Cryptographic Memory Tagging:

Towards Stateless Integrity

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Project Overview

- **Memory safety violations** (Use After Free, Buffer Overflow, etc) persist, causing unauthorized access, data corruption, and system crashes
- Traditional tagging solutions **require metadata storage**, introducing significant overhead
- **Our approach** implements tagging via a cryptographic pointer framework, allowing memory access control **with near-zero metadata storage**
- Simulated results show good integrity coverage with negligible memory overhead

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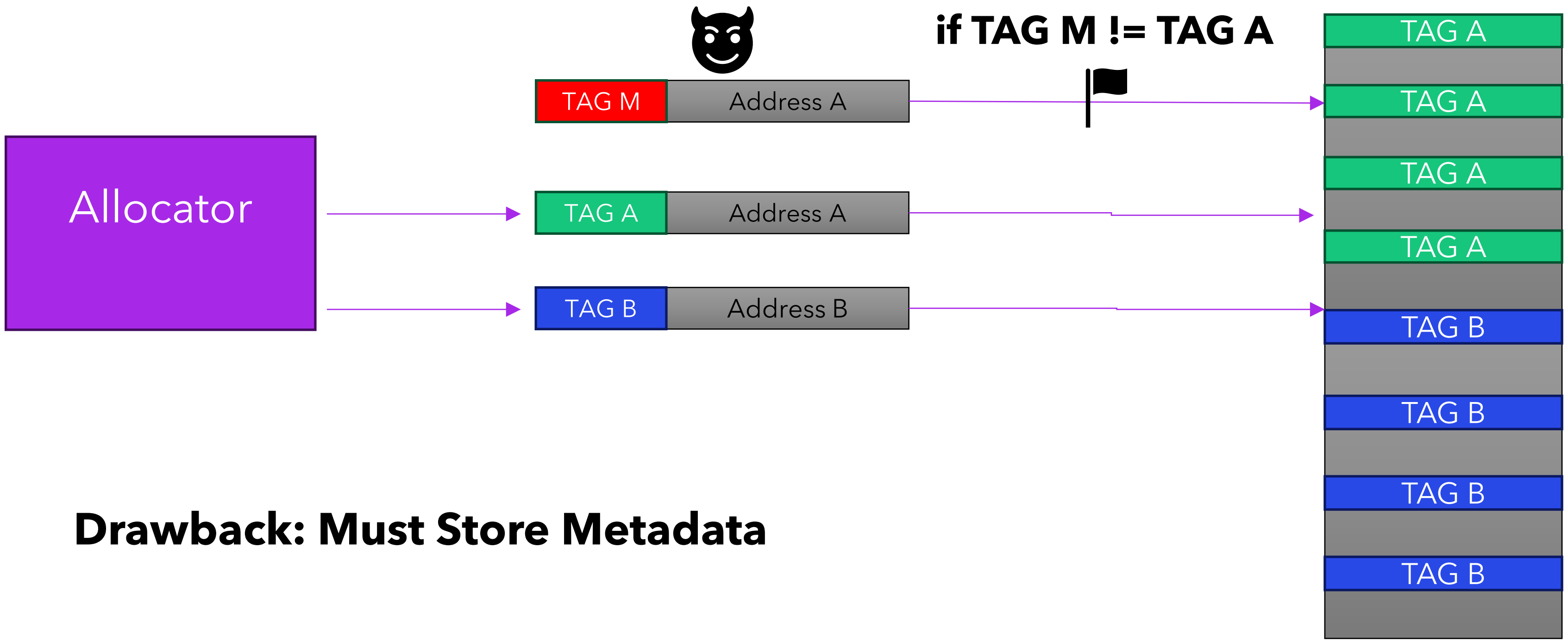
Traditional Memory Tagging



