Computer Architecture

Lecture 12a: Research Presentation

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Bit-Exact ECC Recovery (BEER):

Determining DRAM On-Die ECC Functions by Exploiting DRAM Data Retention Characteristics

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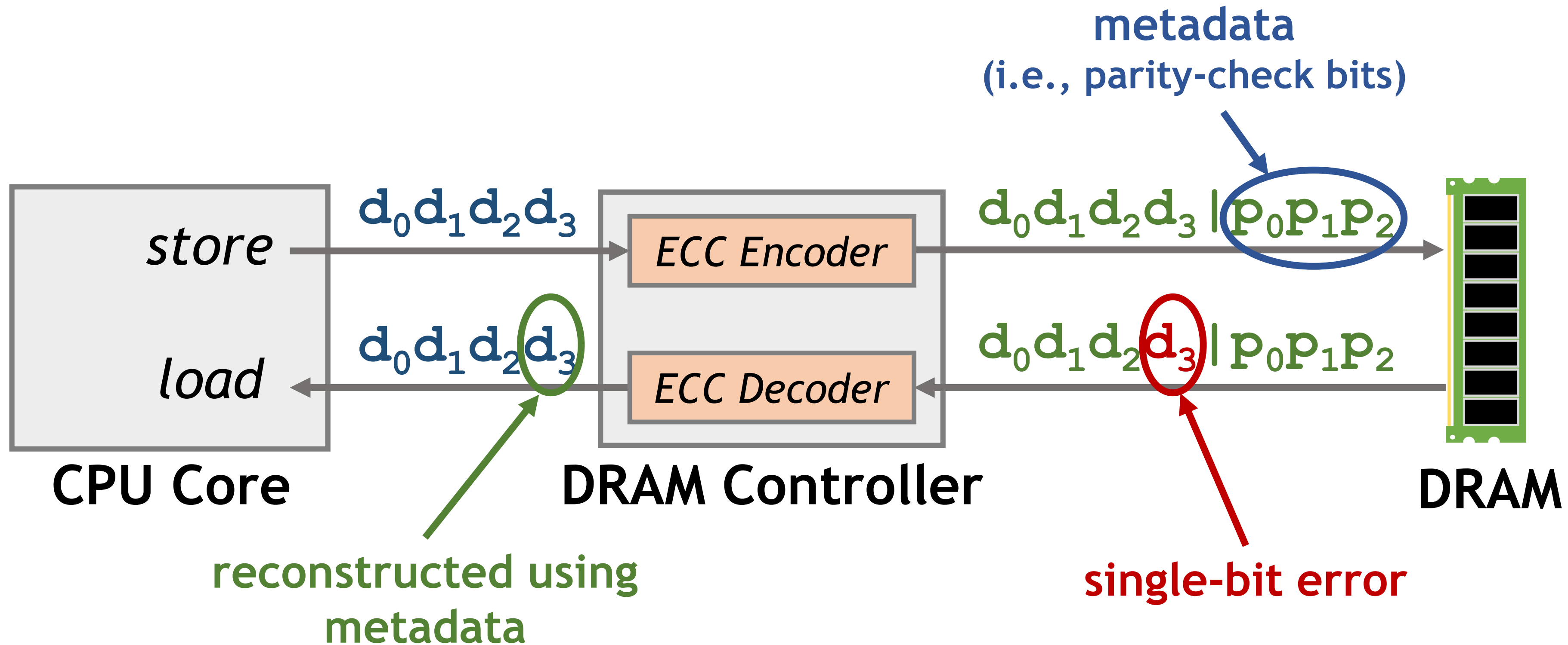
Taha Shahroodi, Hasan Hassan, Onur Mutlu

MICRO 2020

Extended talk for Computer Architecture HS 2020

Error Correction Codes (ECCs)

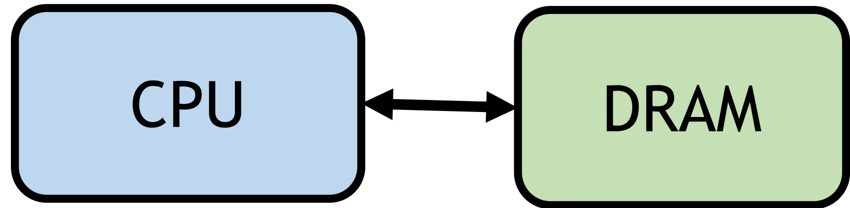
- **Key idea:** add **metadata** that allows the memory controller to reconstruct corrupt data on a bit flip



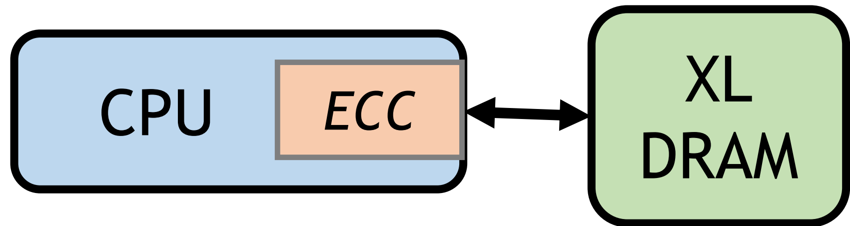
- More metadata allows correcting more errors

Three Types of DRAM Systems

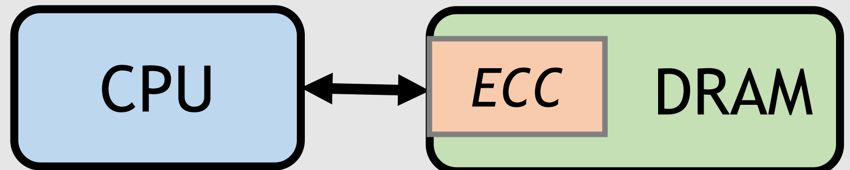
No-ECC



Rank-level ECC



On-Die-ECC



Executive Summary

Problem: DRAM on-die ECC **complicates** third-party reliability studies

- **Proprietary** design **obfuscates** raw bit errors in an **unpredictable** way
- **Interferes** with (1) design, (2) test & validation, and (3) characterization

Goal: understand **exactly how** on-die ECC obfuscates errors

Contributions:

1. **BEER**: new testing methodology that determines a DRAM chip's **unique on-die ECC function** (i.e., its parity-check matrix)
   - Exploits **ECC-function-specific** uncorrectable error patterns
   - Requires no hardware support, inside knowledge, or metadata access
2. **BEEP**: new error profiling methodology that infers the **raw bit error locations** of error-prone cells from the **observable uncorrectable errors**

BEER Evaluations:

- Apply BEER to 80 real LPDDR4 chips from 3 major DRAM manufacturers
- Show correctness in simulation for 115,300 codes (4-247b ECC words)

We hope BEER and BEEP enable valuable studies in the future

Talk Outline

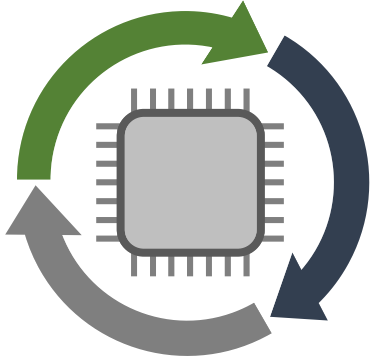
Challenges Caused by Unknown On-Die ECCs

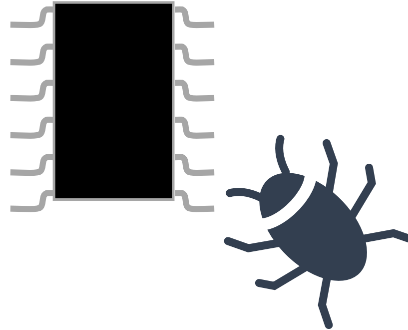
BEER: Determining the On-Die ECC Function

Evaluating BEER in Experiment and Simulation

BEEP and Other Practical Use Cases for BEER

Third-Party DRAM Users





System Architects
Design Error Mitigations

Test Engineers
Third-Party Testing

Research Scientists
Error-Characterization

Need to understand
a DRAM chip's **reliability characteristics**

Inter-chip variation?

