Center for Spintronic Materials, Interfaces, and Novel Architectures

Stochastic Nanomagnets as "P-bits" for Probabilistic Spin Logic (PSL)

Supriyo Datta, Purdue University

Theme 4

Cross Theme 5

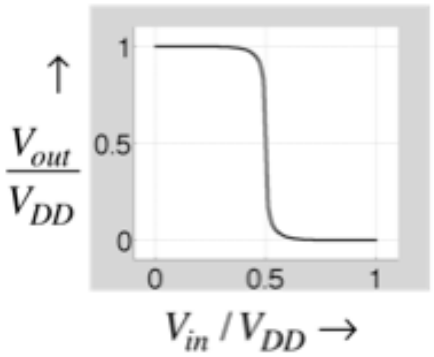
Acknowledgements: Dr. Kerem Camsari, Brian Sutton, Rafatul Faria (Purdue) Dr. Behtash Behin-Aein (GF)

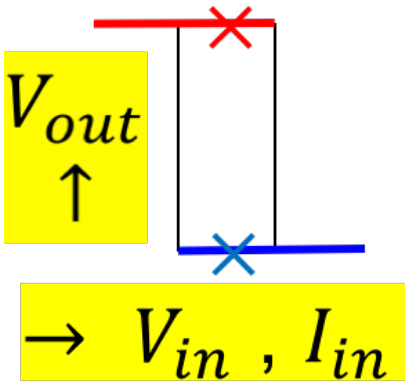
C-SPIN

STARnet

CMOS Inverter "Volatile"

Spin Logic "Non- volatile"





$$\tau = \tau_0 \times \exp\left(\frac{\Delta E}{kT}\right)$$

$\Delta E \sim 50\ kT$ retention time ~yrs

$\Delta E \sim 15\ kT$, retention time ~ ms

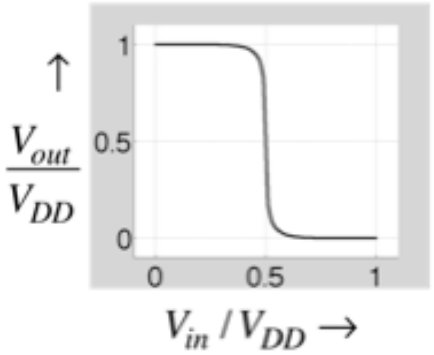
$\Delta E \sim 1\ kT$, retention time ~ ns

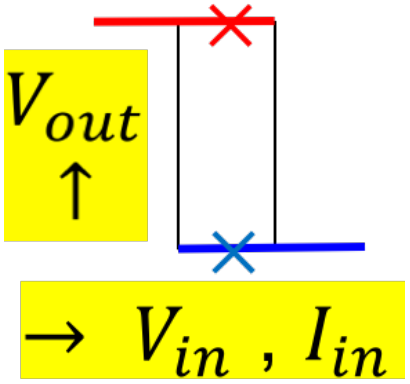
CMOS Inverter "Volatile"

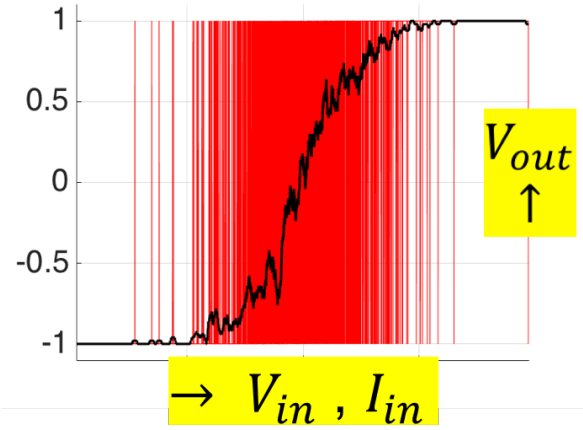
Spin Logic "Non- volatile"

Probabilistic Spin Logic (PSL)

Low ΔE magnets







Biased RNG

$$\tau = \tau_0 \times \exp\left(\frac{\Delta E}{kT}\right)$$

$\Delta E \sim 50\ kT$ *retention time ~yrs*

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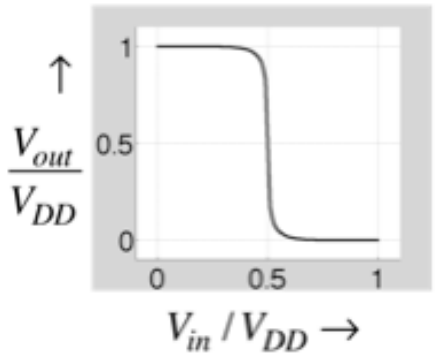
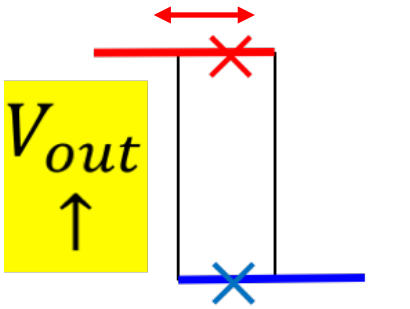
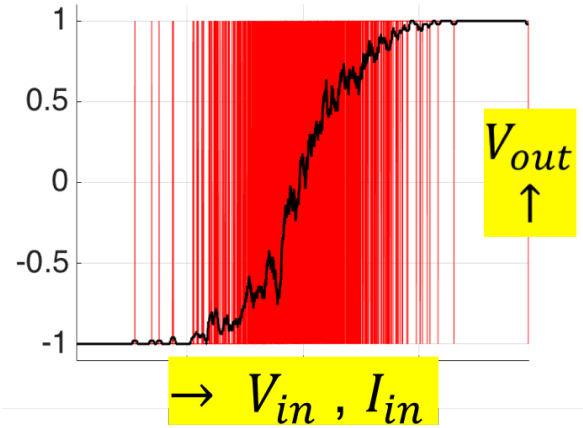


$100\ \mu A$



$1-2\ \mu A$



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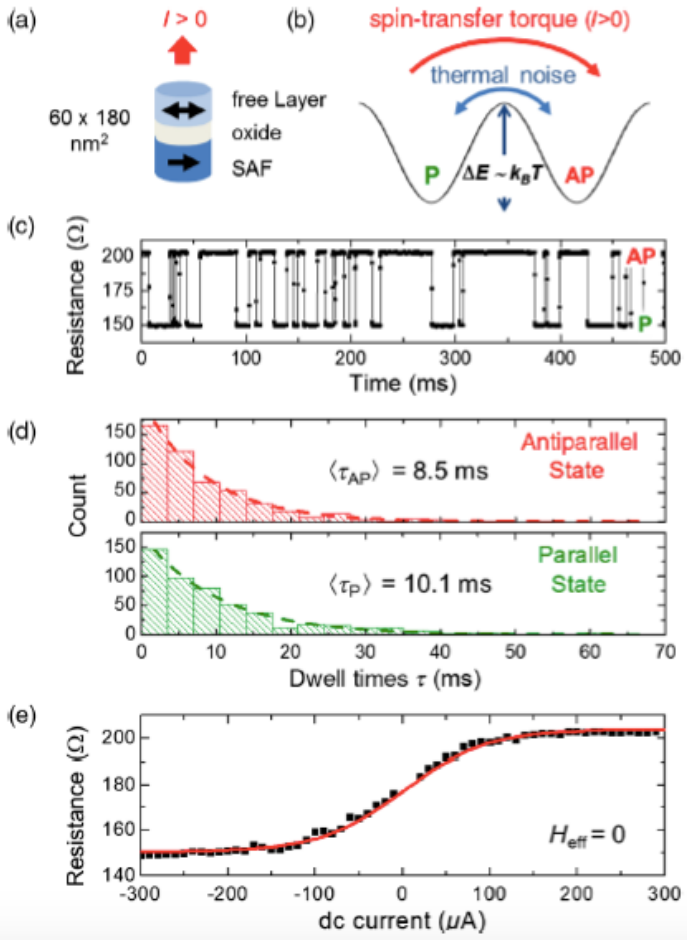
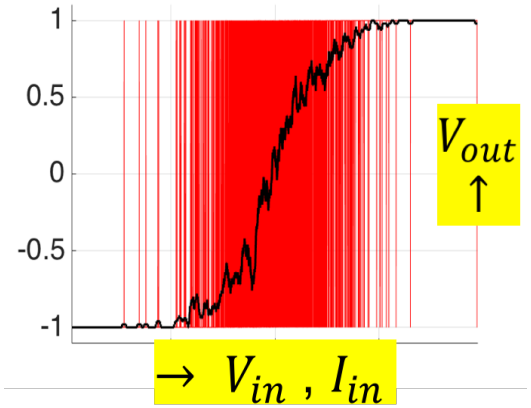
Similar Results on PMA
Majetich group, CSPIN

Experiments: Stochastic MTJ

IMA: Grollier et al. PRA 2014



Building Block for PSL



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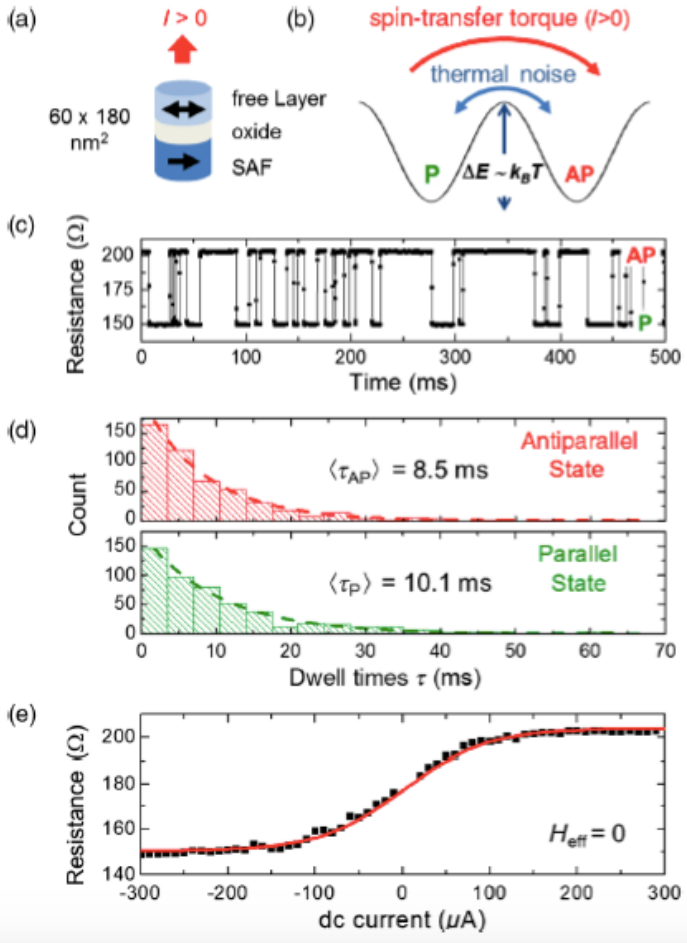
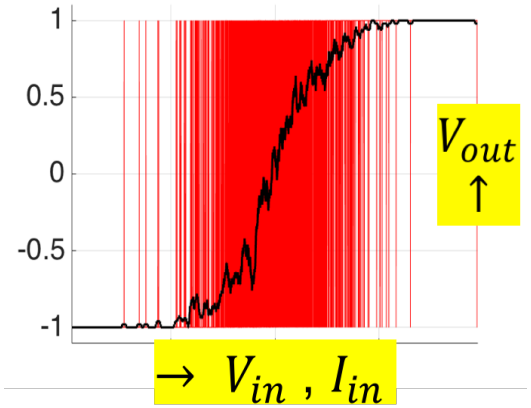


$Low\ \Delta E\ magnets$

MTJ

$$I_{in} \rightarrow m \rightarrow R$$

Building Block for PSL



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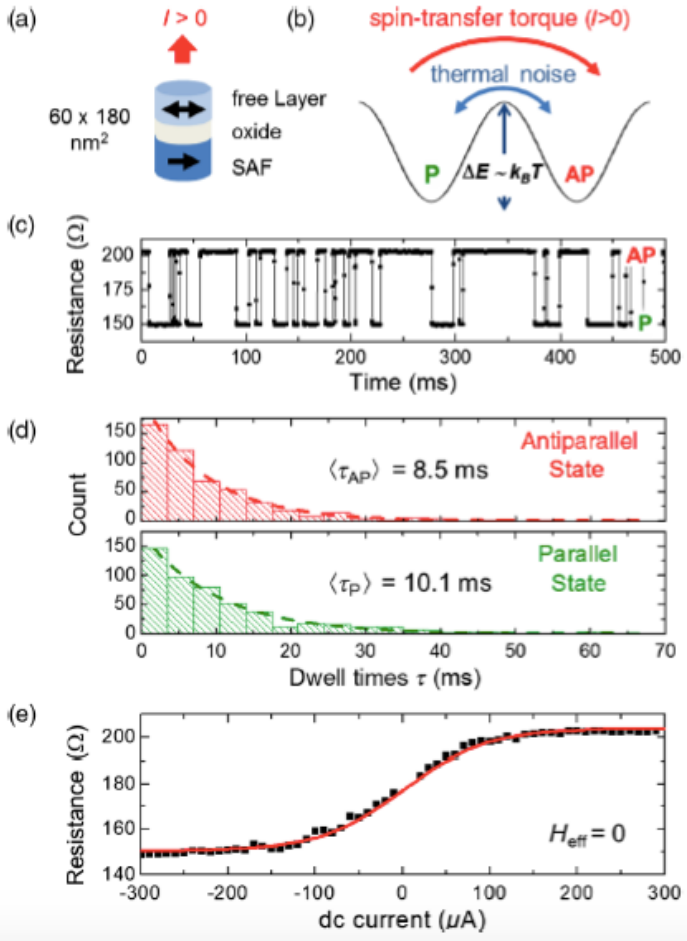


$Low\ \Delta E\ magnets$

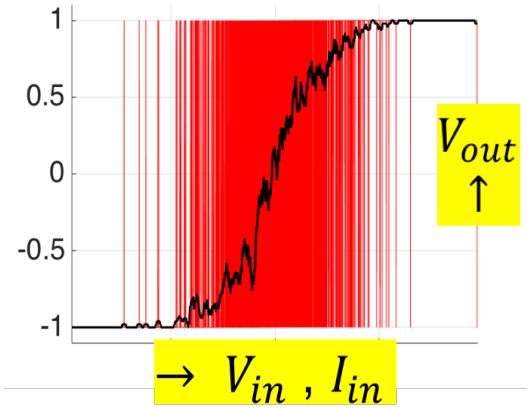
MTJ

$$I_{in} \rightarrow m \rightarrow R$$

"Read" ↓

$$I \leftarrow V$$

Building Block for PSL



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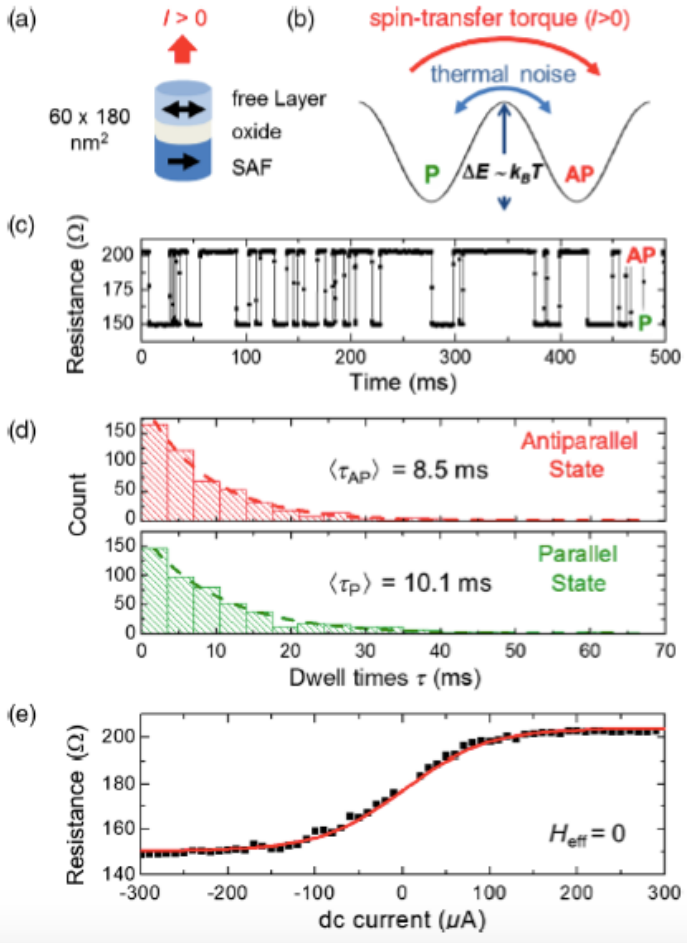

