

# Architectural Aspects in Design and Analysis of SOT-based Memories

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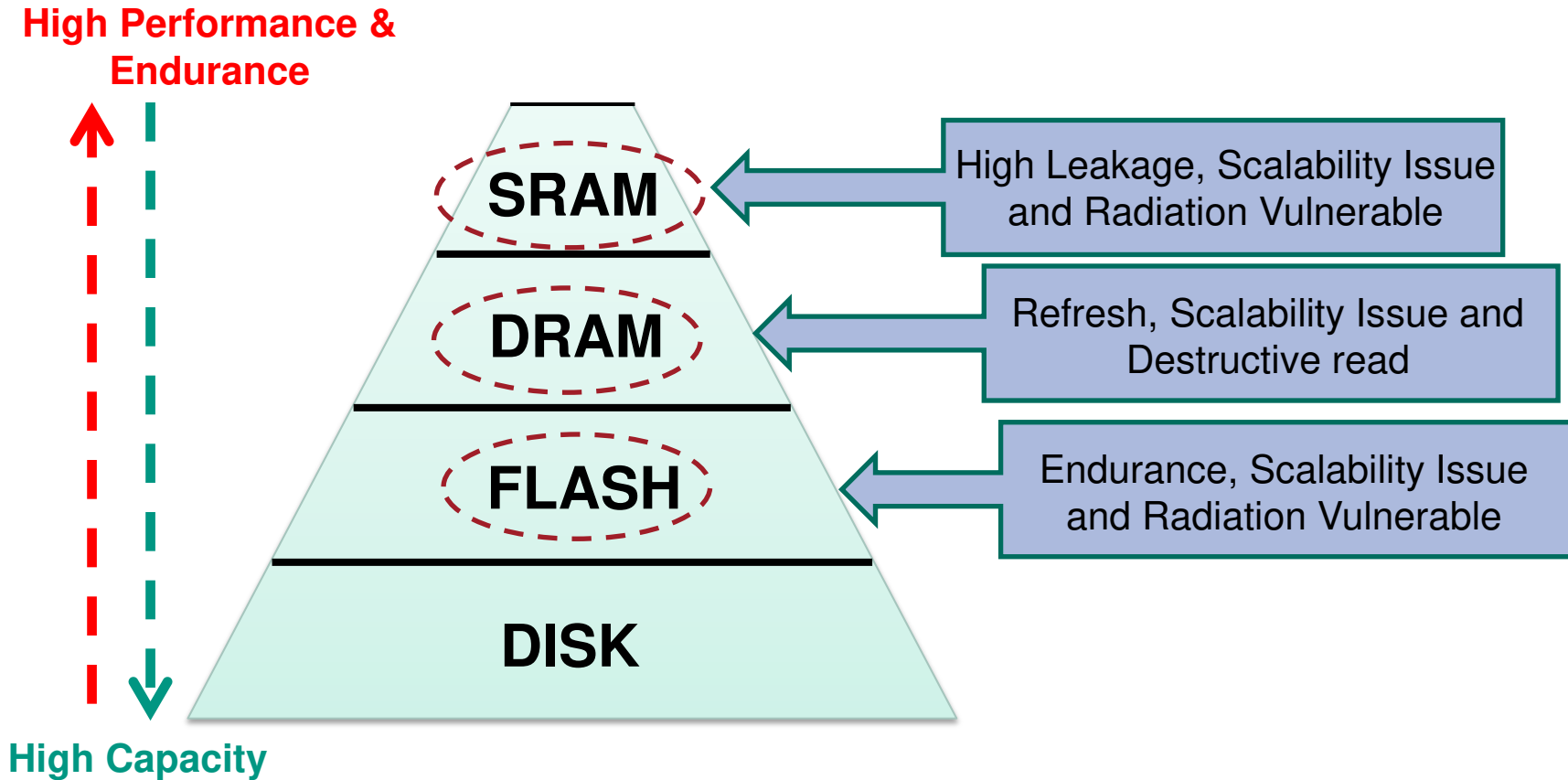
# Outline

- **Motivation**
  
- **SOT based MRAM**
  - STT-MRAM & Limitations
  - Basics of SOT-MRAM
  - Simulation tool flow
  
- **Results**
  - For various memory technologies
  - System-level
  
- **Summary & Conclusion**

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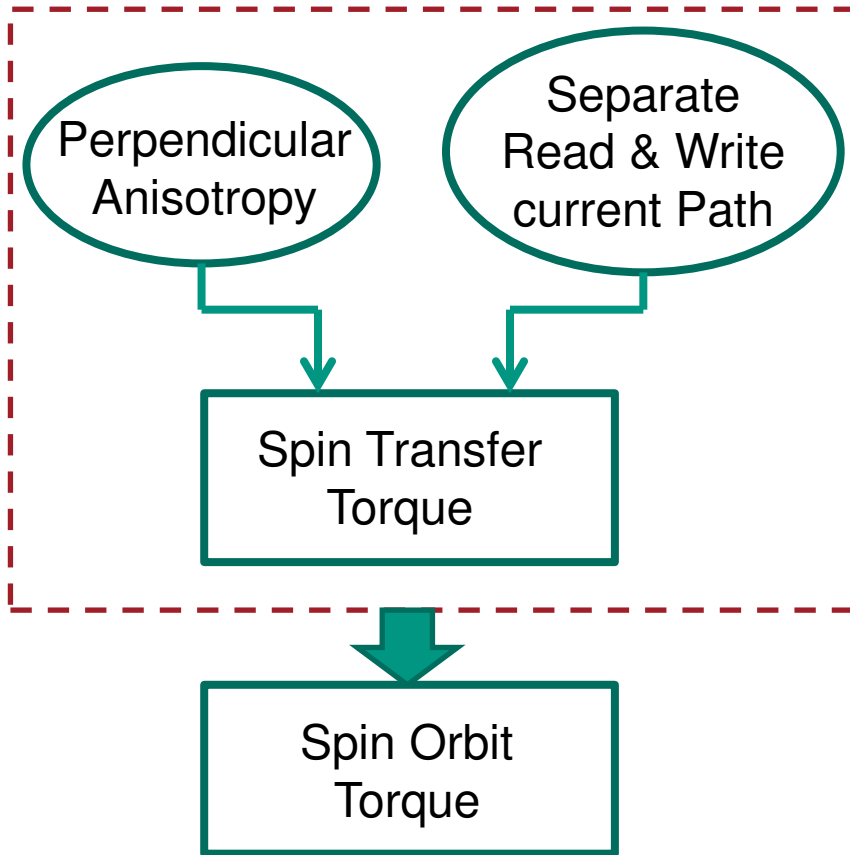
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# Memory Hierarchy



- A Universal Memory Required to overcome these limitations
- Non Volatile Magnetic RAM is promising candidate

