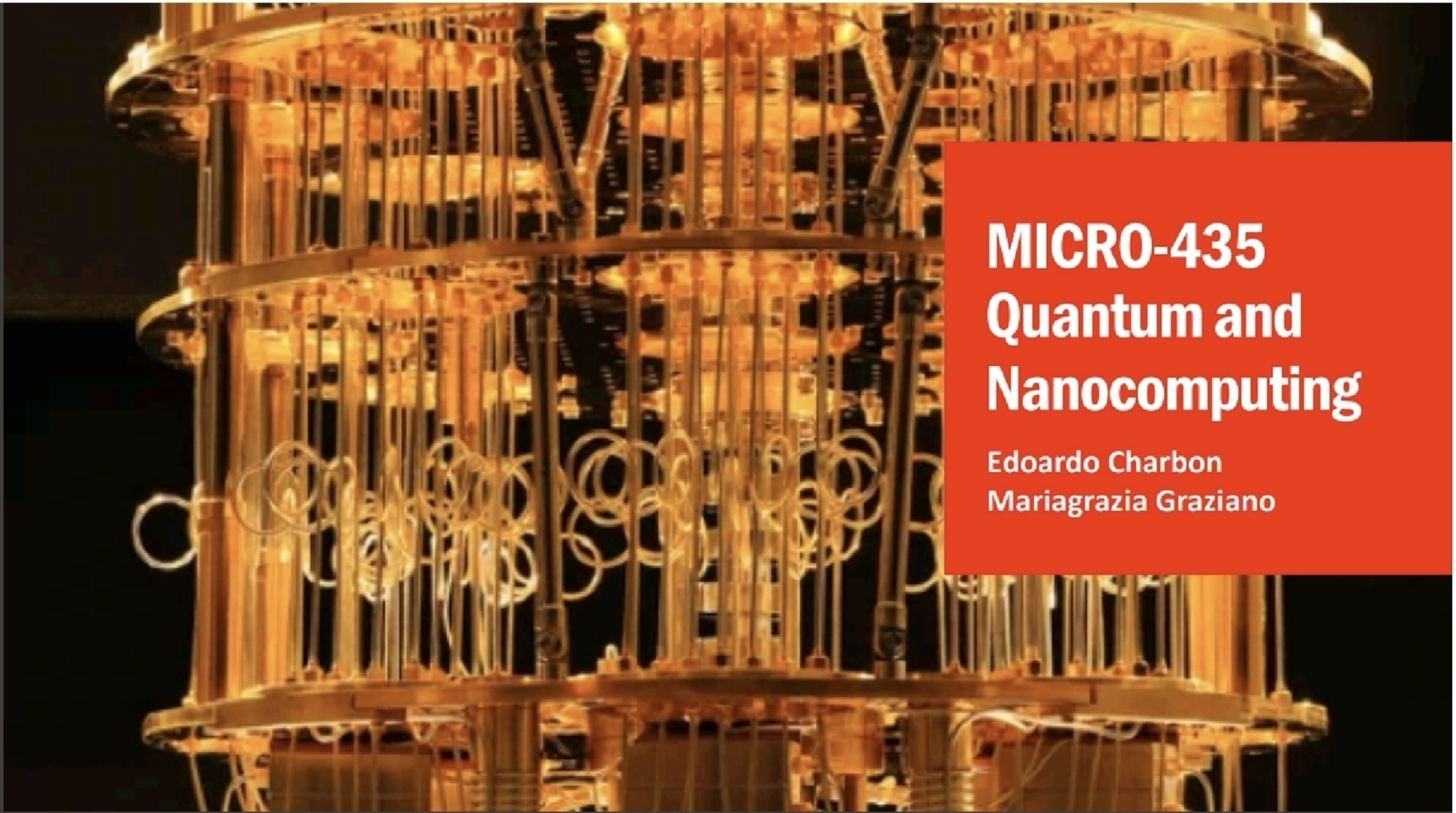


MICRO-435 Quantum and Nanocomputing

Edoardo Charbon
Mariagrazia Graziano

FROM INML TO MORE ADVANCED NANOMAGNETIC STRUCTURES

- DML

NS 2324

FROM INML TO MORE ADVANCED NANOMAGNETIC STRUCTURES

- DML

OBJECTIVES

TOWARD OTHER MAGNETIC STRUCTURES FOR LOGIC & MEMORY

- → DOMAIN MAGNET LOGIC
- → PNML
- → RACETRACK LOGIC
- → SKYRMIONS
- → (SPIN WAVES)

DOMAIN MAGNET LOGIC

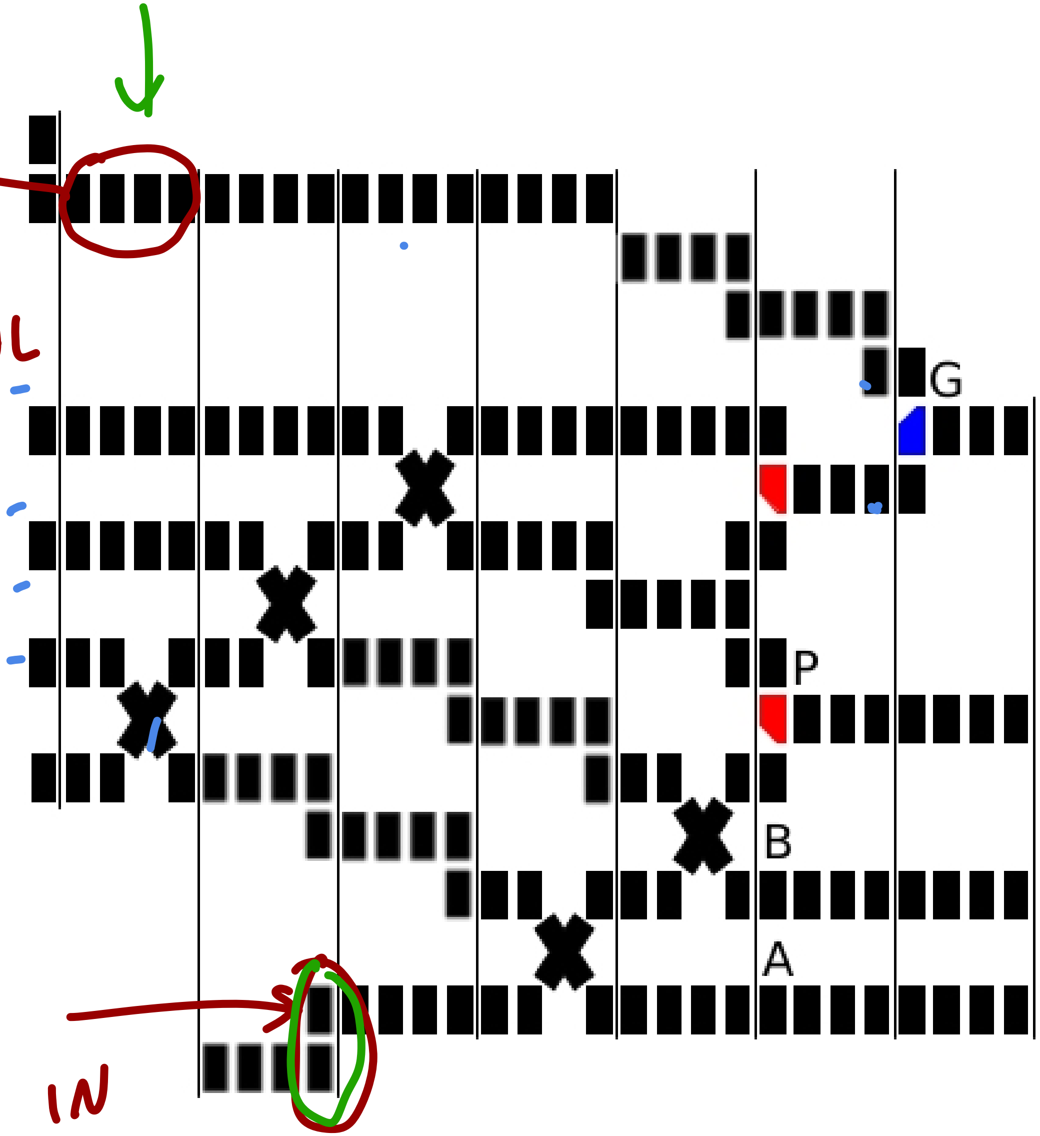
ONE OF THE PROBLEMS OF NML IS THE AREA DUE TO THE LIMITED NUMBER OF MAGNETS IN A CR.ZONE, ESPECIALLY VERTICAL IF NOISE AND TEMP. ARE CONSIDERED

↳ GOOD FOR LOGIC

↳ NOT GOOD FOR INTERCONNECT

EXAMPLE → PROBLEM W A REAL CASE

4 MAGNETS ORIZONTAL PROP.



2 MAGNETS IN VERTICAL PROP. (EXTREME CONSTRAINT)

LOGIC

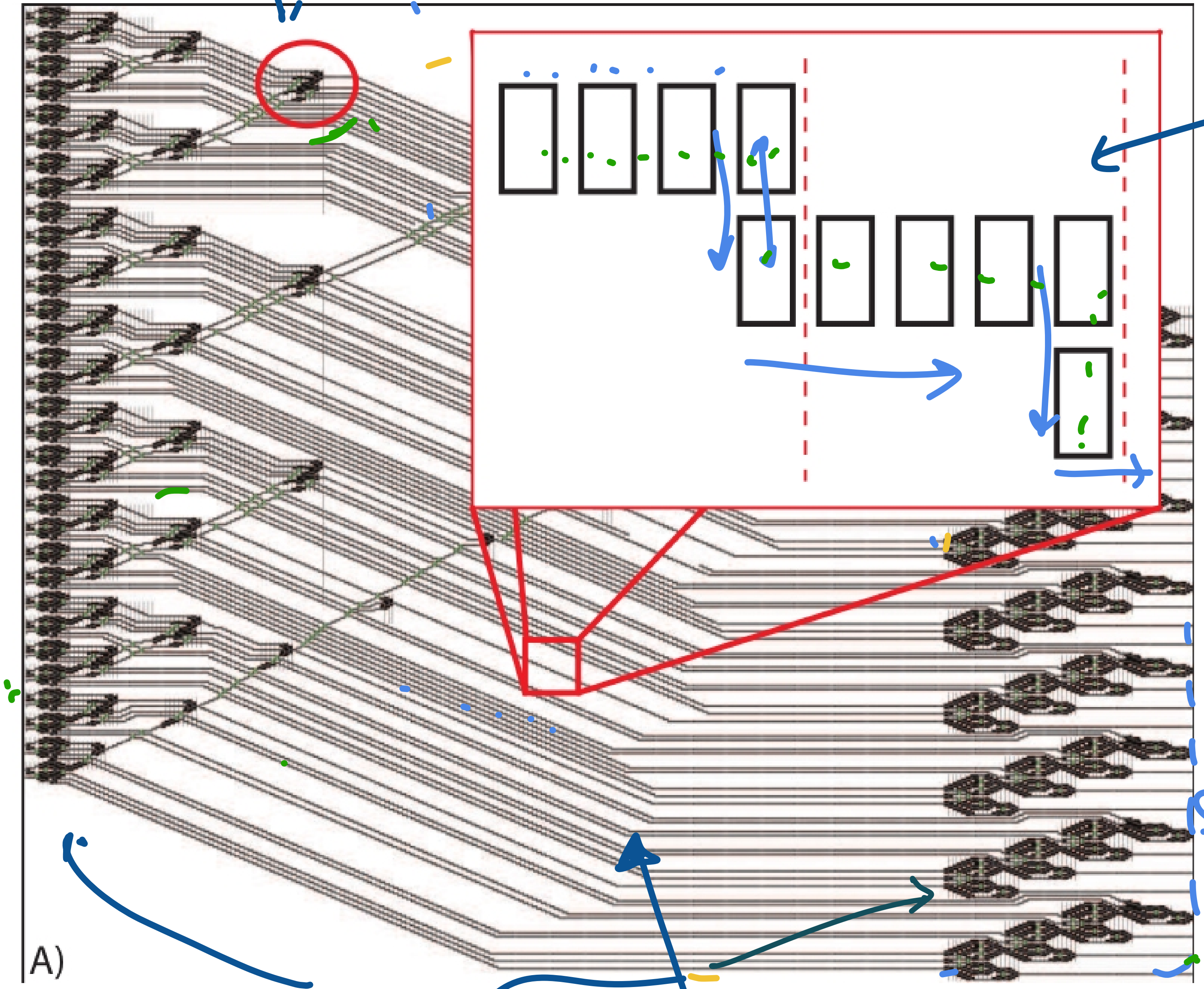
CARRY GENERATION IN A CLA-LIKE STRUCTURE: THE SPARSE TREE P4 ADDER

PENTIUM 4

LAYOUT = TIMING

THE WHOLE P4 ADDER

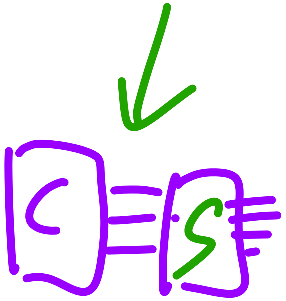
CARRY GENERATION BLOCK



STAIR WISE WIRING

OVERHEAD!

SUM



LOGIC + INTERCONNECTS

CREDITS H.VACCA

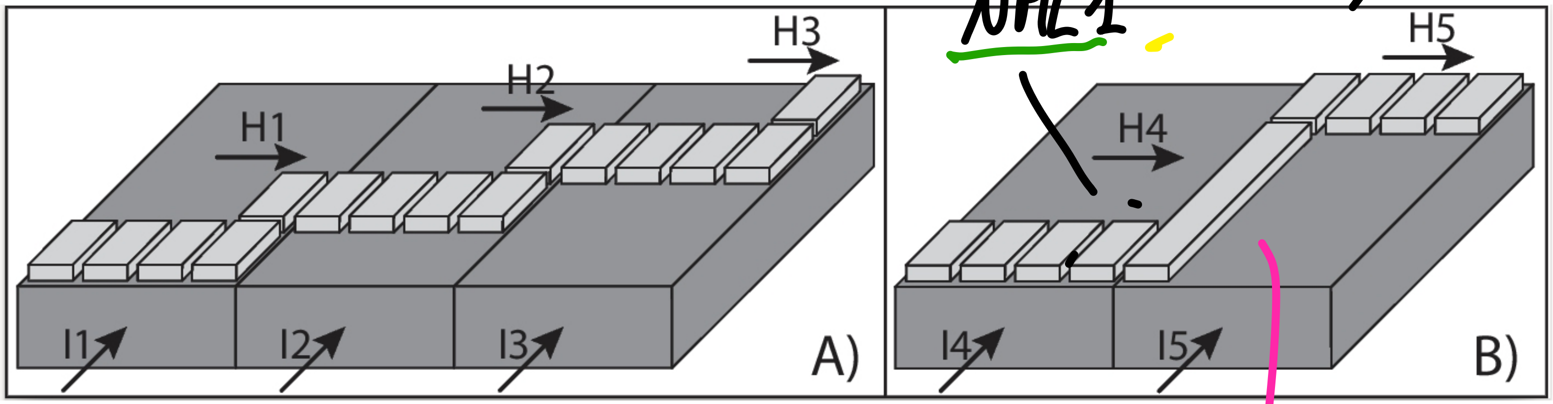
VERTICAL INTERCONNECTIONS NEEDED!

NML

DOMAIN-MAGNET LOGIC

NML 2

NML 1

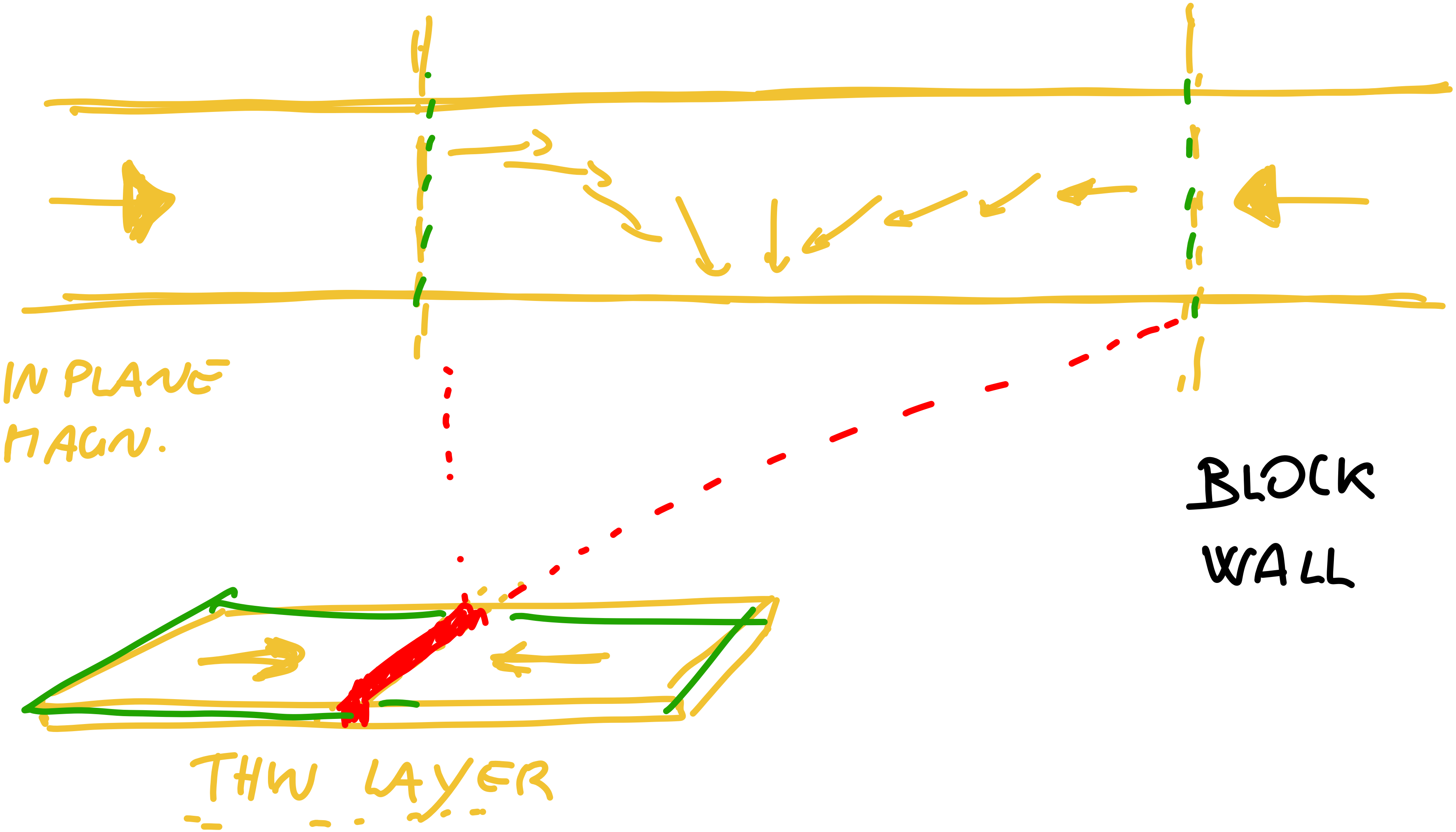


DOMAIN WALL

D.W. LOGIC EXISTS, BUT → (COWBURN GROUP)

DW → NOT GOOD FOR LOGIC
→ GOOD FOR INTERCONNE

DOMAIN WALL (see initial parts)



DOMAIN WALL

→ A PLACE IN THE STRUCTURE THAT MINIMIZES ENERGY IN CERTAIN CONDITIONS

→ EXTERNAL FIELDS (H)

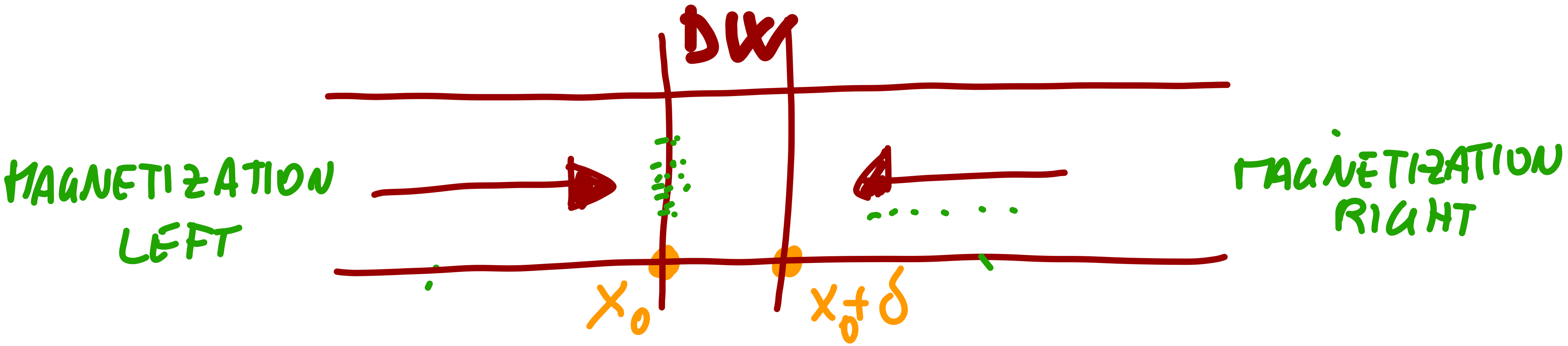
OR/AND

→ CURRENT FLOWING (SPIN POLARIZED)

OR/AND

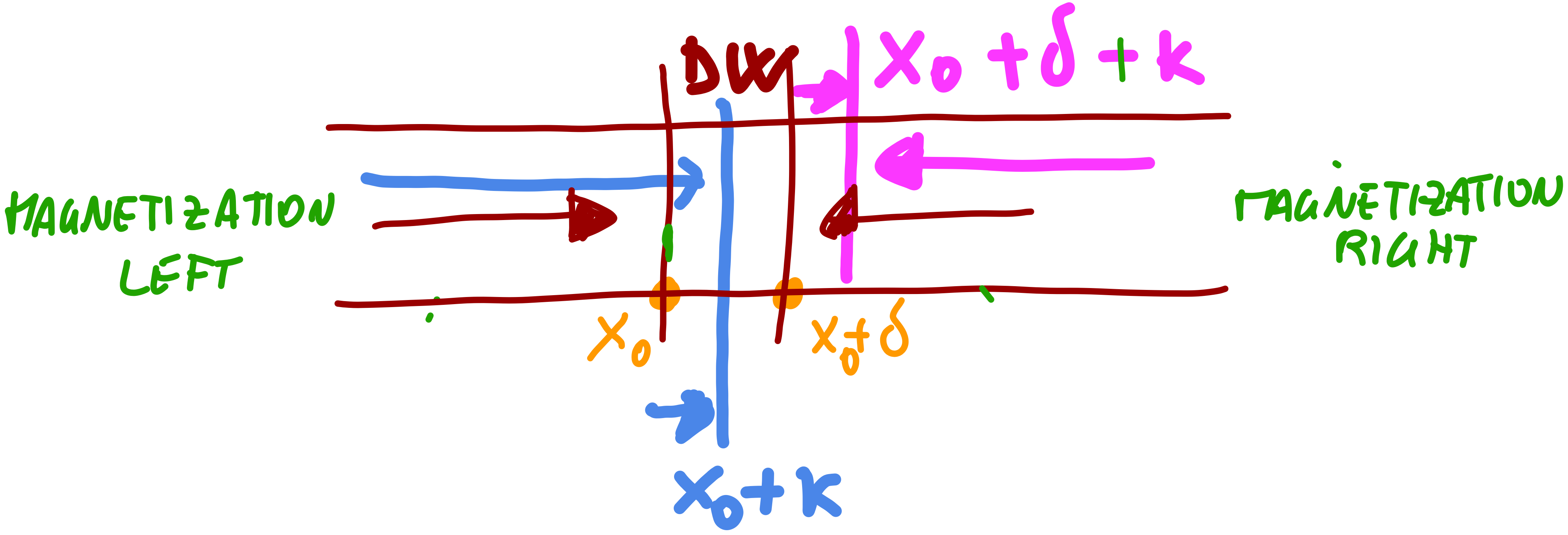
→ TEMPERATURE

⇒ CHANGE THE ENERGY BUDGET AND CAN "MOVE" THE D. W.



IF A MAGNETIC FIELD IS APPLIED IN THE SAME DIRECTION OF THE MAGNETIZATIO IN ONE DOMAIN → THE DOMAIN INCREASES IN SIZE

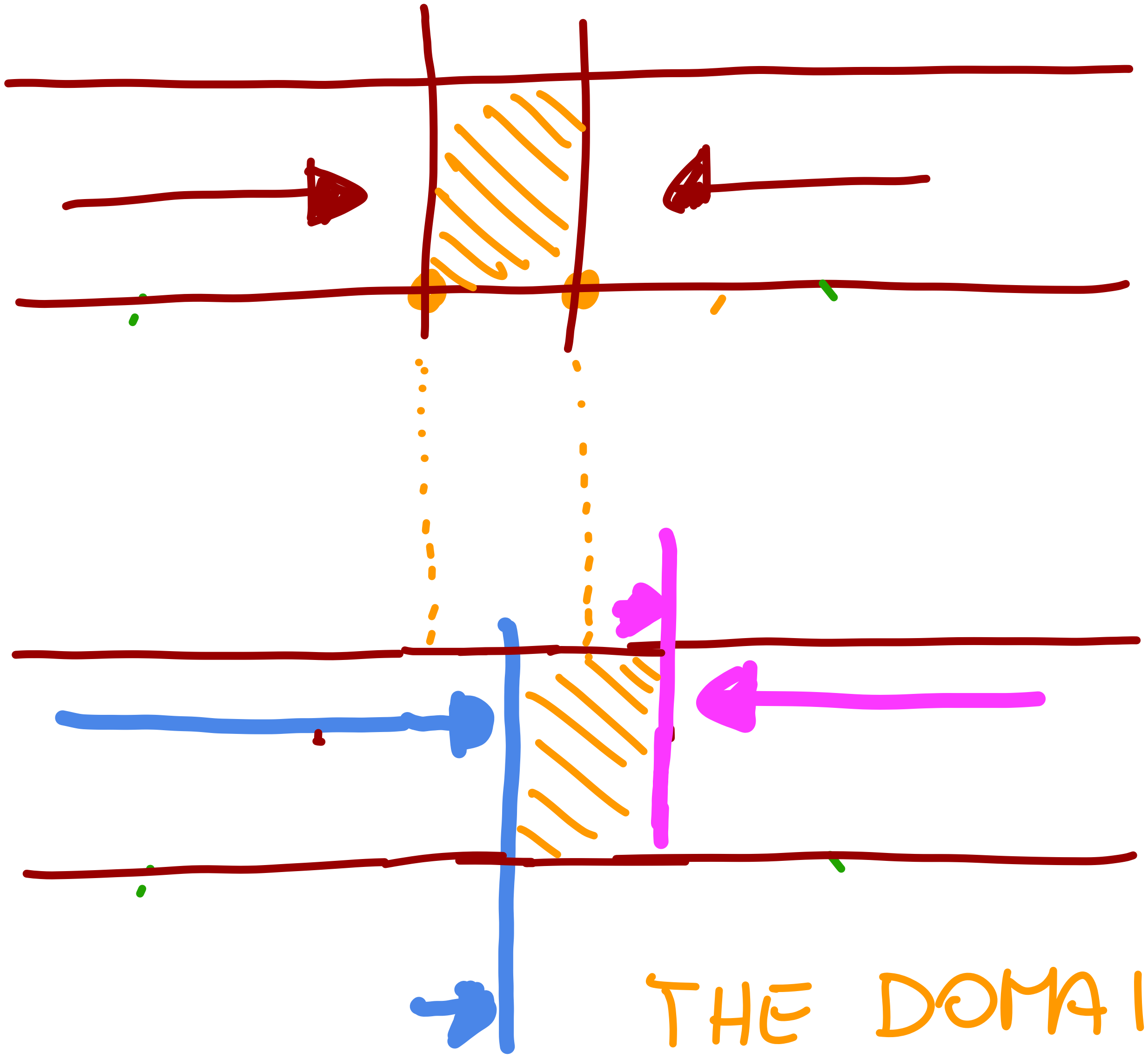
IF A MAGNETIC FIELD IS APPLIED IN THE OPPOSITE DIRECTION OF THE MAGNETIZATION IN ONE DOMAIN → THE DOMAIN DECREASES IN SIZE



IF A MAGNETIC FIELD IS APPLIED IN THE SAME DIRECTION OF THE MAGNETIZATIO IN ONE DOMAIN → THE DOMAIN INCREASES IN SIZE

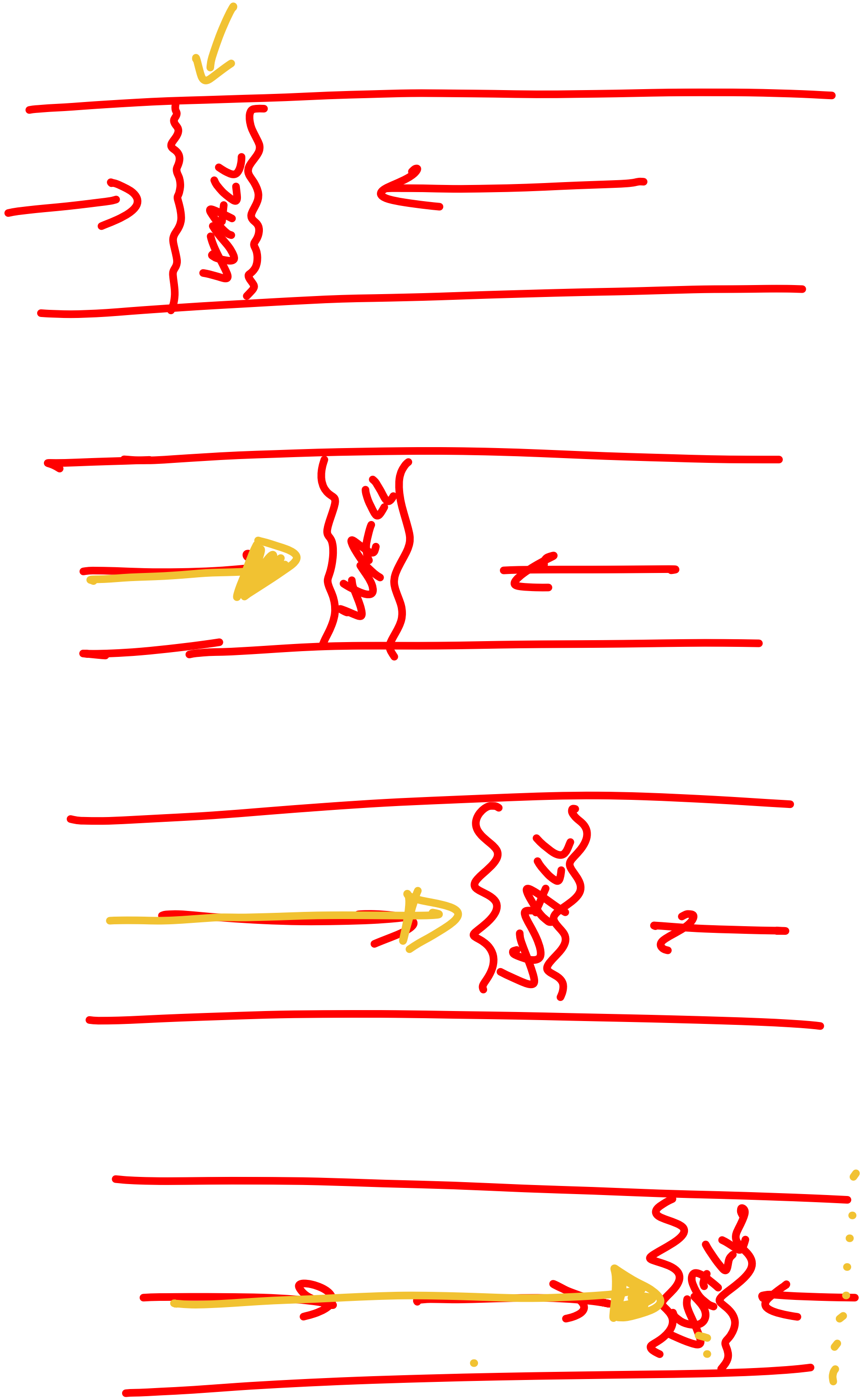
IF A MAGNETIC FIELD IS APPLIED IN THE OPPOSITE DIRECTION OF THE MAGNETIZATIO IN ONE DOMAIN → THE DOMAIN DECREASES IN SIZE

RESULT



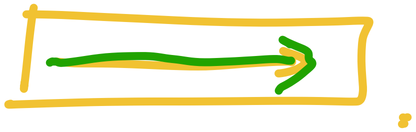
THE DOMAIN WALL

MOVES



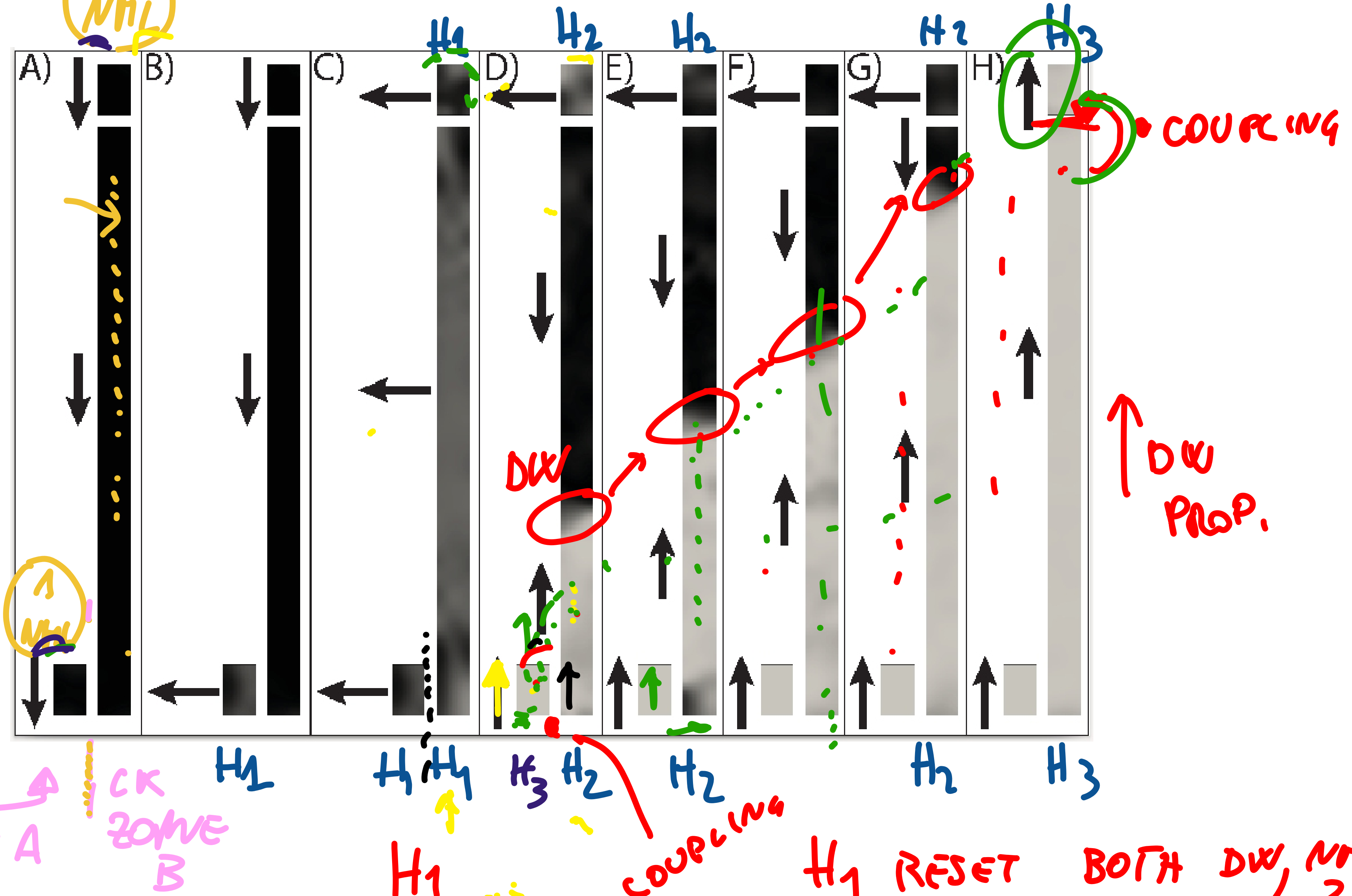
THE PROPAGATION IS FAST ALSO W LONG WIRES