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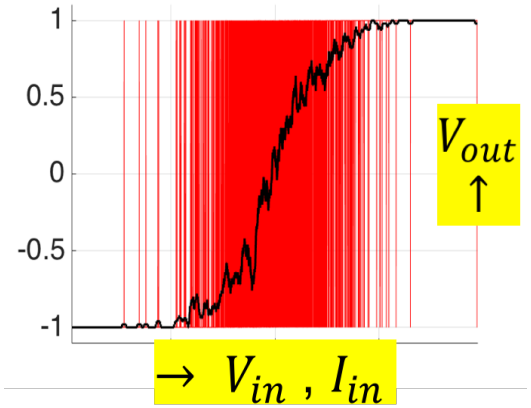
V

Building Block for PSL



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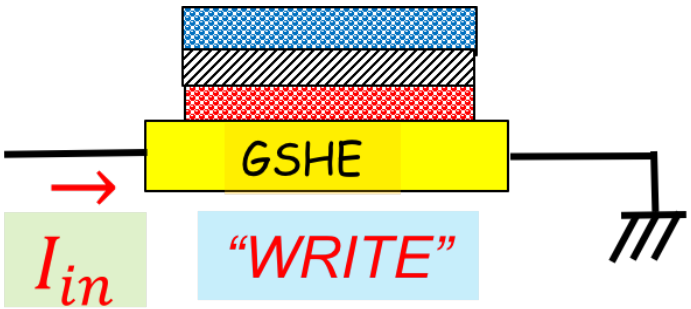

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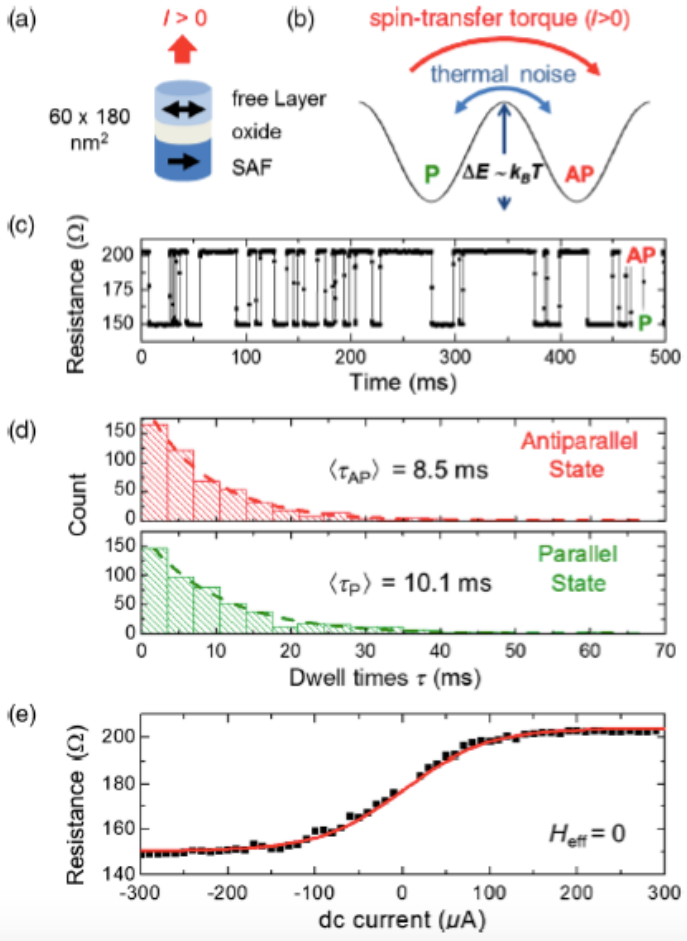


$Low\ \Delta E\ magnets$

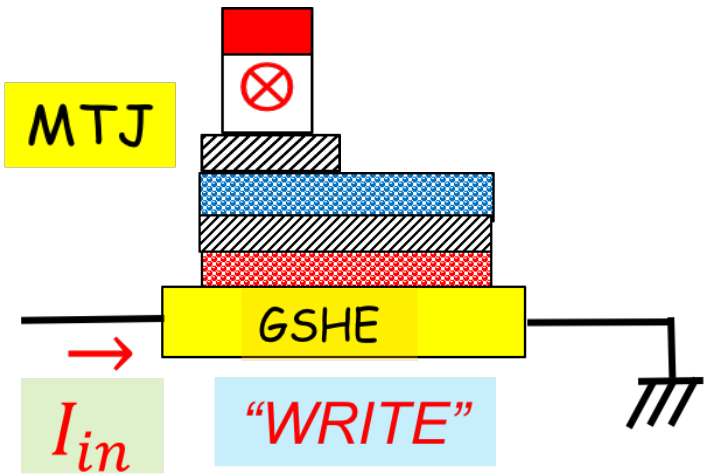
MTJ

$$I_{in} \rightarrow m \rightarrow R$$

"Read" $\downarrow$

V

Building Block for PSL



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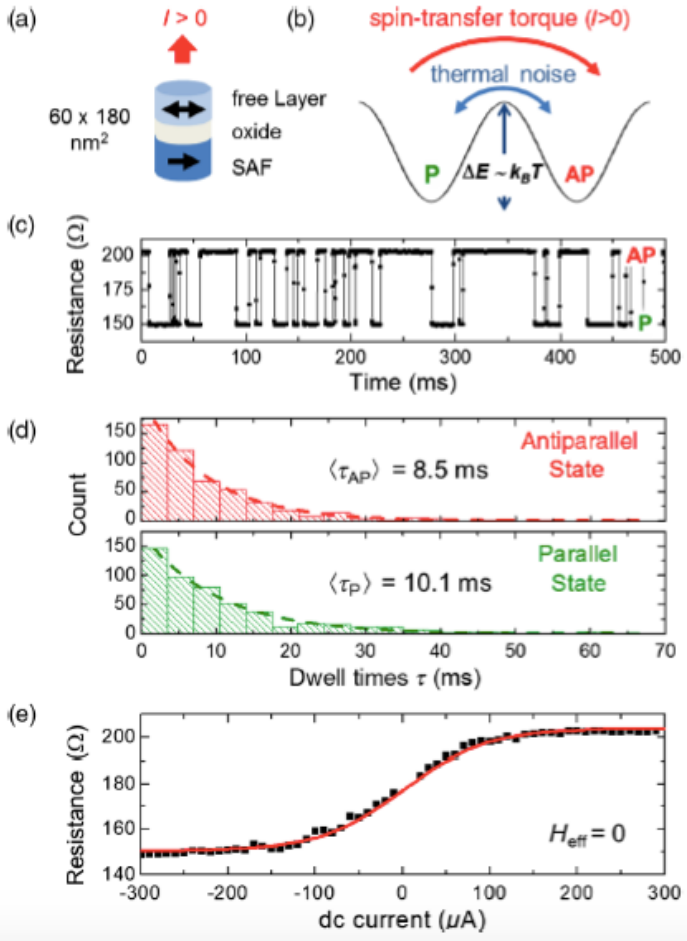

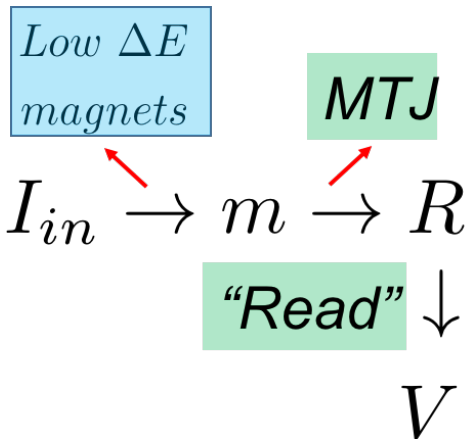

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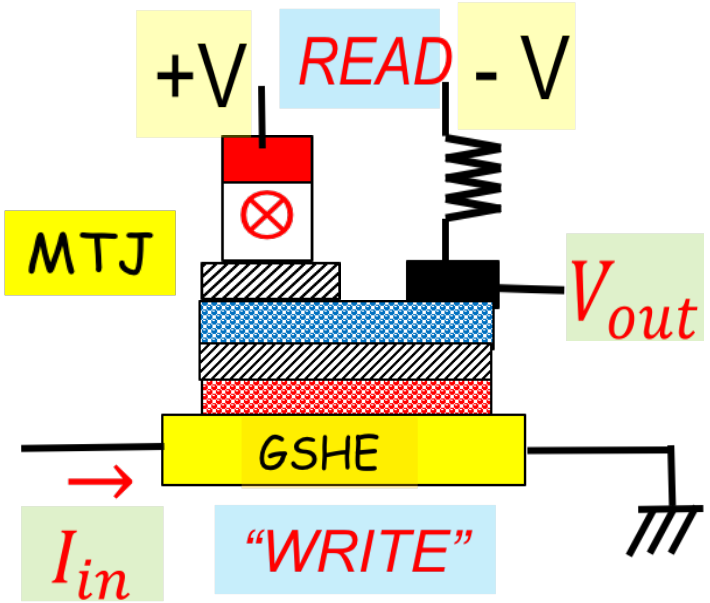
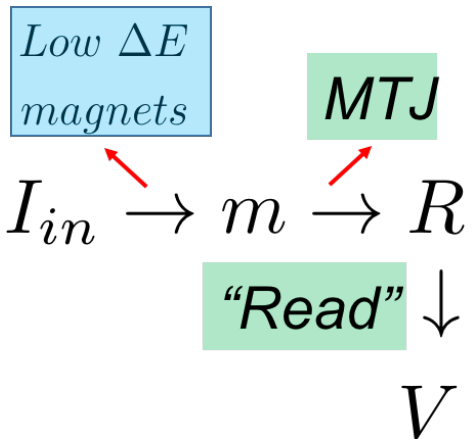


Building Block for PSL

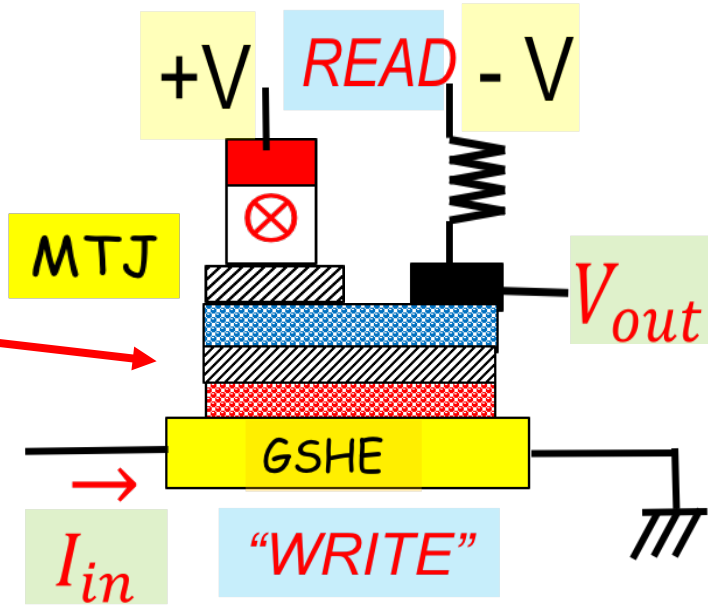
Similar to CSL
(INDEX Center)



- Spin switch (SS)
  Datta et al. APL 2012

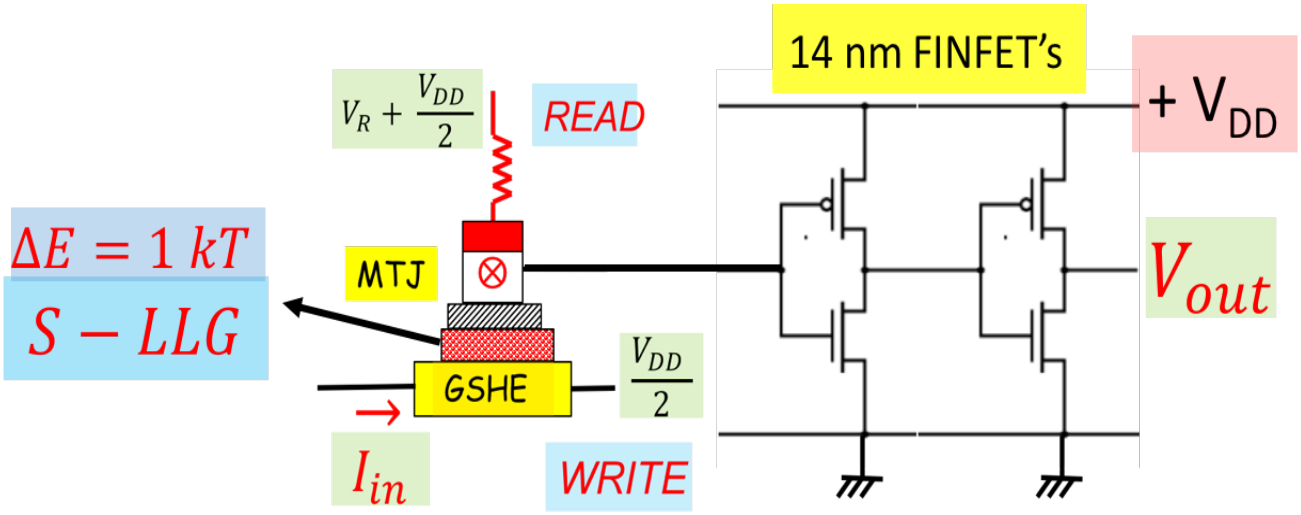
- SS-Neural network
  Vinh et al. APL 2014

