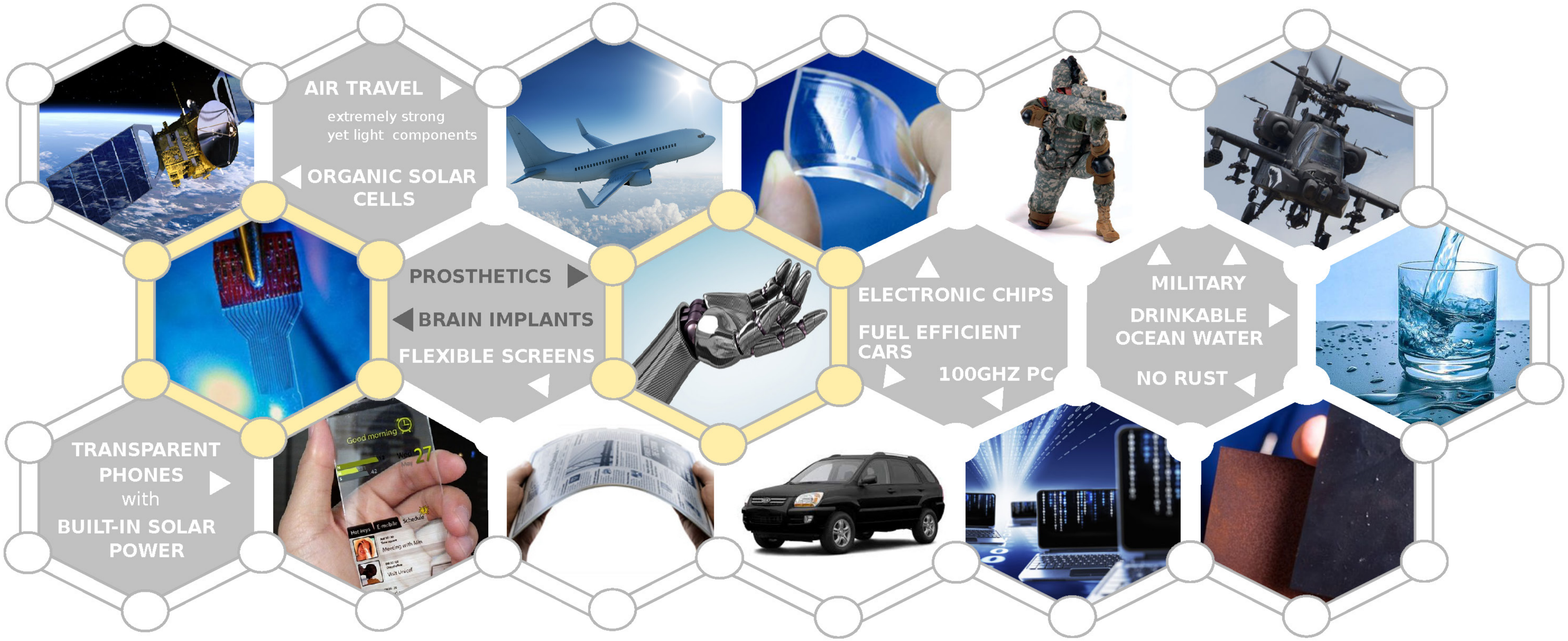
Graphene's Basic Properties

- Lightweight ↦ aerogel 7x lighter than air
- Strongest material ever found ↦ 200x stronger than steel
- Flexible ↦ stretchable by ¼ of its length
- Transparent ↦ absorbs 2.3% of light



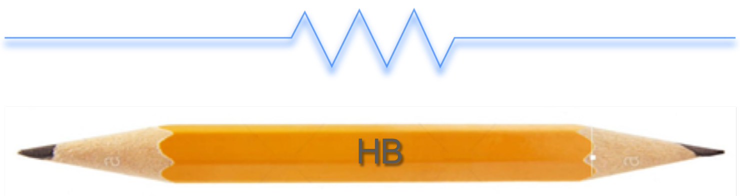


Graphene's Applications

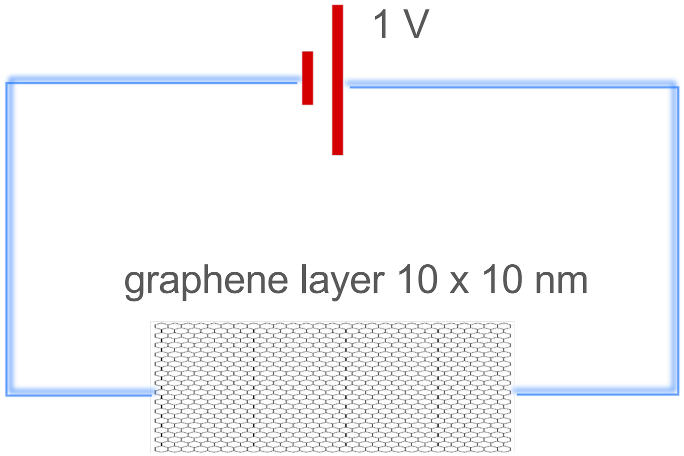


Graphene for Electronic Circuits

$R \cong 20\ \Omega$

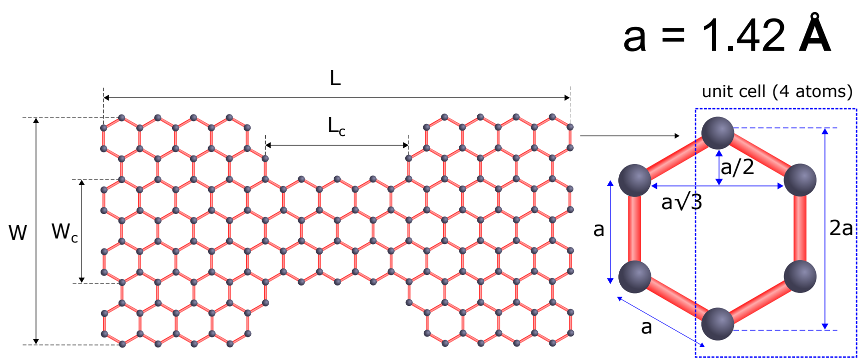


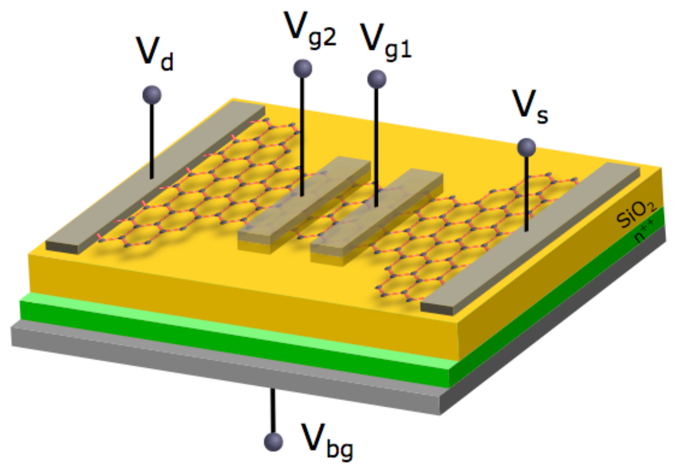
- Always conducting, cannot be turned “OFF”