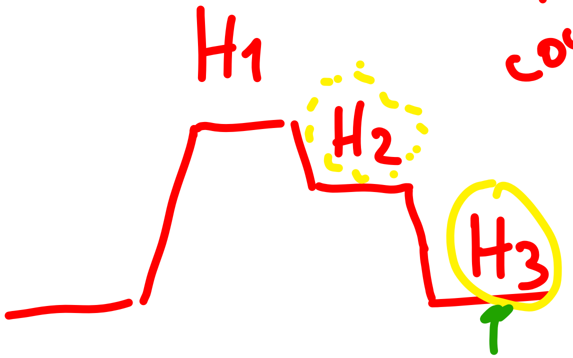
APPLY WITH NML



MICROMAGNETIC SIMULATION

INITIAL MAGNETIZATION





H3

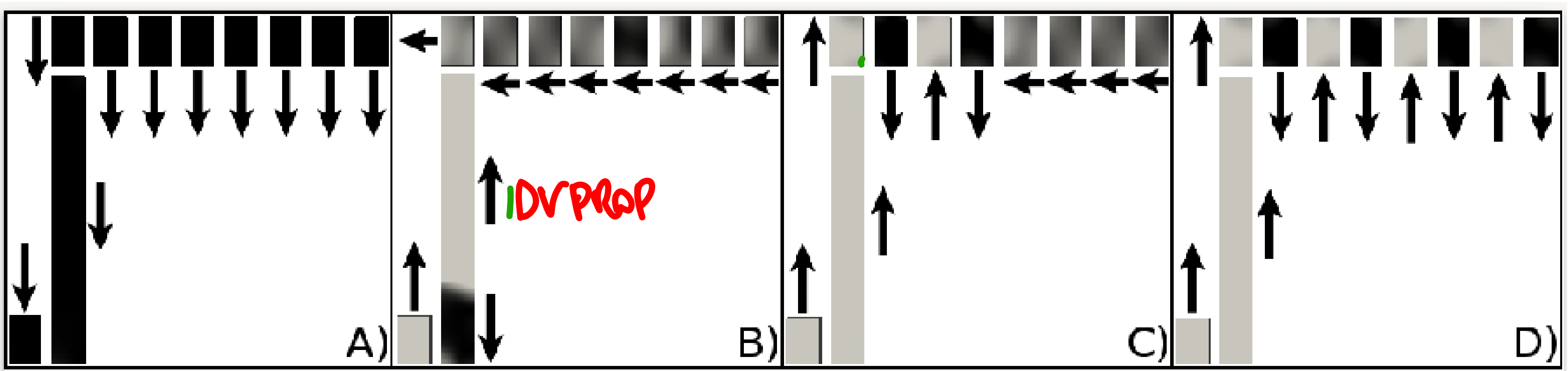
H1 RESET BOTH DW, NML 2

H2 RESET NML2, NOT DW

H3 NO RESET

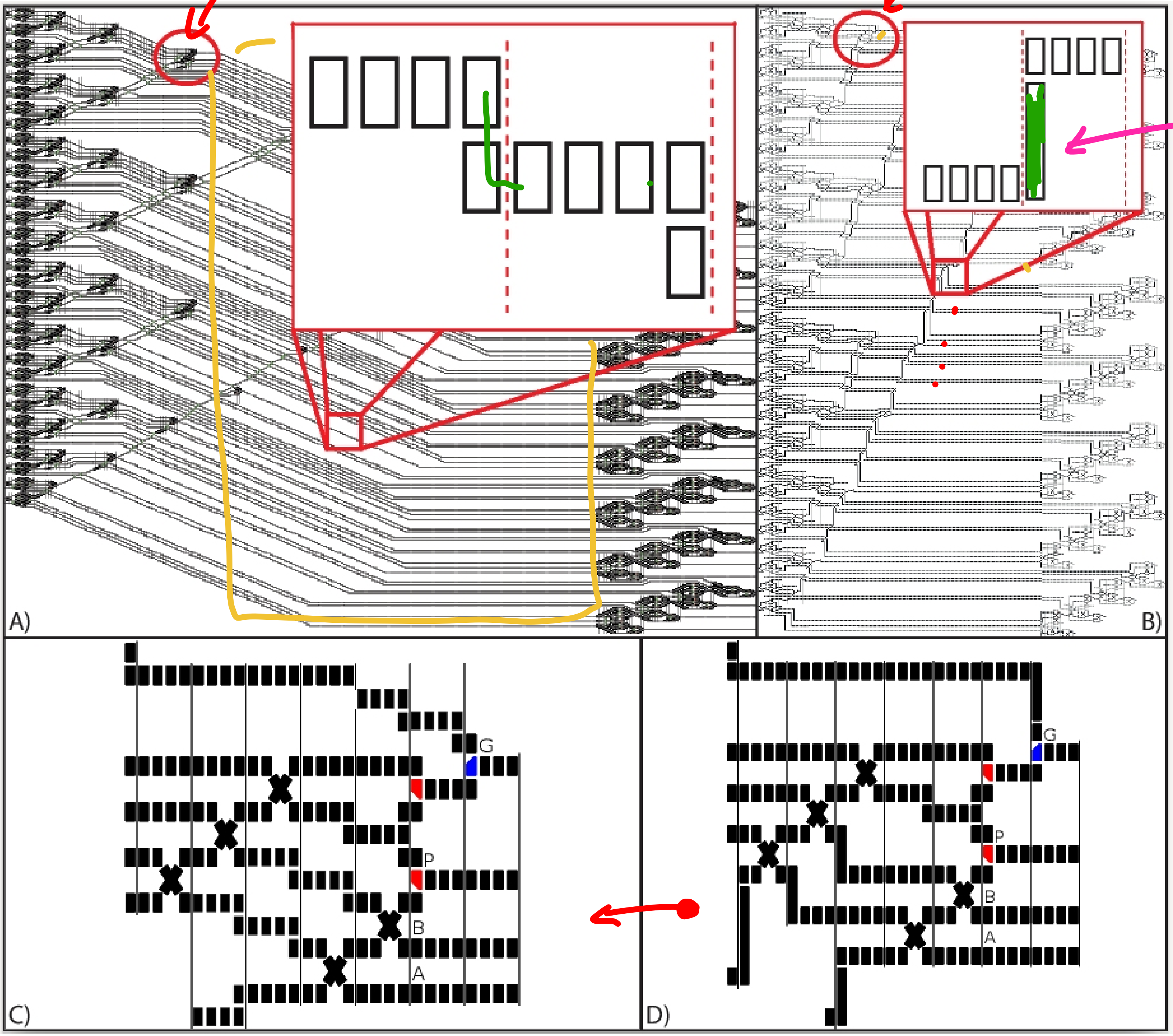
CREDITS.
F.CAIRO

DW + NML LOGIC



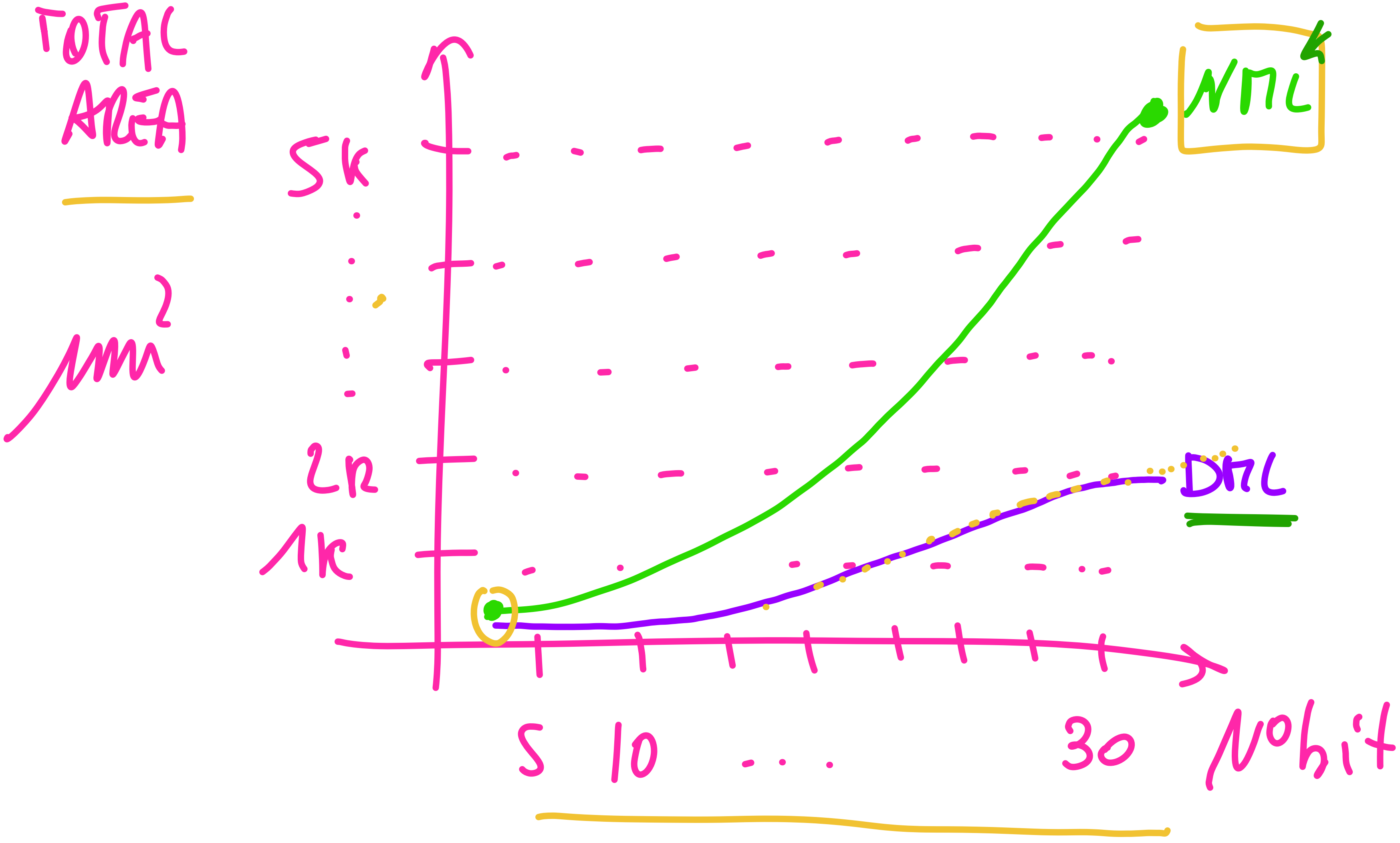
THERE ARE SPECIFIC RELATIONS AMONG

- → APLIDUE OF FIELD
- → WIDTH OF WIRE
- → DISTANCE BETWEEN MAGNETS
- → MATERIAL TYPE



AREA REDUCED
↓
POWER REDUCED

EXAMPLE: IMPACT ON THE P4 ADDER WITH INCREASING N° BITS



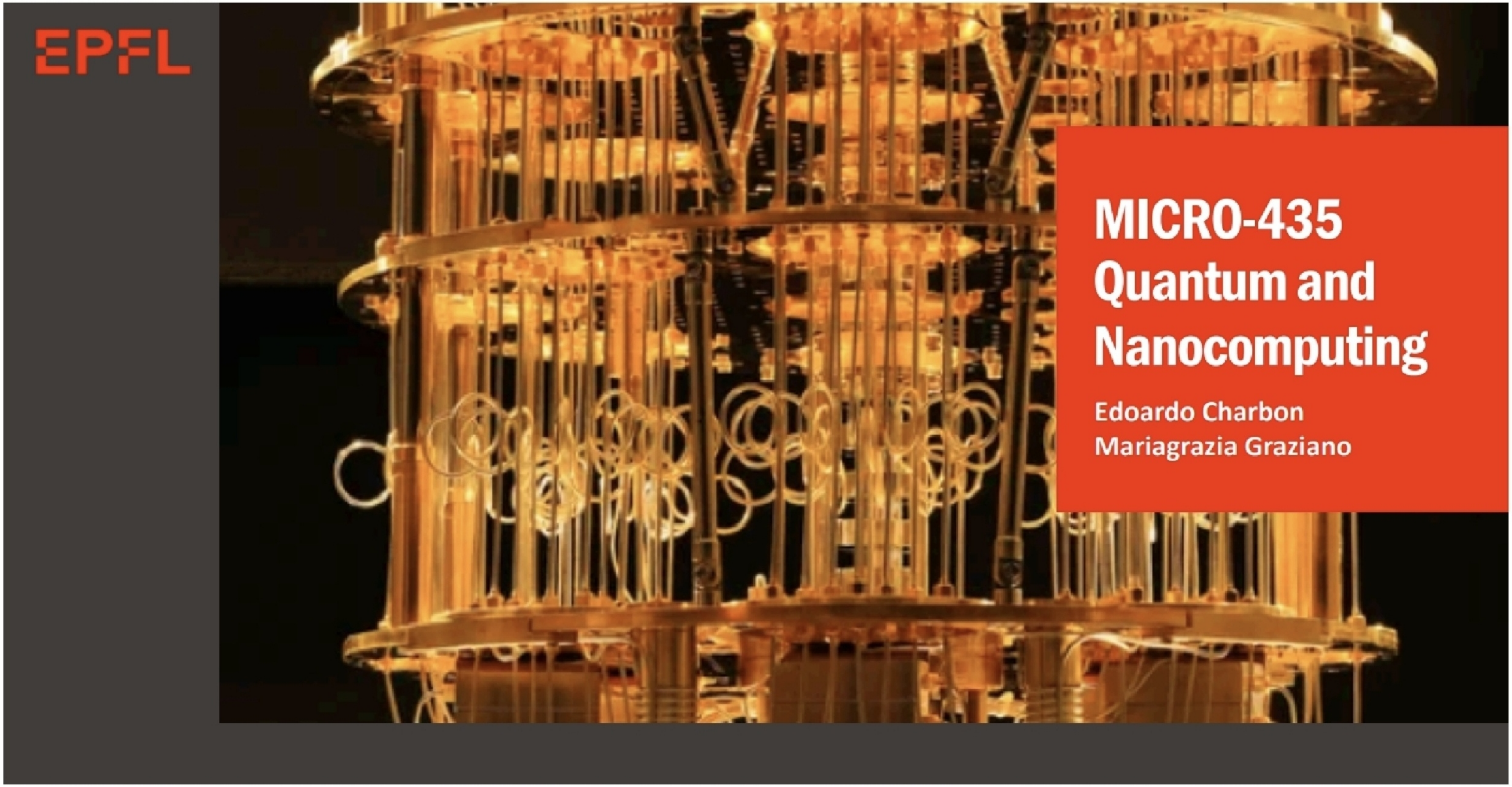
AREA REDUCED ↓ SPEED ↗

↓ POWER REDUCED
(N° CK. ZONES

CRISTALLIZATION

→ MIXING FIELD-COUPLING
WITH DOMAIN-WALL MOTION

- HELPS INFO PROPAGATION
- REDUCES TIME, AREA → POWER


EPFL

MICRO-435 Quantum and Nanocomputing

Edoardo Charbon
Mariagrazia Graziano

FROM iNML TO MORE ADVANCED NANOMAGNETIC STRUCTURES

- pNML

ANOTHER PROBLEM OF NML IS THE CLOCK ZONES ORGANIZATION WITH THE NECESSITY OF CREATING

→ ZONES

→ DIFFERENT CLOCKS SIGNALS

⇓

DOABLE BUT COMPLICATED

↓

ALTERNATIVE: PNML

PERPENDICULAR NANOMAGNETIC LOGIC

COMPARISON

U. NOTRE DAME

NML

- MAGN. // TO PLANE
- PERMALLOY (MOSTLY) (Ni-Fe)
- SHAPE ANISOTROPY
- RESET STATE FORCEDE BY CK. TO PROPAGATE INFO

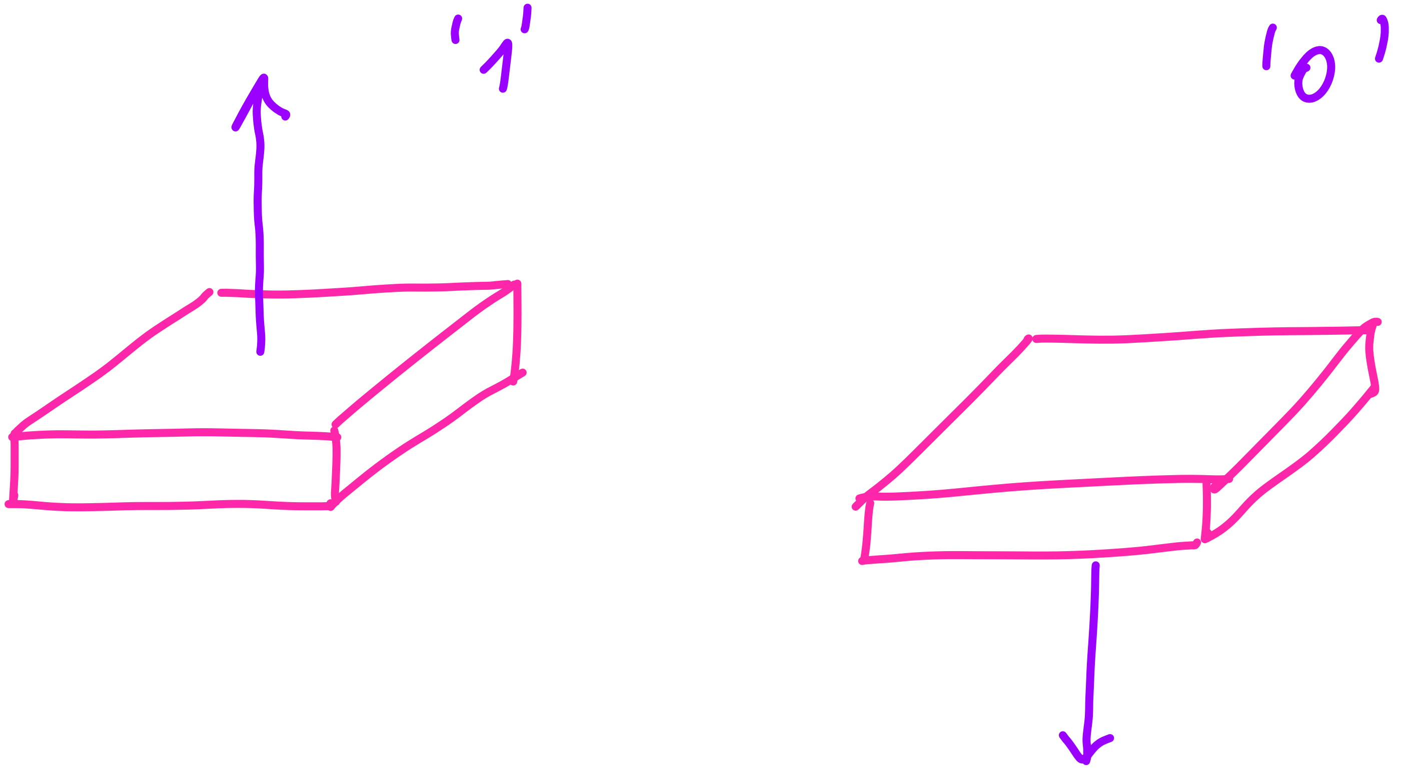
TUM

PNML

- MAGN. ⊥ TO PLANE
- MULTILAYERS OF Co/Pt, Co/Ni, CoFeB
- CRISTALLINE INTERFACE ANISOTROPY
- NO RESET, CK FIELD USED TO INDUCE PROP.
- DW USED FOR INTERCON-NETS AND PROP. LOGIC

- MORE COMPACT
- SIMPE DESIGN
- LESS POWER

PERPENDICULAR MAGNETIC ANISOTROPY (PMA)

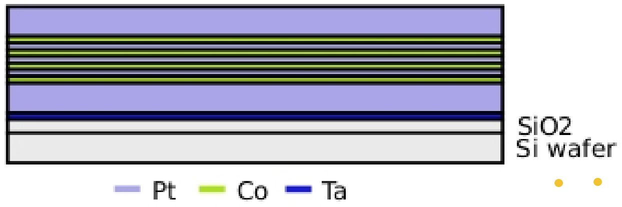


MAGNETIZATION PERPENDICULAR TO THE PLANE

FABRICATION (Co/Pt CASE)

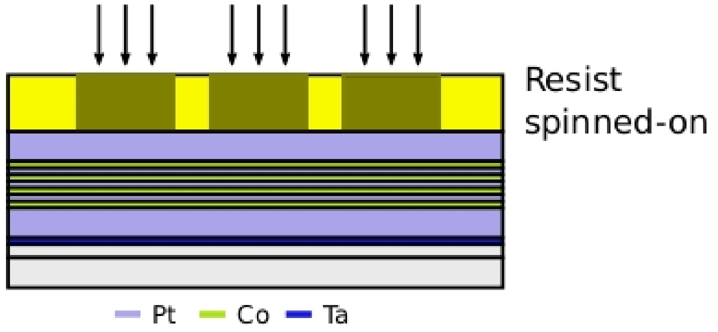
a)

Wafer cleaning and oxidation
+
Co/Pt multilayer deposition



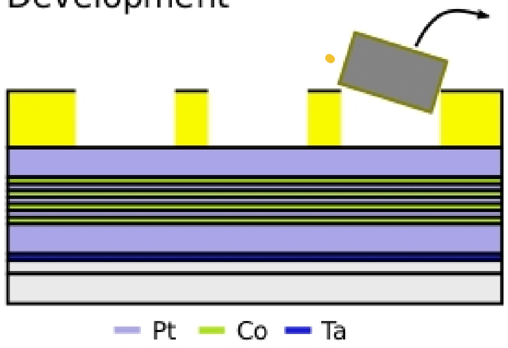
b)

FIB lithography



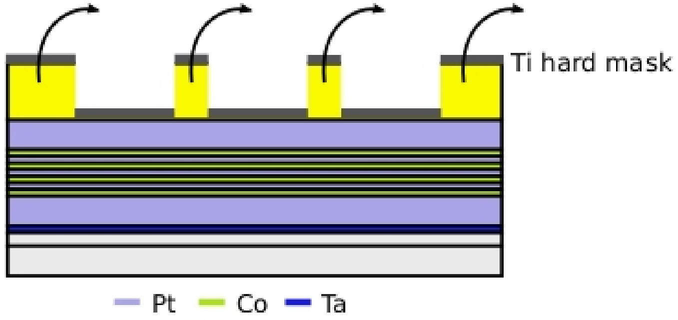
c)

Development



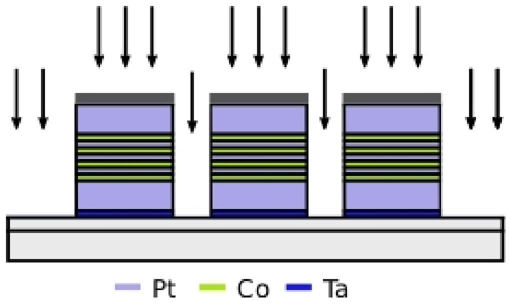
d)

Hard mask evaporation
+
lift-off



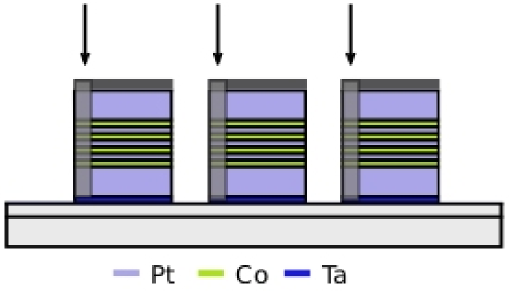
e)

Ion beam etching



f)

Partial FIB irradiation

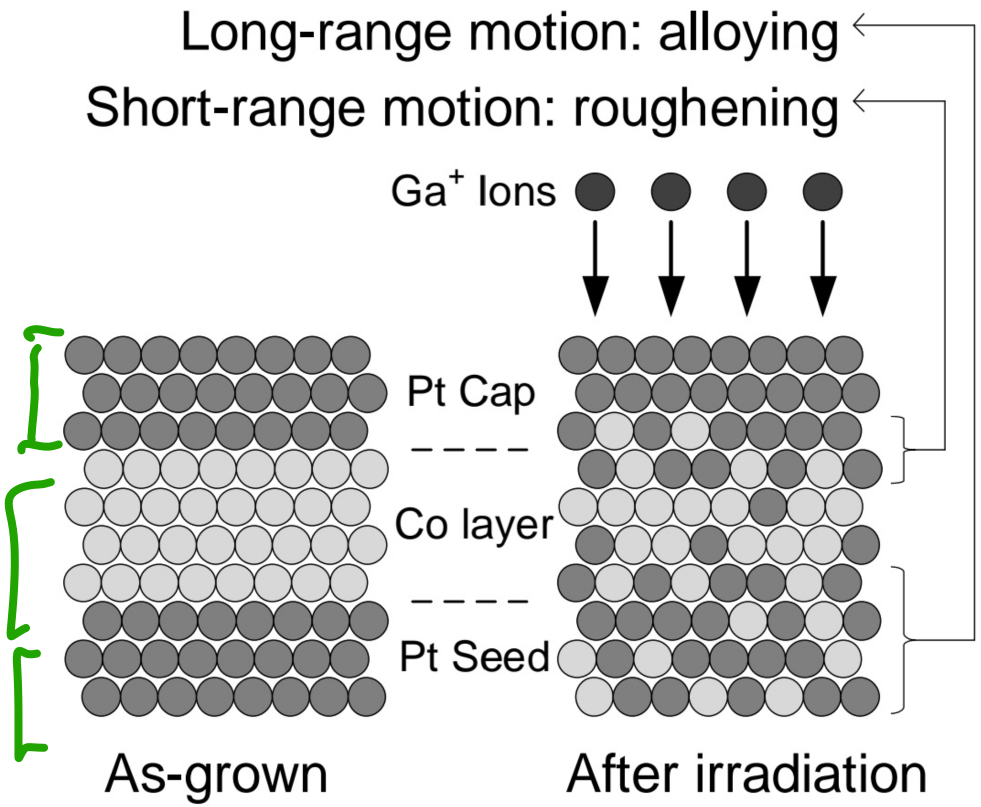


a - e standard process

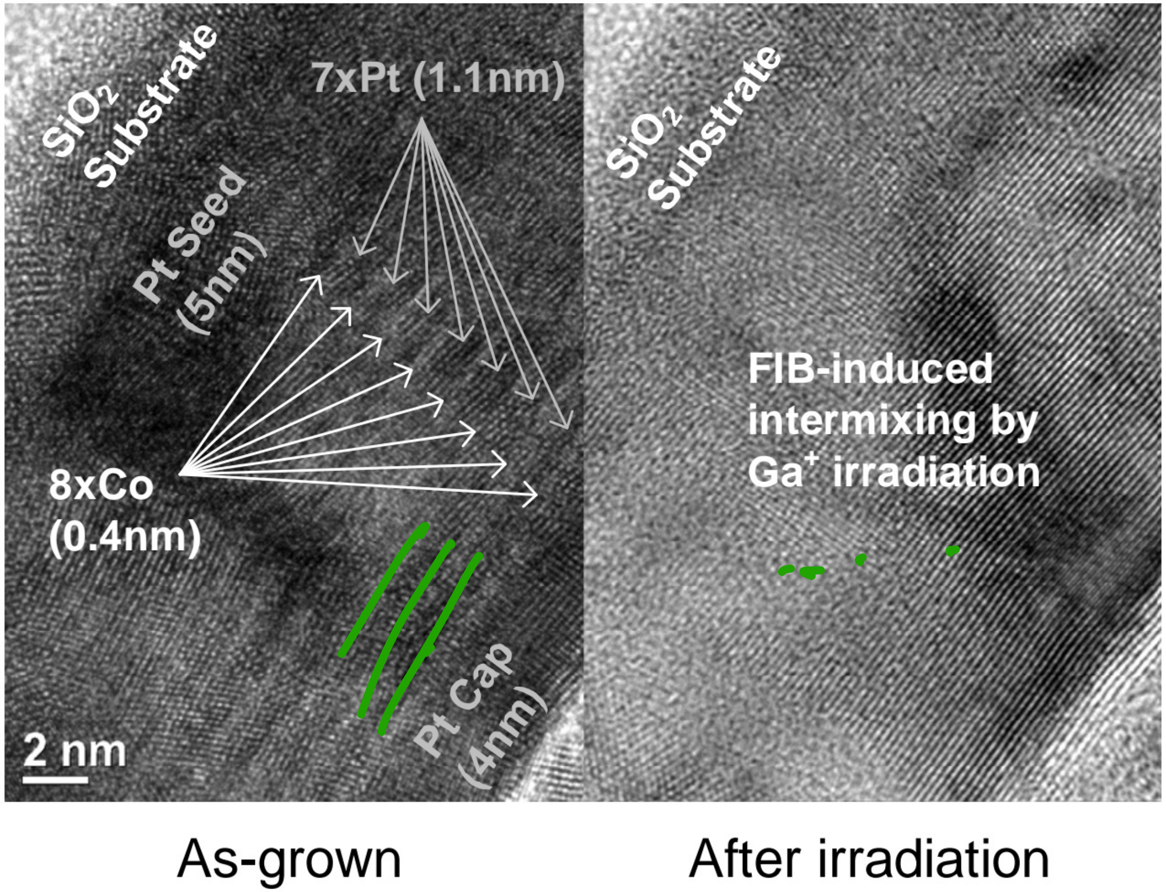
f dedicated
special process

EFFECT OF F.I.B. IRRADIATION

a **Theory of Irradiation induced intermixing**



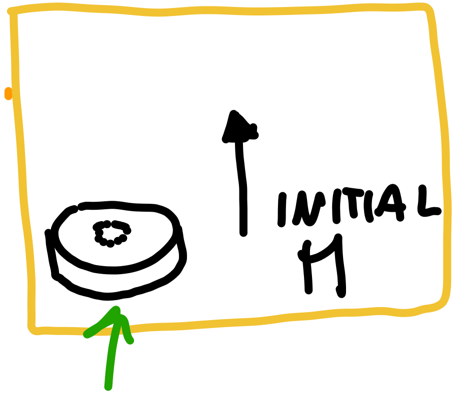
b **TEM images of a Co/Pt multilayer**

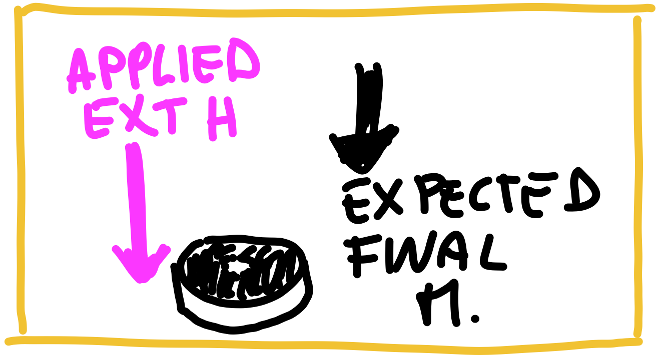


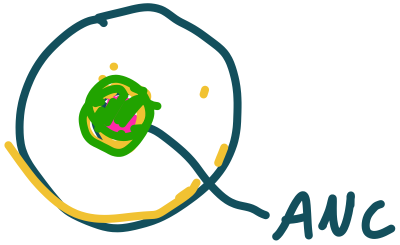
PHD DISSERTATION
TUM
S. BREITKREUTZ-VON GAMM.

ANISOTROPY IS REDUCED

VIDEOS
M.M. SIMULATIONS
MUMAX







EXTERNAL
FIELD
INDUCES
SWITCH

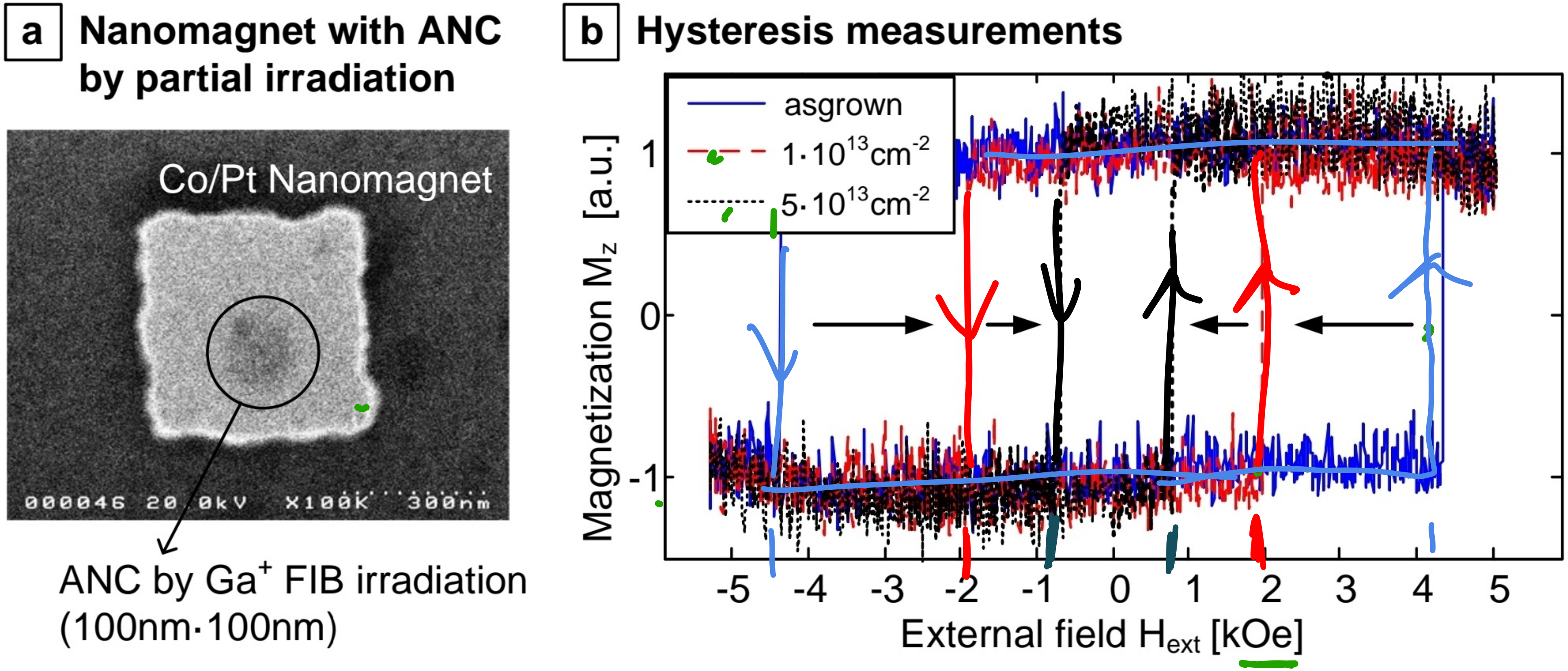
1) DW NUCLEATES & PROP

2) DW NUCLEATES BUT DO NOT PROP

★ Hc
SMALLER

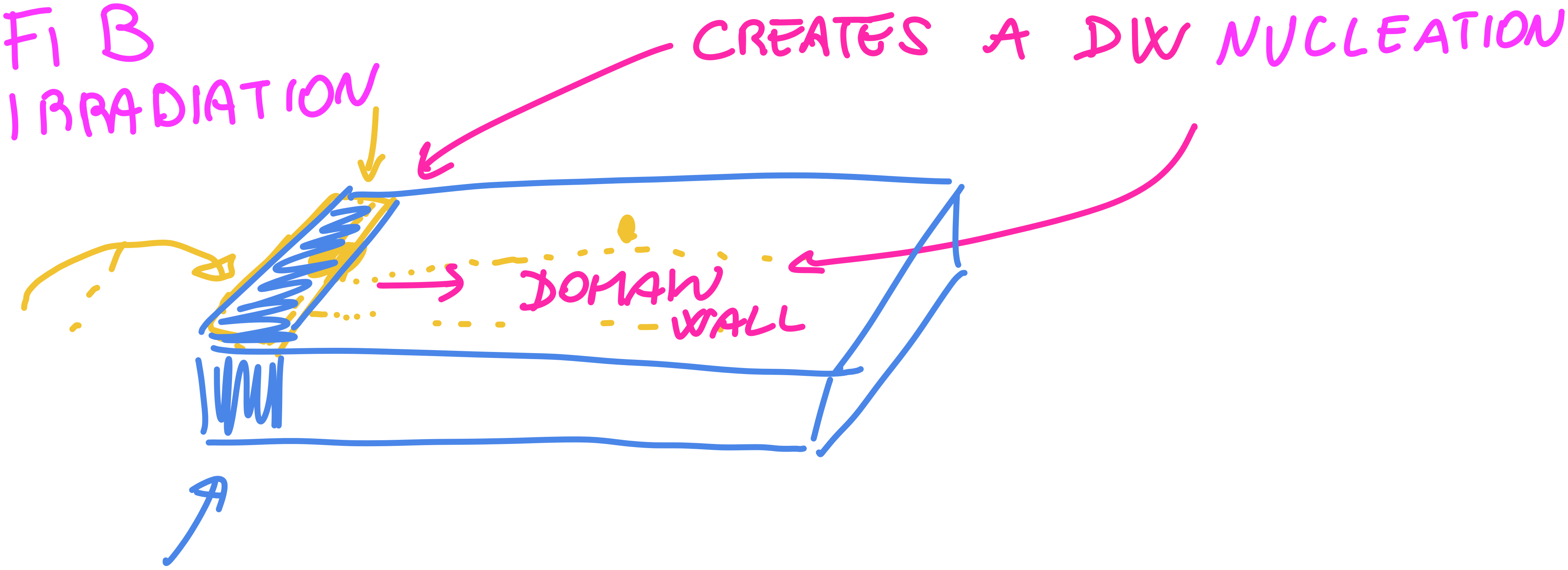
SIMULATIONS
CREDITS . F. RIENTE
MUMAX

EXAMPLE MEASUREMENT: HYSTERESIS ASSOCIATED TO THE EXTERNAL H USED TO SWITCH



HYSTERESIS FOR DIFFERENT IRRADIATION DOSES SUPERPOSED

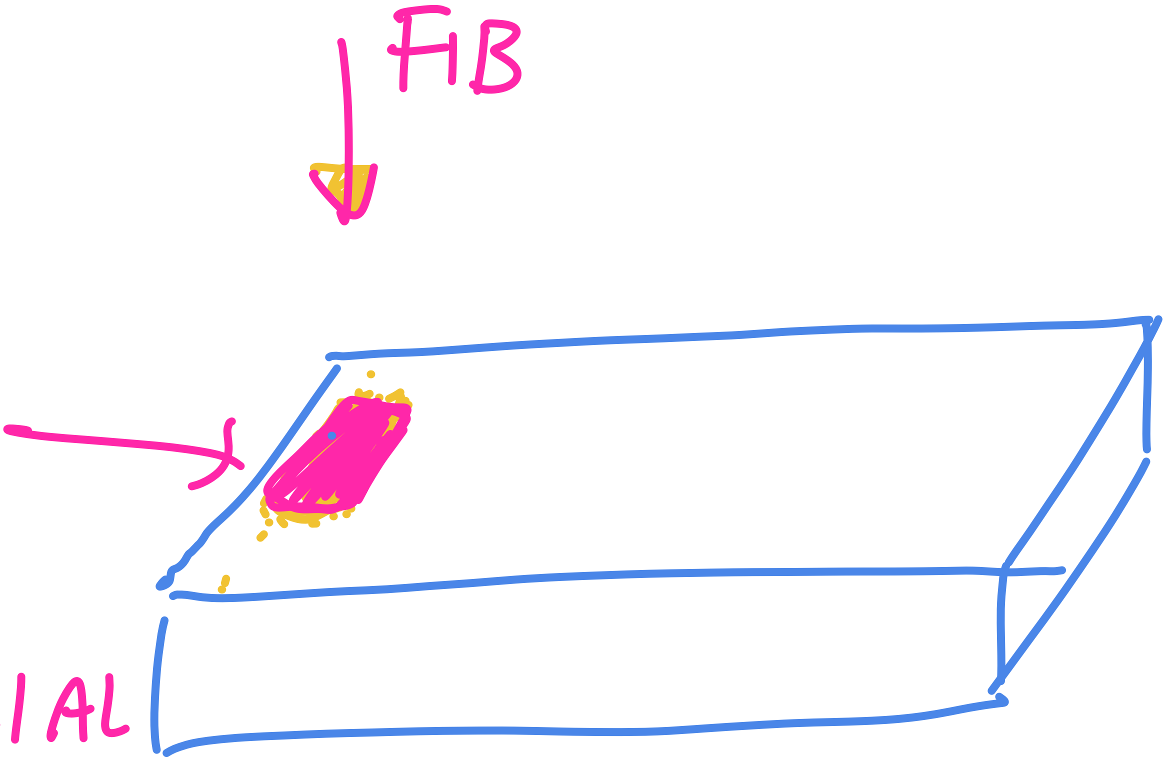
PHD DISSERTATION *
TUM
S. BREITKREUT-VON GAMM.



