

Characterizing Flash Memory: Anomalies, Observations, and Applications

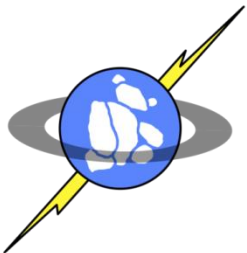
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UCSD CSE
Computer Science and Engineering



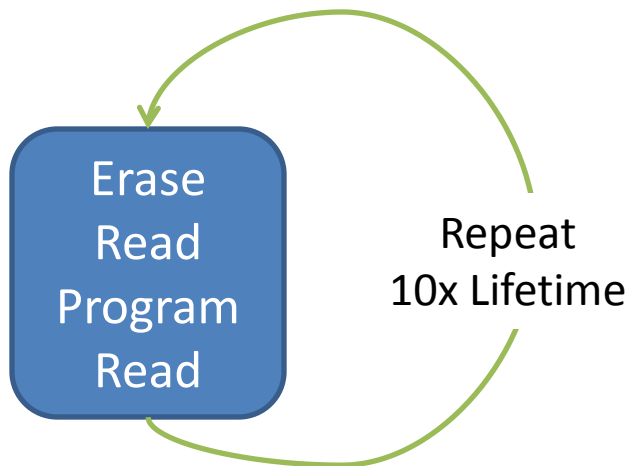
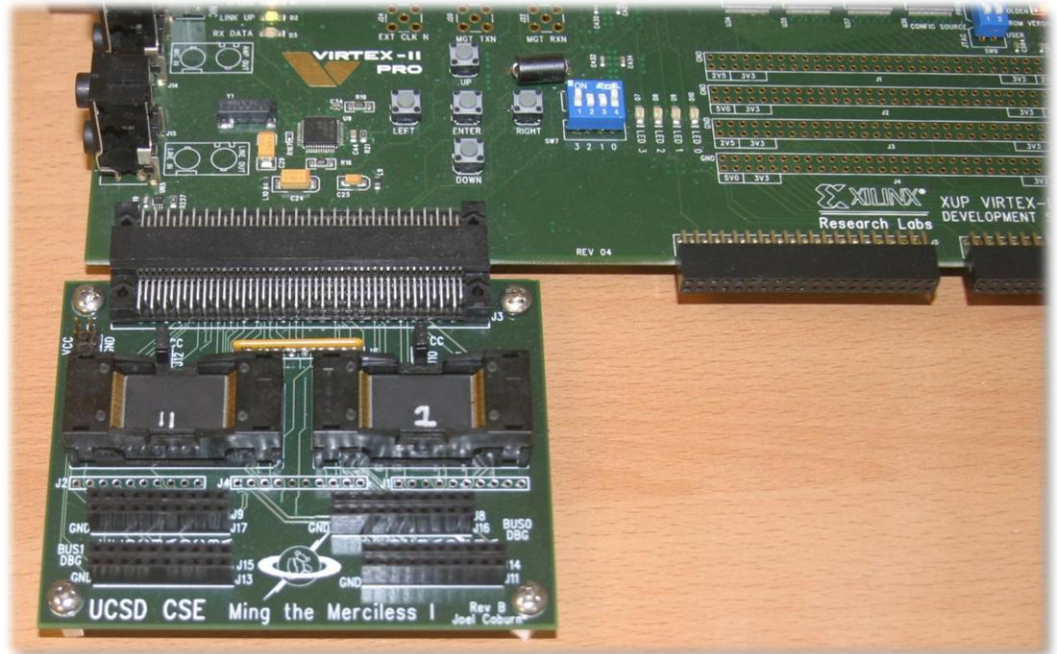
Possible Applications

- Flash Translation Layers (FTLs)
- Operating System control
- Data encodings
- Heterogeneous SSD
- Data retention time



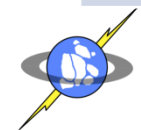
Test Setup

- Custom-Built Daughter Board
- Xilinx XUP Board
- Full-fledge Linux
- Kernel module



The Test Subjects

Chip Name	Manufacturer	Tech Node	Capacity (Gb)	Page Size (B)	Pages/Block	Block/Plane	Planes/Die	Dies
A-SLC2	A		2	2048	64	1024	2	1
A-SLC4	A		4	2048	64	4096	1	1
A-SLC8	A		8	2048	64	4096	2	1
B-SLC2	B	50nm	2	2048	64	2048	1	1
B-SLC4	B	72nm	4	2048	64	2048	2	1
E-SLC8	E		8	2048	64	4096	1	2
B-MLC8	B	72nm	8	2048	128	4096	1	1
B-MLC32	B	50nm	32	4096	128	2048	2	2
C-MLC64	C	43nm	64	8192	128	4096	1	2
D-MLC32	D		32	4096	128	4096	1	2
E-MLC8	E		8	4096	128	1024	1	2



The Tests

Quantify known and unknown properties

- Performance



- Energy Efficiency



- Reliability



The Tests

Quantify known complexities, look for new ones

- **Performance**

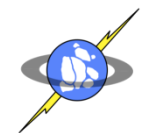
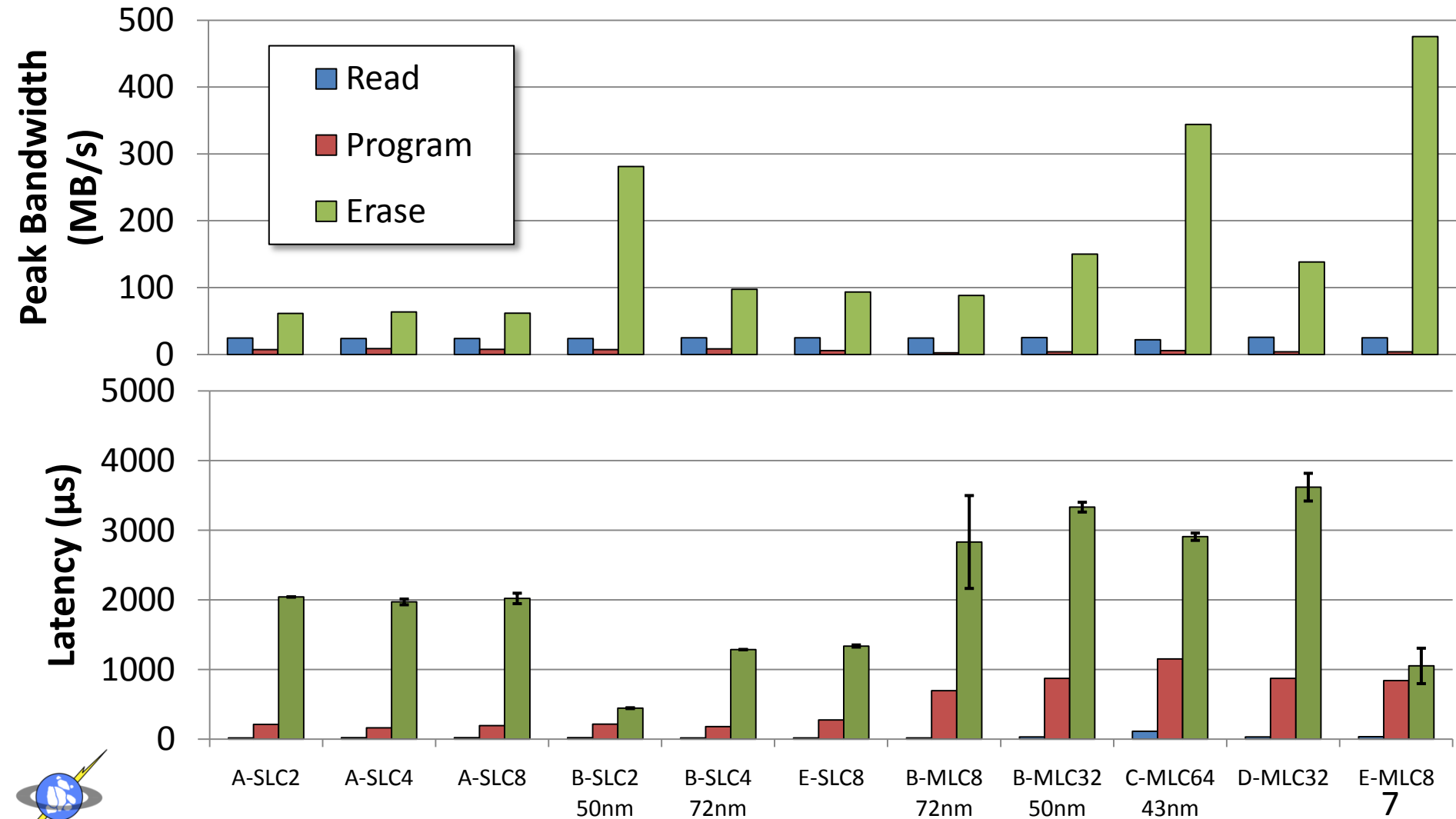