Temperature dependence?

'Weak' cell locations?

Statistical error properties?

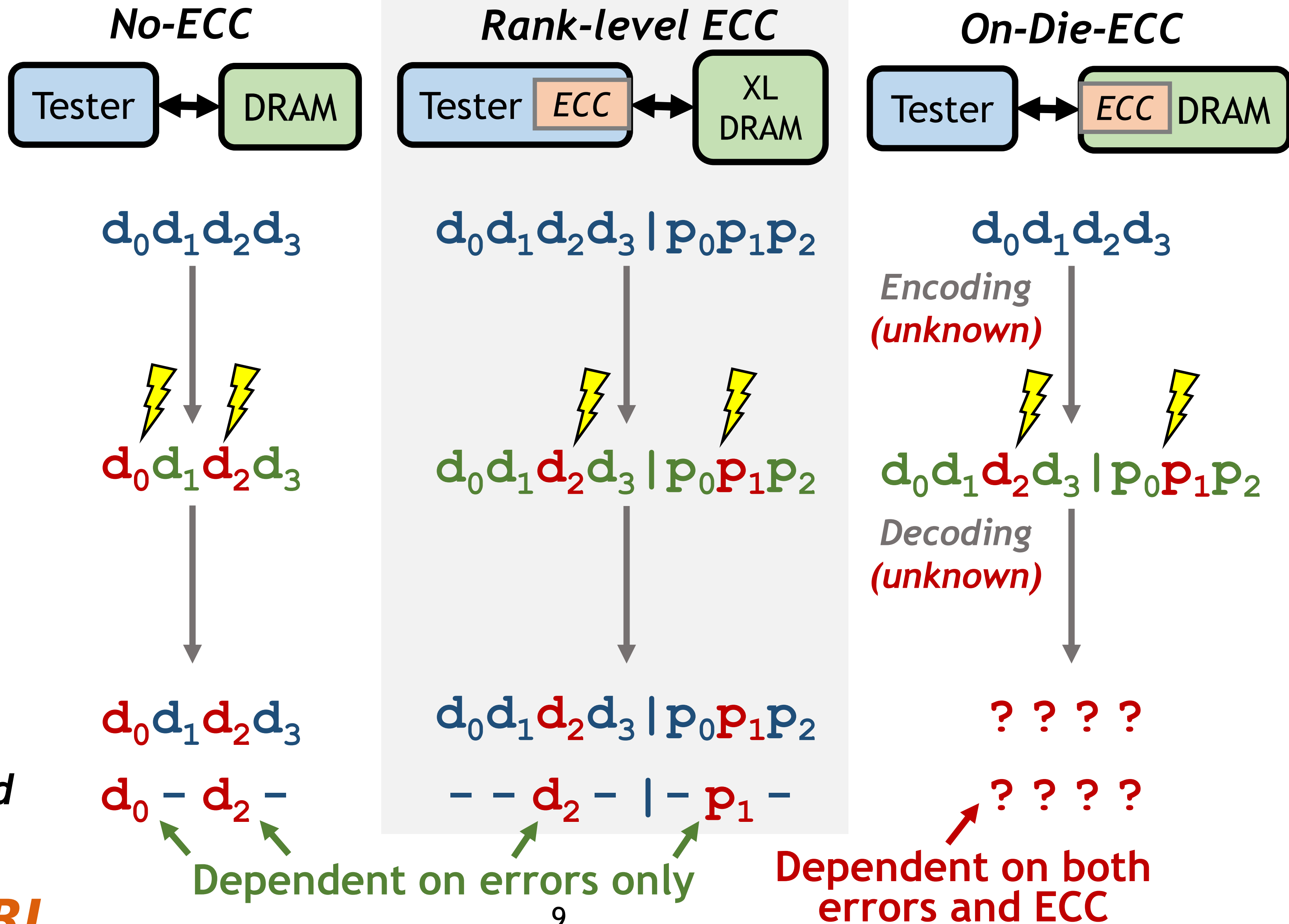
Aggregate failure rates?

Minimum operating timings?

Third-Party DRAM Users

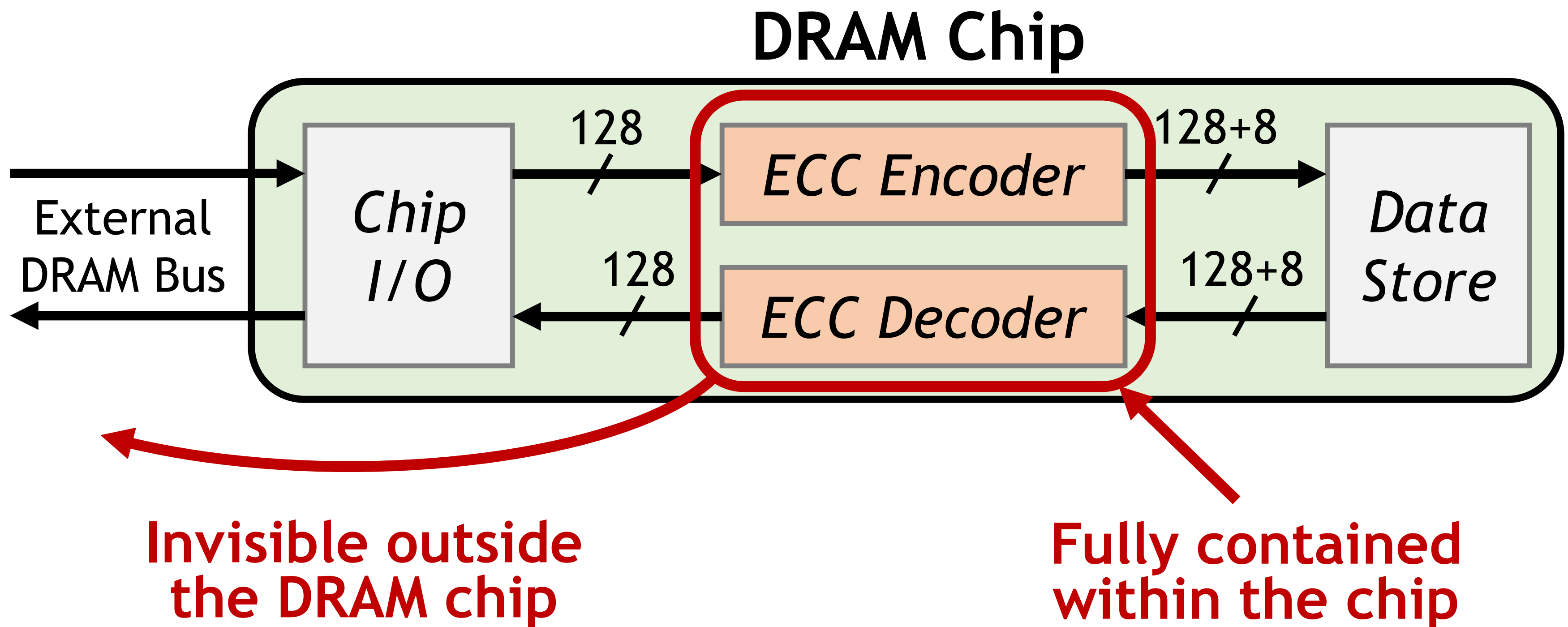
But how do we study
DRAM reliability characteristics?

