PoWER Never Corrupts: Tool-Agnostic Verification of Crash Consistency and Corruption Detection

Hayley LeBlanc, Jacob R. Lorch, Chris Hawblitzel, Cheng Huang, Yiheng Tao, Nickolai Zeldovich, Vijay Chidambaram

🏆 ***Distinguished Artifact Award***

TEXAS The University of Texas at Austin
Microsoft
MIT CSAIL

Motivation: interest from Azure Storage in a **verified persistent memory key-value store**

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Goal 1: new techniques to verify PM systems and beyond

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Goal 2: verify crash consistency without built-in language support

i.e., *tool-agnostic*

Benefits of a tool-agnostic technique

Compatible with nearly all current verification tools

Developers can choose a tool best suited to their system

New storage systems can take advantage of powerful new verification tools

Contributions

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github.com/microsoft/verified-storage

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Challenging interaction with crashes!

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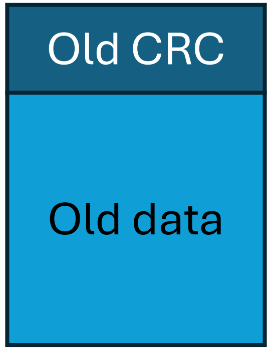

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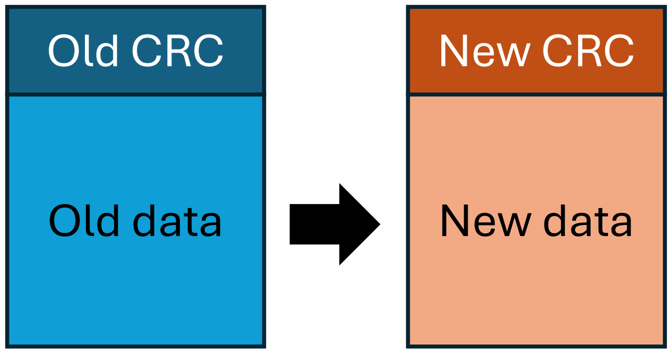

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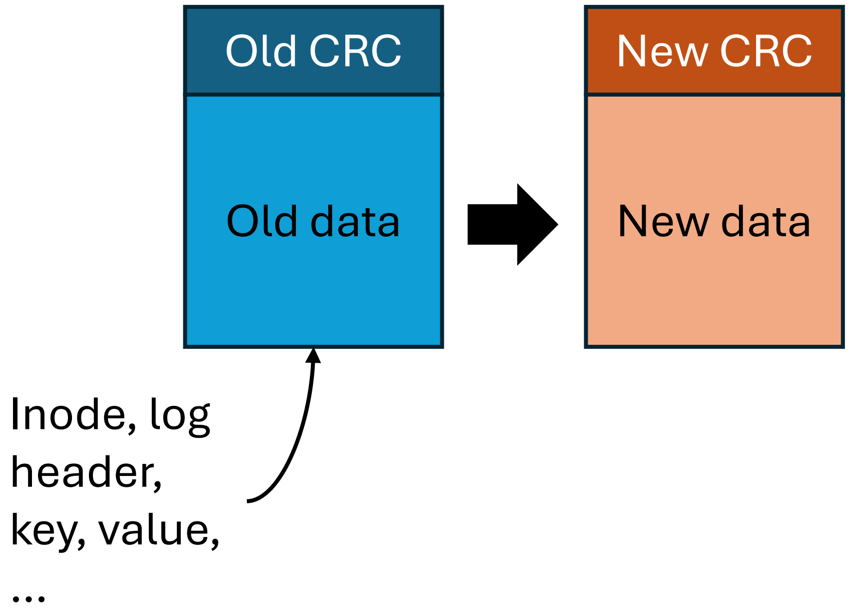

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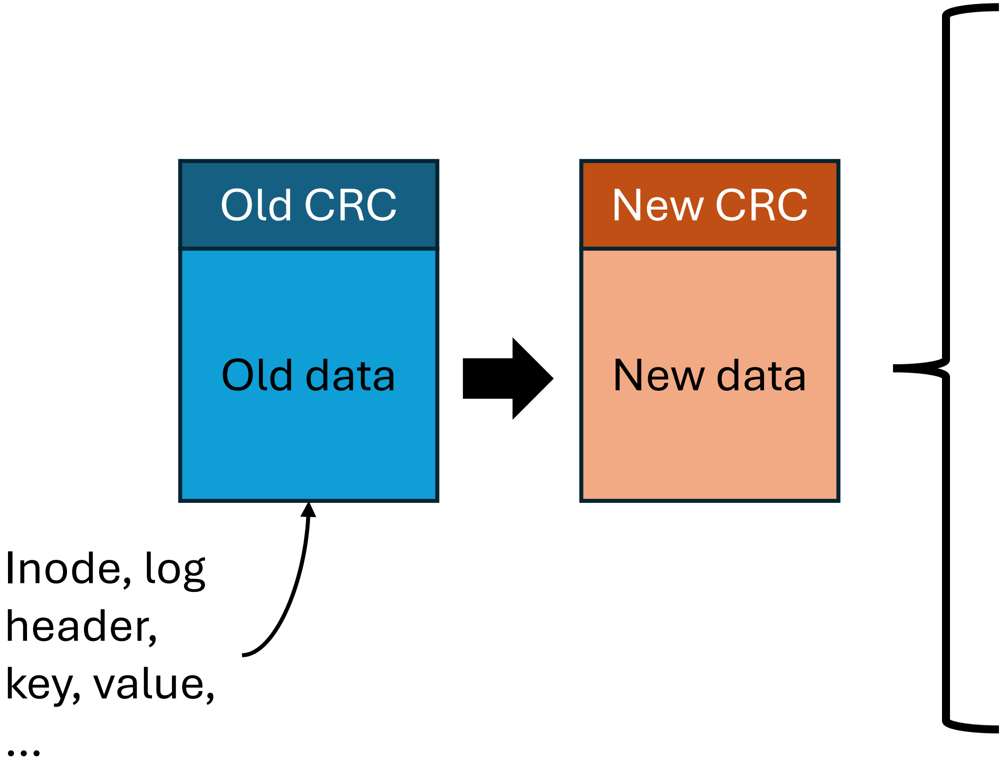

Possible crash states

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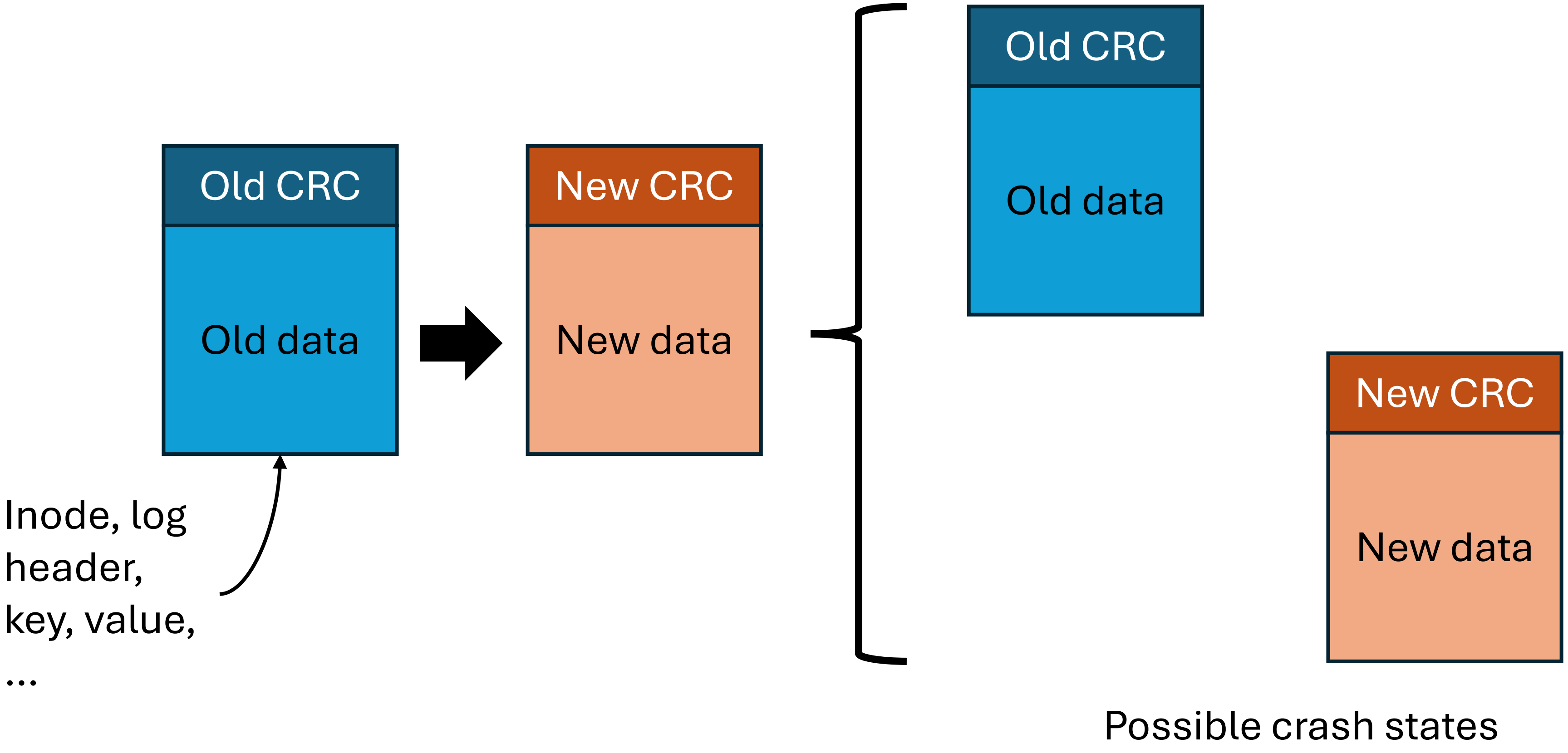

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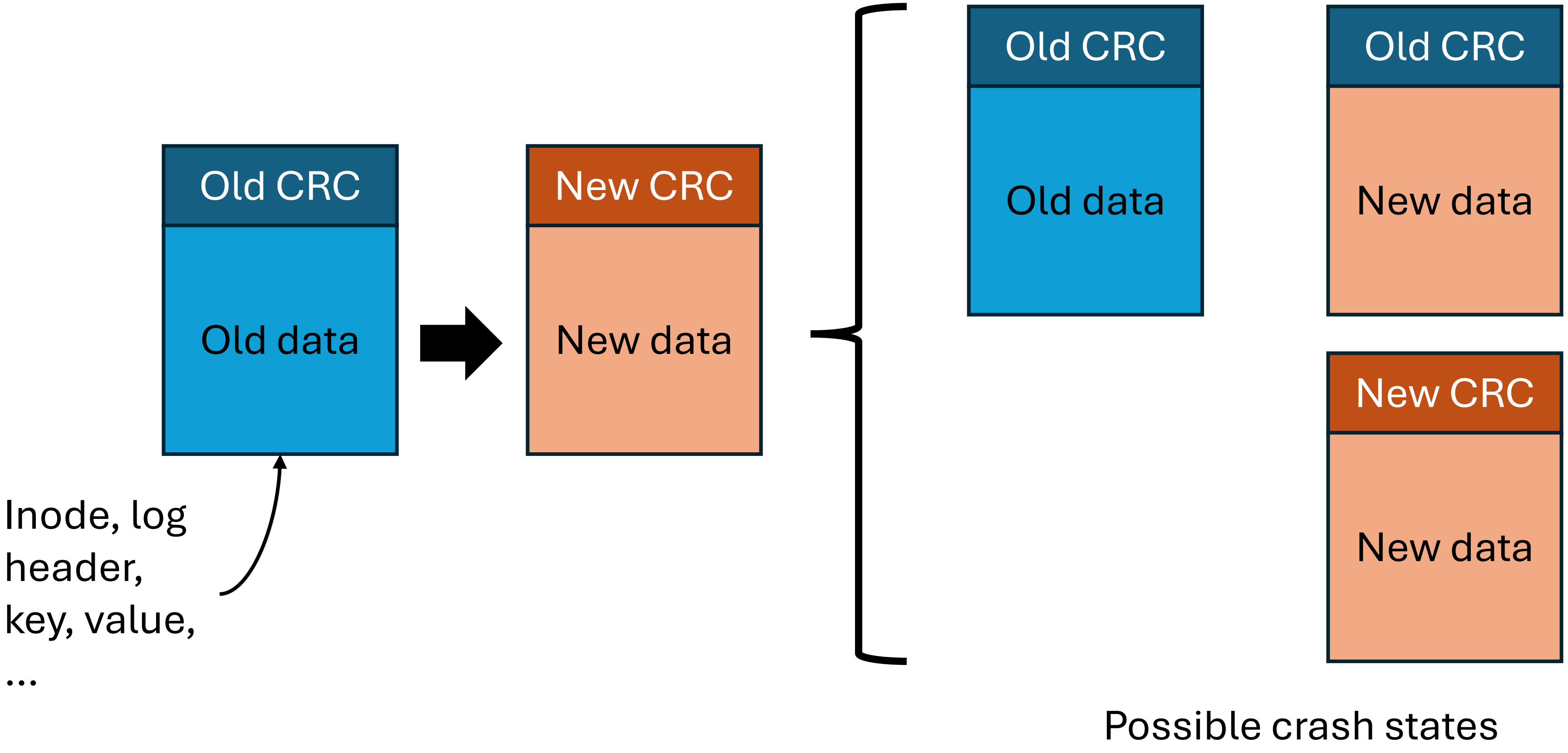

