Logic-in-memory computation using magnetic skyrmions

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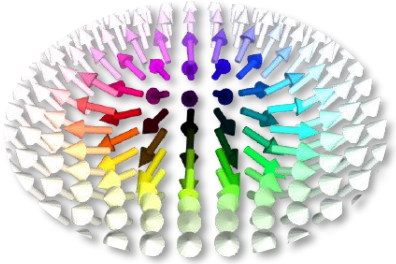
Outline

- Logic-in-memory
- Skyrmion motion in ion irradiated films
- Skyrmions in Synthetic Antiferromagnets
- 1-bit Full Adder
- Cascading and reconfigurability
- Hybrid Demultiplexers

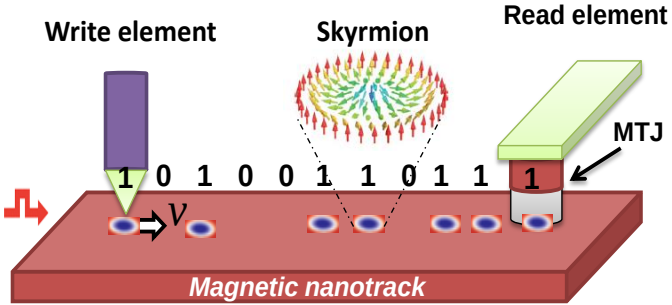
Skyrmions as memory & logic element

FM Skyrmion



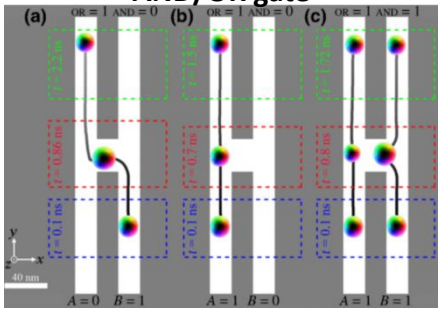
- Nanometer scale
- Chiral and topologically protected
- Fast manipulation by electric current

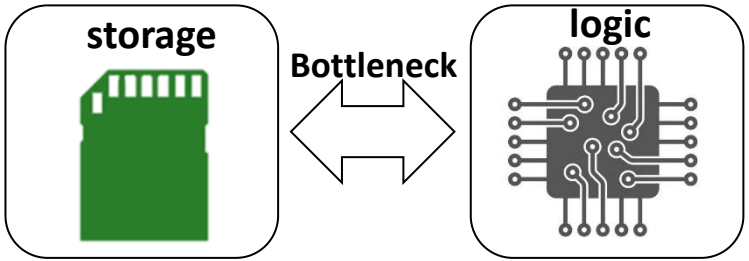
Racetrack memory[1]



Skyrmion logic[2]

AND/OR gate





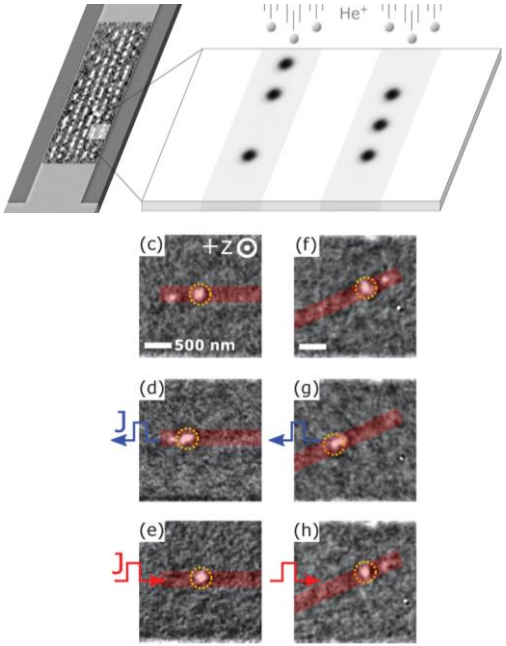
Challenges

- Information is encoded as distance b/w skyrmions→can change with thermal noise
- No interconversion of magnetic to electrical signal or vice versa
- Easy cascading
- Reconfigurability for programmable logic

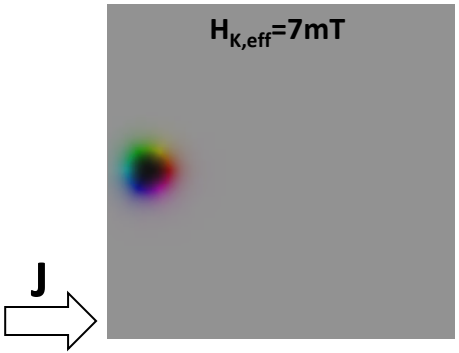
[1] Nat. Nano. 8, 839–844 (2013) ; [2] Phys. Rev. Applied 12, 064053 (2019)