- Power & Energy

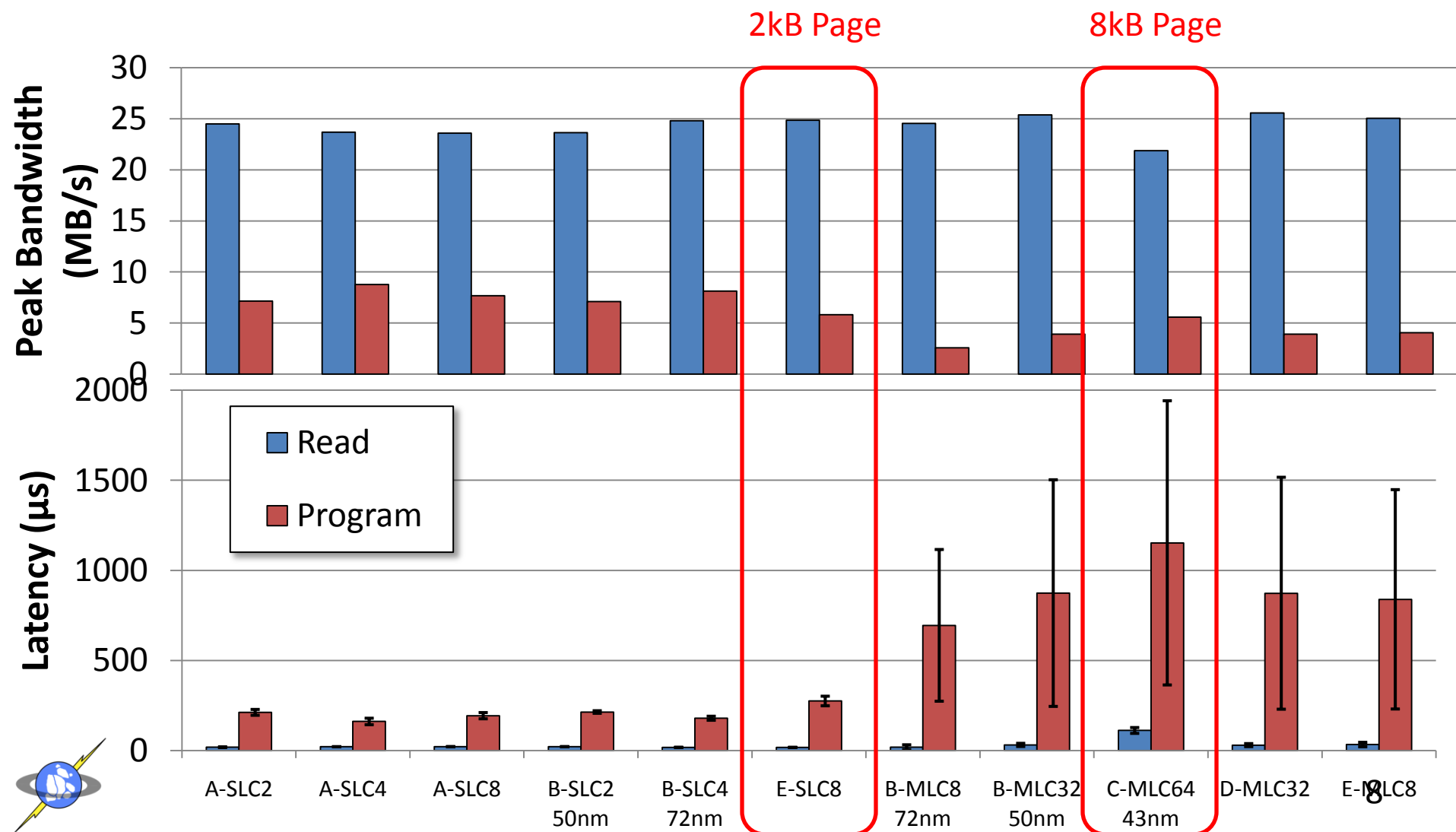
- Reliability



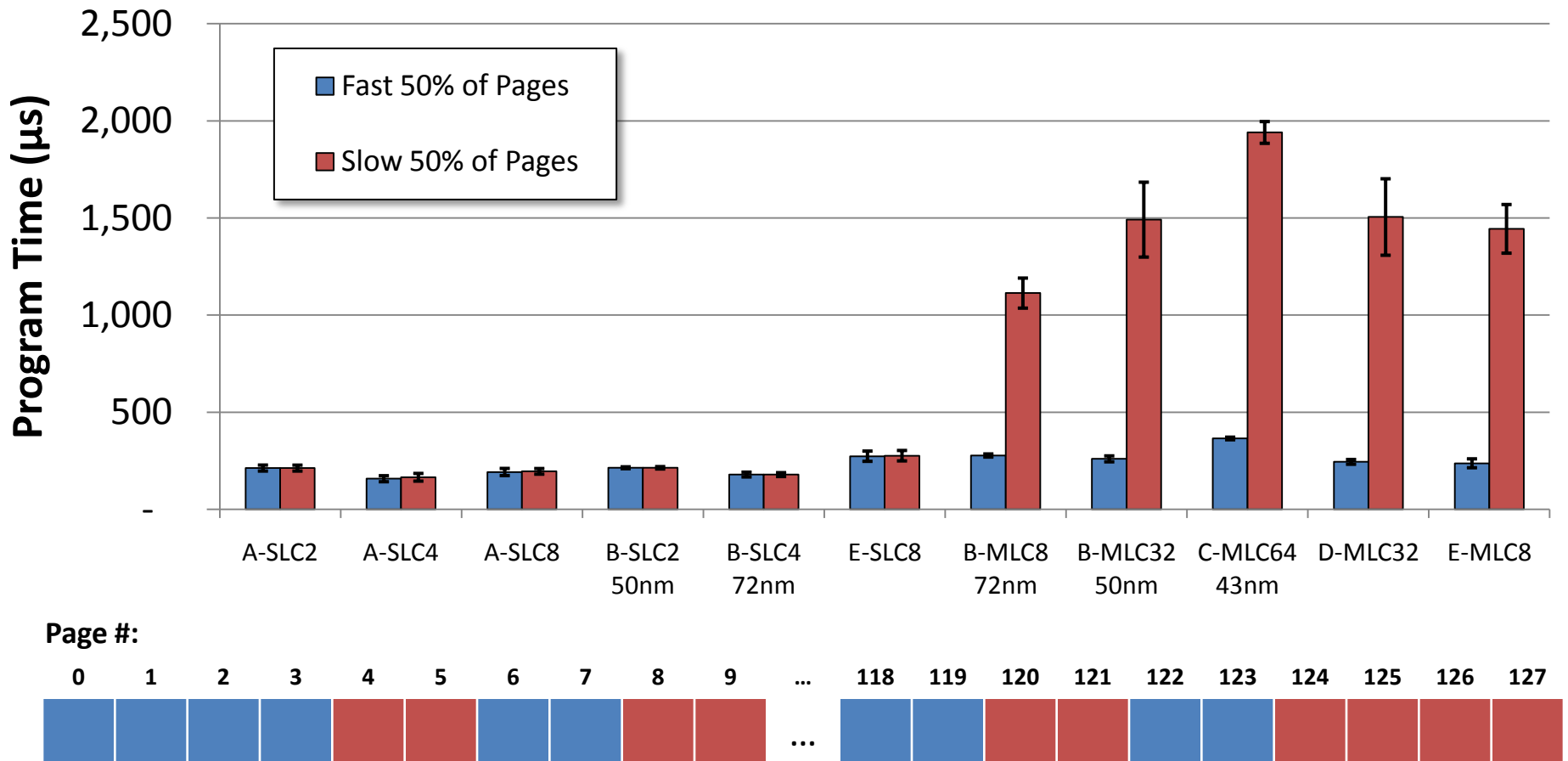
Erase



Read and Program



Program Latency Anomaly



High & Low Order Bits

Flash State

Logical Data

	<u>High Order</u> (fast)	<u>Low Order</u> (slow)
	0	0
	0	1
	1	0
	1	1

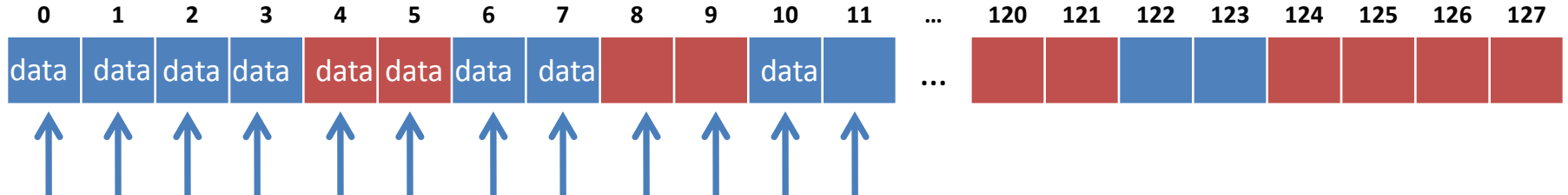


Variation-Aware Interface

Extend Interface from MSR [Birrell et. al., 2005]

“High priority” == write to fast page

“Low priority” == write to any page



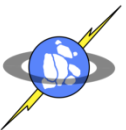
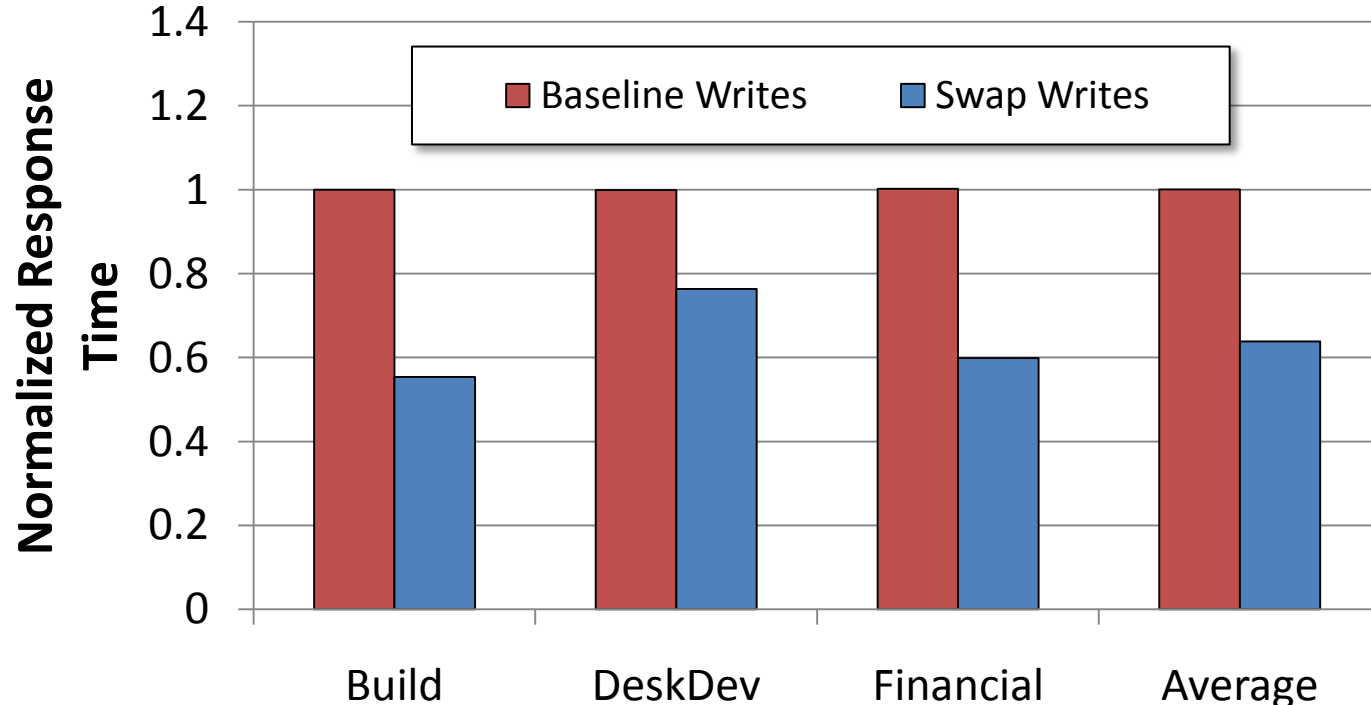