Drawback: Must Store Metadata

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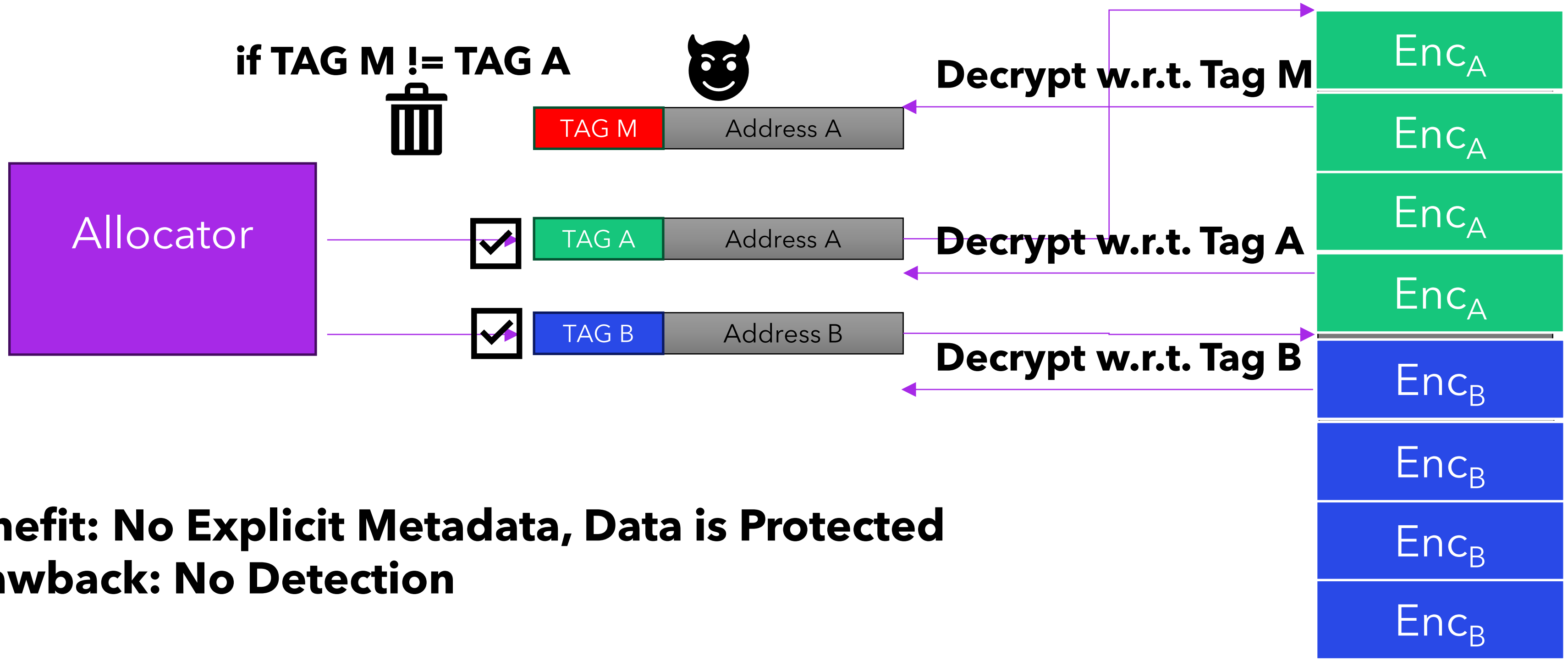
Cryptographic Capability Computing (C3) Memory Safety



Benefit: No Explicit Metadata, Data is Protected
Drawback: No Detection

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Cryptographic Memory Tagging

- **Goal:** Use the C3 encryption framework to perform memory tagging without state
- **Strategy:** Infer integrity from decryption entropy

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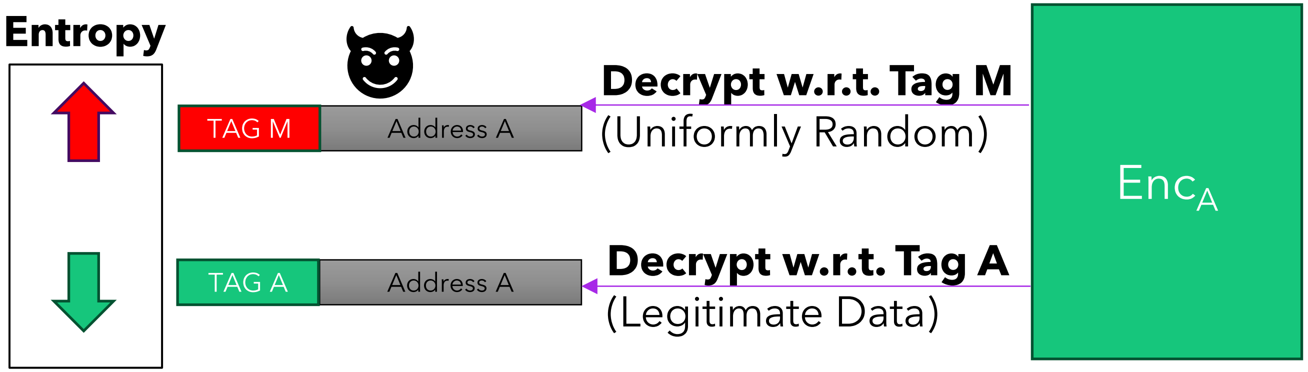
Key Insight: Decryption Entropy