Skyrmion-barrier dynamics

Ion-irradiation for skyrmion guiding



Uniformly irradiated FM

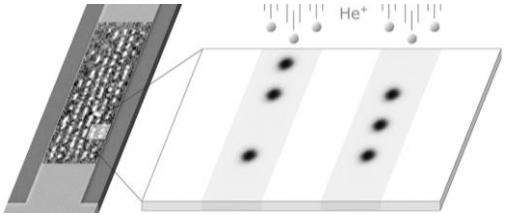


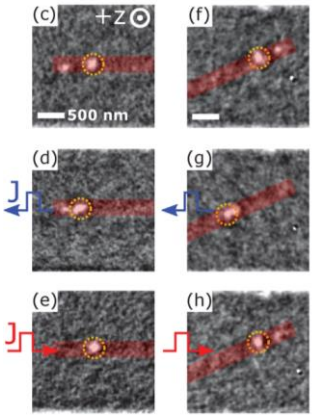
Skyrmion Hall effect is present (θ_{SH}=62°)

R. Juge *et al.*, Nano Lett., 21, 2989−2996 (2021)

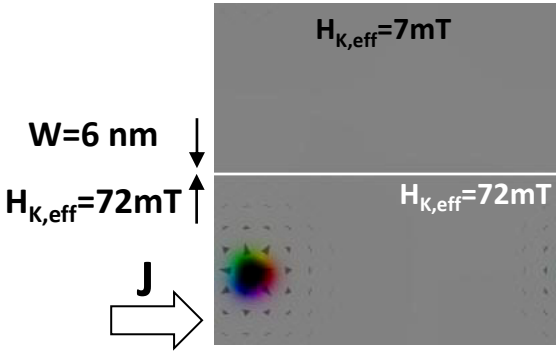
Skyrmion-barrier dynamics

Ion-irradiation for skyrmion guiding





Irradiated FM with a thin non-irradiated barrier

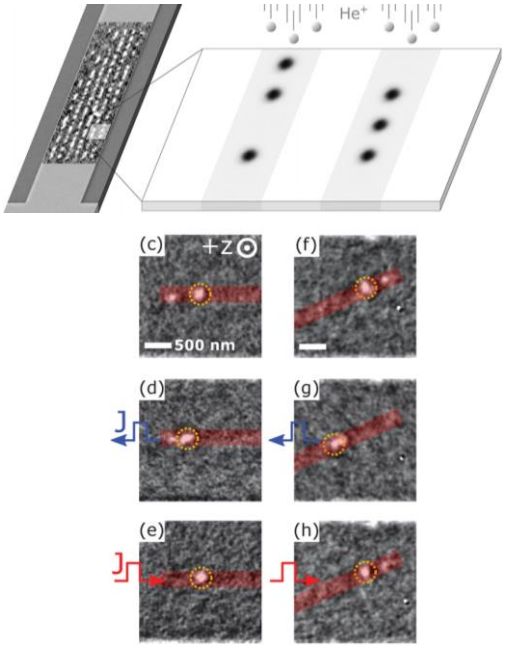


Skyrmion crossover through barrier

R. Juge *et al.*, Nano Lett., 21, 2989−2996 (2021)

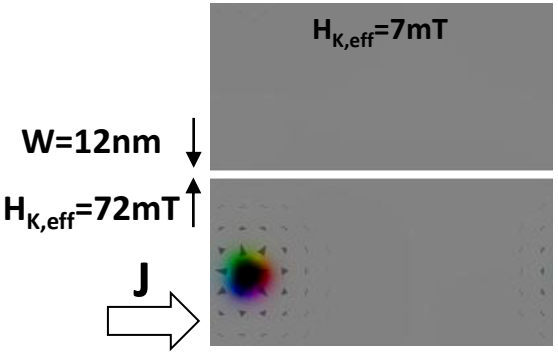
Skyrmion-barrier dynamics

Ion-irradiation for skyrmion guiding

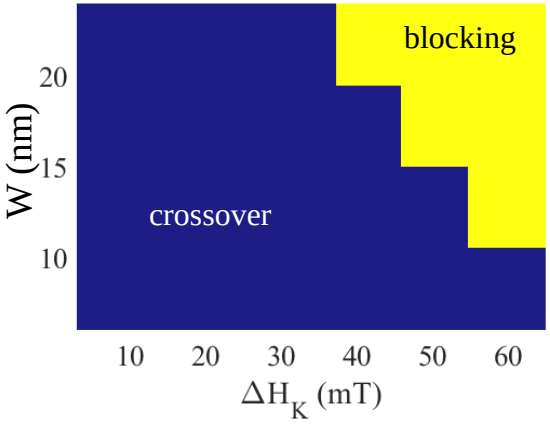


R. Juge *et al.*, Nano Lett., 21, 2989−2996 (2021)

Irradiated FM with a thick non-irradiated barrier

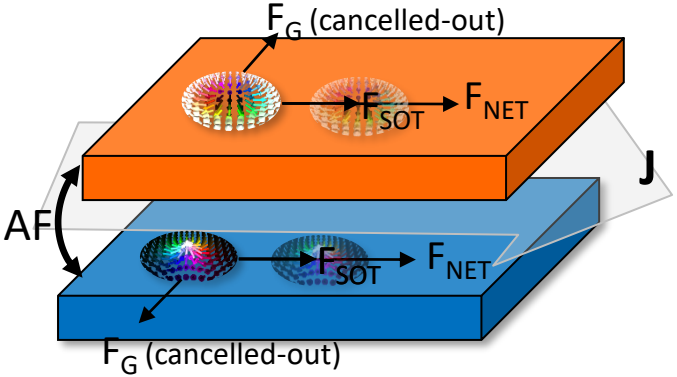


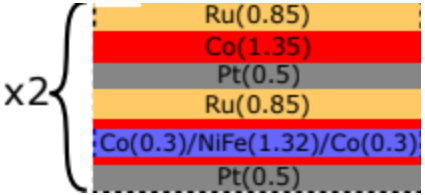
Skyrmion blocked by the barrier



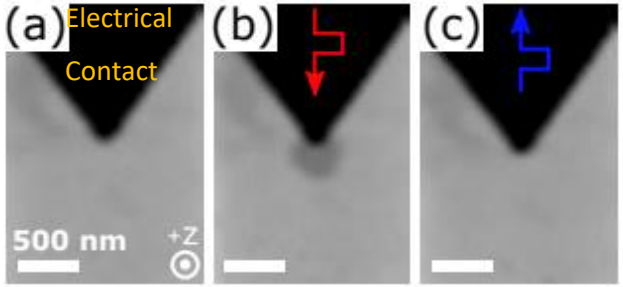
- ***New degree of freedom :*** Tunability of anisotropy barriers opens-up possibility to manipulate skyrmion trajectory for logic and computation

Skyrmions in Synthetic Antiferromagnets (FM/spacer/FM)