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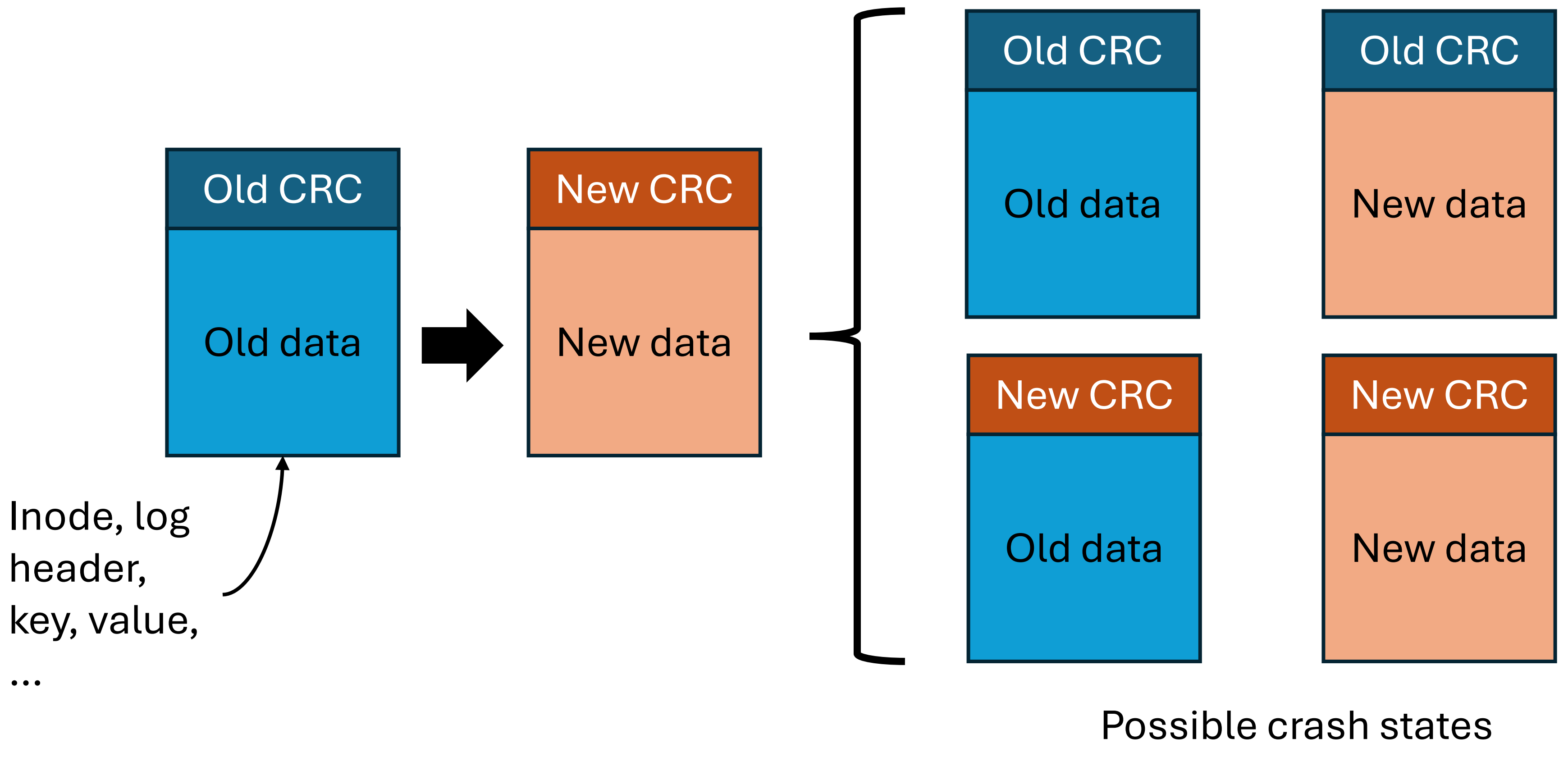

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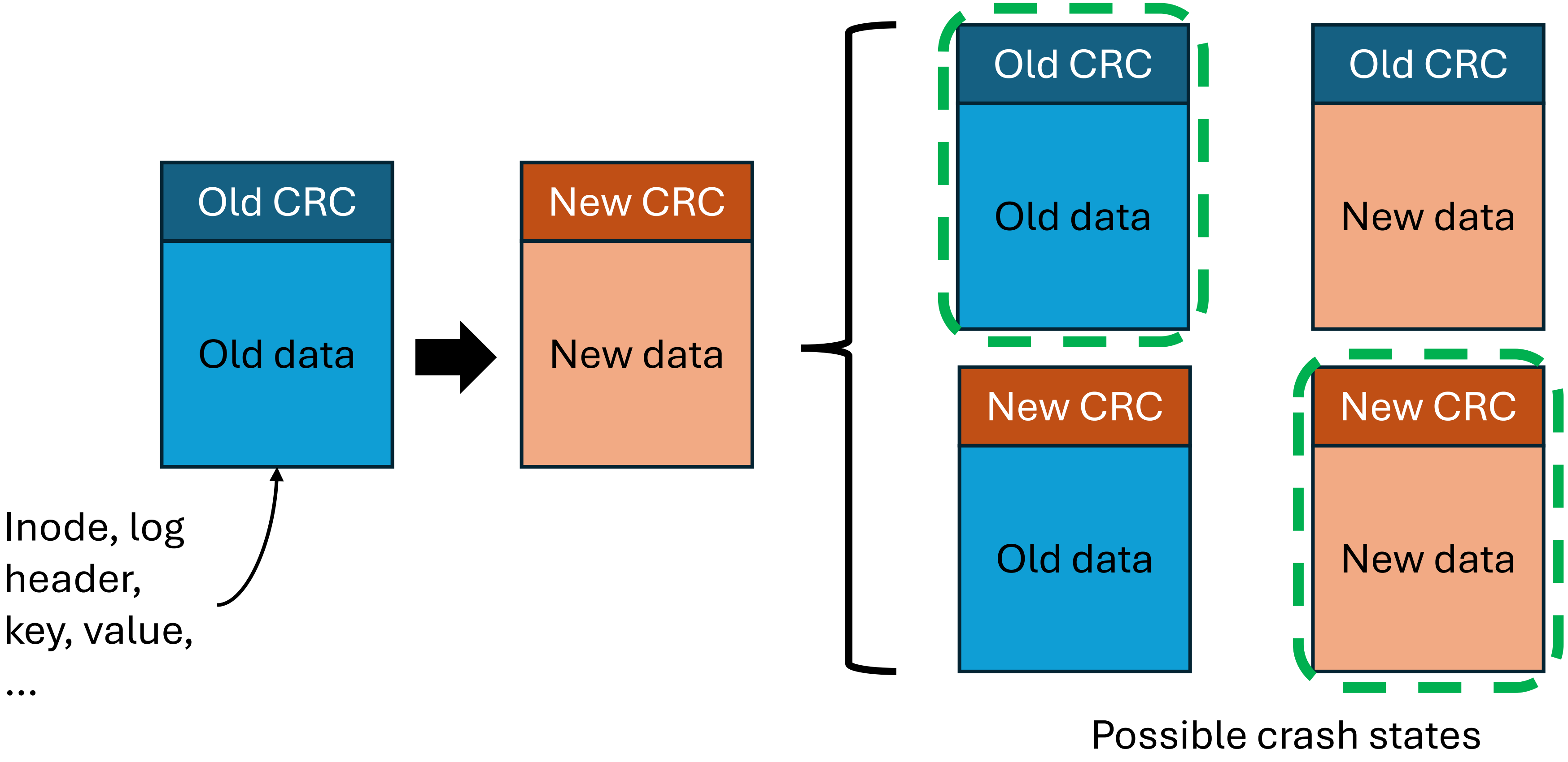

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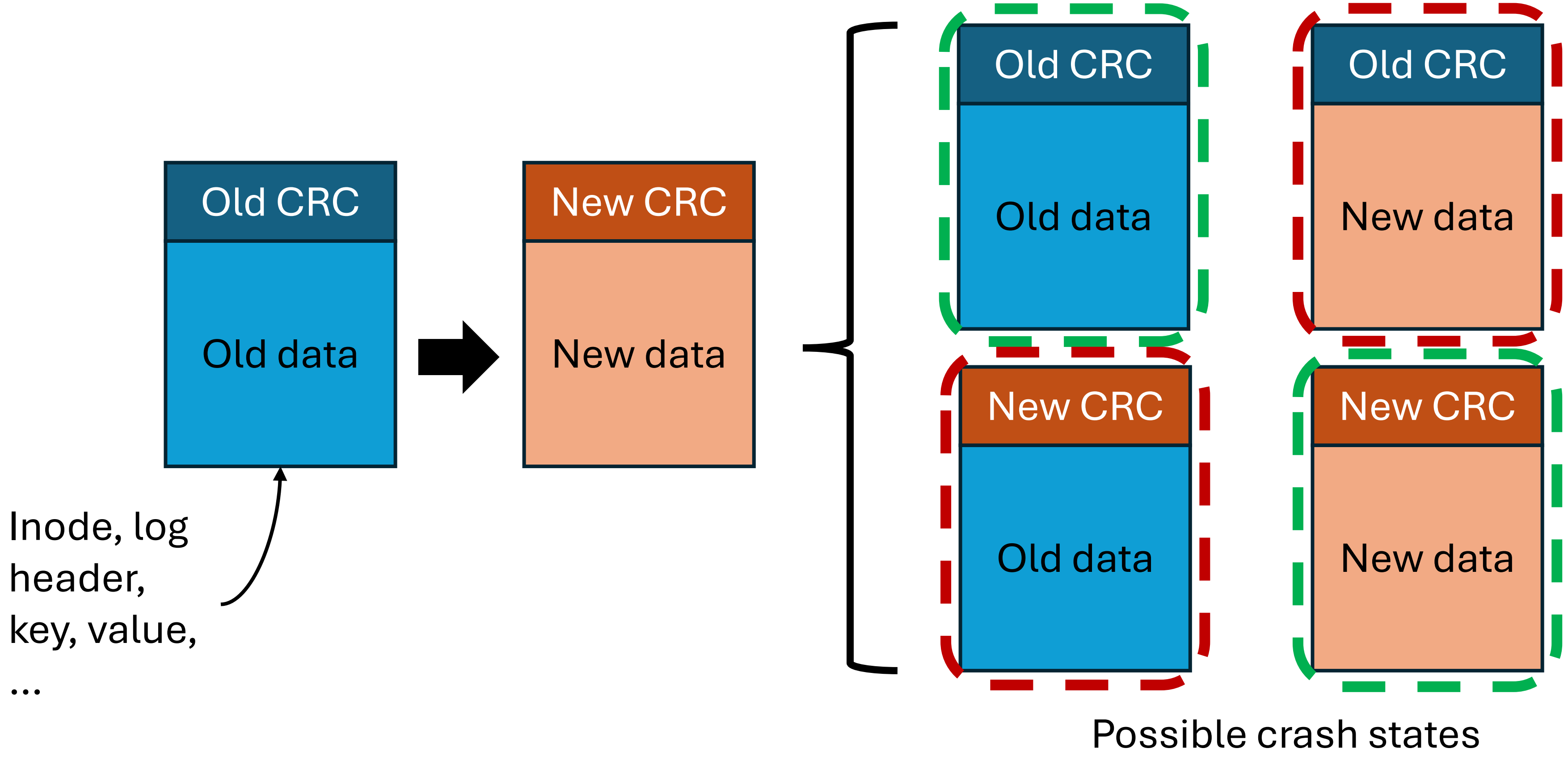