# Motivation



## Results in

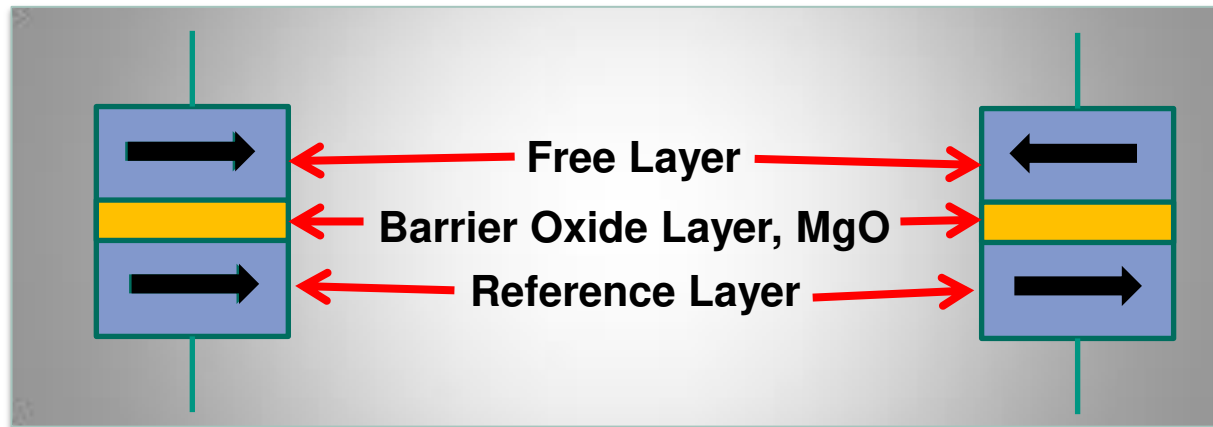
- **Low Write Current**
- **Low Switching Time**
- **Avoid Read Disturb**

- STT-MRAM has potential to become universal memory technology
- However, obstacles are
  - High write current & time
  - “Read Disturb”
- Addressed using Spin Orbit Torque (SOT)

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# Basics of Spin Transfer Torque (STT)

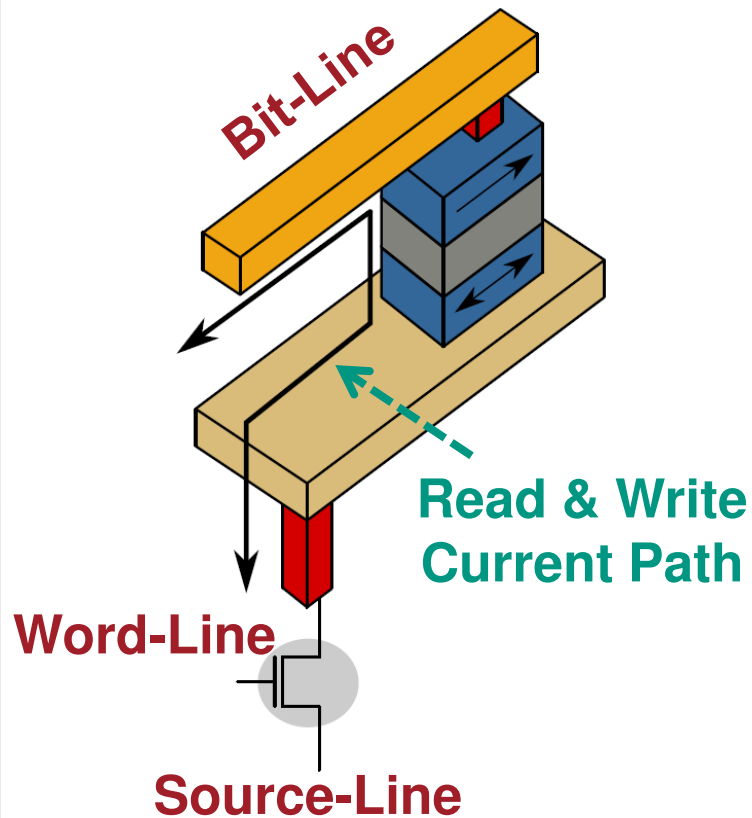


**Parallel Magnetisation (P)**  
**Low Resistance**

**Anti- Parallel Magnetisation (AP)**  
**High Resistance**

- Two ferromagnetic layers separated by a oxide barrier layer
- Magnetic Tunneling Junction (MTJ) Cell is a storing device
- Value stored as a resistance state

# Bit-cell using STT based MTJ cell



- Bit-cell has three terminals:
  - Bit-Line
  - Word-Line
  - Source-Line
- Read current is unidirectional
- Write current is bidirectional
- Possible “Read Disturb”
  - Same path for read and write



# Merits & Demerits of STT

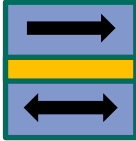
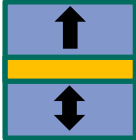
## ■ Merits:

- High Density
- Non-Volatility
- Scalability
- CMOS Compability
- Low Read Latency
- High Endurance
- High Retention
- Radiation Immune

## ■ Demerits:

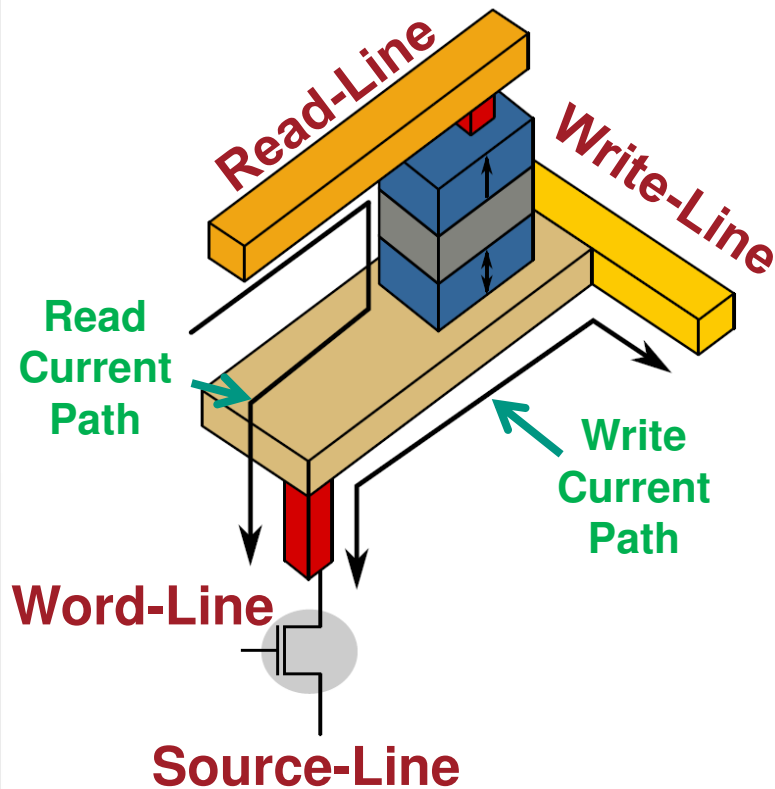
- High Write Power
- High Write Latency
- Aditonal Layer requires
- Read Disturb

# In-Plane Vs Perpendicular Anisotropy

Parameters	In-Plane Magnetic Anisotropy	Perpendicular Magnetic Anisotropy
Diagram		
Ratio of critical switching current to thermal stability, $\frac{I_c}{\Delta}$	$\frac{\alpha}{\eta} \times \left( 1 + \frac{H_d}{2H_k} \right)$ <p>where, <math>\alpha</math>= damping constant,  <math>\eta</math>=STT efficiency, <math>H_d</math> = demagnetization field, <math>H_k</math>=in-plane anisotropy field</p>	$\frac{\alpha}{\eta}$
switching current	High	Low
switching time	More	Less