But with $Low\ \Delta E$ $magnets$



Design using CMOS

PTM from ASU



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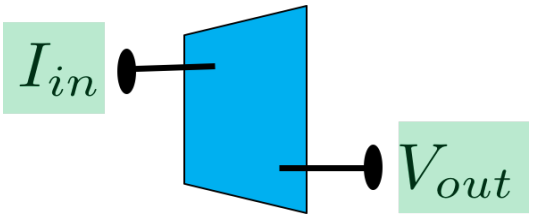
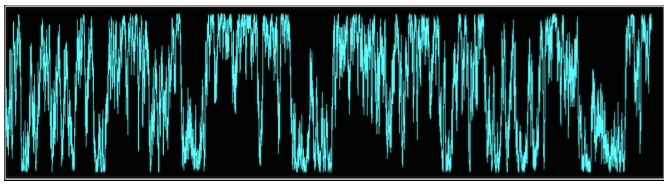
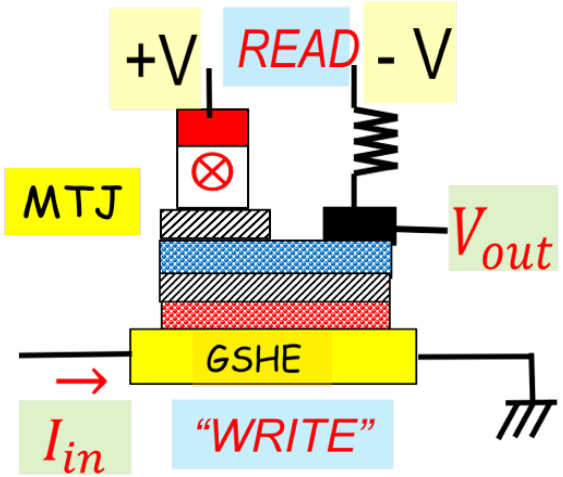




SPICE Simulation

Design without CMOS



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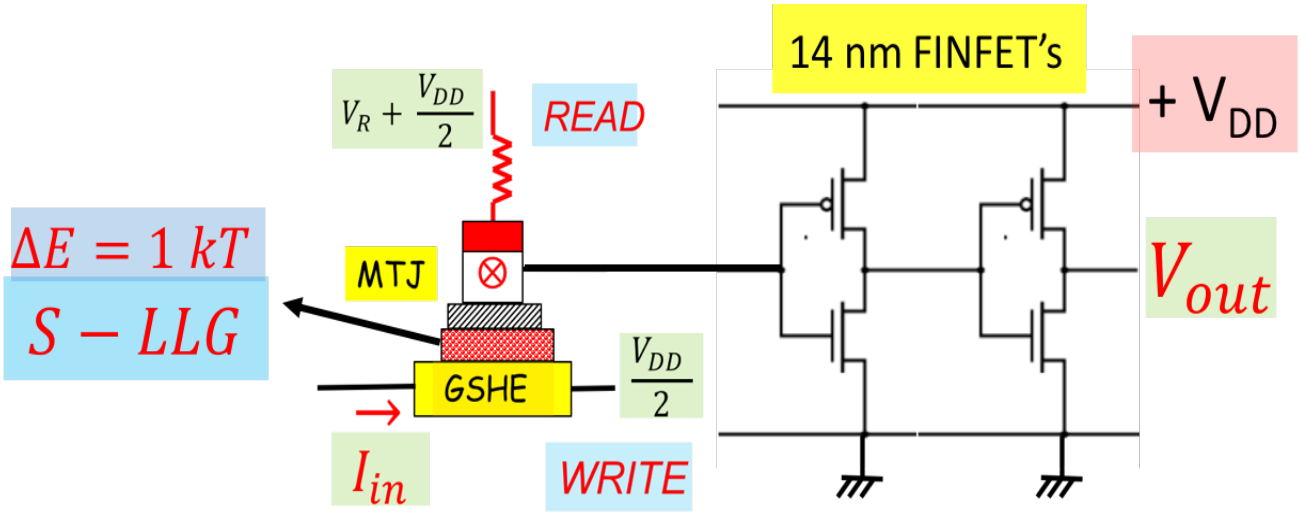

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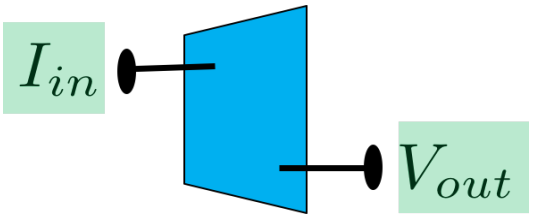

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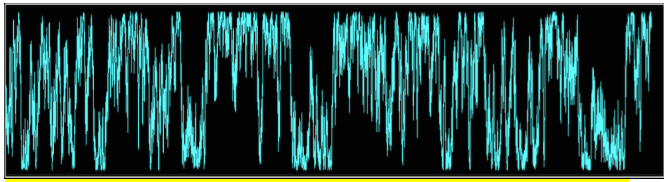

$Low\ \Delta E\ nanomagnets\ provide\ biased\ RNG$

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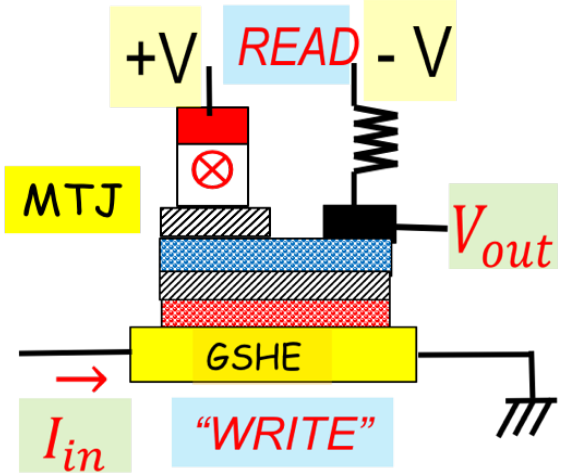
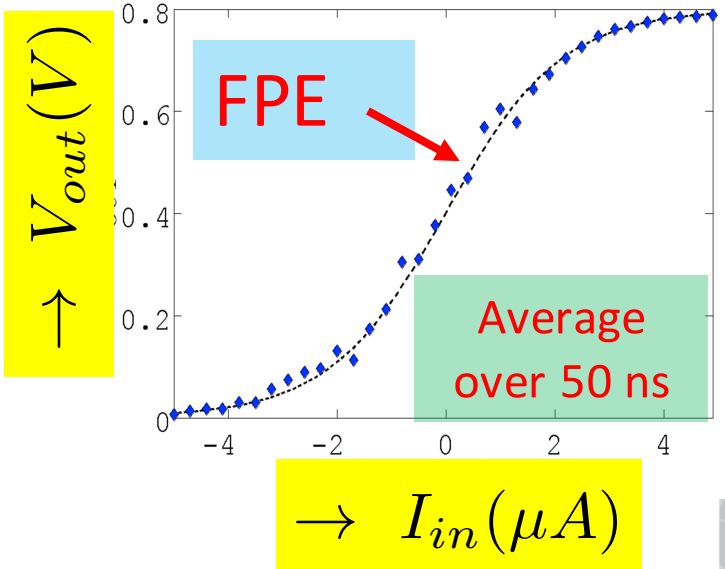
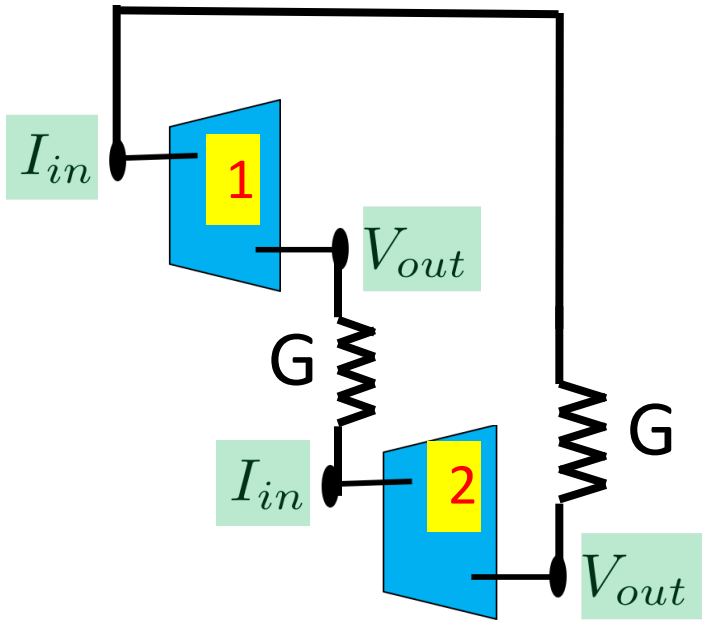
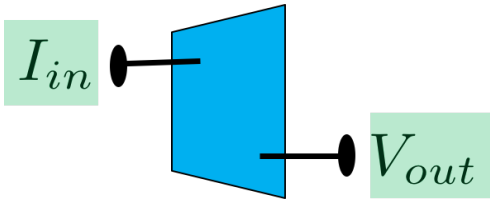




Interconnecting the blocks





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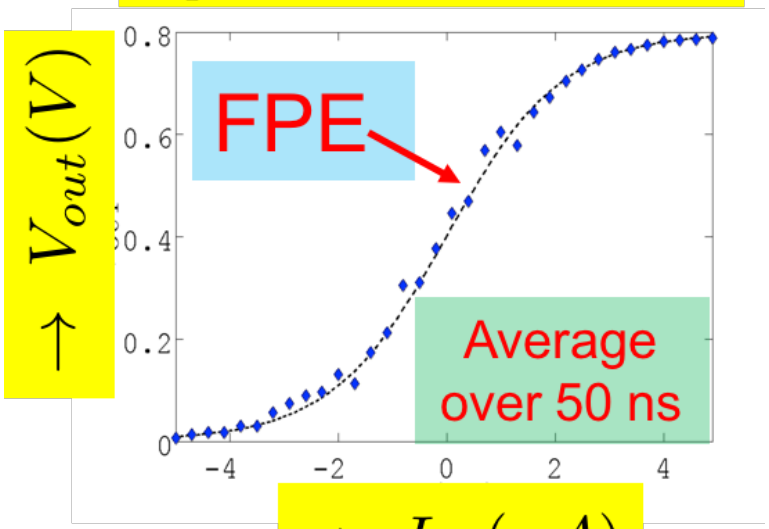

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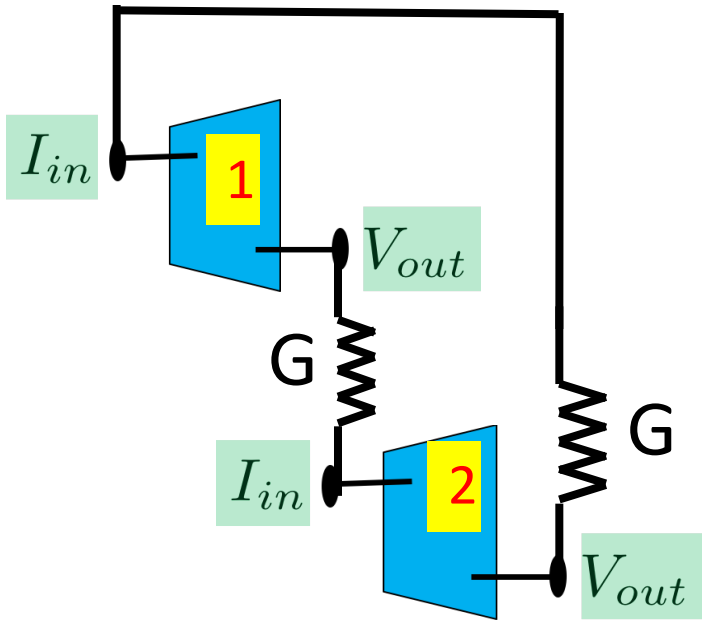
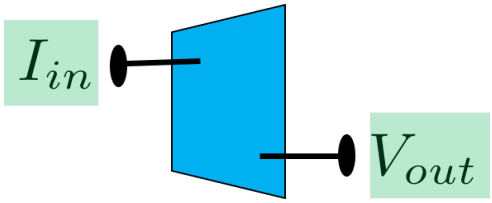
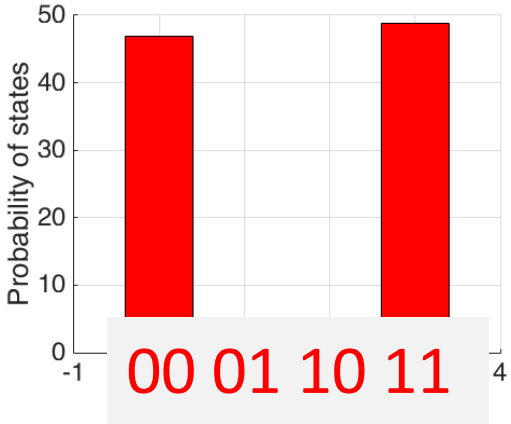
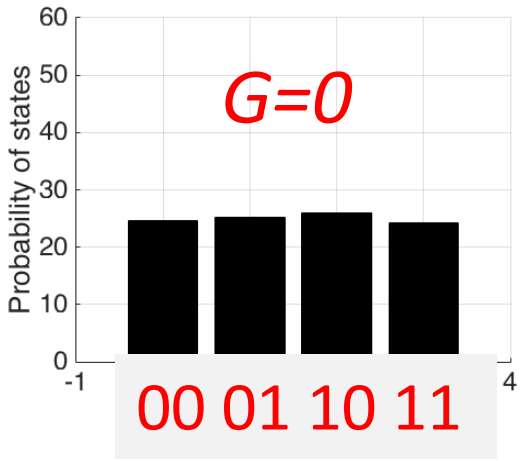




COPY GATE





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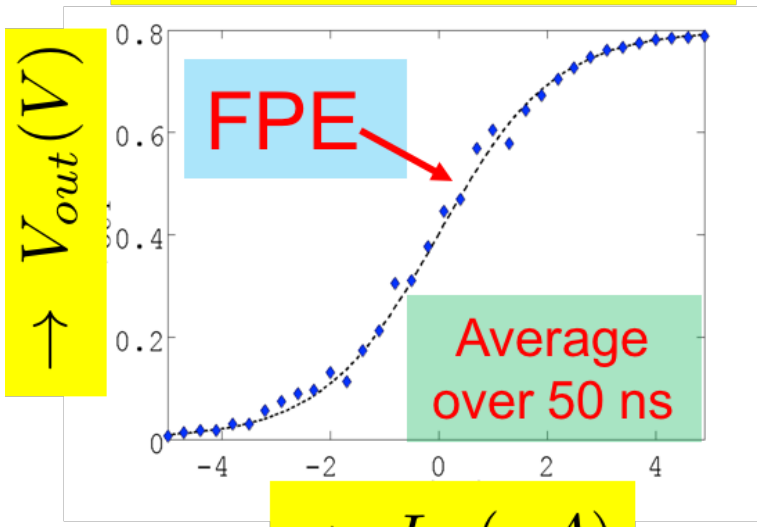