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Binary Entropy Testing

Input: Data Granule

Output: Decision Boolean (high/low Entropy)

A <u>useful</u> binary entropy test:

Uniformly Random Granule : ↑ With provably high probability

Legitimate Data Granule : ↓ For *most** workload data

Let's assume for now we have something like this on hand (see appendix slides)

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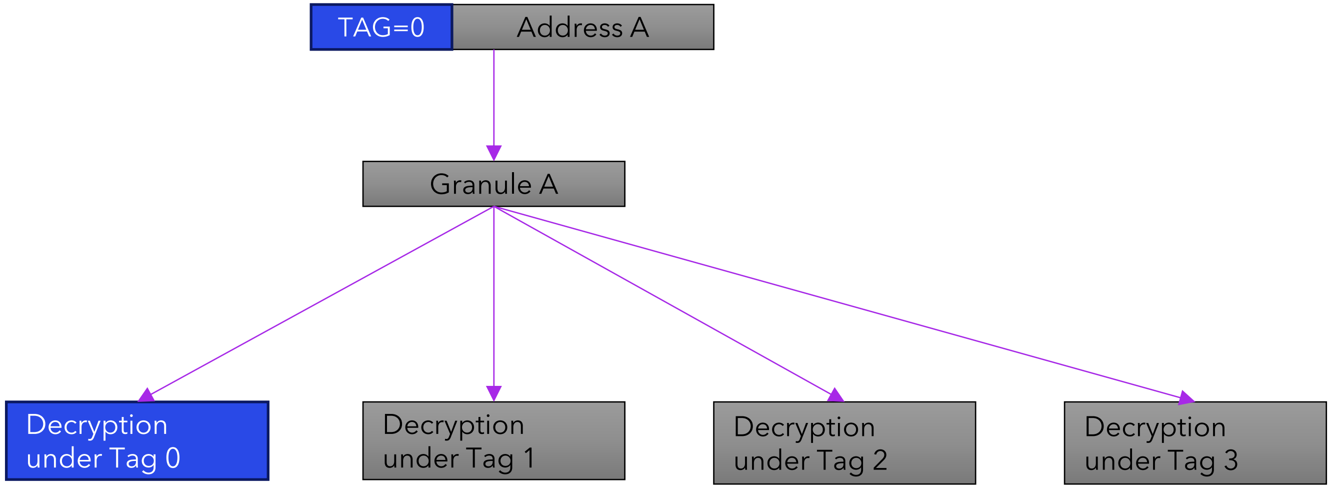
Inferring Integrity

Uniformly Random Granule : With provably high probability

Legitimate Data Granule : For *most** workload data

(Assume 2-bit tags)



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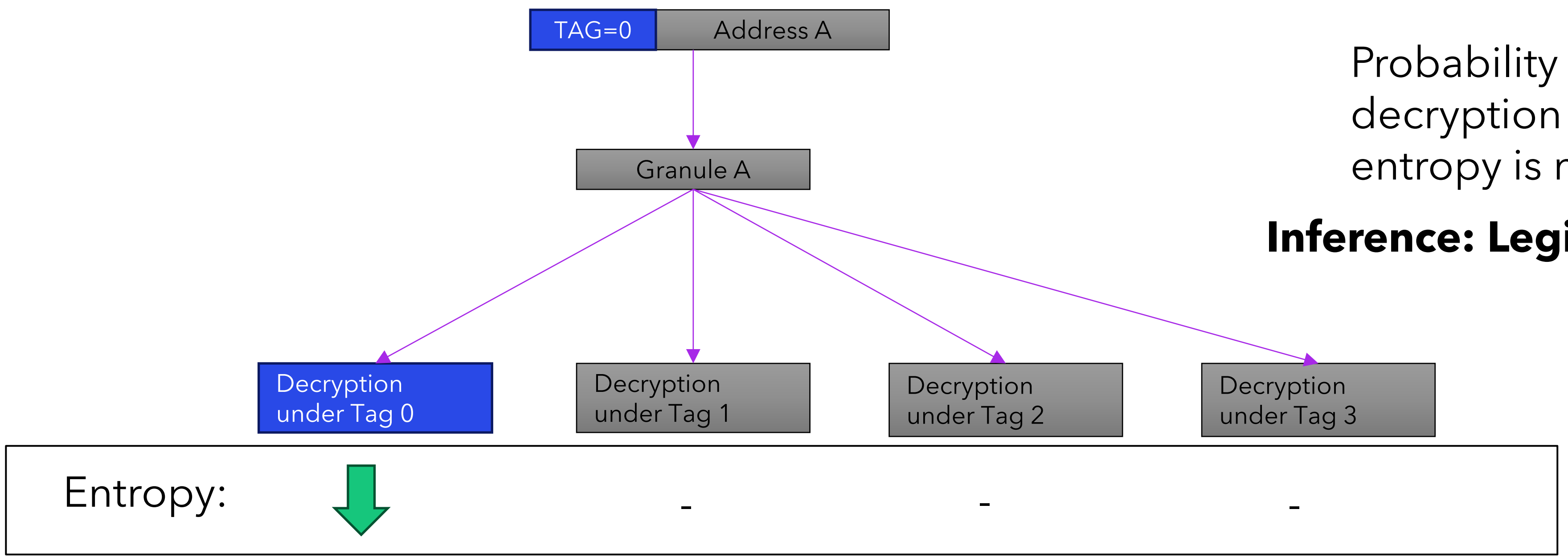