+ Lower latency when it matters

- Increase wear



Improving Paging Latency

- Paging in/out virtual memory == high priority
- Goal: reduce swap latency **40% faster**
- Side effect: Increased Wear **3% increase**



MLC as SLC: Single Mode Level Cell?

Page #:



Average cost per bit

MLC: 31 ¢/Gbit

SLC: 94 ¢/Gbit

MLC is **33%** of SLC

DRAMeXchange

4/10/10



The Tests

Quantify known complexities, look for new ones

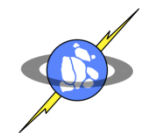
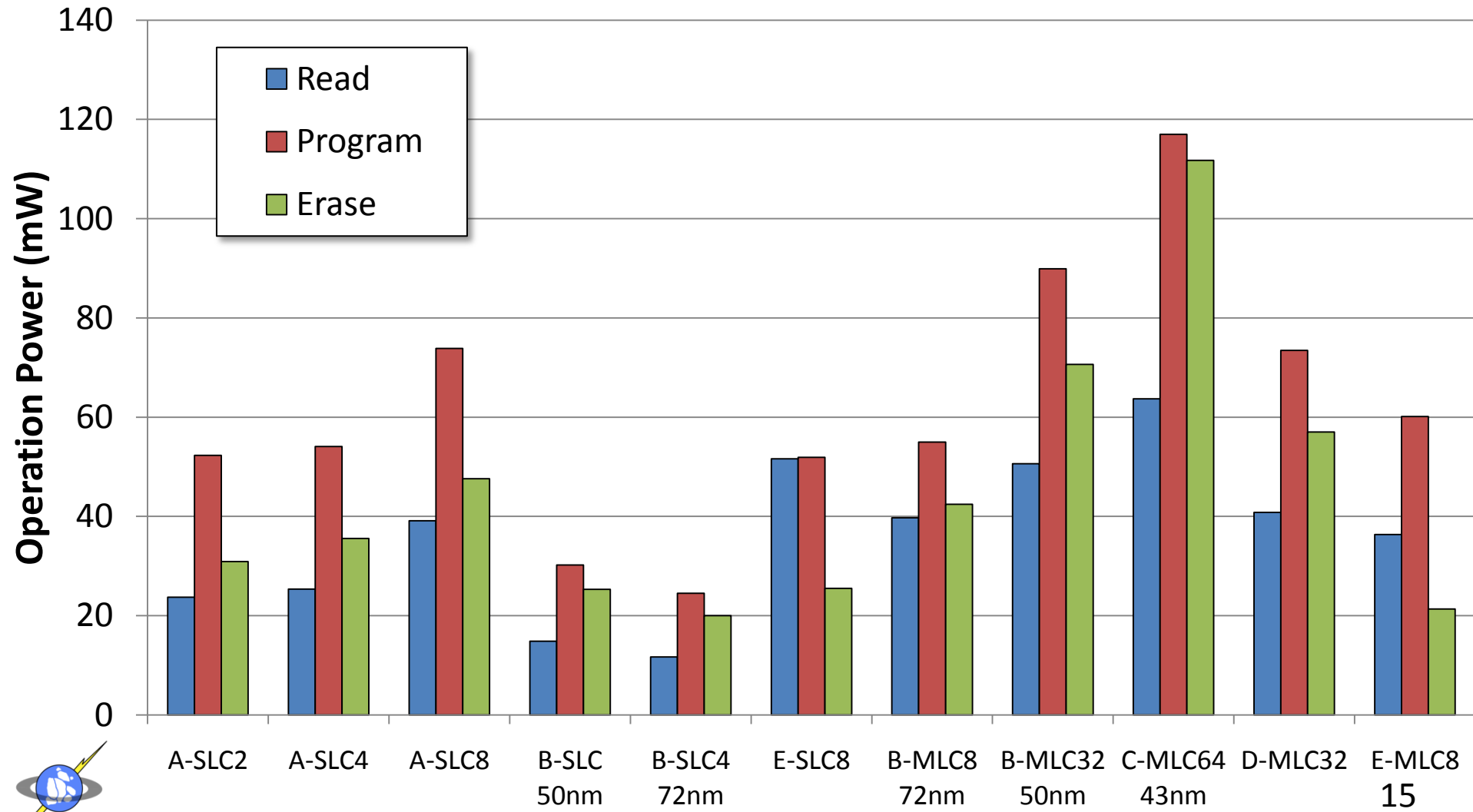
- Performance
- **Power & Energy**
- Reliability



