Normalized Stability: A Cross-Level Design Metric for Early Termination in Stochastic Computing

Di Wu, Ruokai Yin and Joshua San Miguel
University of Wisconsin-Madison

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Outline

- ❑ Primer on stochastic computing
- ❑ Early termination for stochastic computing
- ❑ Metric-based characterization for early termination
- ❑ Evaluation of the metric on applications

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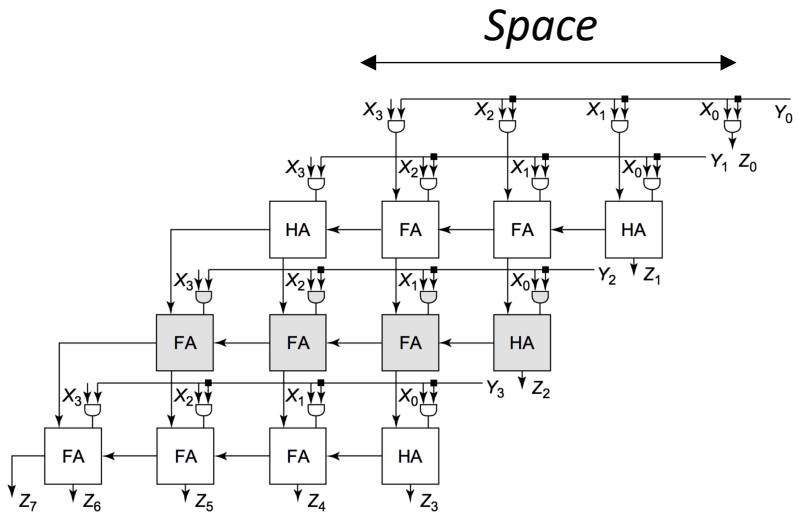
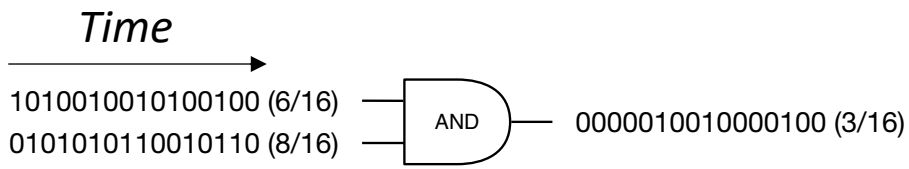
Stochastic Computing – Comparison

- Binary Computing
  - Varying significance in parallel data bits.
  - Spatial domain with complex logic.



Binary multiplier (4-bit data in 1 cycle)

- Stochastic Computing (SC)
  - Equal significance in serial data bits.
  - Temporal domain with simple logic.



SC multiplier (4-bit data in 16 cycles)

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SC Data

- Bit stream with rate coding
  - Valued by the frequency of 1s in the bit stream

A=0.5	1	1	0	1	0	1	1	1	0	0	1	0	0	1	0	0
B=0.5	0	0	1	0	0	1	1	1	0	1	0	1	0	1	0	1
C=0.75	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1	1

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SC Data

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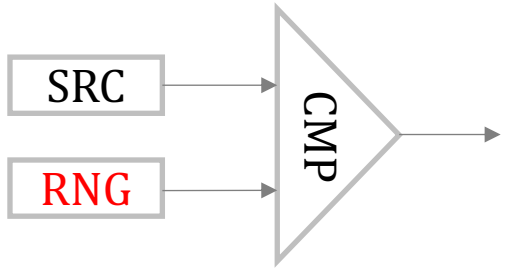
A=0.5	1	1	0	1	0	1	1	1	0	0	1	0	0	1	0	0
B=0.5	0	0	1	0	0	1	1	1	0	1	0	1	0	1	0	1
C=0.75	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1	1

  - Generated by comparing source data with random numbers



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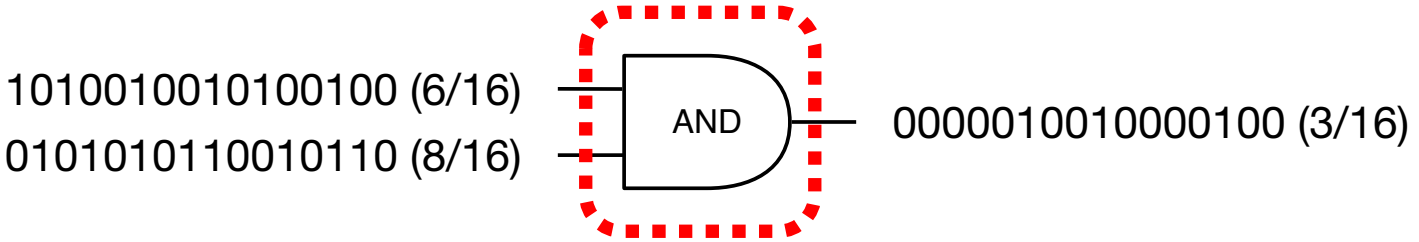
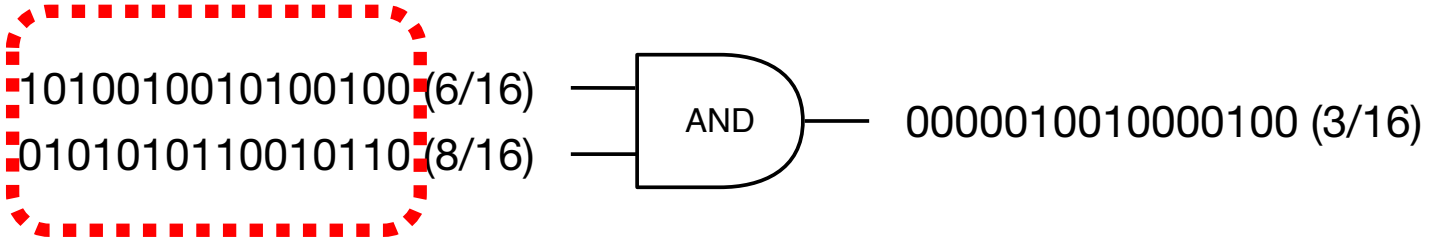
Pros & Cons of SC



AND gate as multiplier

- Pros: computing unit
  - Low area and power
  - High parallelism

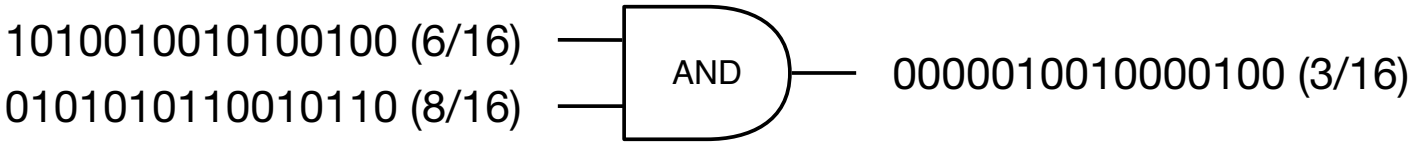
Pros & Cons of SC



n-bit data require 2^n cycles, i.e., exponentially increasing latency

- Pros
  - Low area and power
  - High parallelism
- Cons: data representation
  - Inaccuracy due to randomness
  - Long latency

Pros & Cons of SC



- Pros
  - Low area and power
  - High parallelism
- Cons
  - Inaccuracy due to randomness
  - Long latency

Joint effect:
Undetermined energy efficiency

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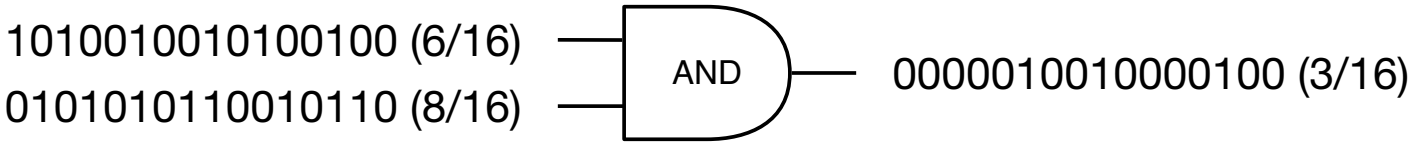
Pros & Cons of SC



- Pros
  - Low area and power
  - High parallelism
- Cons
  - Inaccuracy due to randomness
  - Long latency