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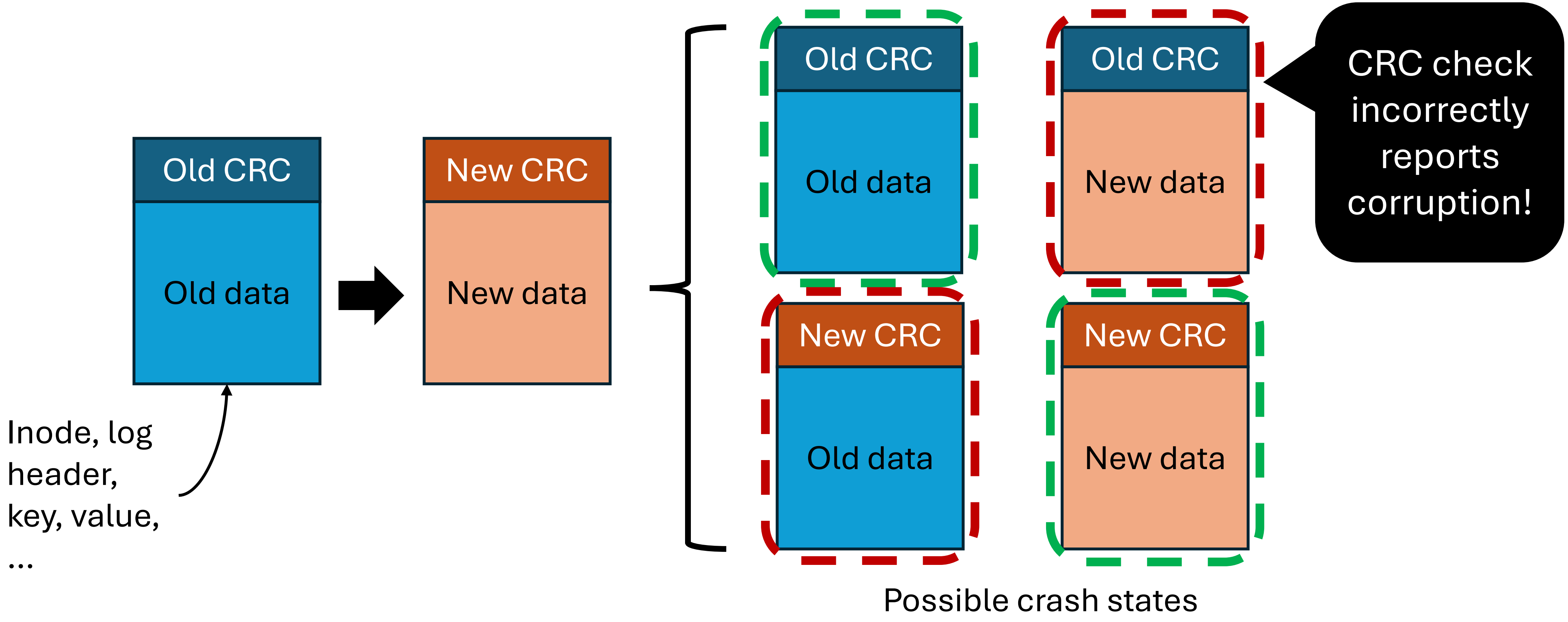

Ensuring crash consistency

Prior testing work: construct and check possible crash states

- eXplode (OSDI ‘06), CrashMonkey (OSDI ‘16), Hydra (SOSP ‘19), Yat (ATC ‘14), Vinter (ATC ‘22), Chipmunk (EuroSys ‘23), …

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We can **statically prove** ALL crash states consistent via verification!

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How to prove intermediate crash states consistent?

Prior work: crash conditions

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Key insight: crash-consistency proof requirements can be written as **preconditions**!

Can be done in nearly any verification tool!

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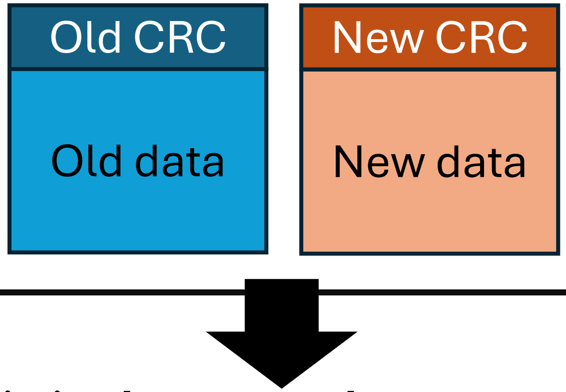


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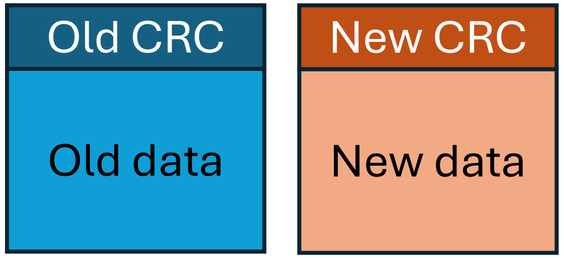


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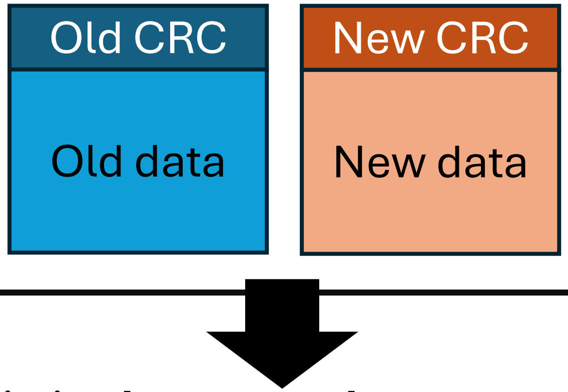


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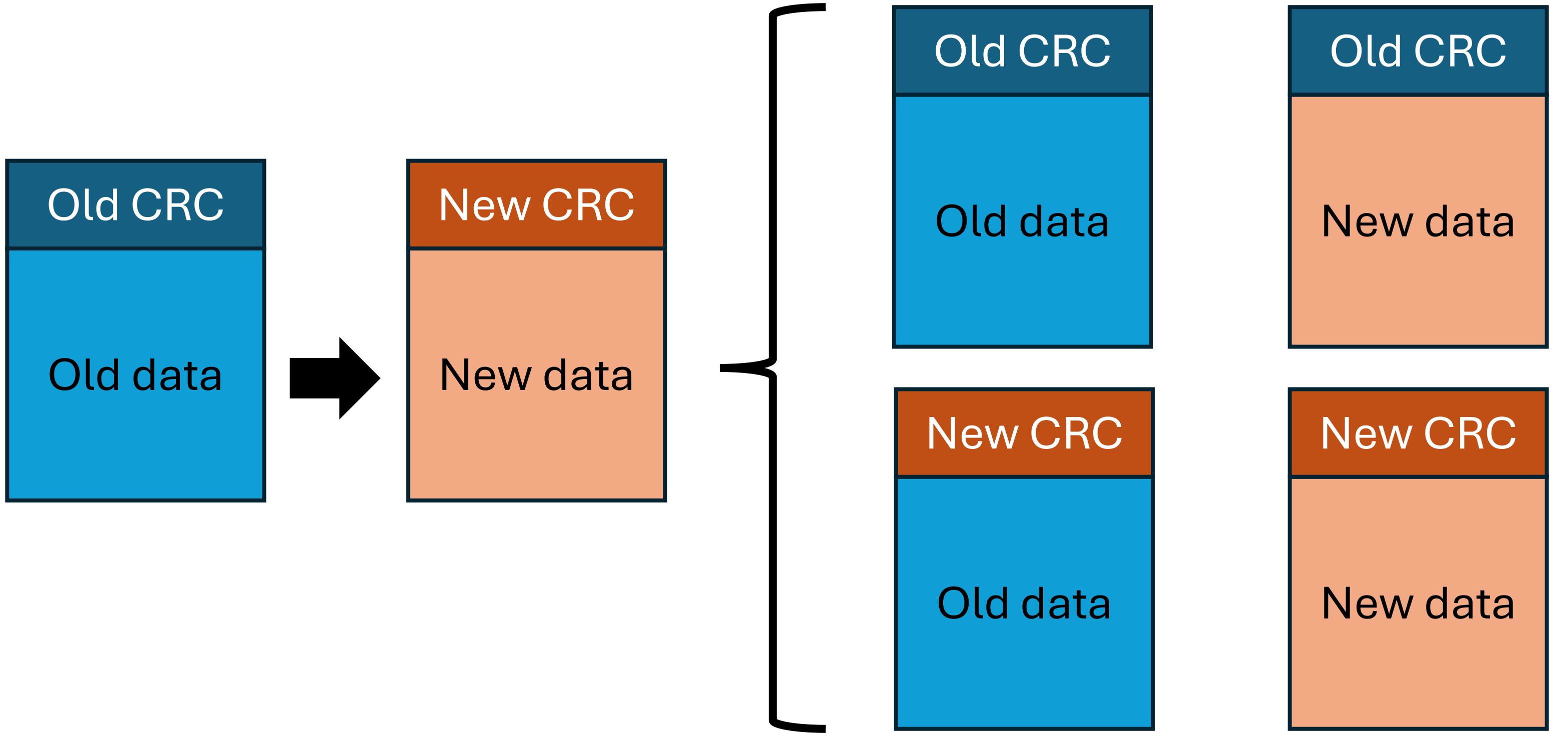
Satisfy precondition ==> prove crash consistency!

See paper for…

- Detailed description of PoWER technique
- Strategies for writing crash-consistency proofs
- Discussion of proofs that PoWER is sound
- PoWER and concurrency