- Perpendicular magnetic anisotropy
  - Low switching current
  - Less switching time
- “Read Disturb“ still remains challenge

# Spin Orbit Torque

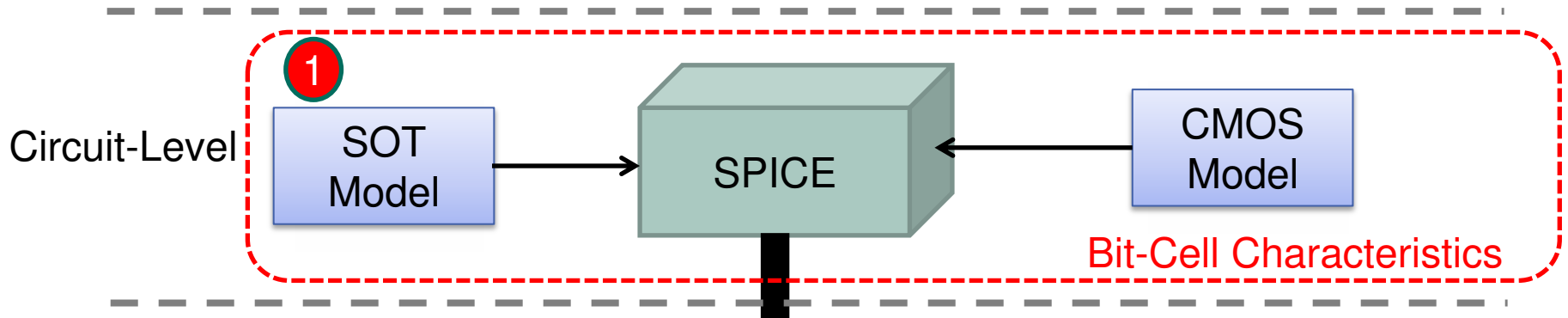


- Separate read and write current paths
  - One additional terminal
  - No read disturb
  - Need not to maintain ratio of  $I_{\text{Read}}/I_{\text{Write}}$
- Less current required to flip due to parallel magnetization
- Fast switching

# STT-MRAM VS SOT-MRAM

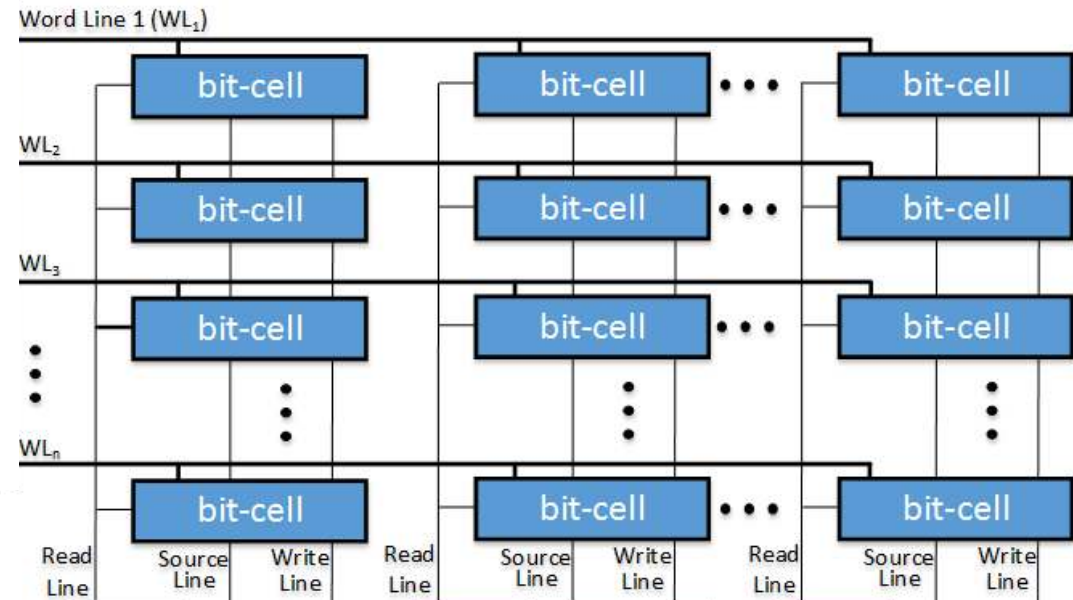
Parameter	STT-MRAM	SOT-MRAM
Bit-cell Terminals (1T1MTJ type)	3	4
Access Transistor	8F	2F
Current ( $\mu\text{A}$ )	750	100
Write Current Period (ns)	11	0.3
Read Disturb	High Probability	Almost Nil
Read Energy (pJ)	1.8	1.8
Write Energy (pJ)	3.9 (reset)/3.4(set)	0.1
Switching Behavior	Asymmetrical	Almost Symmetrical
Magnetic Anisotropy	In-Plane	Perpendicular

# Tool Simulation Flow



# Basic Memory Architecture

- Word-line drive the access transistor of bit-cell
- Write Enable =1, for write operation
- Write Enable =0, for read operation



# Simulation models

## ■ STT-MTJ

- SPICE modelling framework presented in [ W. Guo, JAP-2010]