Joint effect:
Undetermined energy efficiency

Improve energy efficiency with early termination

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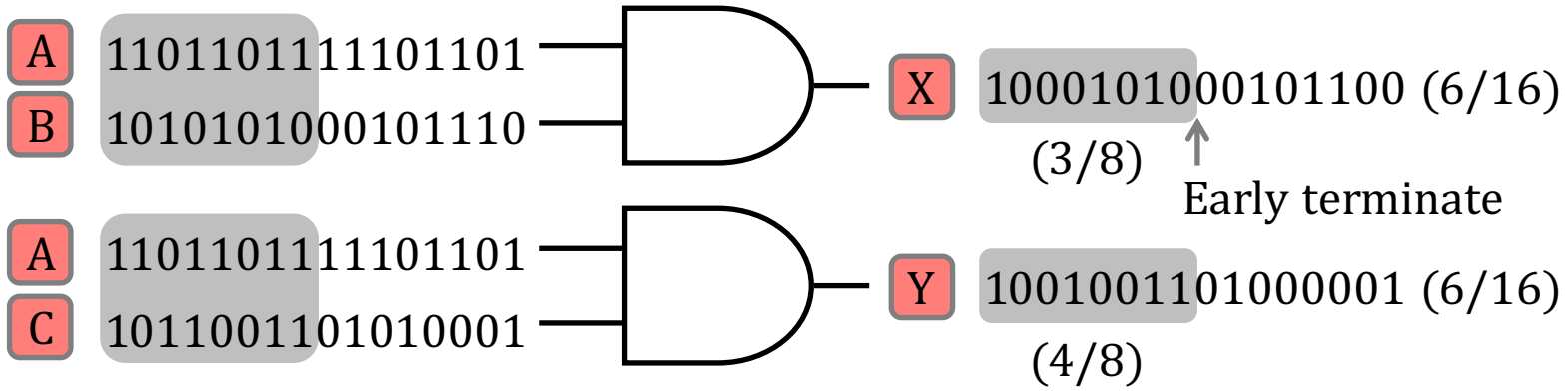
Early Termination

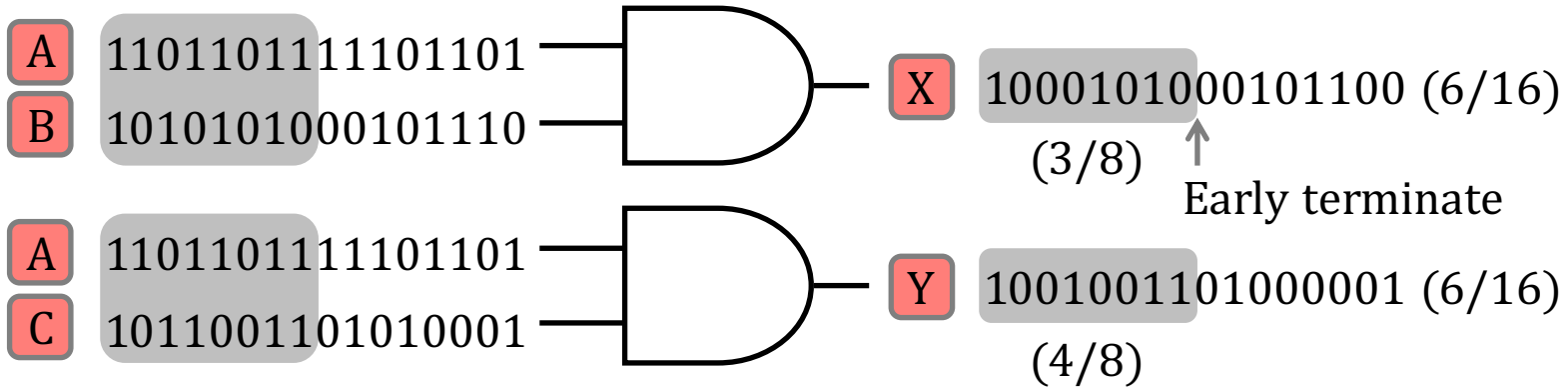
- Early termination (ET) enables high energy efficiency



  - X can be terminated without error using half cycles

Early Termination

- Early termination (ET) enables high energy efficiency



  - X can be terminated without error using half cycles

- New metric for characterizing early termination
  - Normalized stability

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Normalized Stability

- Capability
  - Unit level:
    - Identify the competitiveness for ET
  - Application level:
    - Explore design space for ET
    - Predict the timing for ET

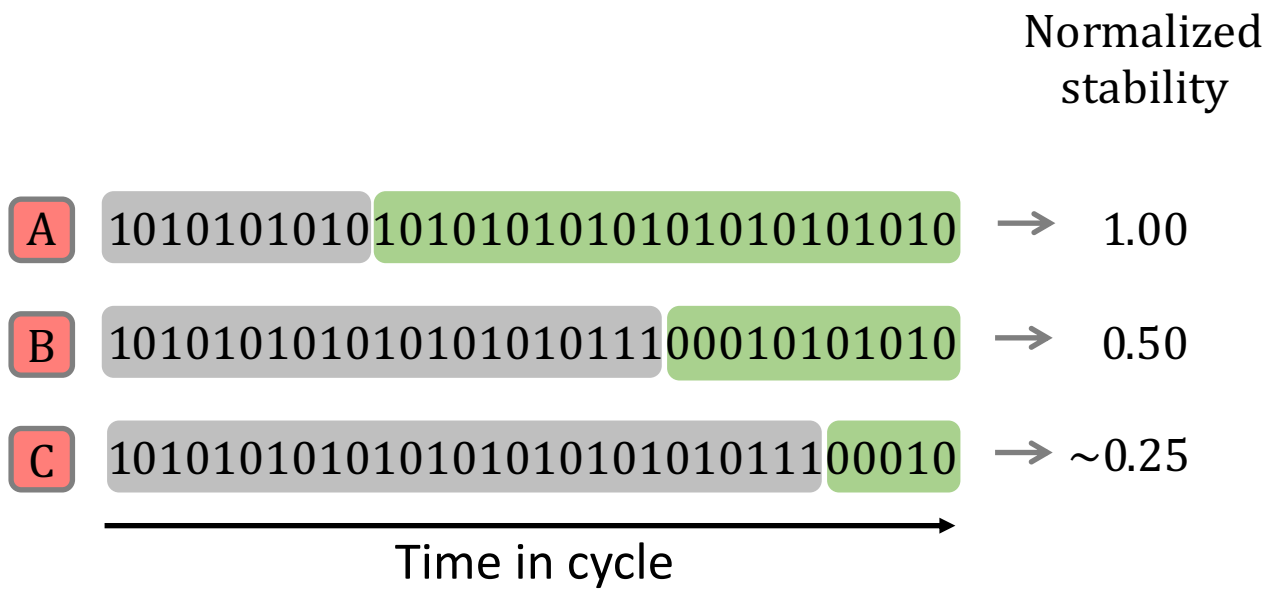
Normalized Stability

- Definition
  - How long a bit stream has been stable within a pre-defined accuracy budget, normalized to the maximum achievable stable duration

Normalized Stability

- Definition
  - How long a bit stream has been stable within **a pre-defined accuracy budget**, normalized to the maximum achievable stable duration

5% error, adapted from approximate computing



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Normalized Stability

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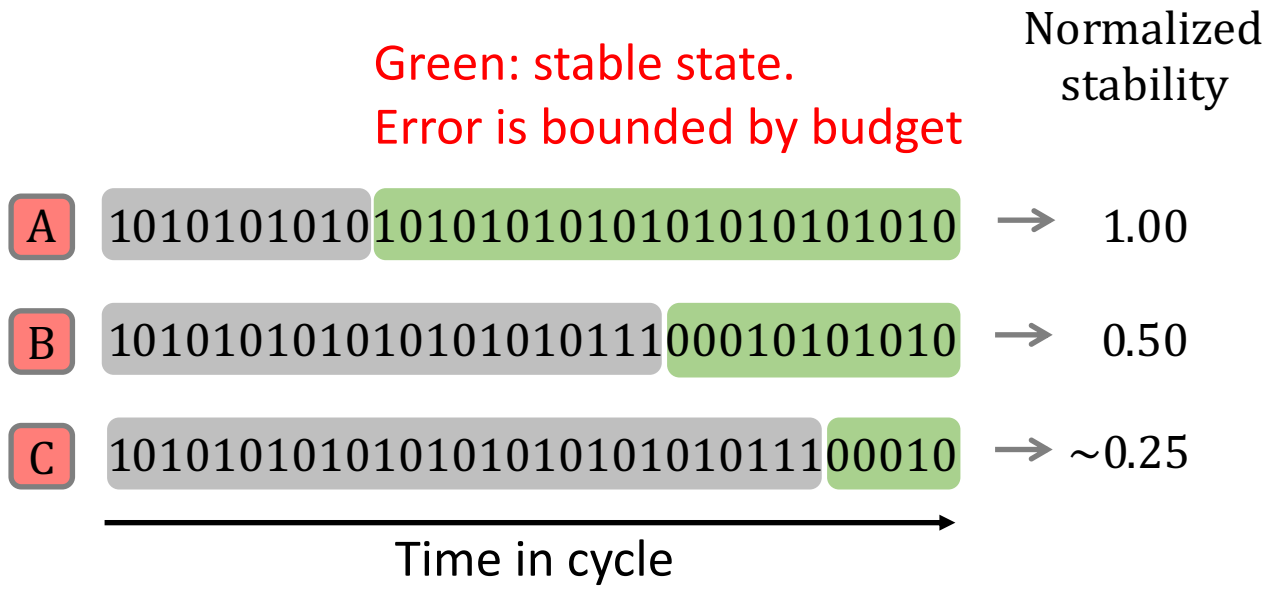