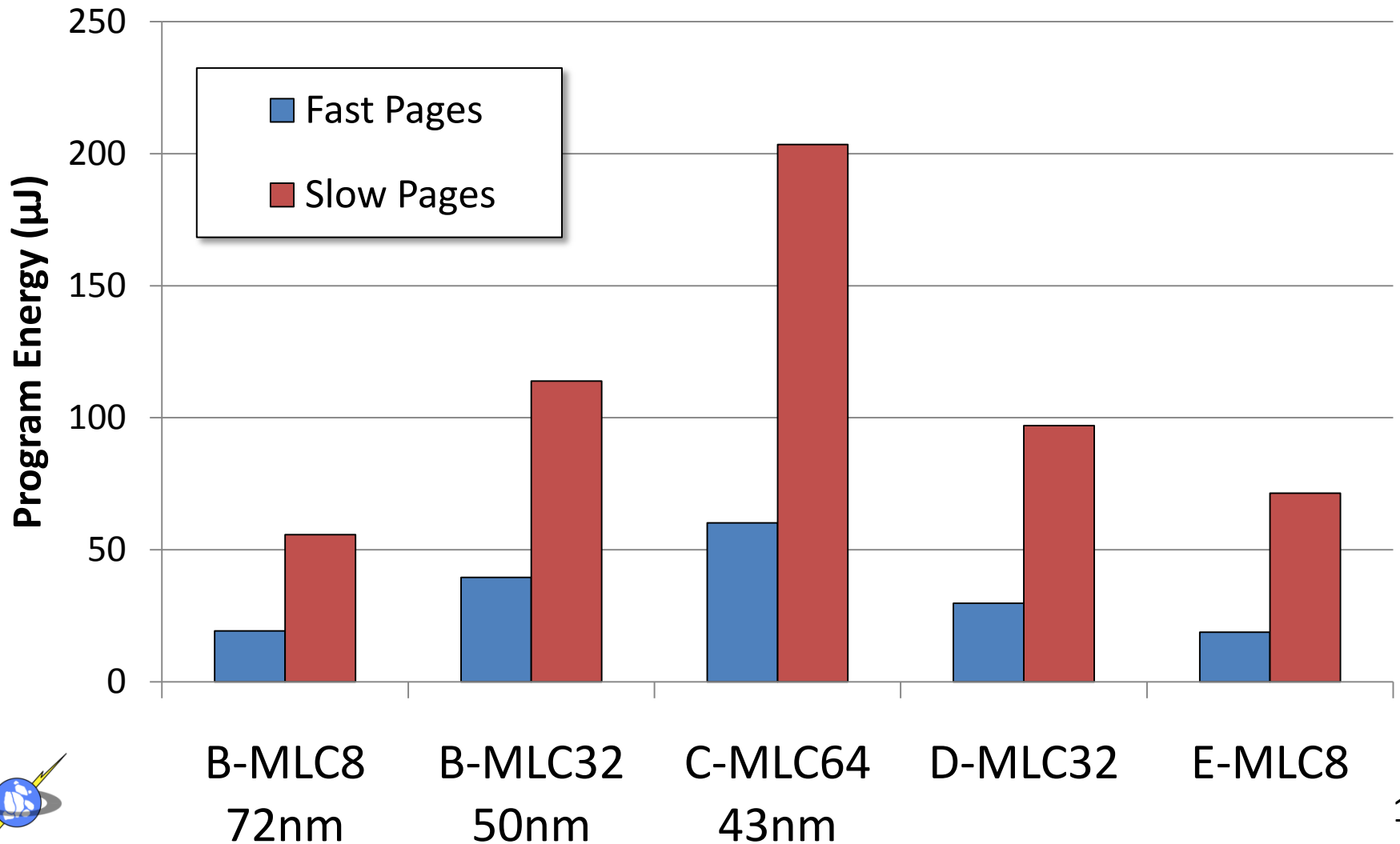
From a representative datasheet →

	Typ	Max	Unit
Sequential read	45	90	mW
Program	45	90	mW
Erase	45	90	mW

Peak Power



Energy: MLC



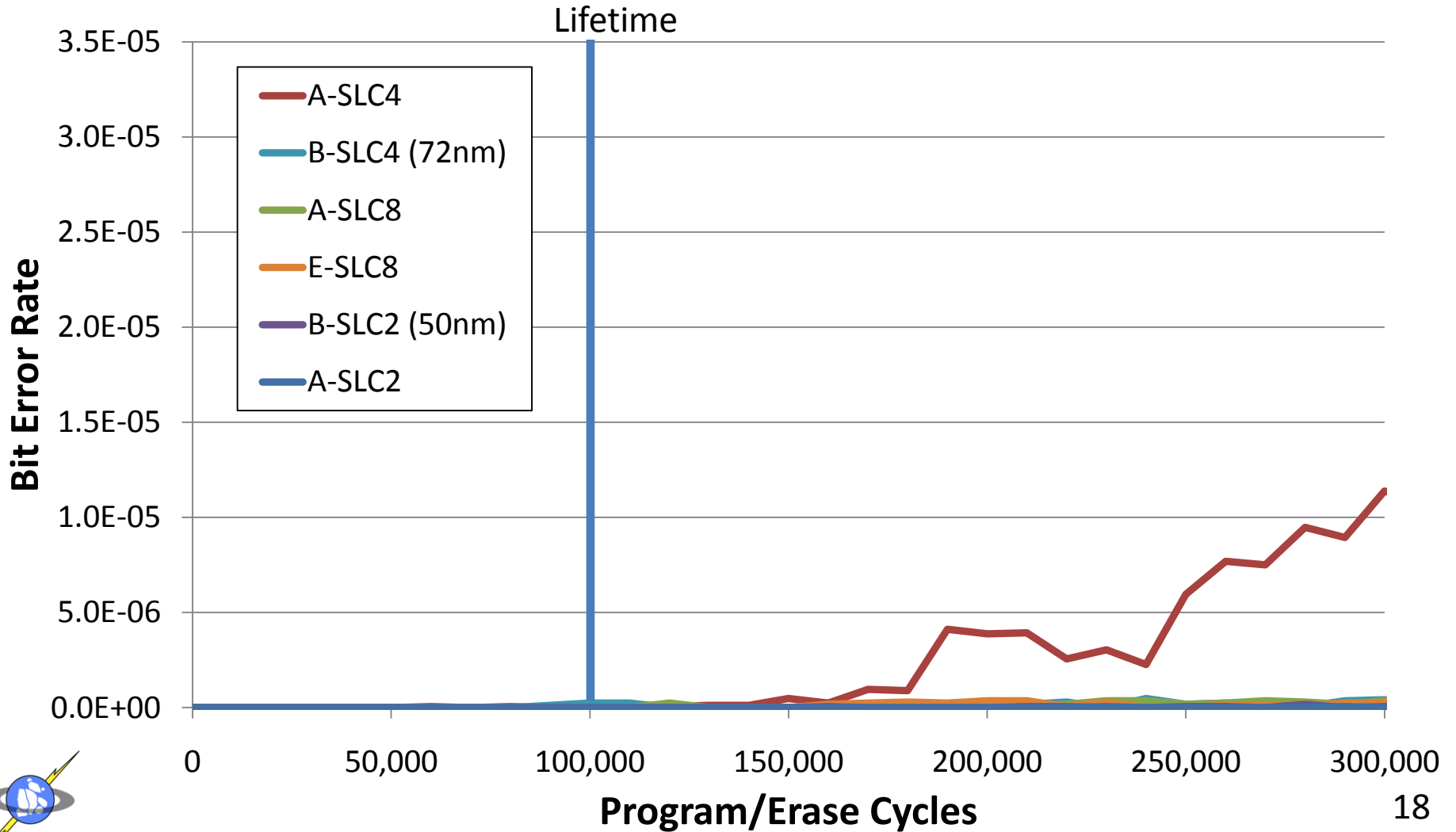
The Tests

Quantify known complexities, look for new ones