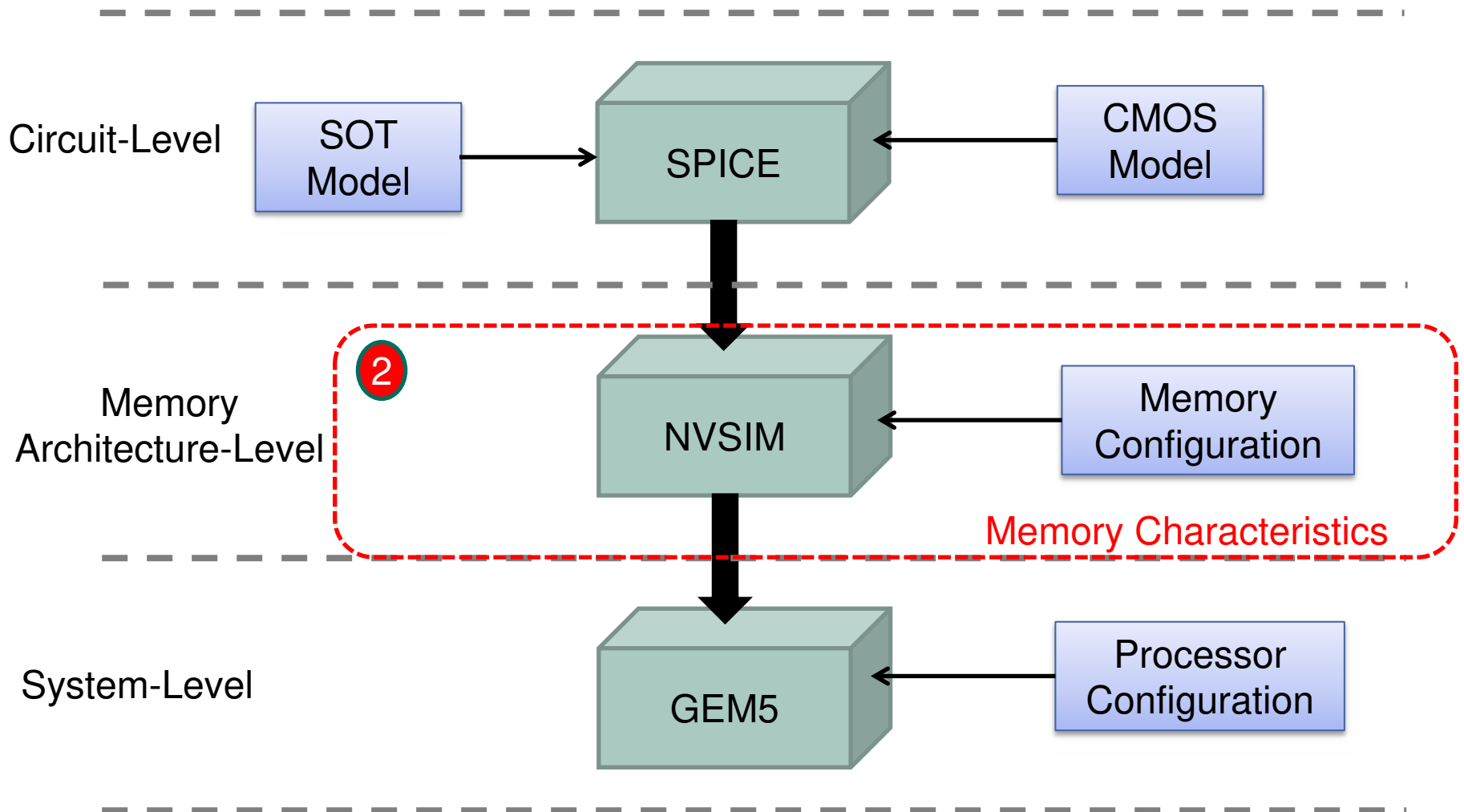
## ■ SOT-MTJ

- Compact Verilog-A framework presented in [ K. Jabeur, IJESSE-2013]

## ■ CMOS

- General purpose TSMC 65nm models.