When entering stable state, early termination can be enabled

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Normalized Stability

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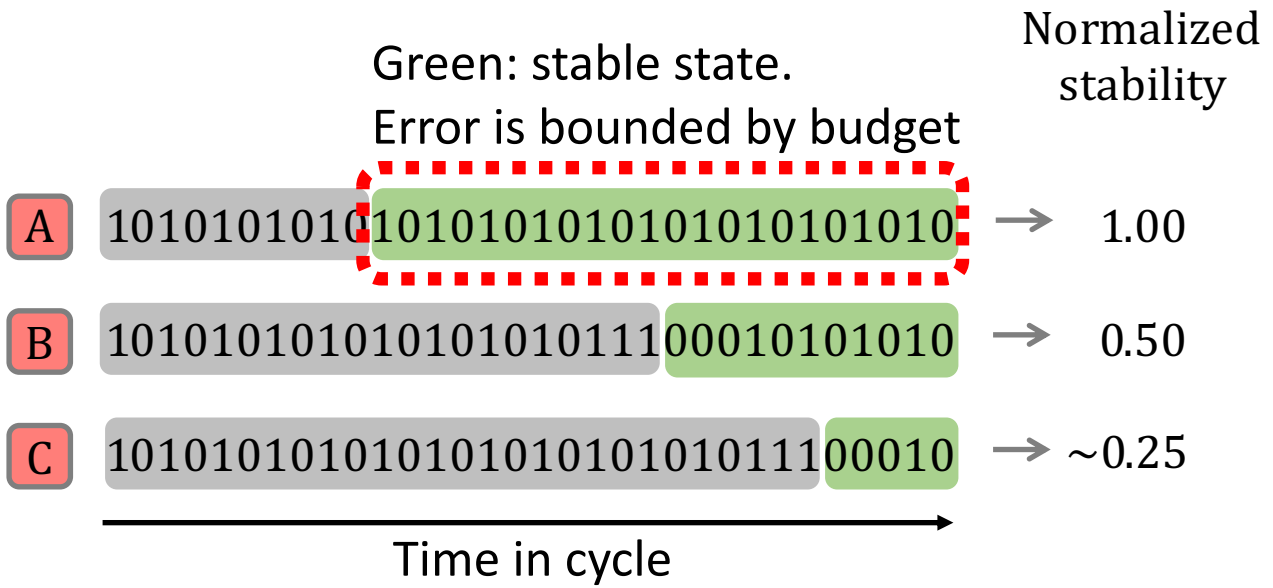

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Normalized Stability

- Definition
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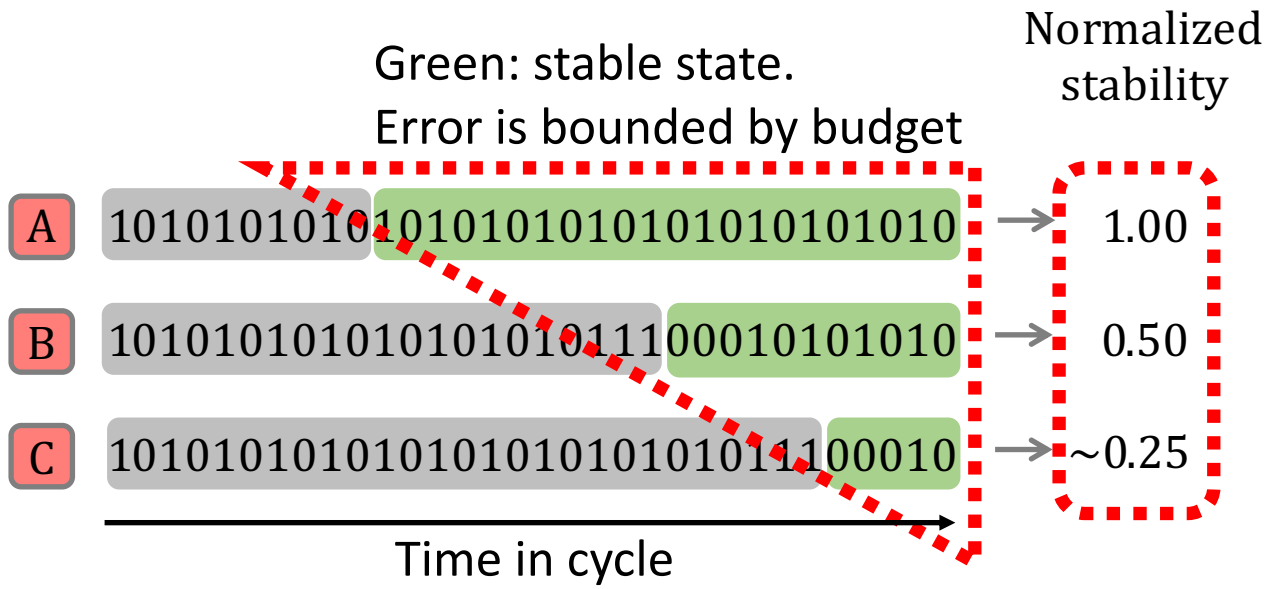

A higher value indicates earlier termination

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Evaluate Normalized Stability

- Capability
  - Unit level:
    - Identify the competitiveness for ET
  - Application level:
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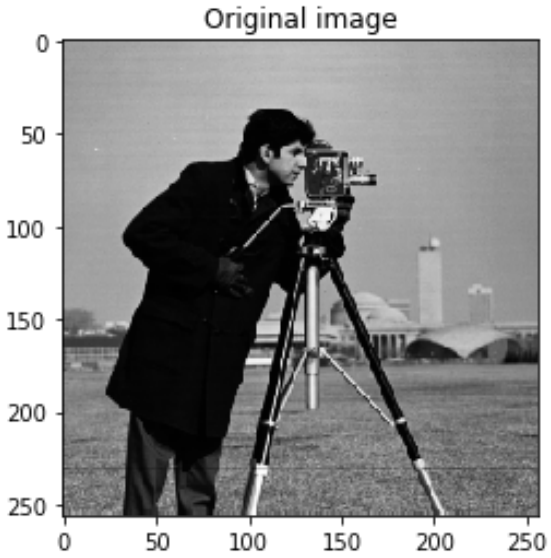
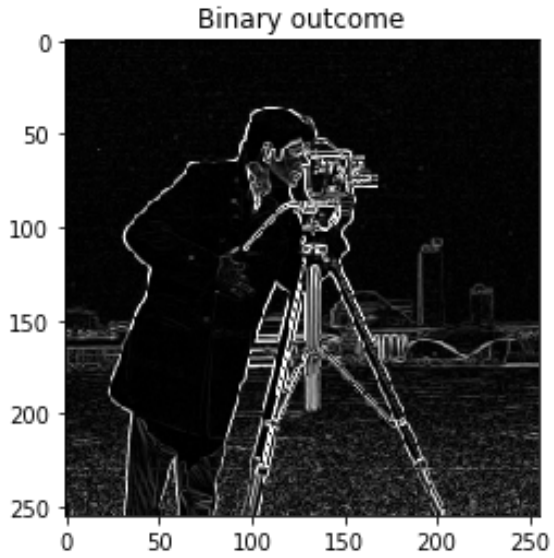
    - Predict the timing for ET