MIXES THE LAYERS OF Co/Pt MULTILAYER STACK

↳ IT REDUCES → MAGNETOCRISTALLINE ANISOTROPY AT INTERFACE BETWEEN 2 MAGNETS

REDUCES THE FIELD NECESSARY TO SWITCH!



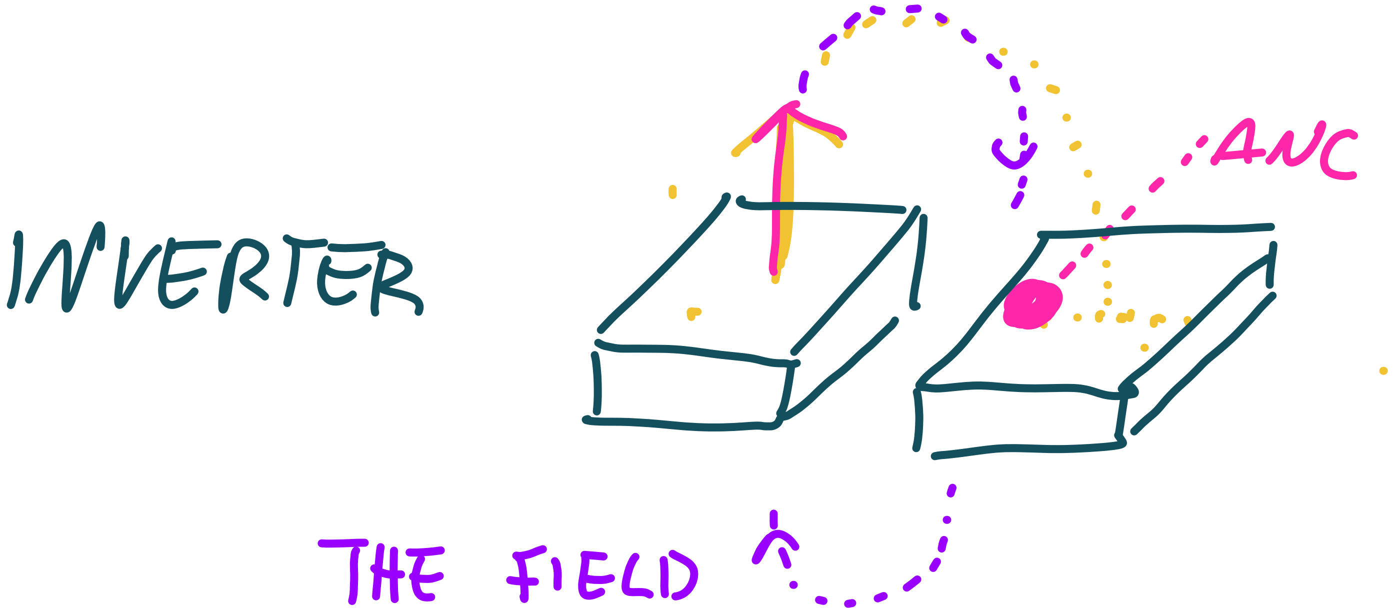
ANC

ARTIFICIAL NUCLEATION CENTER

- GIVEN A MATERIAL -
- " A GEOMETRY
- " A ANC TYPE

COERCIVITY H_c → THE SWITCHING FIELD NECESSARY TO NUCLEATE THE DW CHANGES

INFLUENCE BETWEEN 2 MAGNETS



THE FIELD GENERATED BY THE NEAR MAGNET INDUCES A CHANGE THROUGH THE ANC

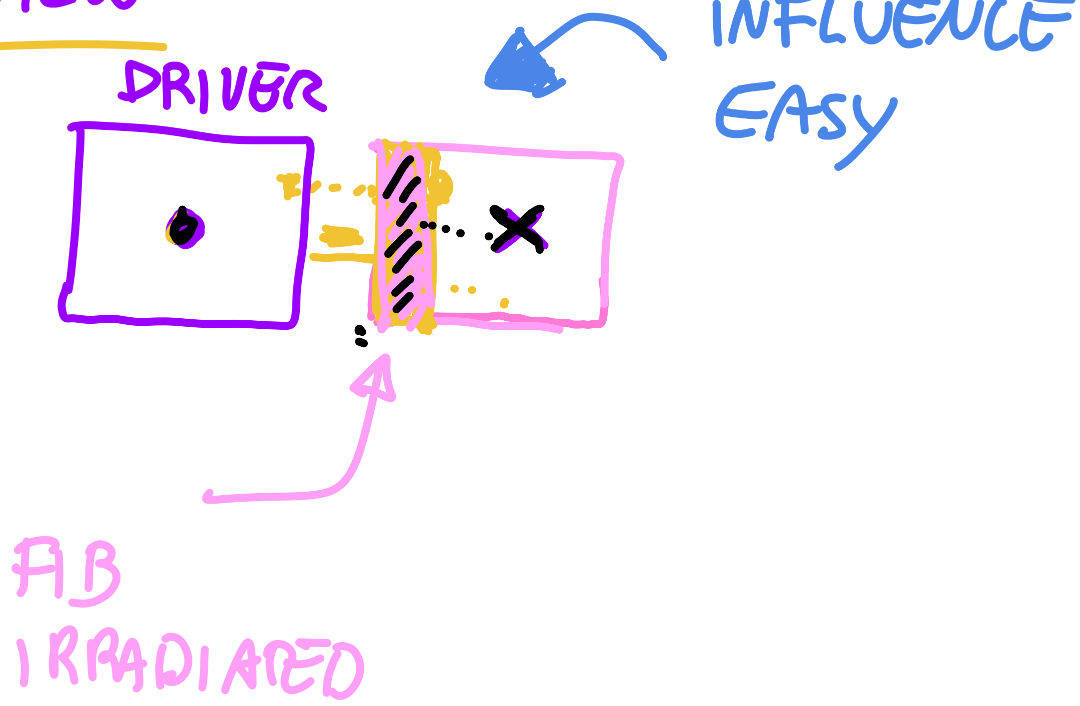
VIDEO – MICROMAGNETIC SIMULATION

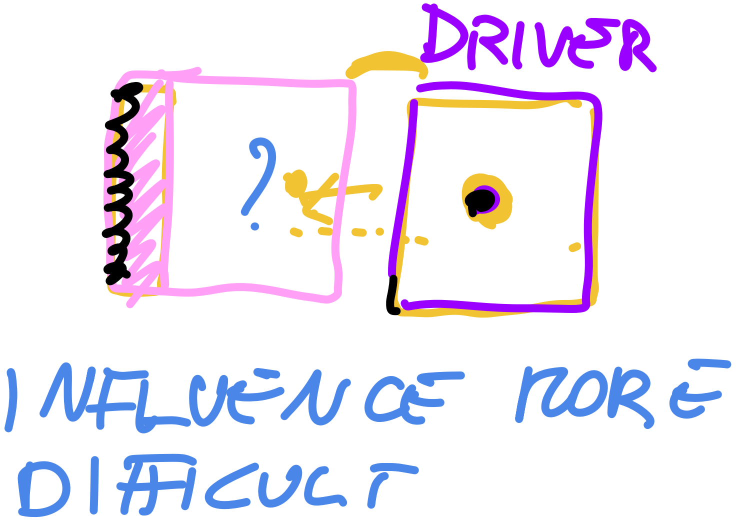
CREDITS F.RIENTE

THE FIB IRRADIATION GUARANTEES THE FLOW DIRECTIONALITY:

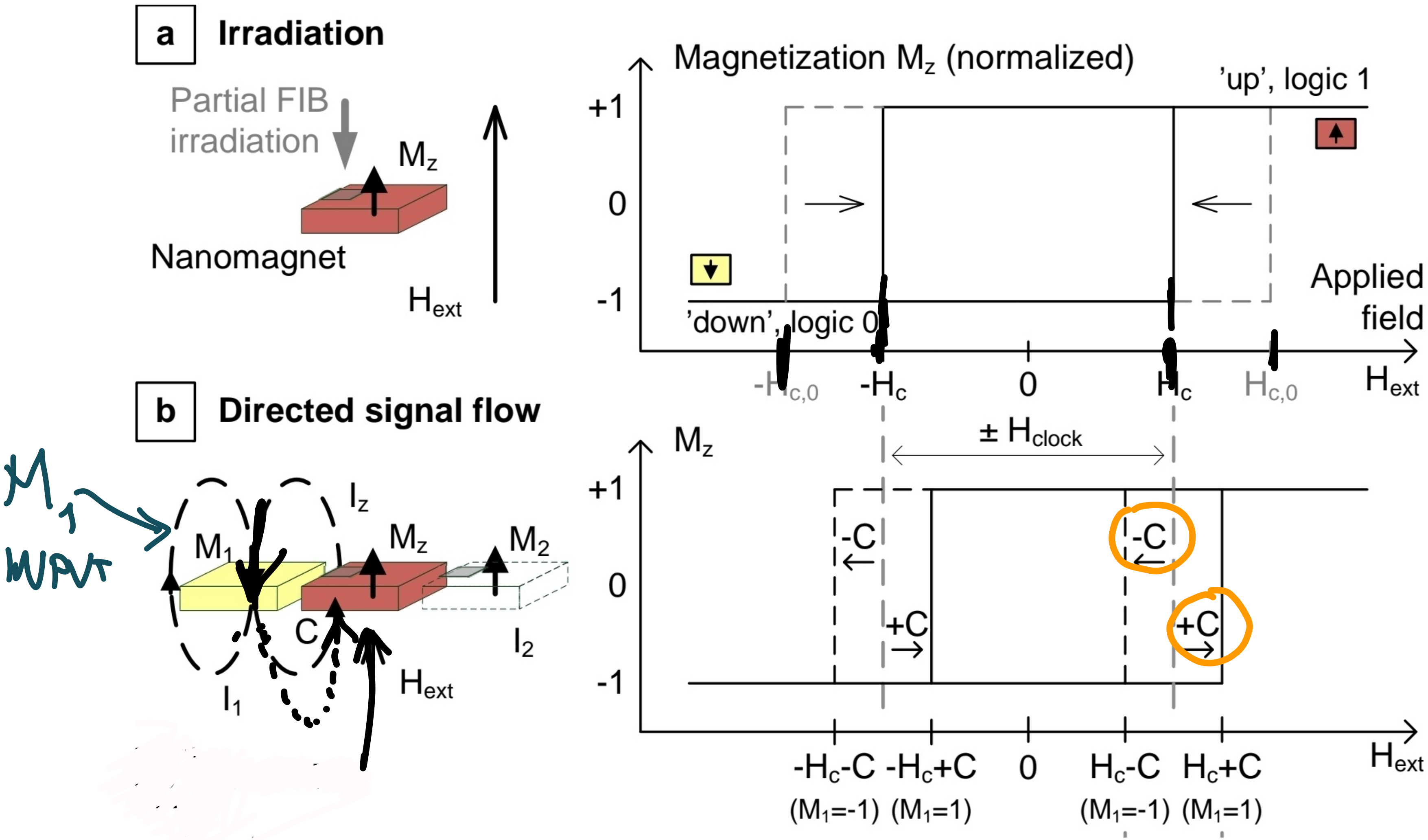
ONE PART OF THE MAGNET IS "SENSITIZED"

TOPVIEW





ANC, HEXT, INPUT



SINGLE MAGNET, ANC
+
HEXT
⇓
ANC REDUCES HYSTERESIS

MAGNET WITH ANC
+
HEXT
+
INPUT MAGNET

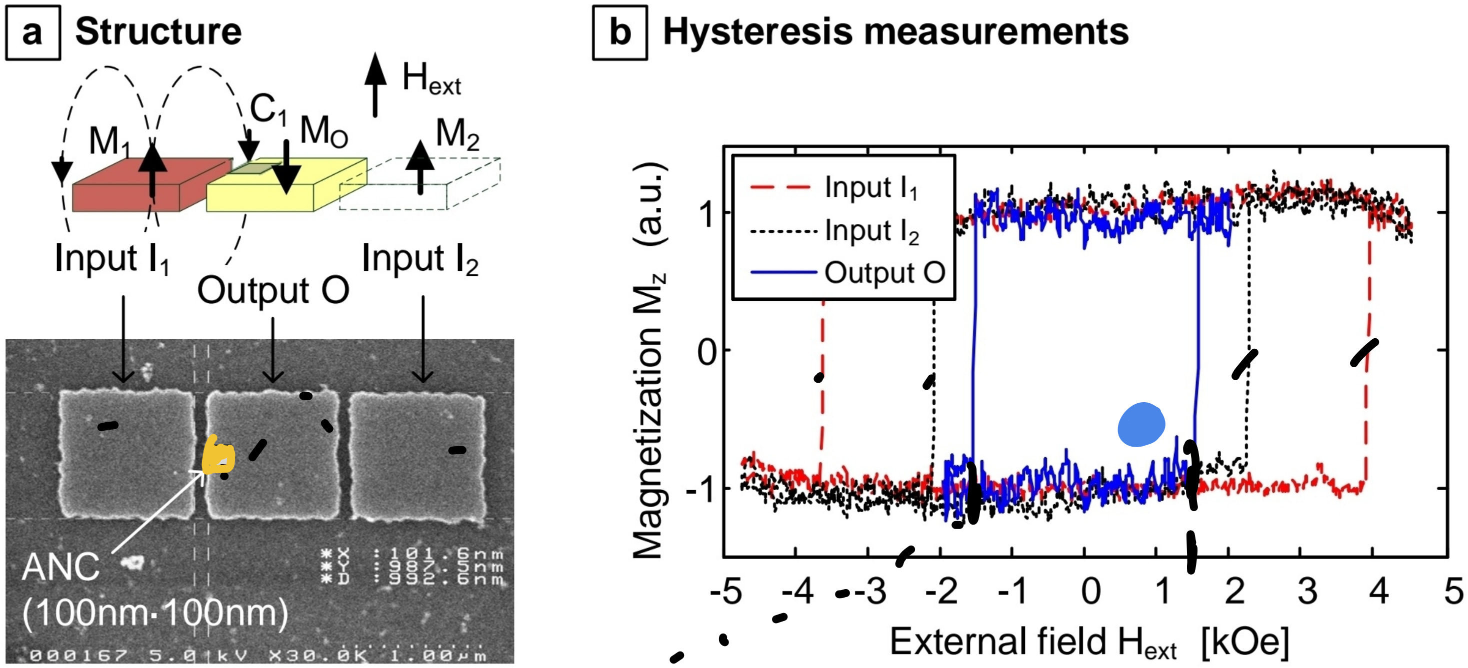
THE FIELD INDUCED BY INPUT, COUPLING C, SHIFTS THE HYSTERESIS ⇒ IN SUPERPOSITION OR IN OPPOSITION WITH HEXT

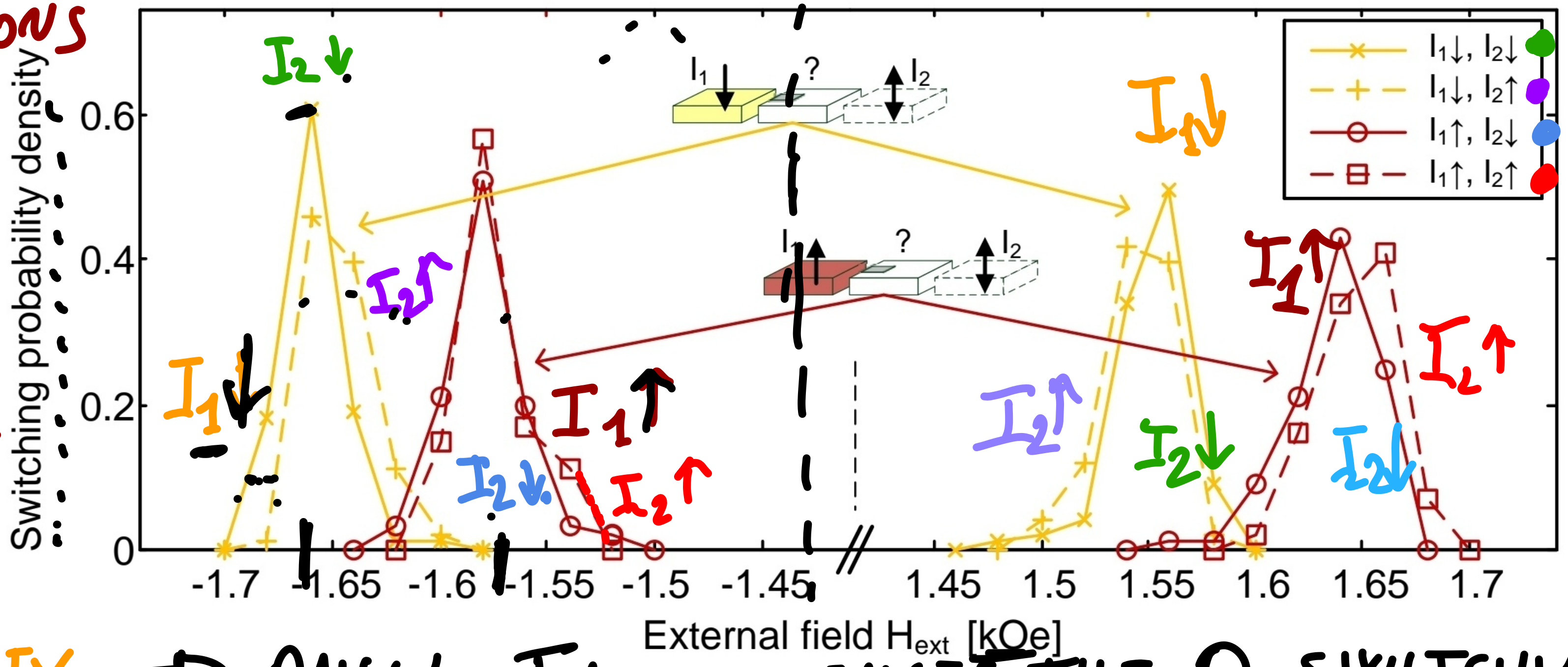
PROOF OF DIRECTIONALITY

- CENTRAL MAGNET IRRADIATED, ANC

- INPUTS
  I_1 LEFT
  I_2 RIGHT
  CONFIGURED IN 4 POSSIBLE COMBINATIONS

- CENTRAL MAGNET O MEASURED: HYSTERESIS ●
  SWITCHIN PROBABILITY





MAGN. 2 IS TOO FAR

⇒ ONLY I_1 INFLUENCES THE O SWITCHING!

OVERALL, HOW IS THE INFO FLOW ORGANIZED?

→ SUPPORT OF AN EXTERNAL CK FIELD
Hck

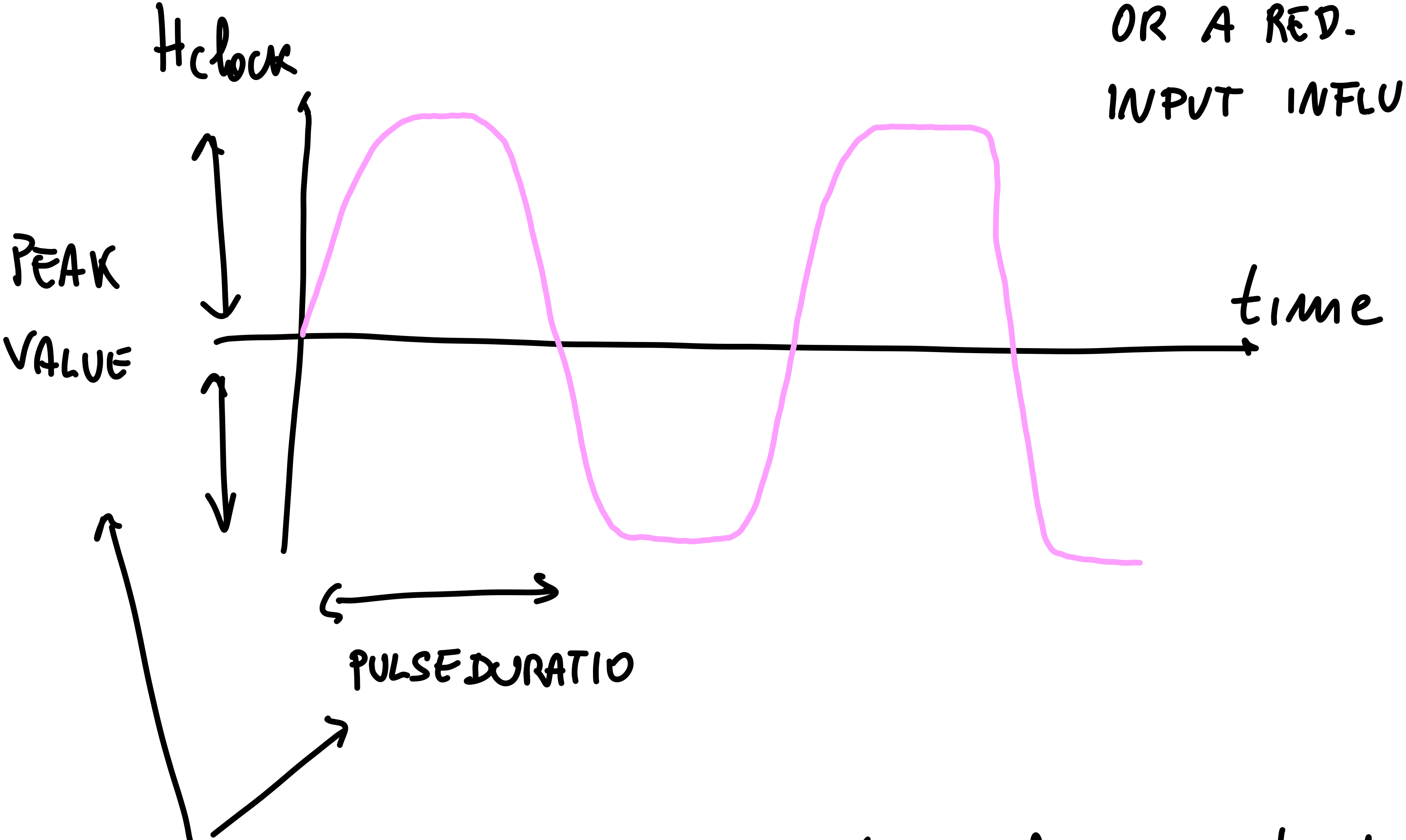
NO PHASES!

→ A UNIQUE Hck FOR ALL THE CIRCUIT, SINE WAVE, DIRECTION ⊥ TO PLANE

UP WAVE COHERENT WITH UP MAGNETIZATION

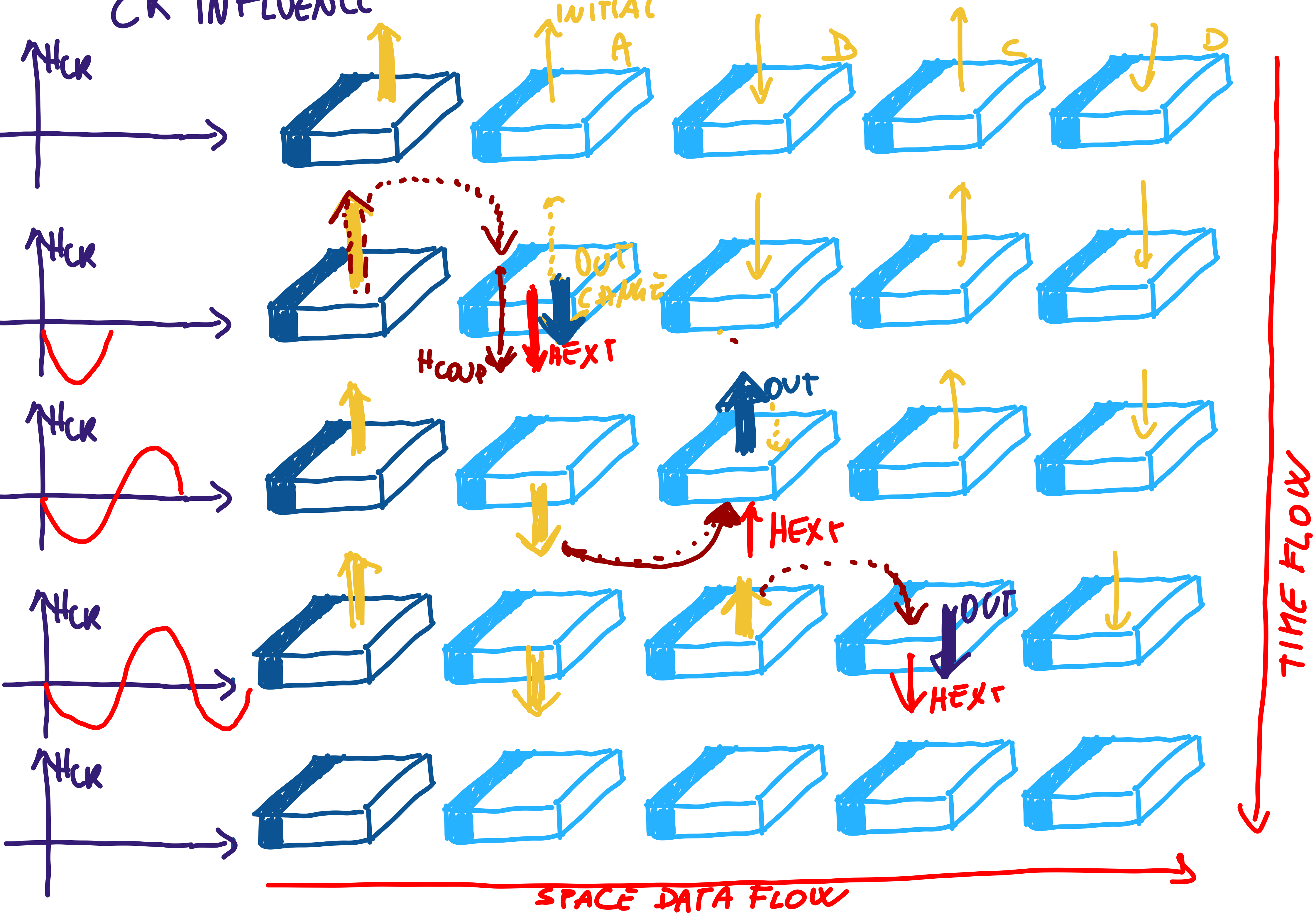
DOWN WAVE COHERENT WITH DOWN MAGN.

HCLOCK : GIVES A PUSH OR A RED. TO INPUT INFLUENCE

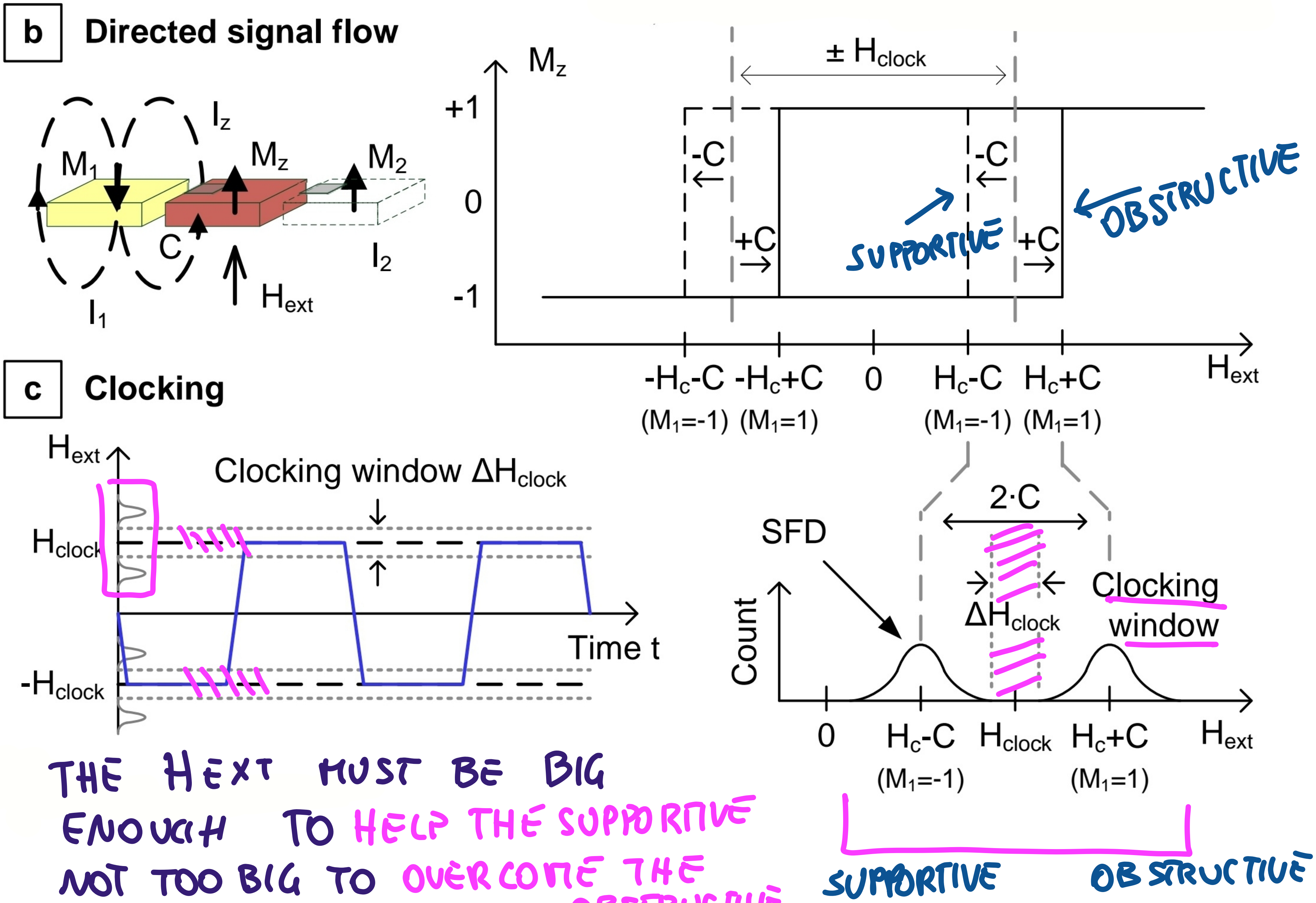


TO BE DEFINED PROPERTY (see after, considerations on speed)