Testing and Error Characterization

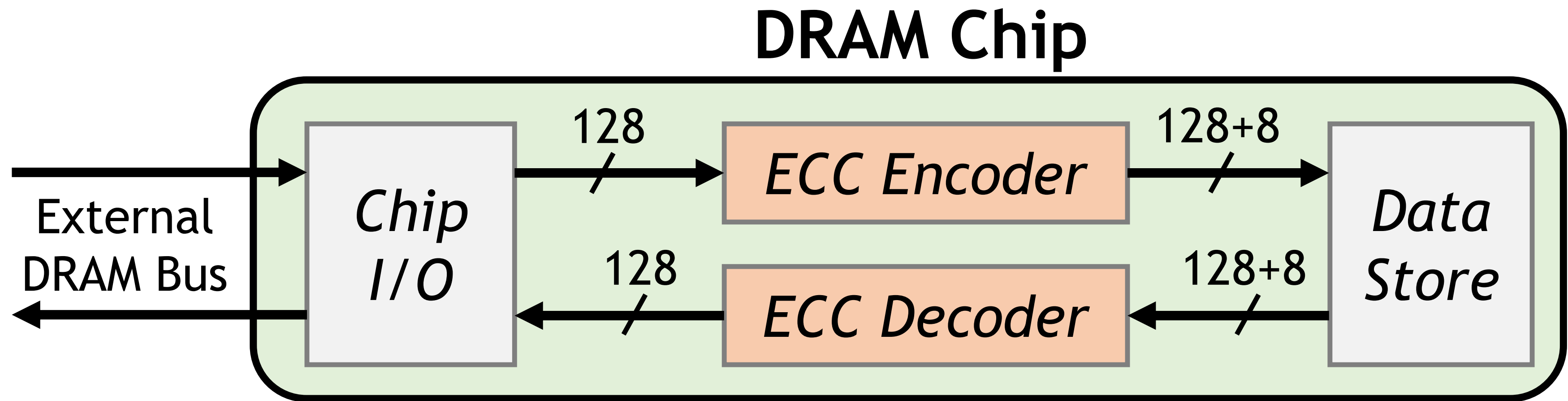


A Typical DRAM On-Die ECC Design

- 128-bit single-error correcting (SEC) Hamming code



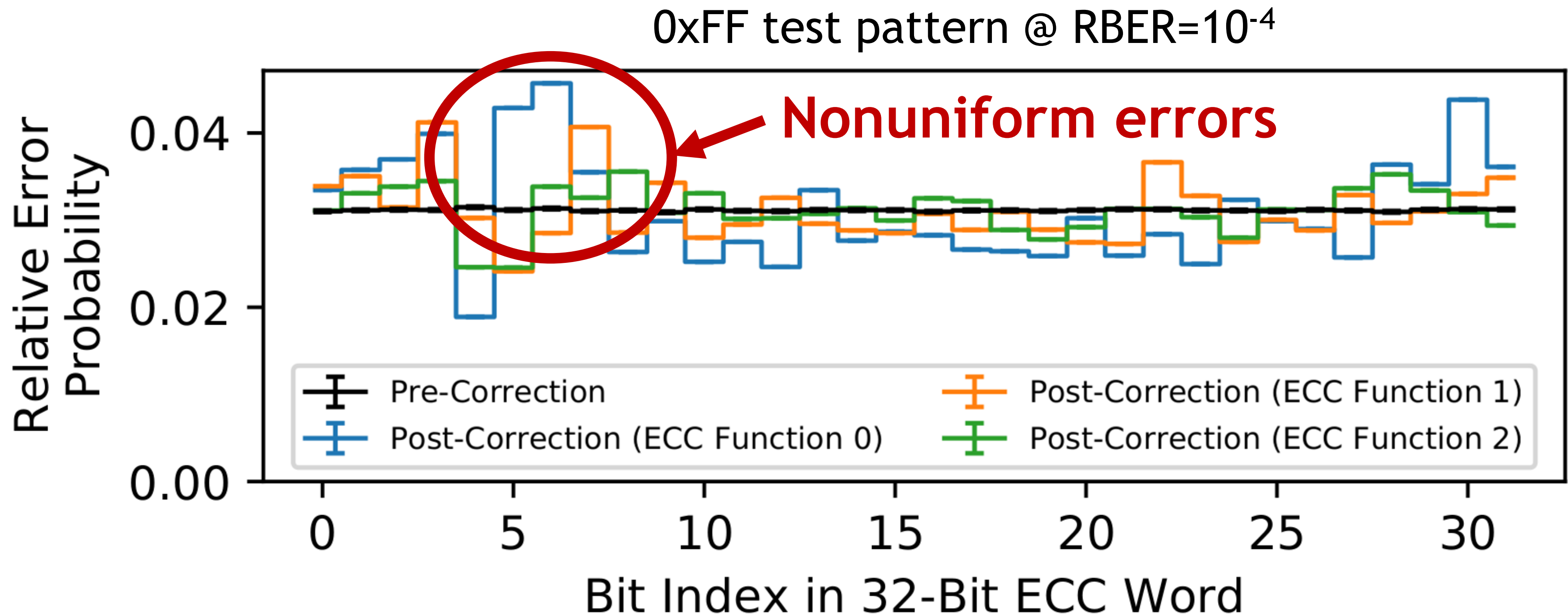
A Typical DRAM On-Die ECC Design



- Many ways to implement a 128-bit Hamming code
  - Different **ECC functions**
    - Known as **parity-check matrices** (i.e., ***H*-matrices**)
    - All correct 1 error, but act **differently** on 2+ errors
- Manufacturers are free to choose any design
  - Circuit optimization goals (e.g., area, power)
  - Details are **highly proprietary** (even under NDA)

Effect of Different On-Die ECC Designs

- Simulating **uniform-random errors** in a 32b ECC word



- 32-bit single-error correction Hamming codes
- Three different parity-check matrices

Effect of Different On-Die ECC Designs

The **same** error characteristics
can appear very **different**
with different ECC functions

Challenges for Third Parties

System Architects: Designing Error Mitigations

- On-die ECC forces system architects to support **unpredictable**, **chip-dependent** memory reliability characteristics

Test/Validation Engineers: Post-Manufacturing Testing

- On-die ECC **hides** the root-causes of uncorrectable errors and **defeats** test patterns designed to target physical cells

Research Scientists: Error-Characterization Studies

- On-die ECC **conflates** raw bit errors with ECC artifacts, effectively **obfuscating** the true physical cell characteristics

Challenges for Third Parties

These challenges all arise
from the **inability** to predict
how ECC transforms error patterns

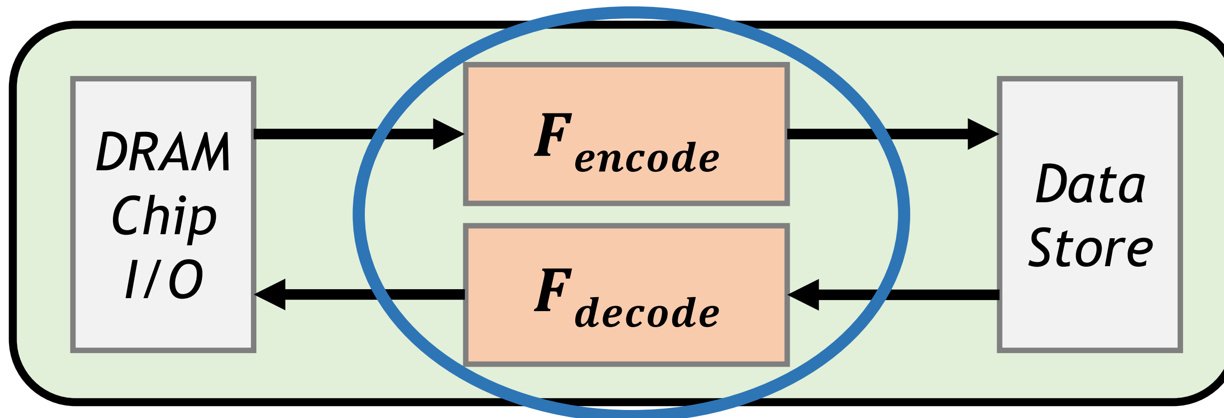
Overcoming Challenges of On-Die ECC

Our goal: Determine the on-die ECC function **without**:

(1) hardware support or tools

(2) prior knowledge about on-die ECC

(3) access to ECC metadata (e.g., syndromes)



- Reveals how on-die ECC scrambles errors (BEER)
- Allows inferring raw bit error locations (BEEP)

Talk Outline

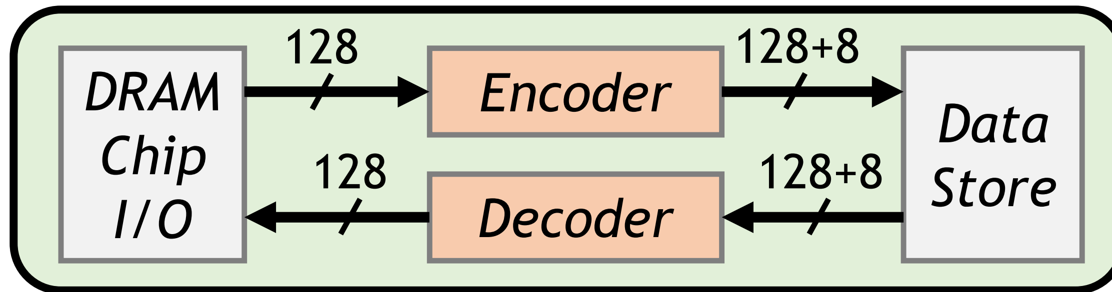
Challenges Caused by Unknown On-Die ECCs

BEER: Determining the On-Die ECC Function

Evaluating BEER in Experiment and Simulation

BEEP and Other Practical Use Cases for BEER

Typical On-Die ECC Function



- Encoder and decoder both use **linear operations**

Encoder

dataword $\boldsymbol{d} = [\bullet\ \bullet\ \bullet\ \bullet]$

$\boldsymbol{d}$ $[\bullet\ \bullet\ \bullet\ \bullet] * \boldsymbol{G}$

codeword $\boldsymbol{c} = [\bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet]$

Define the ECC function

Decoder

dataword′ $\boldsymbol{d'} = [\bullet\ \bullet\ \bullet\ \bullet]$

$\boldsymbol{H} * \boldsymbol{c'}$ $[\bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet]^T$

codeword′ $\boldsymbol{c'} = [\bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet\ \bullet]$

Error Correction During Decoding

- Two-step decoding algorithm: **syndrome decoding**
  1. Calculate an **error syndrome** that points to error(s)
  2. Correct detected errors (if any)

Correctable Errors

$$H * c' = s$$

s points to the error location (if any)

Uncorrectable Errors

$$H * c' = s$$

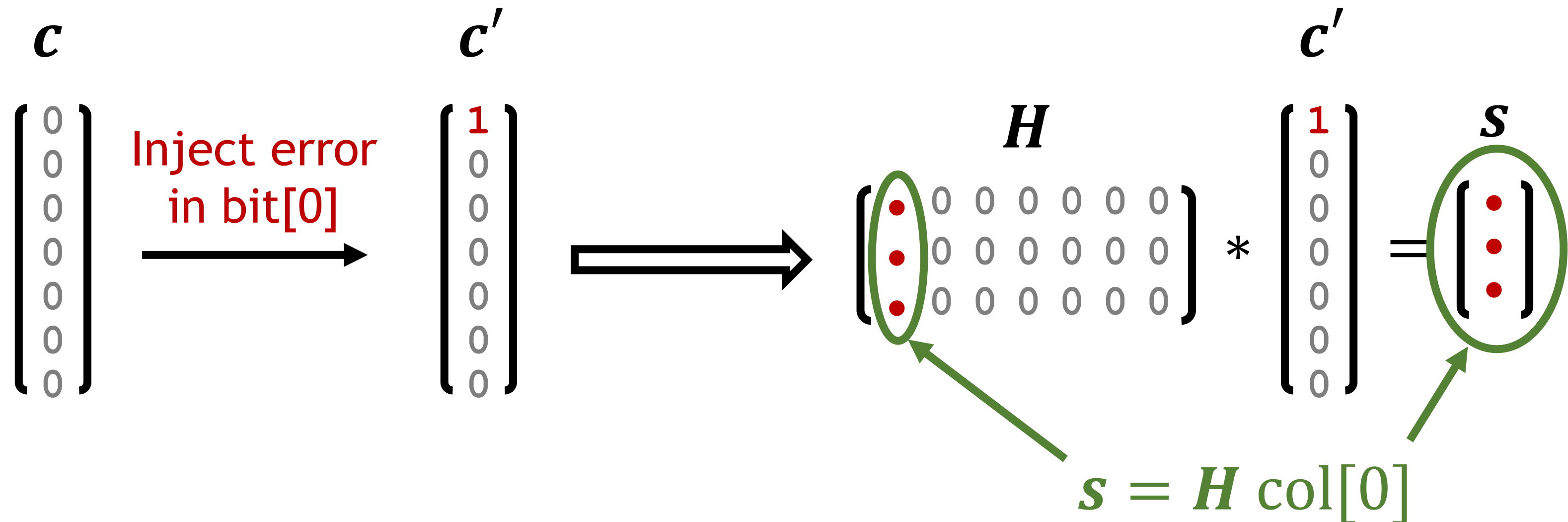
s points to an arbitrary H-dependent position

Error Correction During Decoding

Key idea: exploit the $\boldsymbol{H}$-dependence of uncorrectable errors to disambiguate ECC functions

Determining the On-Die ECC Function

- **Approach:** iteratively isolate linear components of $\boldsymbol{H}$
  - Demonstrated by [Cojocar+, SP'19] for rank-level ECC



- Can systematically extract each column of $\boldsymbol{H}$
- Determine entire $\boldsymbol{H}$ by extracting all columns