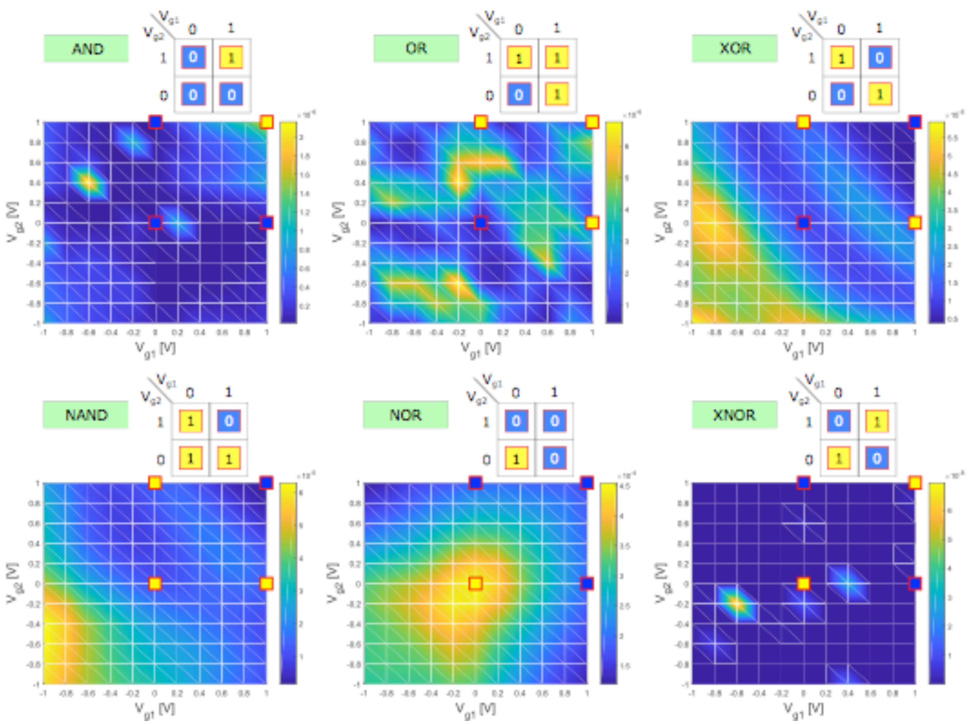


$R = 3\ k\Omega$

Graphene Based Computing







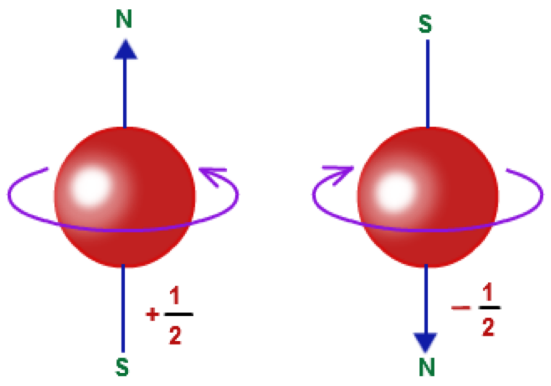
vs CMOS 15nm:

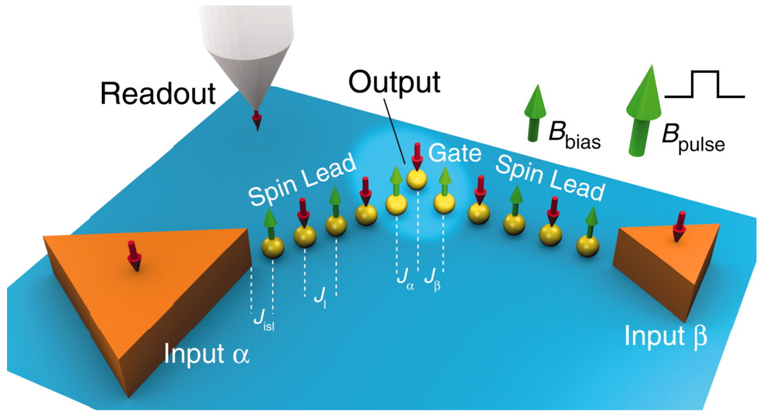
- 30x faster
- 4 order of magnitude less active area and power consumption.

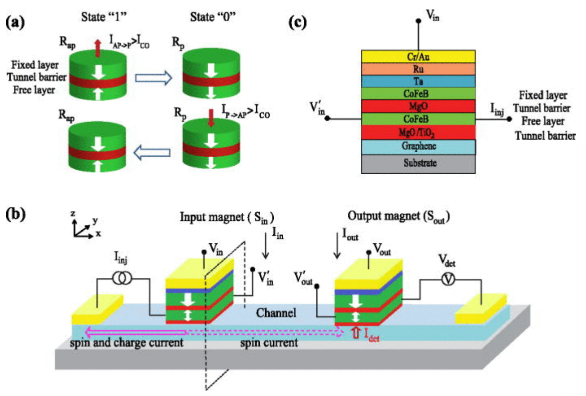
Target:

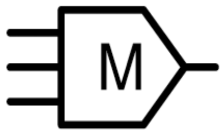
- **Boolean Gates**
- **McCulloch-Pitts Neurons**
- **Spiking Neurons**