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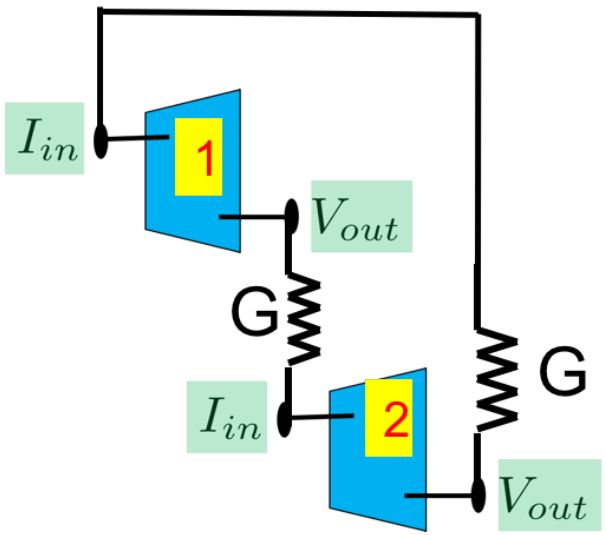
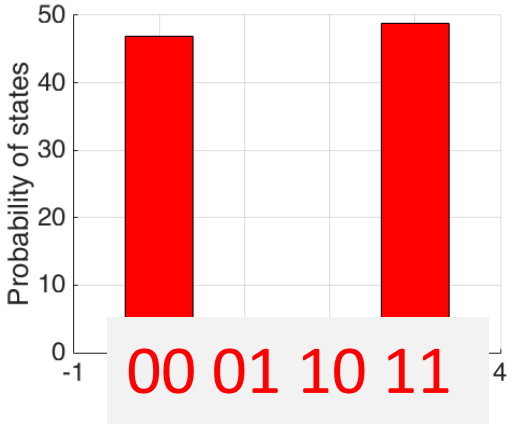
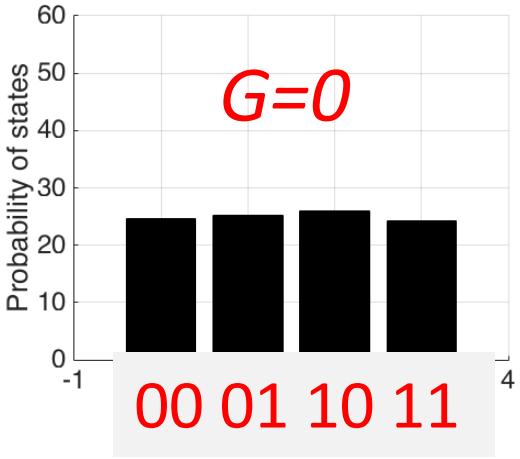


$$\frac{1}{G} \sim \frac{1\ V}{1\ \mu A} \sim 1\ M\Omega$$

COPY GATE





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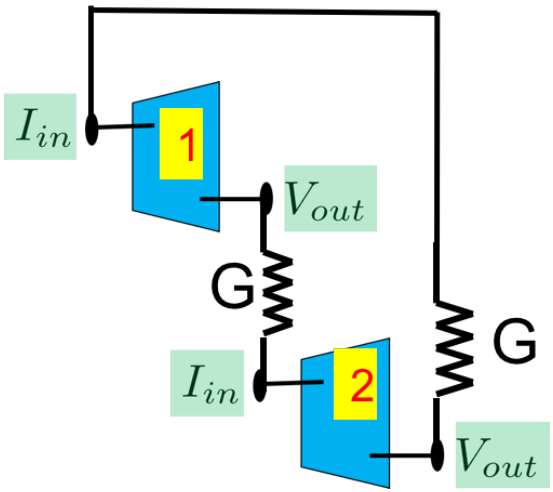
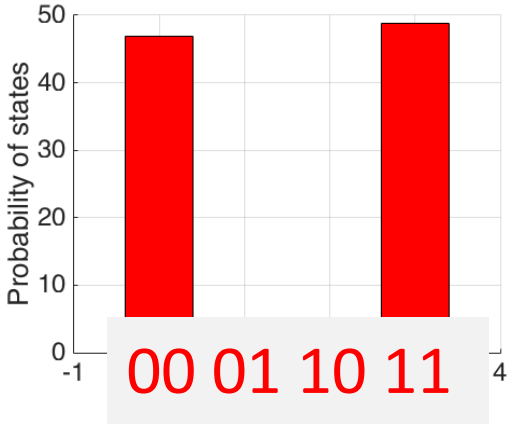
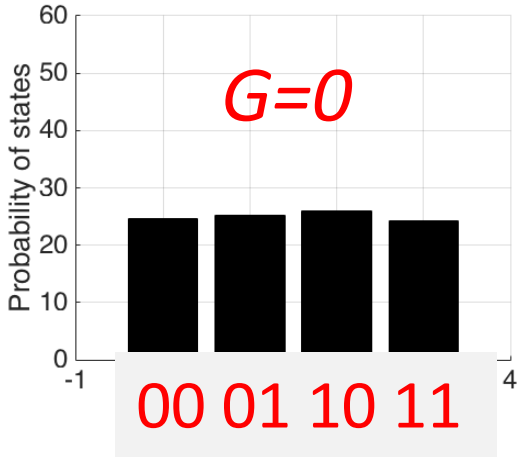


$$\frac{1}{G} \sim \frac{1\ V}{1\ \mu A} \sim 1\ M\Omega$$

$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = \mathsf{G} \begin{bmatrix} 0 & +1 \\ +1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

COPY GATE





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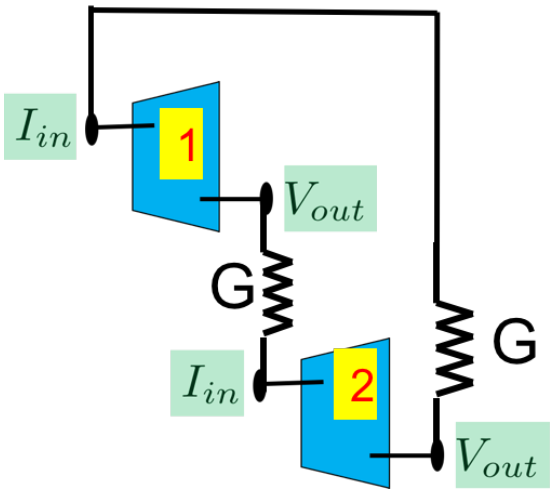

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$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = G \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

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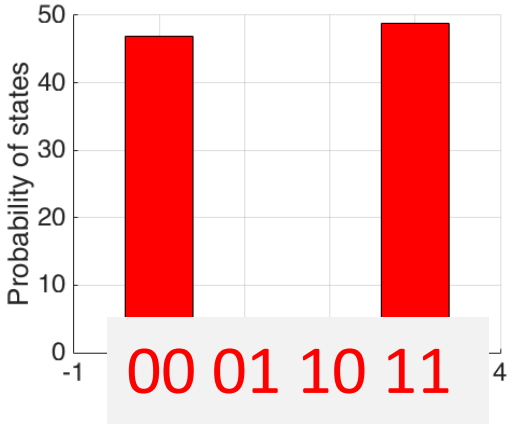

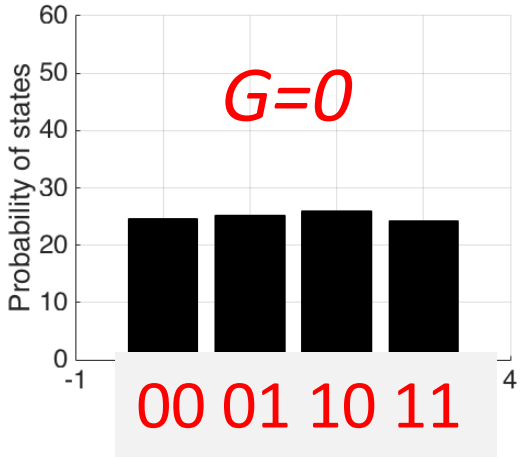

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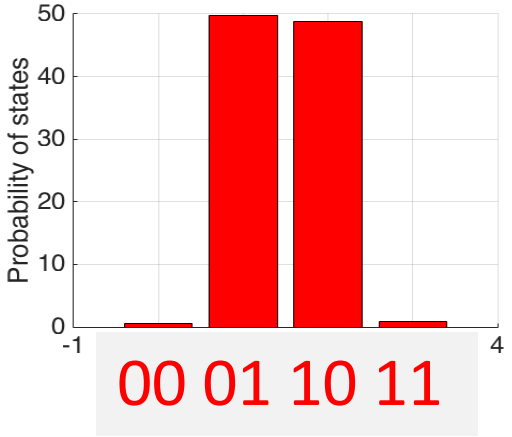
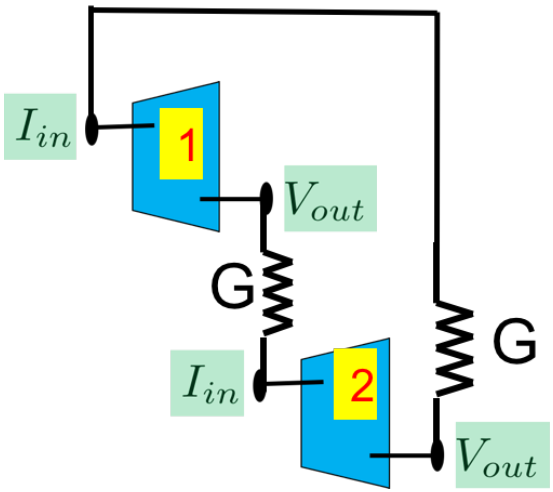
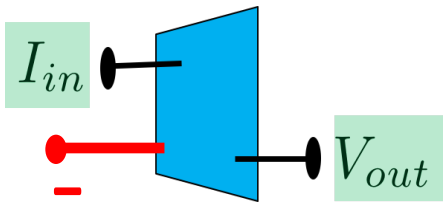
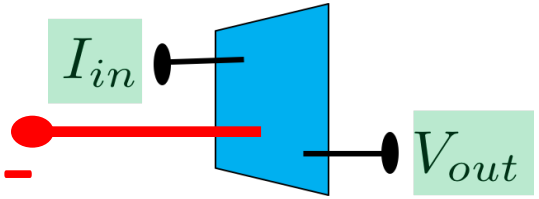






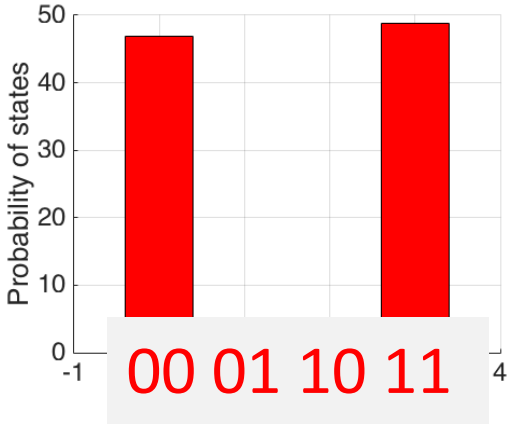
Interconnecting the blocks

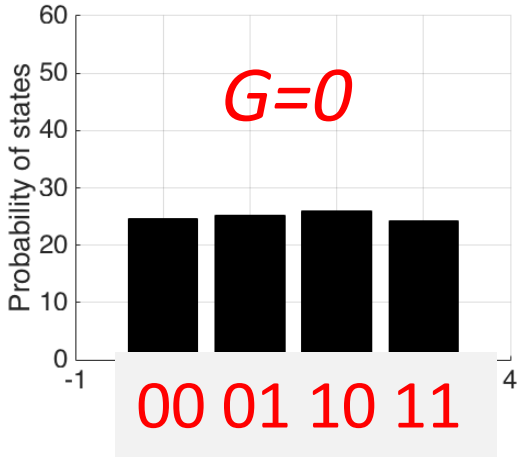


$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = G \begin{bmatrix} 0 & +1 \\ +1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

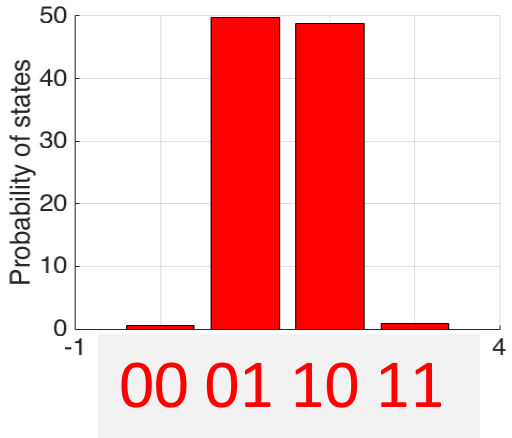
$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = G \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

COPY GATE

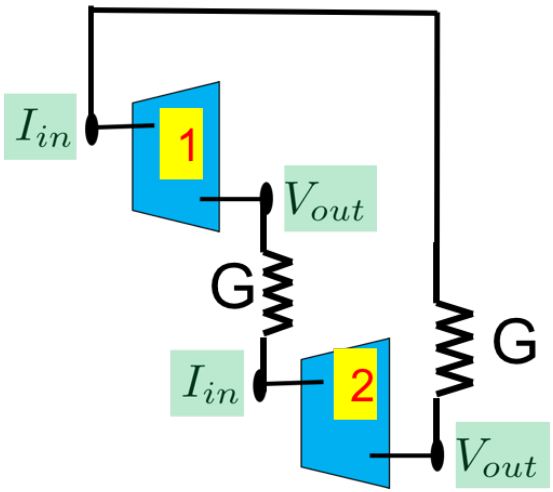


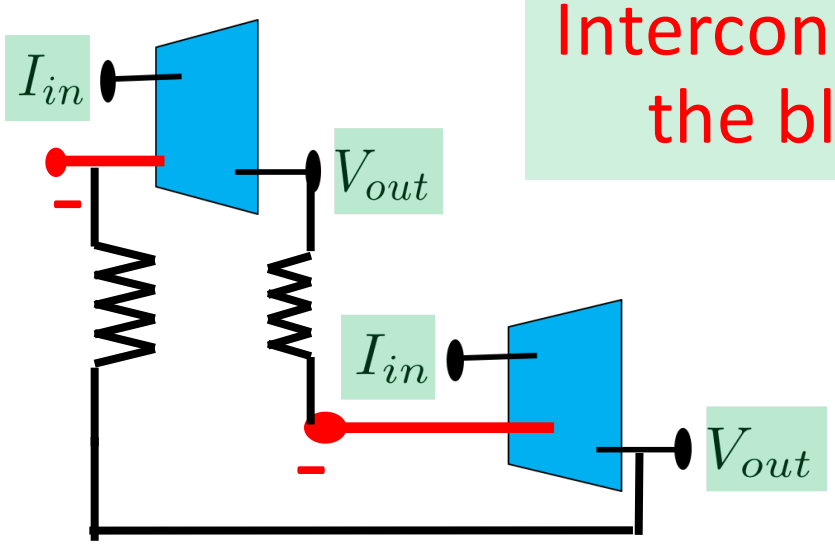


NOT GATE



Interconnecting the blocks

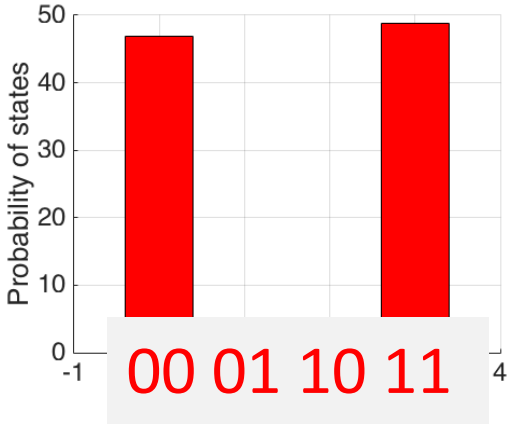


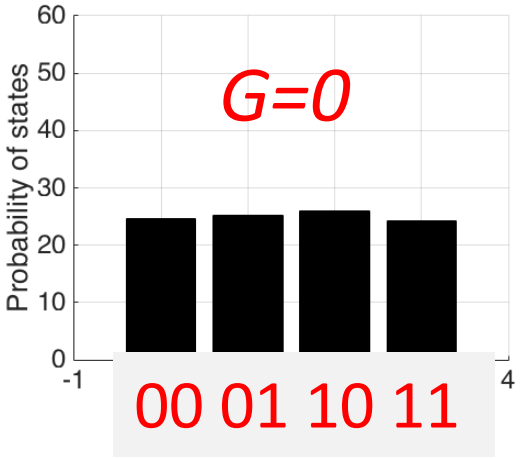


$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = G \begin{bmatrix} 0 & +1 \\ +1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