# Tool Simulation Flow



2

Memory Characteristics

System-Level

Circuit-Level

Memory Architecture-Level

SOT Model

SPICE

CMOS Model

NVSIM

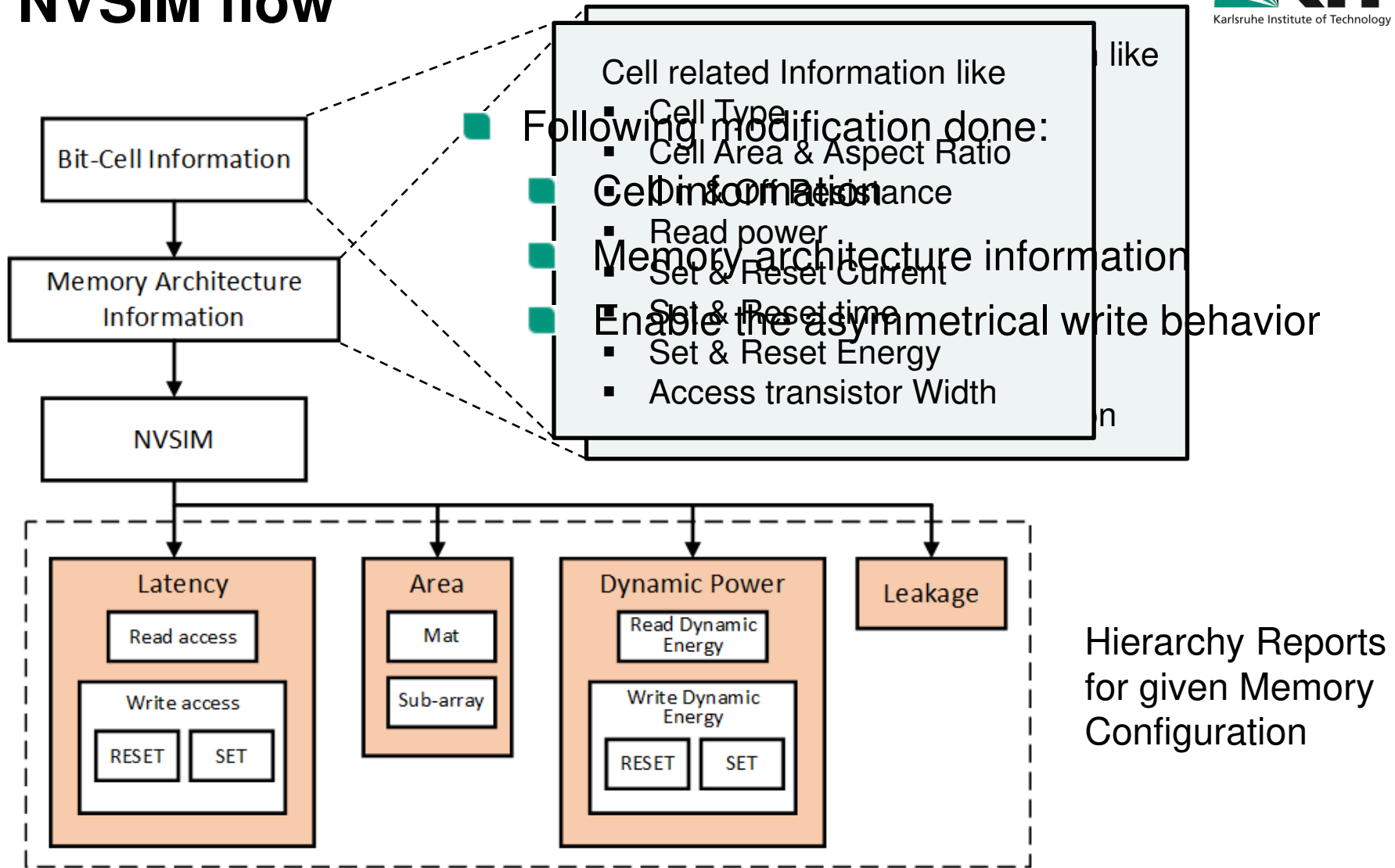
Memory Configuration

GEM5

Processor Configuration

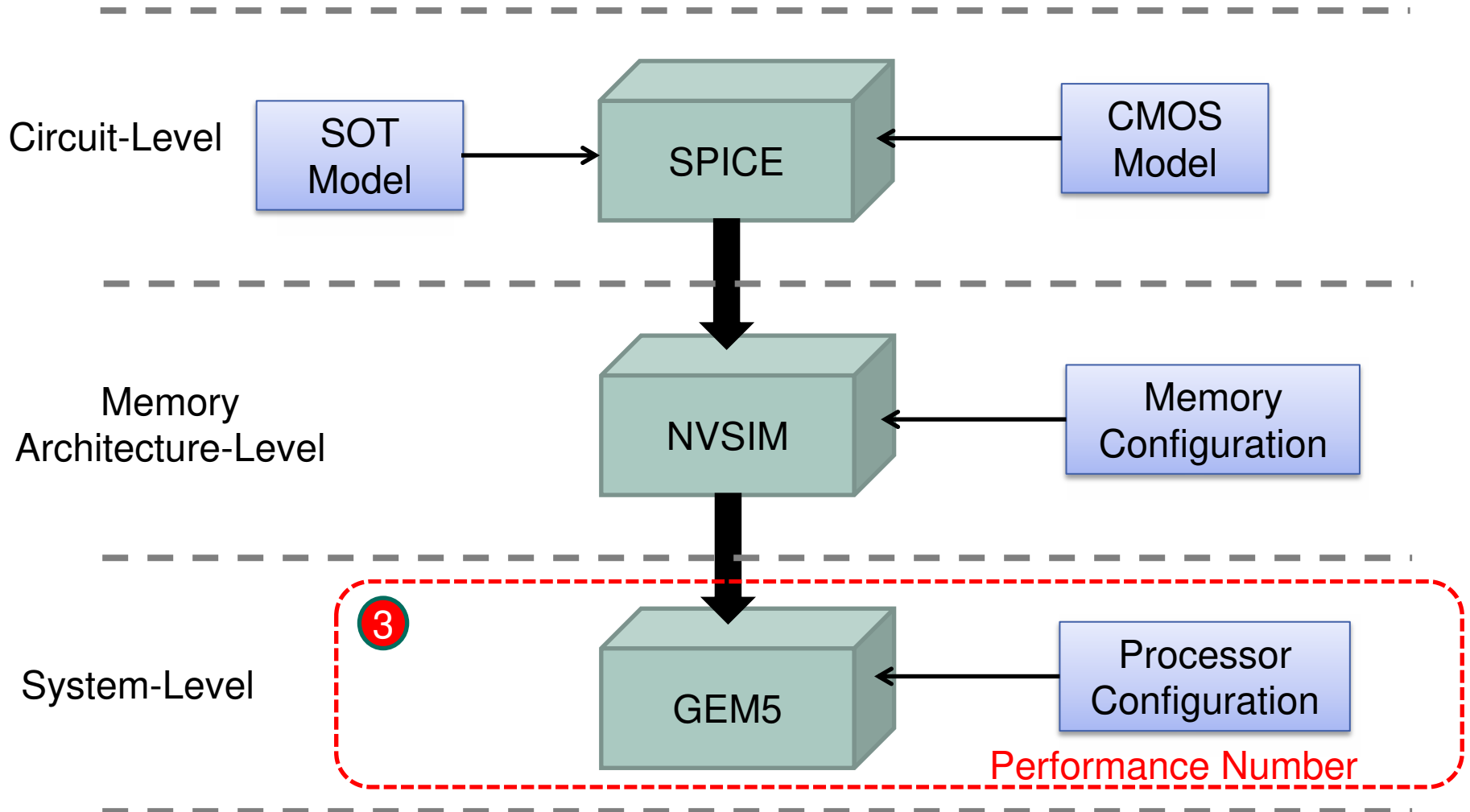


# NVSIM flow

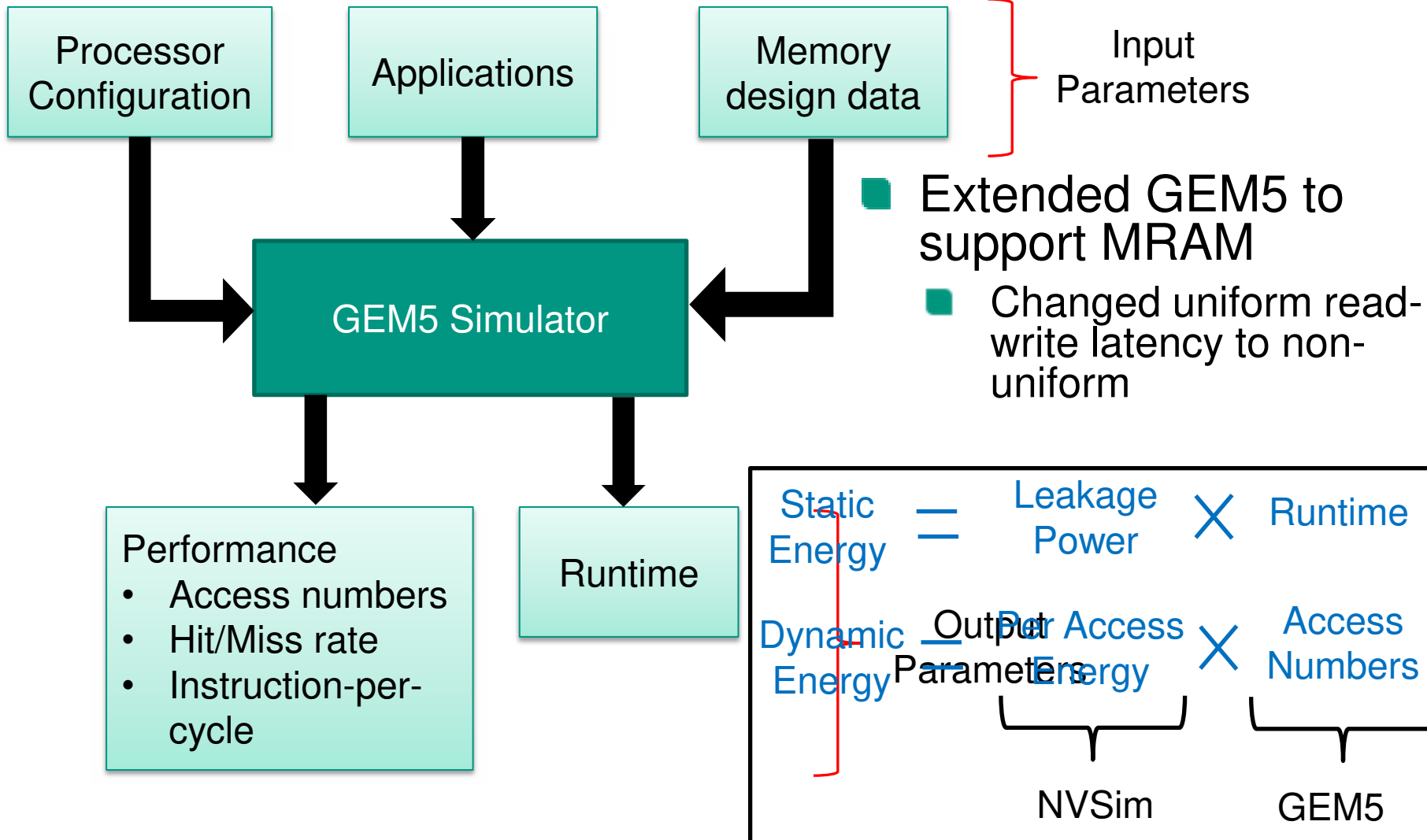


Hierarchy Reports  
for given Memory  
Configuration

# Tool Simulation Flow



# Input & Output Parameters



# Outline

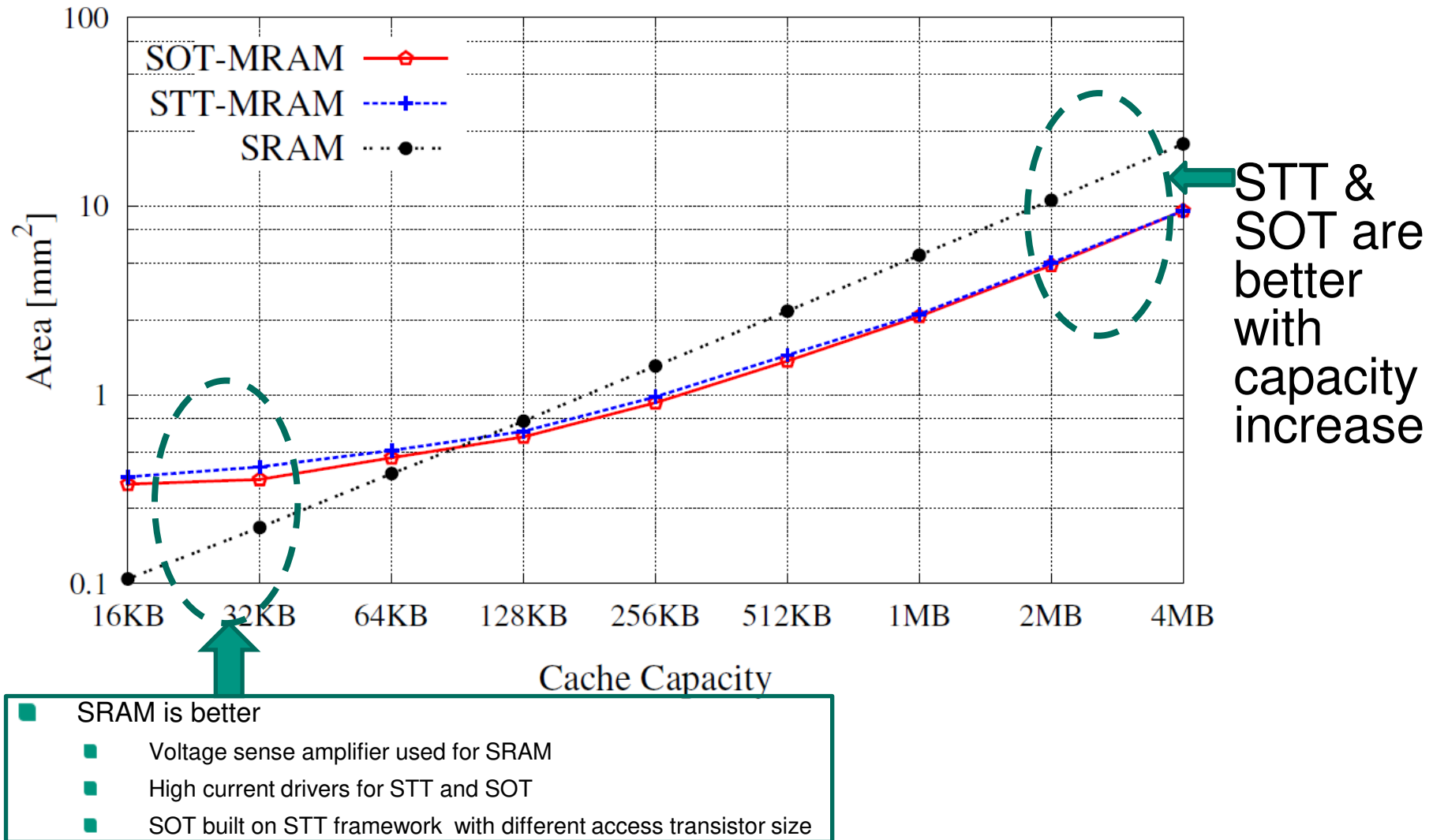