Determining the On-Die ECC Function

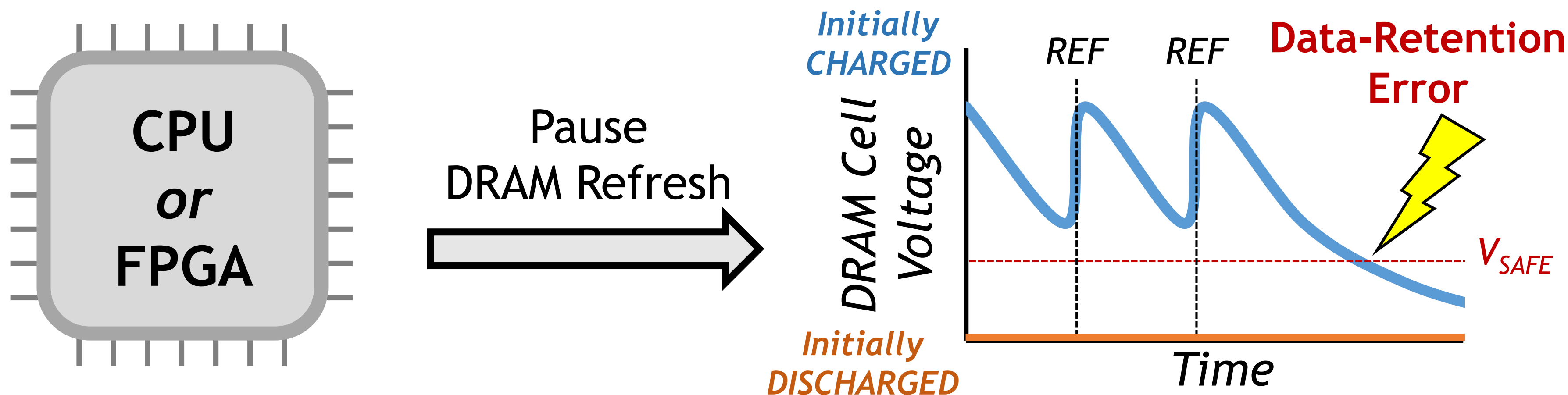
$\boldsymbol{H}$

On-die ECC causes two **challenges:**

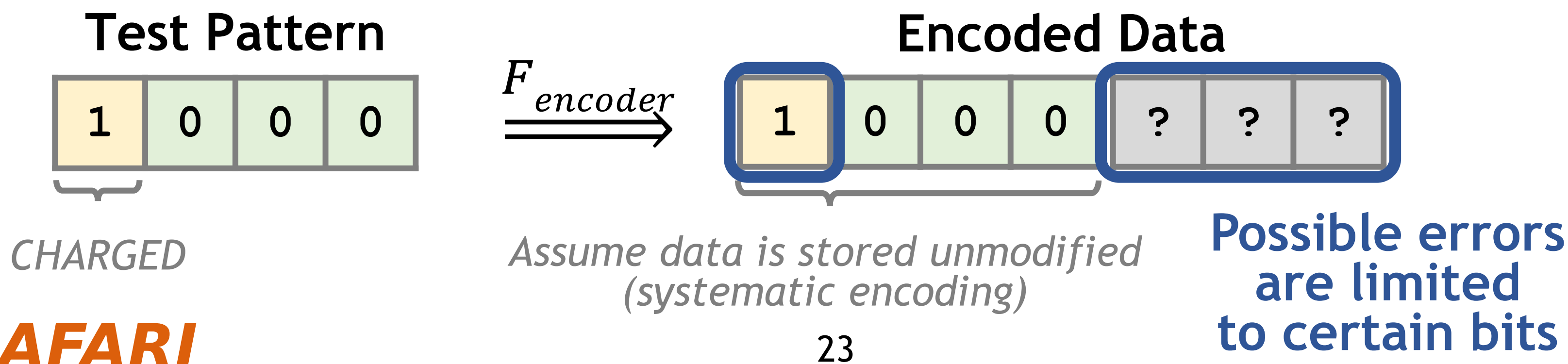
1. No way to inject errors in `bit[n]`
2. No way to observe error syndromes

Challenge 1: Injecting Errors

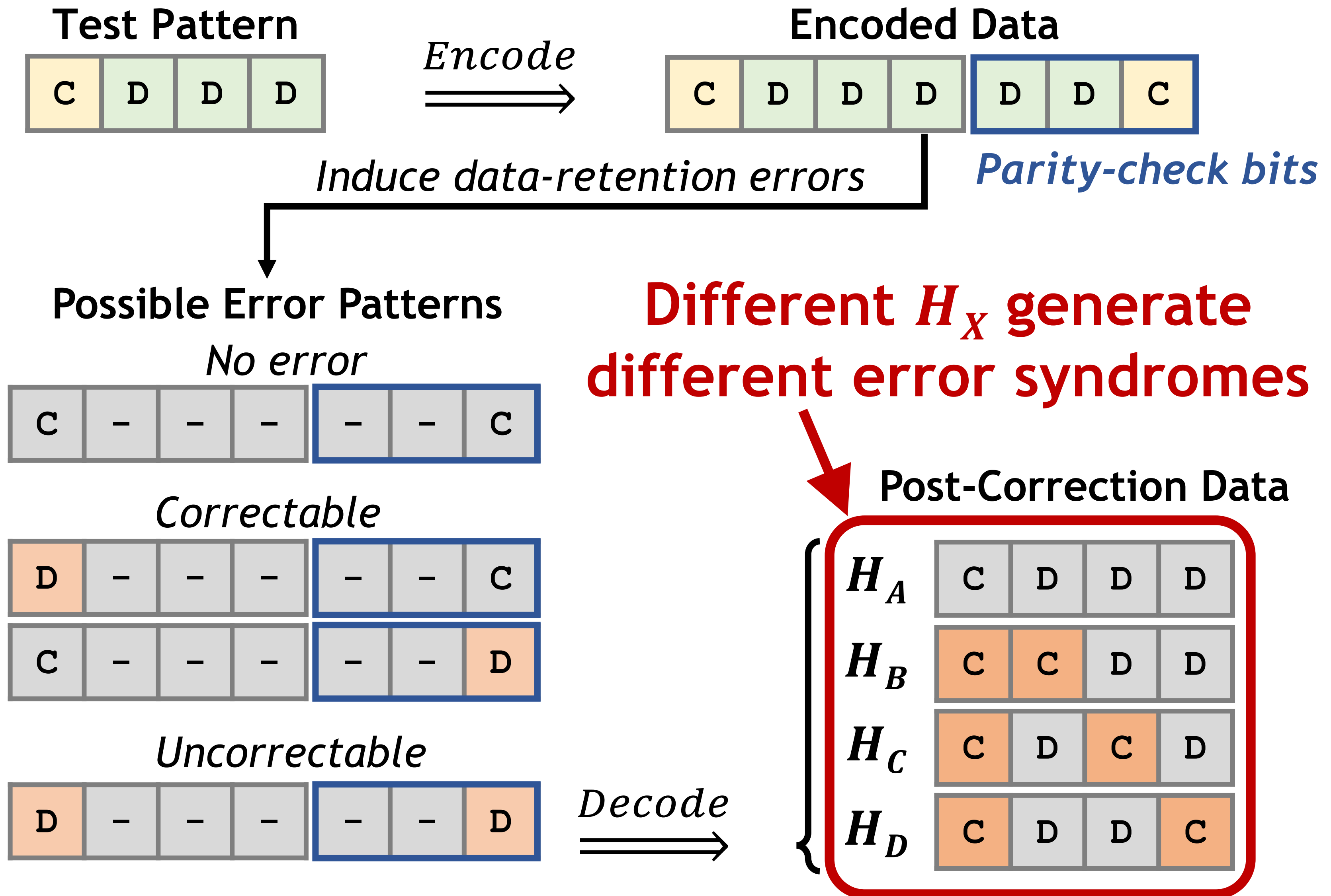
- **Key idea:** deliberately induce data-retention errors



- Difference between CHARGED and DISCHARGED cells allows us to restrict errors to specific bit positions