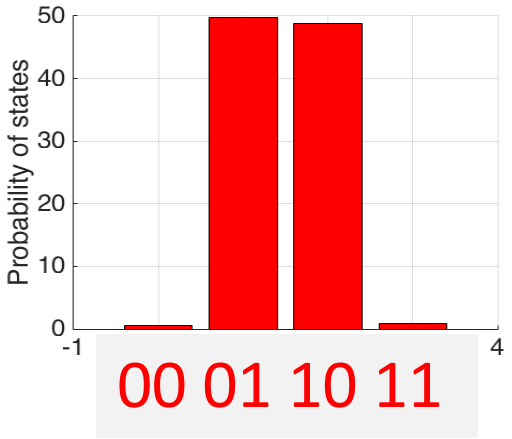
$$\begin{bmatrix} I_{in}(1) \\ I_{in}(2) \end{bmatrix} = G \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} V_{out}(1) \\ V_{out}(2) \end{bmatrix}$$

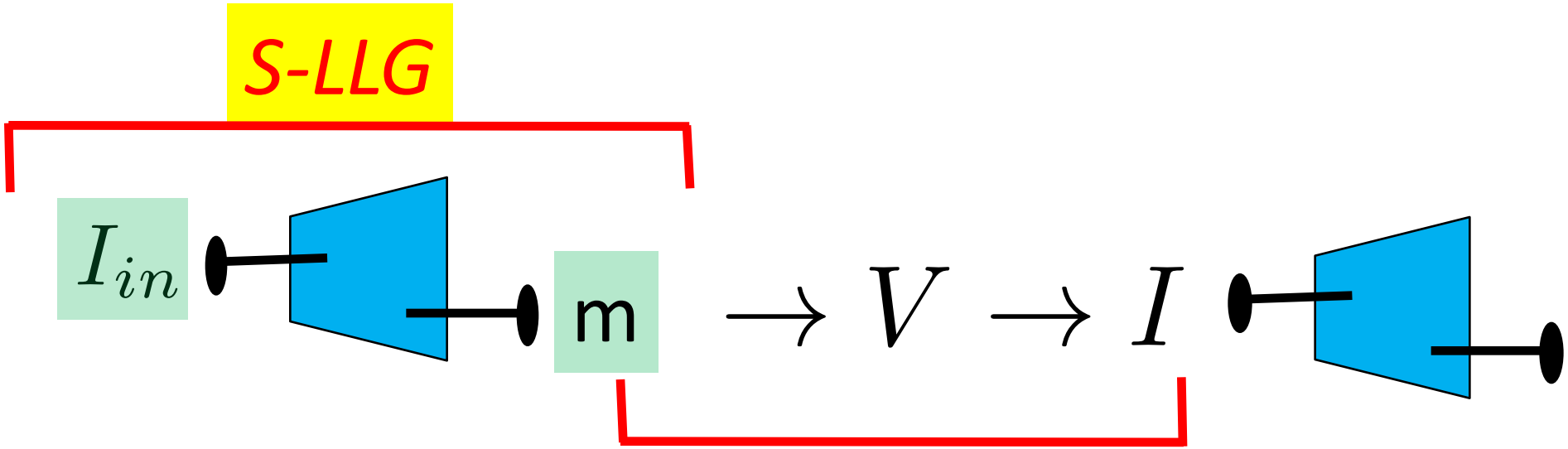
COPY GATE





NOT GATE



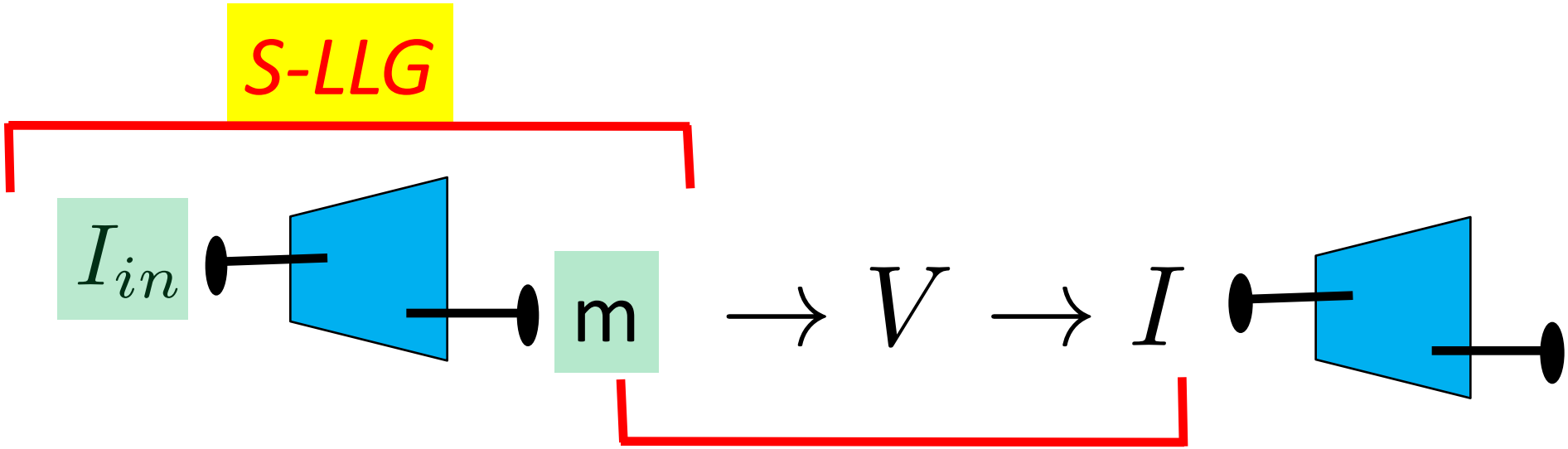


- Implicit

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

- Explicit
  - With CMOS
  - Without CMOS

Essential physics of PSL

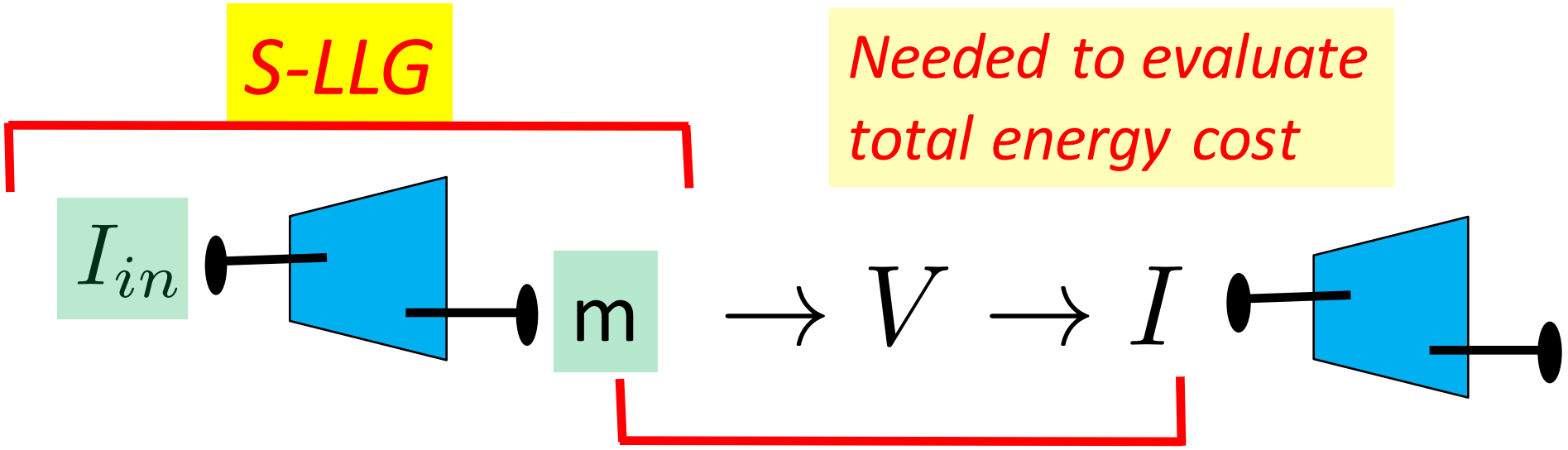


- Implicit

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

- Explicit
  - With CMOS
  - Without CMOS

Essential physics of PSL



- Implicit

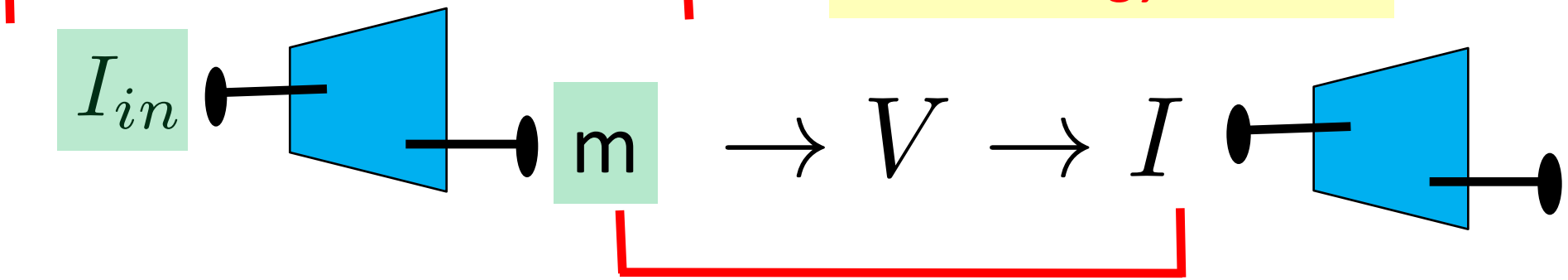
$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

- Explicit
  - With CMOS
  - Without CMOS

Essential physics of PSL

S-LLG

Needed to evaluate total energy cost



$$\Delta E = 1.1\ kT$$
$$H_K = 600\ Oe$$
$$\alpha = 0.01$$
$$\Delta t = .001\tau_c$$
$$\tau_c = \left(\alpha\gamma H_K\right)^{-1}$$

- Implicit

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

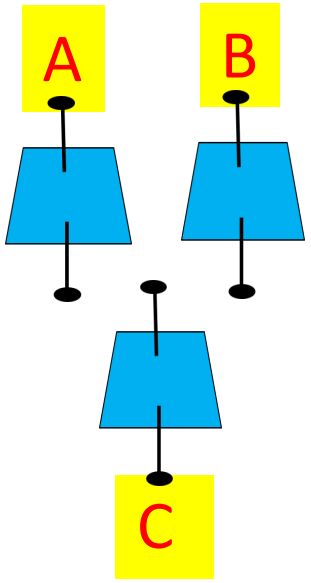
- Explicit
  - With CMOS
  - Without CMOS

AND / OR / XOR

$$\{I\} = I_0 \left(\{h\} + [J]\{m\}\right)$$

AND

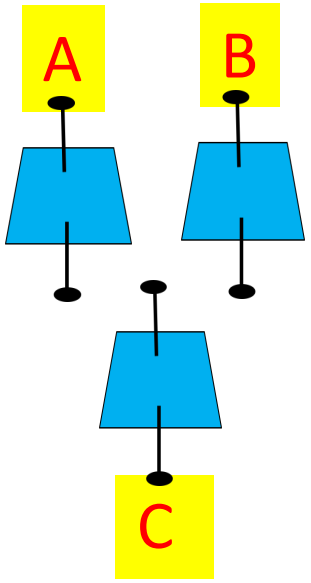
C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



AND / OR / XOR

AND

C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



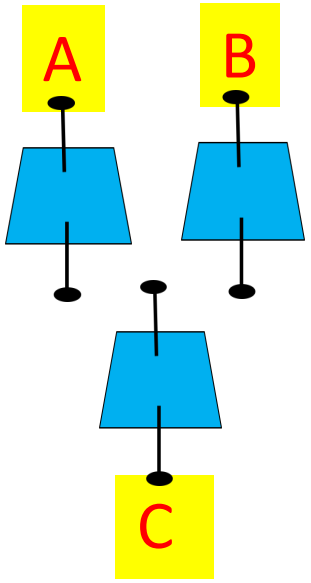
$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \qquad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

AND / OR / XOR

AND

C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \quad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

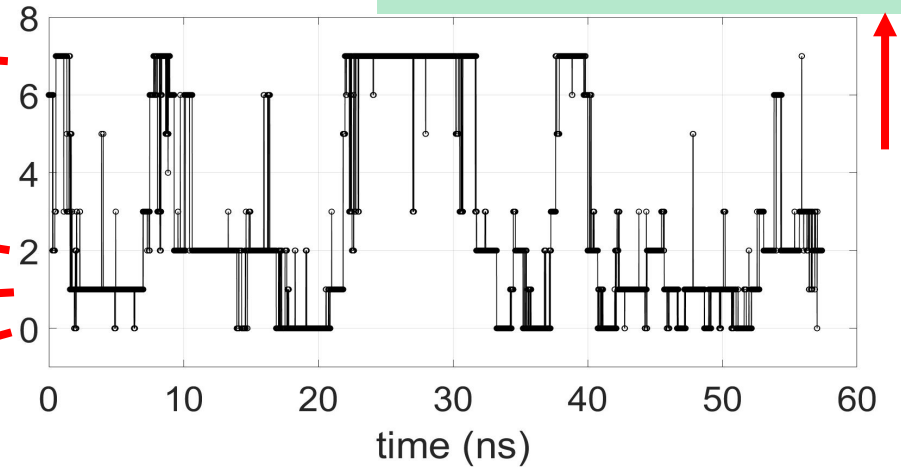
2^2 C +2^1 B + 2^0 A

111

010

001

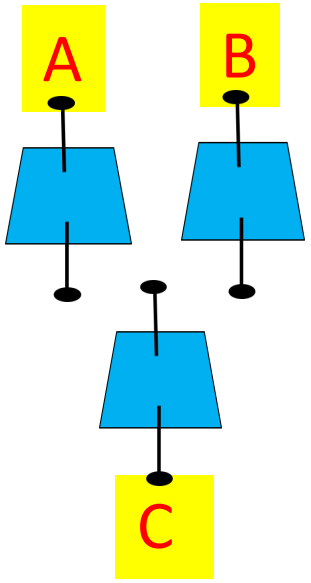
000



AND / OR / XOR

AND

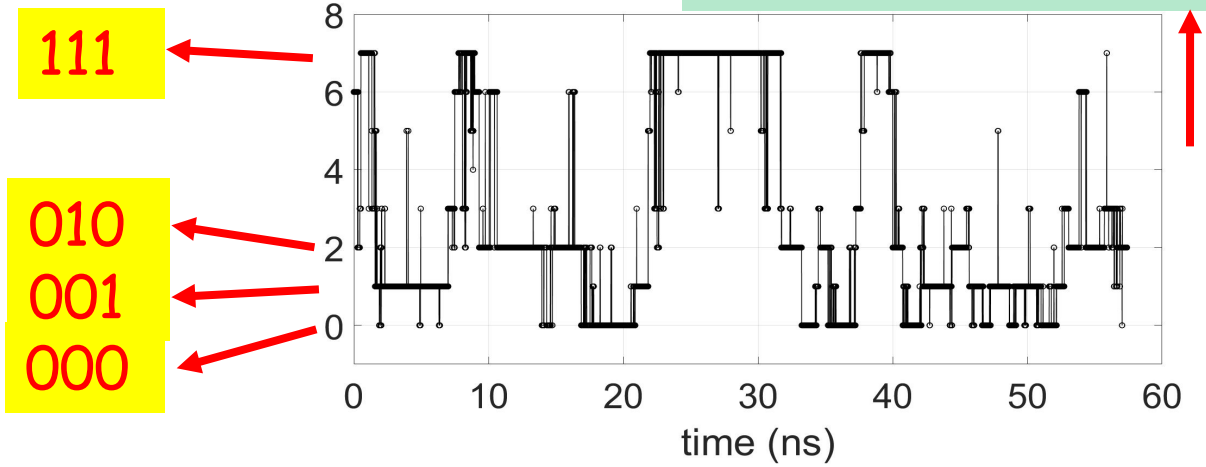
C	B	A
0	0	0
0	0	1
0	1	0
1	1	1

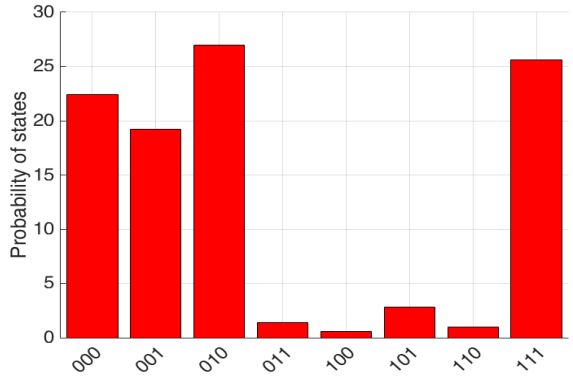


$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \quad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