Evaluate Normalized Stability

- Target application
  - SC edge detection





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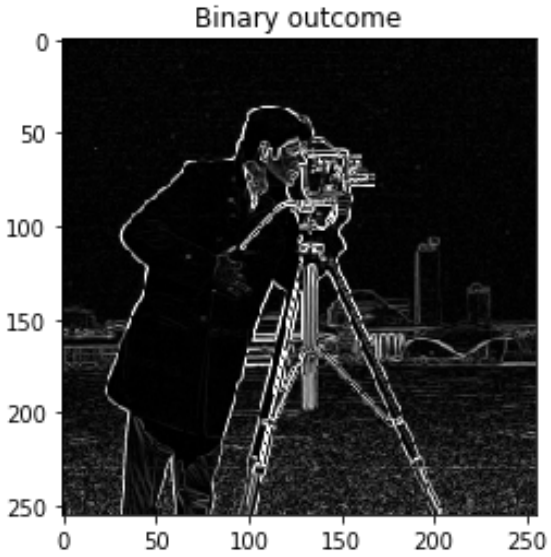
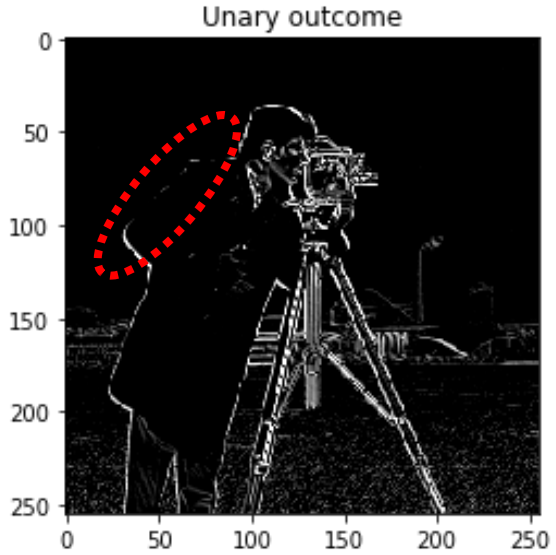
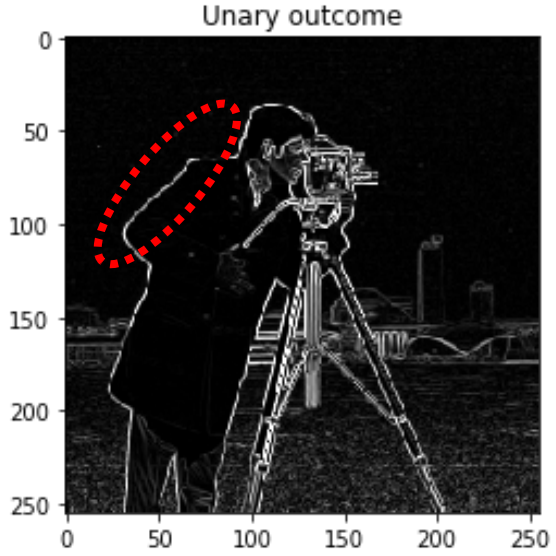
Unit-level Evaluation

- Final results with varying units





Combinational adder



Counter-based adder

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Unit-level Evaluation

- Flux normalized stability (NS)
  - Output-to-input NS for SC units
  - A higher value indicates the ability for earlier termination

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Unit-level Evaluation

- Flux normalized stability (NS)
  - Output-to-input NS for SC units
  - A higher value indicates the ability for earlier termination

Assume input NS = 0.5

Op.	Error budget	Combinational	Counter-based
Add	5%	0.92	0.98
	10%	0.97	0.99

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Unit-level Evaluation

- Flux normalized stability (NS)
  - Output-to-input NS for SC units
  - A higher value indicates the ability for earlier termination
    - Better SC units yield higher flux NS

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Unit-level Evaluation

- Flux normalized stability (NS)
  - Output-to-input NS for SC units
  - A higher value indicates the ability for earlier termination
    - Better SC units yield higher flux NS
    - Increase error tolerance

Assume input NS = 0.5

Op.	Error budget	Combinational	Counter-based
Add	5%	0.92	0.98
	10%	0.97	0.99

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Evaluate Normalized Stability

- Capability
  - Unit level:
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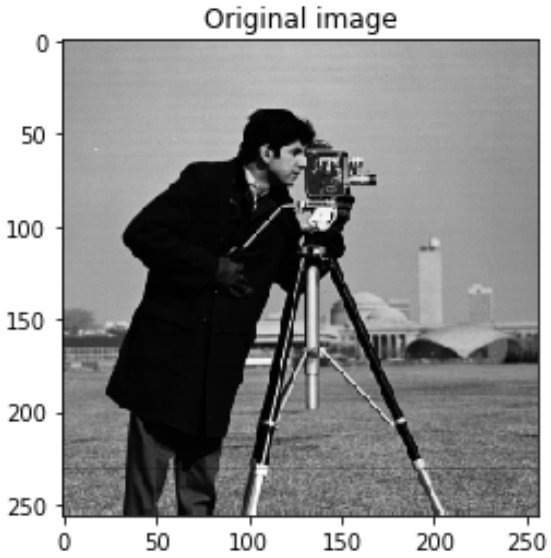
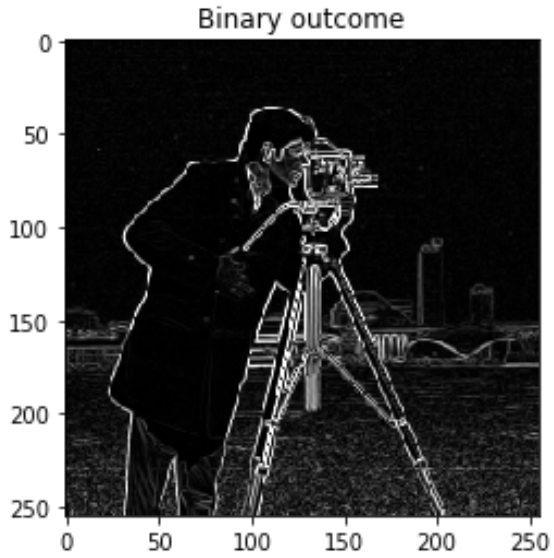
Evaluate Normalized Stability

- Target application
  - SC edge detection





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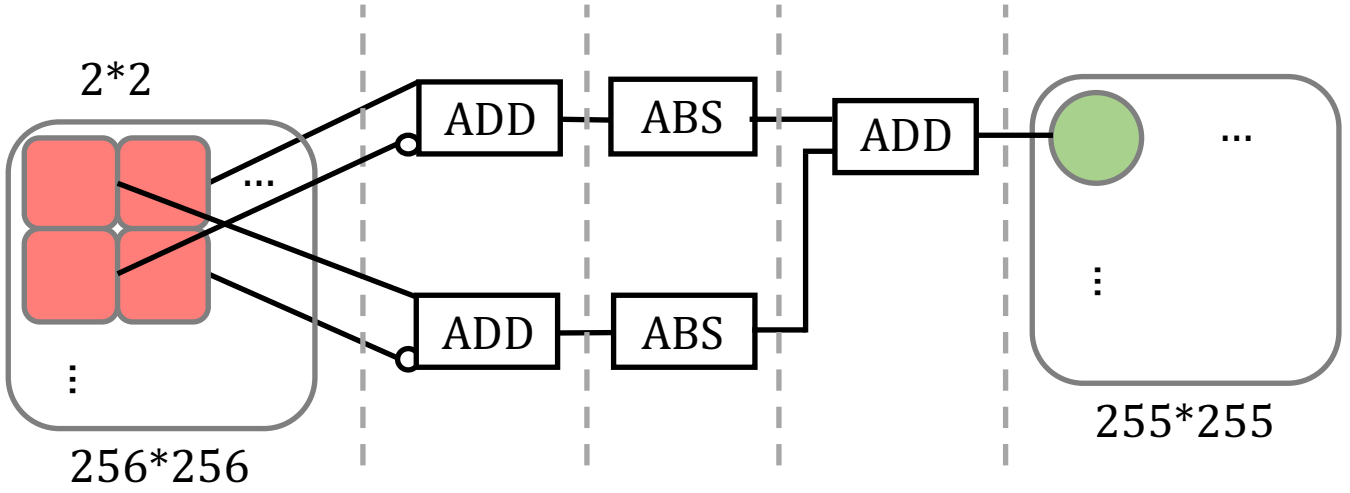
App-level Evaluation

- Higher flux NS enables earlier termination

Adder	Error Budget	NS				ET Cycle
Comb.	5%	0.97	0.95	0.20	0.18	838
CNT		0.97	0.97	0.97	0.97	34