Challenge 2: Inferring Error Syndromes

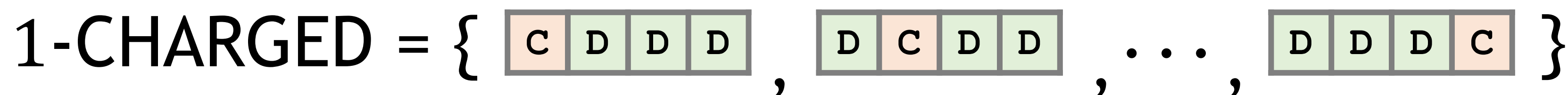


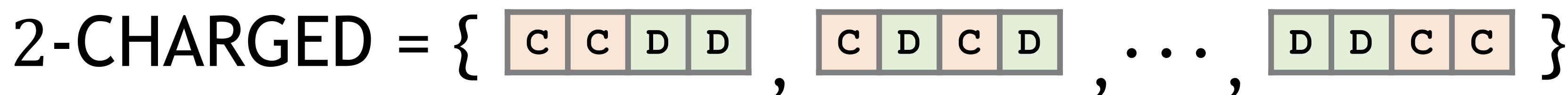
Challenge 2: Inferring Error Syndromes

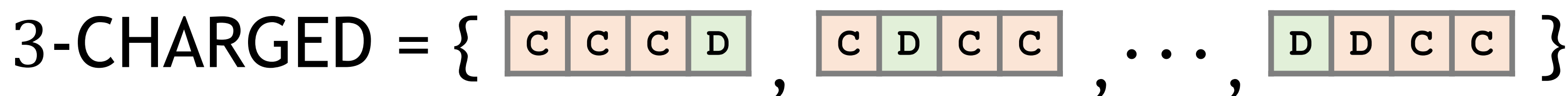
We can **differentiate** error syndromes from **uncorrectable error** patterns

Choosing a Set of Test Patterns

- We consider the "n-CHARGED" test patterns:







- Our paper explains that the combined {1,2}-CHARGED patterns are sufficient to identify the ECC function
- For each test pattern, we find **all possible** uncorrectable errors that can occur
  - Exploit **uniform-randomness** of data-retention errors
  - Even one DRAM chip provides millions of samples
    - E.g., 2 GiB DRAM module yields 2^{24} 128-bit words

BEER: Bit-Exact ECC Recovery

1. Experimentally induce data-retention errors using {1,2}-CHARGED test patterns

2. For each test pattern, identify all possible uncorrectable errors

3. Solve for the ECC function with the observed behavior using a SAT solver

Talk Outline

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BEEP and Other Practical Use Cases for BEER

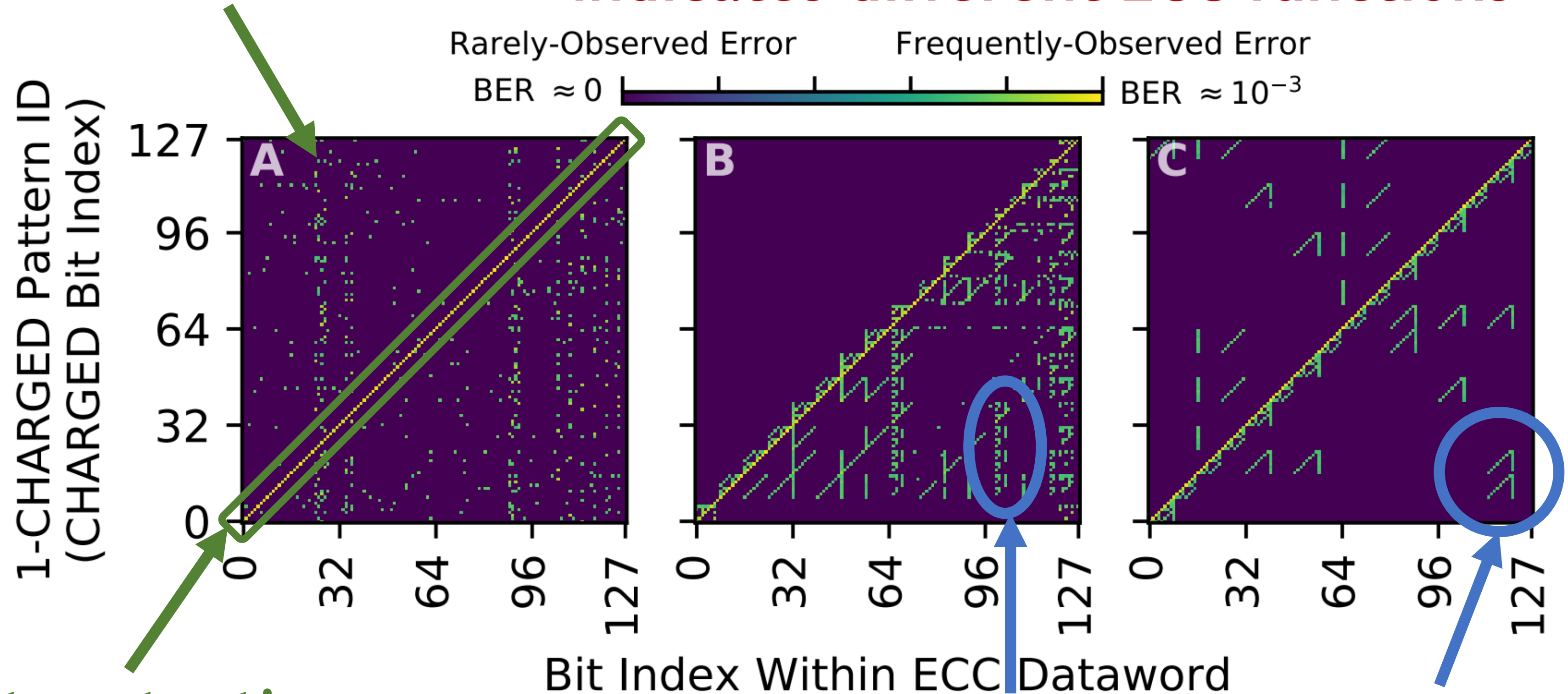
Experimental Methodology

- 80 LPDDR4 chips from 3 DRAM manufacturers
  - Manufacturers **anonymized** as ‘A’, ‘B’, and ‘C’
  - Temperature-controlled testing infrastructure
  - Control over DRAM timings (including refresh)

- **Refresh windows** between 1-30 minutes at 30-80°C
  - Leads to **bit error rates** (BERs) between 10^{-7} and 10^{-3}
  - BERs **far larger** than those of unwanted soft errors

Applying BEER to LPDDR4 Chips

- Study the uncorrectable errors in the 1-CHARGED patterns



Applying BEER to LPDDR4 Chips

1. **Different manufacturers** appear to use **different** on-die ECC functions

2. Chips of the **same model number** appear to use **identical** ECC functions

(shown in our paper)

Solving for the ECC Function

- We use the **Z3**[†] **SAT solver** to identify the $\boldsymbol{H}$-matrix
  - We demonstrate BEER for SEC Hamming codes, but it should readily extend to **all** linear block codes (e.g., BCH)
- We **open-source** our BEER implementation on **GitHub**
  - https://github.com/CMU-SAFARI/BEER
- Unfortunately, we face two **limitations** to validation:
  1. No way to check the **final results** since we cannot see into the on-die ECC implementation
  2. We cannot share our final matrices due to **confidentiality** reasons

[†]L. De Moura and N. Bjørner, "Z3: An Effient SMT Solver," TACAS, 2008.