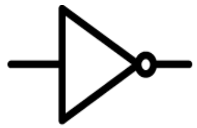
Spintronics

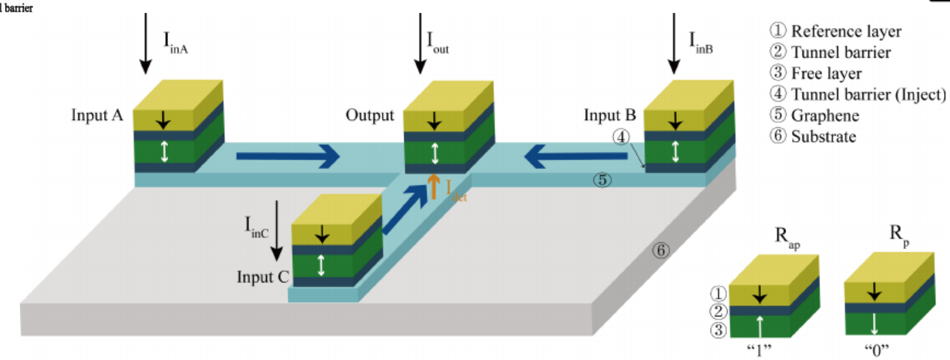










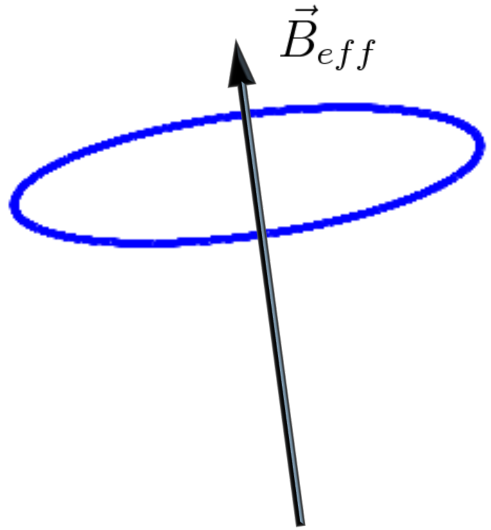


Spin Waves

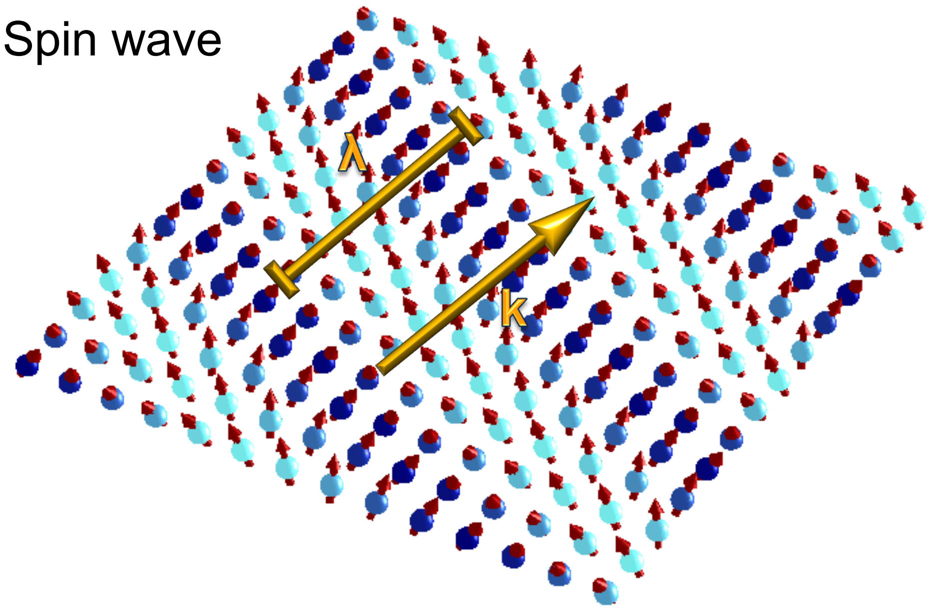
- Landau-Lifshitz torque equation

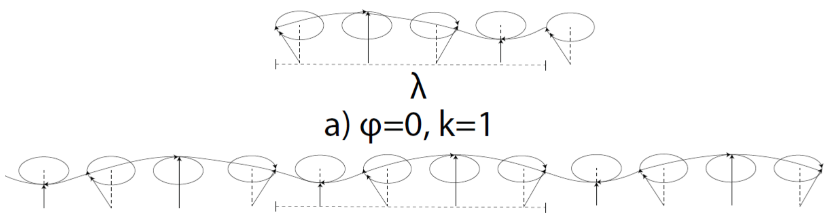
$$\frac{d\vec{M}(t)}{dt} = -\gamma_0\left(\vec{M}(t) \times \vec{B}_{eff}(t)\right)$$

$$\vec{B}_{eff} = \vec{B}_0(t) + \vec{B}_{ex} + \vec{B}_{demag} + \vec{B}_{ani} + \cdots$$