Probability of incorrect decryption with low entropy is near-zero

Inference: Legitimate Access

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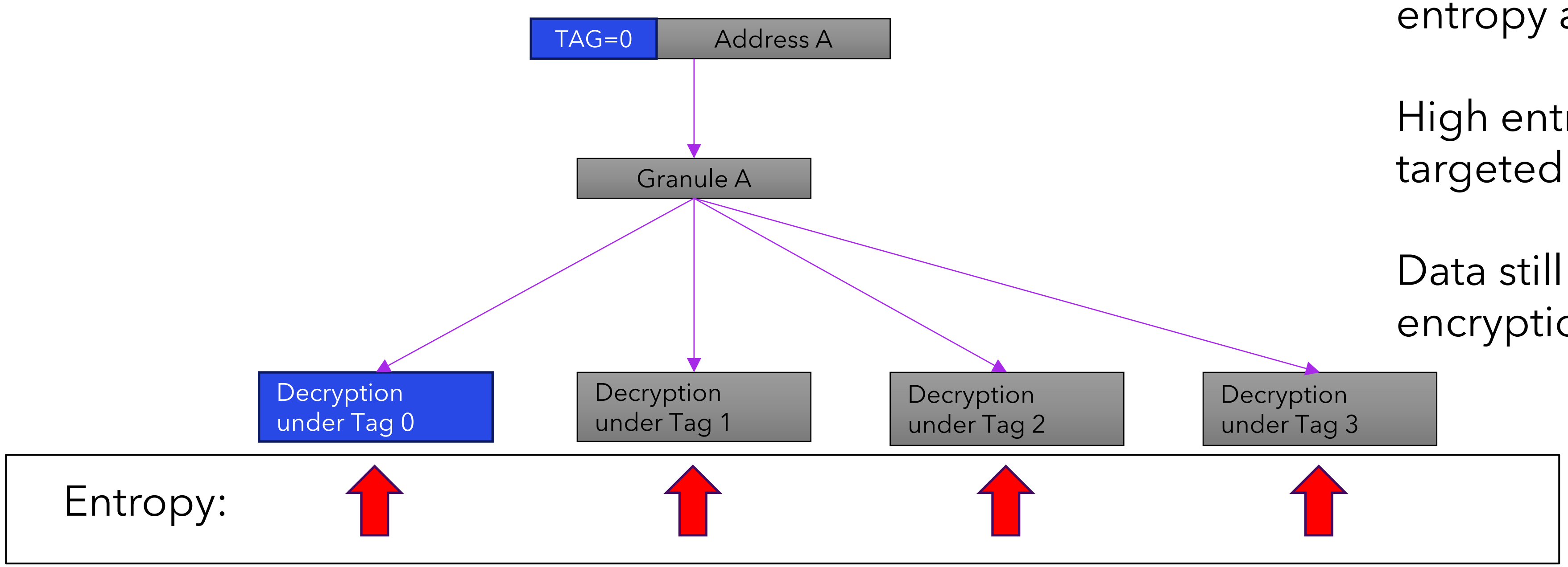
Inferring Integrity

Uniformly Random Granule : With provably high probability

Legitimate Data Granule : For *most** workload data

(Assume 2-bit tags)



The true decryption is high entropy and indistinguishable

High entropy data typically isn't targeted

Data still protected by encryption.