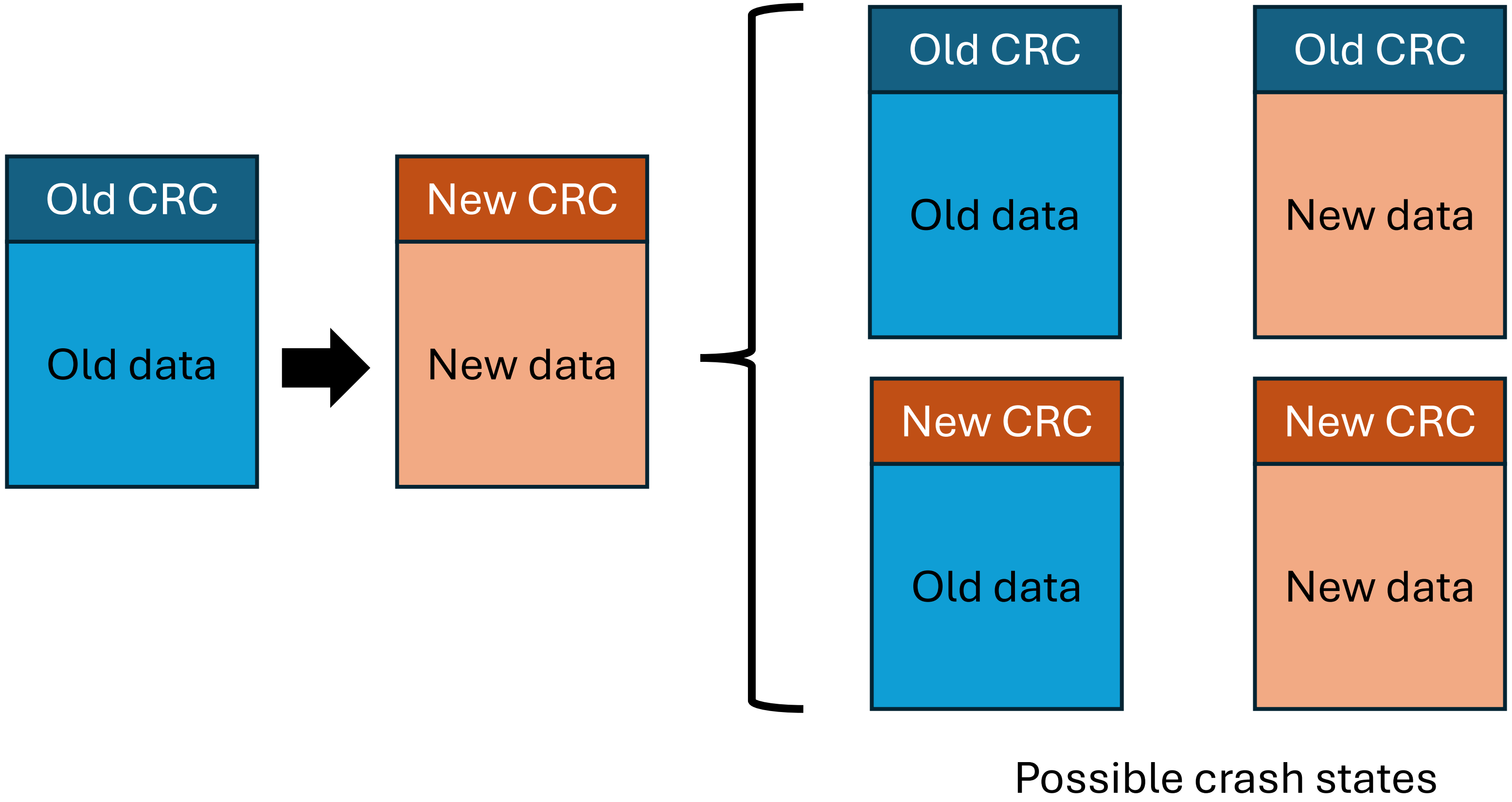
Back to our example



Possible crash states

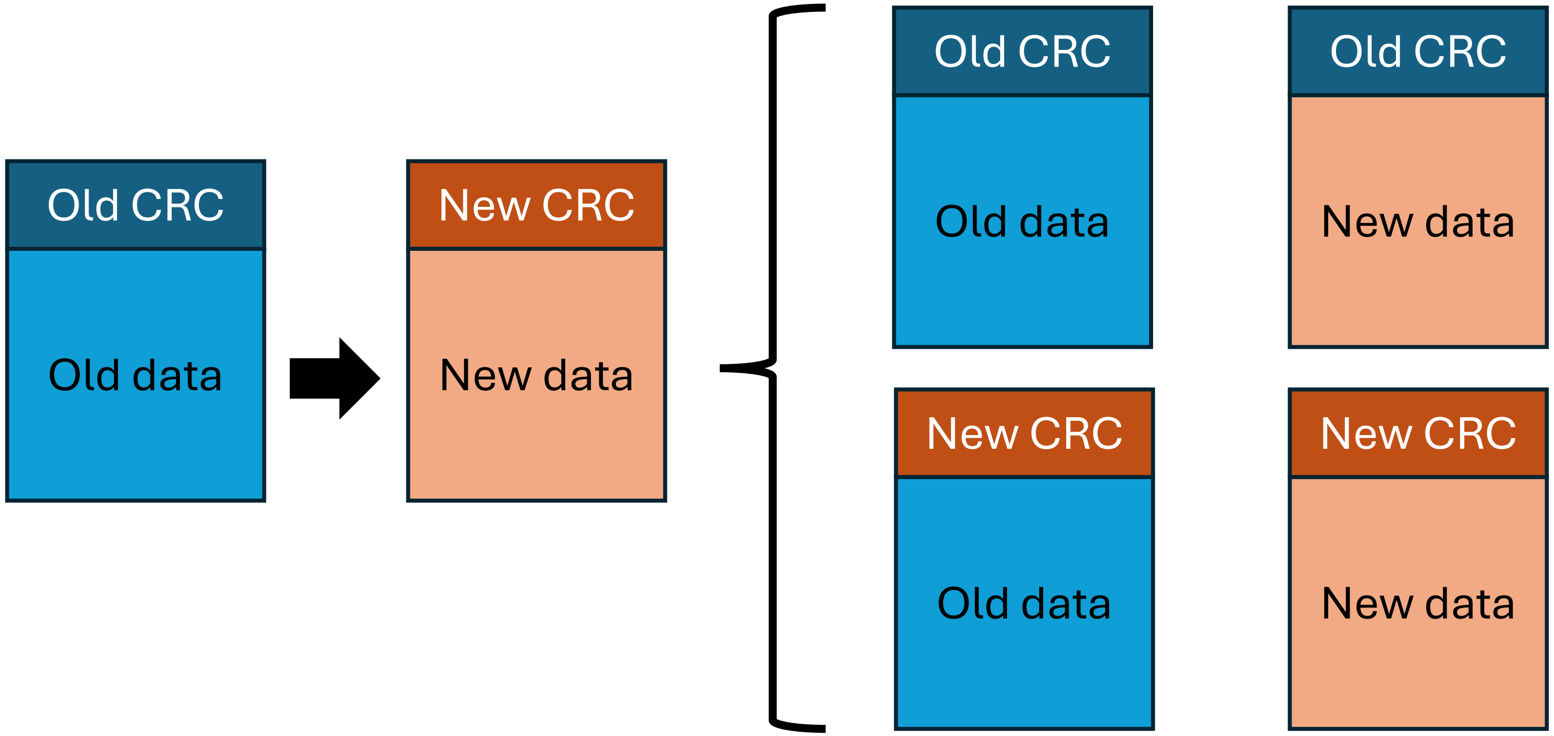
Back to our example

How do we implement this operation in a crash-consistent way?



Block-based systems

Atomic block-sized writes → 1 CRC per block



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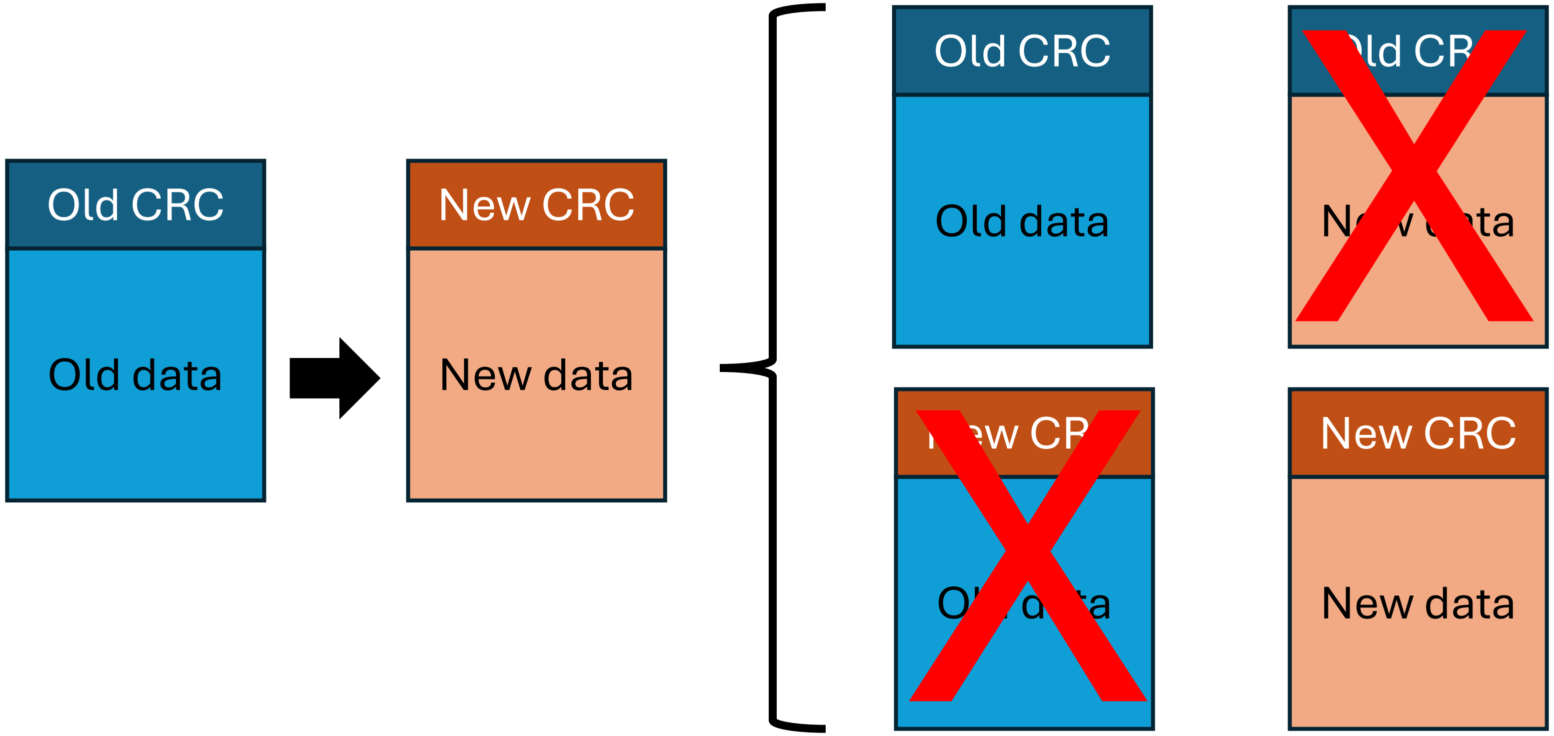

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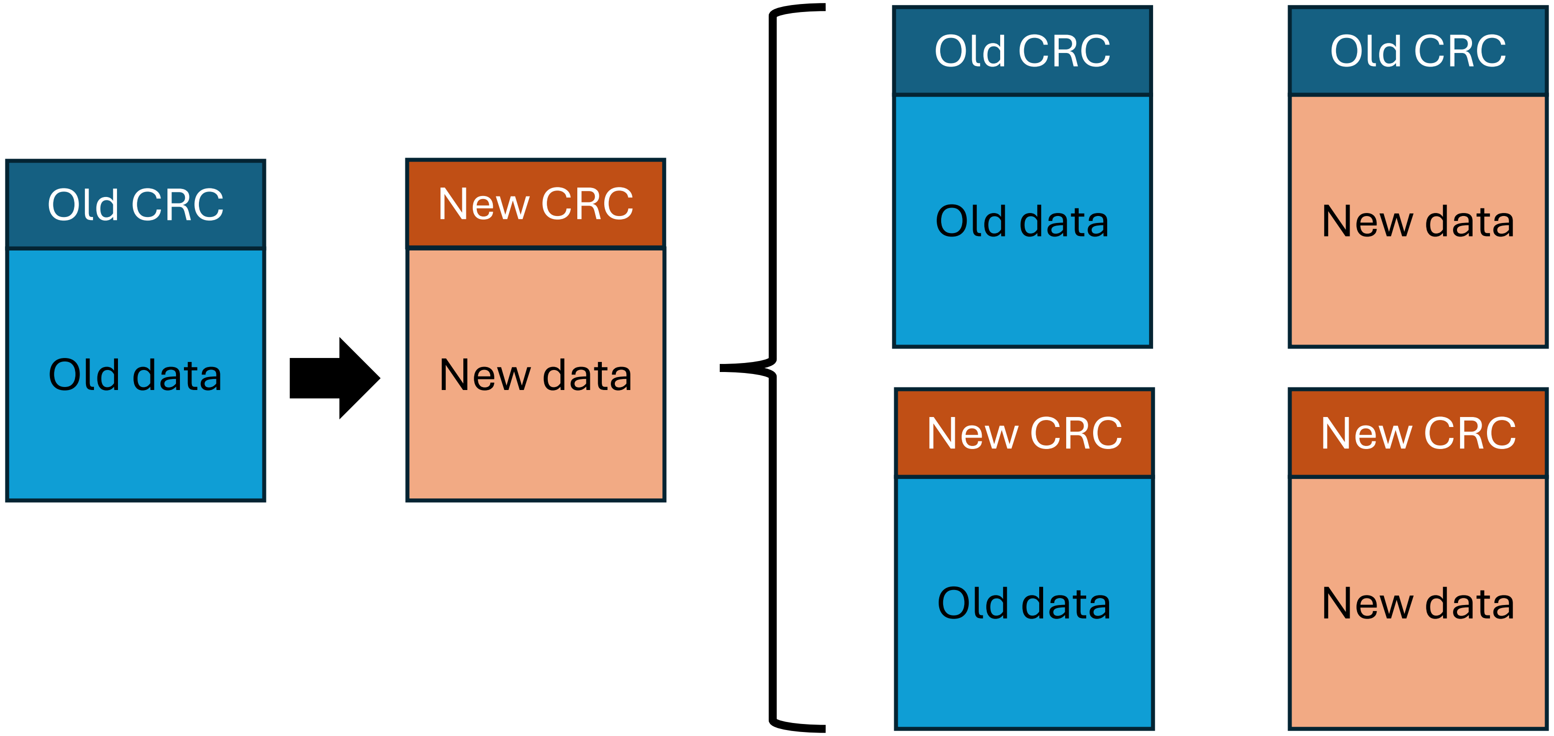

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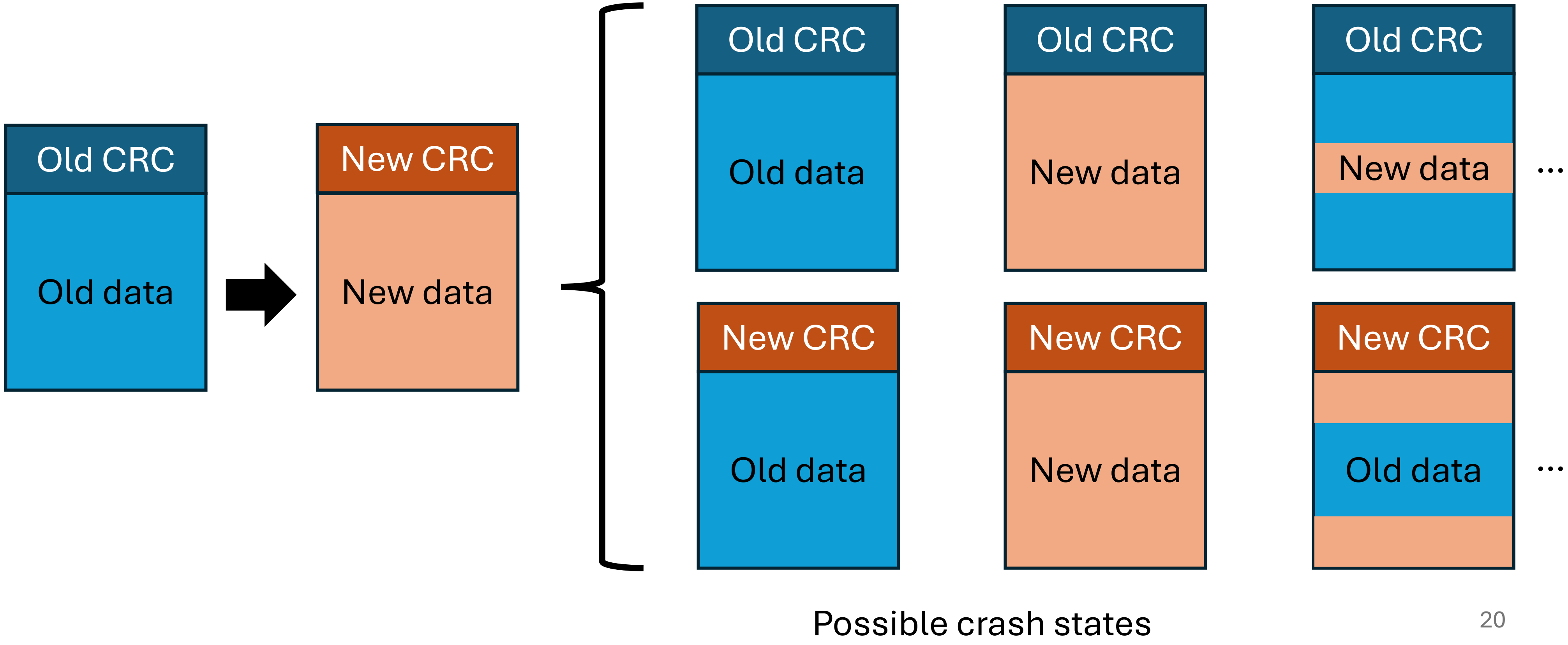