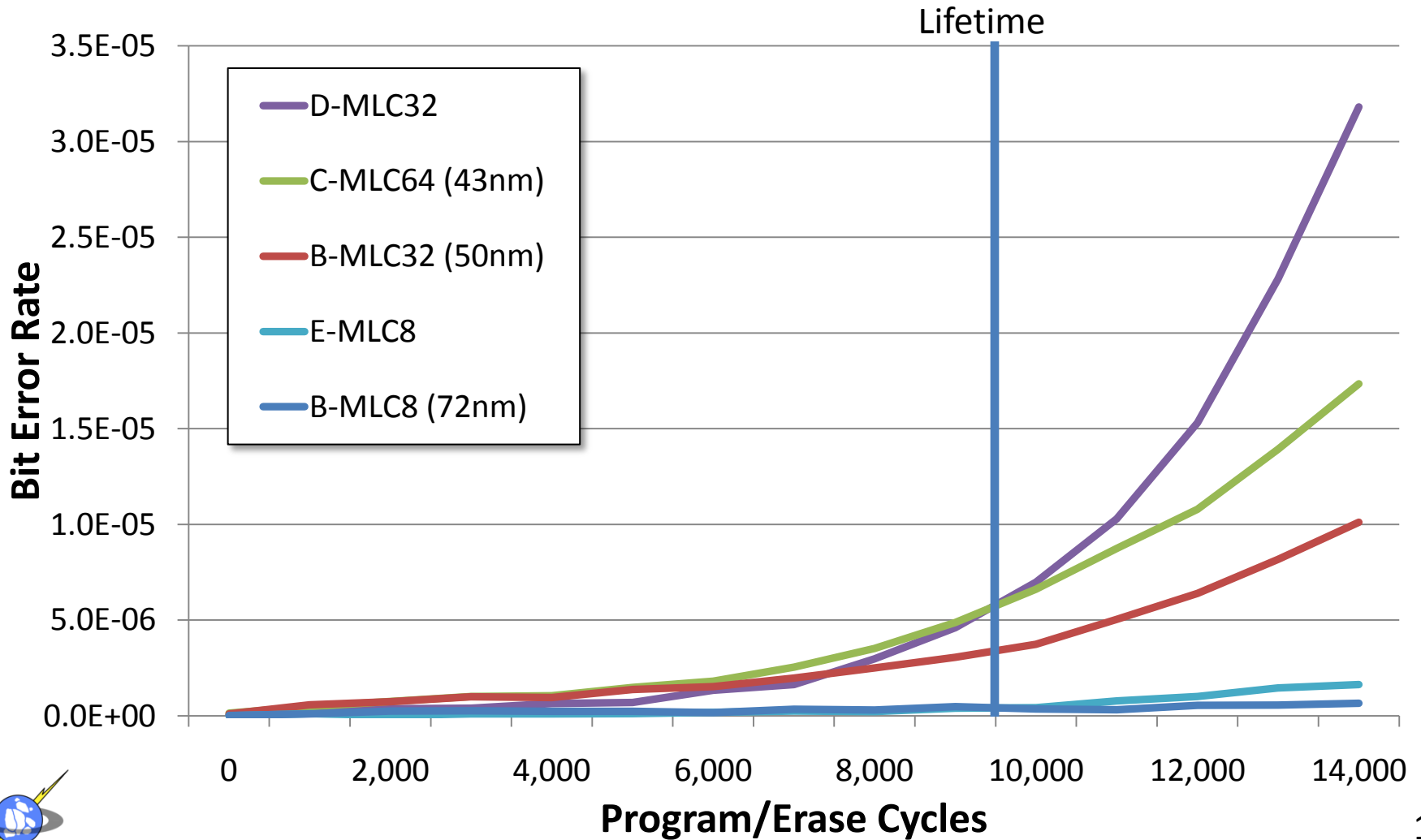
- Performance
- Energy Efficiency
- **Reliability**



SLC Wear Out

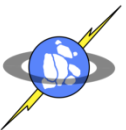
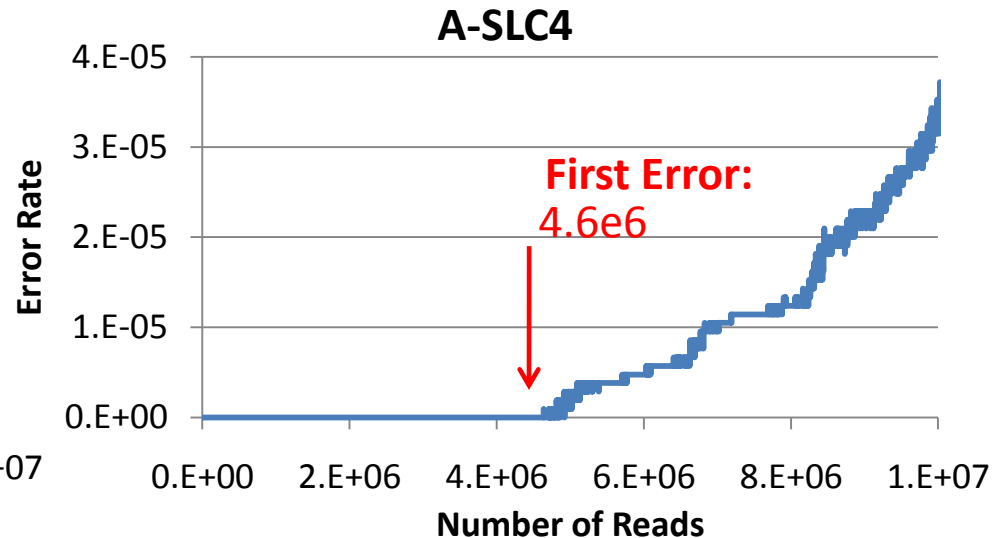
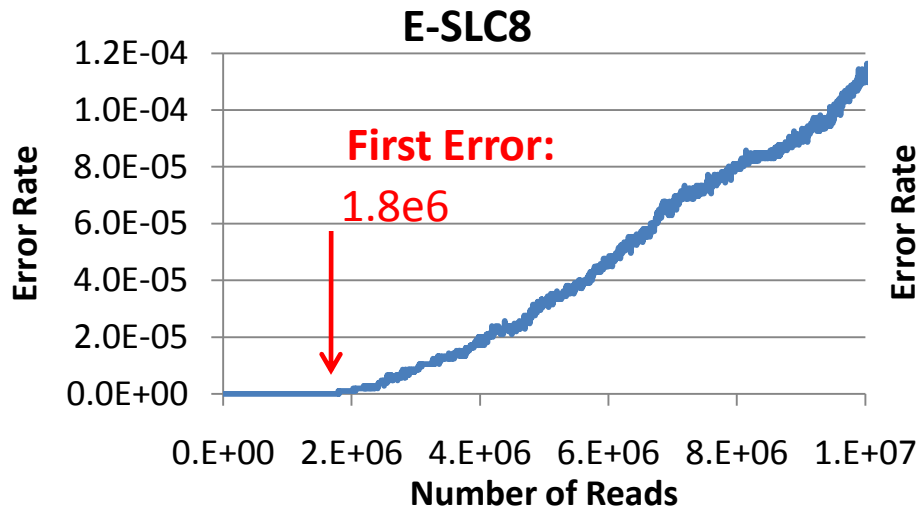