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# Comparison of various Memory Technologies

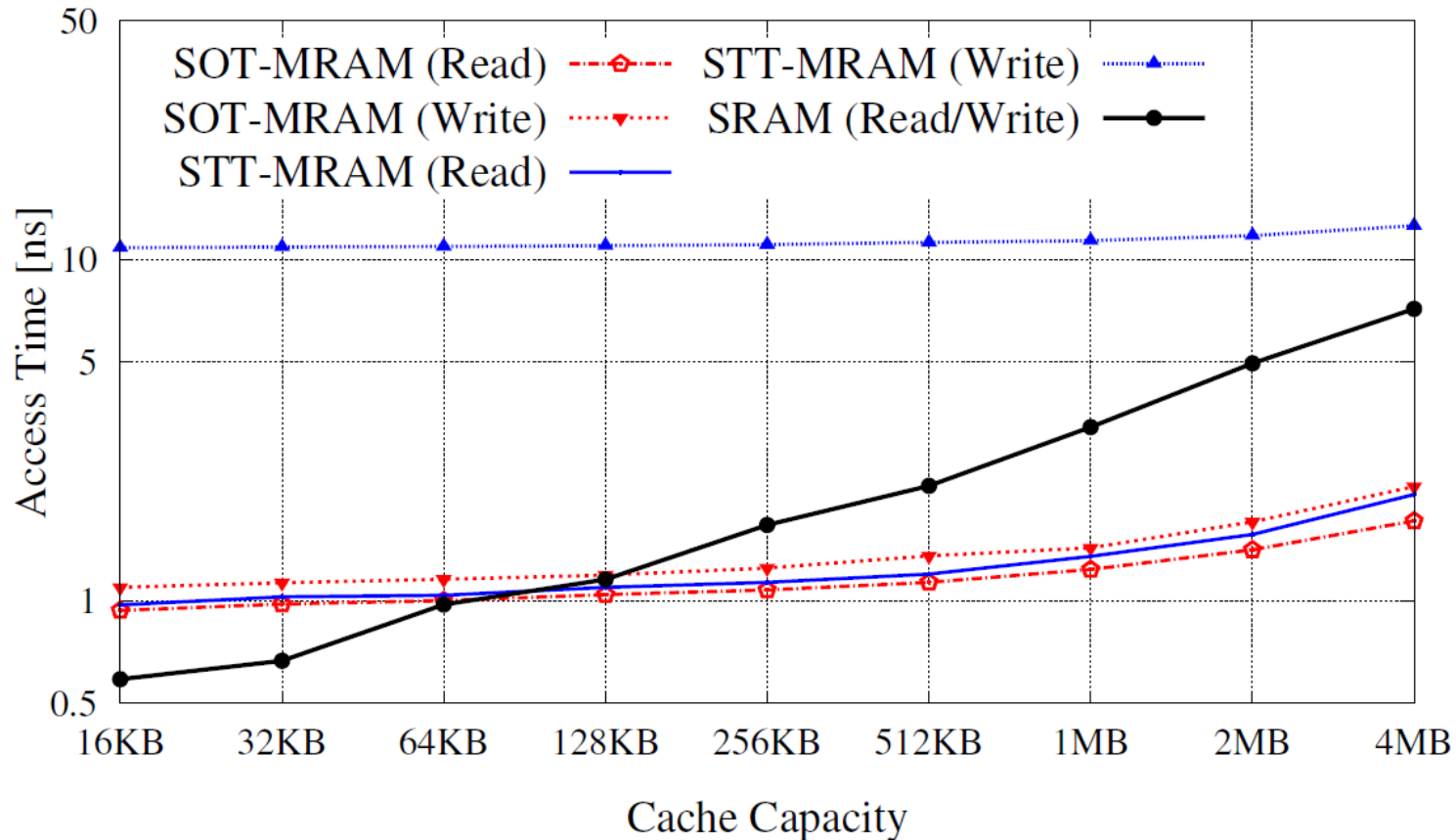
Parameters	SRAM	NAND FLASH	STT- MRAM	SOT- MRAM	PC- RAM	R- RAM
Area [mm <sup>2</sup> ]	2.8	0.2	1.6	<b>1.5</b>	0.3	0.7
Read Latency [ns]	2.2	565	1.2	<b>1.13</b>	0.6	1.2
Write Latency [ns]	2.0	2 × 10 <sup>5</sup>	11.2	<b>1.4</b>	150	21
Read Energy [pJ]	587	3921	260	<b>247</b>	363	193
Write Energy [pJ]	355	6902	2337	<b>334</b>	63670	592
Leakage [mW]	932	77	387	<b>254</b>	153	115