Solving for the ECC Function

We validate BEER in **simulation** to:

1. Evaluate **correctness**
2. **Overcome** confidentiality issues
3. Test a **larger** set of ECC codes

Simulation Methodology

- We use the EINSim† DRAM error-correction simulator

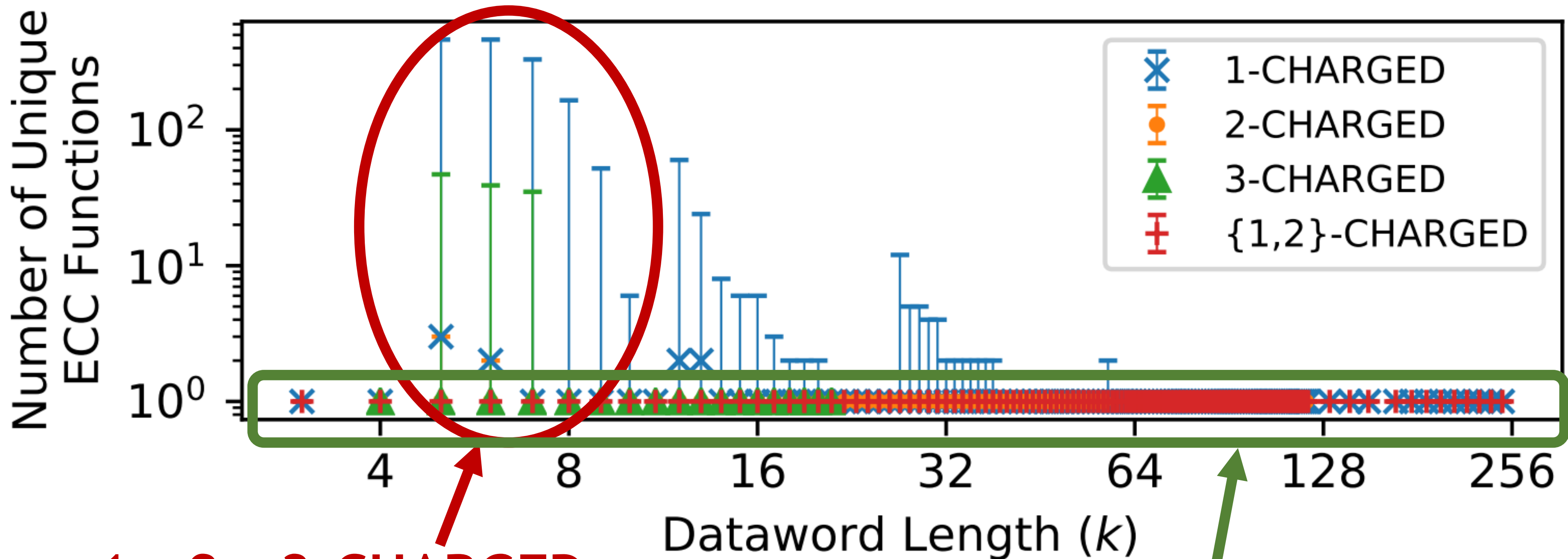
- We simulate 115,300 different SEC Hamming codes
  - ECC dataword lengths from 4 to 247 bits
  - 1-, 2-, 3-, and {1,2}-CHARGED test patterns

- For each test pattern:
  - Simulate 10^9 ECC words (≈14.9 GiB for 128-bit words)
  - Simulate data-retention errors with BER between 10^{-5} and 10^{-2}

†Patel et al., "*Understanding and Modeling On-Die Error Correction in Modern DRAM: An Experimental Study Using Real Devices*," DSN, 2019.

BEER Correctness Evaluation

- Evaluate the number of SAT solutions found by BEER
  - Shows whether the 'unique' solution is identified



1-, 2-, 3-CHARGED patterns individually do not always succeed

{1,2} -CHARGED patterns succeed for all test cases

BEER Correctness Evaluation

BEER **successfully** identifies the ECC function using the **{1,2}-CHARGED** test patterns

Two Other Evaluations in the Paper

1. Practicality of BEER's SAT problem
   - Measure SAT problem runtime and memory consumption
   - Negligible for short codes (i.e., < 1 minute, < 1 MiB RAM)
   - Realistic for long codes given that BEER is run offline
     - e.g., 57.1 hours + 6.3 GiB RAM for 128-bit code

2. Analytical experimental runtime analysis
   - Majority time is spent waiting for data-retention errors
   - 4.2 hours of testing per chip in our experiments

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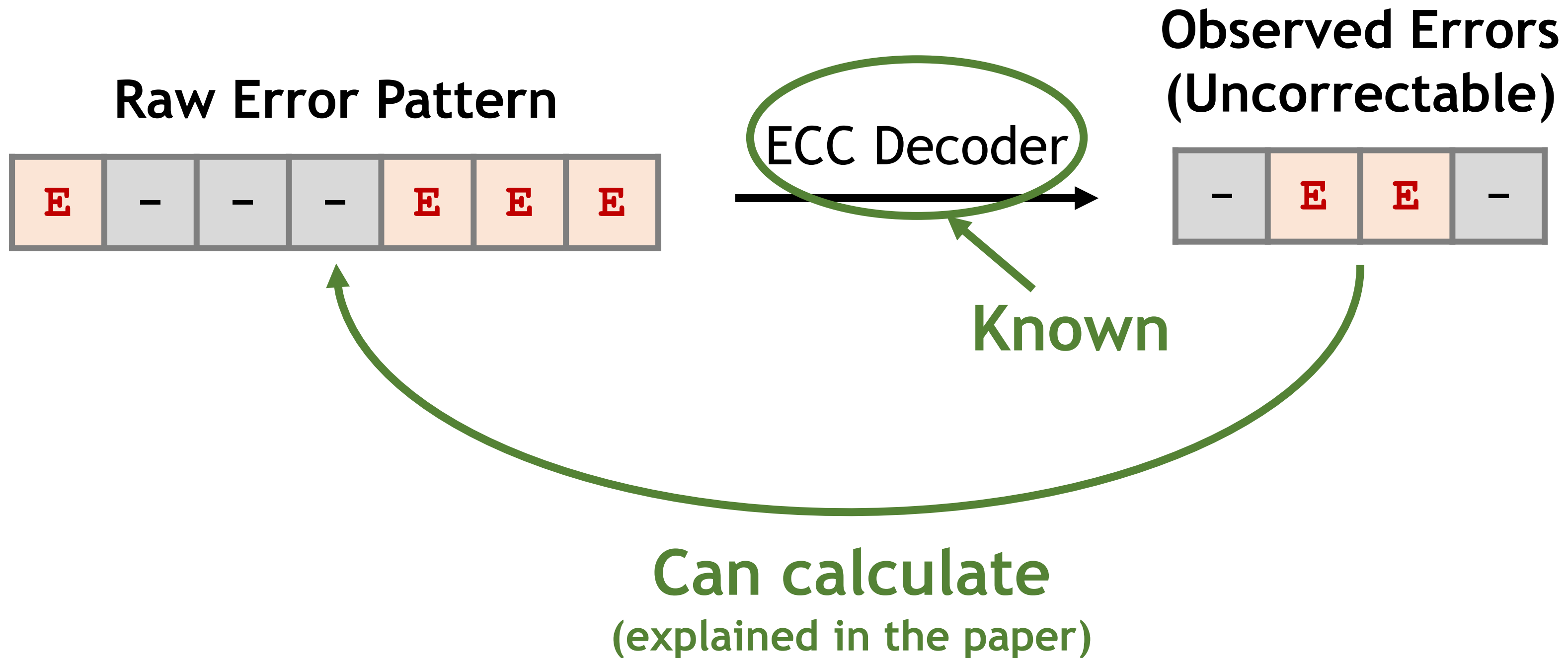
Practical Use Cases for BEER

Error Profiling

BEEP: identifying **raw bit error** locations corresponding to observed **post-correction errors**