Inference: Ambiguous

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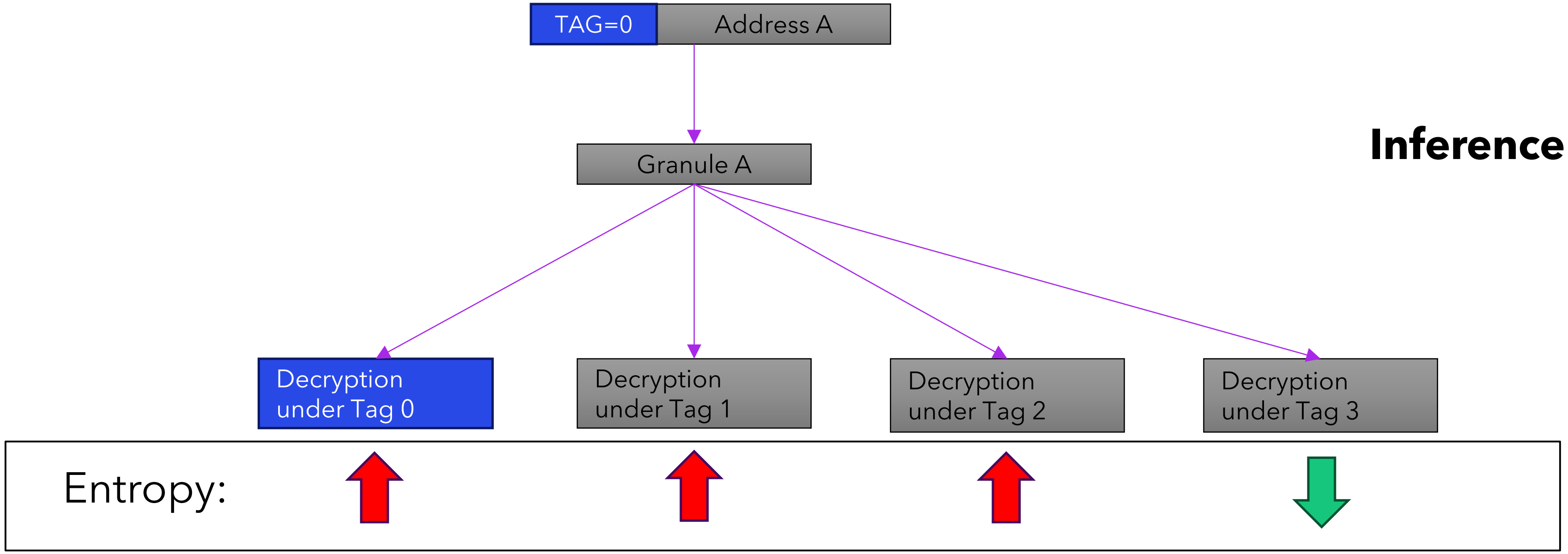
Inferring Integrity

(Assume 2-bit tags)



Inference: Potential Violation

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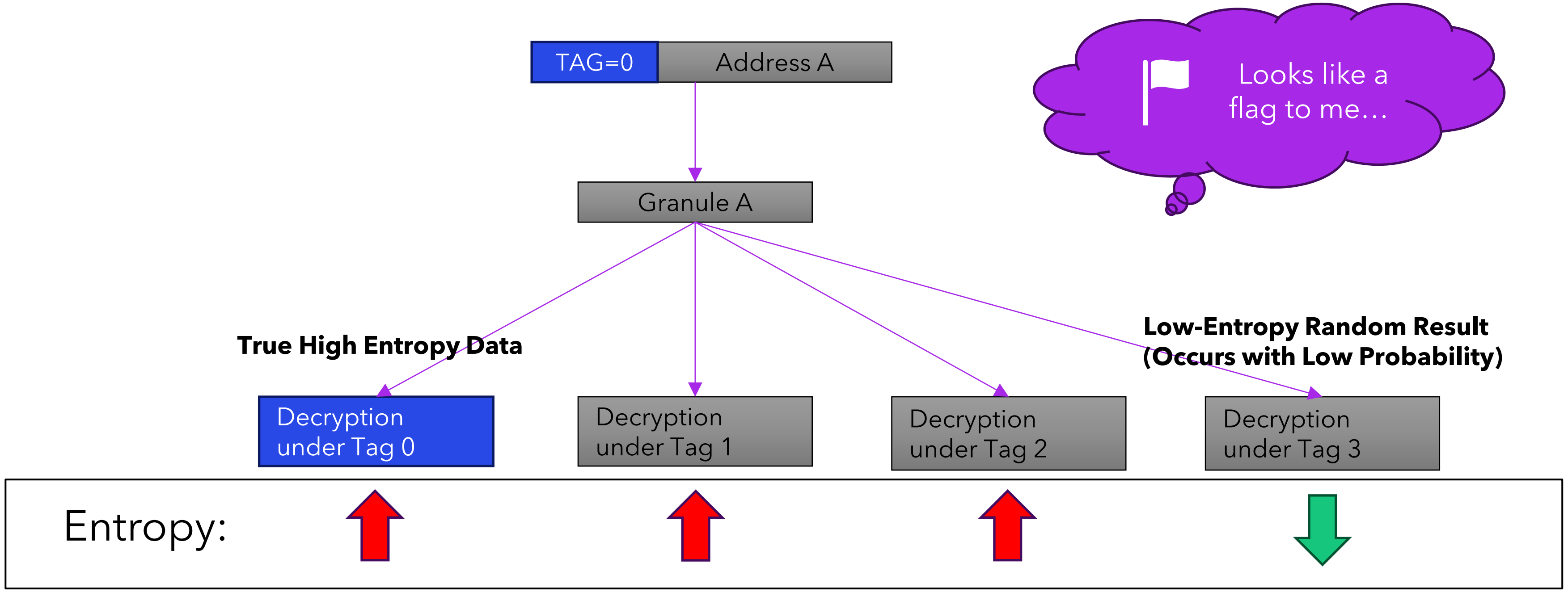
False Positive Flagging