- Values are extracted using NVSim for
  - 512 Kbyte capacity
  - Latency optimization

# Area Comparison for various memory sizes

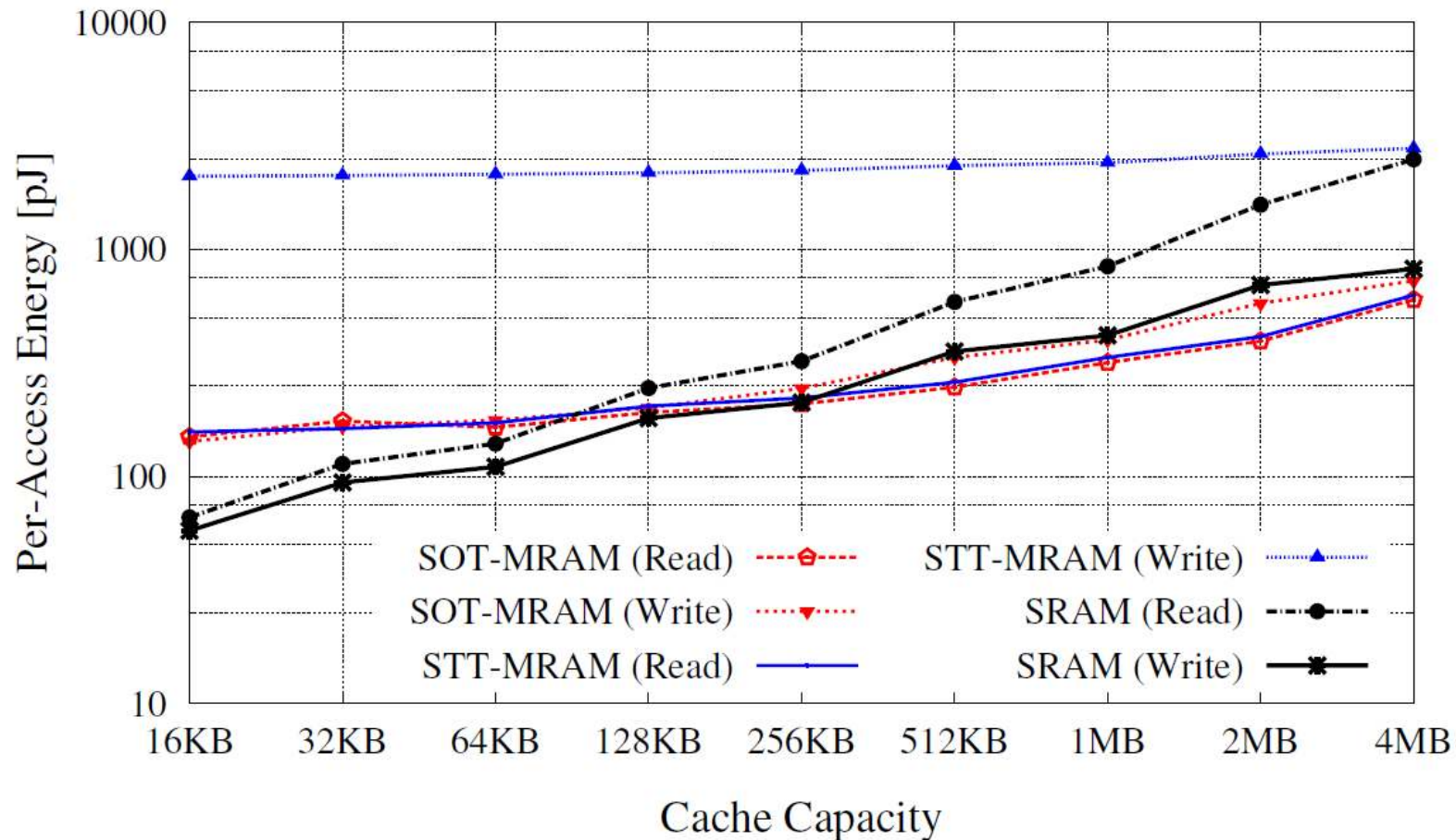


# Read & Write Latency Comparison



- SRAM varies linearly with capacity increase
- STT & SOT, remain almost flat with capacity increase