- Spin wave

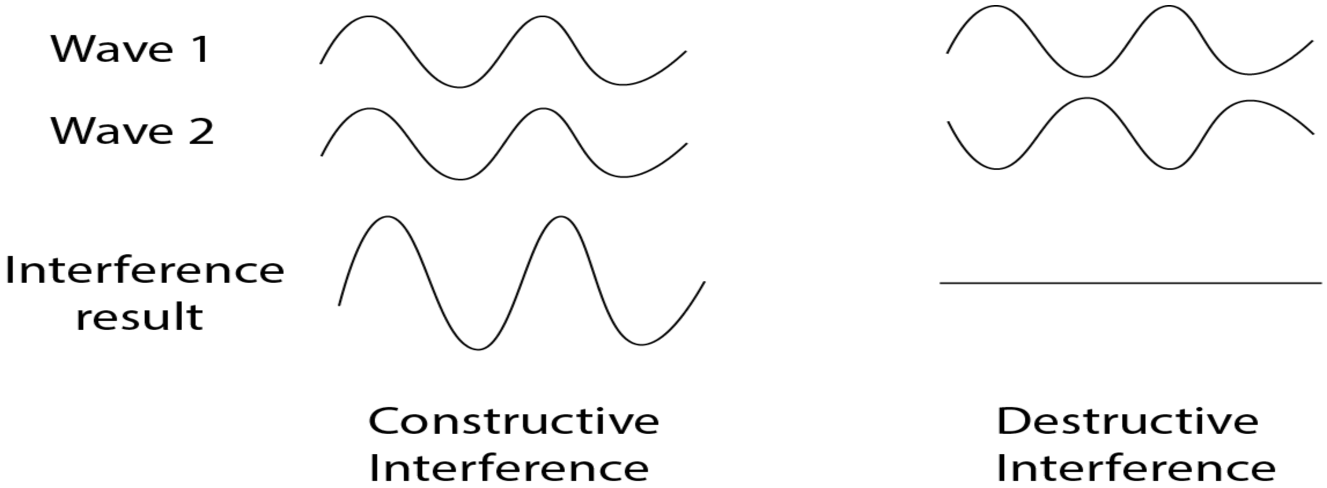




a) φ=0, k=1

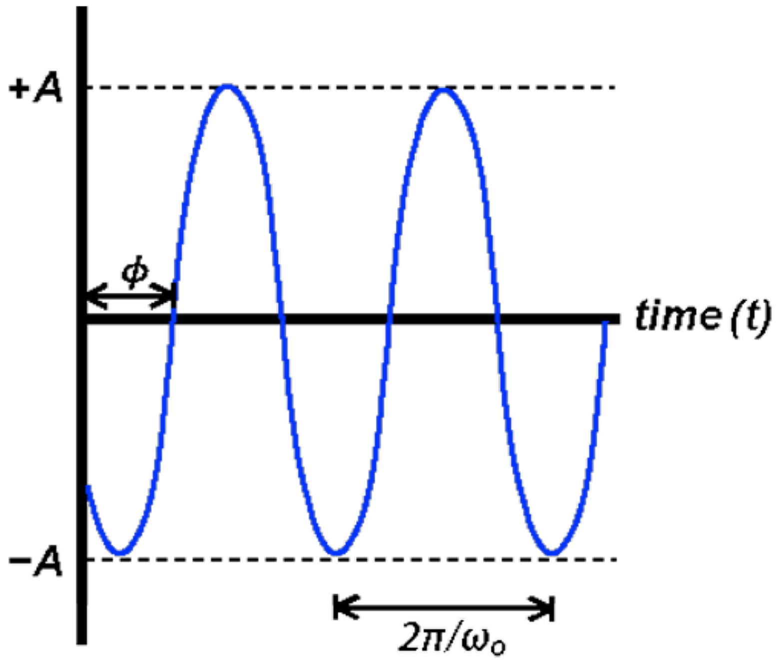
b) φ=π, k=3

Wave Interference

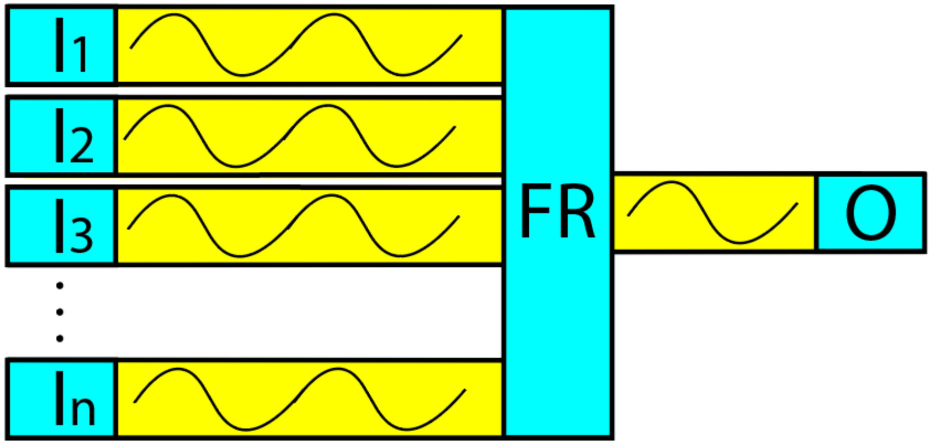


Information Encoding

- ❑Spin Wave Amplitude (A)
- ❑Spin Wave Phase (Φ)
- ❑Spin Wave Frequency (ω)



SW Logic Gate

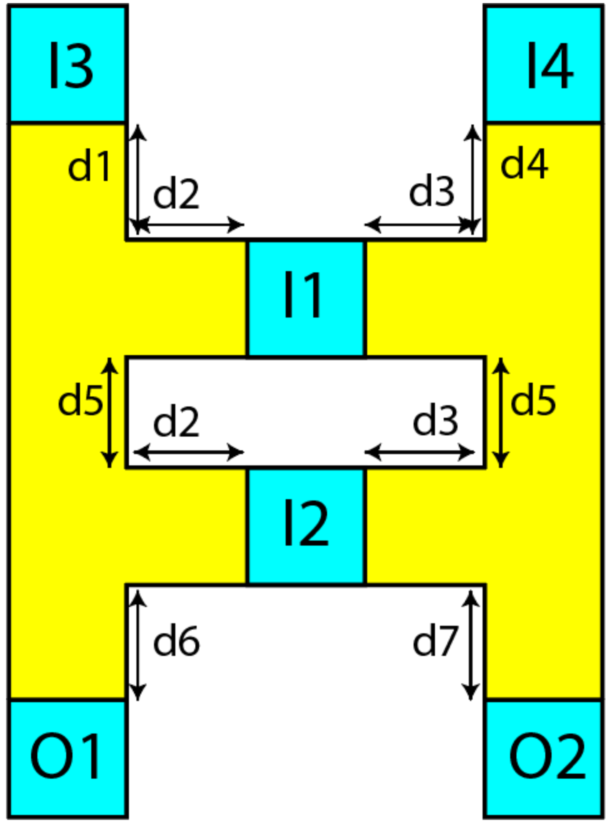


- **Inputs (I_1, I_2, .. I_n) are excited at the same frequency.**
- **FR is the functional region which determine if the function is MAJ, XOR, XNOR, …**
- **O is the output cell.**

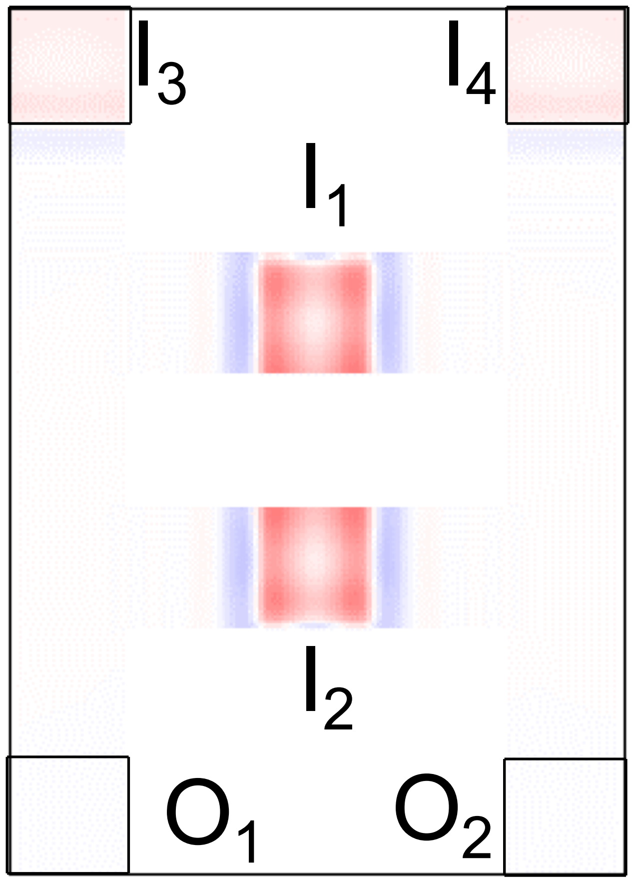
MAJ3 Gate with Fanout = 2

- MAJ(a,b,c) =>
- I_1 = a, I_2 =b, and I_3 = I_4 = c
- O_1 = O_2 = MAJ(a,b,c)