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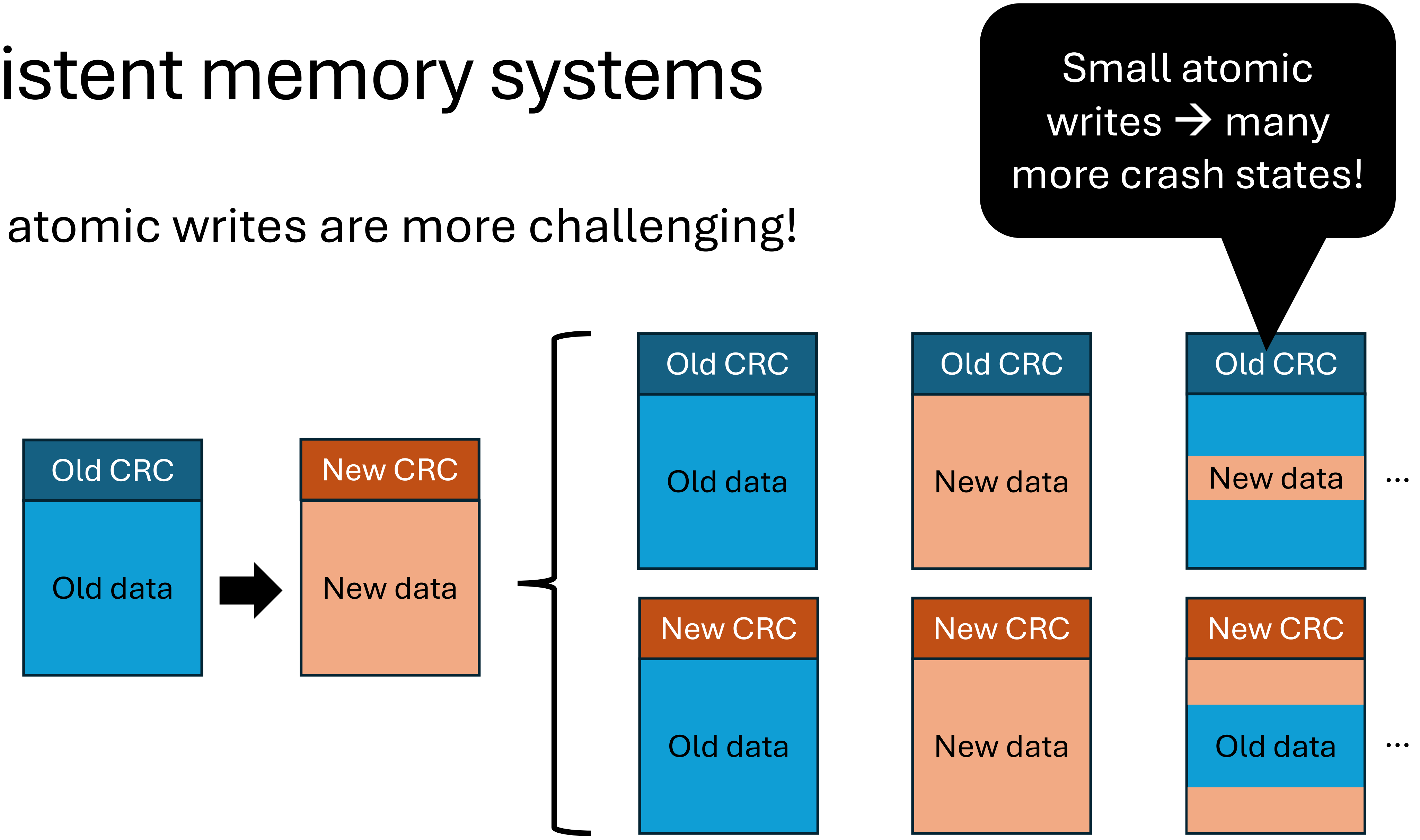

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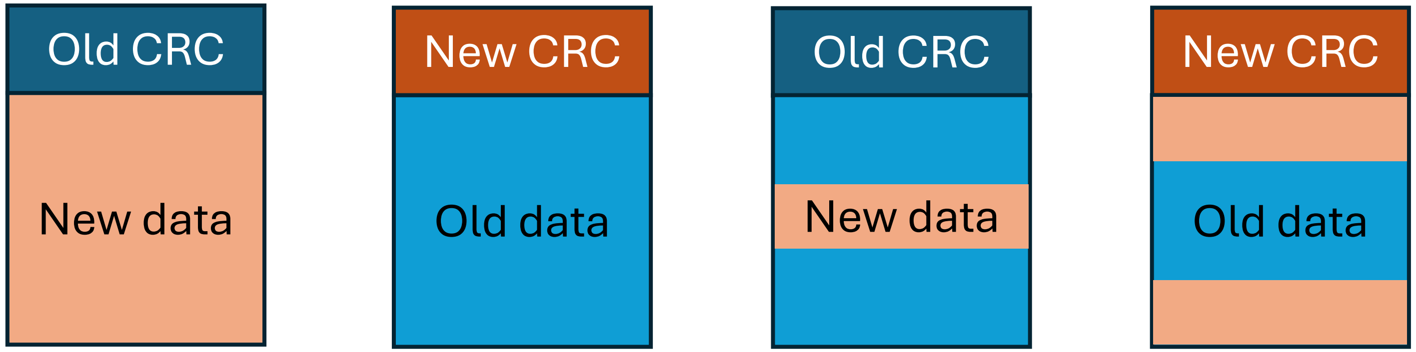

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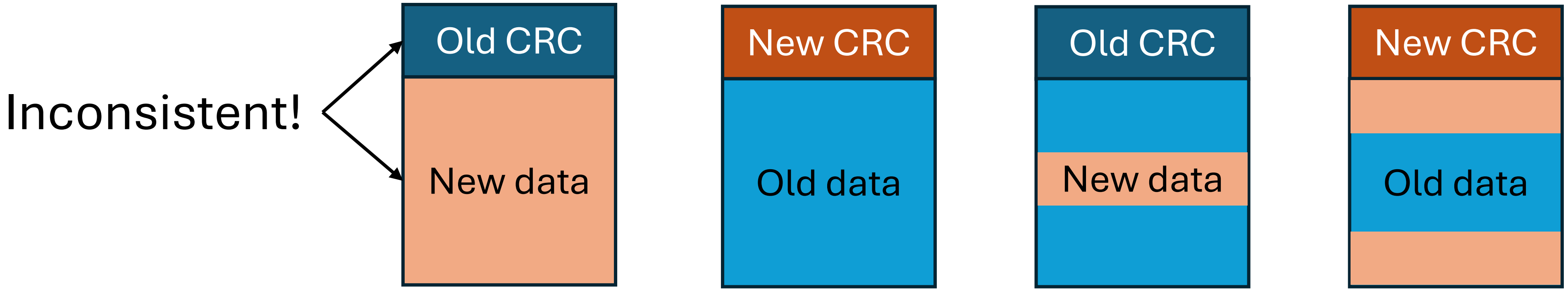

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Prior work found CRC atomicity bugs (LeBlanc EuroSys '23)

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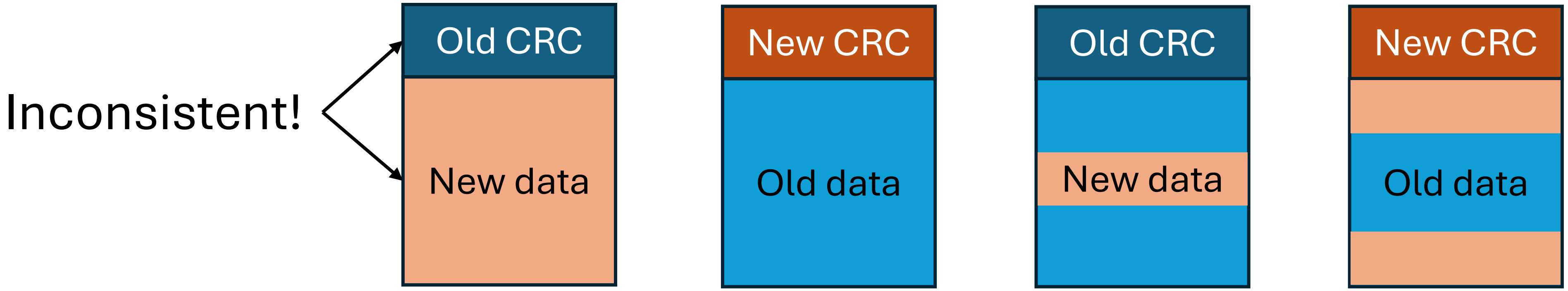

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Verified code should work even in rare, worst-case scenarios

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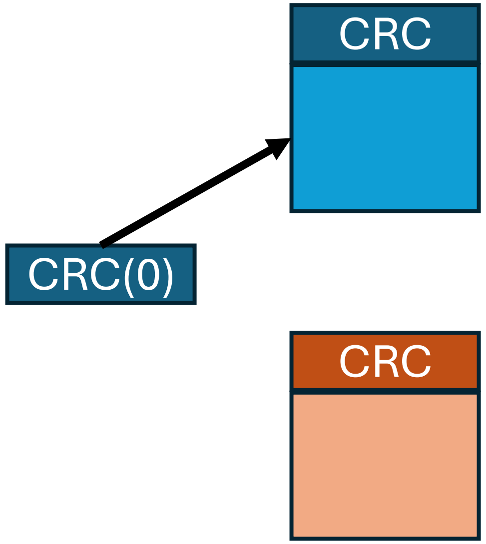

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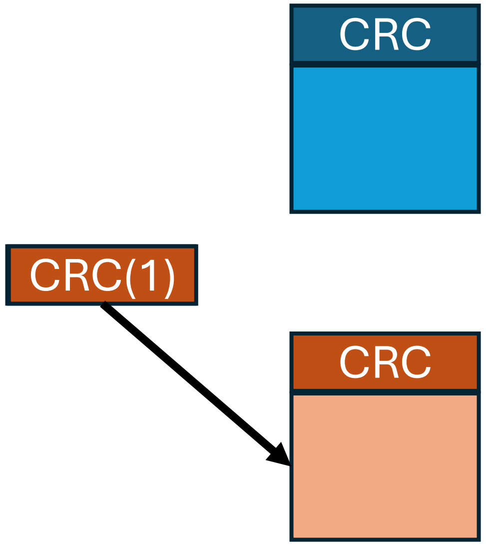

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Two possible 8-byte values: CRC(0), CRC(1)

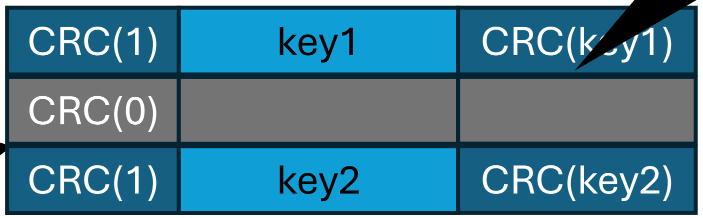
Store Boolean value and checksum in same 8 bytes

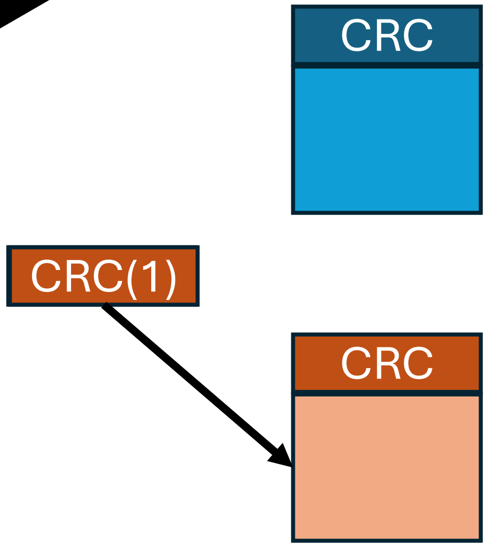
Supports crash-atomic updates!

Capybara systems use CDBs:

- As a validity "bit"
- For atomic data+CRC updates via CoW-like technique

Broadly useful primitive developed *because* of verification!