2^2 C +2^1 B + 2^0 A

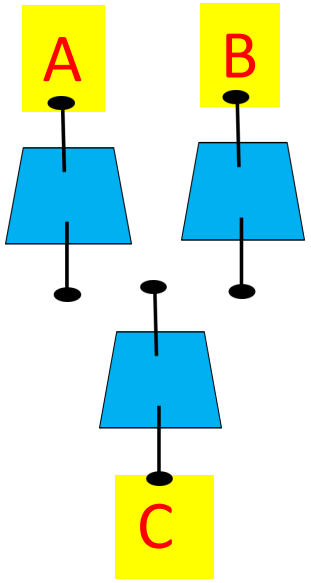




AND / OR / XOR

AND

C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \quad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

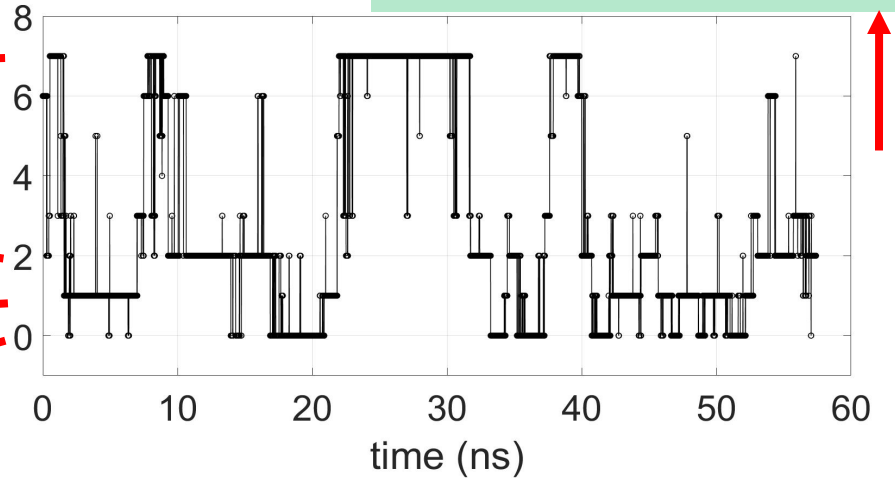
2^2 C +2^1 B + 2^0 A

111

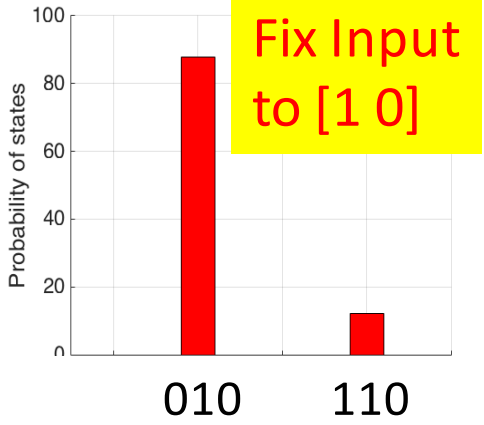
010

001

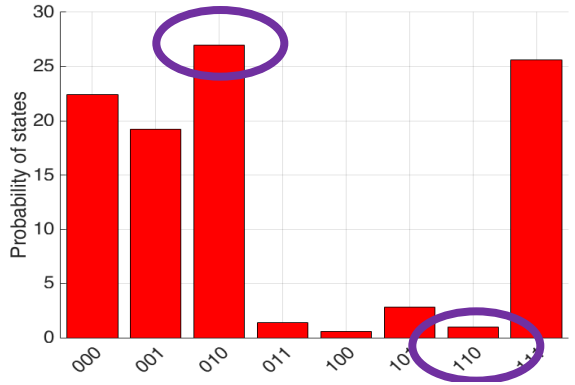
000



Can make [010] ~100%



Fix Input to [1 0]



C-SPIN

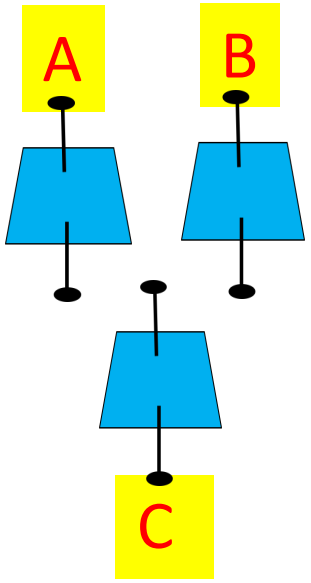
CSPIN Focus Session

STARnet

AND / OR / XOR

AND

C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \quad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

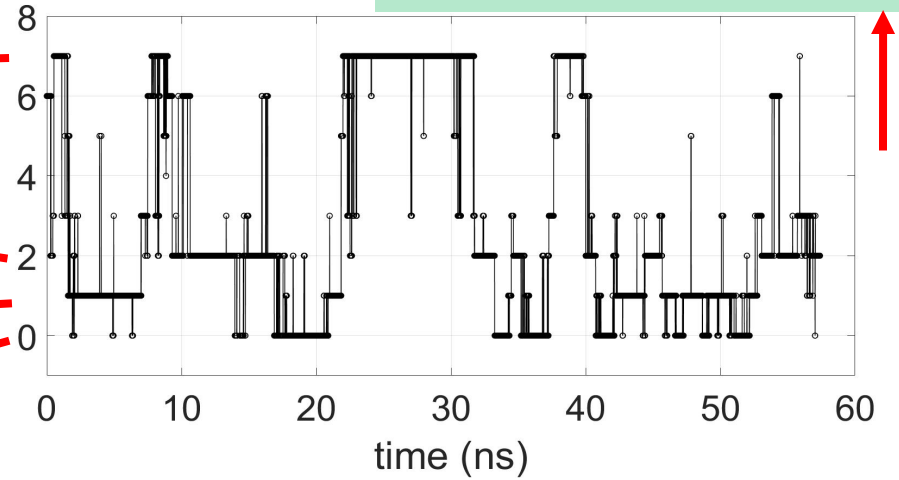
2^2 C +2^1 B + 2^0 A

111

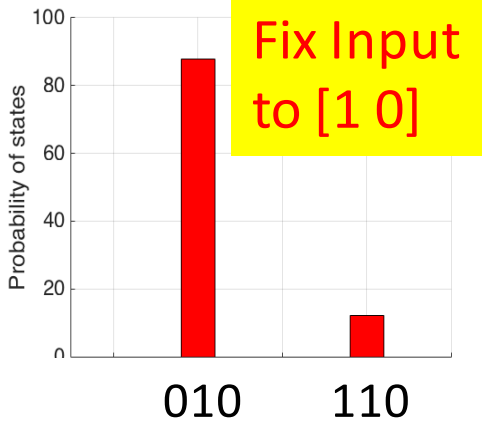
010

001

000

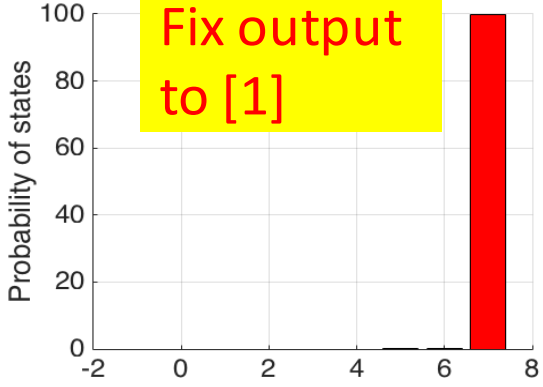


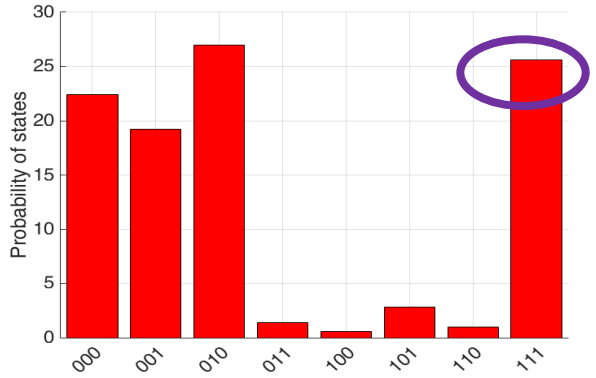
Can make [010] ~100%



Fix Input to [1 0]

Fix output to [1]





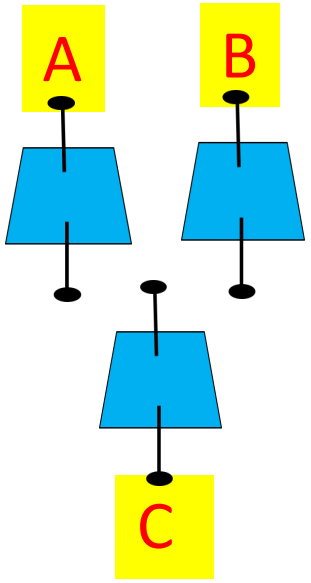
C-SPIN

STARnet

AND / OR / XOR

AND

C	B	A
0	0	0
0	0	1
0	1	0
1	1	1



$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

$$\begin{Bmatrix} -2 \\ 1 \\ 1 \end{Bmatrix} \quad \begin{bmatrix} 0 & +2 & +2 \\ +2 & 0 & -1 \\ +2 & -1 & 0 \end{bmatrix}$$

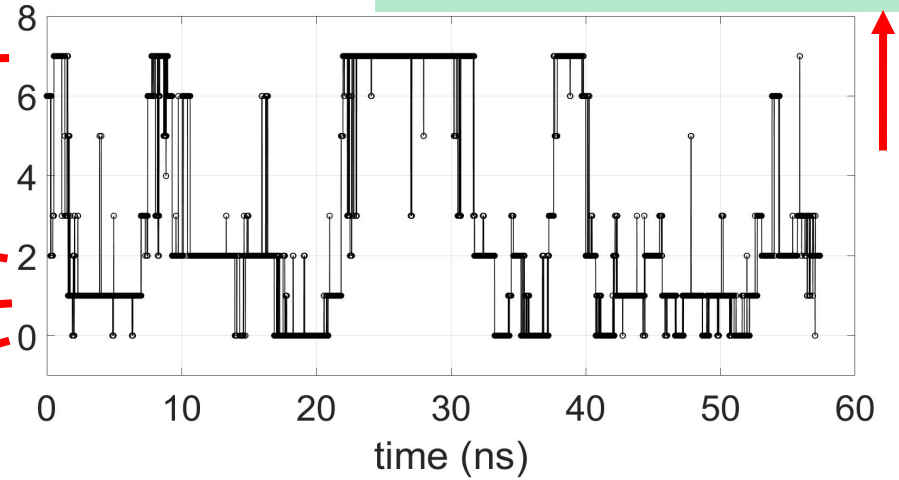
2^2 C +2^1 B + 2^0 A

111

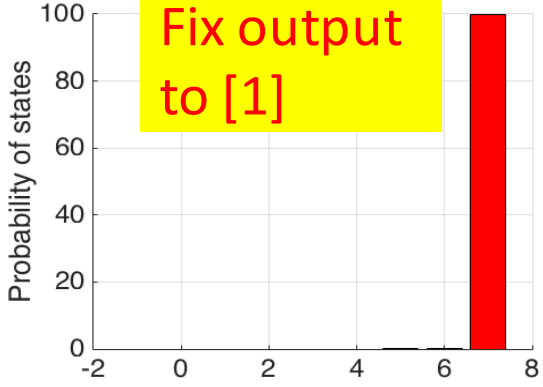
010

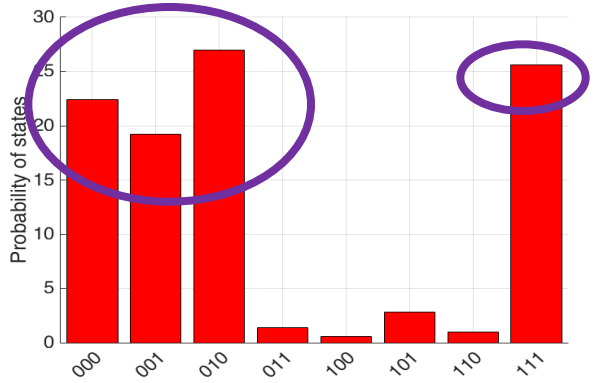
001

000



Fix output to [1]





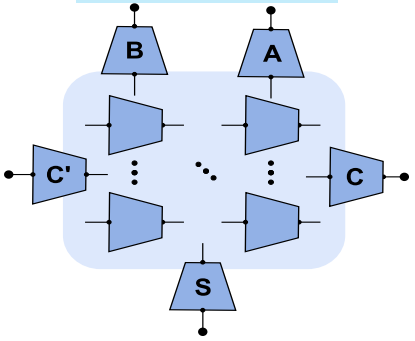
C-SPIN

STARnet

32-bit adder

$$\{I\} = I_0 \left(\{h\} + [J]\{m\}\right)$$

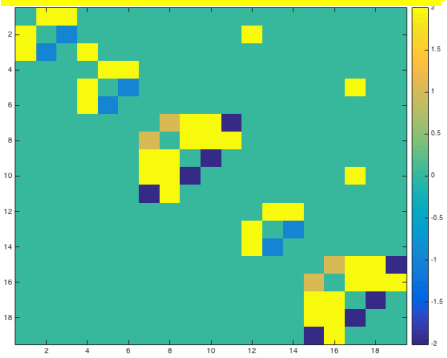
19 blocks



$$J = 0, \pm 1, \pm 2$$

Sparse & Quantized

Full adder : [J]