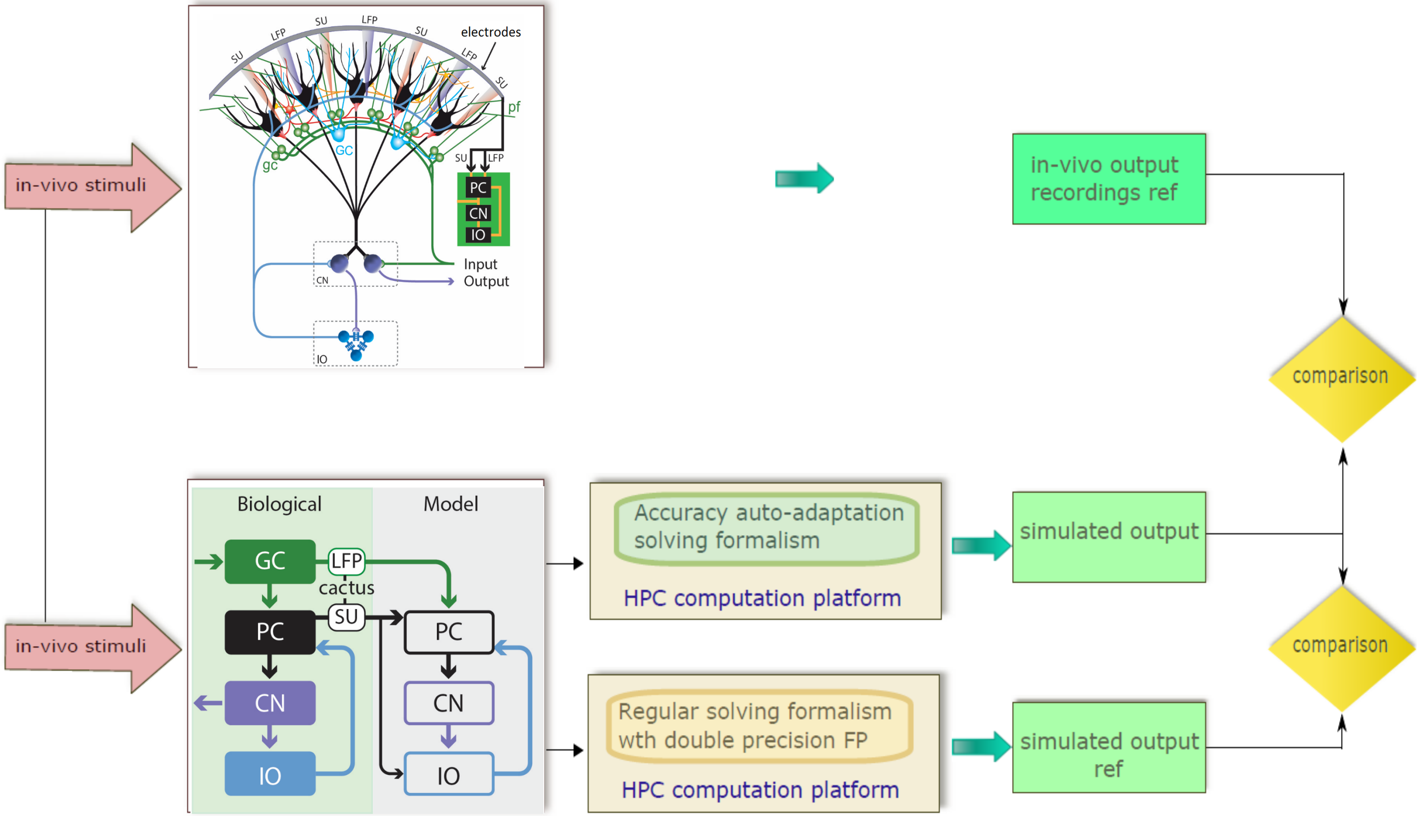
- $d_1=d_2=d_3=d_4=d_5= n\ \lambda$
  - n=1,2,3, …
  - Constructive interference (if SWs in-phase)
  - Destructive interference (if SWs out-of-phase)
- $d_6=d_7= n\ \lambda$ (non-inverted output)
  - n=1,2,3, …
- $d_6=d_7= (n/2)\ \lambda$ (inverted output)
  - n=1,3,5, …



SW Propagation



Brain Simulation & Neural Computing



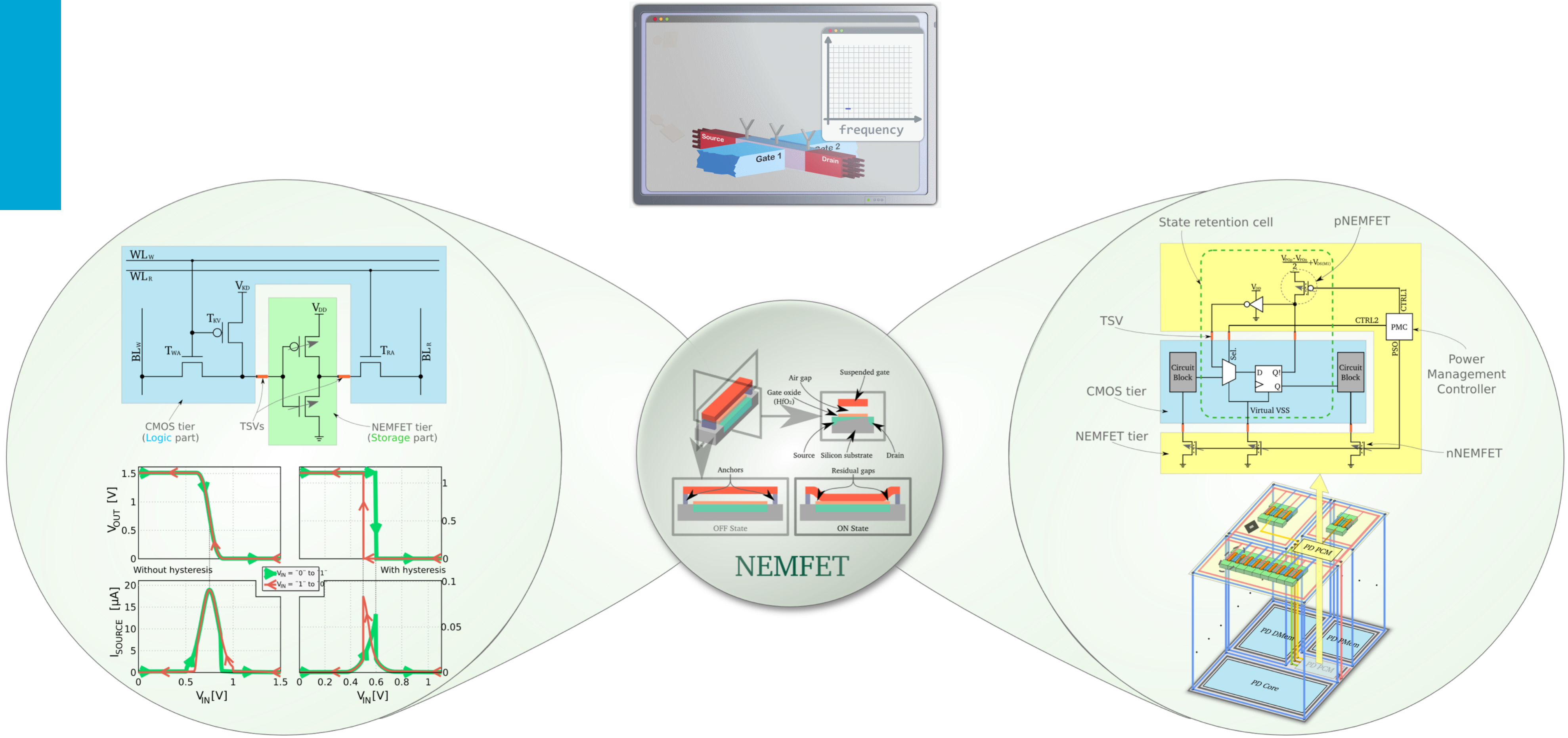
Required
- Accuracy (Output Correctness)
- Real Time Reaction (ms)
- Biocompatibility (Graphene)
- Adaptive Precision