Use better SC units



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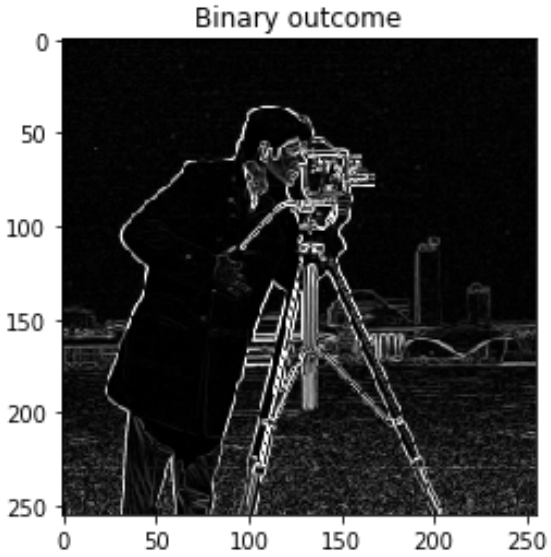
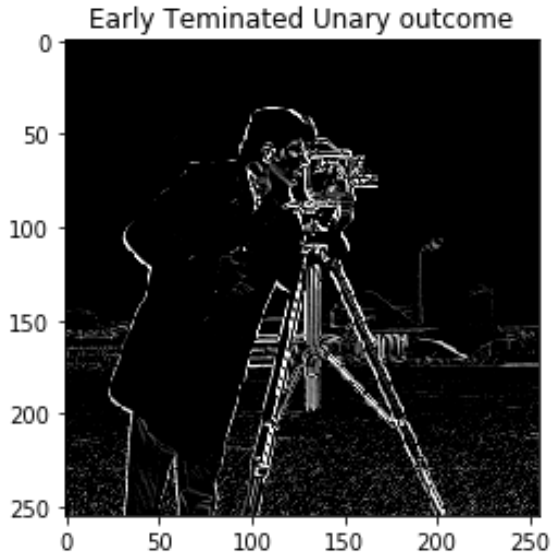
App-level Evaluation

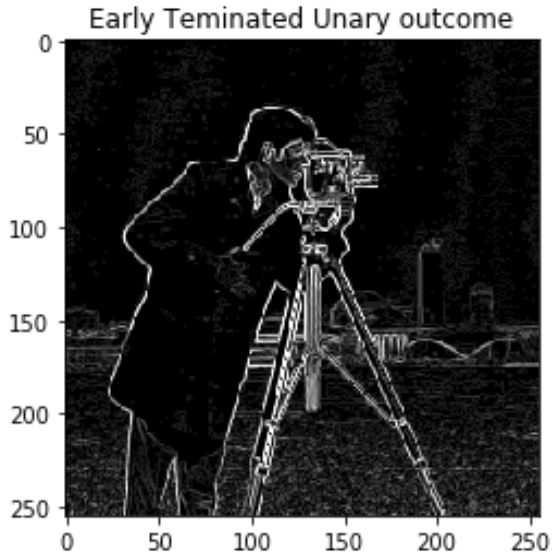
- Better SC units





Combinational adder

Error tolerance 5%



Counter-based adder

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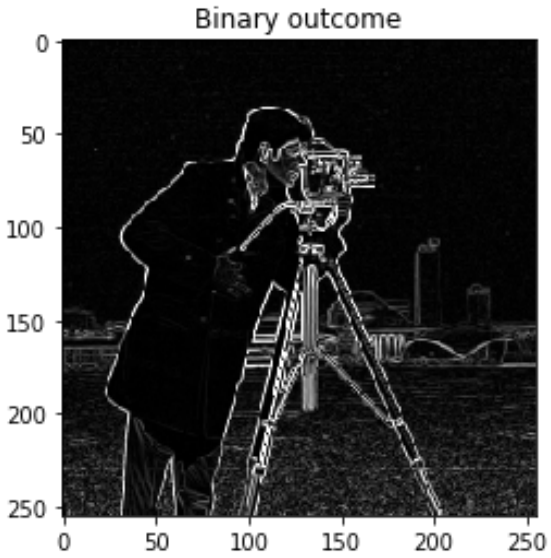
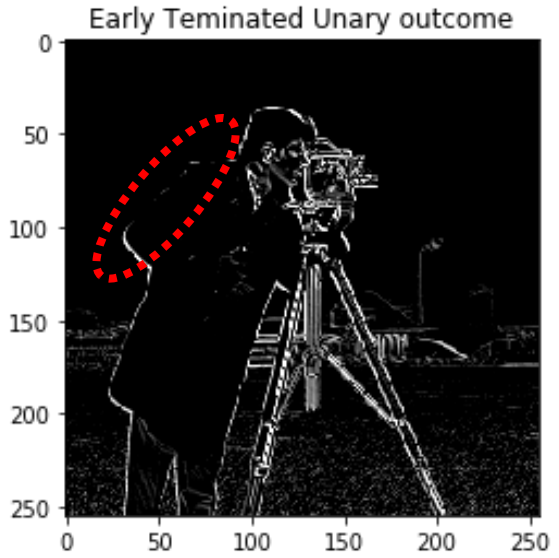
App-level Evaluation

- Better SC units





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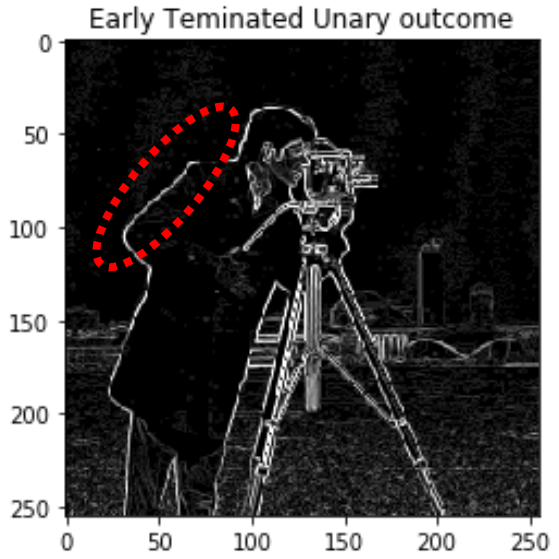

Counter-based adder

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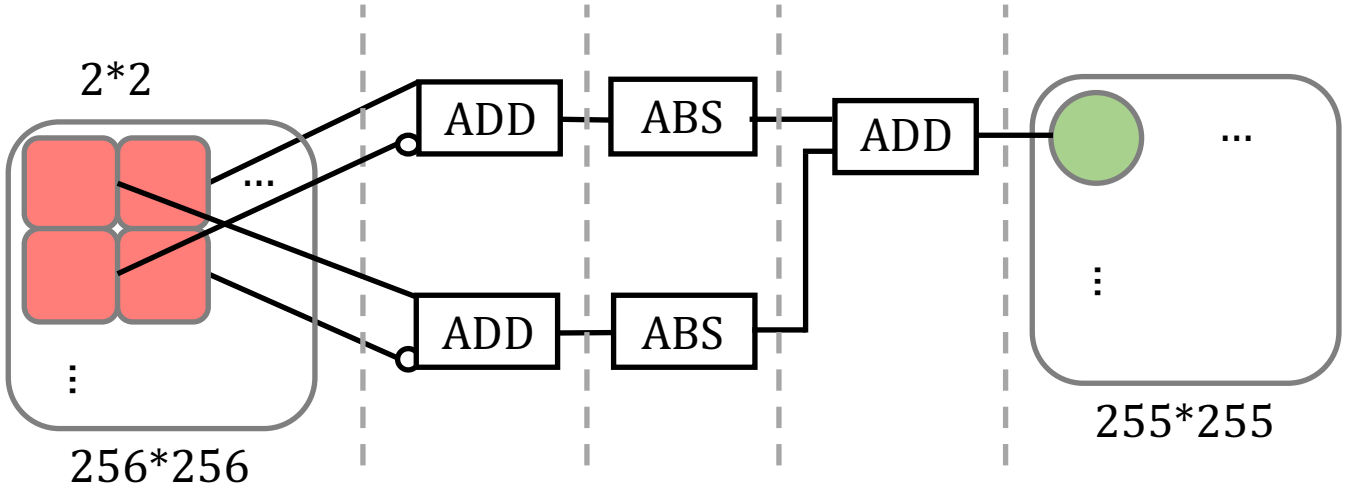
App-level Evaluation

- Higher flux NS enables earlier termination

Adder	Error Budget	NS				ET Cycle
Comb.	5%	0.97	0.95	0.20	0.18	838
	10%	0.99	0.98	0.32	0.31	702

Increase error tolerance.



https://github.com/diwu1990/UnarySim/blob/master/sw/test/metric/test_metric_normstability_edge_detect_detail.ipynb