(Assume 2-bit tags)



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False Positive Table

- The false positive table is the **only introduced state**.

- The table's expected size **linearly correlates** with the probability incorrect decryptions display low entropy, which can be tuned via entropy test parameters

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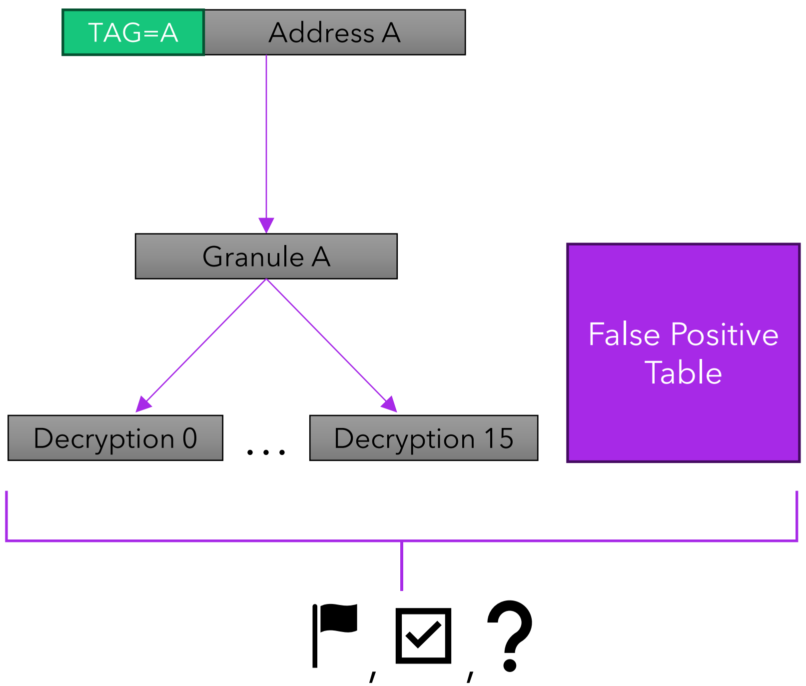
CMT Execution Path

Step 1: Verify Access (Read and Writes)