Goal: Neuro-prosthetics

TU Delft

Quantum & Computer Engineering

"Zero Energy" with Nano Electromechanical FETs



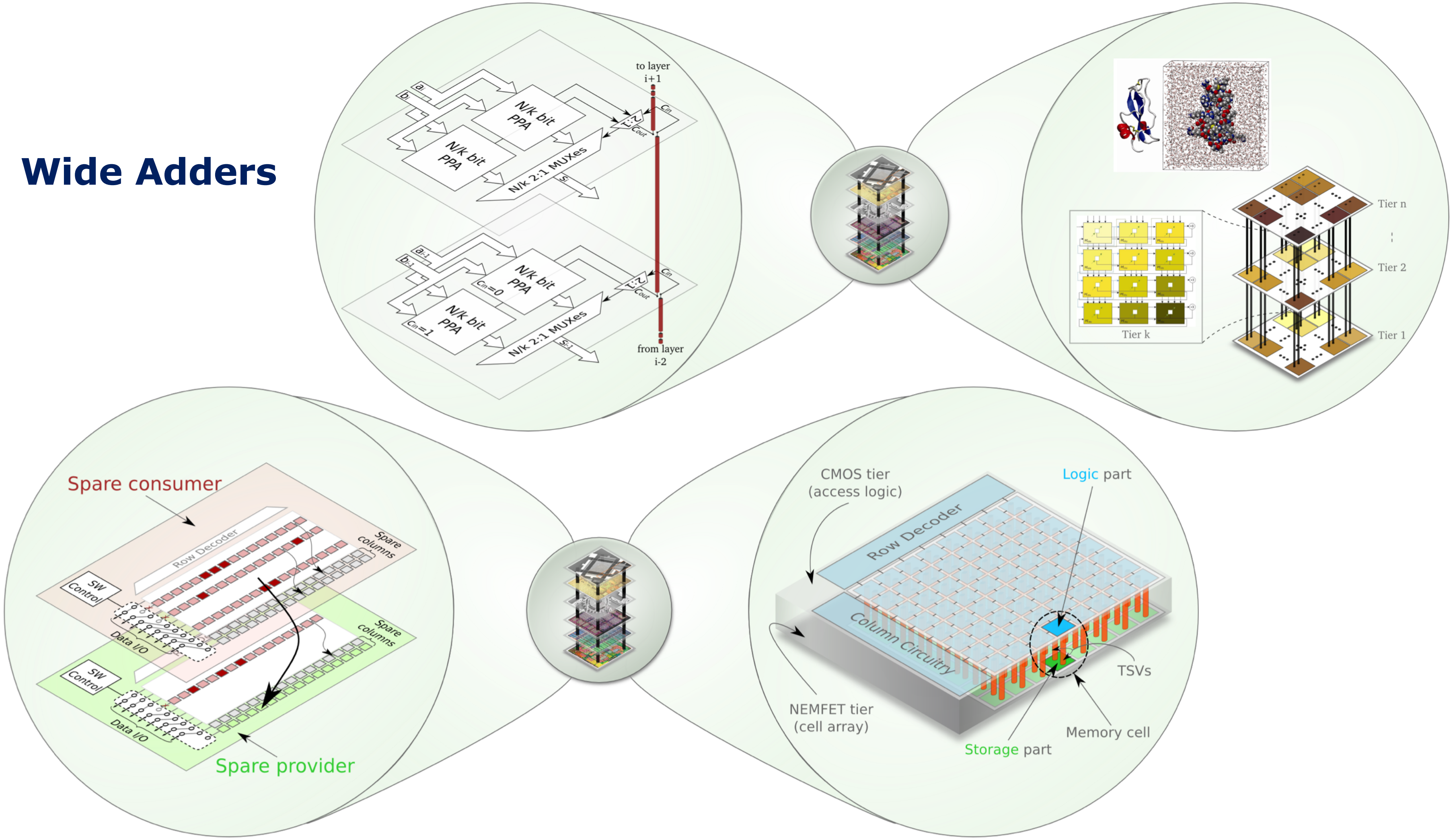
- **Hybrid Memory**
- **Short Circuit Free Logic**