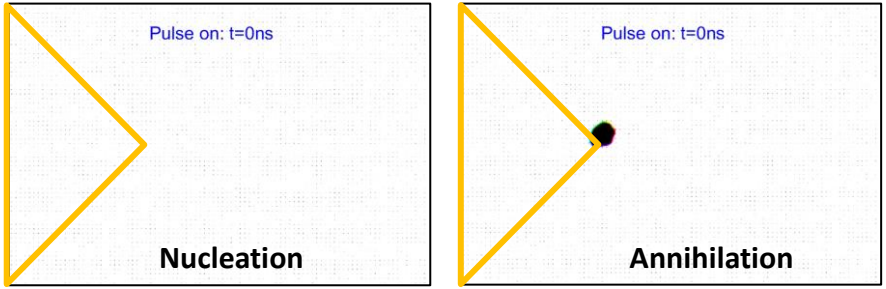




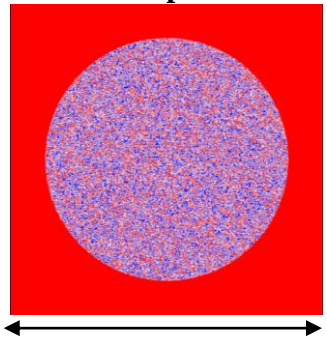
Experiments

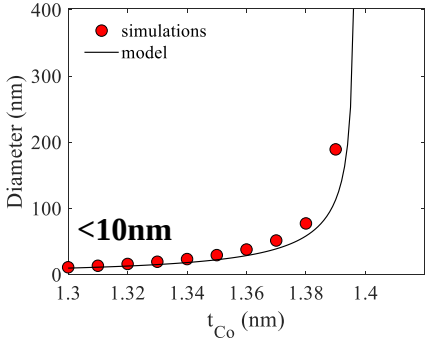


Micromagnetic Simulations



Nucleation with LASER pulses

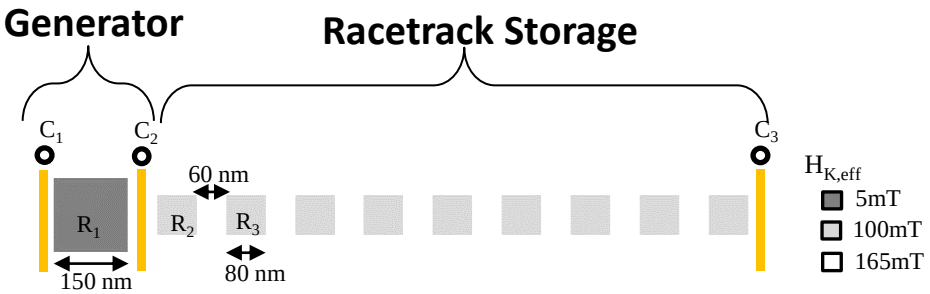