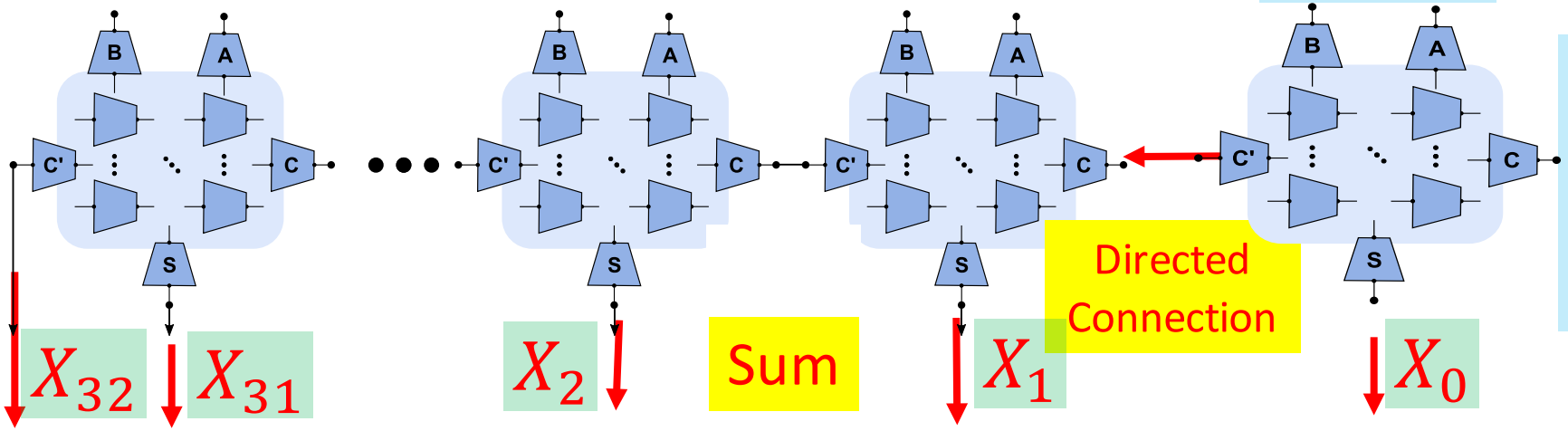


32-bit adder

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

Input bits

19 blocks

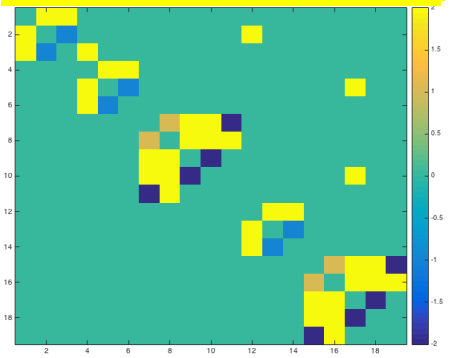


19x32 = 608 blocks

$$J = 0, \pm 1, \pm 2$$

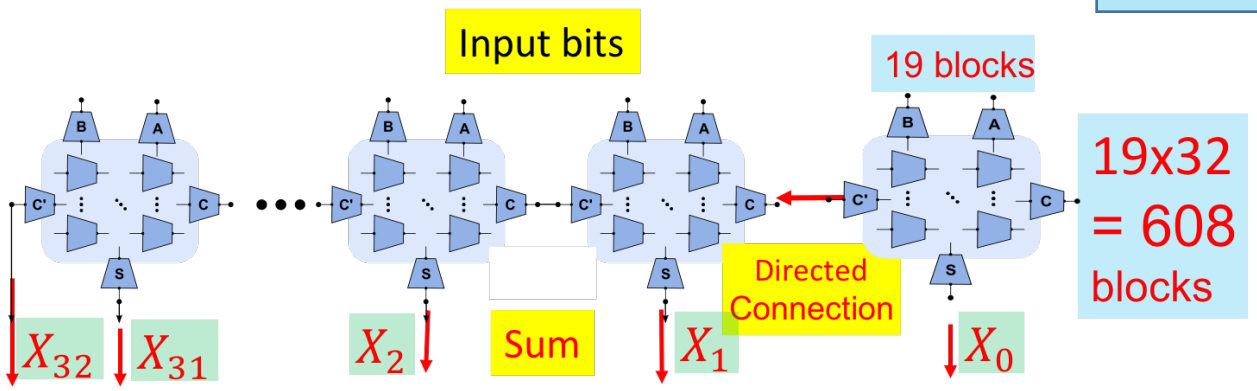
Sparse & Quantized

Full adder : [J]



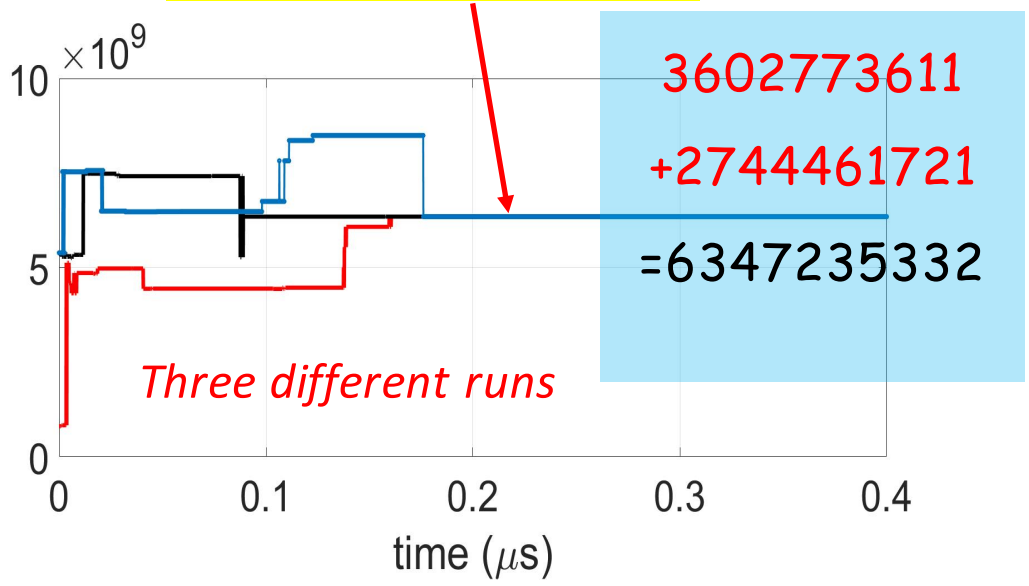
32-bit adder

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$



$$\sum_p 2^p X_p$$

Correct answer !!



3602773611

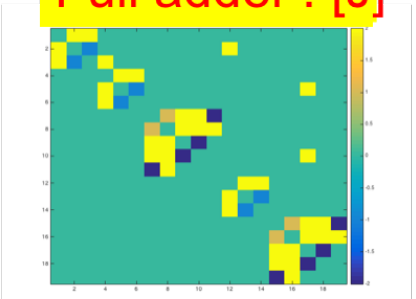
+2744461721

=6347235332

$$J = 0, \pm 1, \pm 2$$

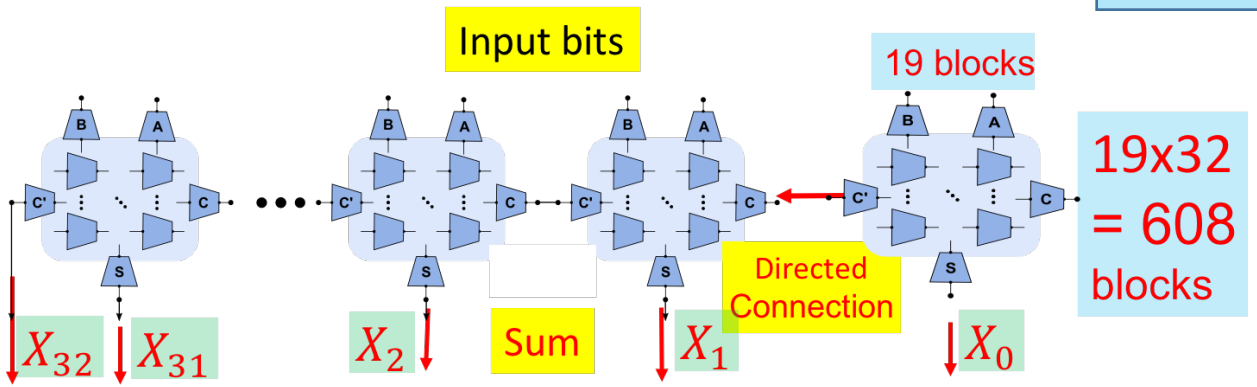
Sparse & Quantized

Full adder : [J]



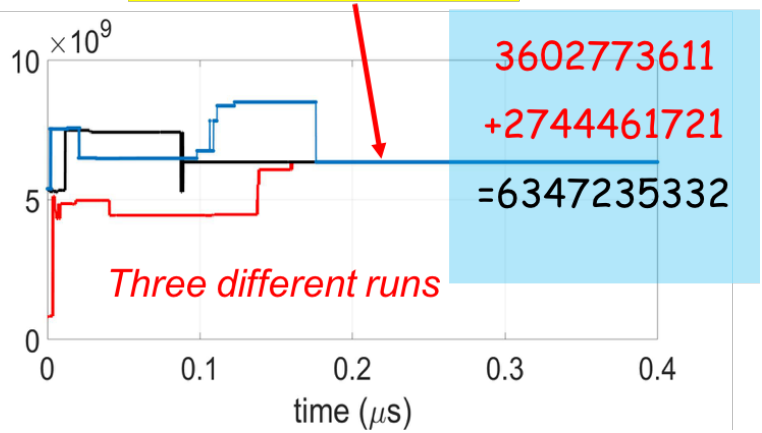
32-bit adder

$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$



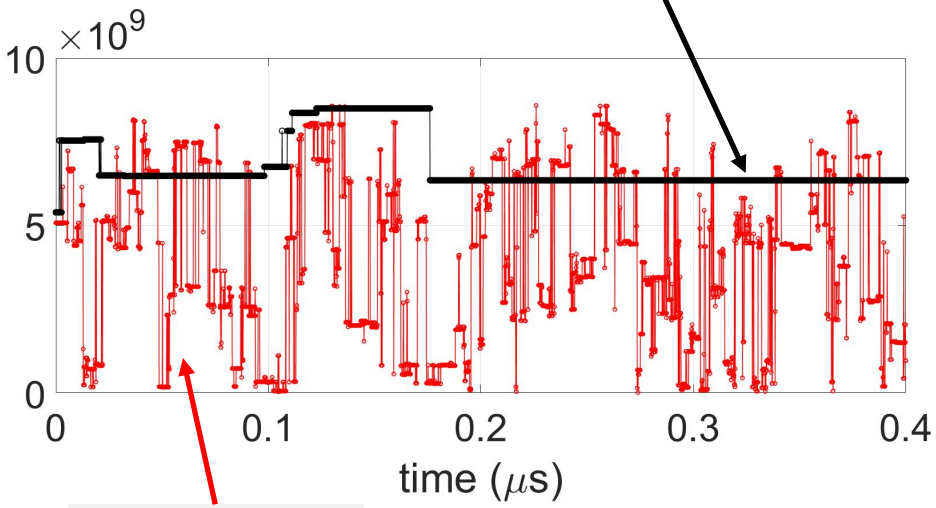
19x32 = 608 blocks

$\sum_p 2^p X_p$



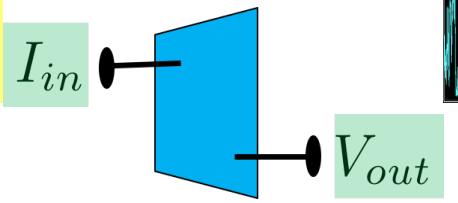
3602773611
+2744461721
=6347235332

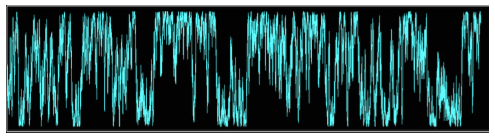
Correct answer with proper connections



Weak connections

Probabilistic Spin Logic (PSL)

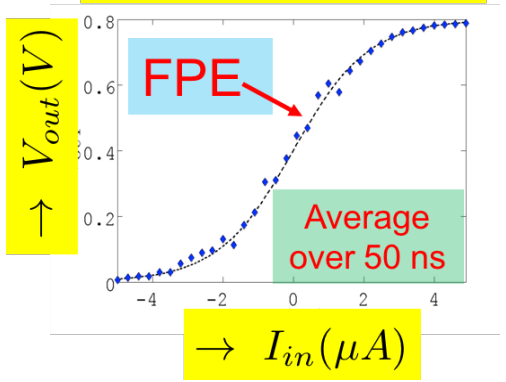




Low ΔE nanomagnets provide biased RNG

"P-bit"

S-LLG



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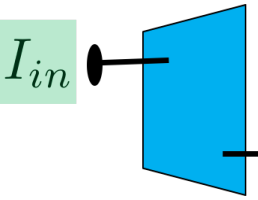

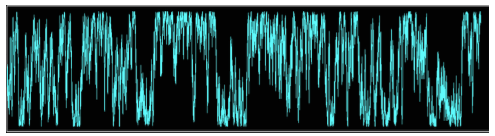

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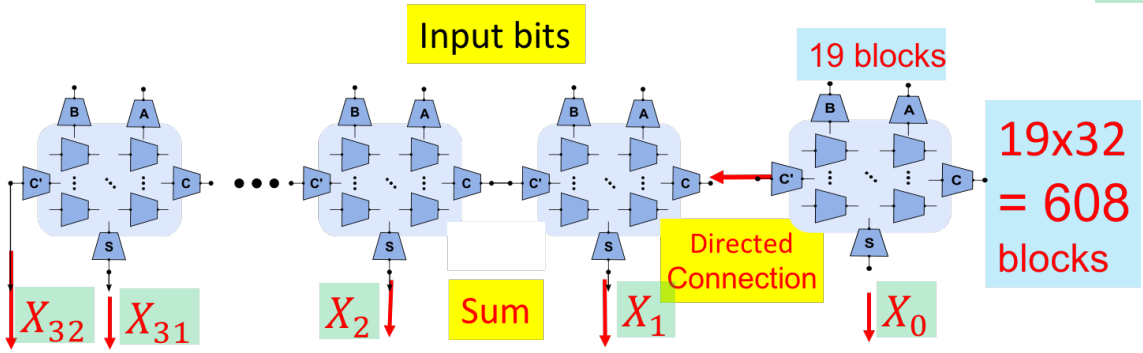

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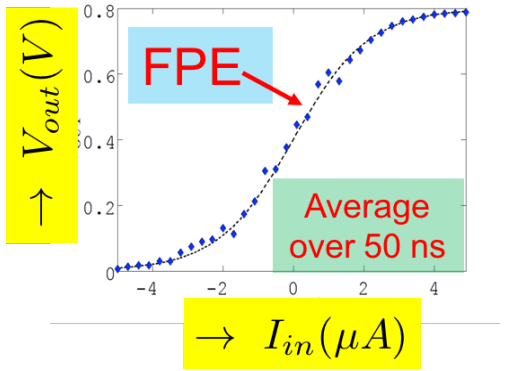
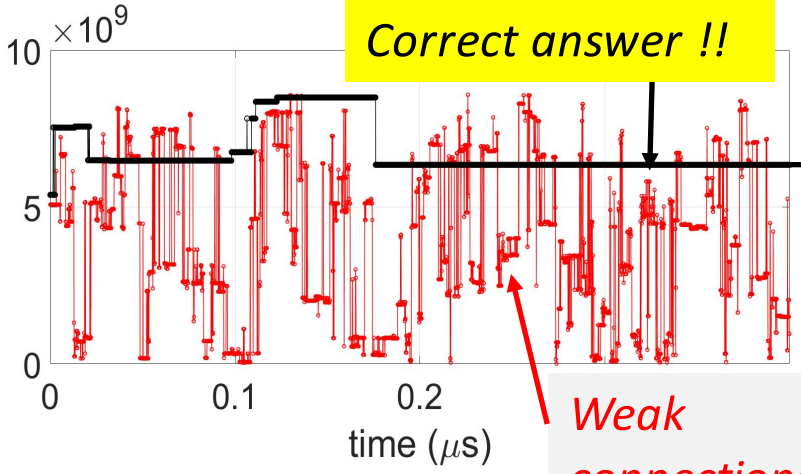
S-LLG





Correct answer !!