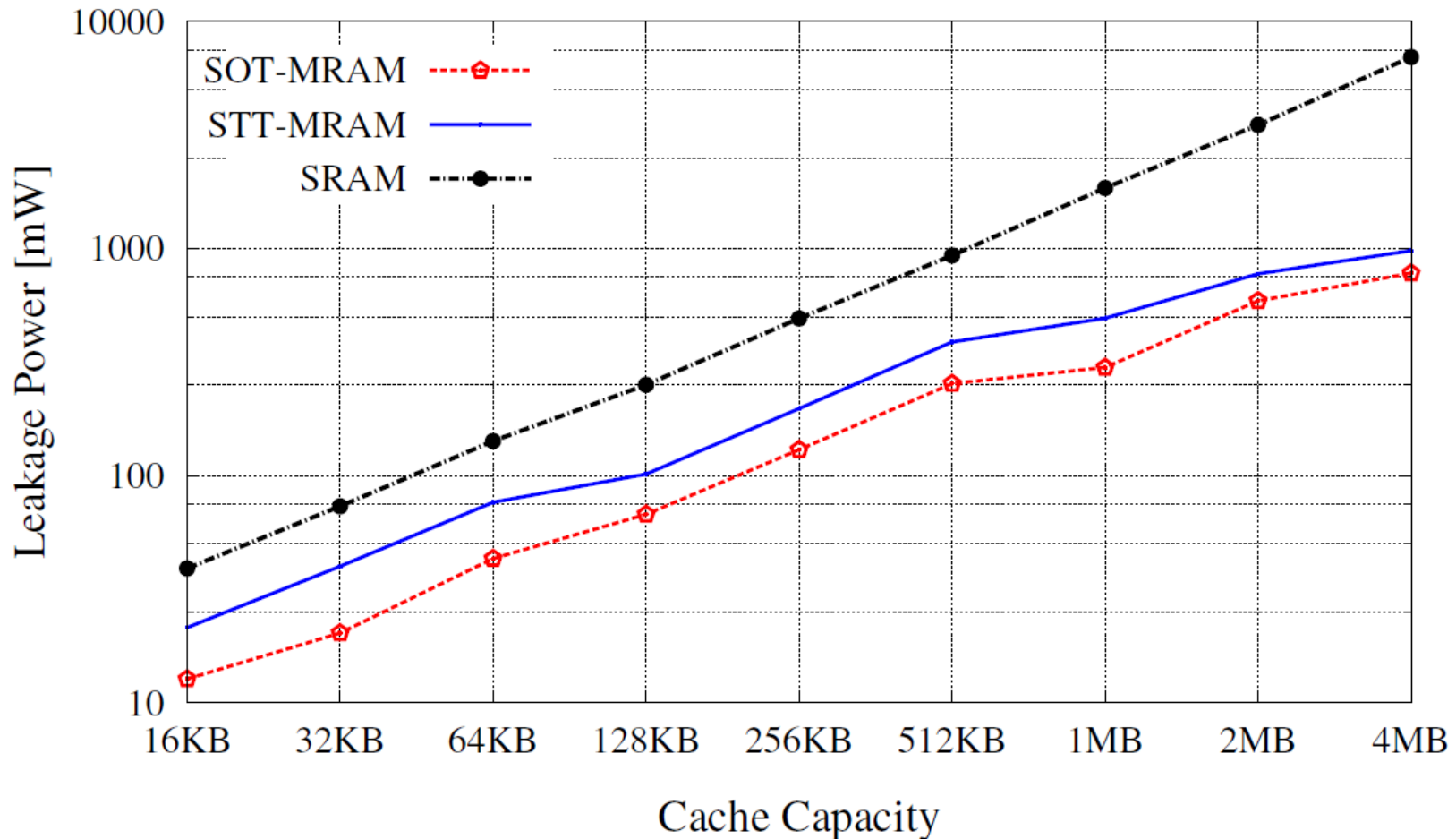
# Energy Comparison



■ SOT has almost same read & write access energy



# Leakage Comparisons

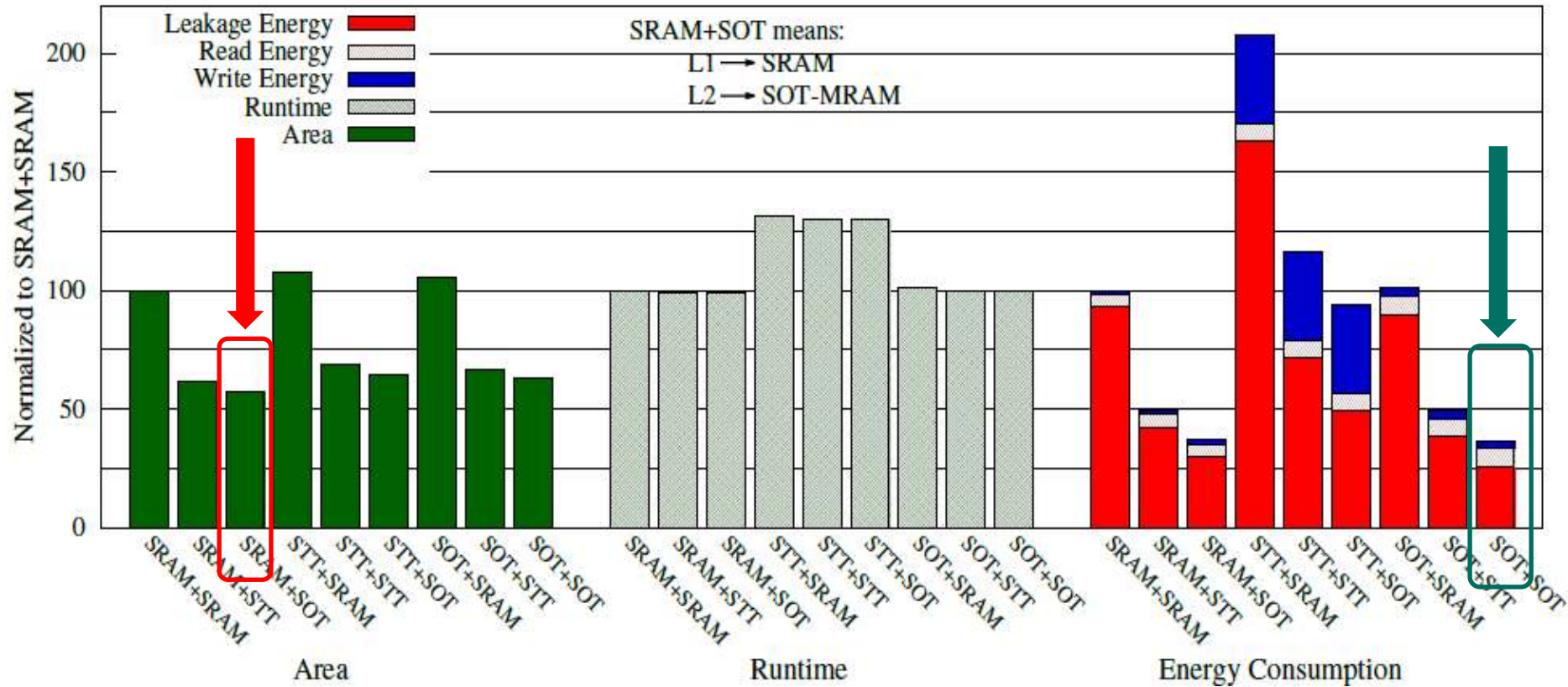


- SRAM varies linearly with capacity increase
- STT & SOT, leakage is due to periphery circuits

# System-Level Evaluation

- Configuration details for Experiments:
  - Processor : single core, 3 GHz
  - L1-Cache : 32 Kbyte with 64B Data Width
  - L2-Cache : 512 Kbyte with 64B Data Width
- Application (MiBench):
  - BasicMath, BitCnt, Qsort, Dijkstra, Patricia, StrSearch, SHA, CRC, FFT

# Comparisons with Various Cache conf.



- SRAM+SOT is best area combination.
- SOT+SOT is best energy configuration

# Benchmark Analysis

	Runtime [ms]				Energy [mJ]			
	SRAM+SRAM	SRAM+STT	SRAM+SOT	SOT+SOT	SRAM+SRAM	SRAM+STT	SRAM+SOT	SOT+SOT
BasicMath	61.4	59.8	59.8	60.5	66.4	31.6	23.6	22.8
BitCount	130.1	130.1	130.1	130.1	133.8	63.0	45.6	40.4
CRC	998.8	998.8	998.8	1025.5	1075	531.5	398.1	395.7
Dijkstra	62.7	62.4	62.4	62.6	75.5	41.2	32.9	36.8
FFT	176.1	175.4	175.3	176.1	191.9	95.5	72	71.6
Patricia	49.1	46.7	46.7	47.6	54.6	25.8	19.5	19.4
QSort	35.2	34.9	34.9	34.9	36.7	17.6	12.7	11.6
SHA	23.3	23.3	23.3	23.3	26.1	13.4	10.3	10.7
StringSearch	1.5	1.5	1.5	1.5	1.7	0.9	0.7	0.7
Average	170.9 (100 %)	170.0 (99 %)	170.0 (99 %)	173.3 (101 %)	184.6 (100 %)	91.2 (49 %)	68.4 (37 %)	67.7 (36 %)

- SOT only solution is best for low power.
- For runtime, the best combination is SRAM+SOT.

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# Summary & Conclusion

- Developed hybrid memory architecture based on SOT-MRAM
  - A cell-level information is extracted using SPICE simulations
  - NVSim tool is explored to estimate the design data
  - Many applications run using GEM5 simulator
- SOT is the best solution for low power
- Overall best is hybrid memory architecture SRAM+SOT