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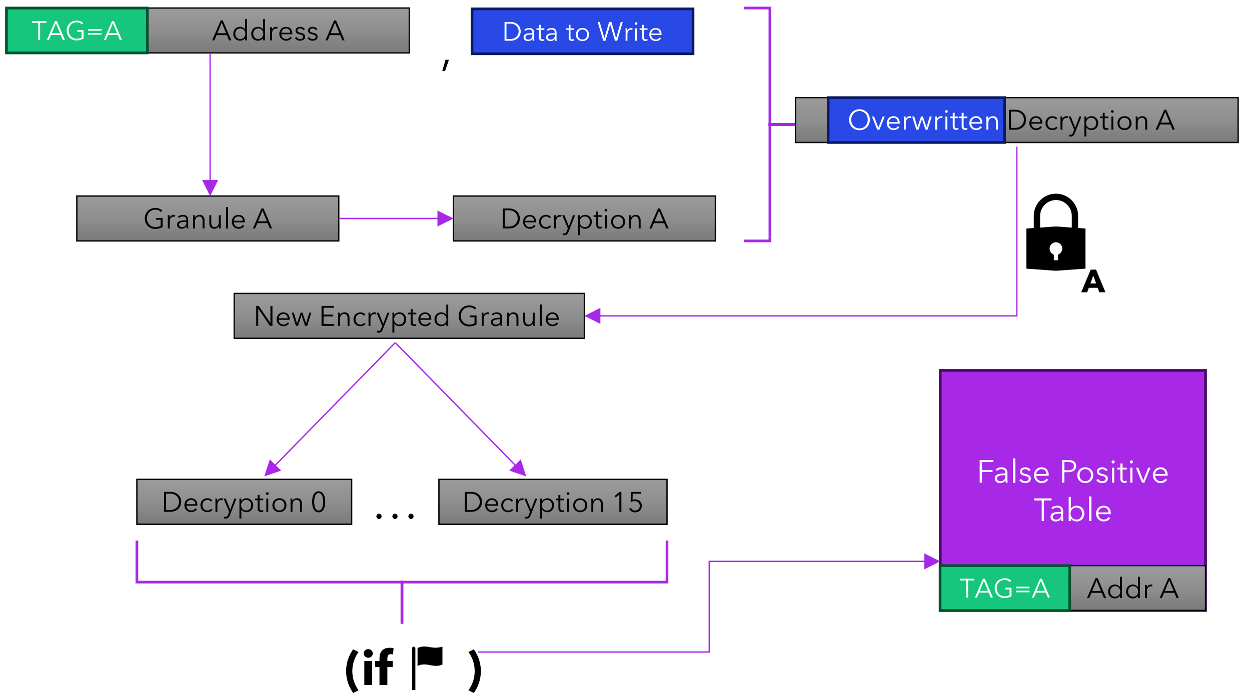
CMT Execution Path

Step 2: Catch False Positives (Write Only)



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Efficacy Experiment

Aimed at quantifying **integrity coverage** and **lookup overhead** across active granules:

- Whenever an allocated granule is accessed by the workload, log or update its integrity outcome in a **memory map**.
- Each time a granule is freed, remove the granule from the map.
- **Every million accesses**, record the verification status of the entire active memory image.
- Calculate the **geometric mean** over these data points to report average portions for each workload.

Implemented CMT using Intel Simics-based simulator

Conducted over SPEC CPU2017 testing suite

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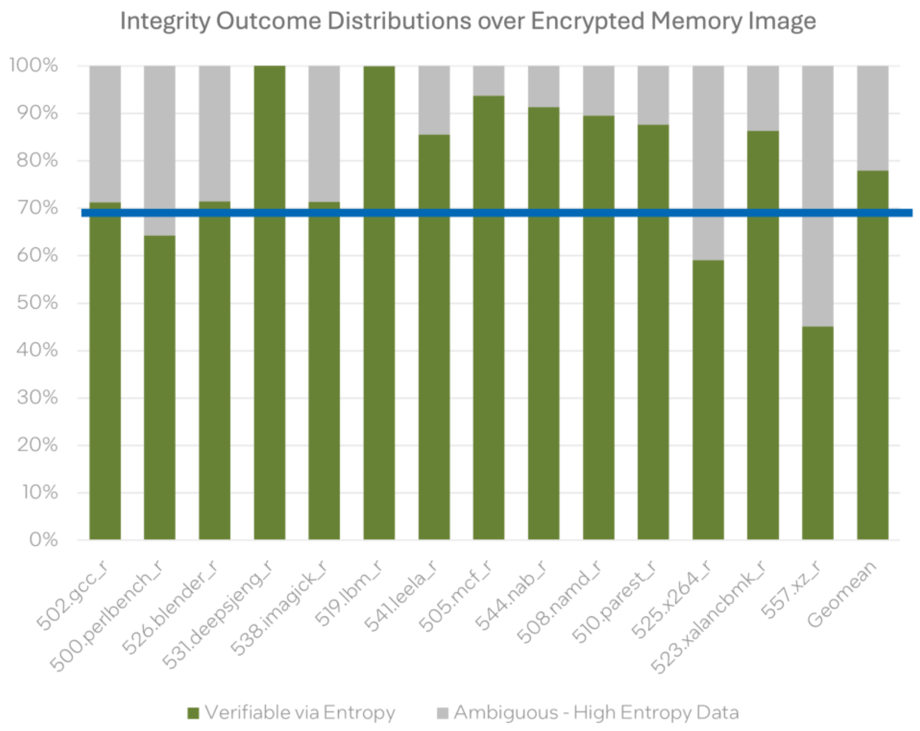
Efficacy over Active Memory Image

- Geometric Mean of 80% coverage across workloads
- Less than <0.1% of operations resulted in a lookup
- Only 3 workloads fall below 70%, all of which store large amounts of high entropy data (ex. xz)



Conclusion

Cryptographic Memory Tagging achieves memory safety and data integrity with minimal overhead, providing a comprehensive, stateless approach to protecting modern computing systems.