CapybaraKV

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Designed for Azure Storage use case

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Persistent-memory key-value store written in Verus

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Concurrent, crash-atomic operations on fixed-size item and list values

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~25KLOC (15K proof)

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Persistent-memory key-value store written in Verus

Concurrent, crash-atomic operations on fixed-size item and list values

~25KLOC (15K proof)

Verifies in <1 min on most machines

Similar or better performance to unverified systems pmem-Redis, pmem-RocksDB, Viper (see paper)

Conclusion

github.com/microsoft/verified-storage

ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

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🏆 ***Distinguished Artifact Award***

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- Crashes and corruption impact data differently
- Rigor of verification can help develop broadly useful techniques

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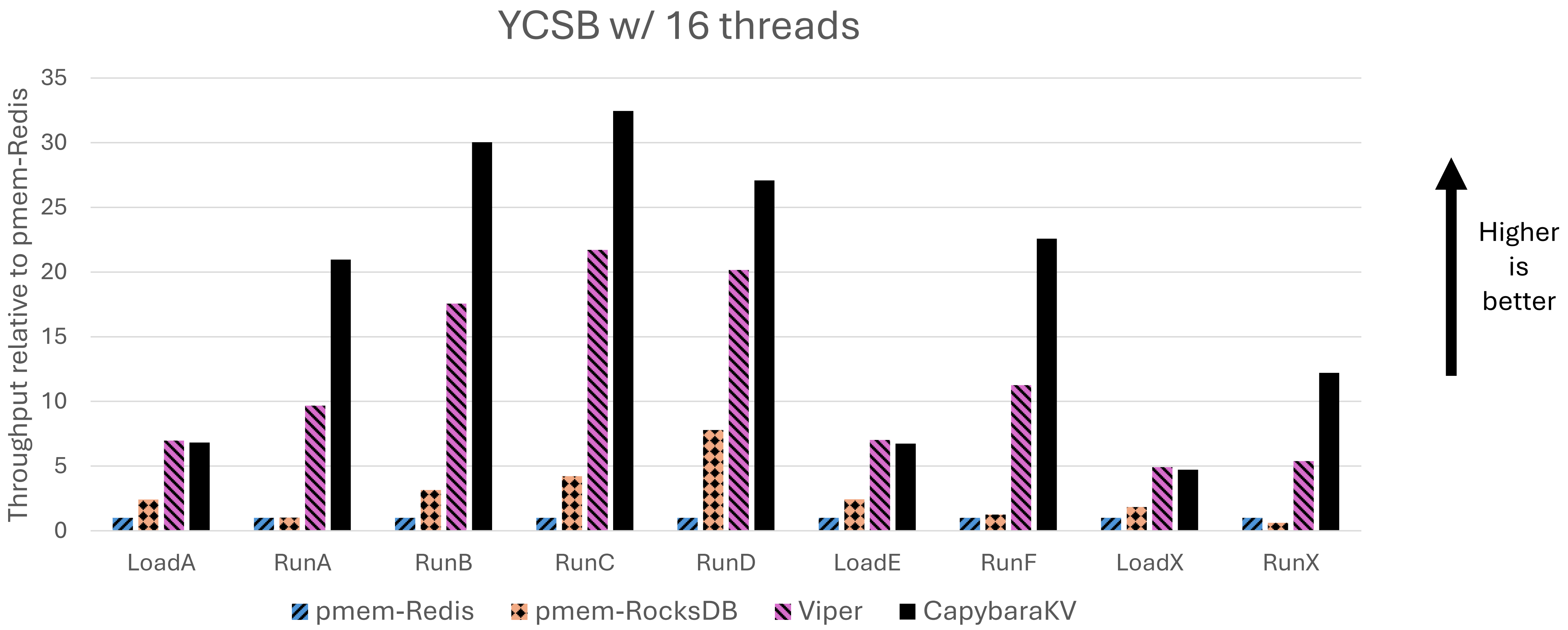
Additional slides

Evaluation: YCSB



CapybaraNS

PM notary service written in Dafny

Demonstrates that PoWER works w/ tools besides Verus

Built and verified in ~3 person days

~1.5KLOC (673 proof)

PoWER limitations

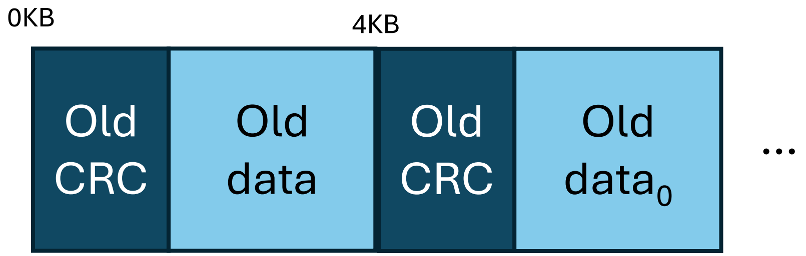
- Not *all* verifiers support the required standard features
  - PoWER also requires quantifiers and ghost variables
  - Push-button verifiers like TPot or Yggdrasil may not support PoWER
- Cannot support arbitrary fine-grained concurrent writes to shared storage regions
- Correctness depends on specifications and correctness of verifier/compiler

CapybaraKV limitations

- Requires storage space to be statically allocated at initialization
  - Other evaluated systems can grow/shrink dynamically
  - We configure Viper to allocate sufficient space at init for fair comparison
  - Not fundamental
- Keeps all keys in memory -- increases memory footprint and startup time
  - Pmem-Redis and Viper also keep all keys in memory
  - Not fundamental
- Sharded concurrency approach does not allow concurrent writes to different records

Crash-consistent CRCs

Block-sized atomic writes: one CRC per block



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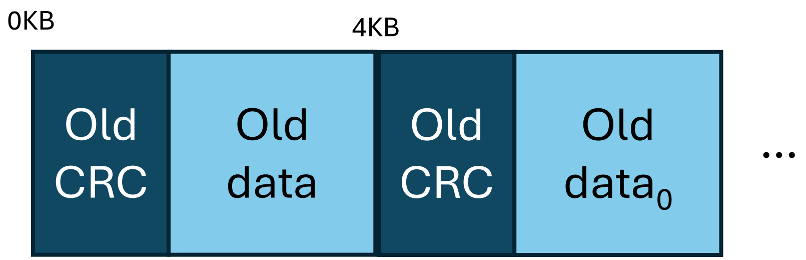

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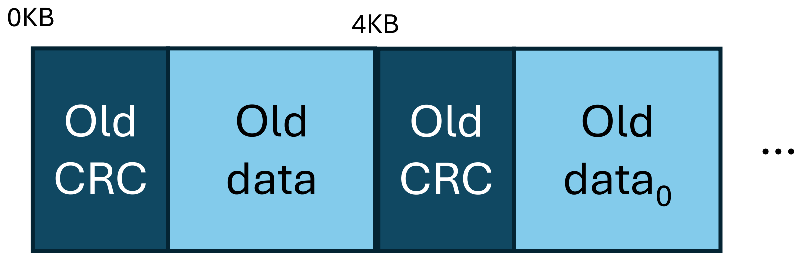

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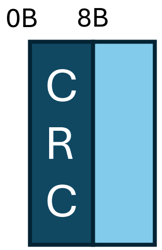

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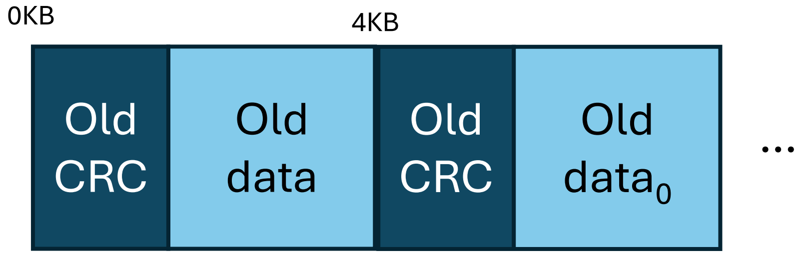

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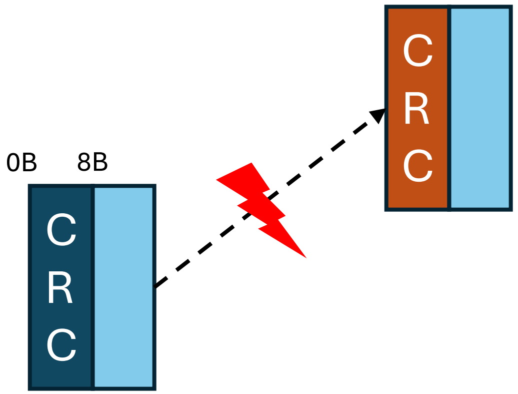

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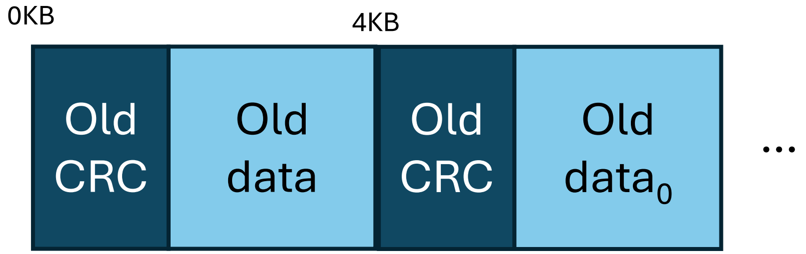

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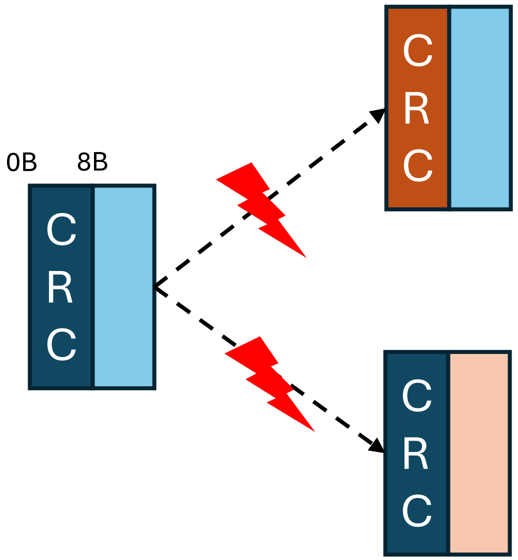

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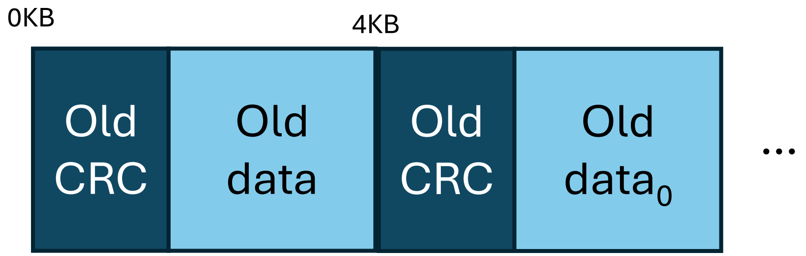

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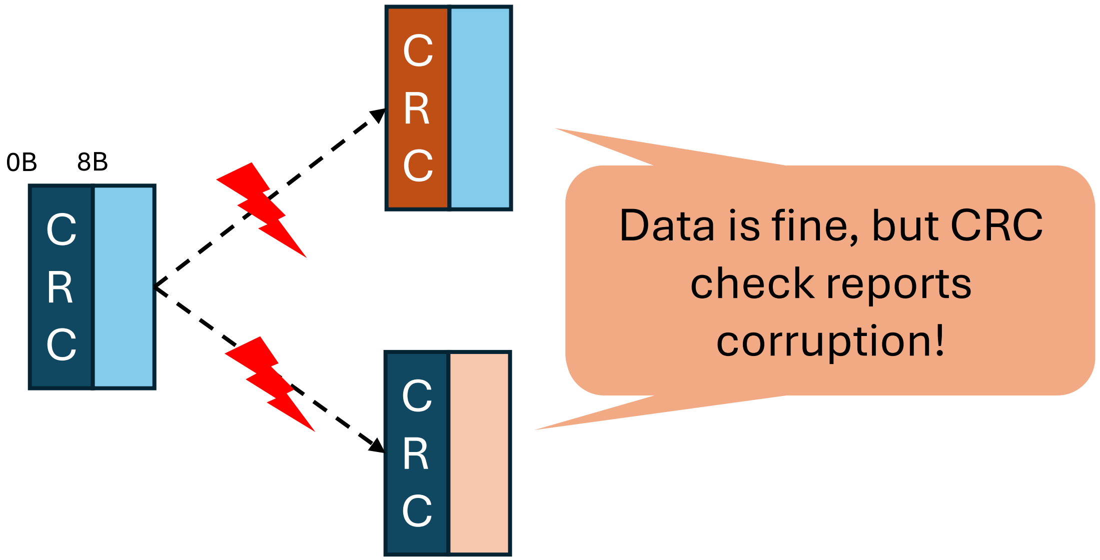