MLC Wear Out

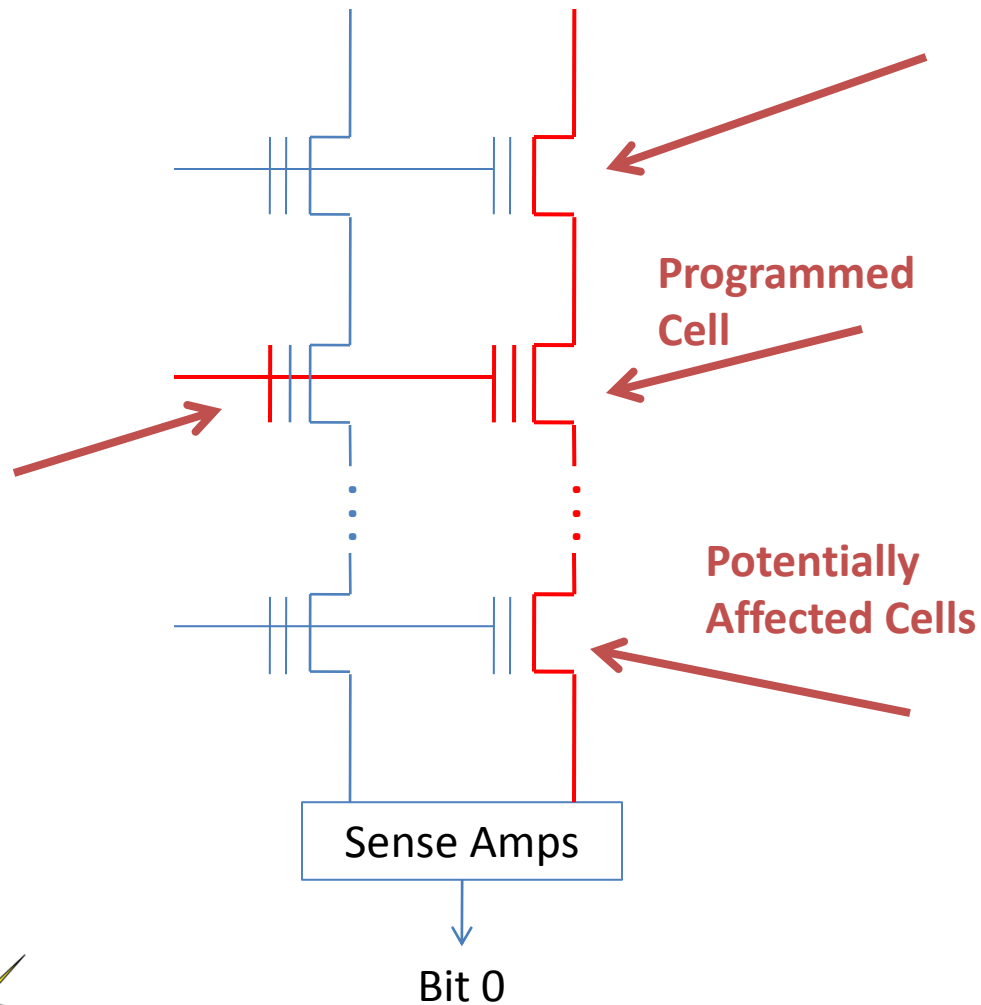


Read Disturb

The degradation of a bit by **reading** that cell or another.



Program Disturb



The degradation of a bit by **programming** that cell or another

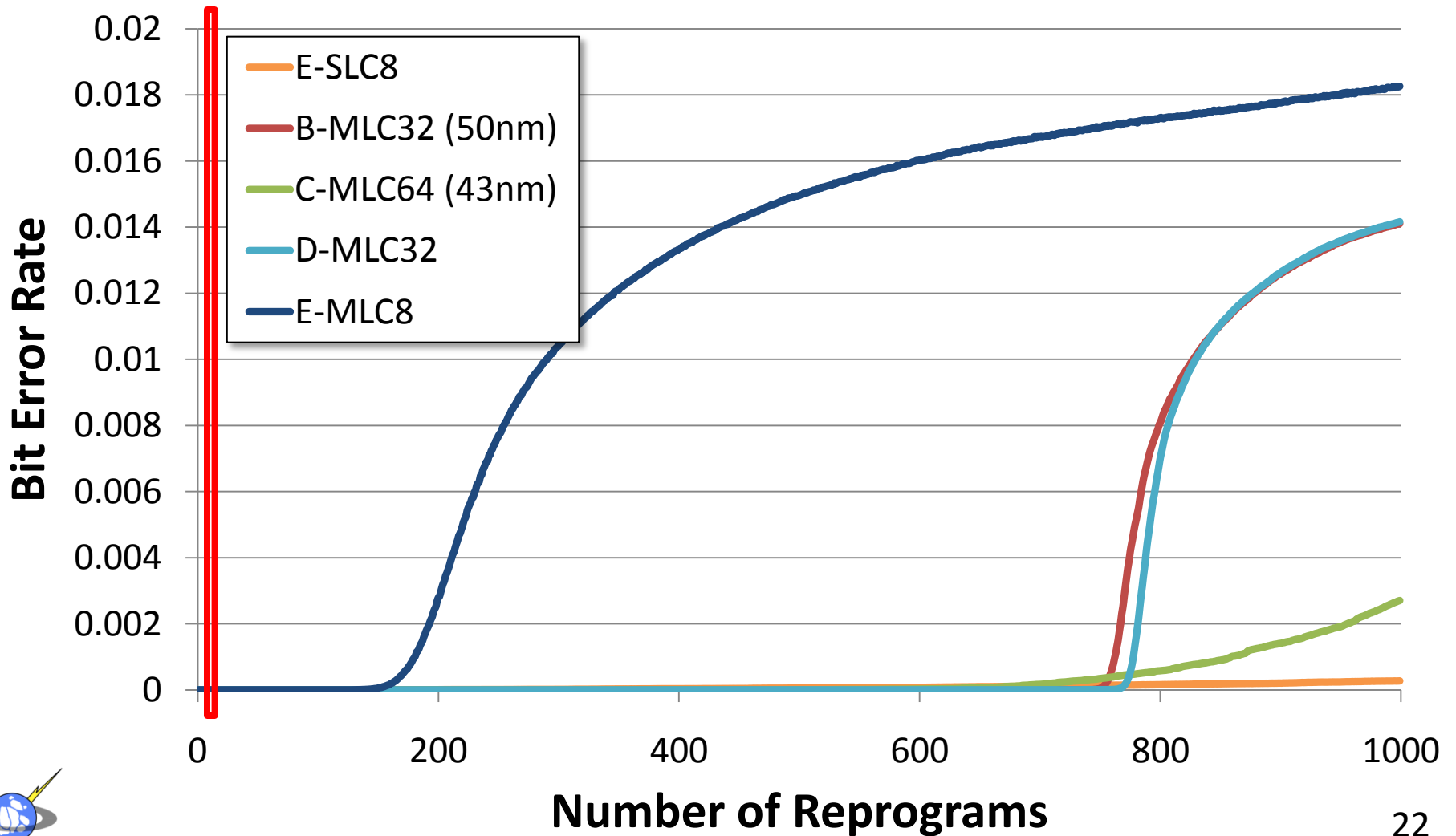
Procedure:

Erase Block

Repeat:

Program new data
to one page

Program Disturb



Program Disturb: 1 reprogram



- SLC: no errors for at least one reprogram



- MLC: errors for reprograms of certain pages



Write-Once Memory (WOM) Codes

Old Byte: 01110110

New Byte: 10000111

Logical Bits	First Generation	Second Generation
00	111	000
01	110	001
10	101	010
11	011	100

Program: 01 11 01 10
 Reprogram: 10 00 01 11

Physical	110	011	110	101	1 st Gen.
Physical	010	000	110	100	2 nd Gen.