CK INFLUENCE

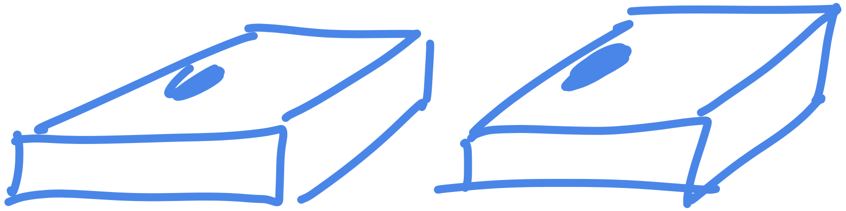


THE CLOCKING WINDOW

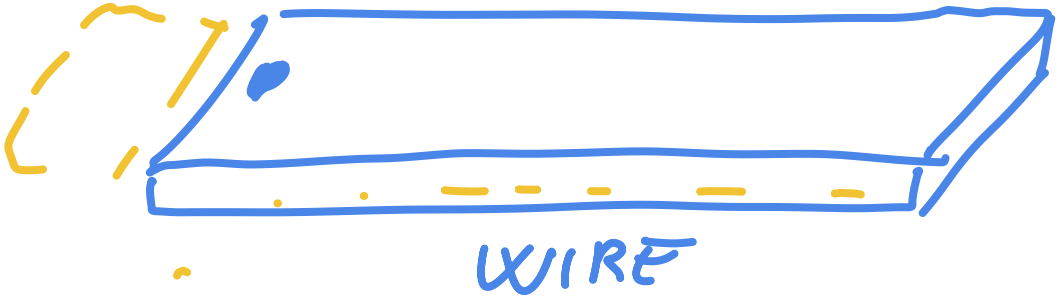


* THE HEXT MUST BE BIG ENOUGH TO HELP THE SUPPORTIVE NOT TOO BIG TO OVERCOME THE OBSTRUCTIVE

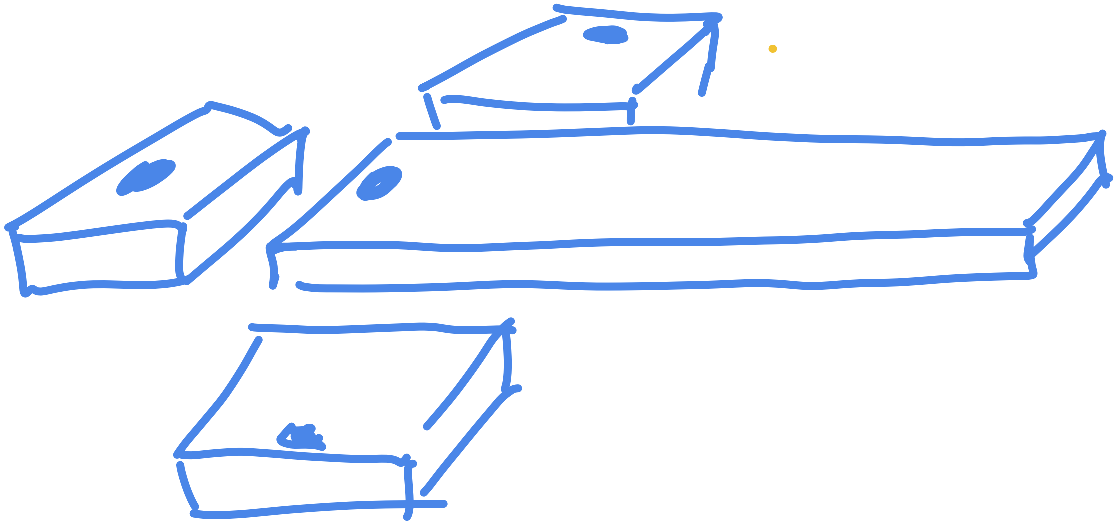
INFORMATION ELABORATION- BASIC BLOCKS



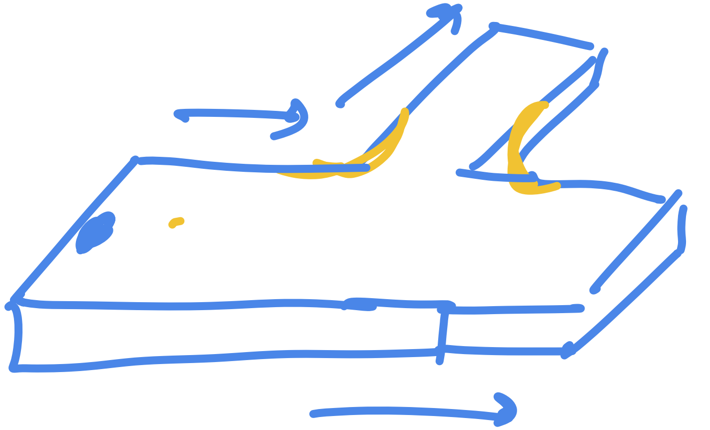
INVERTER



WIRE

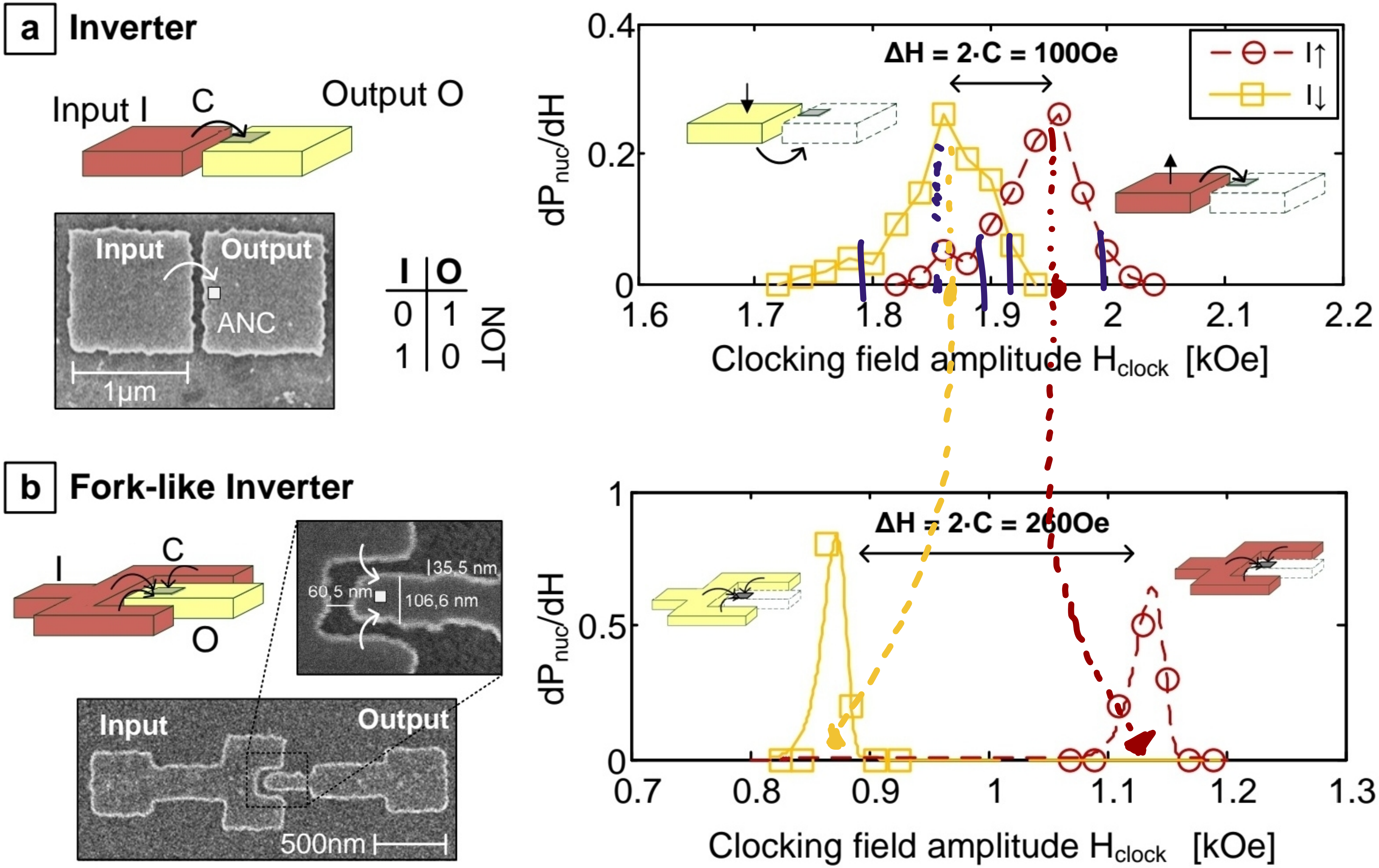


MAJORITY VOTER



TWO WAY BRANCH

INVERTER: BASIC AND IMPROVED



I	O
0	1
1	0

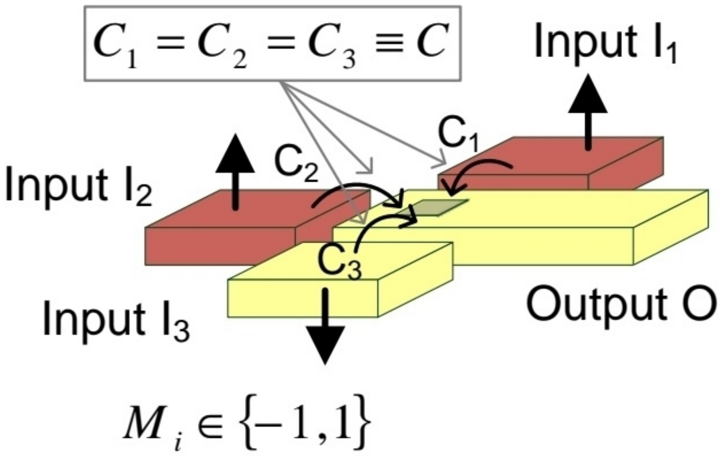
NOT

BETTER SEPARATION, CLEAR INPUT↓ OUTPUT

*

MAJORITY VOTER (MINORITY?)

a **Concept**



b **Majority operation**

$$C_{eff} = C \cdot (M_1 + M_2 + M_3)$$

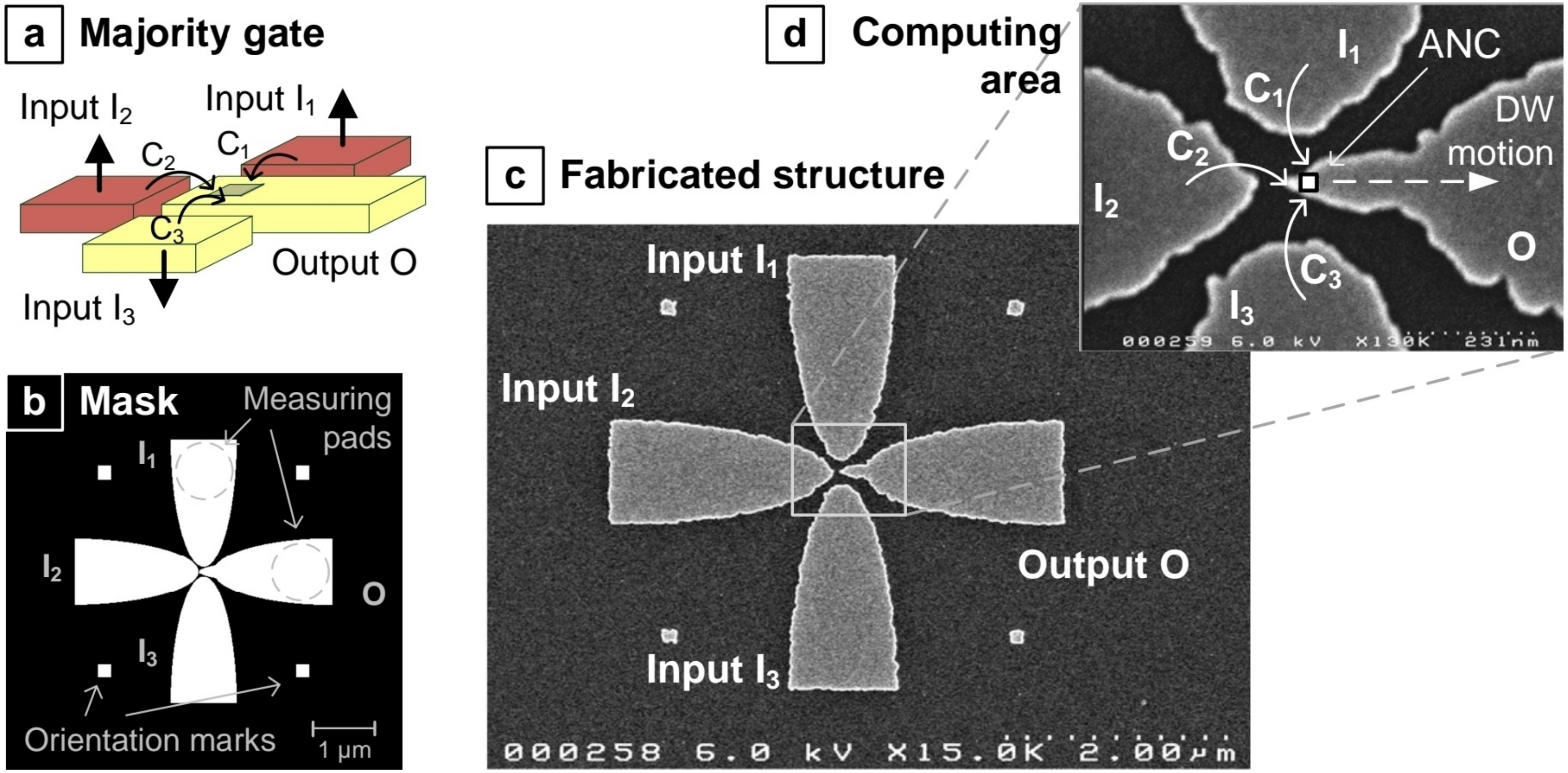
$$\Rightarrow \boxed{M_O = -sign(M_1 + M_2 + M_3)}$$

$$\Rightarrow \boxed{O = \overline{\mathrm{M}(I_1, I_2, I_3)}}$$

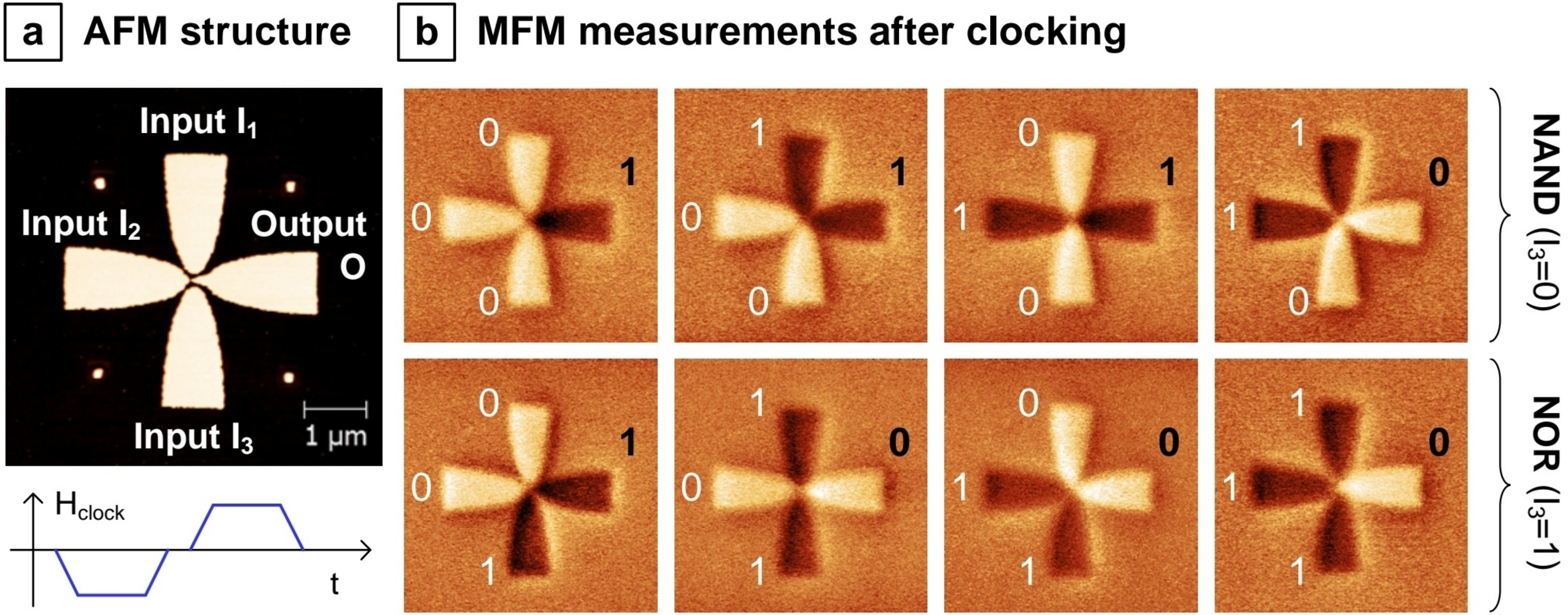
c **Truth table**

I1	I2	I3	O	
0	0	0	1	NAND
0	1	0	1	
1	0	0	1	
1	1	0	0	
0	0	1	1	NOR
0	1	1	0	
1	0	1	0	
1	1	1	0	

DEMONSTRATION



M.V. / AND/OR DEMONSTRATION

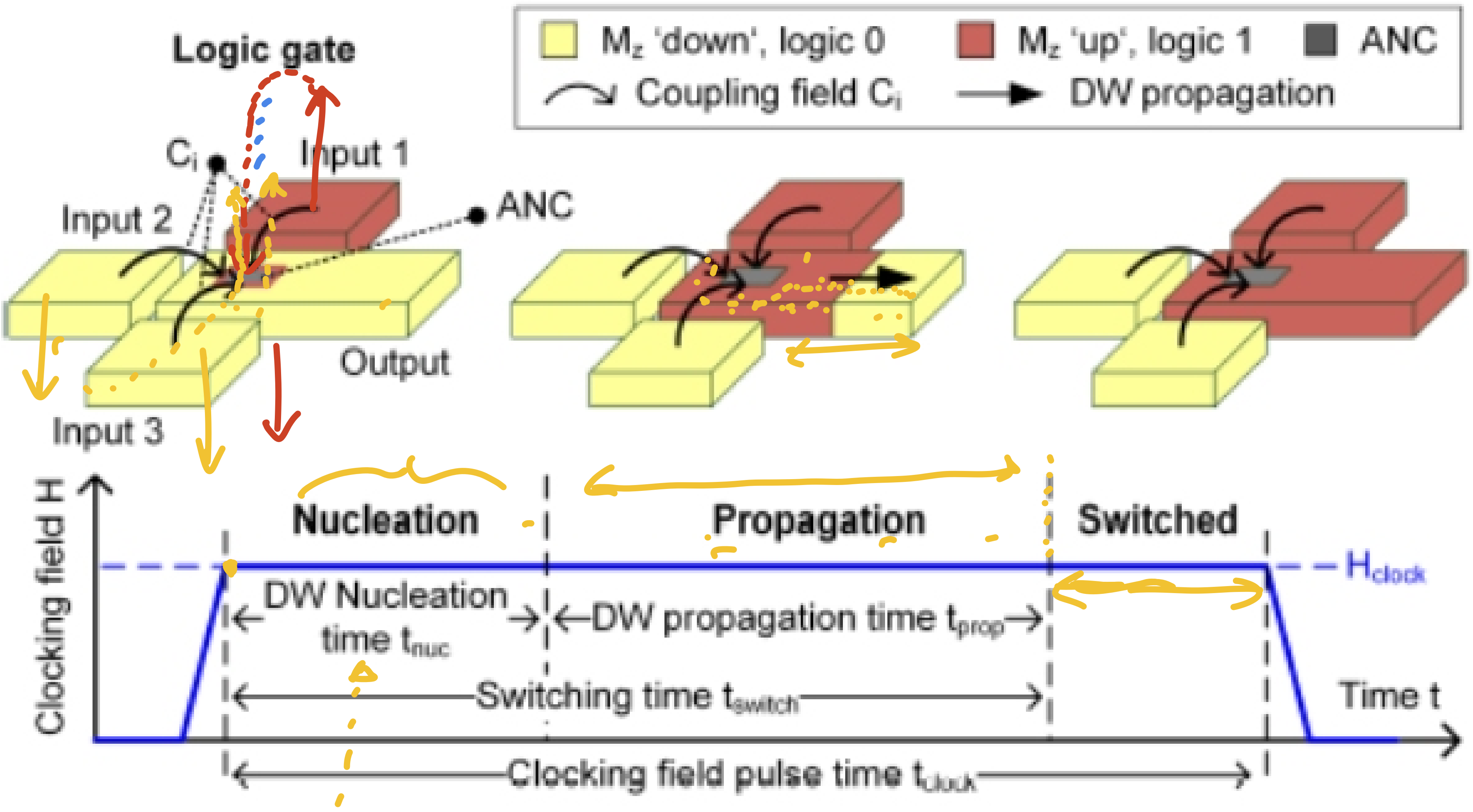


a **AFM structure**

b **MFM measurements after clocking**

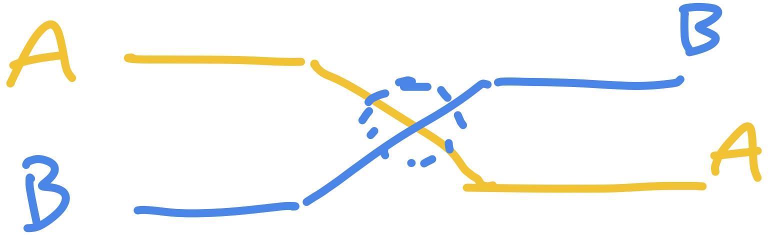
*

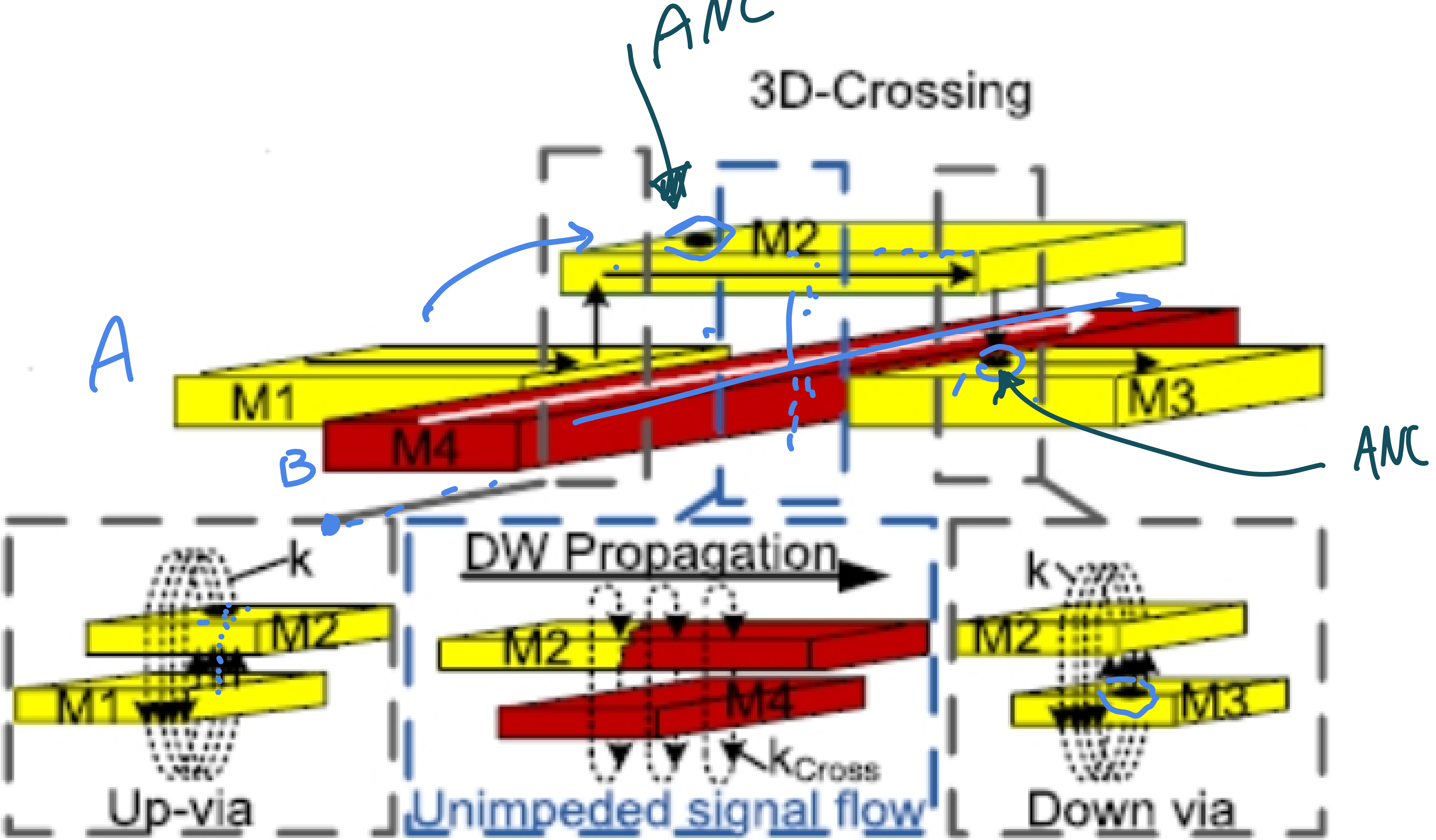
CLOCK PULSE DEFINITION



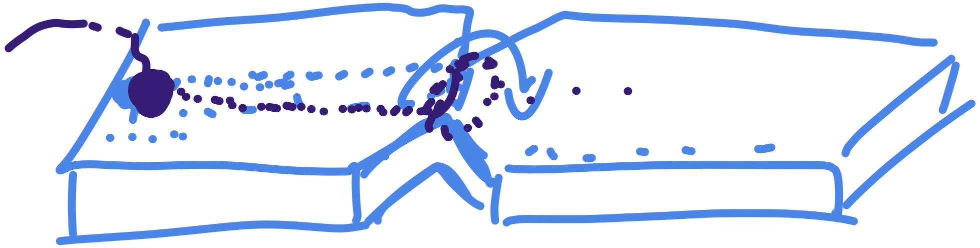
*

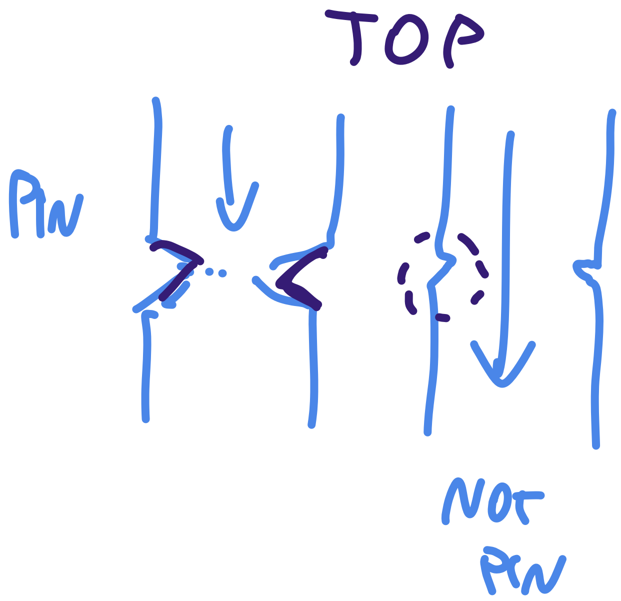
CROSSING


A
B
B
A


ANC
3D-Crossing
M2
A
M1
M4
B
M3
ANC
k
M2
M1
Up-via
DW Propagation
M2
M4
k_{Cross}
Unimpeded signal flow
k
M2
M3
Down via

NOTCH

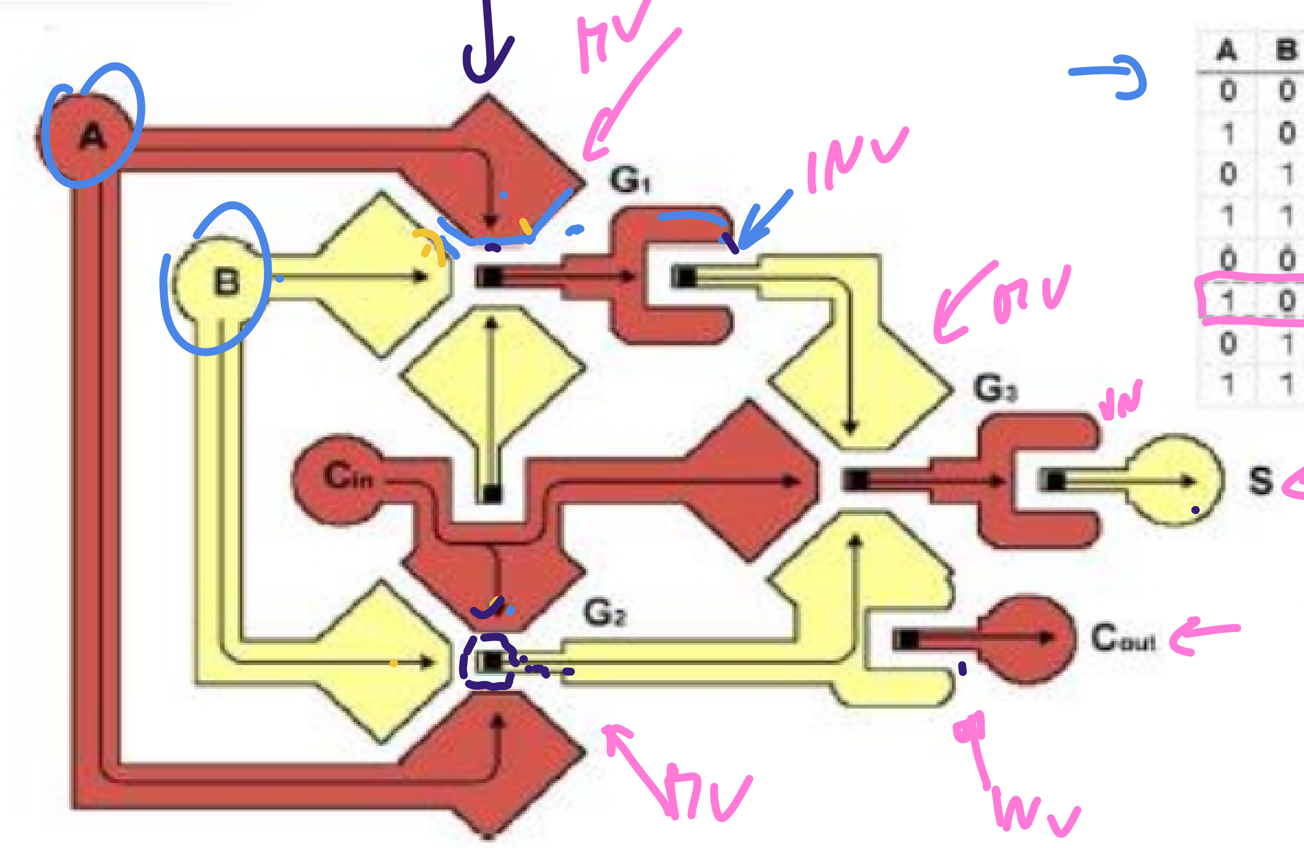


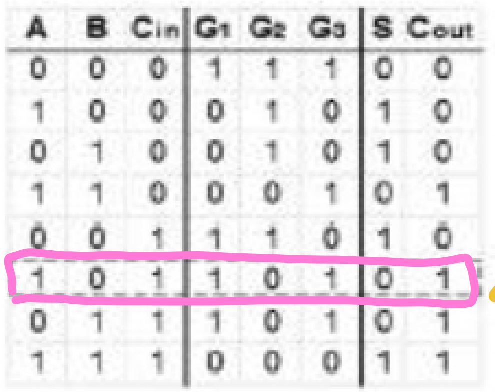


PINS THE PROPAGATION

TO DEPIN → EXTERNAL FIELD HAS TO BE APPLIED

TRY TO DECRIPT !





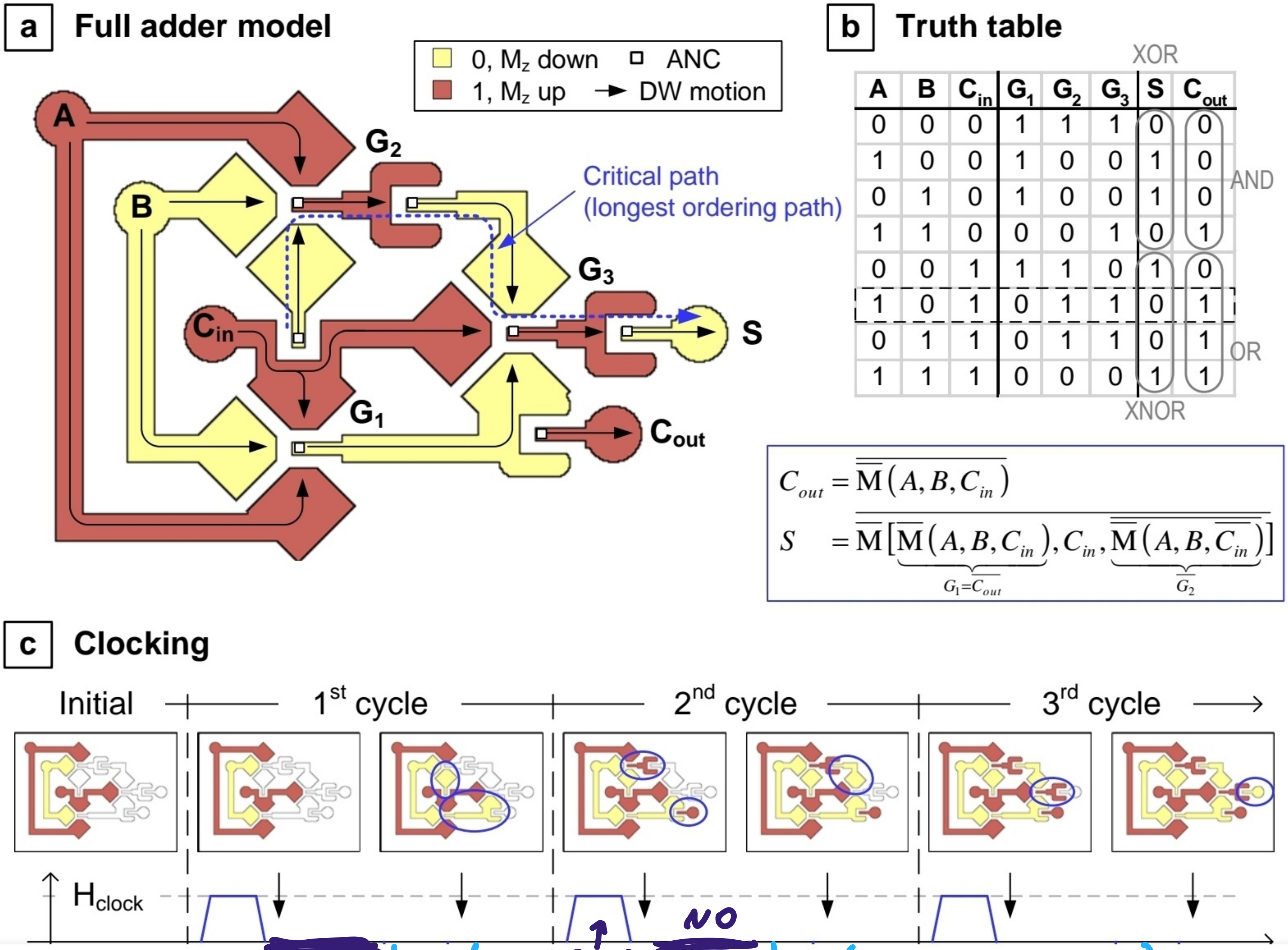
A	B	C_{in}	G_1	G_2	G_3	S	C_{out}
0	0	0	1	1	1	0	0
1	0	0	0	1	0	1	0
0	1	0	0	1	0	1	0
1	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
1	0	1	1	0	1	0	1
0	1	1	1	0	1	0	1
1	1	1	0	0	0	1	1

🟨	0, down
🟥	1, up
k:	coupling field
■	ANC
→	DW propagation

FABRICATED _ DEMOSTRATED

equivalent circuit ??