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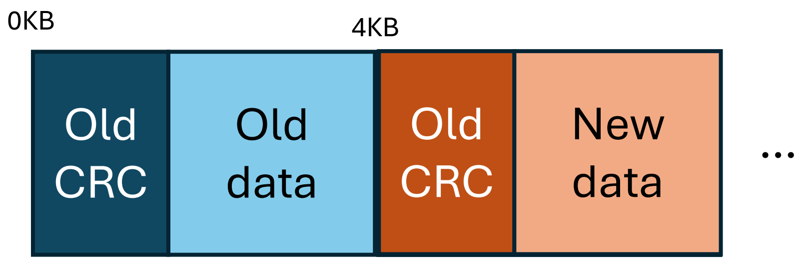

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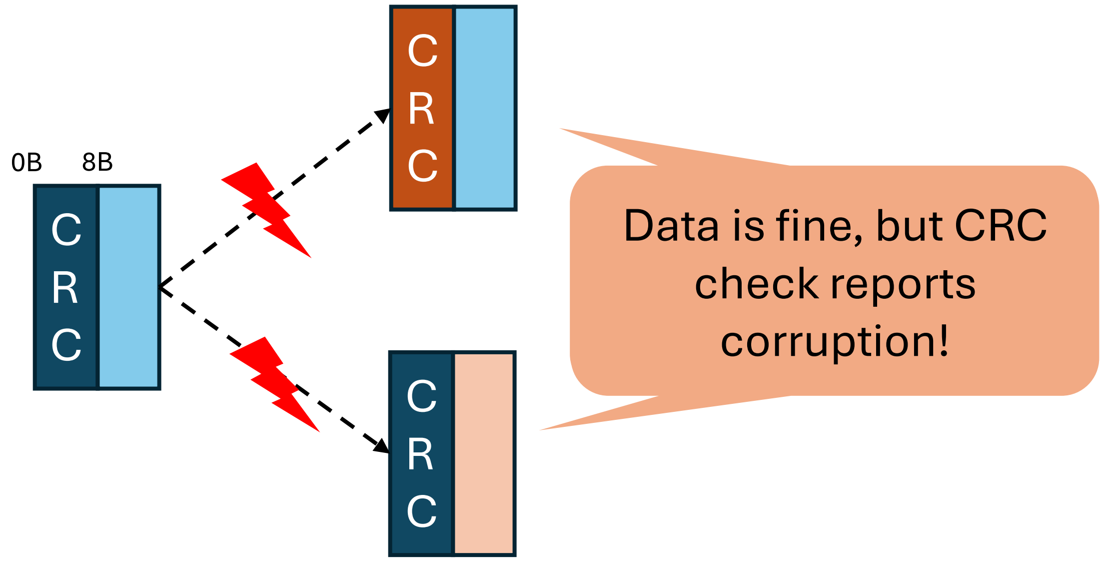
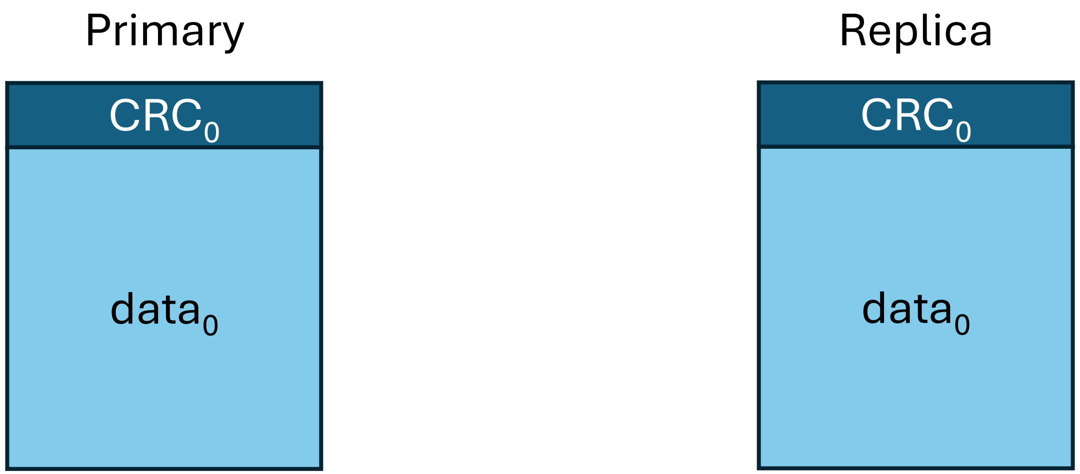


Prior work: Tick-Tock algorithm

Introduced in NOVA-Fortis file system (Xu SOSP ’17)



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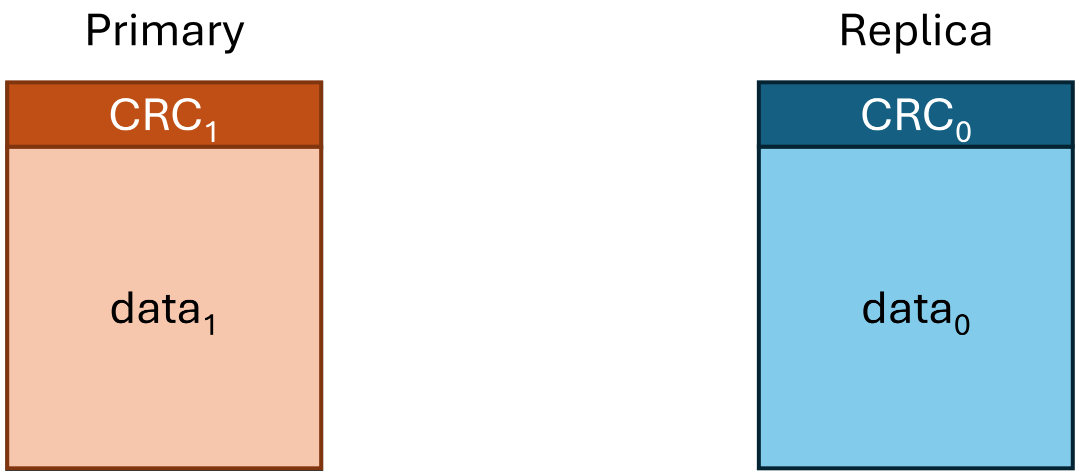

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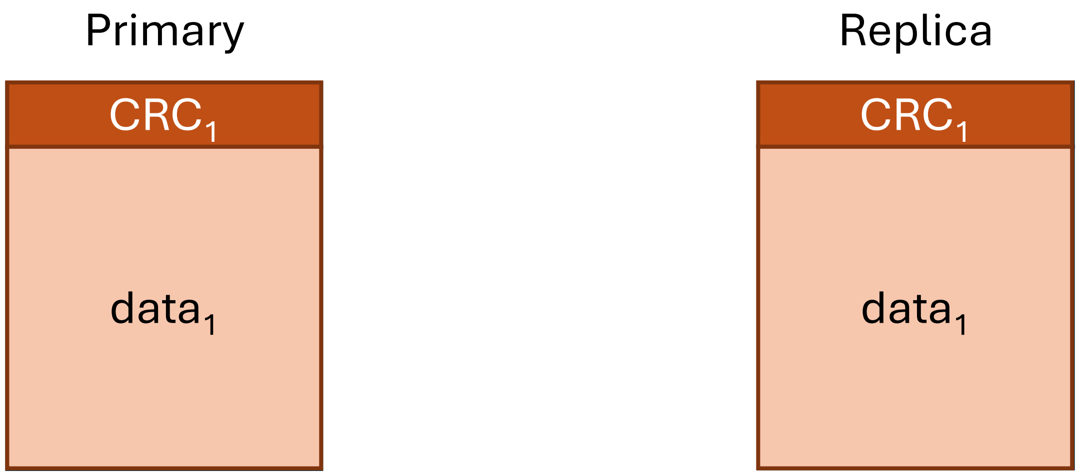

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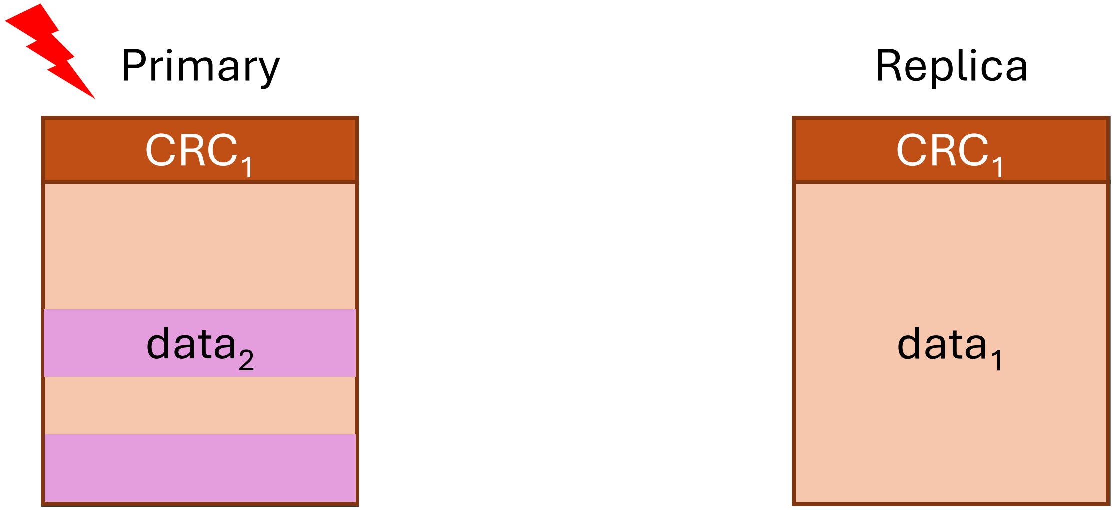

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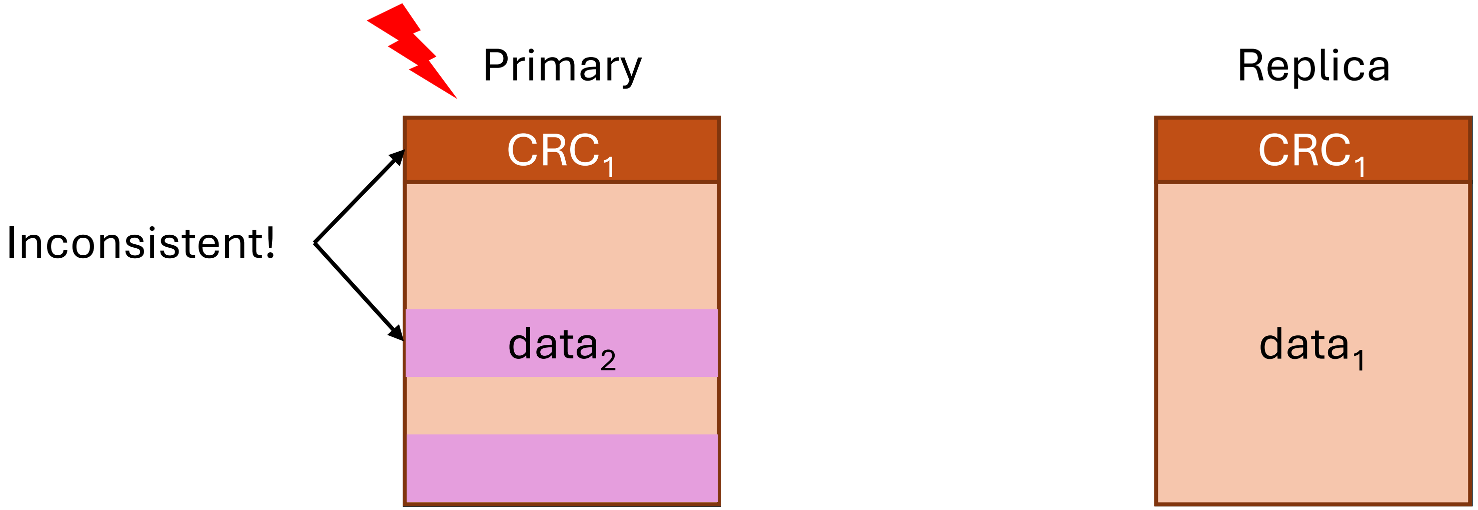