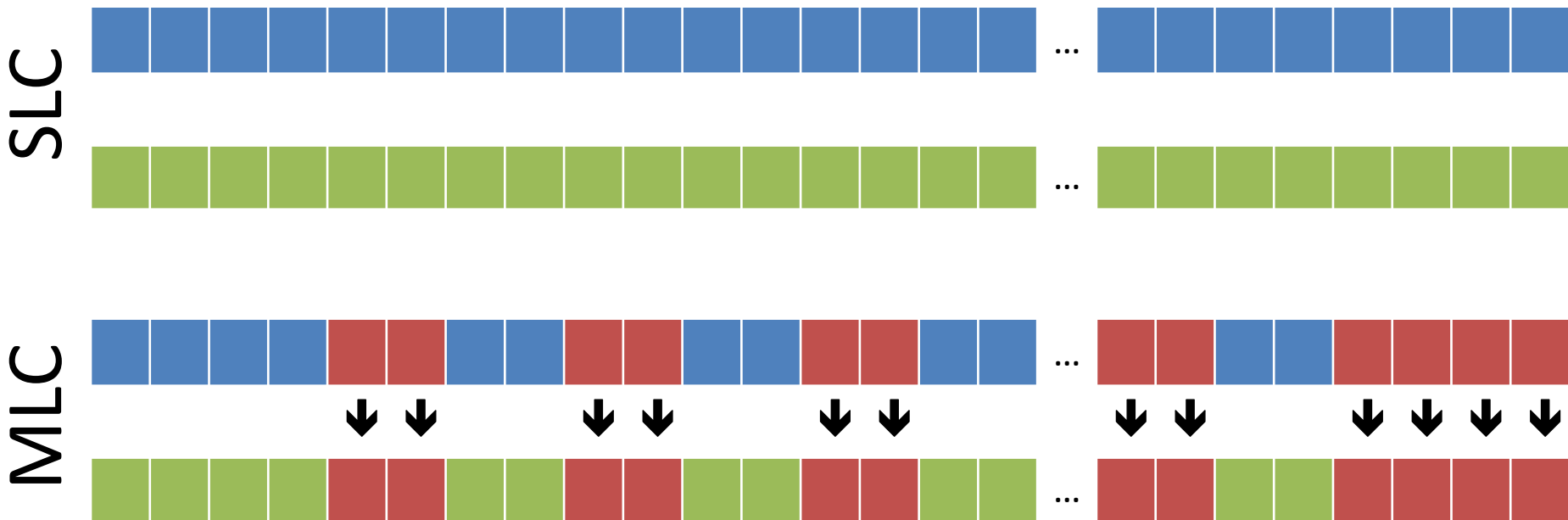


WOM Codes and Flash

Procedure: Erase, Program, Reprogram, Repeat

WOM-safe: can be reprogrammed – use WOM encoding

WOM-unsafe: can't be reprogrammed – don't encode



Effective Lifetime

How many logical bits can we program per erase?