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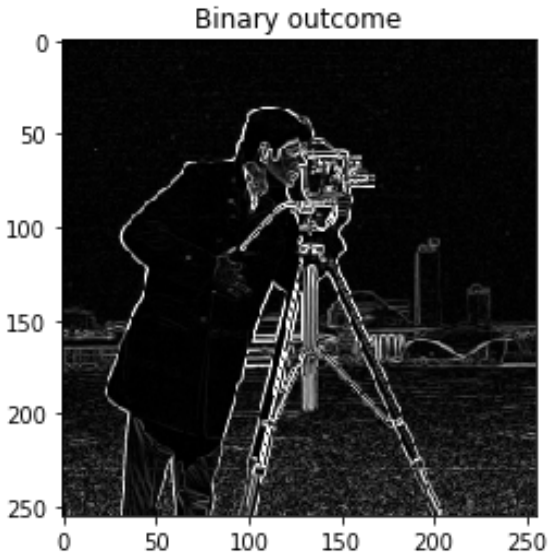
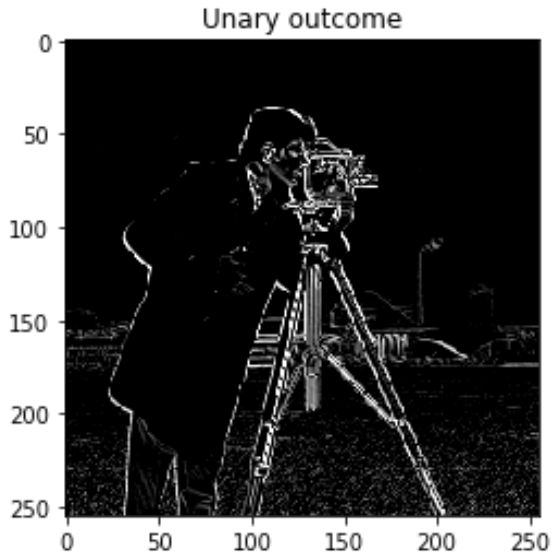
App-level Evaluation

- Higher error tolerance





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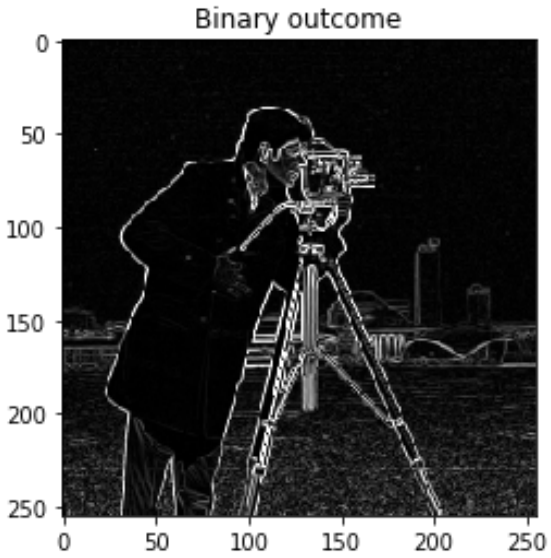
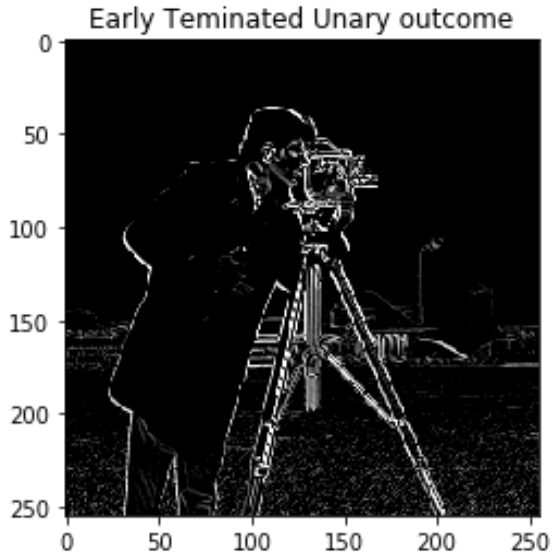
App-level Evaluation

- Higher error tolerance

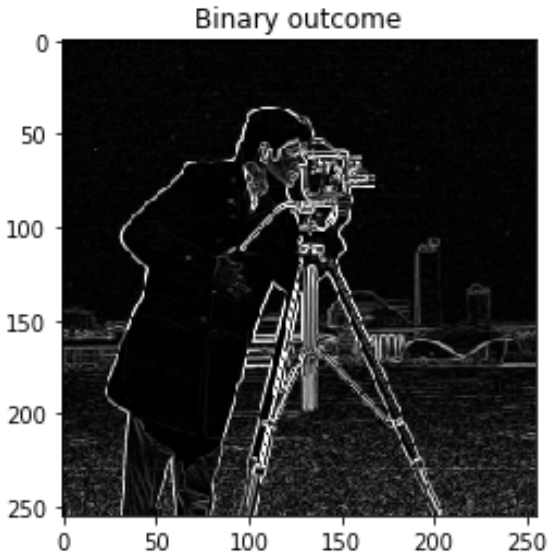


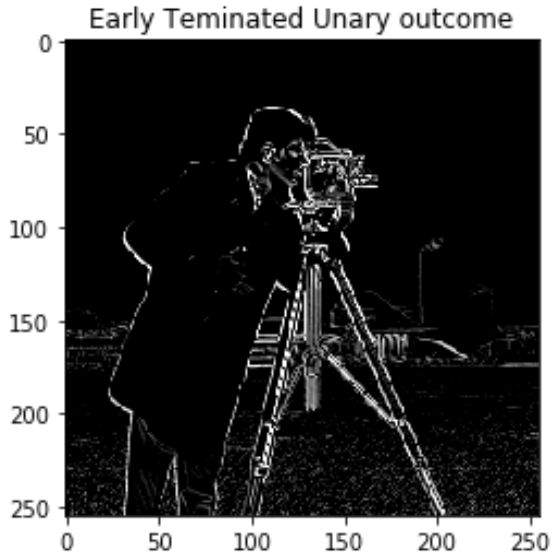


Error tolerance 5%

App-level Evaluation

- Higher error tolerance





Error tolerance 10%

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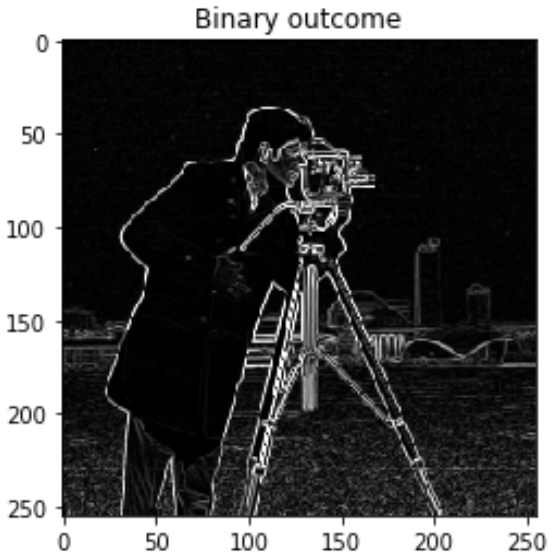
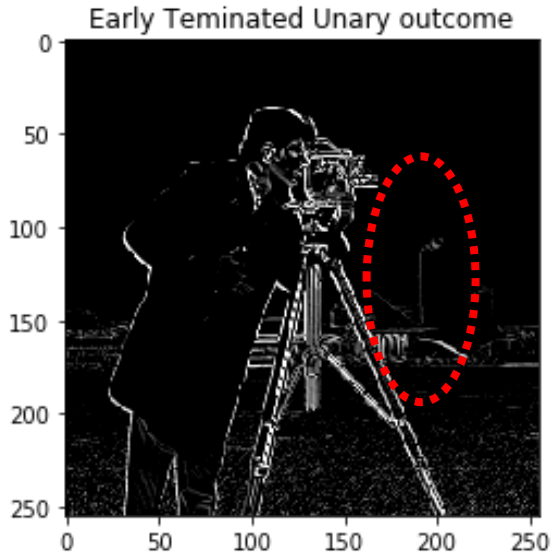
App-level Evaluation

- Higher error tolerance





Error tolerance 10%

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Evaluate Normalized Stability

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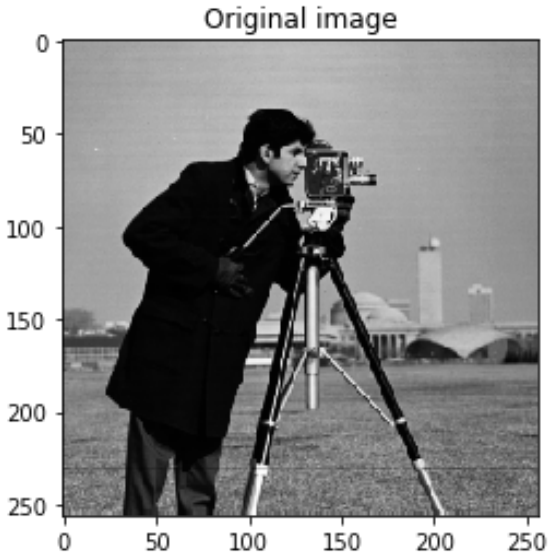