F.A. DYNAMICS



A	B	C_{in}	G_1	G_2	G_3	S	C_{out}
0	0	0	1	1	1	0	0
1	0	0	1	0	0	1	0
0	1	0	1	0	0	1	0
1	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
1	0	1	0	1	1	0	1
0	1	1	0	1	1	0	1
1	1	1	0	0	0	1	1

$$C_{out} = \overline{\overline{\mathrm{M}}}(A,B,C_{in})$$

$$S = \overline{\mathrm{M}\left[\underbrace{\overline{\mathrm{M}}(A,B,C_{in})}_{G_1=\overline{C_{out}}}, C_{in}, \underbrace{\overline{\overline{\mathrm{M}}(A,B,\overline{C_{in}})}}_{\overline{G_2}}\right]}$$

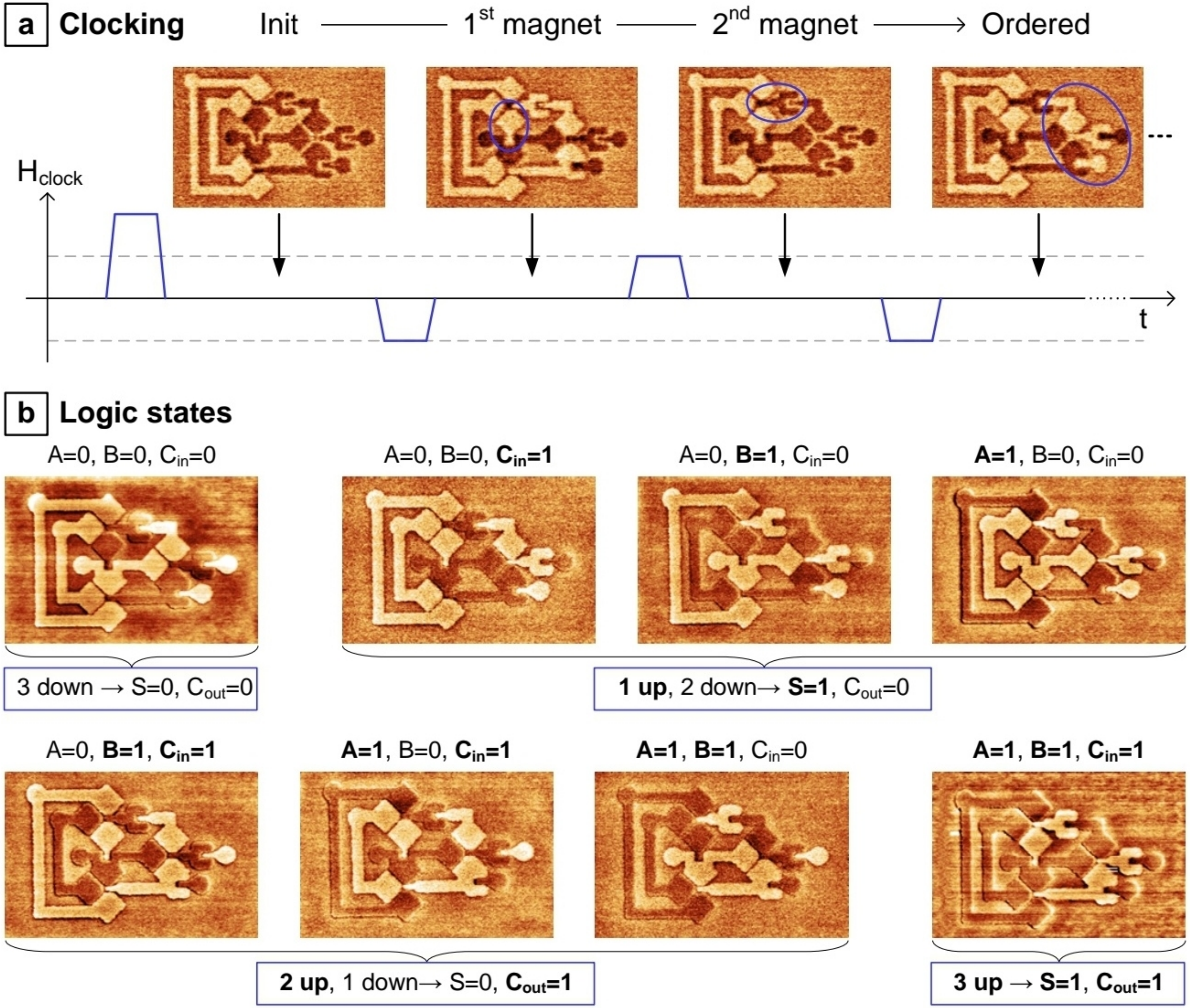
STOP, MEMORY

PROP 1 DW

NO PROP

PROP W 2 DW

F.A. FULL DEMONSTRATION



EXERCISES

- create AND / OR
- XOR / XNOR
- RIPPLE CARRY ADDER 4 bits

FURTHER CONSIDERATIONS ON PNML

A couple of consideration on PNML

(see L. Notes for further optional discussions on PNML model)

to guarantee a correct signal propagation, and so the correct behavior of the PNML circuit the switching process should be completed during the CLOCK FIELD PULSE TIME

$$\boxed{\underline{t_{clock}} > t_{nuc} + t_{prop}}$$

nuc = NUCLEATION

prop = PROPAGATION

NUCLEATION

→ it means to REVERS the CURRENT MAGNETIZATION STAT IN THE ANC

→ it REQUIRES A FIELD H_{NUC} that REDUCES THE ENERGY BARRIER

$H_{NUC} \geq H_{ANI}$ ← MODELED BY STONER-WOHLFARTH MODEL

$$H_{ANI} = \frac{2\, K_{eff,ANC}}{\mu_0 M_S}$$

M_S = saturation magnetization of magnet

$K_{eff,ANC}$ = EFFECTIVE ANISOTROPY in ANC

each magnet is caracterized by a unique anisotropy term, which depends on crystal structure, the geometry, the material

The EFFECTIVE FIELD H_{eff}, that should be the H_{NUC}

is INFLUENCED BY THE SUPERPOSITION OF

→ EXTERNAL FIELD H_{CLOCK}

→ COUPLING FIELD OF THE SURROUNDING MAGNETS $C_{eff} = \sum_{i=1}^{N} C_i M_i$, where

influence the energy barrier which increases or decreases according to the parallel or antiparallel state of input magnetization w.r.t. current state

M_i is the NORMALIZED MAGNETIZATION OF A NEARBY MAGNET $\{1,-1\}$

C_i is the coupling field of an input

$$\boxed{H_{eff} = H_{CLOCK} - C_{eff}}$$

PROPAGATION

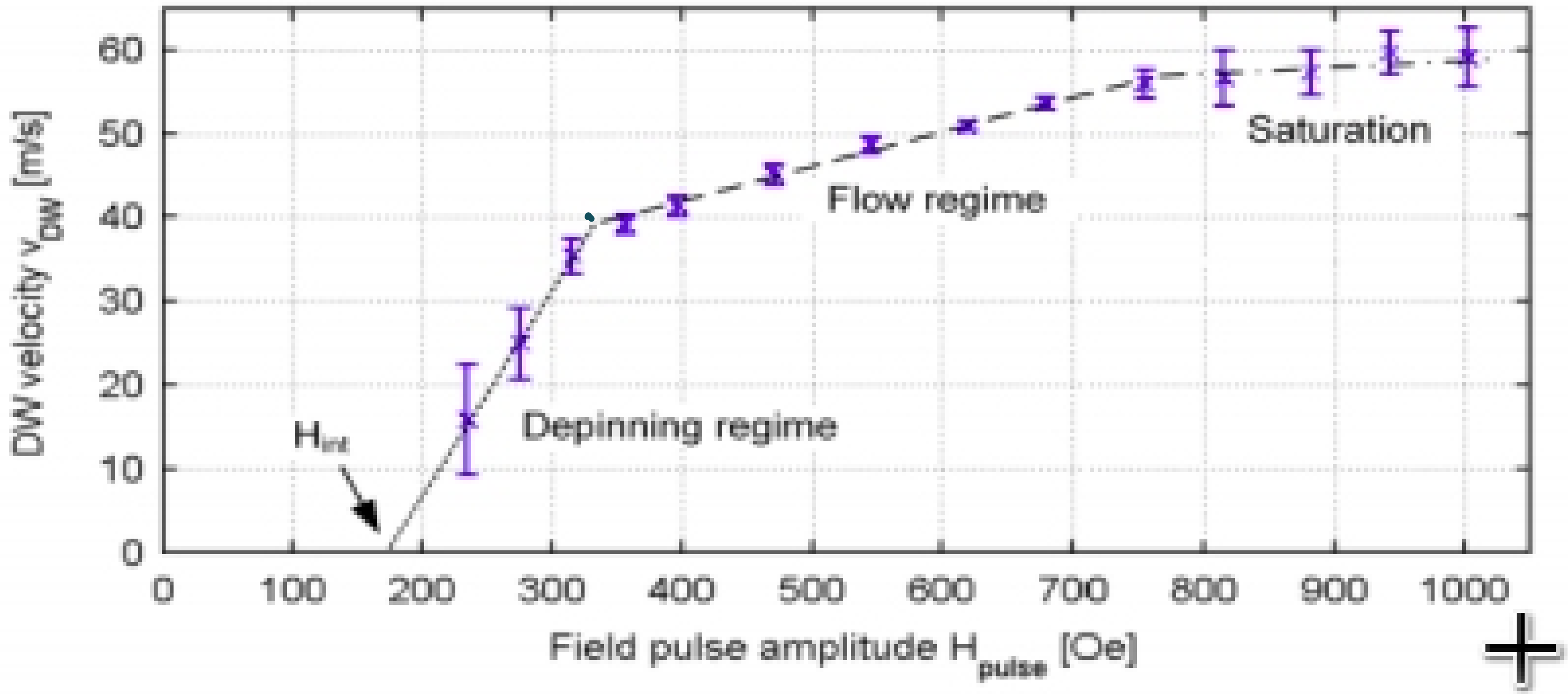
ONCE THE NANOMAGNET IS NUCLEATED BY THE EFFECTIVE FIELD H_{eff}, THE MAGNETIC STATE HAS TO PROPAGATE ALONG THE STRUCTURE, VIA THE CLOCKING FIELD

3 REGIMES IN THE PROPAGATION VELOCITIES

DEPINNING REGIME → applied field is smaller than the DEPINNING FIELD

FLOW REGIME → applied field is greater than the DEPINNING FIELD

SATURATION REGIME → Velocity saturates to a constant values



in FLOW REGIME $v_{DW}(H_z \gg H_{int}) = v_0 + \mu_w (\underline{H_z} - H_{int})$

the velocity depends linearly on the applied field H_z

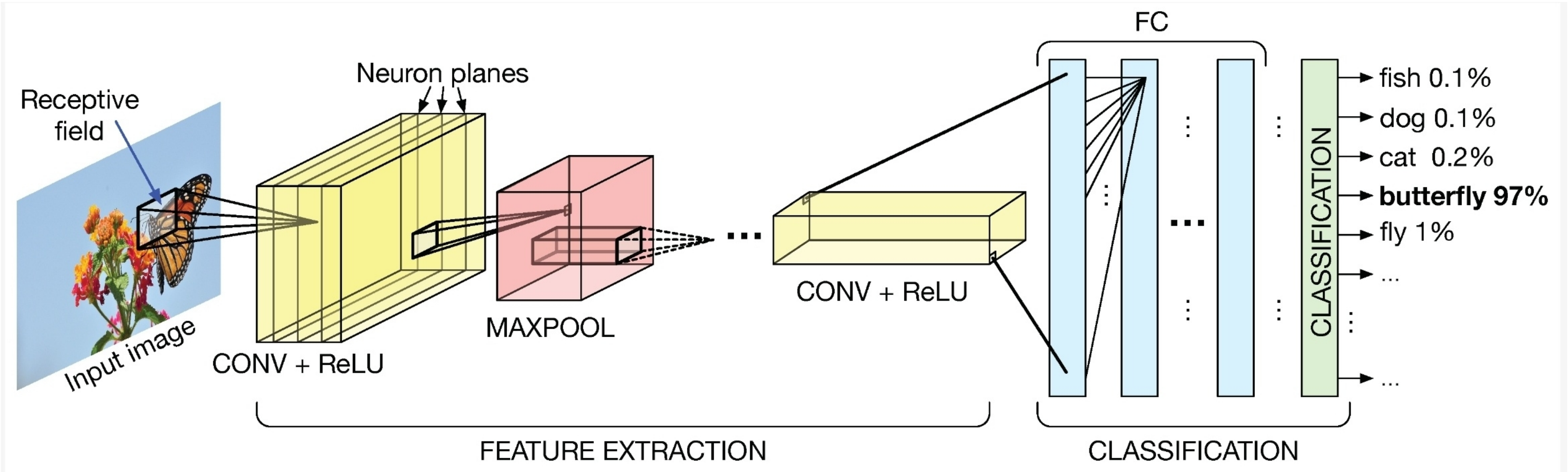
$\rightarrow t_{prop} = \ell_{MAG} / v_{DW}(H_z - H_{int})$ ℓ_{mag} LENGHT OF MAGNET

PNML
EXAMPLE APPLICATION
FOR
LOGIC-IN-MEMORY

LIM FOR CNN

CONVOLUTIONAL NEURAL NETWORK

CNN FOR IMAGE RECOGNITION

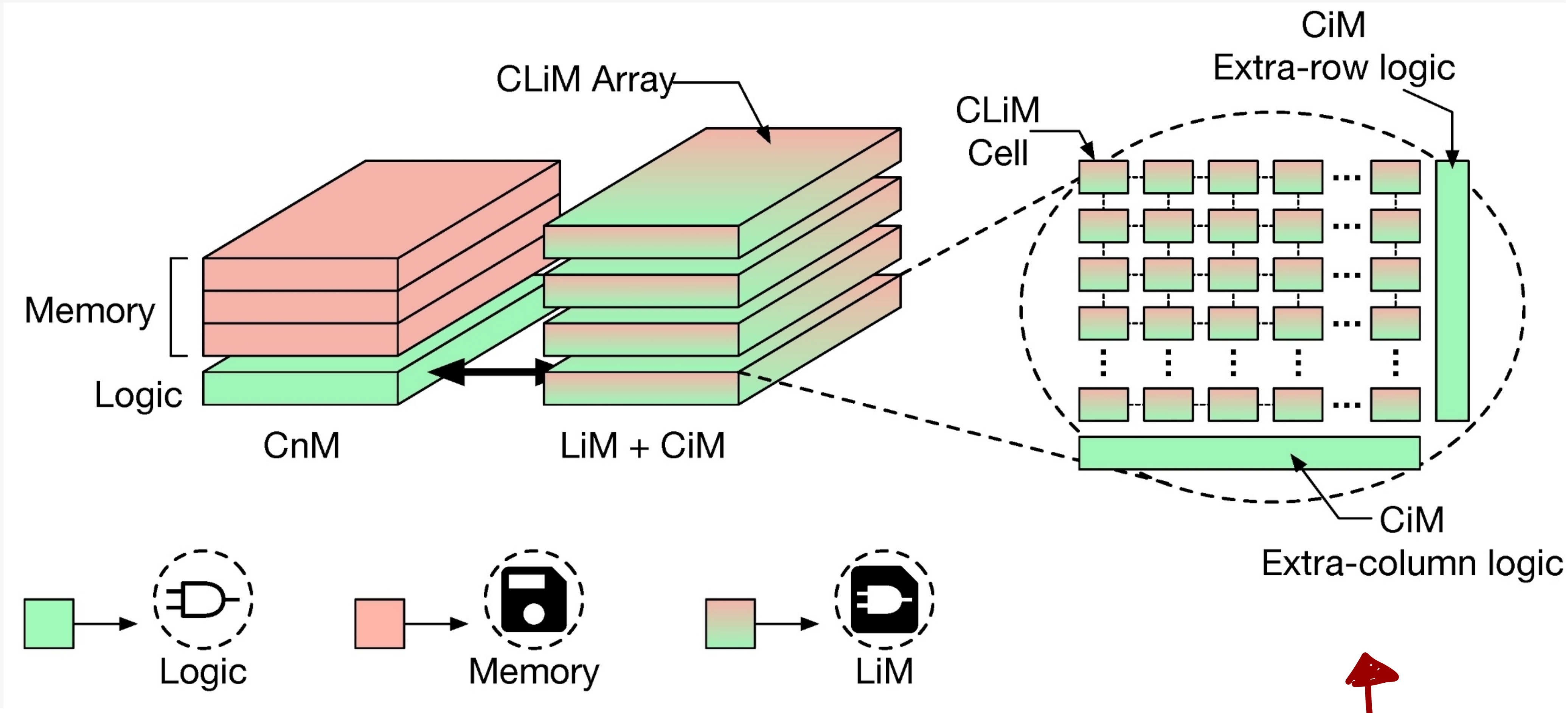


REQUIRES SEVERAL NESTED STEPS

MANY ADDITIONS AND MULTIPLICATIONS

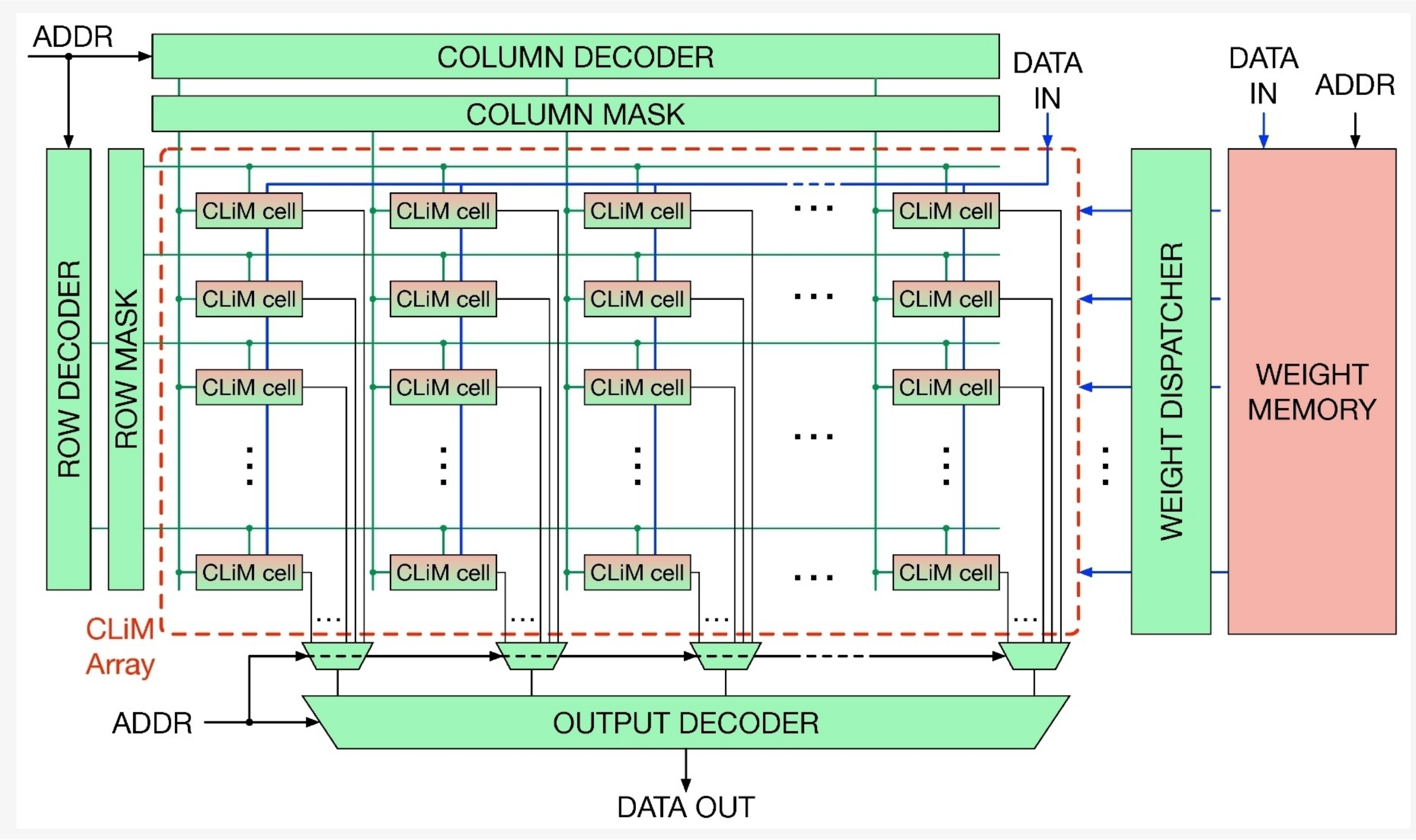
SEVERAL RIPETITIVE ACCESS TO MEMORY

IMPLEMENTED USING
-MEMORY -LOGIC
+ CLIM STACK

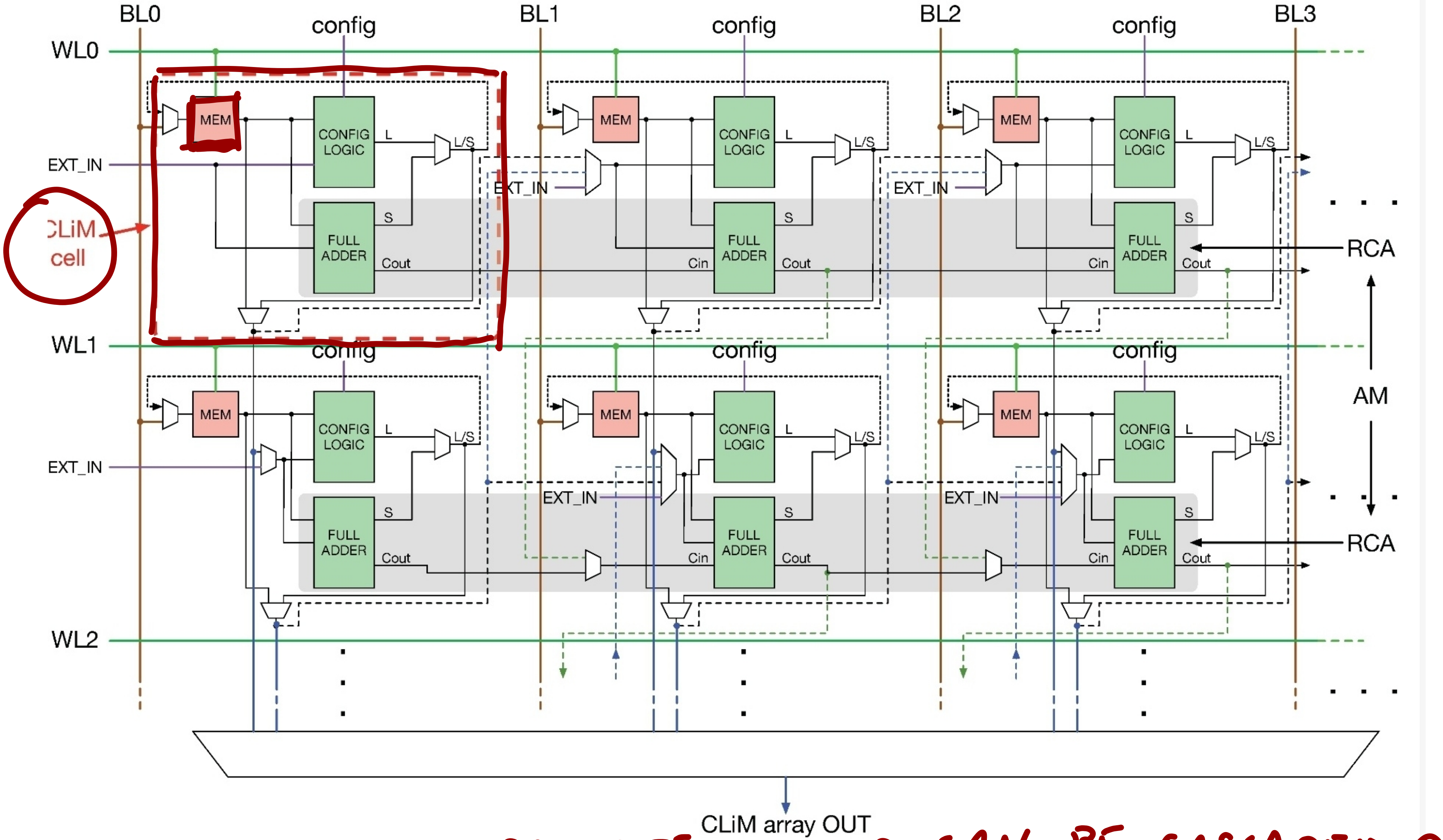


CLIM = CONFIGURABLE LOGIC IN MEMORY

CLIM ARRAY


ADDR
COLUMN DECODER
COLUMN MASK
DATA IN
DATA IN
ADDR
ROW DECODER
ROW MASK
CLiM cell
WEIGHT DISPATCHER
WEIGHT MEMORY
CLiM Array
ADDR
OUTPUT DECODER
DATA OUT

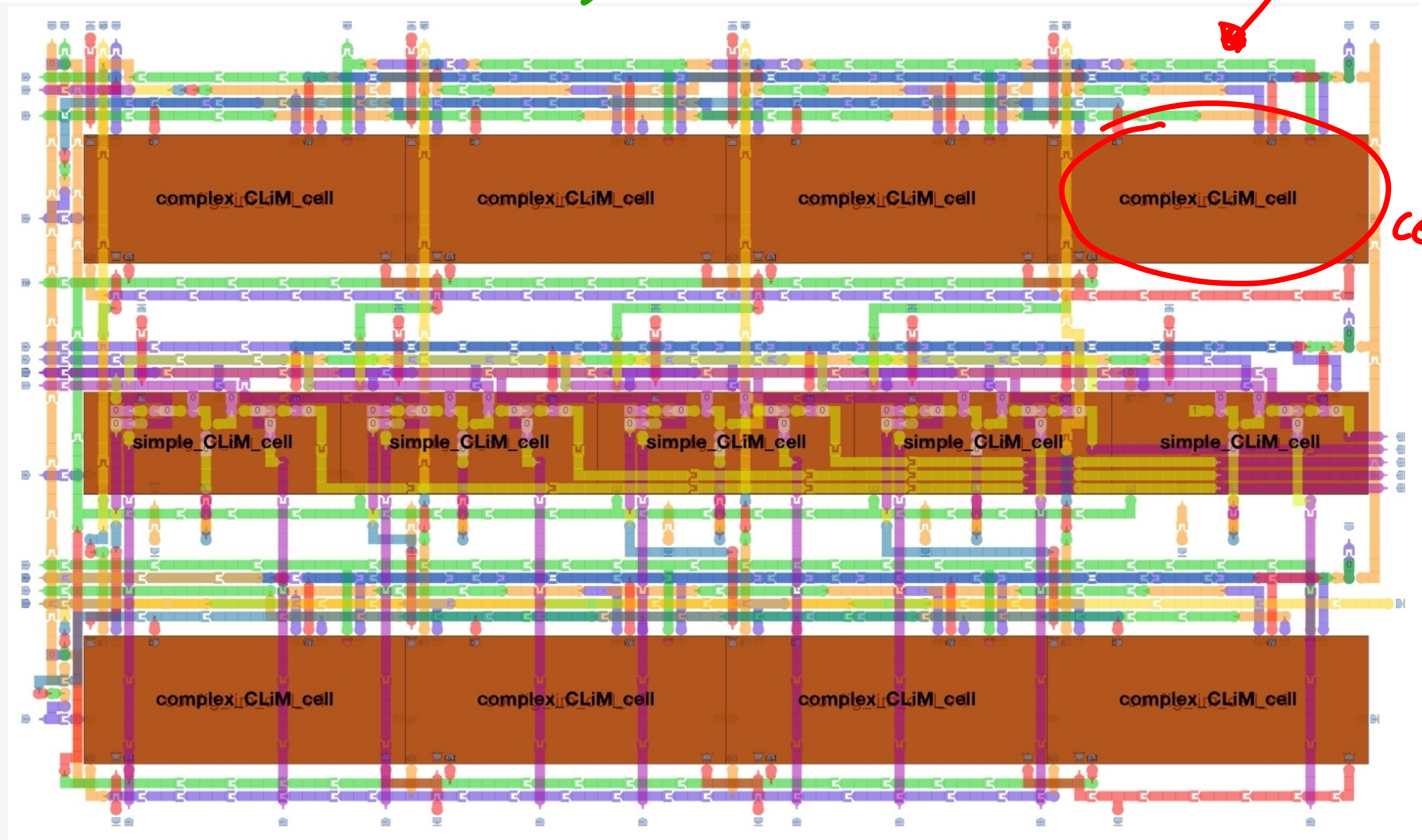
CLIM ARRAY INNER VIEW + CLIM CELL DETAILS



CELL CAN WORK SEPARATELY OR CAN BE CASCADED OR WORK IN PARALLEL

IMPLEMENTATION OF CLIM ARRAY USING PNML

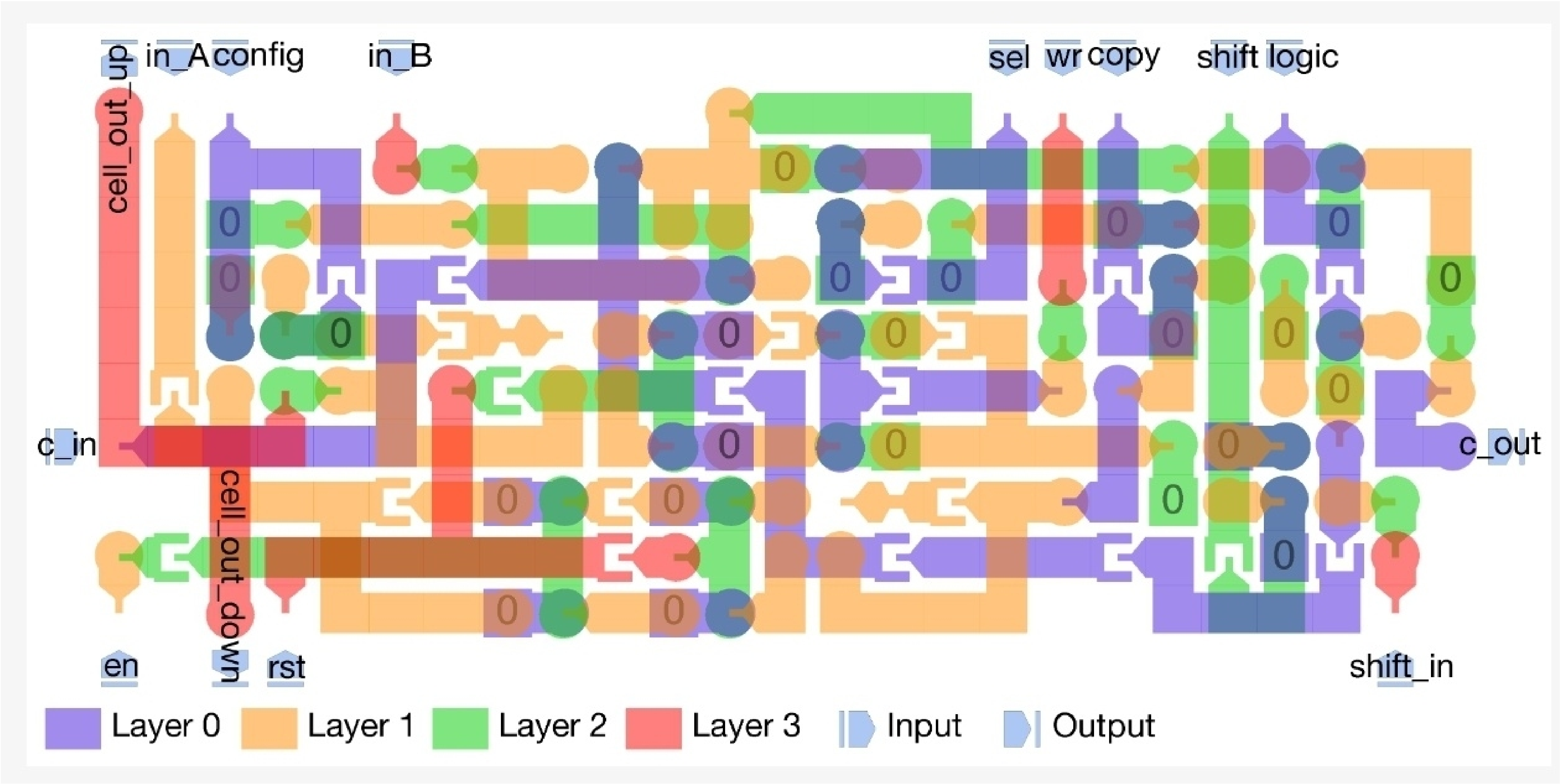
MULTILAYER PNML STACK



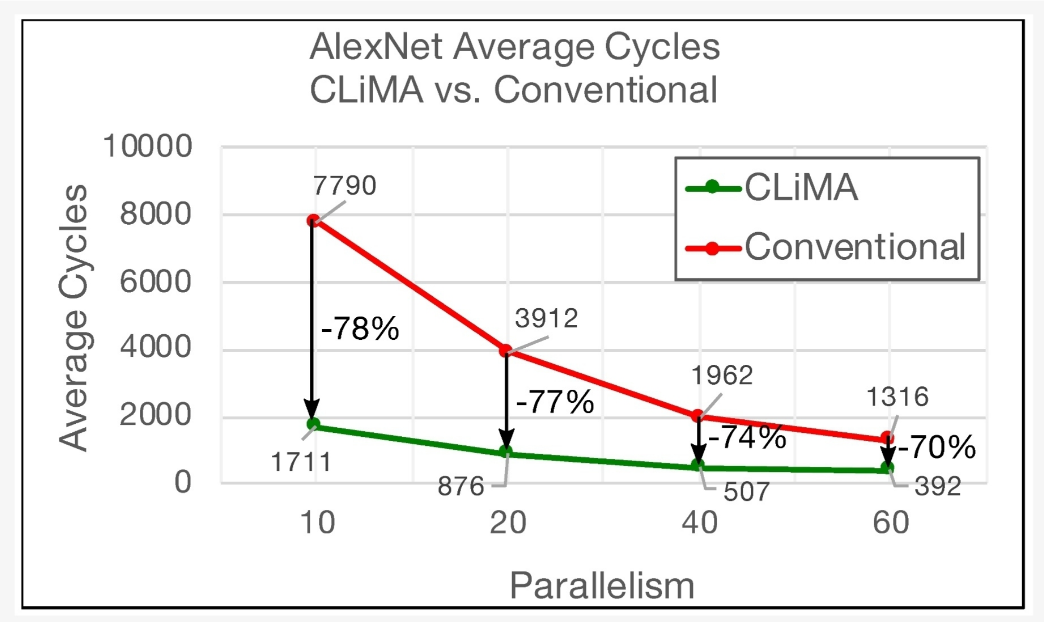
CONNECTIONS

CELL

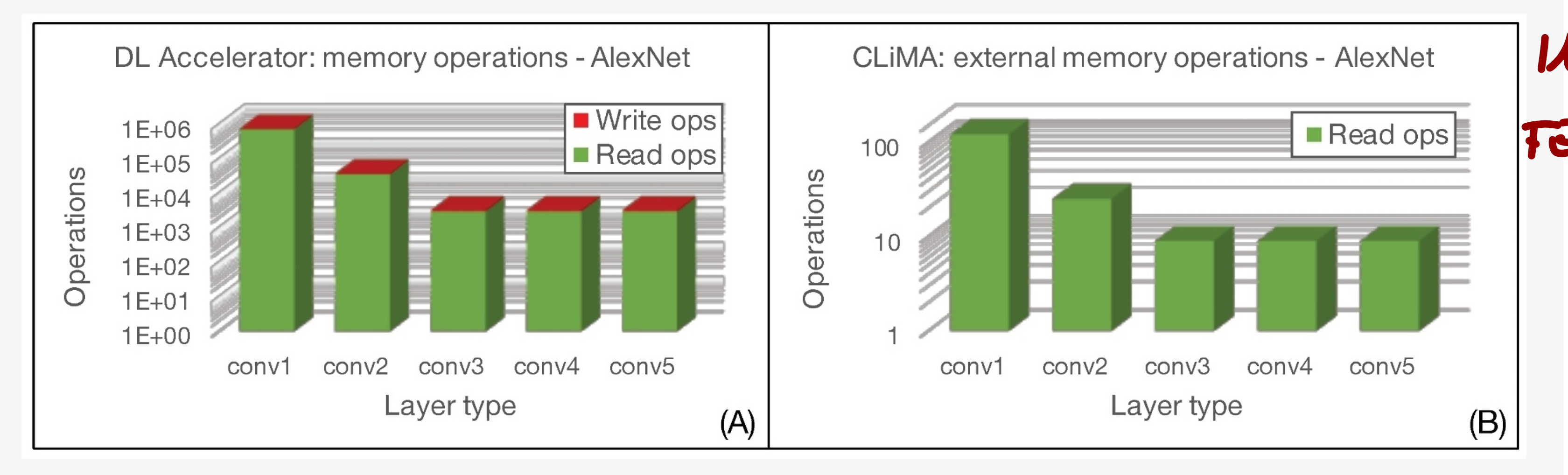
SINGLE CELL IMPLEMENTED USING MULTILAYER PNML FULLY RESPECTING ALL TECH. LIMITATIONS

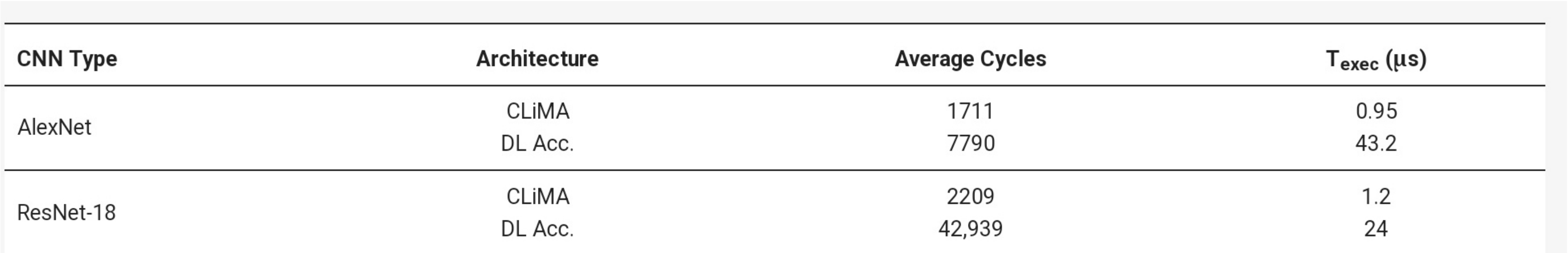


FULL CUSTOM OPTIMIZED DESIGN



- THE CLIMA ARCHITECTURE REDUCES THE N. OF ACCESS TO MEMORY
- EXEUUTION TIME IS REDUCED
- PNML FURTHER FAVOURS OPTIMIZATION EMBEDDING BOTH LOGIC AND STORAGE INTRINSIC FEATURES