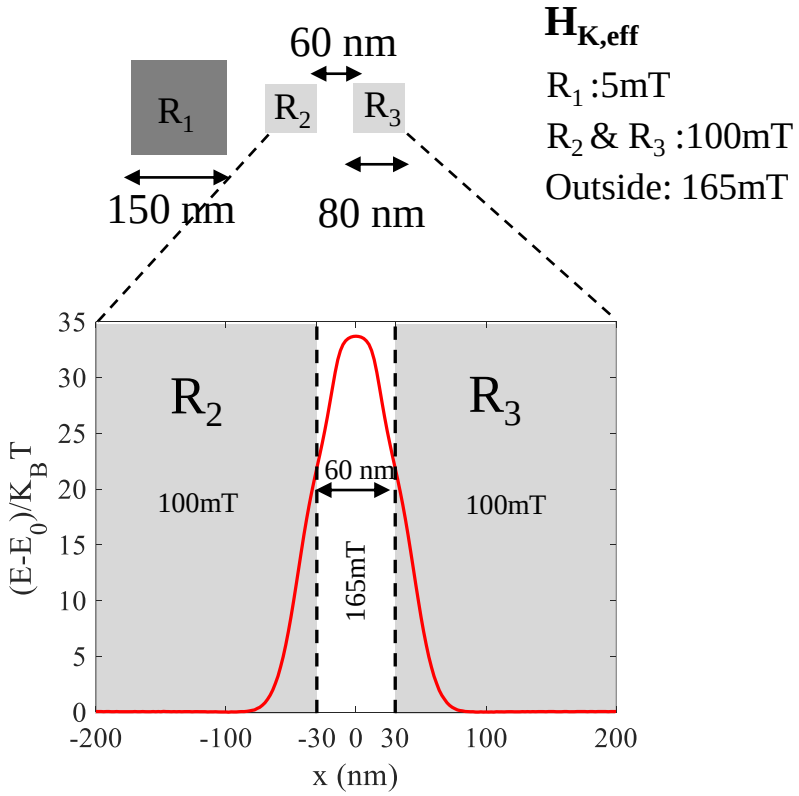


Tunable Skyrmion size

R. Juge, N. Sisodia, *et al.*, (Nat. Commun 13, 4807 (2022))

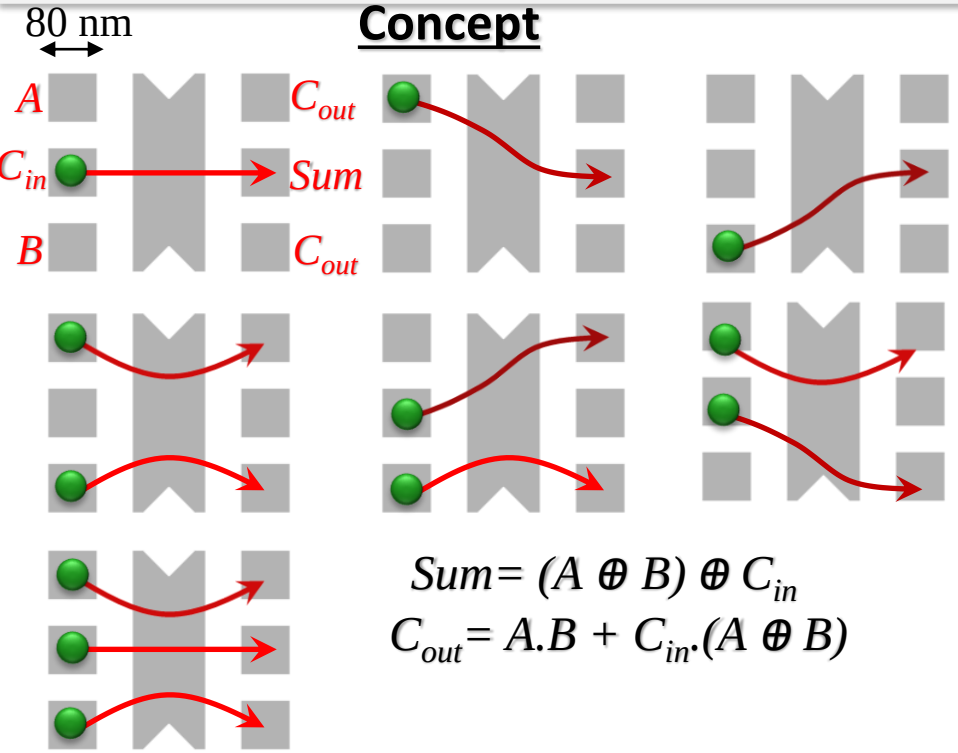
Skyrmion based racetrack memory by confining skyrmions