Hybrid Power Management

TSV Based 3D Architecture

Systolic Fourier Transform

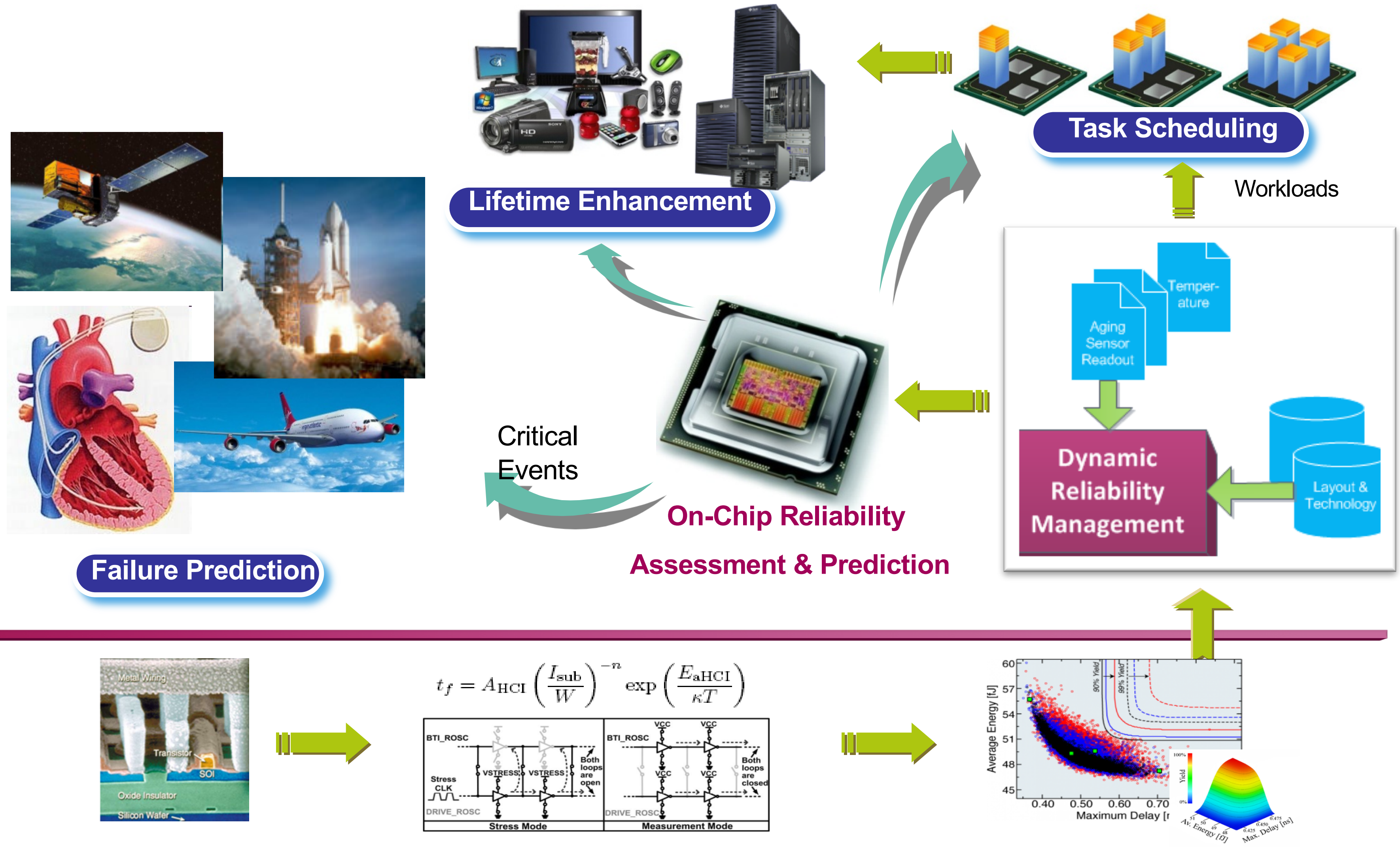
Wide Adders



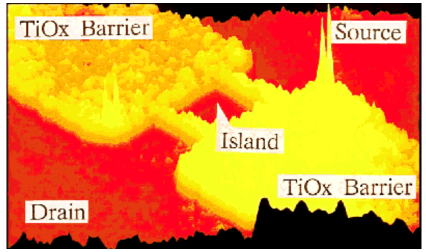
Inter-die Memory Repair

- **Polyhedral Memory**
- **LDPC Enhanced Memory**

Dynamic Reliability Management

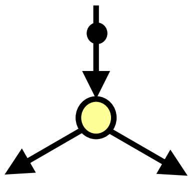


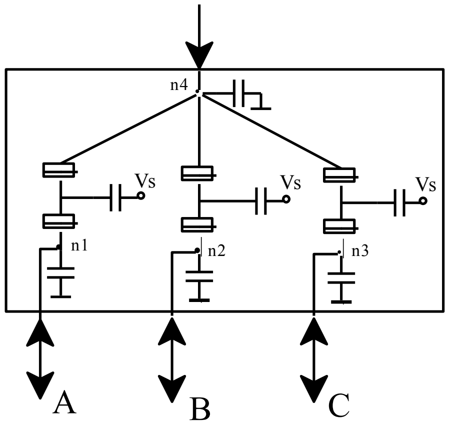
Noise Driven Computing - Brownian Circuits



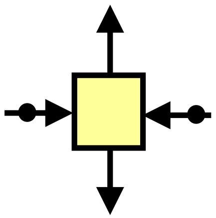
- **Tokens are Representing Signals**
- **Noise and Fluctuations to Drive the Computation**
- **Single Electron Tunneling Junctions**
- **Primitives (Hub, Conservative Join)**