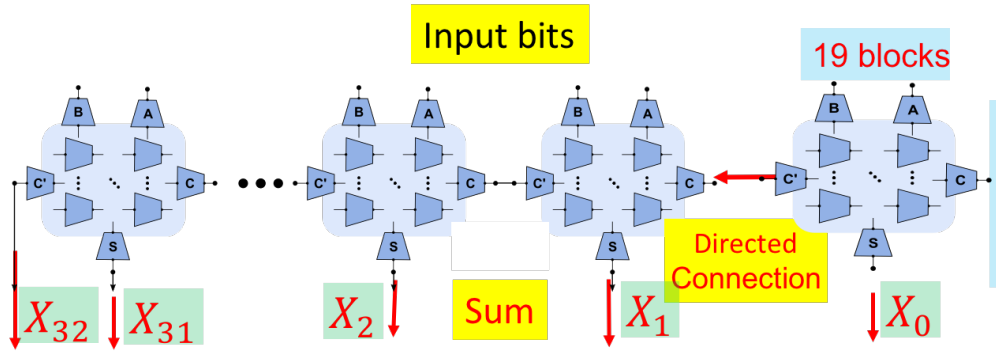
3602773611

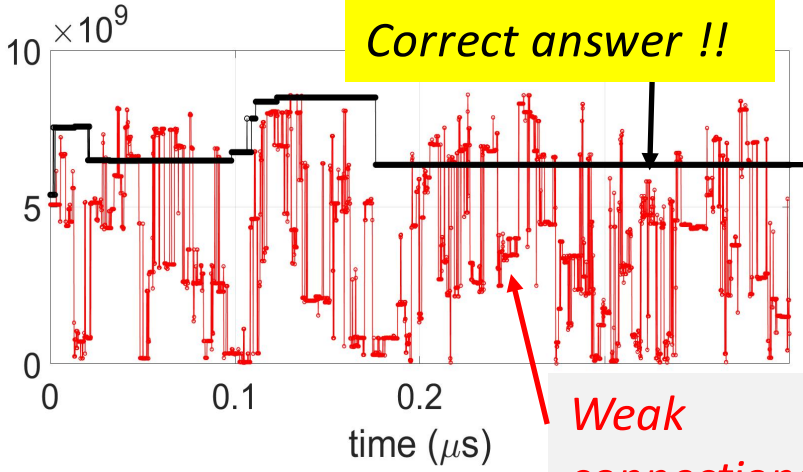
+2744461721

=6347235332

Weak connections

Probabilistic Spin Logic (PSL)





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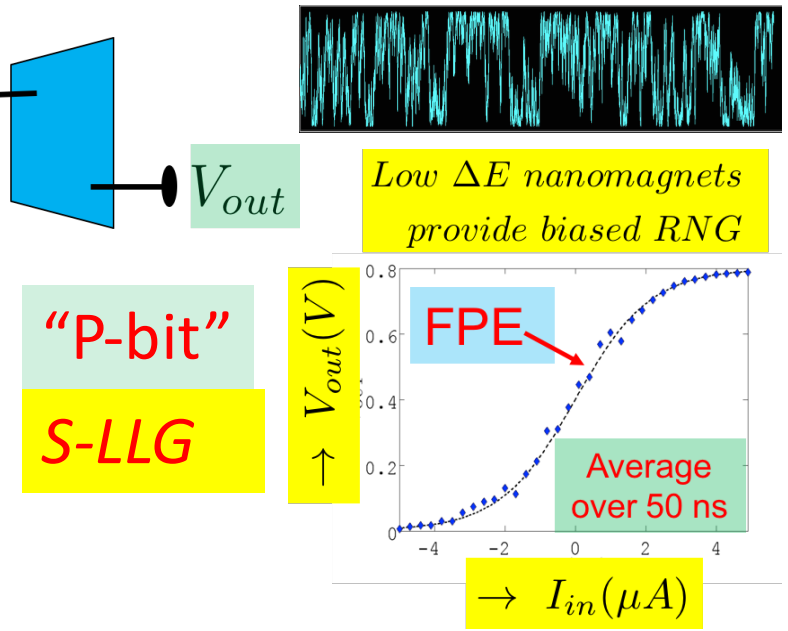


$$\{I\} = I_0\left(\{h\} + [J]\{m\}\right)$$

"Pseudo –"
Boltzmann machines

- Boolean logic

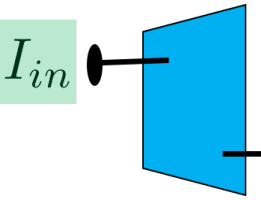
$$J = 0, \pm 1, \pm 2$$

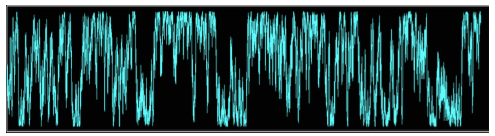
- Character recognition
- NP-hard problems

C-SPIN

STARnet

Probabilistic Spin Logic (PSL)





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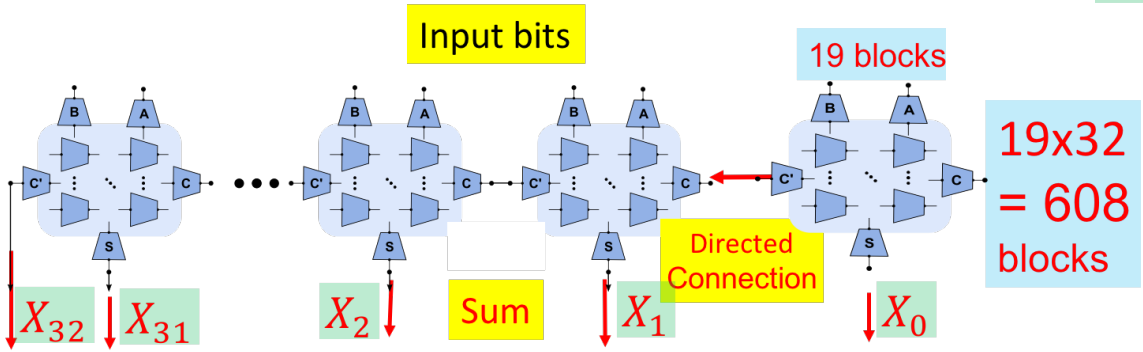
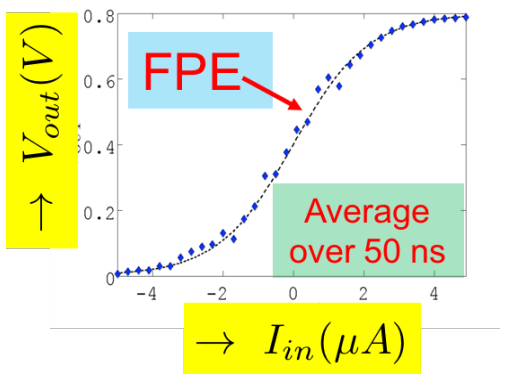
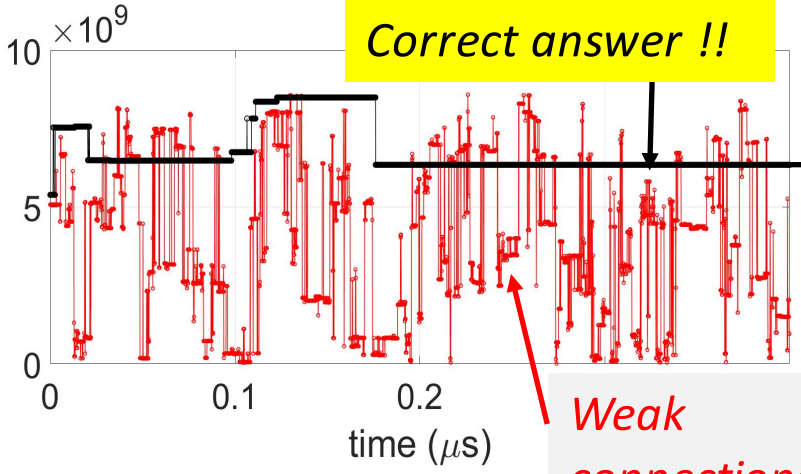


19x32 = 608 blocks

"P-bit"

S-LLG





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"Pseudo –" Boltzmann machines

Acknowledgements

Dr. Kerem Camsari

Rafatul Faria, Brian Sutton (Purdue)

Dr. Behtash Behin-Aein (GF)

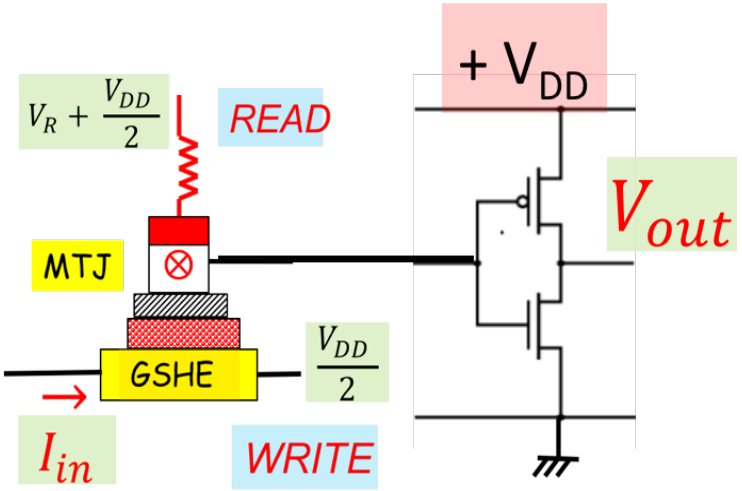
Poster by Brian Sutton

- Boolean logic

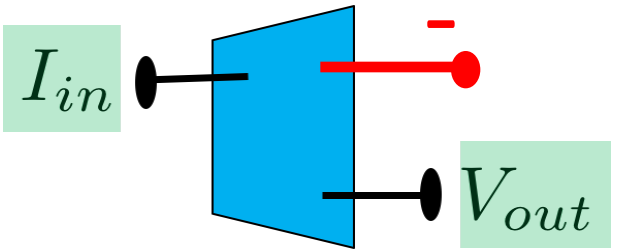
$$J = 0, \pm 1, \pm 2$$

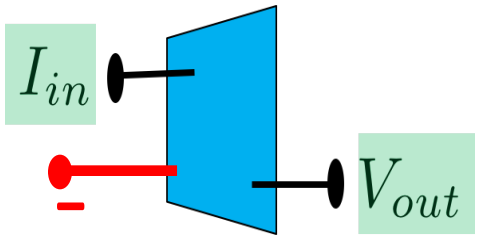
- Character recognition
- NP-hard problems

Design using CMOS

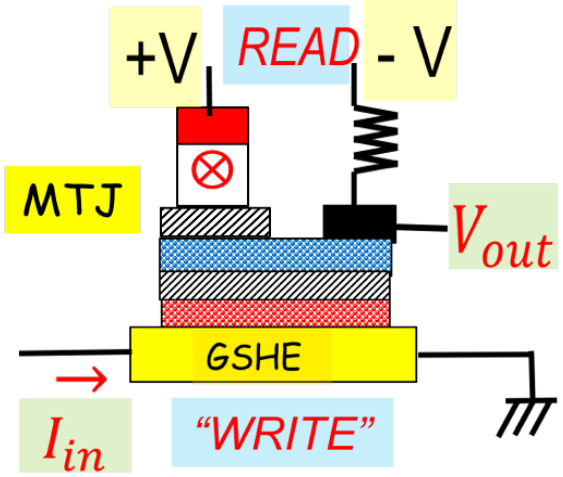


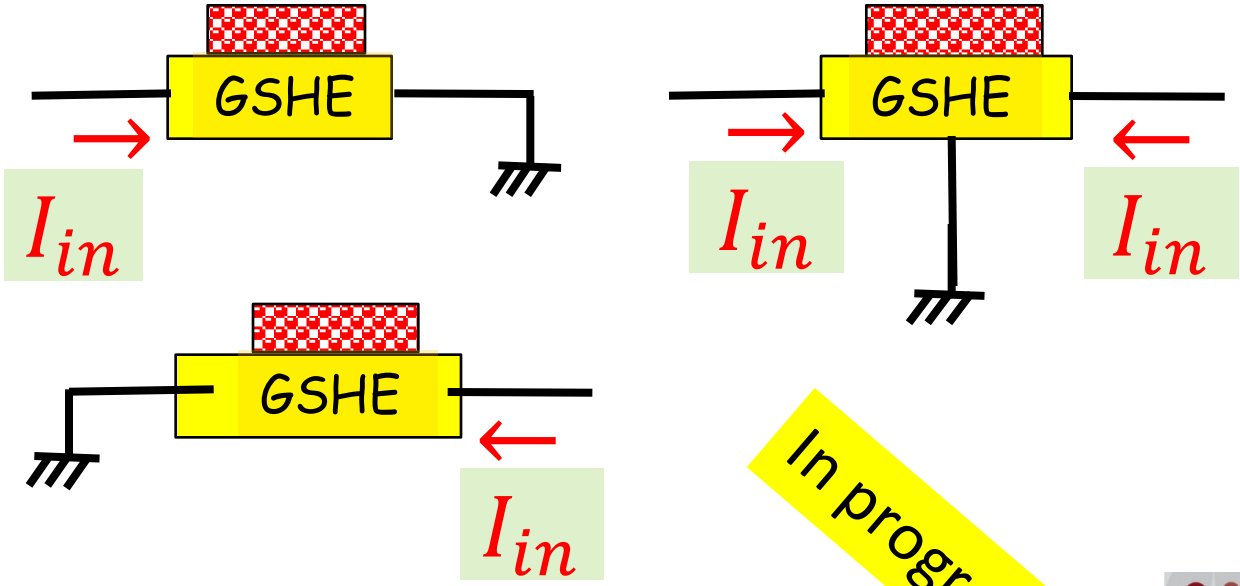
Negative weights





Design without CMOS





In progress