1-Bit Full Adder (FA) design

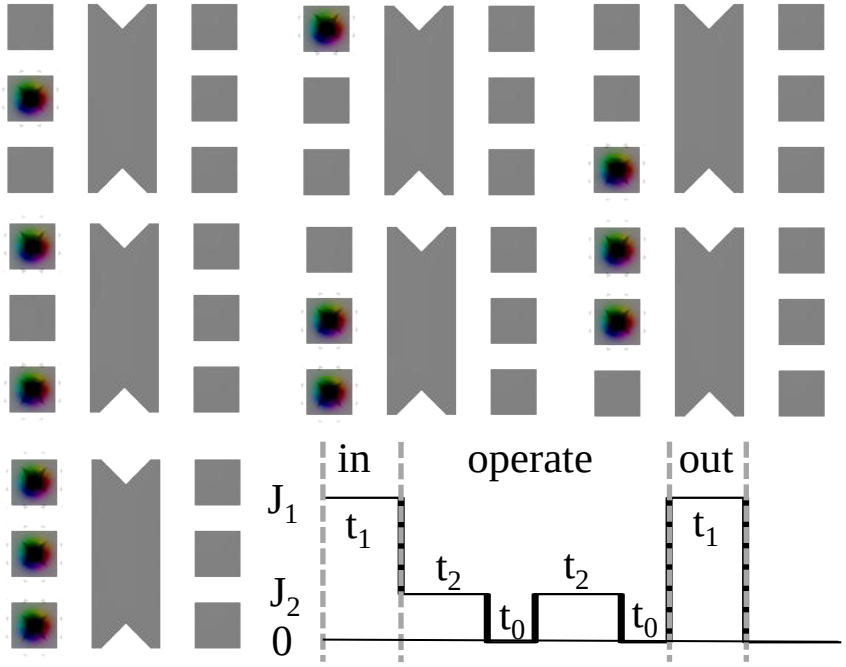
Concept



$$Sum = (A \oplus B) \oplus C_{in}$$

$$C_{out} = A.B + C_{in}.(A \oplus B)$$

Micromagnetic Validation



t_0=0.5ns; t_1=0.8ns, t_2=0.9ns

J_1=60 MA.cm^{-2} J_2=20 MA.cm^{-2}

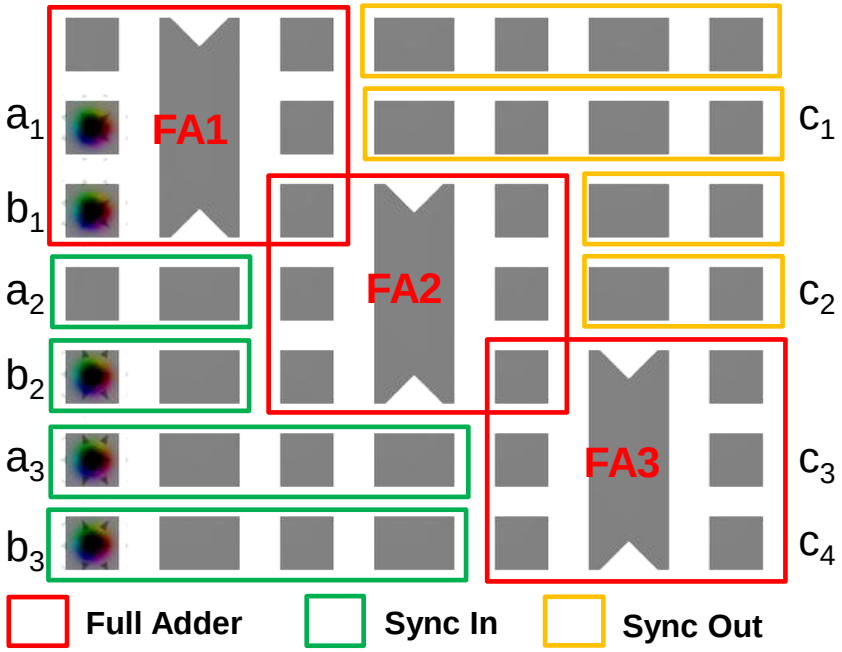
1 Sk input : Skyrmion moves either straight or is deflected by notches to Sum output (Sum=1, C_{out}=0)

2 Sk input : Skyrmions repel each other and are collected in carry output (Sum=0, C_{out}=1)

3 Sk input : All 3 skyrmions move towards 3 outputs (Sum=1, C_{out}=1)

3-bit ripple carry FA with cascading

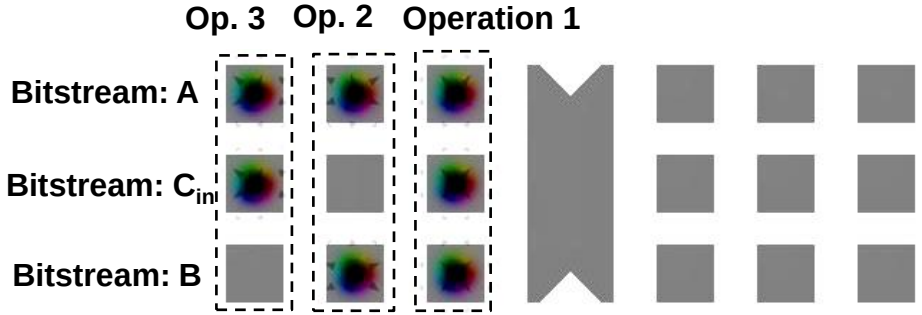
3-bit ripple carry FA



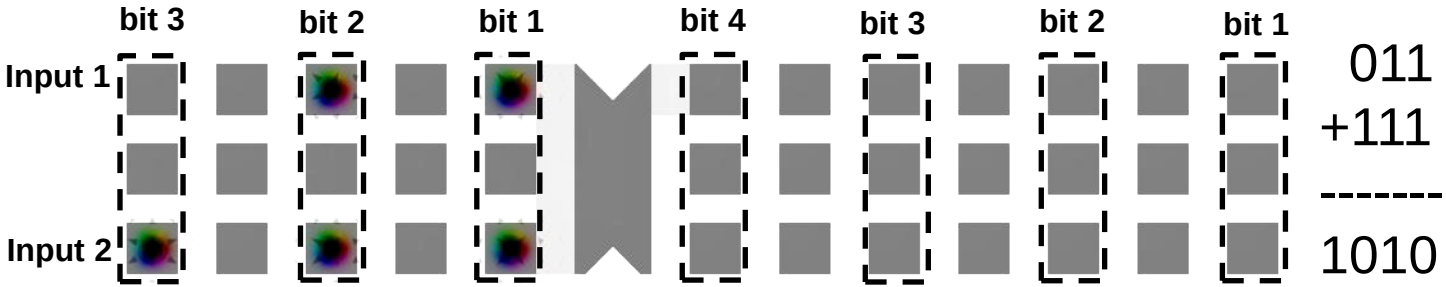
- Straightforward to cascade
- Synchronization can be implemented with "Sync-in" and "Sync-out" logic elements