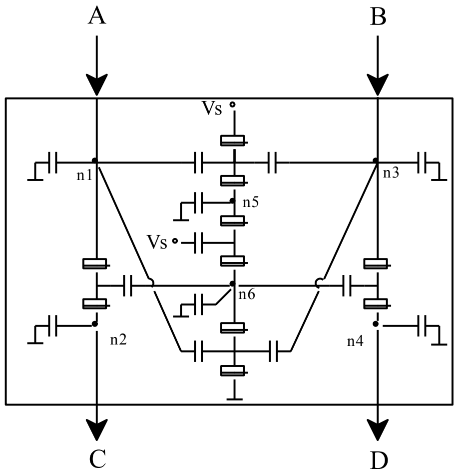
Hub

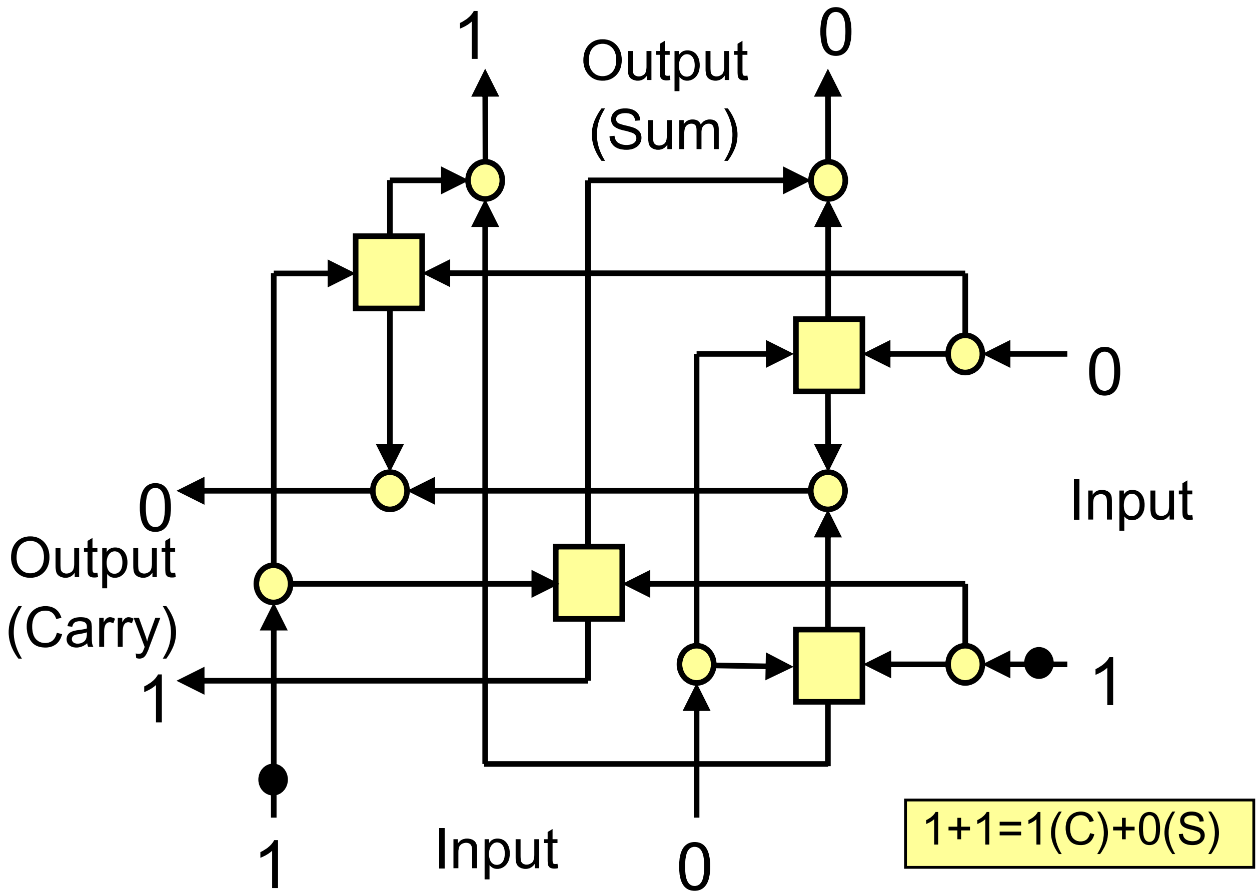




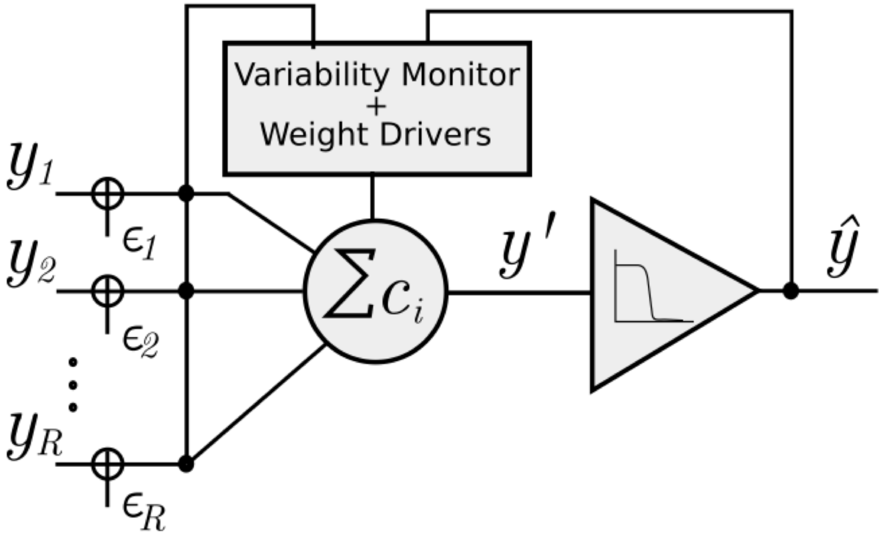
CJoin



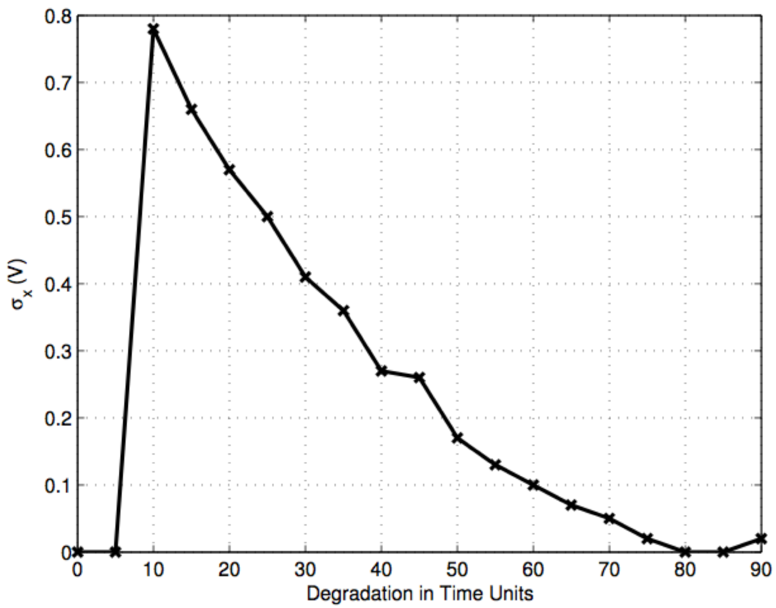


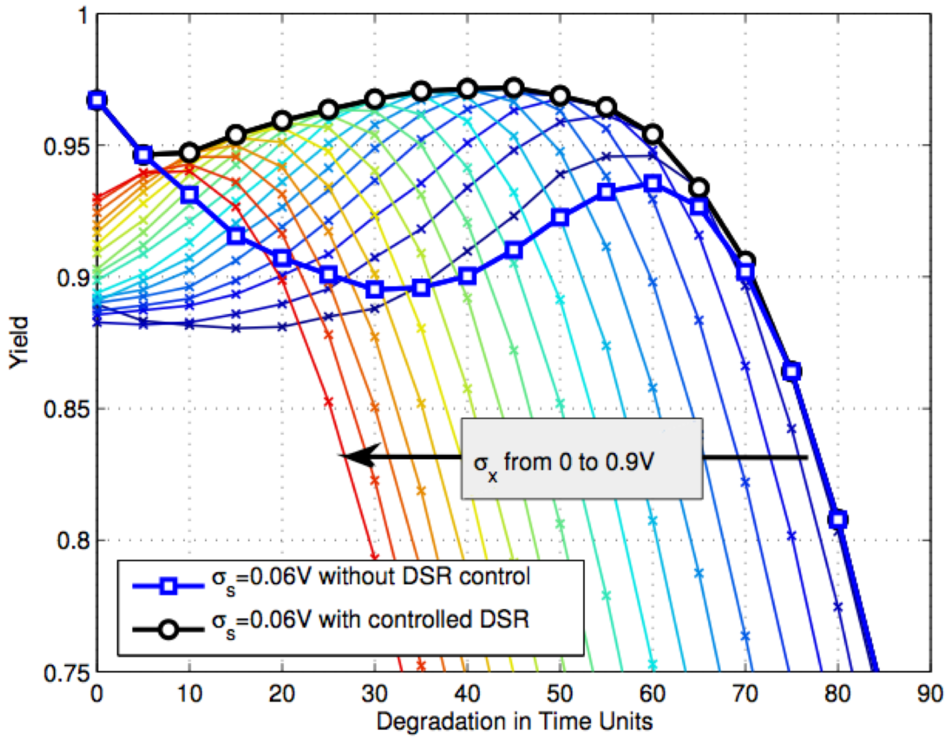


Noise Enabled Fault Tolerance (Reliability Enhancement)



- Adaptive Averaging Cell with R replicas.
- Input noise $\varepsilon_i \sim N(0,\sigma_x)$ to create Dynamic Stochastic Resonance reliability peaks regardless of aging (degradation level).





Thank you! Questions?