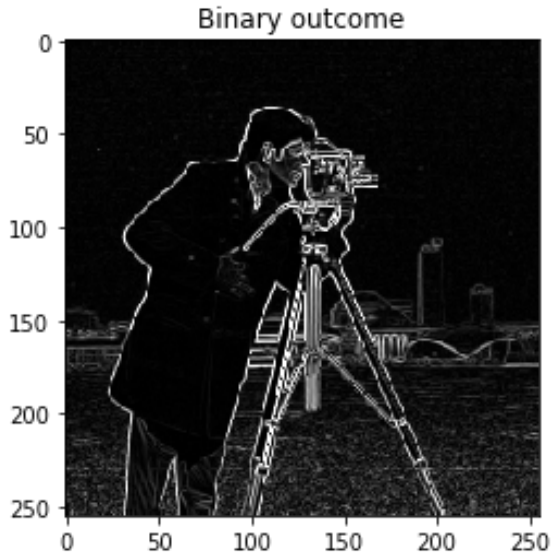

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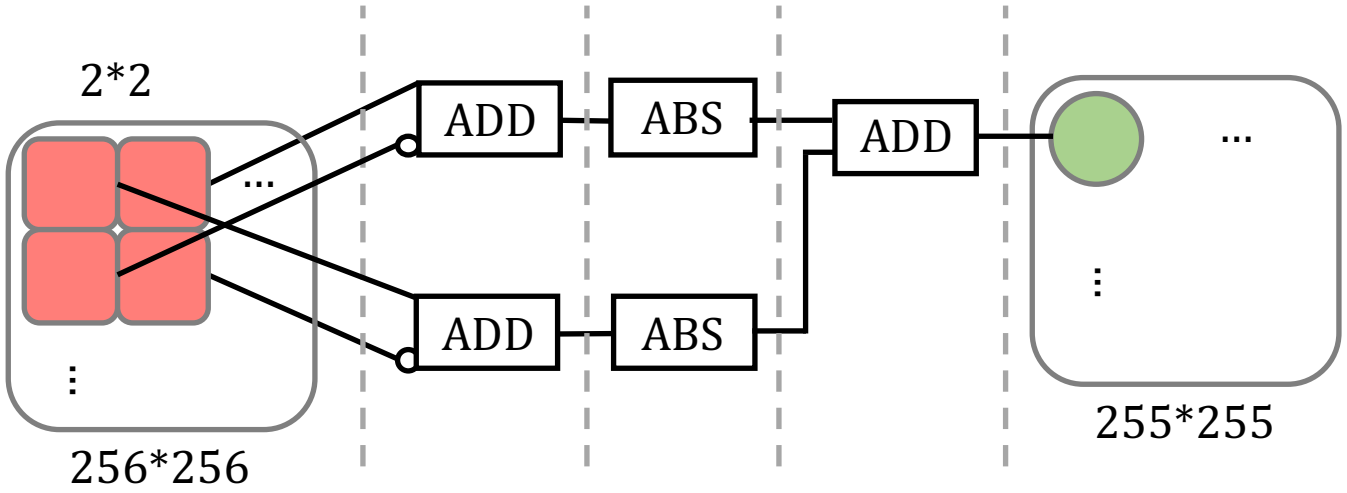
App-level Evaluation

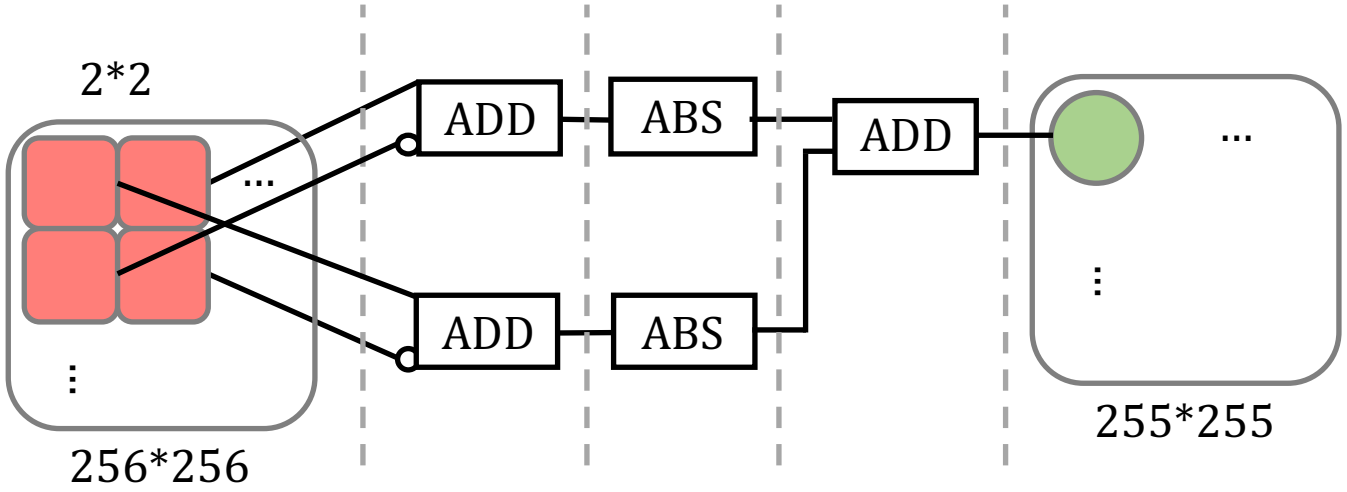
- Prediction of early termination



App-level Evaluation

- Prediction of early termination

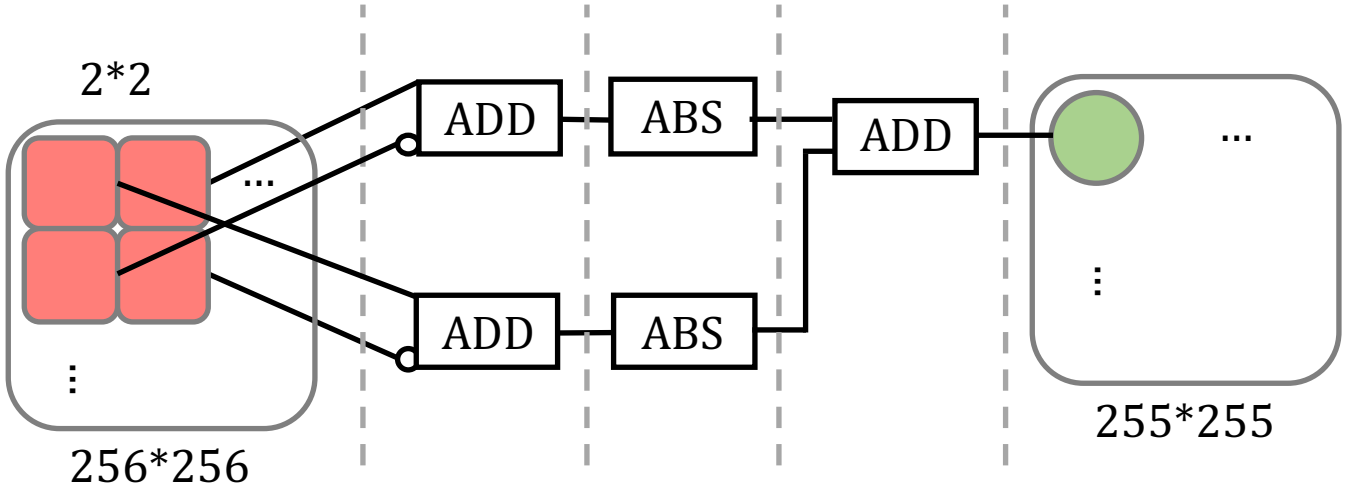
Phase	Output NS	Early termination cycle	Output Error
Train			5%



App-level Evaluation

- Prediction of early termination

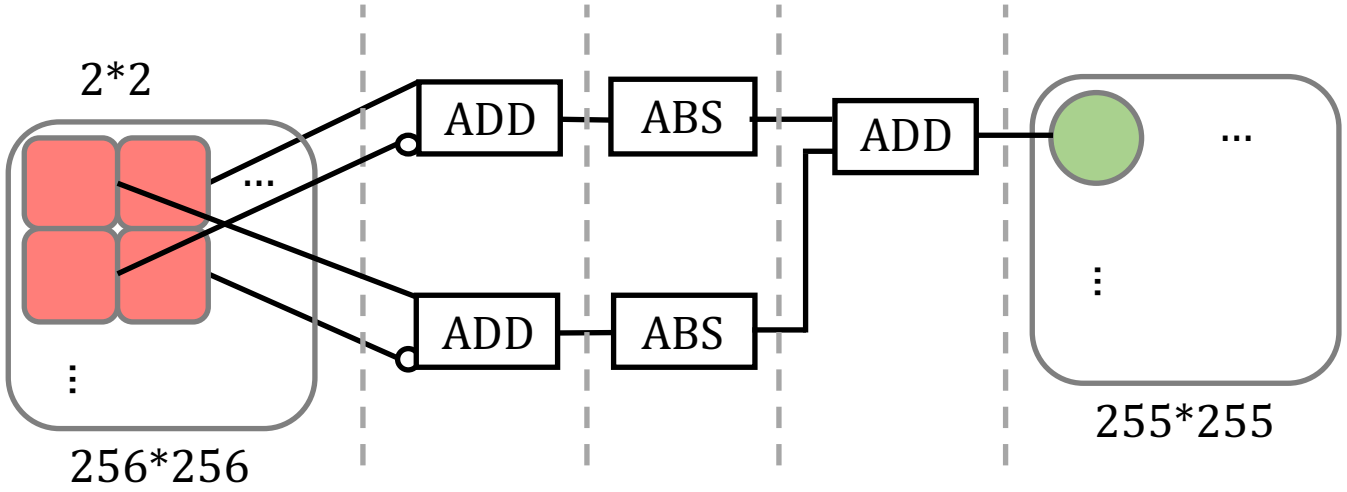
Phase	Output NS	Early termination cycle	Output Error
Train	0.82		5%