General Exp.	Test Case
$a_3a_2a_1$ $+b_3b_2b_1$ ---------- $c_4c_3c_2c_1$	101 +111 ------- 1100

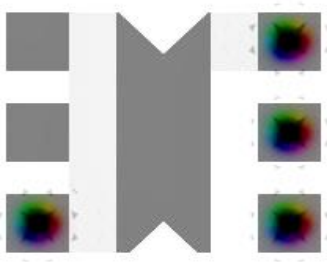
Serial 1-bit FA



3-Bit FA without cascading



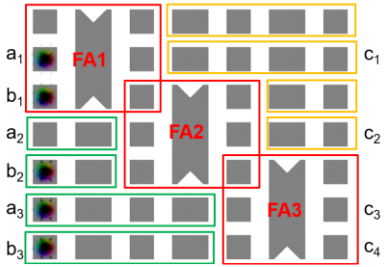
H_K (cells)< H_K (Shaded) H_K (barrier)



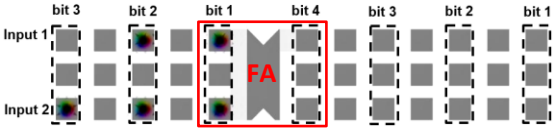
Negative polarity pulse applied

- Modification of barriers allows individual control over outputs
- Reduced design complexity as no cascading is required for multi-bit FA operations
- Synchronization is supported intrinsically by design and does not require any extra logic elements

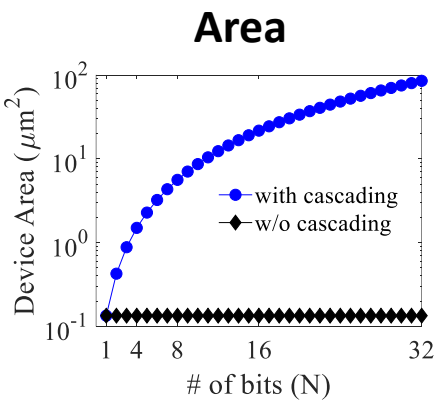
Comparing 3-Bit FA with and w/o cascading

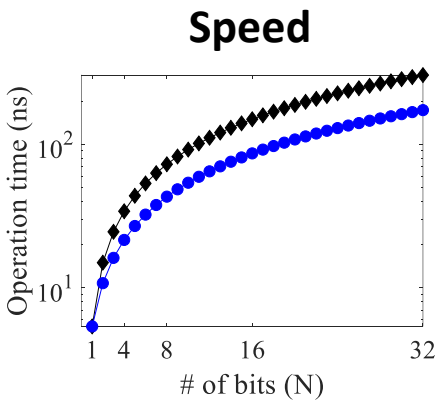


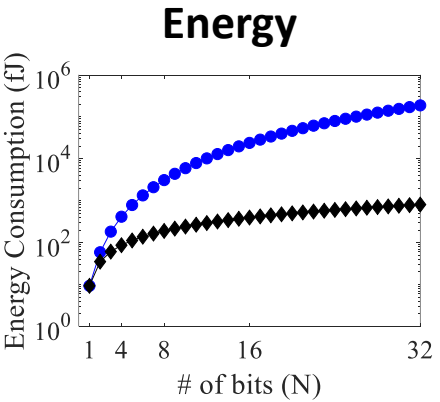
3-bit FA with Cascading



3-bit FA w/o Cascading







- In the w/o cascaded version, the device area is independent of number of bits
- Sending the carry-out back to input stage in w/o cascaded design, an extra delay is introduced which nearly doubles the operation time
- As number of bits increase, w/o cascaded design consumes significantly less energy