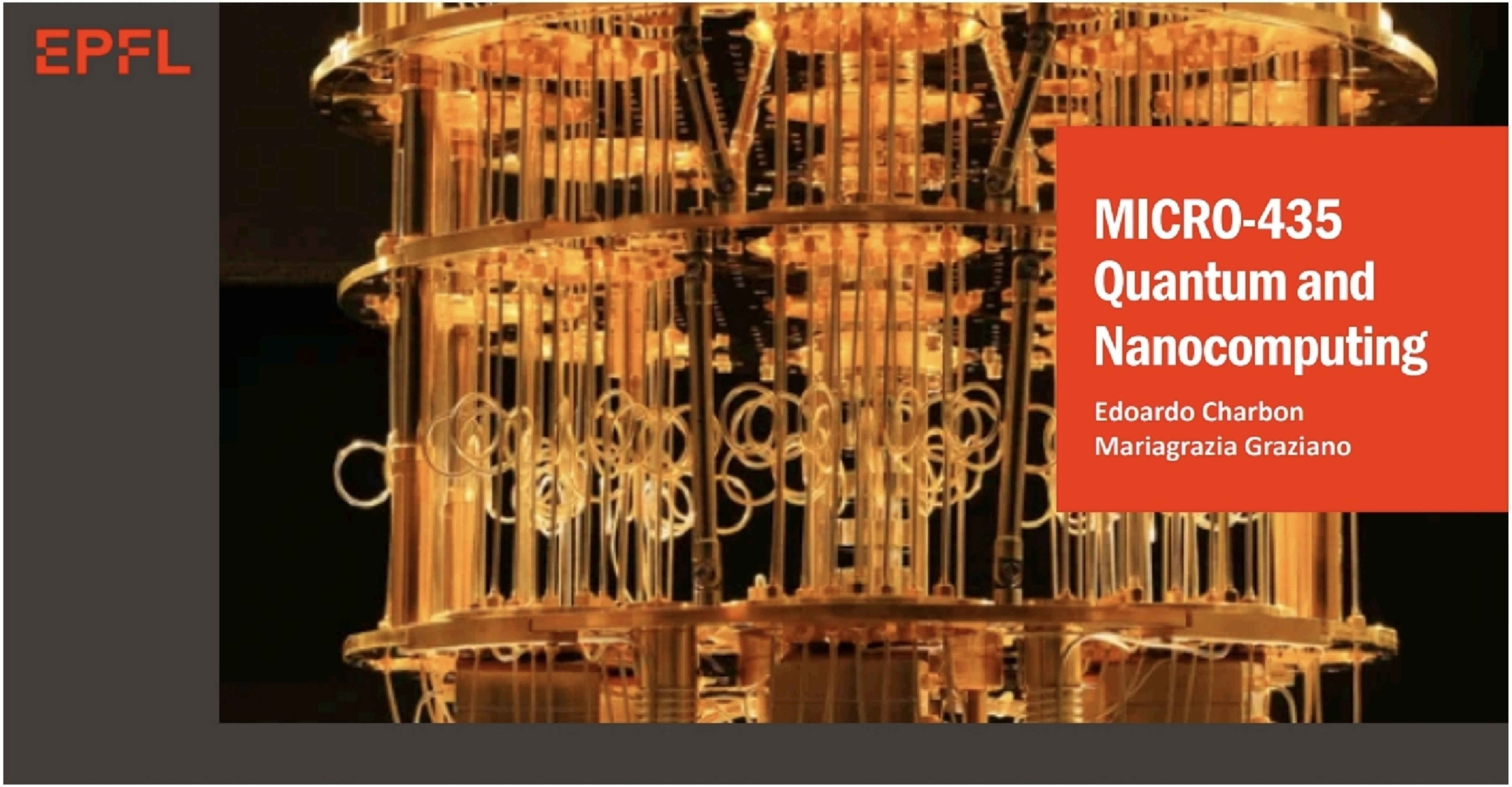




CNN Type	Architecture	Average Cycles	T_{exec} (µs)
AlexNet	CLiMA DL Acc.	1711 7790	0.95 43.2
ResNet-18	CLiMA DL Acc.	2209 42,939	1.2 24

CRISTALLIZATION

- PNML : MIXES NML PRINCIPLE AND DW PROPAGATION
- A MIX AMONG: MAGNET INTERACTION
  AND
  Hext. FIELD SOLVES NML
  PROBLEMS
- Hclock IS GENERAL, NO PHASES
- ALLOWS MULTILAYER ORGANIZATION
- SPEED CAN IMPROVE , WITH SHRINKING



MICRO-435
Quantum and Nanocomputing

Edoardo Charbon
Mariagrazia Graziano

RACETRACKS & SKYRMIONS

OBJECTIVES

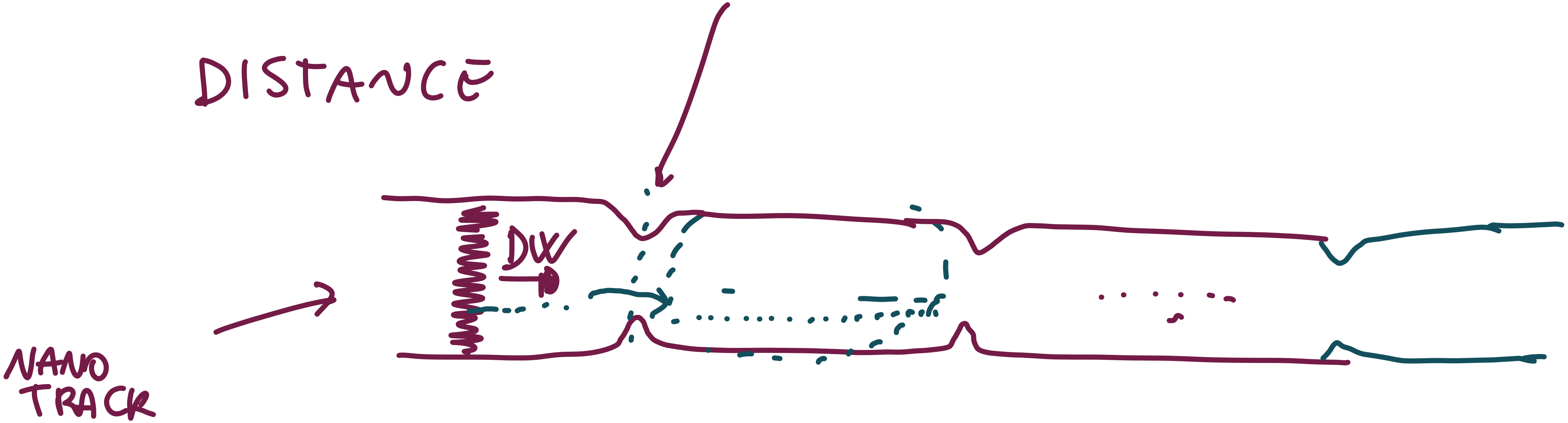
SOME MORE SPINTRONICS

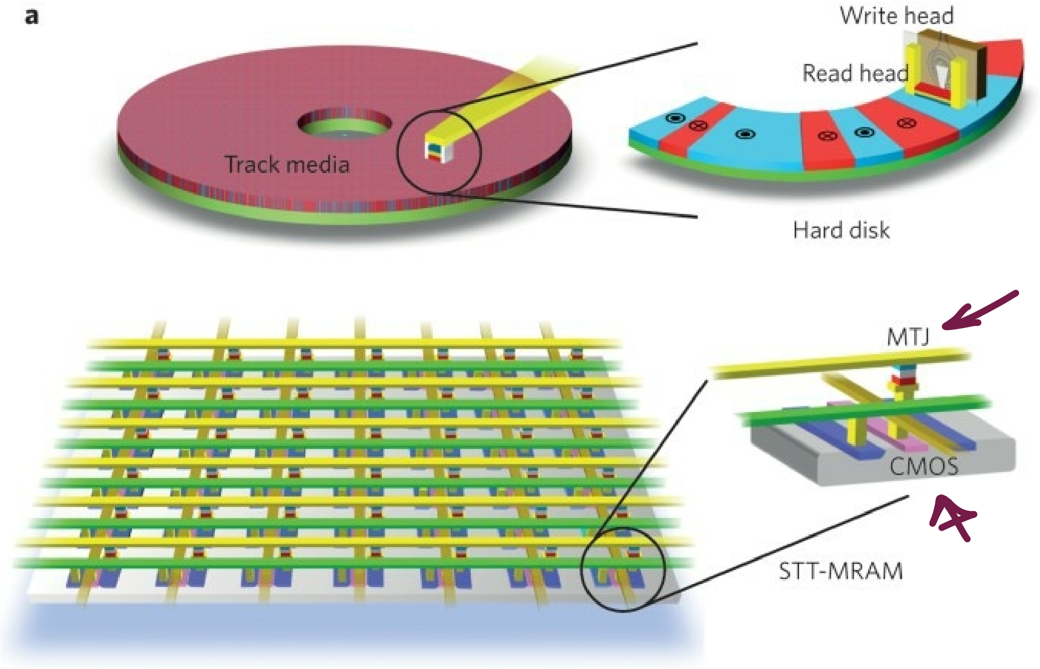
① → RACETRACK MEMORY & LOGIC based on PNML

② → SKYRMIONS : basics, MEMORY & LOGIC

① RACETRACK LOGIC & MEMORY

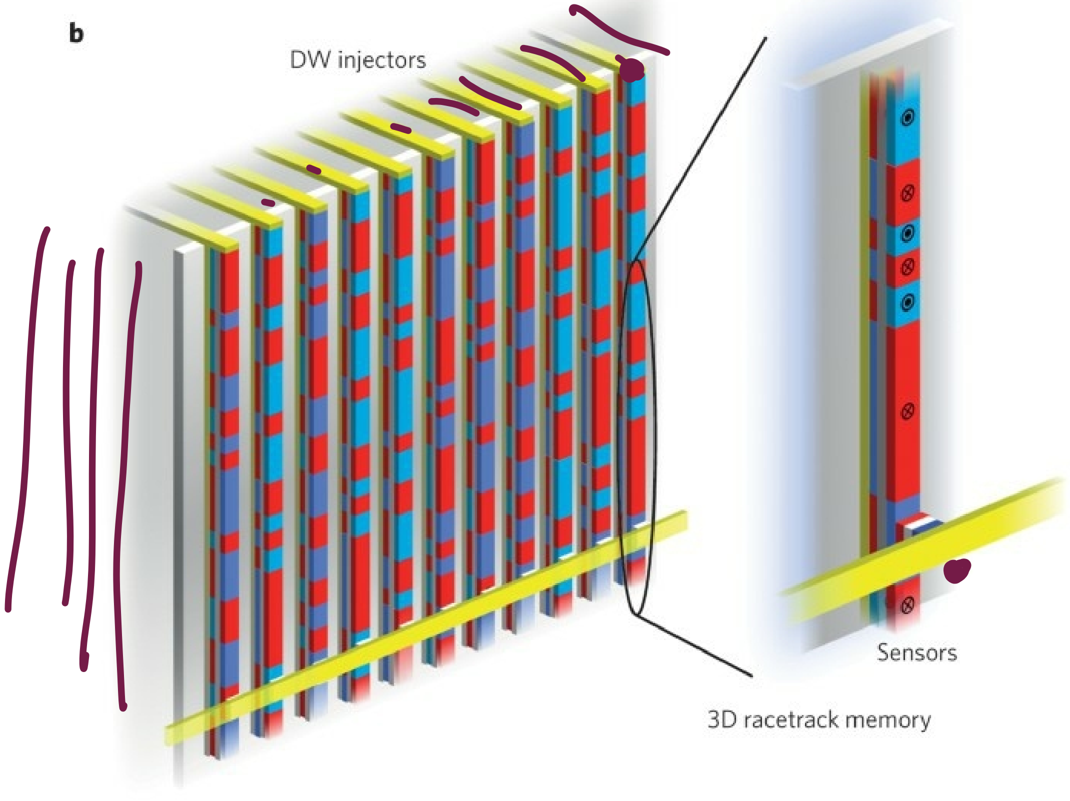
THE RACETRACK MEMORY CONCEPT EXPLOITS THE PROPAGATION OF DOMAIN WALLS THROUGH NANOMAGNETIC TRACKS SHOWING NOTCHES AT REGULAR DISTANCE





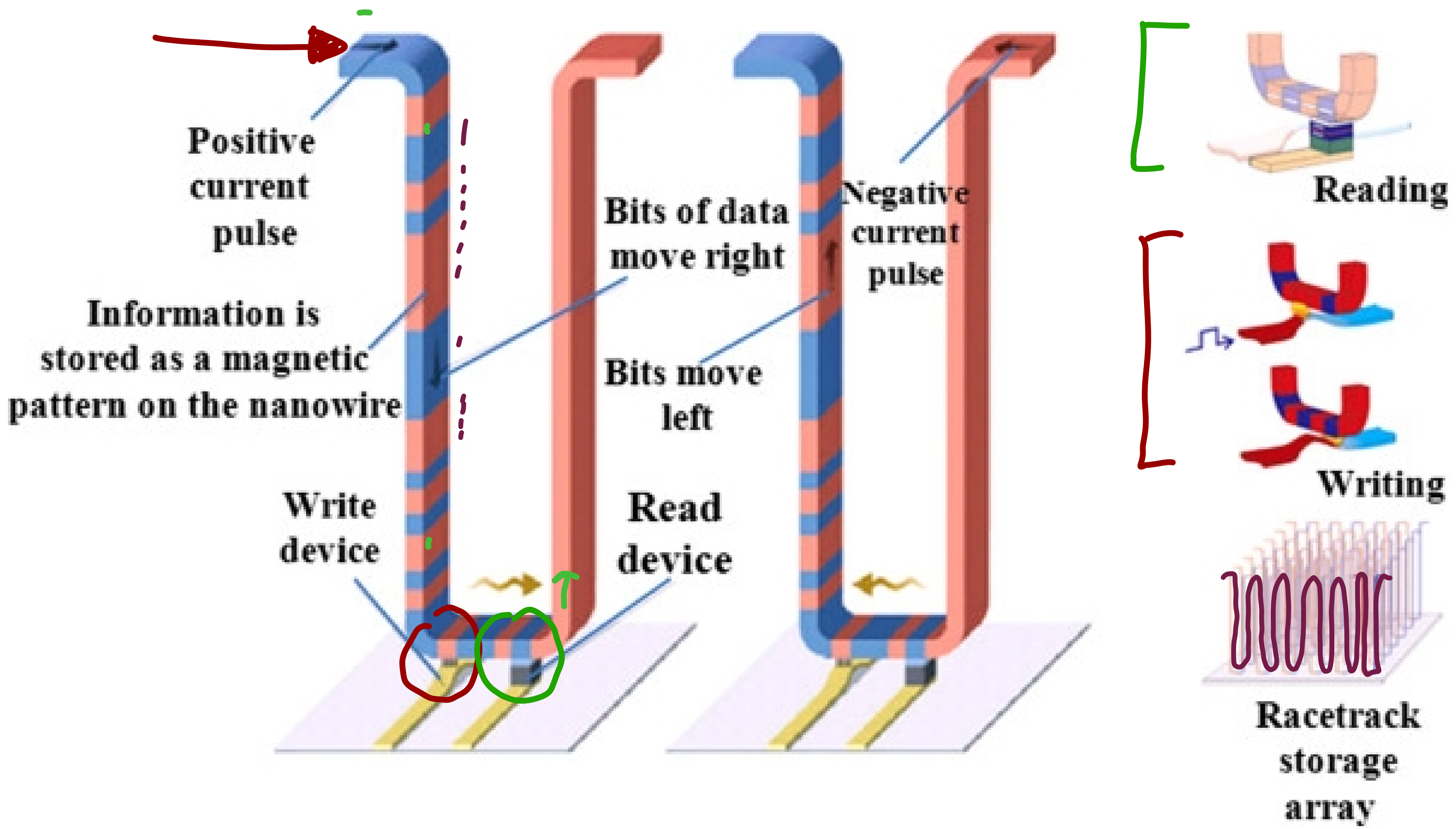
← RECORDING OF A MAGNETIC HARD DISK DRIVE

← MRAM, MTJ MEMORY ELEMENT + ACCESS TRANSISTOR



← RACETRACK MEMORY CONCEPT (PROPOSED BY IBM)

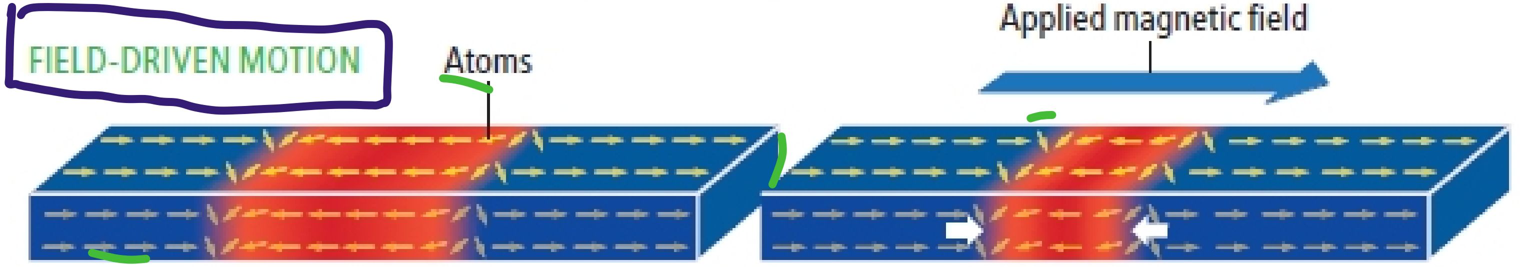
BLUE AND RED REGIONS ARE AREA WITH DIFFERENT MAGNETIZATION (IN PLANE OR OUT OF PLANE)



EXAMPLE OF A STRUCTURE THAT ALLOWS A 3D ORGANIZATION (VERY MUCH COMPACT)

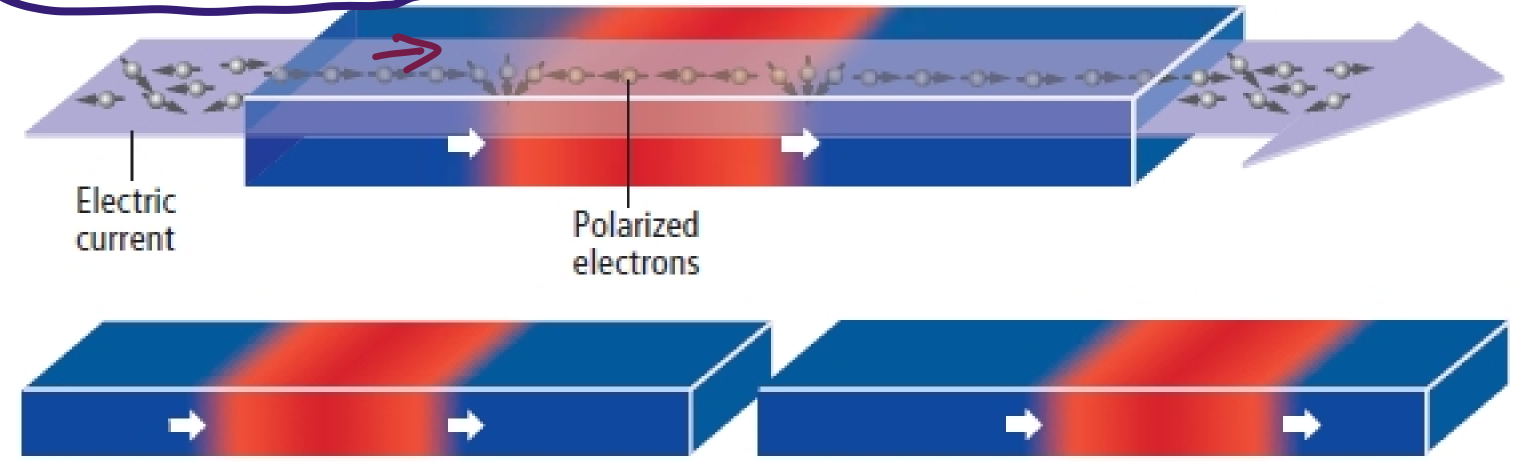
The ability to use an electric current to move magnetic domains along a nanowire is essential to making racetrack memory practical (*bottom*). Older techniques using magnetic fields would be too complicated (*top*).

FIELD-DRIVEN MOTION



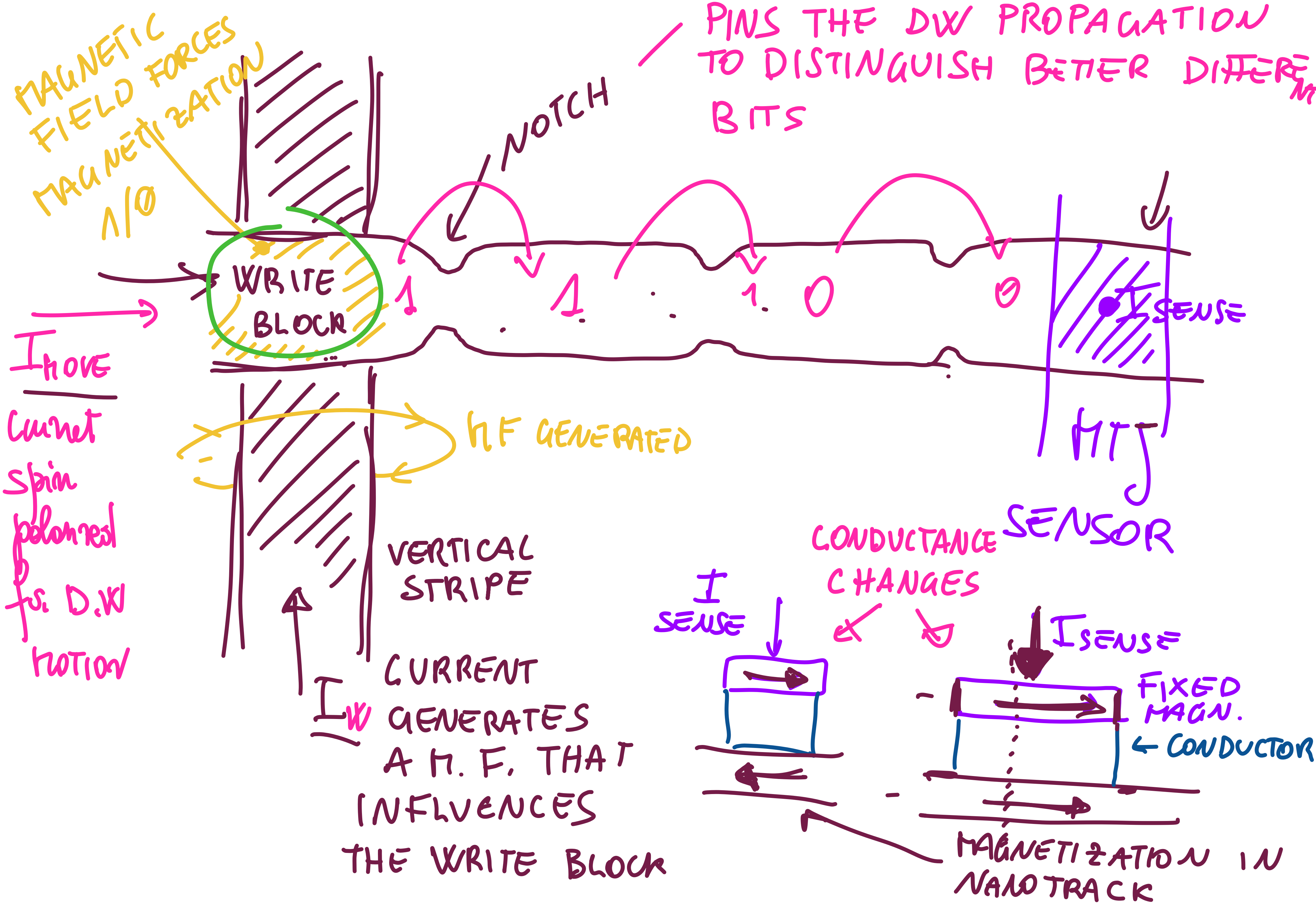
Magnetic domains representing 0s and 1s contain atoms whose intrinsic magnetism (*yellow arrows*) is aligned. The atoms' orientation changes at the domain walls. Applying a field pointing in, say, the 1 direction (*blue arrow*), causes domain wall atoms to turn to the 1 direction, which moves the domain walls (*white arrows*)—but in opposite directions, shrinking the 0 region. Moving the bits along the wire requires a more complicated magnetic field.

CURRENT-DRIVEN MOTION



The electrons (*gray*) of a current in a racetrack become "spin polarized"—their spin and intrinsic magnetism align with the magnetization of the material. When these spin-polarized electrons cross from a 1 region to a 0, their orientations flip. Because spin is a form of angular momentum, which must be conserved, each electron that switches from 1 to 0 must flip an atom in the wire from 0 to 1. Thus, the spin-polarized current moves the 1-0 domain wall along the racetrack. The current moves the 0-1 domain walls in the same direction, so the data bits flow along the wire.

SPIN POLARIZED CURRENT MOVES THE D.W. THROUGH THE TRACK



MAGNETIC FIELD FORCES MAGNETIZATION 1/0

PINS THE DW PROPAGATION TO DISTINGUISH BETTER DIFFERENT BITS

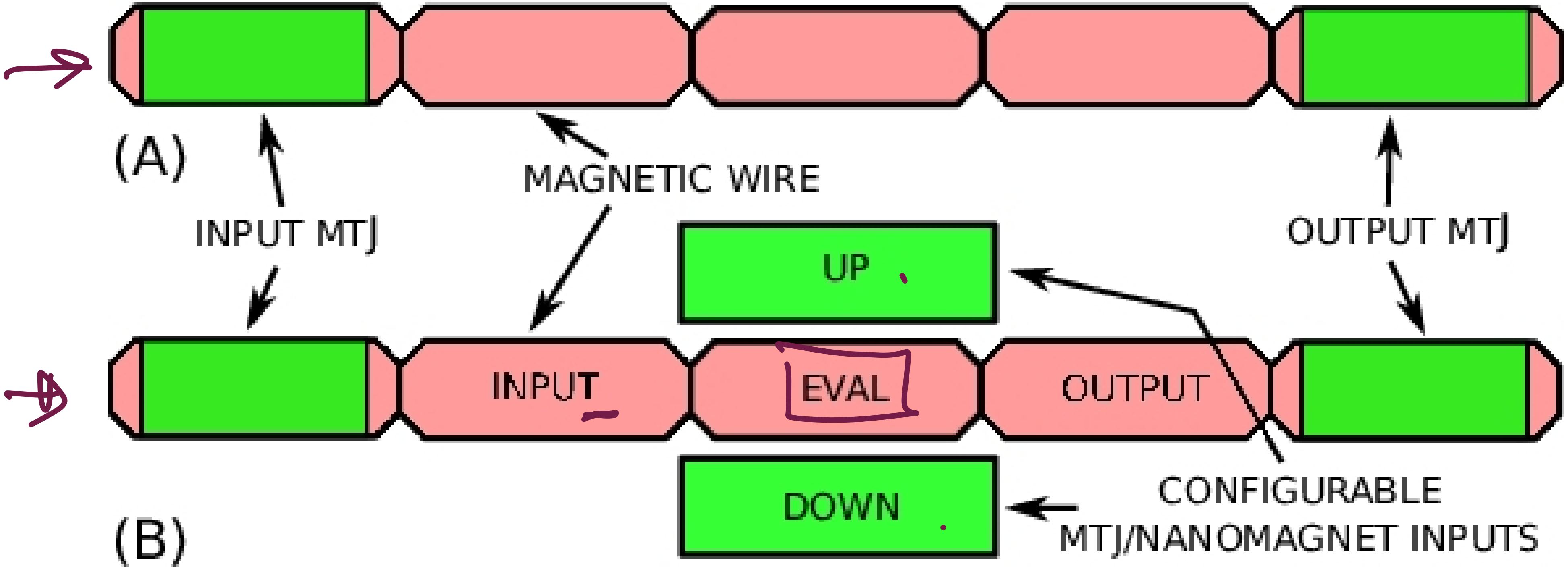
I_{move} current spin polarized for D.W motion

I_W CURRENT GENERATES A M. F. THAT INFLUENCES THE WRITE BLOCK

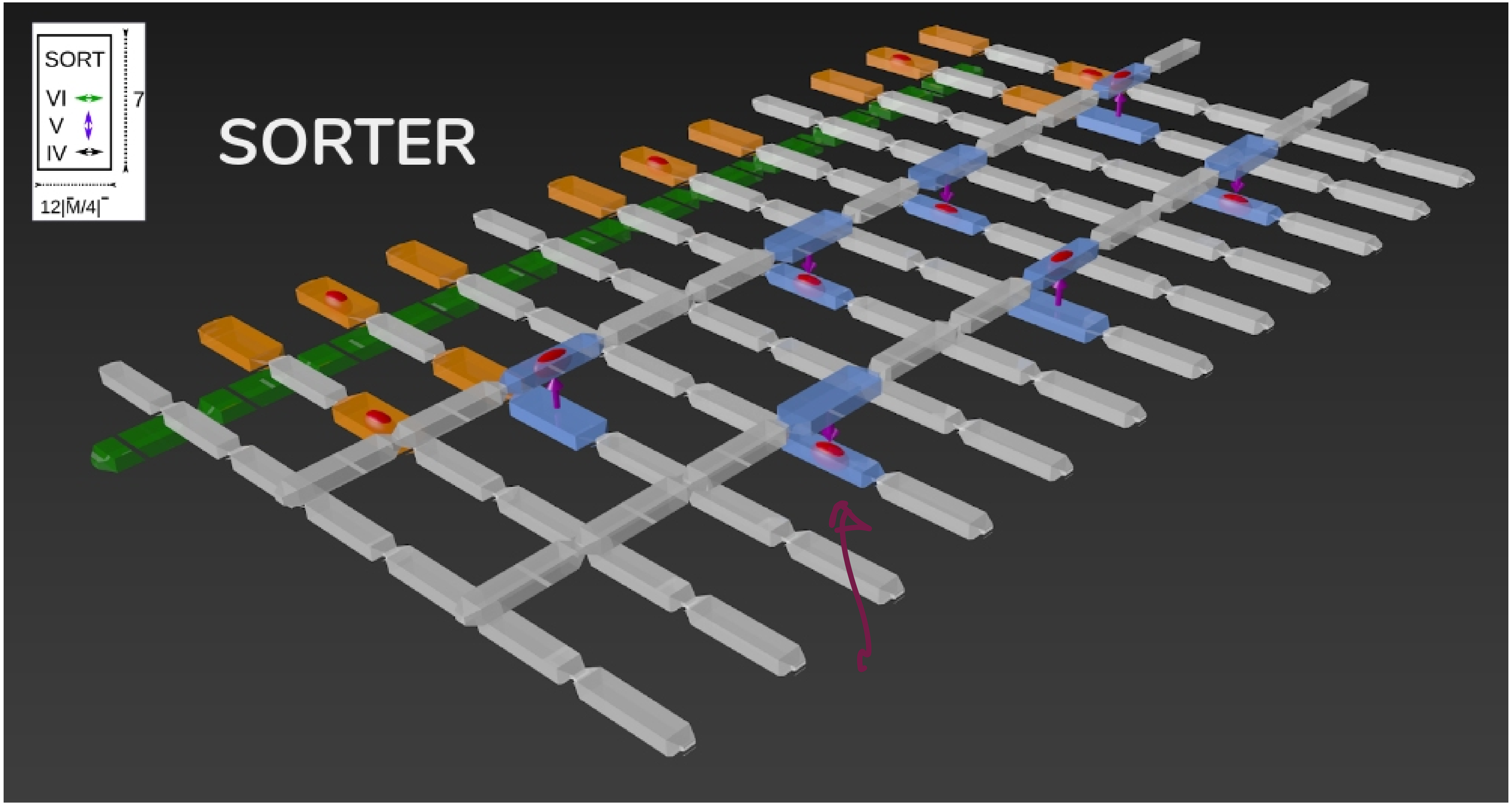
CONDUCTANCE CHANGES

MAGNETIZATION IN NANOTRACK

RACETRACK MEMORY

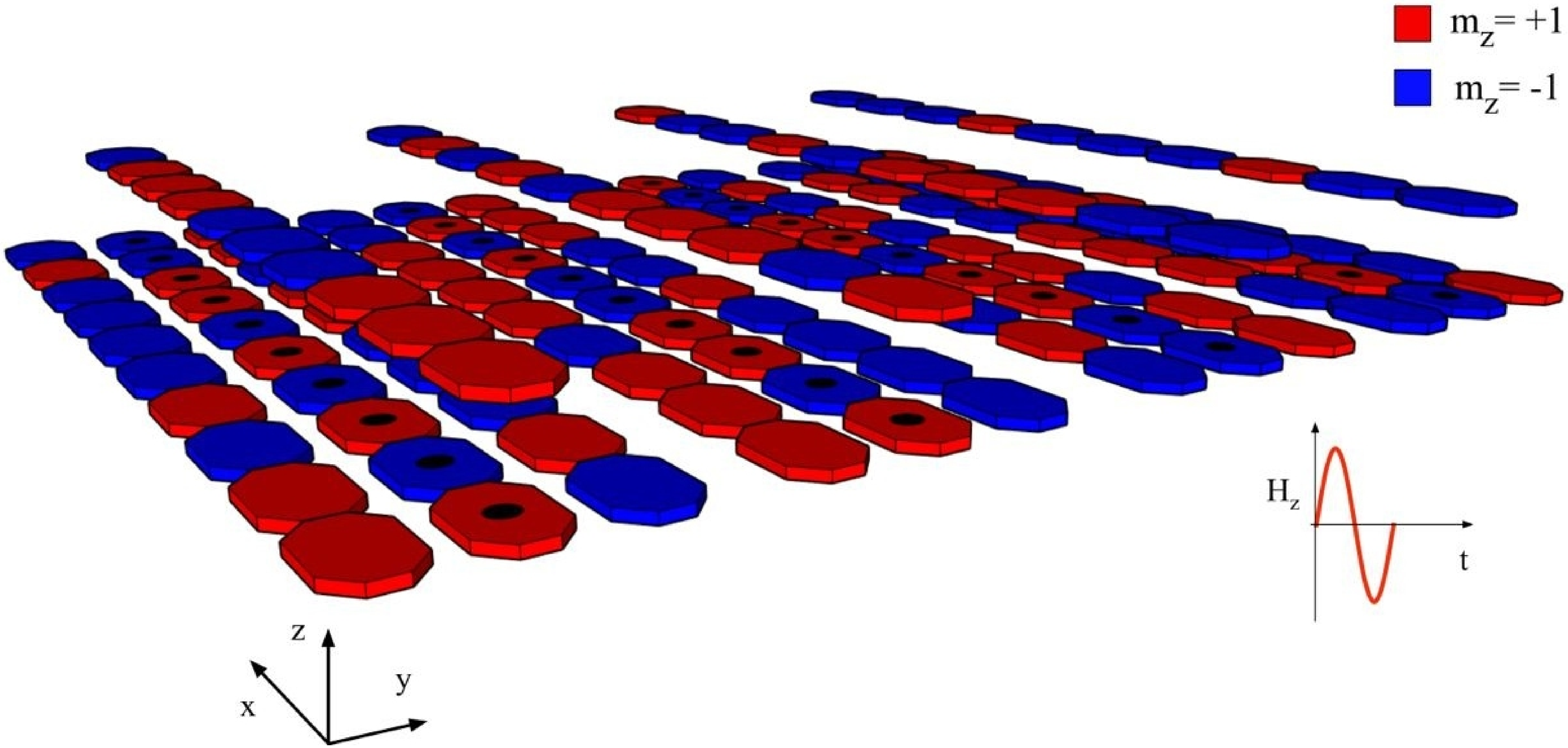


RACETRACK LOGIC : PLACING OTHER NANO MAGNETS NEARBY A BIT A "LOGIC" FUNCTION CAN BE OBTAINED

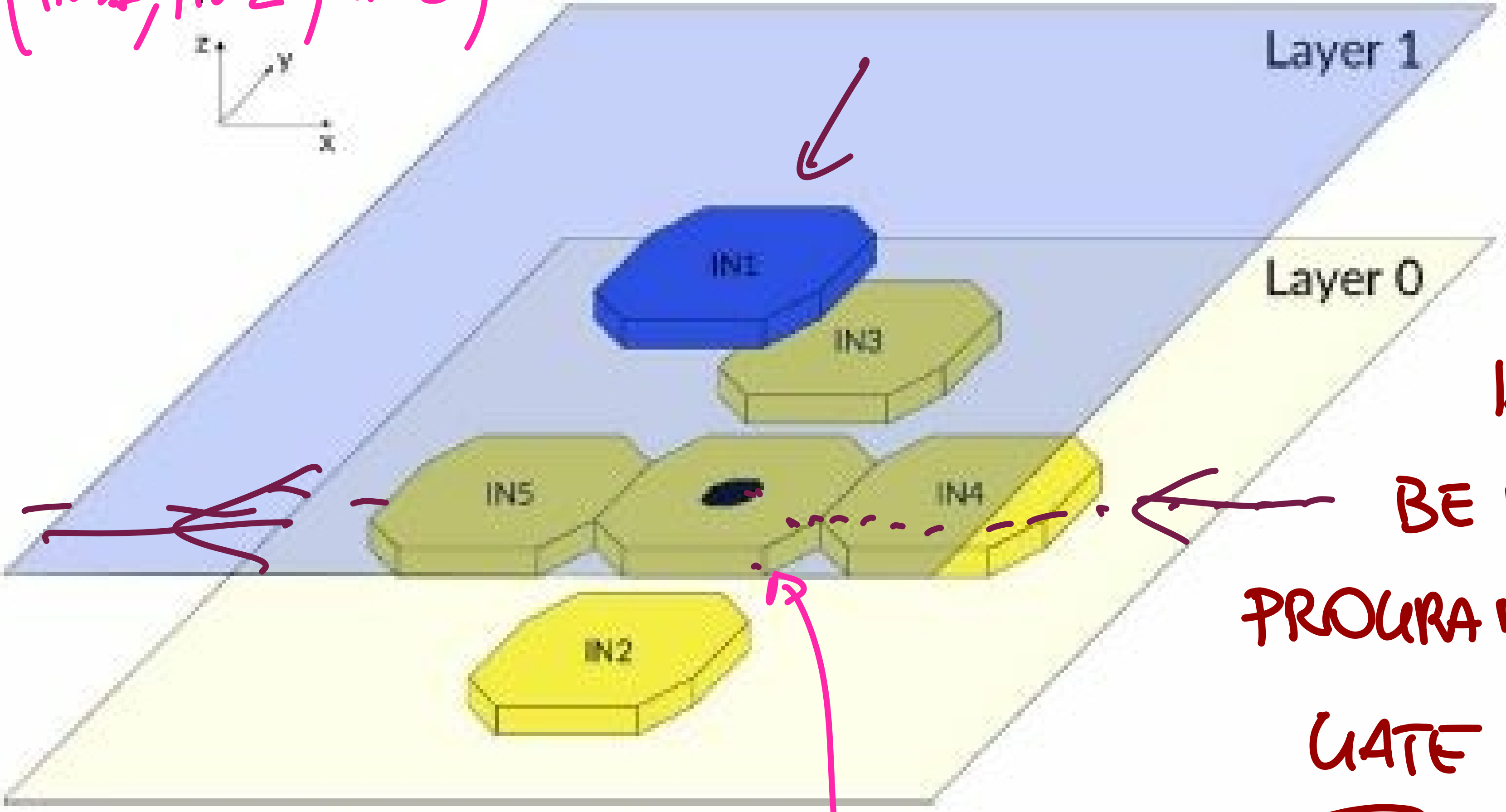


CAN BE THOUGHT AS A 3D ARRAY ALLOWING BOTH STORAGE AND LOGIC

RACETRACK BASED ON PNML FOR MEMORY & LOGIC



$MV(IN1, \overline{IN2}, \overline{IN3})$



IN1 CAN BE USED TO PROGRAM THE GATE AS NAND/NOR

RESULT CELL

PNML VERSION OF RACETRACK LOGIC (PATENTED)

The RACETRACK CAN BE IN EACH OF THE DIRECTION

MOVIE OF A MICROMAGNETIC SIMULATION

→ SHIFT OPERATION

→ COMPUTING OPERATION

EPFL

MICRO-435 Quantum and Nanocomputing

Edoardo Charbon
Mariagrazia Graziano

SKYRMIONS

① → RACETRACK MEMORY & LOGIC based on PNML

② → SKYRMIONS: basics, MEMORY & LOGIC

② SKYRMIONS

HAVE ATTRACTED A LOT OF ATTENTION RECENTLY AS INFORMATION CARRIERS FOR BOTH MEMORIES & LOGIC DEV.