App-level Evaluation

- Prediction of early termination

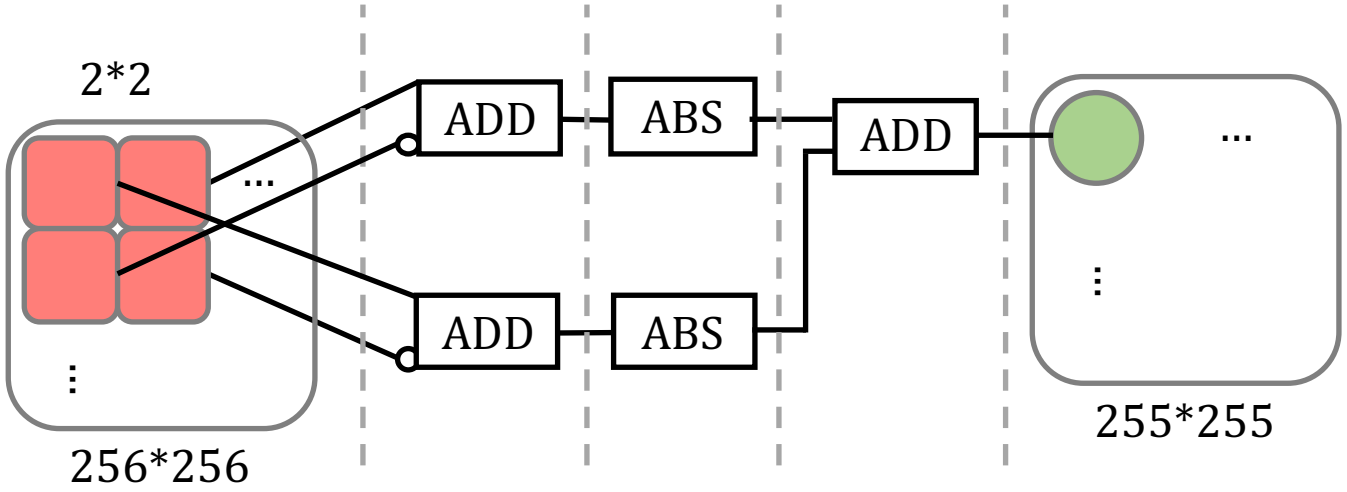
Phase	Output NS	Early termination cycle	Output Error
Train	0.82	184	5%



App-level Evaluation

- Prediction of early termination

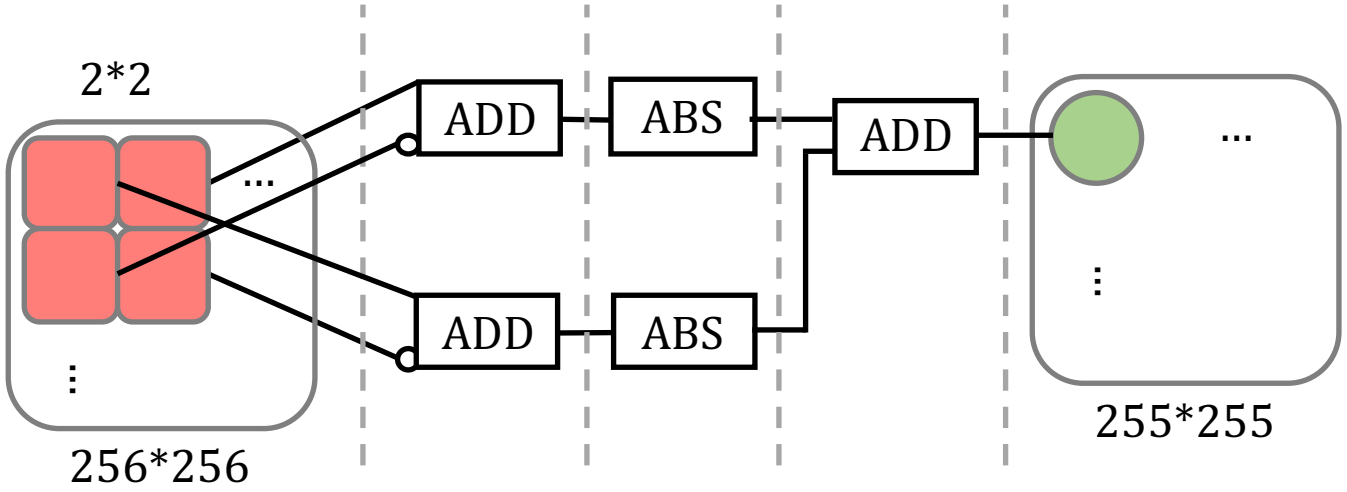
Phase	Output NS	Early termination cycle	Output Error
Train	0.82	184	5%
Test		184	



App-level Evaluation

- Prediction of early termination

Phase	Output NS	Early termination cycle	Output Error
Train	0.82	184	5%
Test		184	2.5%

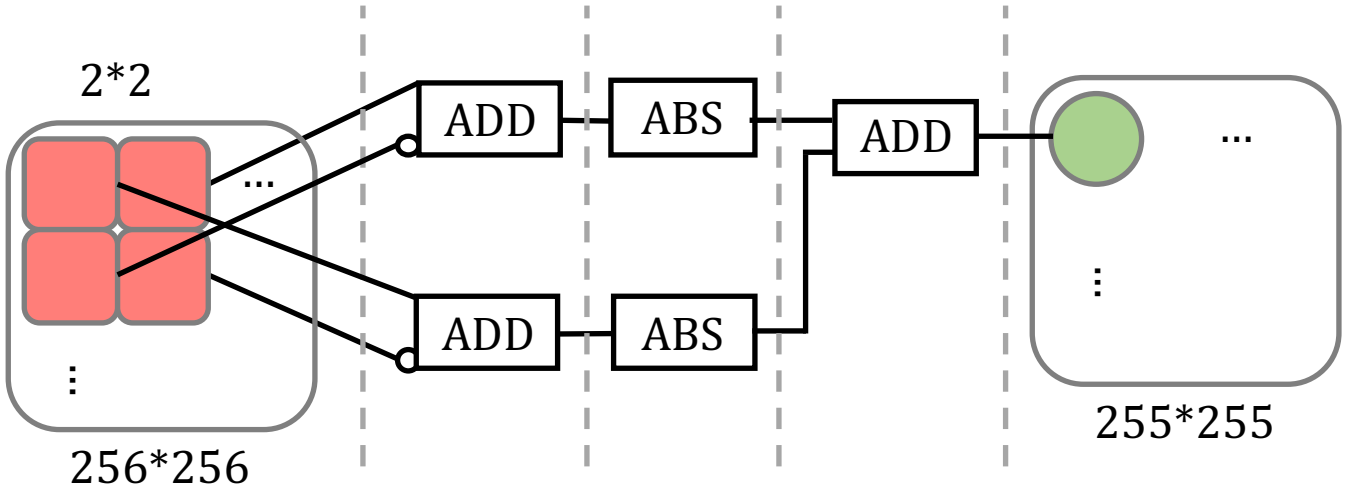


App-level Evaluation

- Prediction of early termination

Phase	Output NS	Early termination cycle	Output Error
Train	0.82	184	5%
Test		184	2.5%

<5%



Implementation

- UnarySim
  - A PyTorch-based simulator for stochastic computing
    - Stream
    - Kernel
    - Metric

- Stability metrics
  - Embedded in UnarySim as a metric component

Di Wu, et al., “uGEMM: Unary Computing Architecture for GEMM Applications”, *ISCA* 2020.

Department of Electrical and Computer Engineering
UNIVERSITY OF WISCONSIN–MADISON

Thank you!
Q & A

Di Wu, Ruokai Yin and Joshua San Miguel
University of Wisconsin-Madison

Department of Electrical and Computer Engineering
UNIVERSITY OF WISCONSIN–MADISON