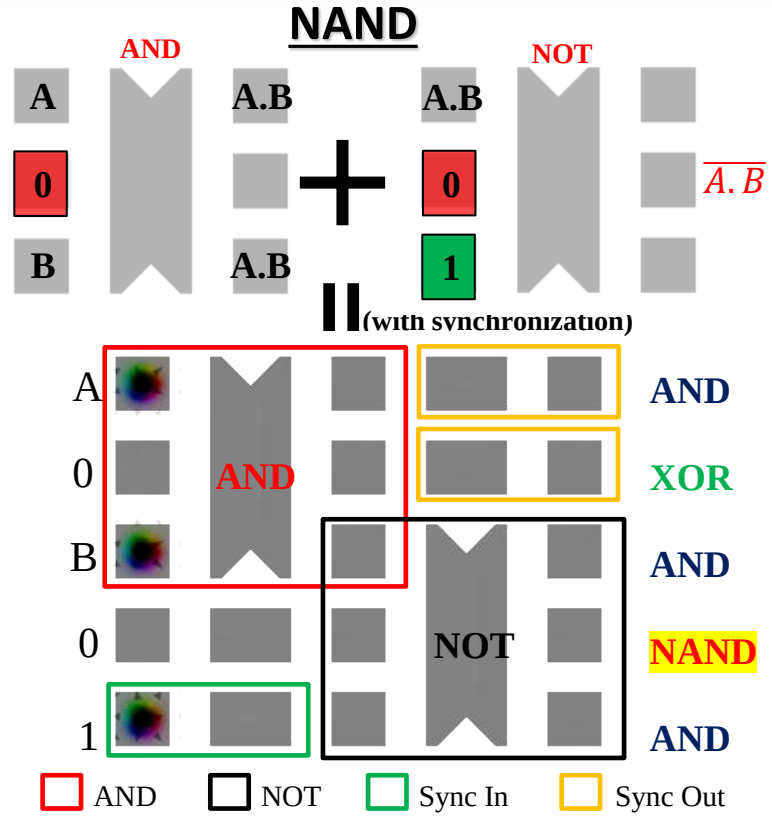
Reconfigurability

NOT/BUFFER Gate

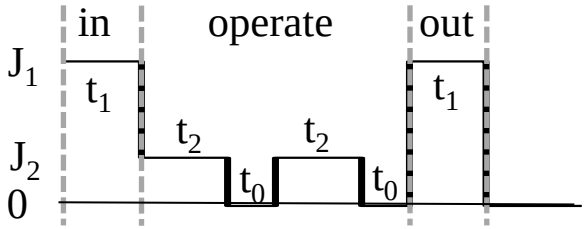
XOR/AND Gate

XNOR/OR Gate

- By fixing inputs, FA can be reconfigured to perform several other logic operations including NAND gate



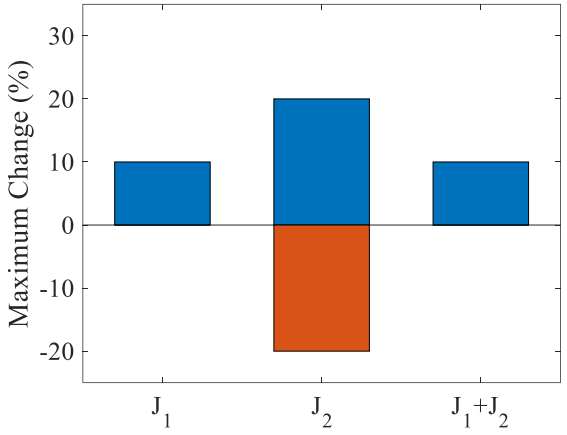
Electrical Tolerances

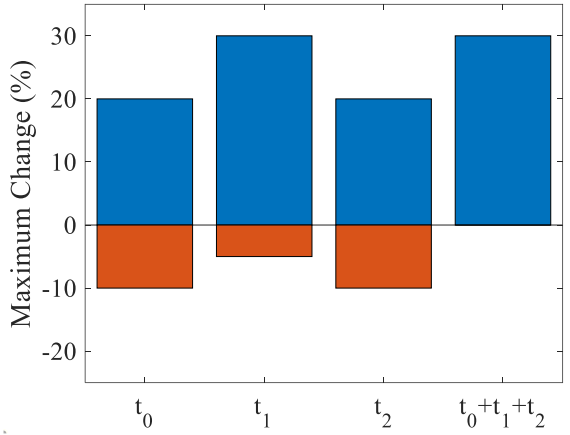


t_0=0.5ns
t_1=0.8ns
t_2=0.9ns

J_1=15 MA.cm^{-2}

J_2=5 MA.cm^{-2}





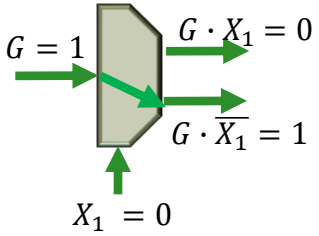
- At minimum, 10% variation in amplitude of electrical current is allowed for all pulses (even higher tolerance for J_2)
- ~30% variation in the pulse width is allowed for all current pulses

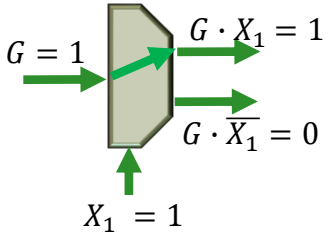
N. Sisodia, *et al.*,"*Robust programmable logic-in-memory skyrmion device using local energy barriers*" (Phys. Rev. Applied 18, 014025 (2022))

Skyrmion based 1-to-2 demultiplexer

Demultiplexer

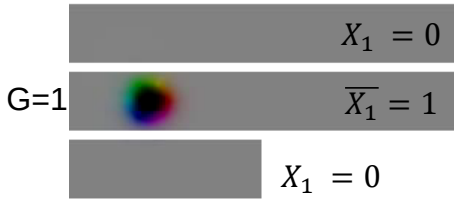
→selector input switches the output path

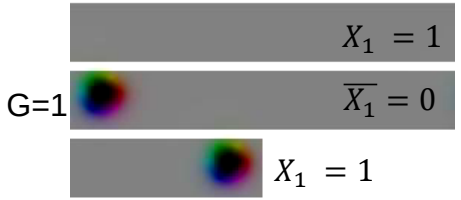




Dmux: Type A

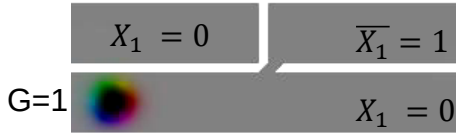
→Sk-Sk repulsion enhances tunnelling
→Selector input X_1 track is below G