SKYRMIONS ARE A BREAKING OF THE MAGNETIZATION ORDER IN A MAGNETIC PLANE

THEY DERIVE FROM THE COMPETITION AMONG

→ FERROMAGNETIC EXCHANGE COUPLING
(makes spin of neighbour atoms aligned)

→ DMI (DZYALOSHINSKII – MORIYA INTERACTION)
(anisotropic exchange interaction)

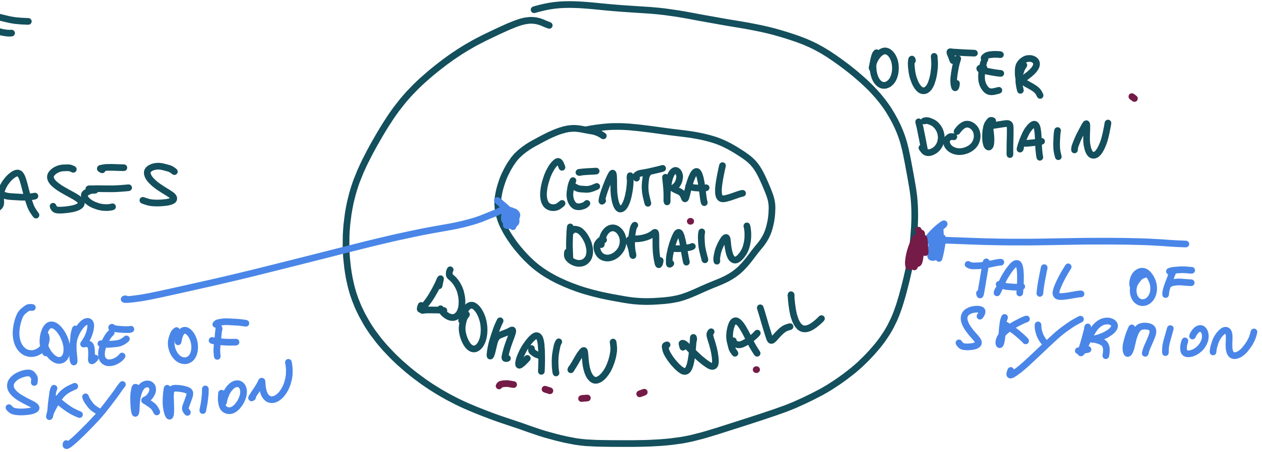
either in → SINGLE LAYERS
→ MULTI LAYERS

↘ see details in LN

→

DEPENDING ON THE TYPE OF DMI 2 TYPES OF SKYRMION RISE

→ IN BOTH CASES



if DOMAIN WALL HAS CIRCULAR CHIRALITY (CK WISE OR ACK WISE)

→ BLOCK SKYRMION

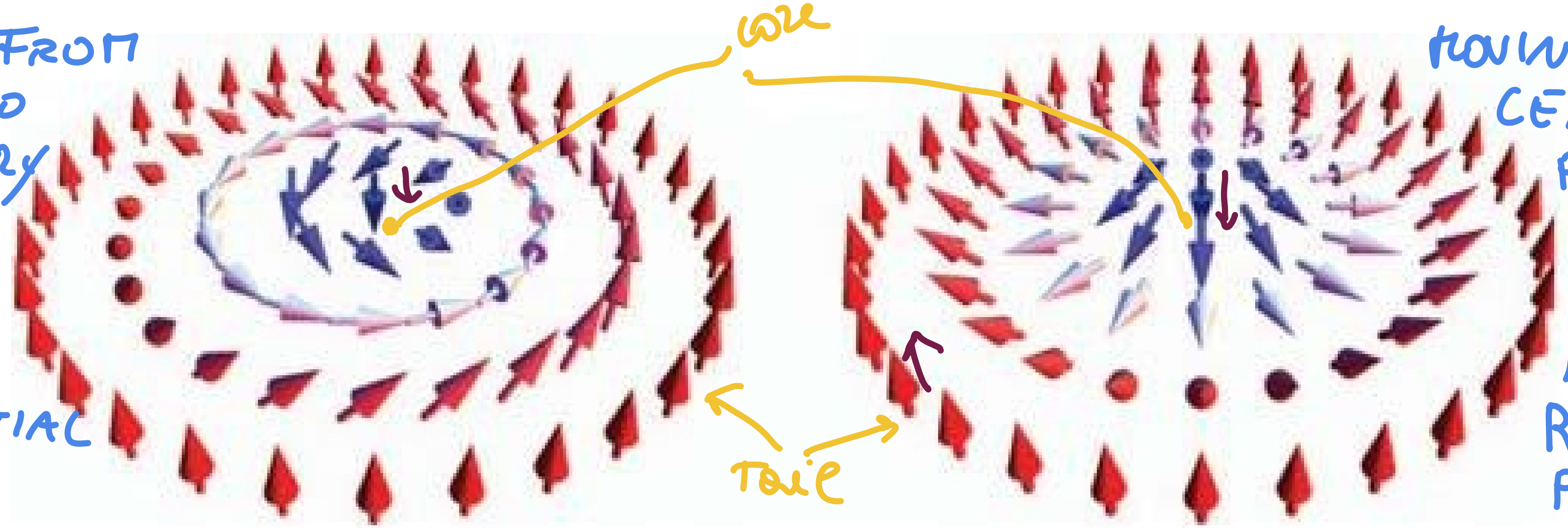
magnetization rotates in the tangential plane

if D.W. HAS RADIAL CHIRALITY (INWARD OR OUTWARD)

→ NEEL SKYRMION

magnetization rotate in radial plane

A SKYRMION IS A TOPOLOGICALLY STABLE CONFIGURATION OF THE MAGNETIZATION TEXTURE OF A FERROMAGNET, SHOWING A WIRLING STRUCTURE

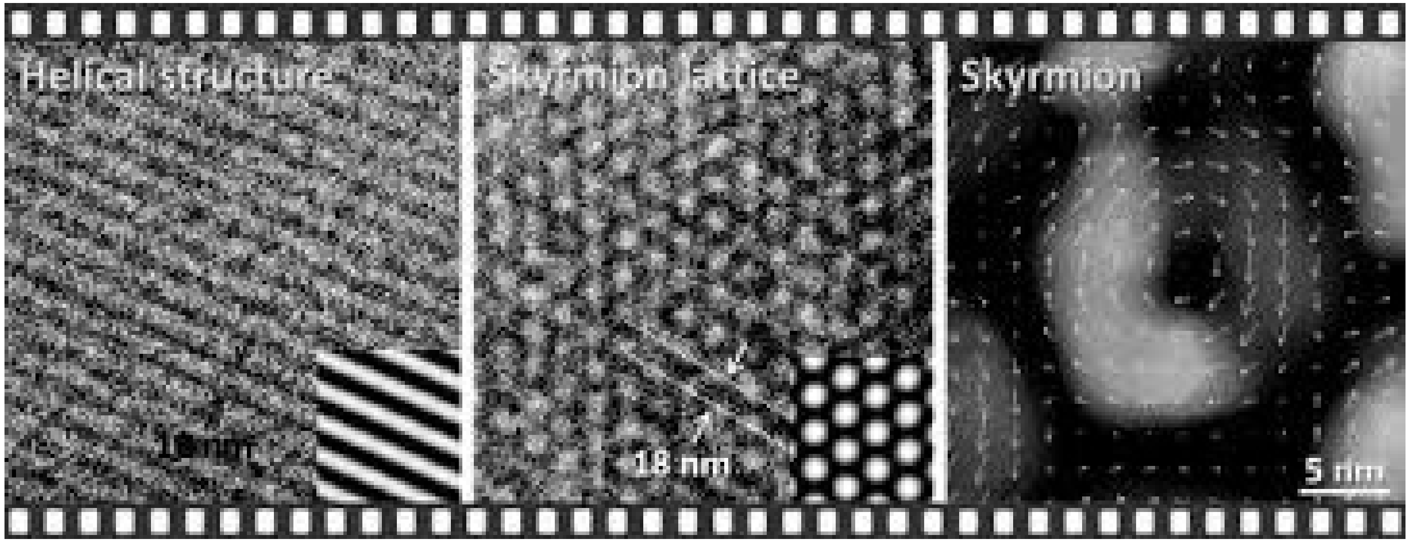


MOVING FROM CENTER TO PERIPHERY SPIN ROTATE IN THE TANGENTIAL PLANE

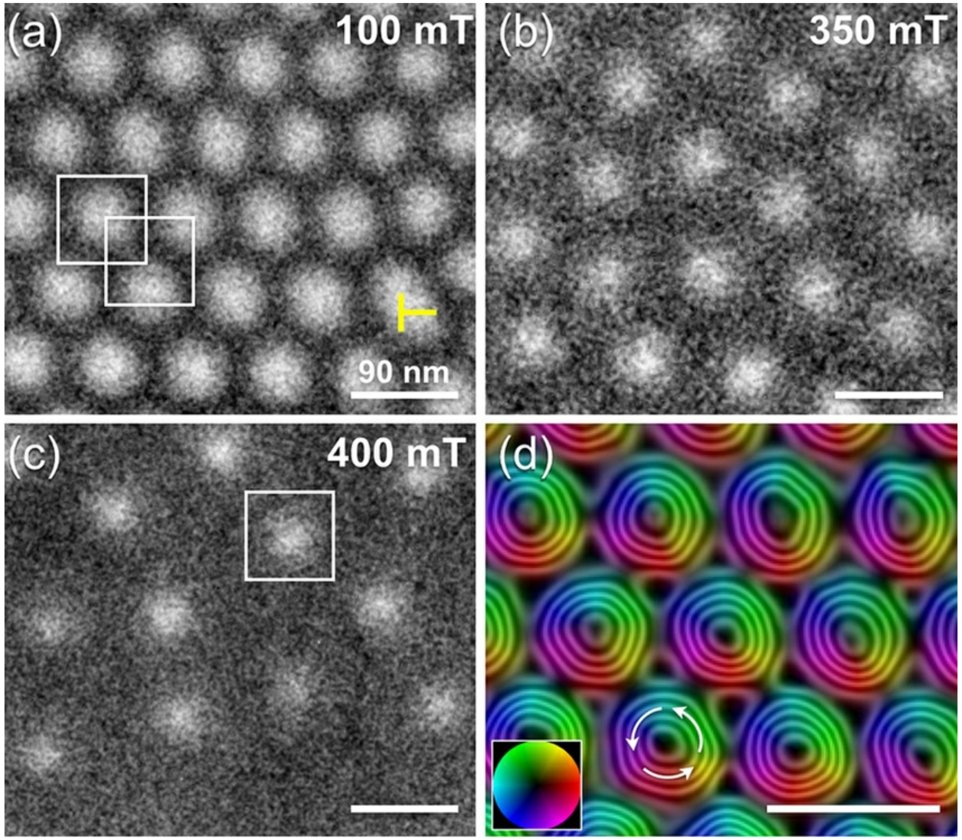
MOVING FROM CENTER TO PERIPHERY SPIN ROTATE IN THE RADIAL PLANE

BLOCH SKYRMION

NEEL SKYRMION



EXPERIMENTAL EXAMPLES



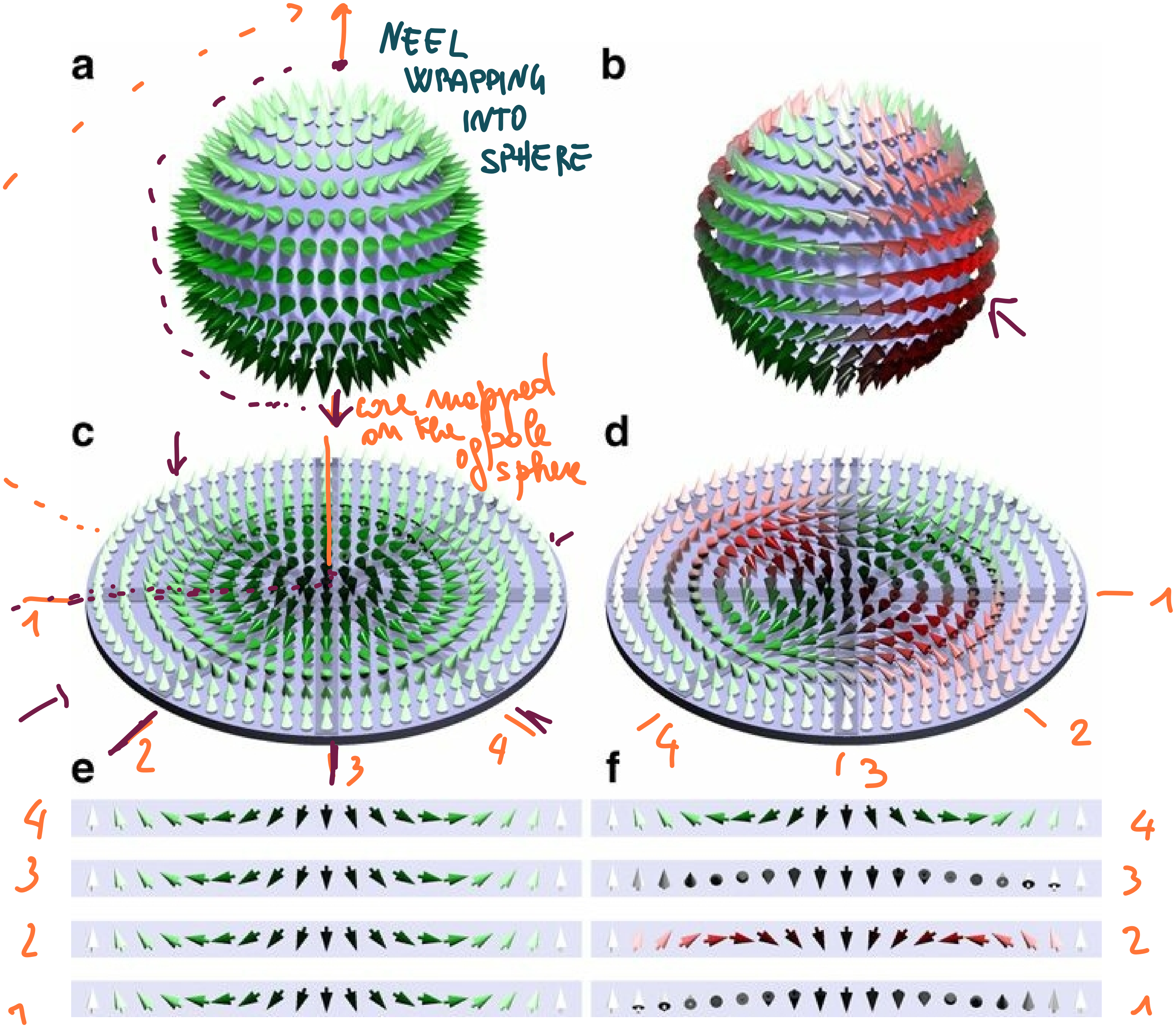
THE STUCTURE IS DESCRIBED BY THE TOPOLOGICAL CHARGE Q (SKYRMION NUMBER)

$$Q = \frac{1}{4\pi} \int dx\, dy \, \left(\partial_x \bar{m} \times \partial_y \bar{m} \right) \cdot \bar{m}$$

WHERE $\bar{m}$ IS THE UNIT VECTOR REPRESENTING THE ORIENTATION OF THE LOCAL MAGNETIC MOMENT

⇓

IN PRACTICE IT COUNTS HOW MANY TIMES THE MAGNETIC SPINS OF THE SK. CAN BE WRAPPED AROUND A UNIT SPHERE all spins in the boundary collected into a single vector



NEEL SK.

$Q = 1$

OTHER PARAMETERS ARE

described in polar coordinates

- VORTICITY NUMBER Q_v (or W)
- HELICITY NUMBER Q_h (or γ)

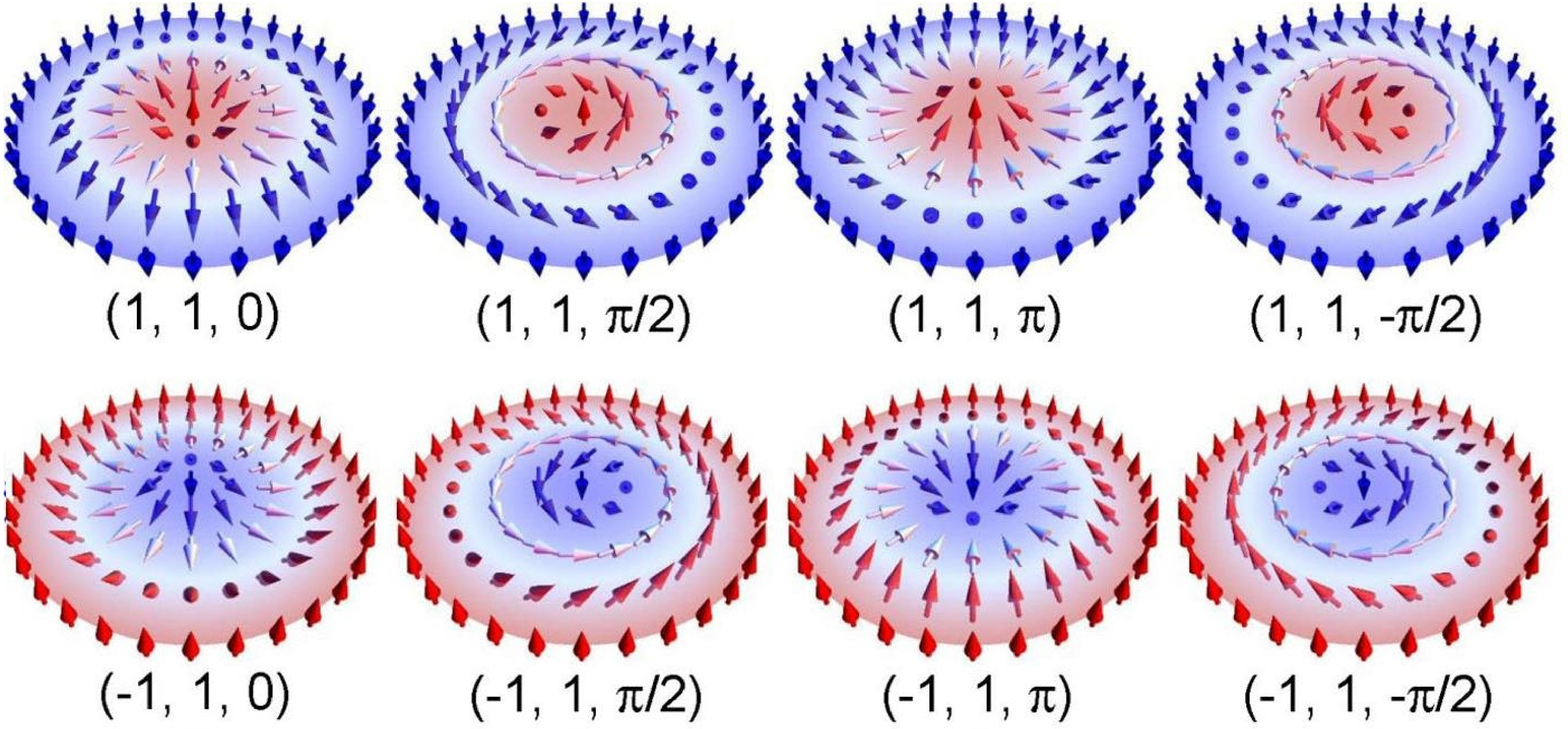
POLARITY (orientation of the sk. center w.r.t. the z-direction of the plane of the material)

$p=+1$ (z direction) $p=-1$ (opposite to z)

So each sk. has 3 identifiers $\boxed{(Q, Q_v, Q_h)}$ and polarity

Here we do not write details on the definitions (see lecture notes for an optional detailed study)

some examples are shown here ↓



BASICS OF SKYRMIONS FUNCTIONALITY FOR APPLICATIONS IN ELECTRONICS

→ S. CREATION

→ S. MOTION

→ S. DETECTION

→ S. MANIPULATION

SKYRMION CREATION

PRINCIPLE: OVERCOME A POTENTIAL BARRIER IN ORDER TO INTRODUCE A TOPOLOGICAL TRANSITION OF THE MAGNETIC TEXTURE

METHODS:

→ MAGNETIC FIELD ← EASY, POOR SCALABILITY

→ LOCAL HEATING ← NEED LOCAL LASER SOURCE, UNPRACTICAL

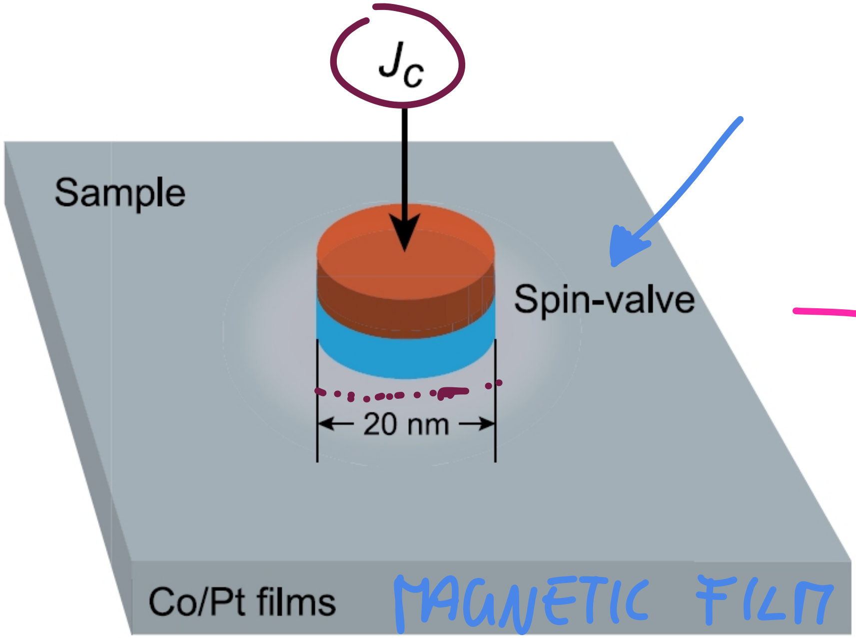
→ ELECTRICAL CURRENT

(COMBINATIONS OF THE 3)

ELECTRICAL CURRENT IS THE MOST USED AND HAS PRACTICAL APPLICABILITY

CURRENT INJECTED BY MEANS OF A SPIN VALVE

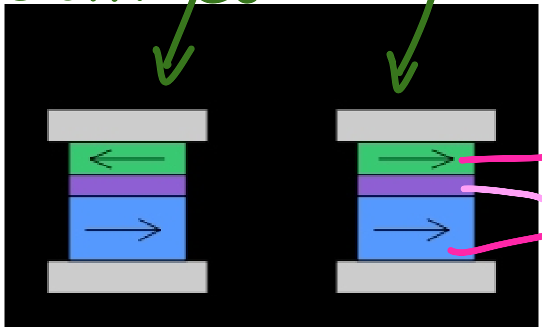
→ THE INJECTED CURRENT IS SPIN POLARIZED



AN ISOLATED → SKYRMION IS CREATED

HIGH RESISTANCE

LOW RESISTANCE



SPIN VALVE

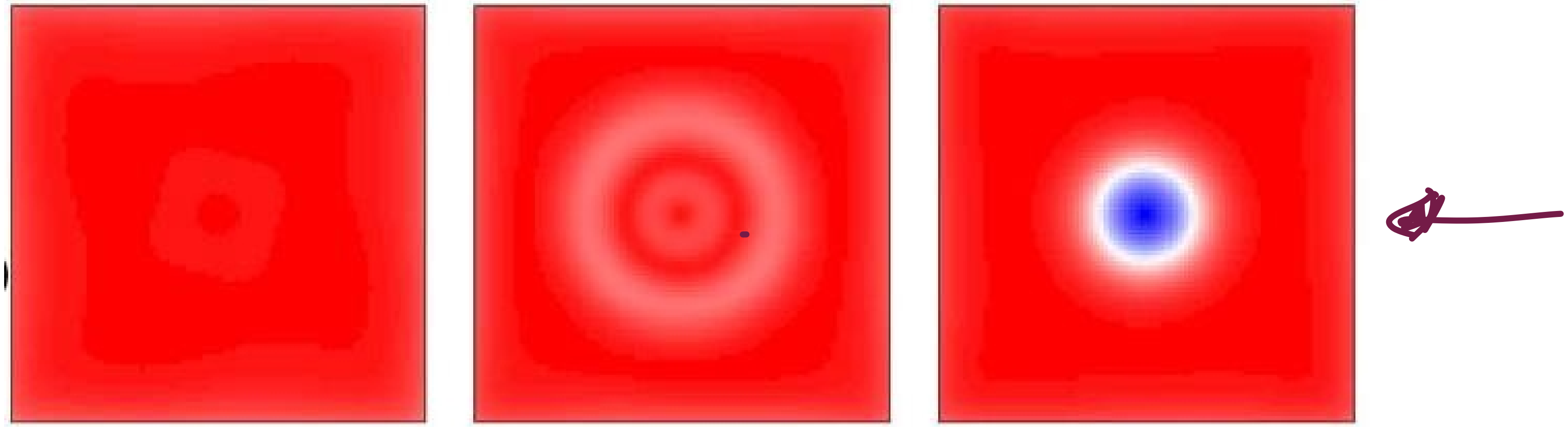
MAGNETIC LAYER

NON MAGNETIC LAYER, IF CONDUCTIVE → MTJ

1 LAYER HAS FIXED MAGNETIZATION (PINNED)

THE OTHER LAYER IS FREE

NO SK. CREATION SK. ↓ CREATED



CREATION TAKES TIME PRODUCING A SHORT DELAY AT A GIVEN CURRENT DENSITY

e.g. 0.04 ms @ $9 \cdot 10^{18}$ A/cm^2

→ DELAY
→ CURRENT DENSITY } IMPORTANT PARAMETERS FOR CREATION

cannot be too high to avoid other issues in the circuit

ANOTHER METHOD FOR CREATION (UNCONVENTIONAL) IS GENERATING A SK. AS A TOPOLOGICAL TRANSITION FROM A DOMAIN WALL, USED IN SKYRMION LOGIC

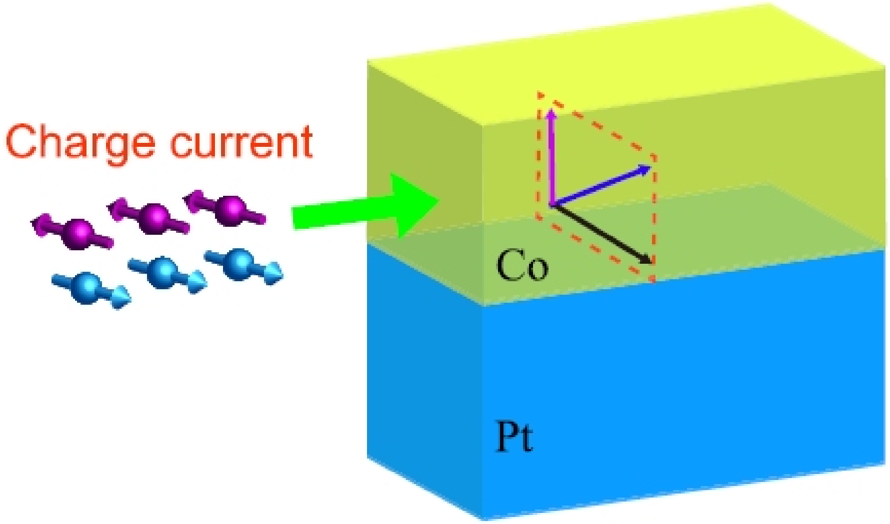
SEE LATER (also a VIDEO)

SKYRMION MOTION ALONG A NANOTRACK → OBTAINED BY A CURRENT

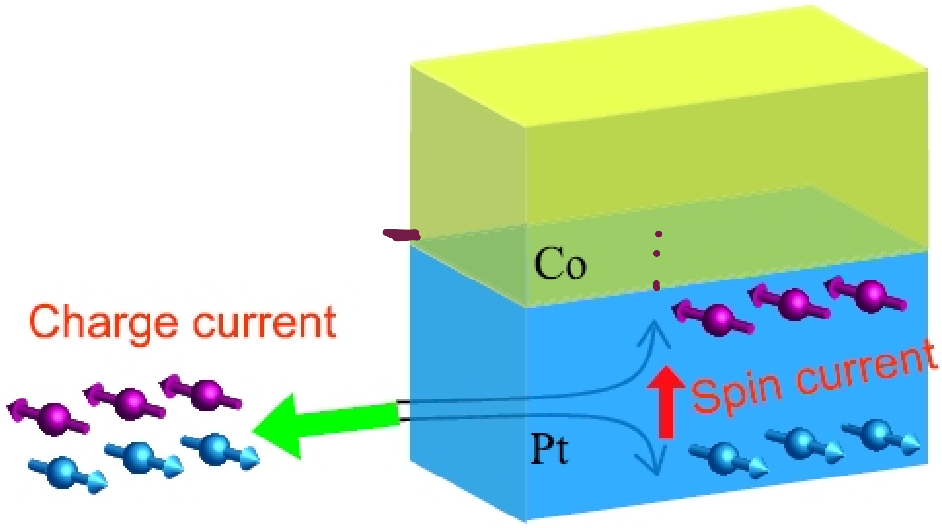
VIA :

- SPIN TRANFER TORQUE (STT)
- SPIN HALL EFFECT (SHE)

STT



SHE



THE SPIN-POLARIZED CURRENT IS INJECTED IN-PLANE ALONG THE NANOTRACK, A FERROMAGNETIC MATERIAL. CHARGES, WITH SAME SPIN, TRANSFER THEIR ANGULAR MOMENTUM TO CHARGES IN THE LAYER, PRODUCING A FLIP IN THE MAGNETIZATION

A CURRENT IS INJECTED IN A HEAVY METAL UNDER THE NANOTRACK, THIS SEPARATE CHARGES WITH DIFFERENT SPINS → SPIN HALL EFFECT.