Open Questions include:

- More nuanced, workload specific entropy tests
- Measuring entropy relative to other decryptions
- Hardware design brainstorming

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Appendix: P-Statelessness

- Let **P** be the probability that a uniformly random string (an incorrect decryption) registers as low entropy.
- In expectation, at most **P** portion of active memory granules have a lookup table entry
- We refer to such a scheme as **P-stateless**

- Goals choosing an entropy test and parameters:
  - Minimize **P**
  - Maintain ability to identify low entropy data

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Appendix: Byte Collision Test

Parameters: Granularity **g**, threshold **t**

- Input: a granule of length **g**
  - Initialize counter to 0
  - Iterate through bytes of granule. For each byte that is a repeat, increment counter by 1
  - Return **high entropy** if counter < t, and **low entropy** otherwise

  - We can express **P**, the probability of an incorrect low entropy result as:

$$P_{\mathrm{BYTE}}(g,t) = 1 - \left(1 - \frac{\sum_{n=1}^{g-t}\left[\binom{256}{n}\sum_{k=0}^{n}(-1)^k\binom{n}{k}(n-k)^g\right]}{256^g}\right)^{15}$$

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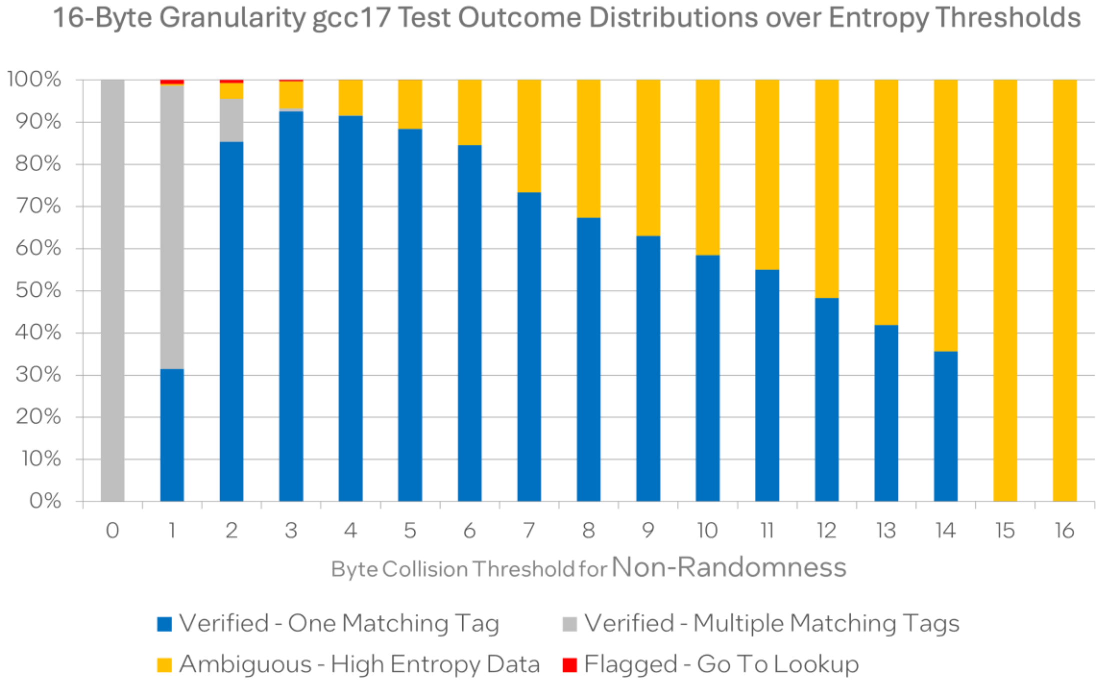
Appendix: Parameter Selection

Choice of **g = 16**:

- Generated stable entropy results
- Consistent with SOTA (ARM MTE)

Choice of **t = 4**:

- Reduces **P** while maintaining efficacy
- Larger **t** values can further minimize **P**, but trade off efficacy



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