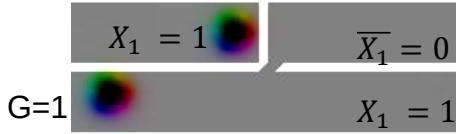




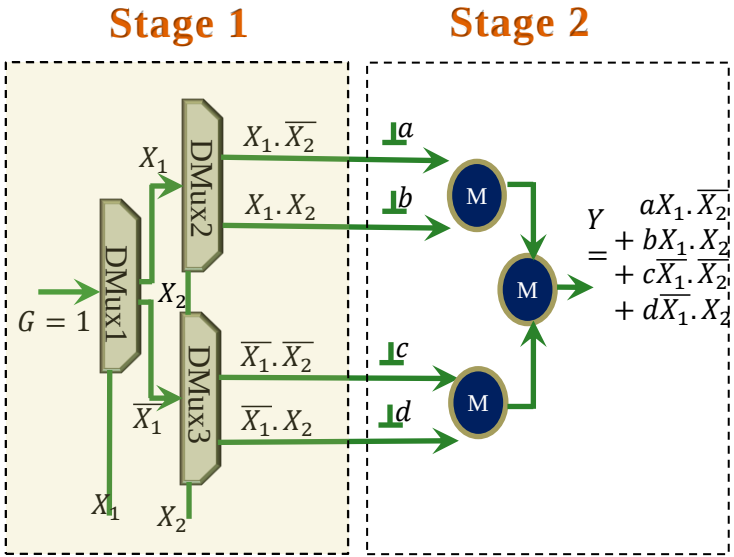
Dmux: Type B

→Sk-Sk repulsion blocks tunnelling
→ Selector input X_1 track is above G

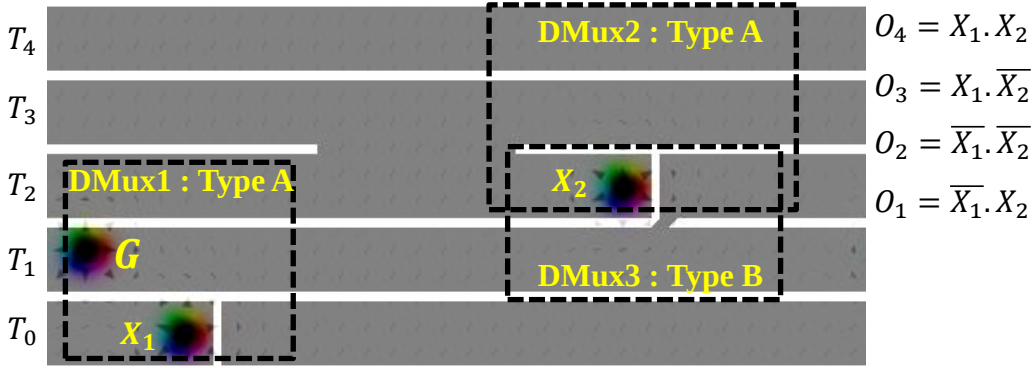




Universal logic based on cascaded demultiplexers



Micromagnetic Design & Validation : Stage 1



Test Case : $X_1 = 1;\ X_2 = 1$

N. Sisodia, *et al.*,"*Programmable skyrmion logic gates based on skyrmion tunneling*" (Phys. Rev. Applied 17, 064035 (2022))

What next?

- Deterministic operations may be difficult to achieve due to imperfections in device (pinning) and thermal noise→ possibility of stochastic computing
- Focus on techniques which utilize the collective dynamic behaviour of skyrmions → reservoir computing
- Higher level modelling needed for complex/large scale circuits

Related publications →

- N. Sisodia, *et al.*,"*Robust programmable logic-in-memory skyrmion device using local energy barriers*" **Phys. Rev. Applied 18, 014025 (2022)**
- N. Sisodia, *et al.*,"*Programmable skyrmion logic gates based on skyrmion tunneling*" **Phys. Rev. Applied 17, 064035 (2022)**
- R. Juge, N. Sisodia**,** *et al.*, *Skyrmions in synthetic antiferromagnets and their nucleation via electrical current and ultra-fast laser illumination* **Nat. Commun. 13, 4807 (2022)**)
- R. Juge, *et al.*, *Helium Ions Put Magnetic Skyrmions on the Track* **Nano Lett., 21, 2989−2996 (2021)**

Thank you for your attention !

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Qiang Zhang
Van Tuong Pham
Kumari Gaurav Rana
Brice Sarpi
Nicolas Mille
Stefan Stanescu
Rachid Belkhou
Mohamad-Assaad Mawass
Nina Novakovic-Marinkovic
Florian Kronast

- **This work is supported by DARPA TEE grant**

Markus Weigand
Joachim Gräfe
Sebastian Wintz
Simone Finizio
Jörg Raabe
Lucia Aballe
Michael Foerster
Mohamed Belmeguenai
Justin M. Shaw
Hans T. Nembach
Laurent Ranno