BEEP: Profiling for Raw Bit Errors

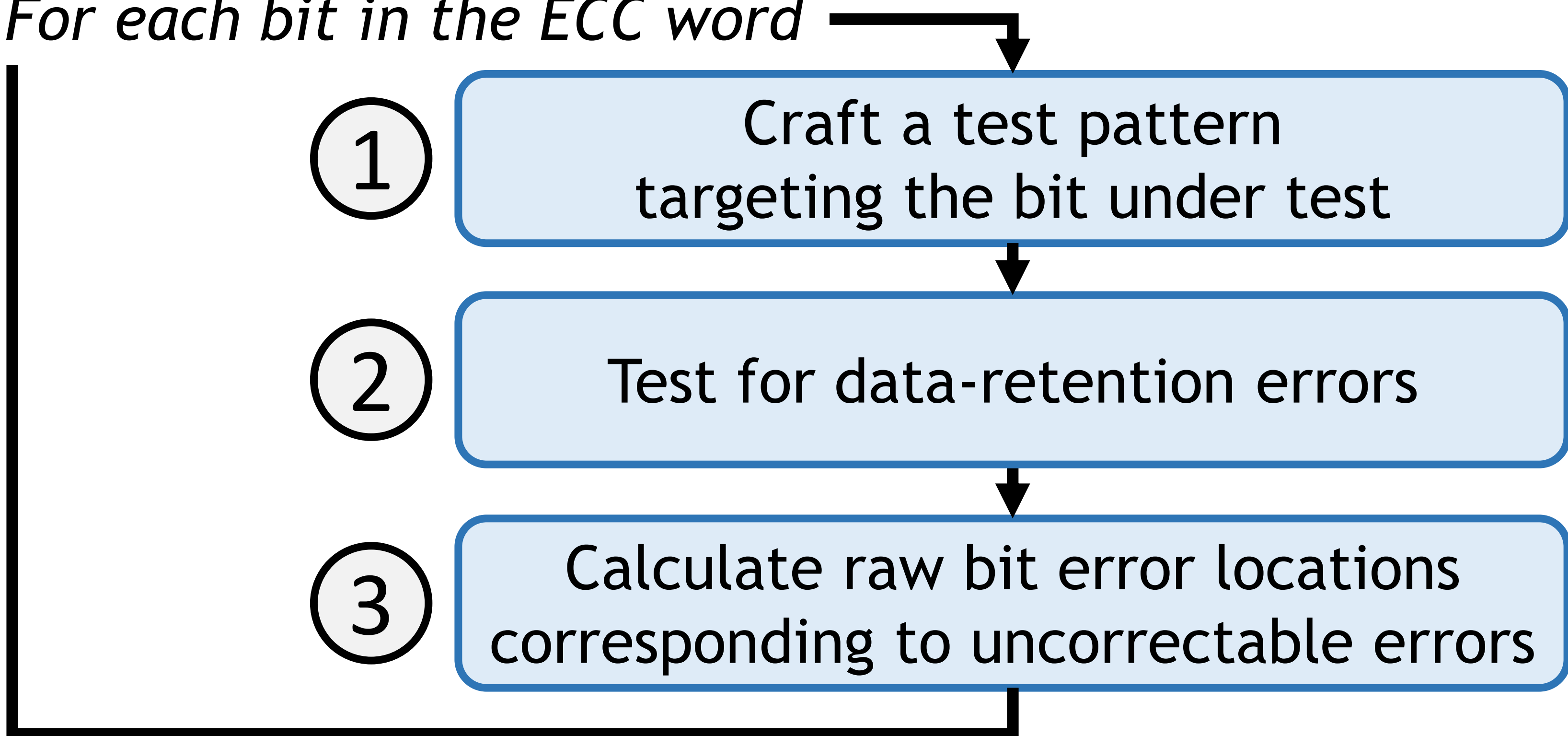
- **Key idea:** knowing the ECC function (i.e., via BEER) enables calculating raw bit error positions



- BEEP infers which **physical cells** are susceptible to data-retention errors using **only** the observed errors

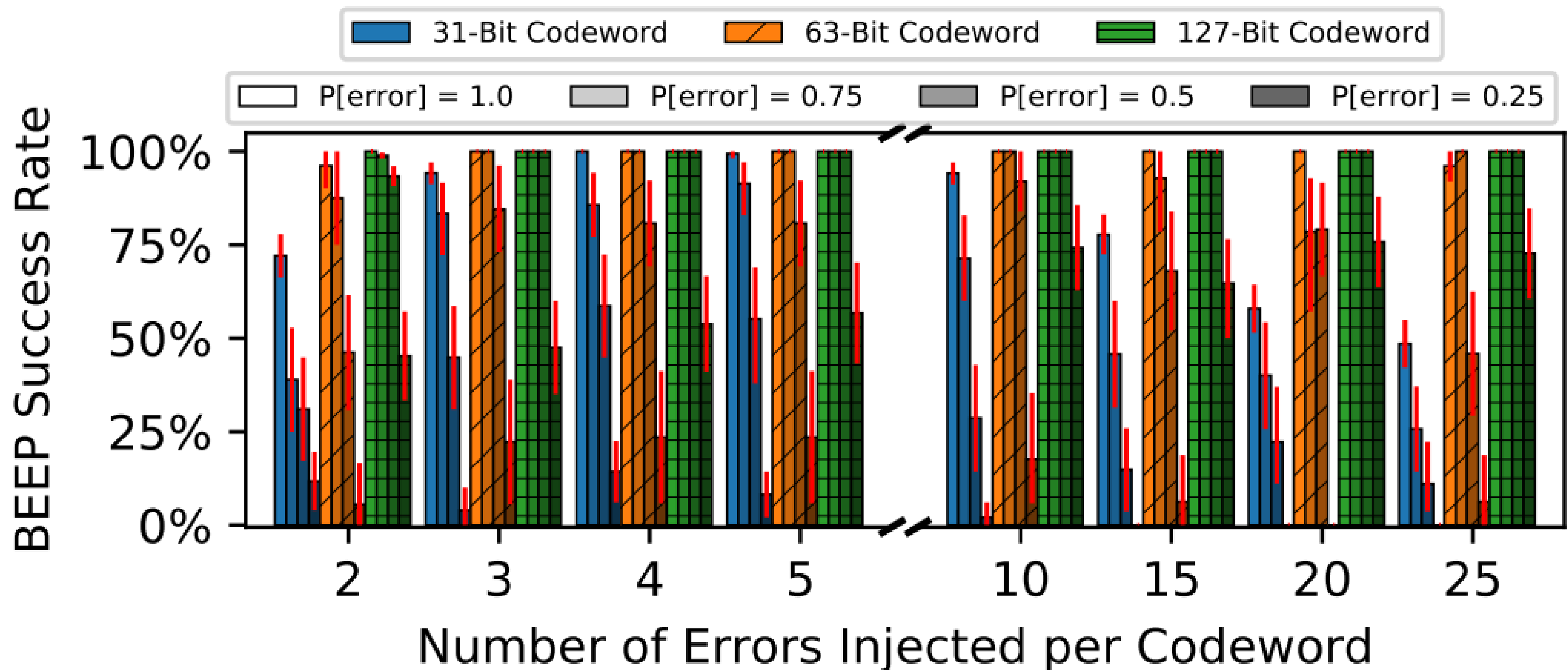
BEEP: High-Level Algorithm

- Iteratively test each bit in the ECC word and keep track of the error-prone cells it identifies



Evaluating BEEP's Accuracy

- We evaluate BEEP's **success rate** of identifying raw bit errors in simulation
  - Varying ECC word lengths and bit error rates
  - 100 ECC words simulated per measurement



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Evaluating BEEP's Accuracy

BEEP is **more successful** for:

1. **Longer** ECC words
2. **Higher-probability** errors

Other Information in the Paper

- **Formalism** for BEER and the n-CHARGED test patterns
- **BEER** evaluations using **experiment** and **simulation**
  - Sensitivity to experimental noise
  - Analysis of experimental runtime
  - Practicality of the SAT problem (i.e., runtime, memory)
- **BEEP** evaluations in **simulation**
  - Accuracy at different error rates
  - Sensitivity to different ECC codes and word sizes
- Detailed discussion of **use-cases** for BEER
- Discussion on BEER's **requirements** and **limitations**

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