A SPIN-POLARIZED CURRENT IS INJECTED IN THE NANO-TRACK

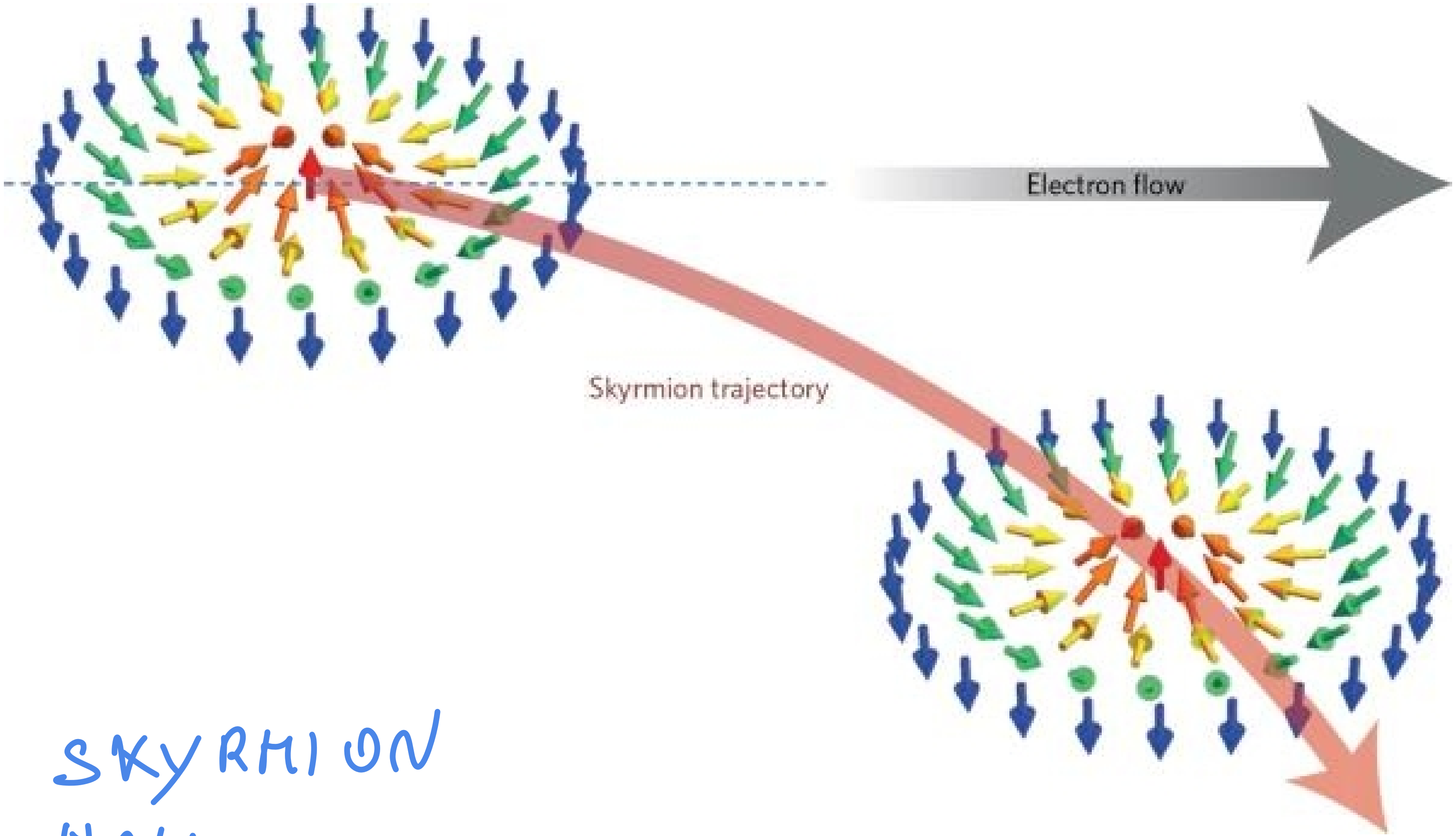
ONCE THE CURRENT IS INJECTED IT STIMULATES SKYRMION MOTION

→ WITH A VELOCITY LONGITUDINAL TO THE NANO TRACK PROPORTIONAL TO THE CURRENT

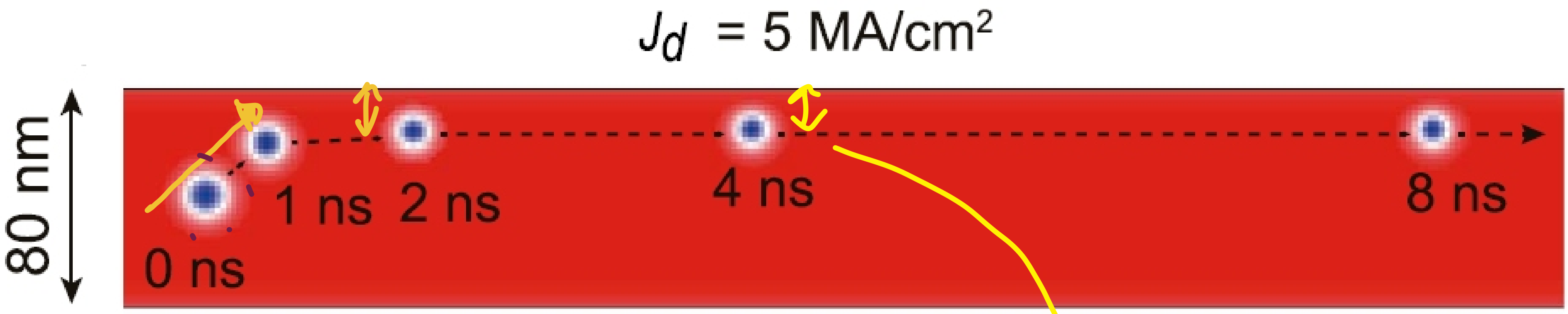
→ AT THE BEGINNING THE SK. HAS A TRANSVERSAL VELOCITY IN ADDITION TO THE LONGITUDINAL

↳ DUE TO MAGNUS FORCE, INTRINSICALLY INCREASES WHEN SK. MOVES

↳ CALLED SKYRMION HALL EFFECT



SKYRMION
HALL
EFFECT



SKYRMION MOTION TRAJECTORY

THE TRANSVERSE MOTION STOPS AT SOME DISTANCE FROM THE EDGE

DUE TO REPULSIVE INTERACTION FORCE VITH THE EDGE

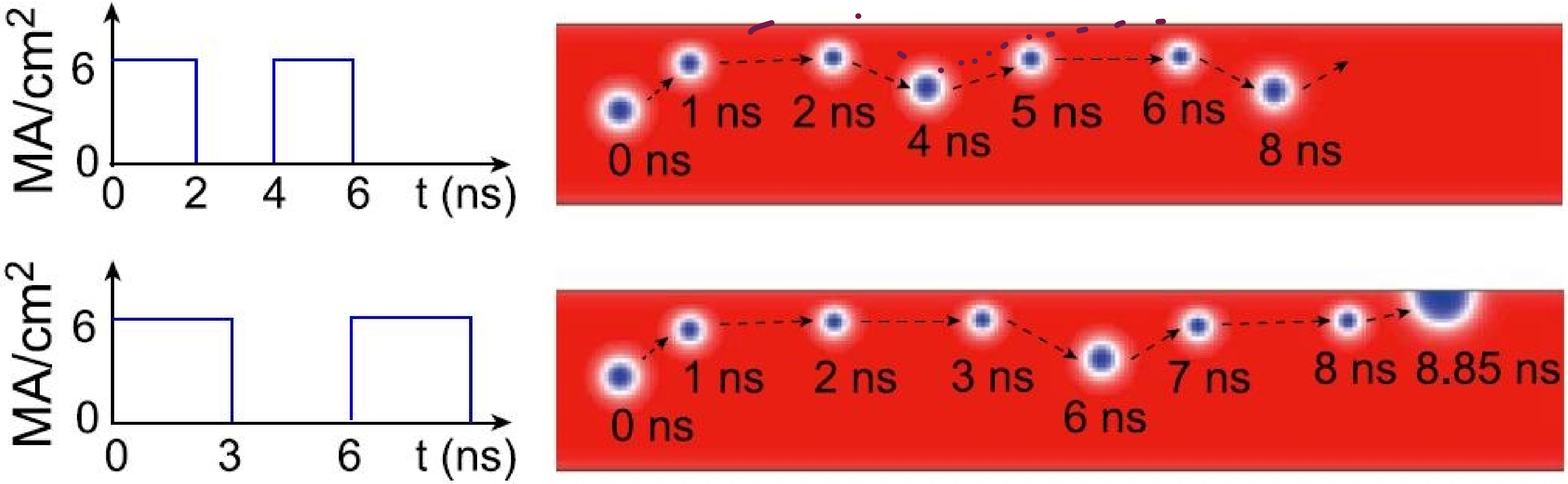
- IF THE CURRENT IS TOO BIG THE SK. COULD BE ANNIHILATED

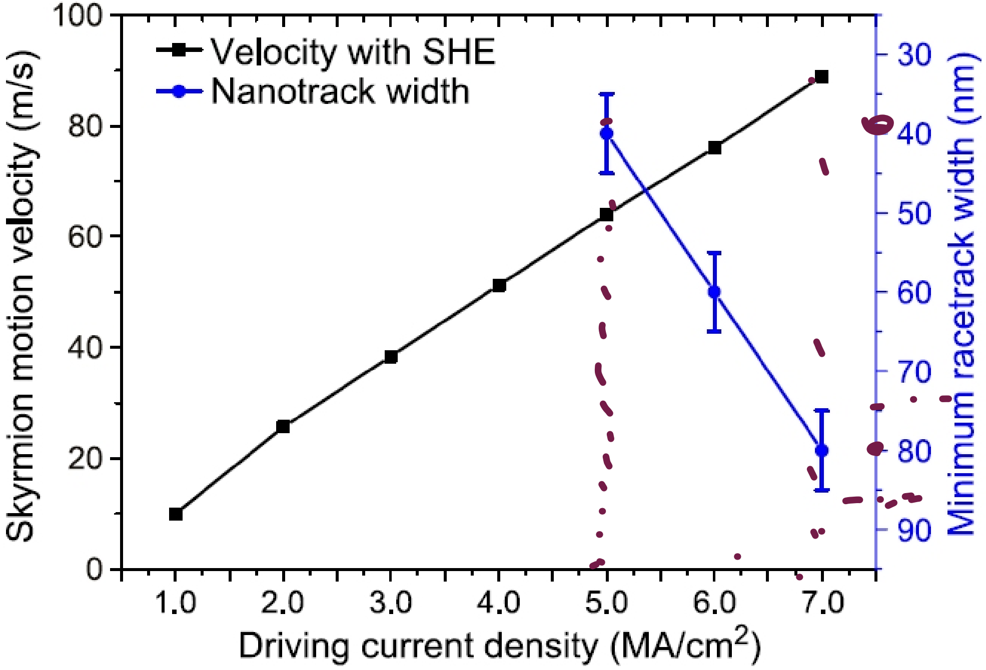
(see later VIDEO)

IF THE CURRENT IS SWITCHED OFF THE SK. MOVES AWAY FROM THE EDGE TO THE CENTER OF THE NANOTRACK (repulsive interaction with the edge)

→ A CURRENT PULSE SEQUENCE INSTEAD OF A DC CURRENT IS MORE FAVORABLE FOR PRACTICAL USE (PWM)

→ A TRADE OFF BETWEEN CURRENT DENSITY, PWM, SK. MOTION VELOCITY, NANOTRACK WIDTH EXISTS, TO BE OPTIMIZED


MA/cm2
6
0
0
2
4
6
t (ns)
0 ns
1 ns
2 ns
4 ns
5 ns
6 ns
8 ns
MA/cm2
6
0
0
3
6
t (ns)
0 ns
1 ns
2 ns
3 ns
6 ns
7 ns
8 ns
8.85 ns


Velocity with SHE
Nanotrack width
Skyrmion motion velocity (m/s)
0
20
40
60
80
100
Minimum racetrack width (nm)
30
40
50
60
70
80
90
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Driving current density (MA/cm2)

SKYRMION DETECTION

TOPOLOGICAL HALL EFFECT

(resistivity changes depending on local magnetization)

MAGNETO-RESISTANCE EFFECT

(MTJ)

→ BETTER IN PRACTICAL APPLICATION

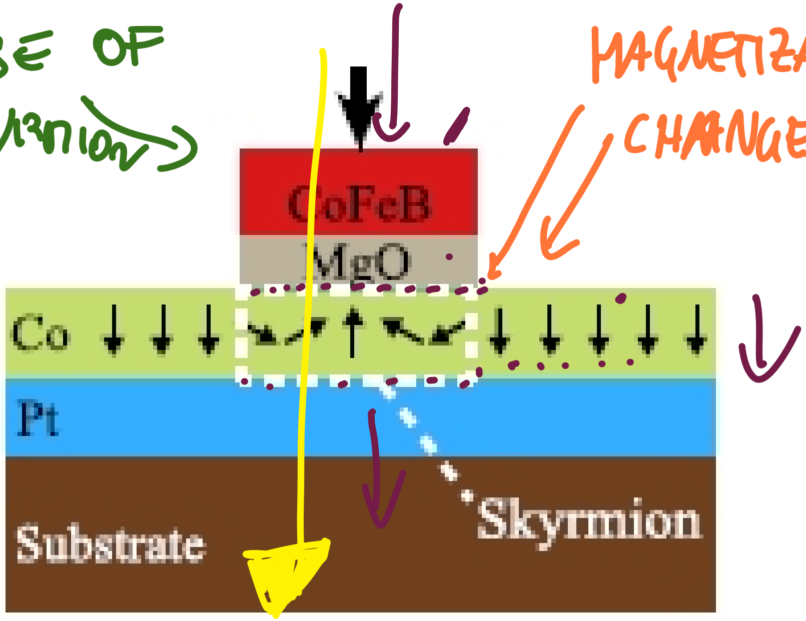
A CURRENT FLOW THROUGH THE MTJ

ALLOWS TO SENSE THE CONDUCTANCE CHANGE

← MATERIAL CONDUCTANCE CHANGES ←

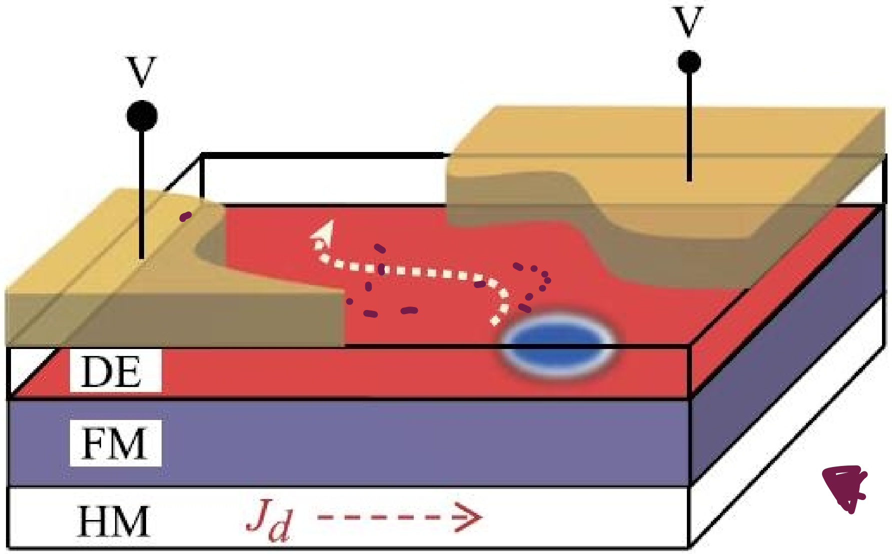
SISE OF SKYRMION

MAGNETIZATIO CHANGES



SKYRMION MANIPULATION

→ SPEED & DIRECTION CAN BE CONTROLLED



AN ELECTRIC FIELD CONTROLLED MAGNETIC ANISOTROPY CAN BE CREATED TO FAVOUR A LOWER OR HIGHER ENERGETIC STATES

PLACING ELECTRODES ALONG A NANOTRACK A SKYRMION CAN BE MOVED STEP-BY-STEP. IT CAN BE GUIDED ALONG IRREGULAR PATH WITH CONTROLLABLE SPEED.

VIDEOS

SIMULATIONS BY G. PALMERI (former student)
MUMAX

A- SQUARE, 1 SK., MAGN. FIELD ↗ ↘ ⇒ SK. ↗ ↘

B- SK. MOVEMENT UNDER J, NO TRACK EDGES

BT- LIKE B, WITH $T = 300K$, J ↓ to avoid explosion

C- SQUARE, 1 SK, $T = 300K$, $J = 0$ ⇒ SK MOVES

D- SK MOVEMENT UNDER J, EDGES PRESENT; J ↗ ⇒ SK. EXPLODES

E- WORDS IN 2 TRACKS 111, 101 PROPAGATE AT CONSTANT SPEED
→ with these parameters in 100 μm ⇒ 1500 SK.
→ with maximum densities > 5500 SK. in 100 μm (in theory)

U- SK → DW + DOWNCONVERSION PNML

V- DW → SK (a bubble)

VT- like V, $T = 300K$, requires a magn field to stabilize

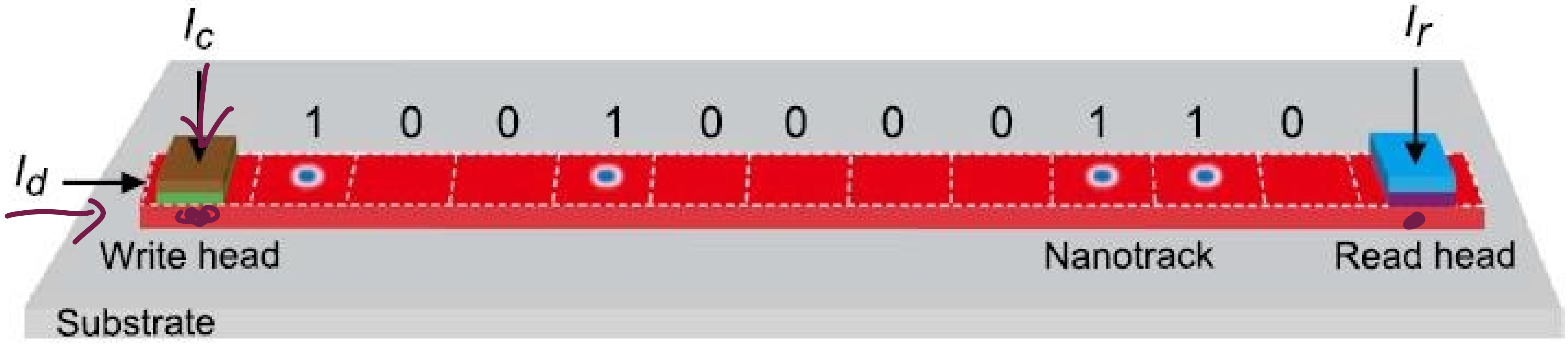
EXAMPLE OF APPLICATION : ① MEMORY ② LOGIC

SKYRMION BASED RACETRACK MEMORY

- → VERY HIGH PACKAGE DENSITY DUE TO NANOSCALE SIZE
- → VERY LOW ENERGY DUE TO LOW DEPINNING ENERGY
- → ROBUST DATA STABILITY IN PRESENSE OF DEFECT

↑ IN COMPARISON WITH DW RACETRACK

TYPICAL STRUCTURE



WRITE HEAD → SK. CREATION

NANOTRACK → SK. MOTION

READ HEAD → SK. DETECTION

BINARY DATA IS ENCODED AS

1 →	PRESENCE OF SK.
0 →	ABSENCE OF SK.

WRITE HEAD → inject I_C SPIN-POLARIZED

I_D DRIVING CURRENT TO MOVE THE SK.

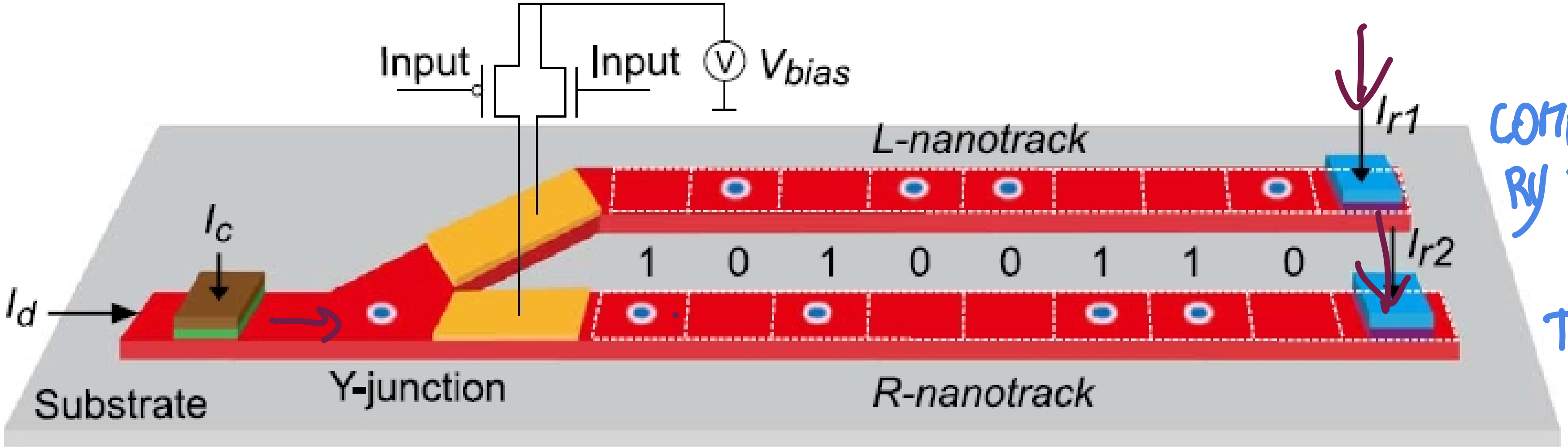
I_R SK. IS DETECTED THROUGH THE MTJ

A PROBLEM : MOTION & DETECTION ARE NOT ROBUST if PROCESS VARIATION AND THERMAL FLUCTUATION

→ in a long track the real sequence can be difficult to detect because spacing btw. 2 SK. may be variable

↓

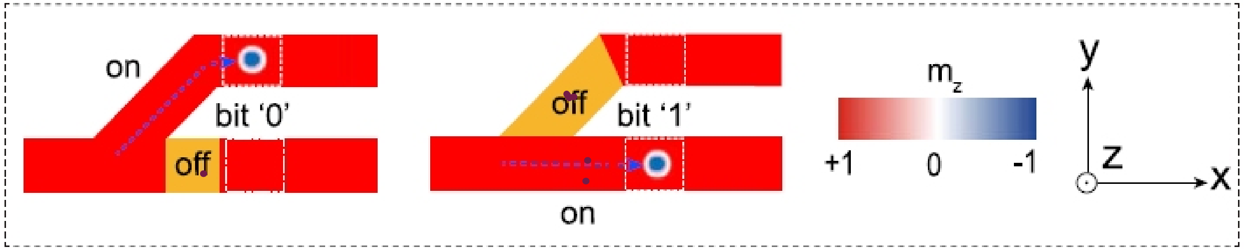
A POSSIBLE SOLUTION IS TO USE A DIFFERENTIAL STRUCTURE



COMPLEMENTA
RY TRACK

TRACK

THE SK. IS PRESENT ONLY ON ONE OF THE 2 TRACKS



R TRACK DISABLED

SK. MOVED TO L-TRACK

L TRACK DISABLED

SK. MOVED TO R-TRACK

READING IS DIFFERENTIAL:

- MORE ROBUST
- DENSITY IS SACRIFICED

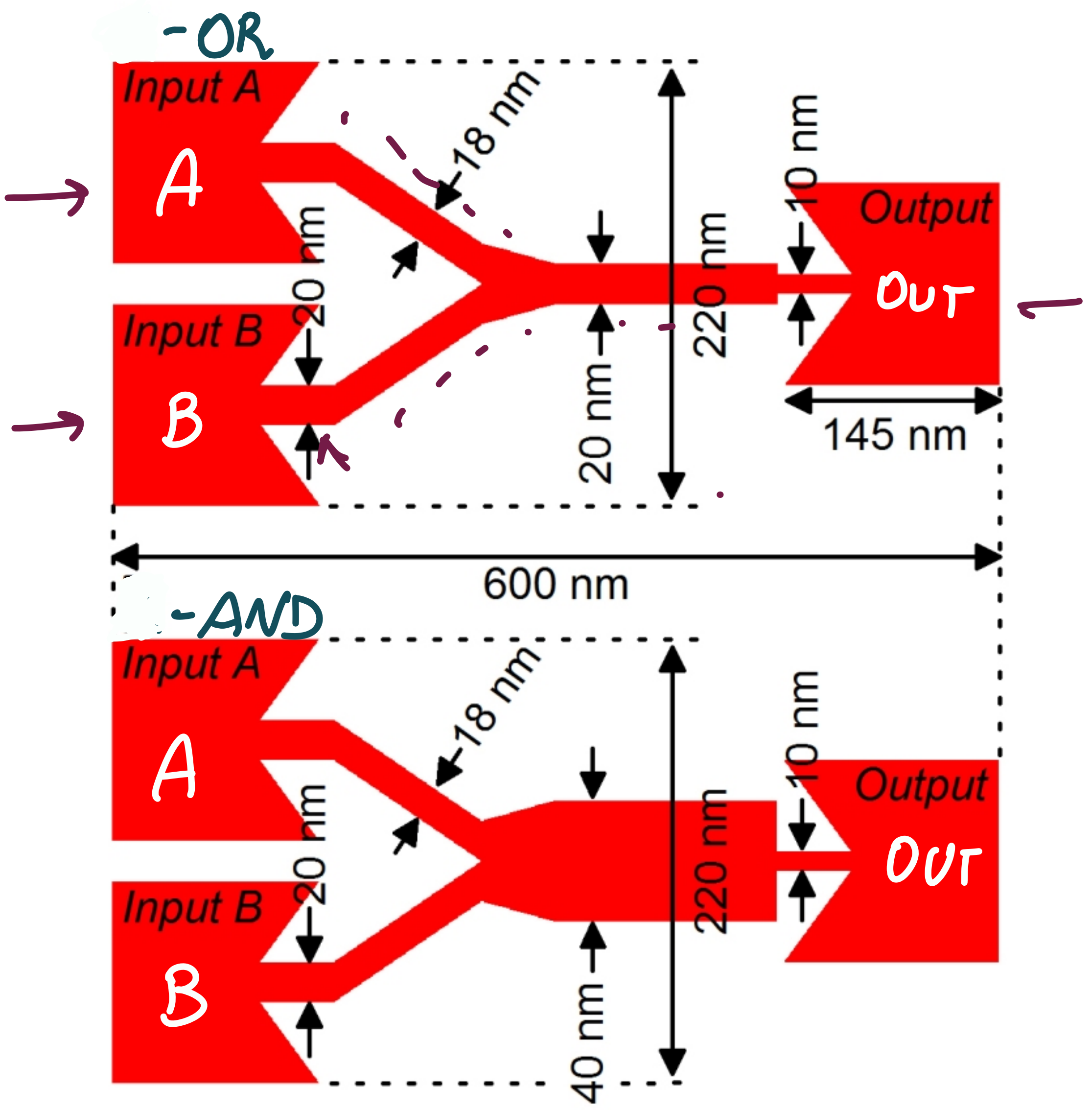
SKYRMION BASED LOGIC GATES

FUNDAMENTAL IS THE

Y-JUNCTION

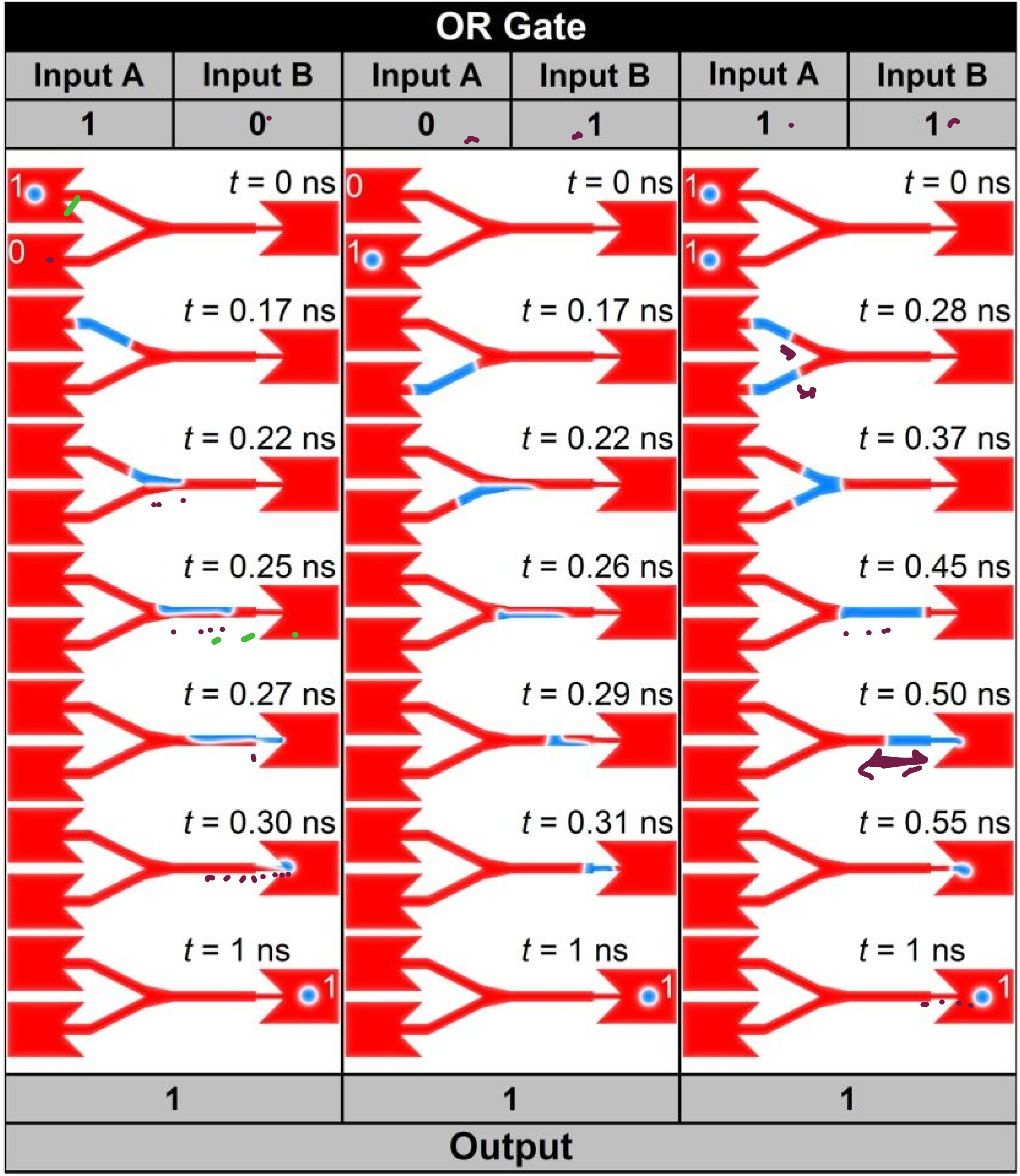
SK. PRESENT → LOGIC 1

SK. ABSENT → LOGIC 0



WORKING PRINCIPLE

CONVERSION OF A DW INTO A SKYRMION AND VICE-VERSA



1 SK FROM A , NO SK FROM B

→ 1 SK PASSES IN THE DW

→ 1 SK EXITS IN OUT

0 + 1 = 1

1 SK FROM A, 1 SK FROM B

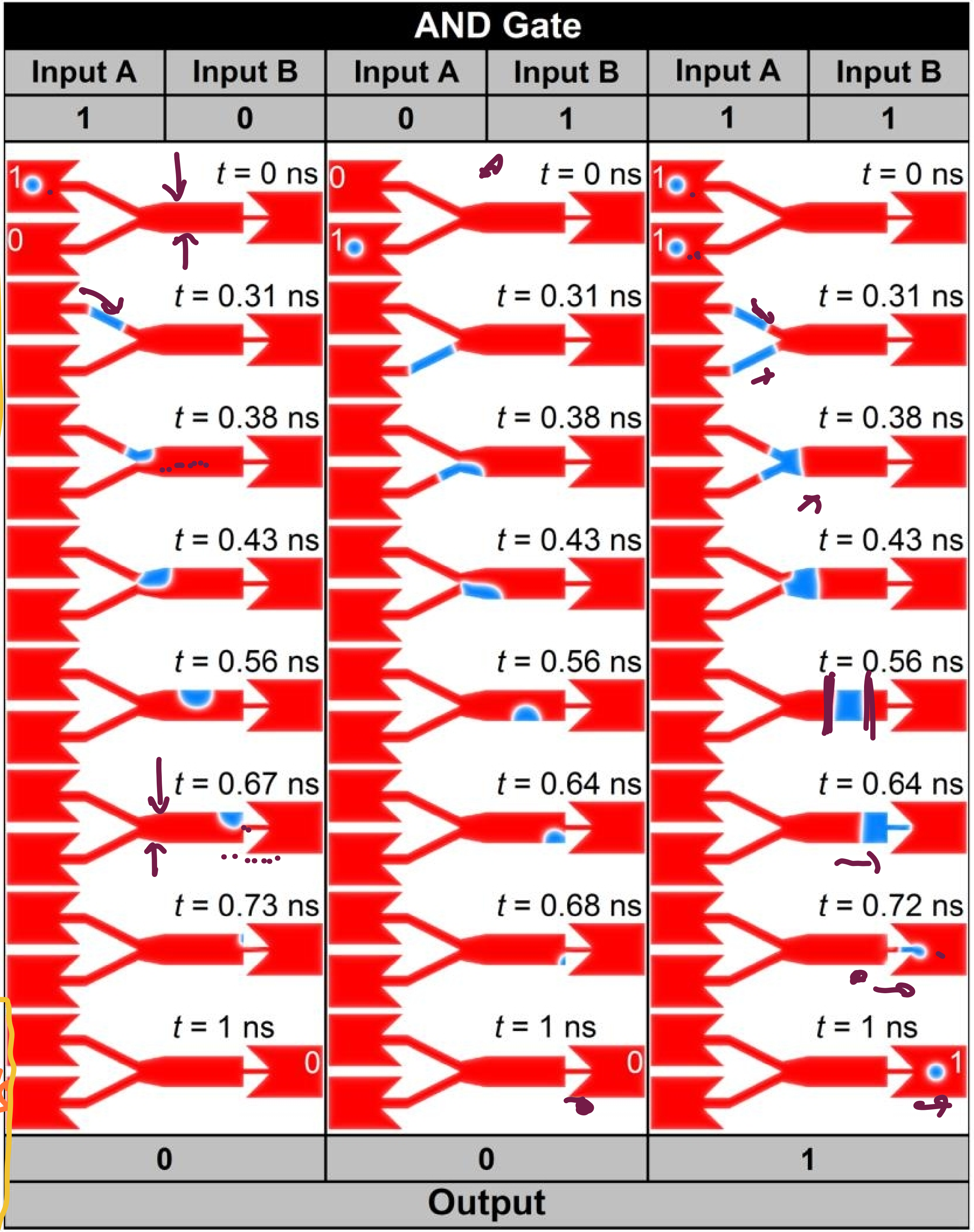
→ ONLY 1 SK EXITS ON THE OUT

CASE 0 · 0 = 0
IS LIKE OR CAS

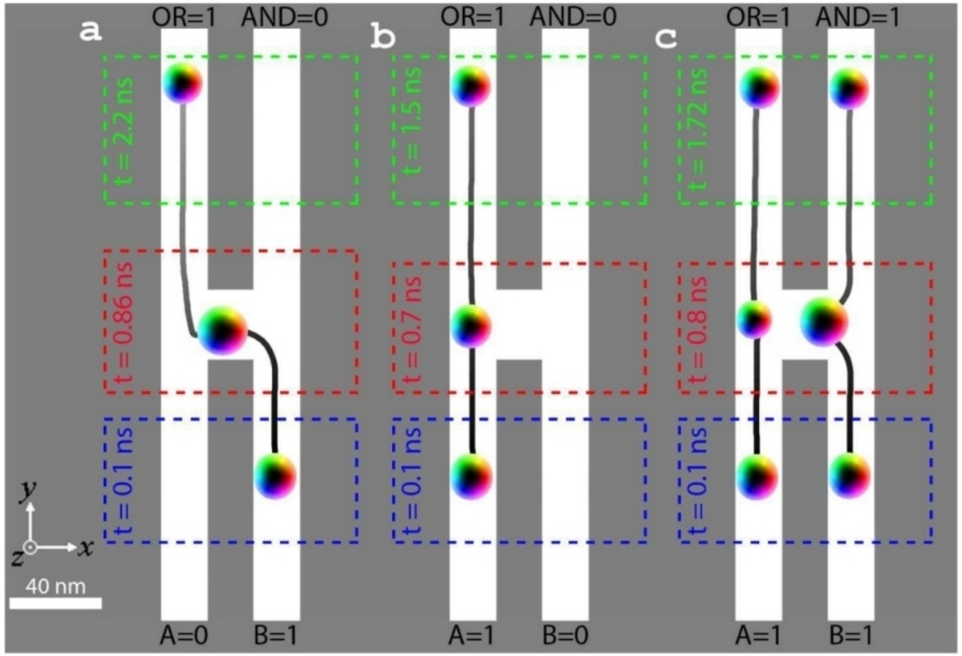
CASE 0 · 1 = 0
1 · 0 = 0

WHEN ONLY 1 SK IS PRESENT, IT MUST DISAPPEAR
→ THE CENTRAL CHANNEL IS ENLARGED
→ THERE ARE NOT THE CONDITIONS FOR CONVERSION IN SK.
→ SK. DISAPPEARS IN THE EDGES

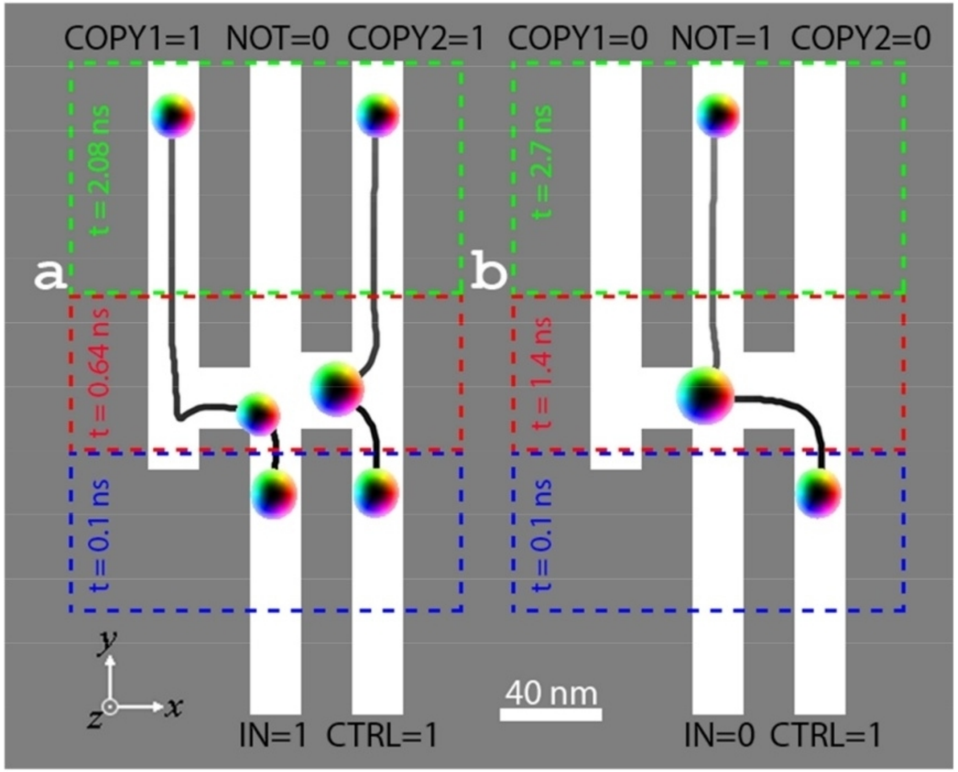
CASE 1 · 1 = 1
→ TOPOLOGICAL CONDITIONS ALLOW THE DW TO GENERATE A SK



ANOTHER METHOD TO CREATE LOGIC



(a)



(b)

CHALLENGES

- → MATERIALS : are to be searched for and optimum for process variations and controllability
- → MAGNUS FORCE : to avoid SK. destruction solution have to be found, e.g. adding local energy barriers
- → THERMAL STABILITY : search for thermally stable material to allow size reduction

FINAL REMARKS

HAPPY TO SHARE

IT HAS BEEN A PLEASURE