SLC

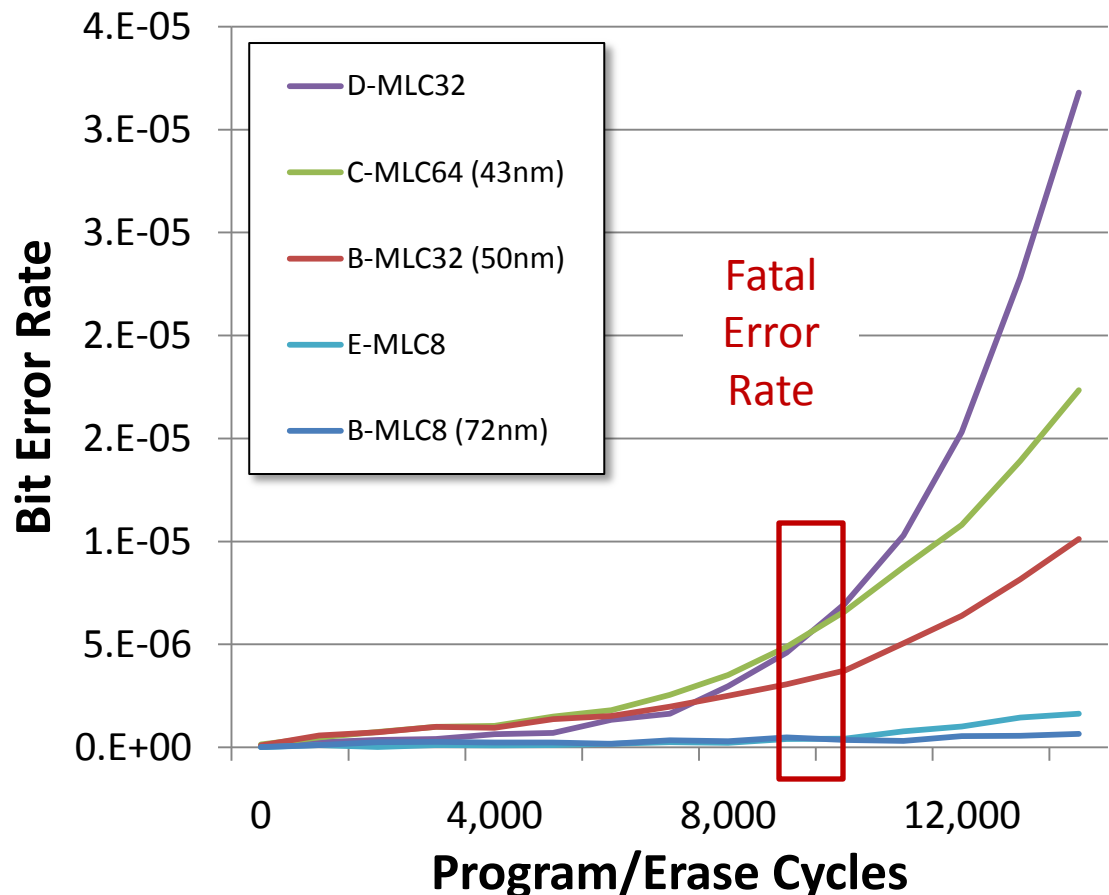
$$2 * \frac{2}{3}$$

= 33% increase

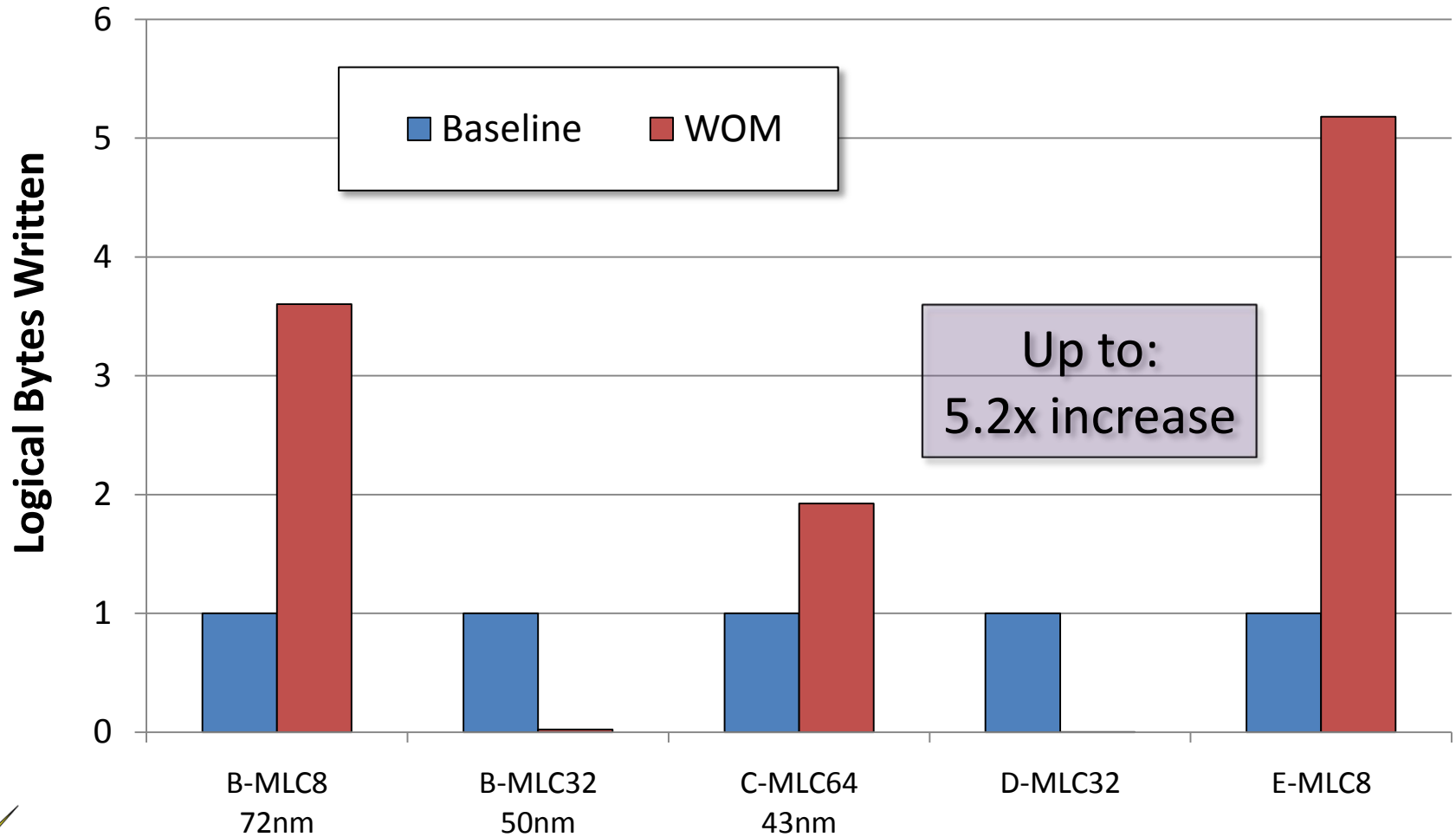
MLC

$$\frac{1}{2}(2 * \frac{2}{3}) + \frac{1}{2}(1)$$

= 16.5% increase



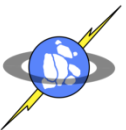
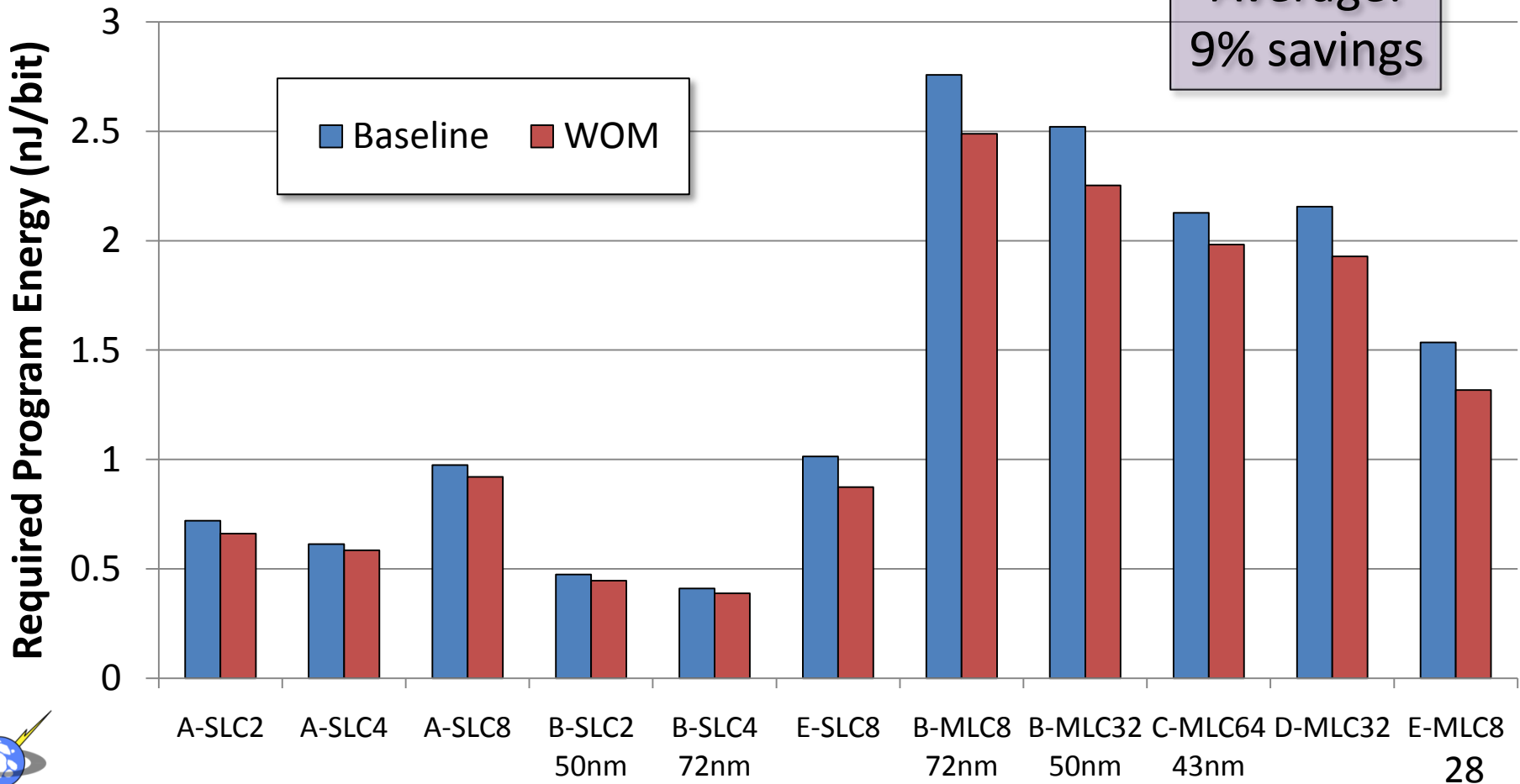
WOM Codes - Lifetime Extension



WOM Codes – Energy Reduction

Fewer erases per written bit

Average:
9% savings



Future Work

- Chips & Commands
 - more chips, higher densities
 - Other operations: cached, multi-plane
- Effects
 - Data retention
 - Data Dependence
 - Radiation Tolerance
 - Delay between Operations
- Applications
 - Error correction codes
 - Data encodings
 - New Applications
 - Interface Modifications

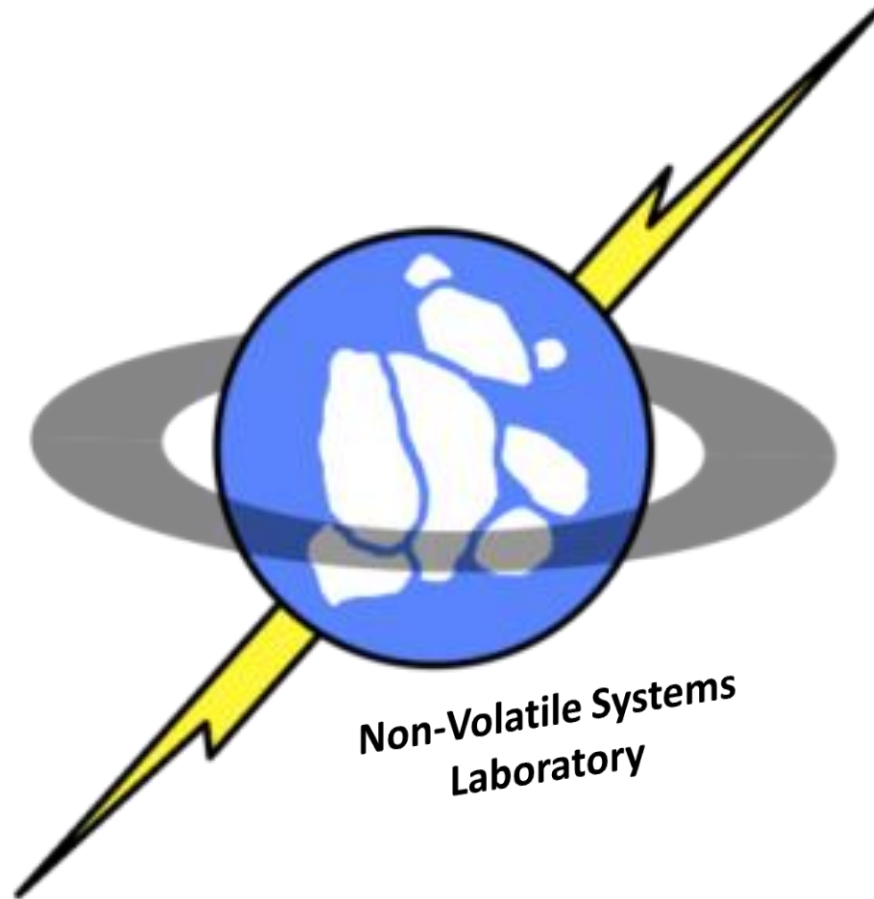


Conclusion

- Flash Memory beyond the datasheet
- Variation-Aware Interface:
 - **Latency** Reduction: average of **40%**
 - **Energy** Savings: average of **13%**
- Write Once Memory (WOM) Encoding
 - **Lifetime** Extension: up to **5.2x**
 - **Energy** Savings: average of **9%**



Thank You



Non-Volatile Systems
Laboratory