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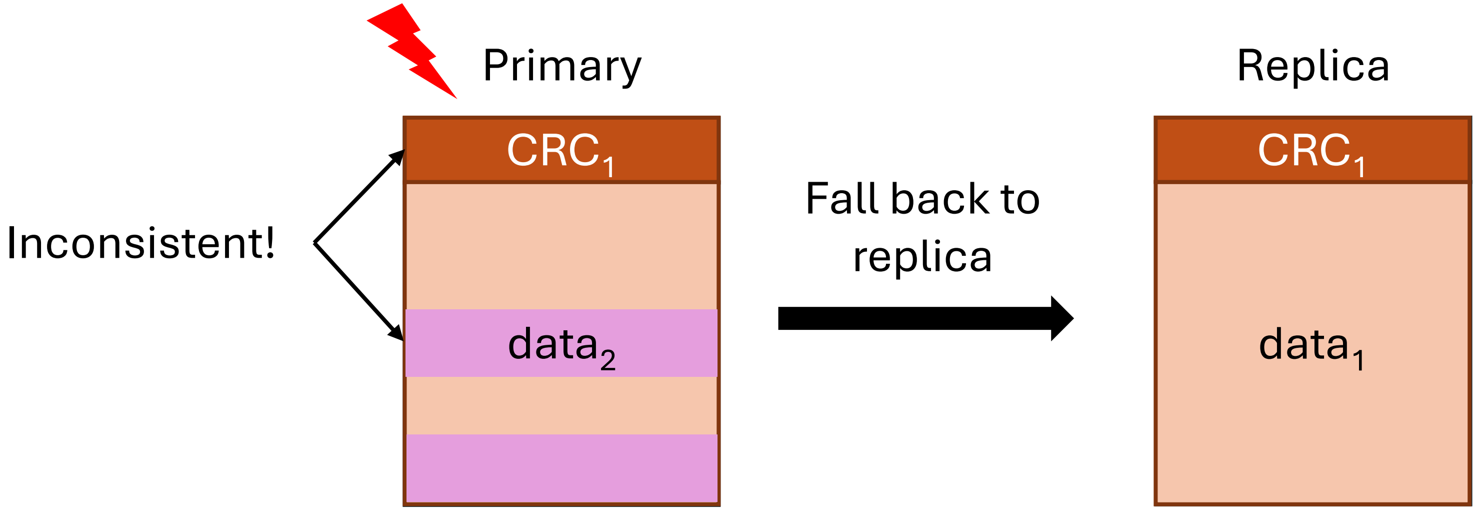

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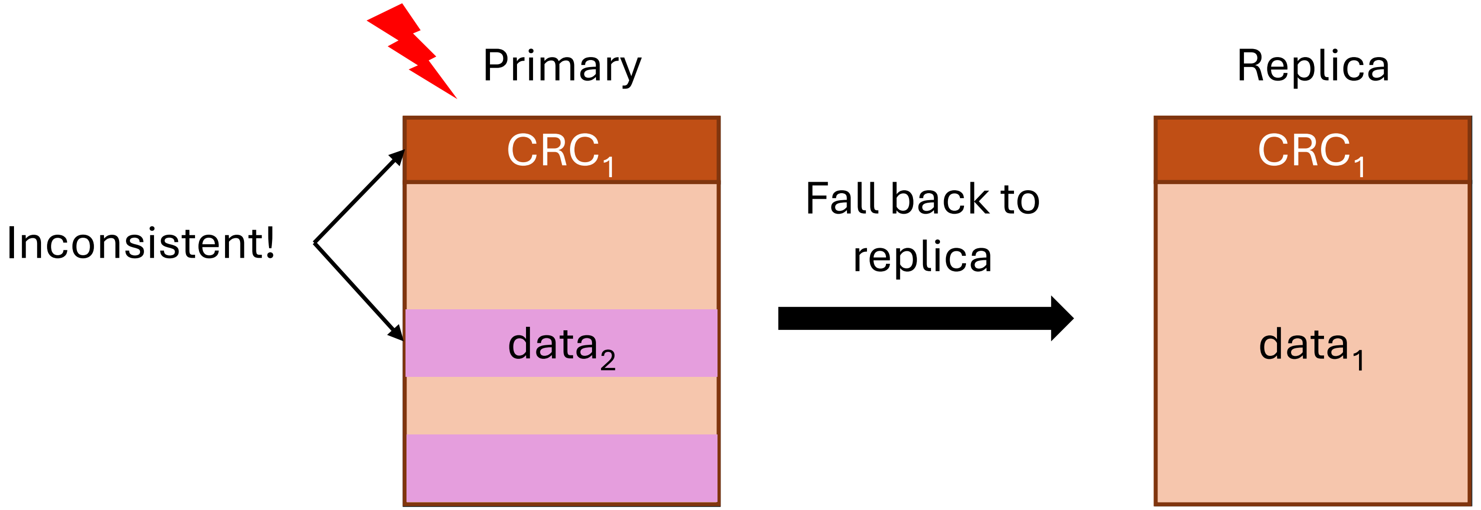

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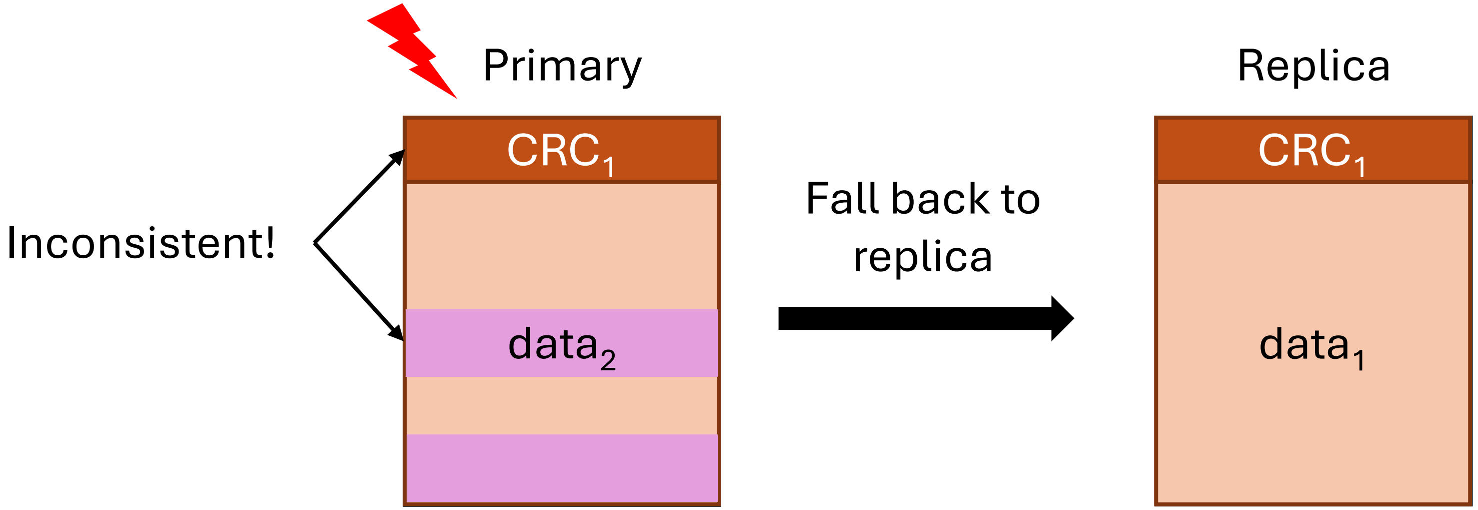

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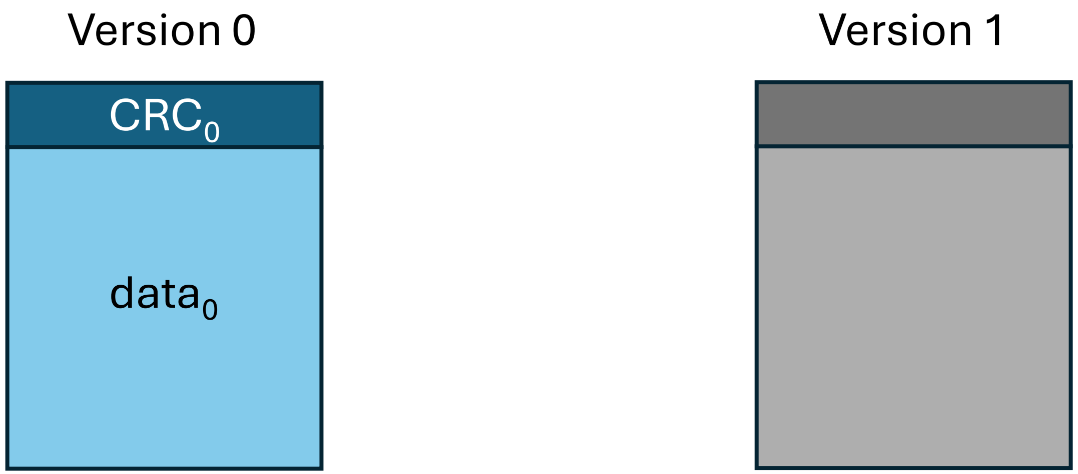
CRCs designed to detect random bit flips, not torn writes

Corruption-detecting Boolean example



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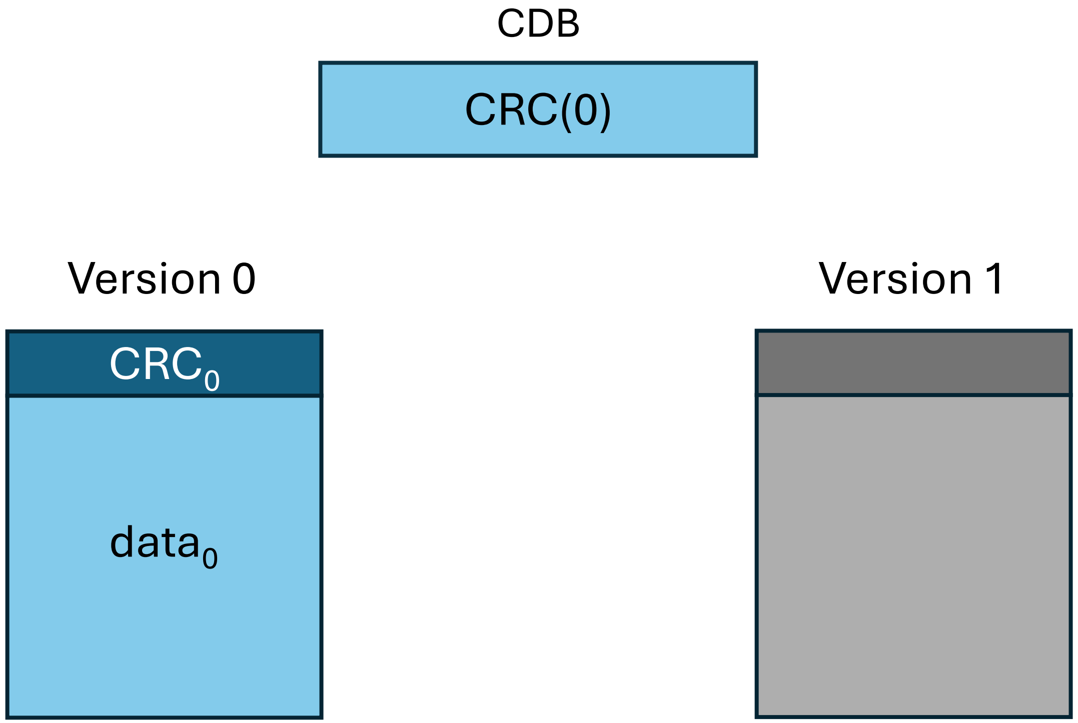

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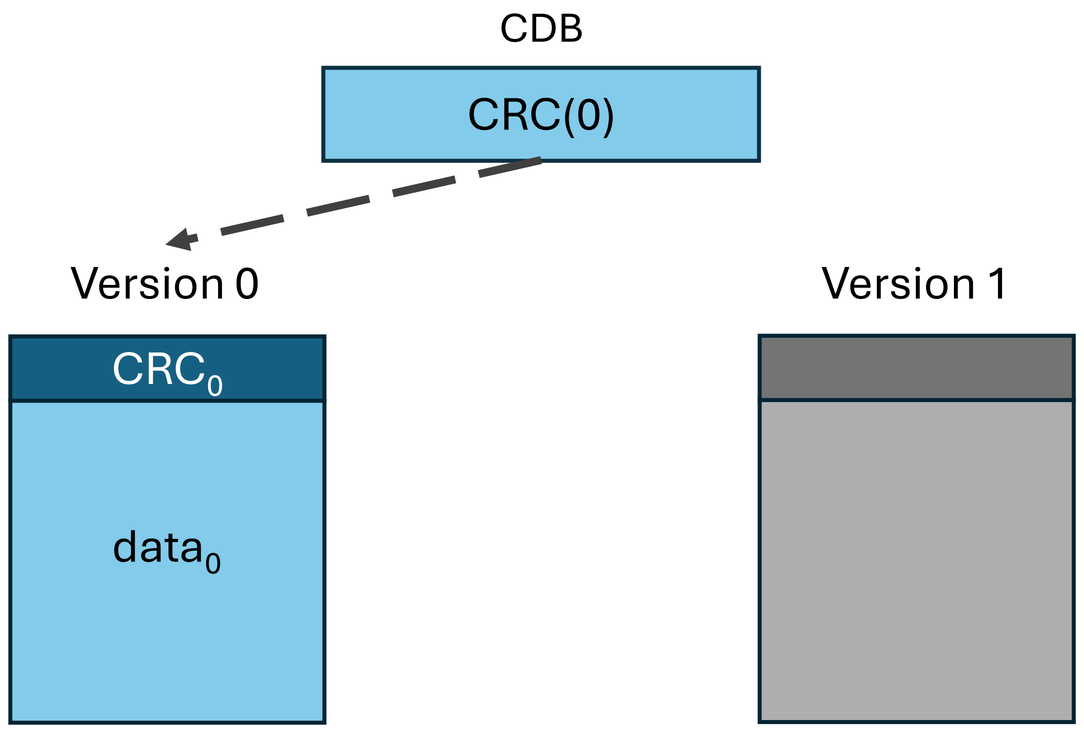

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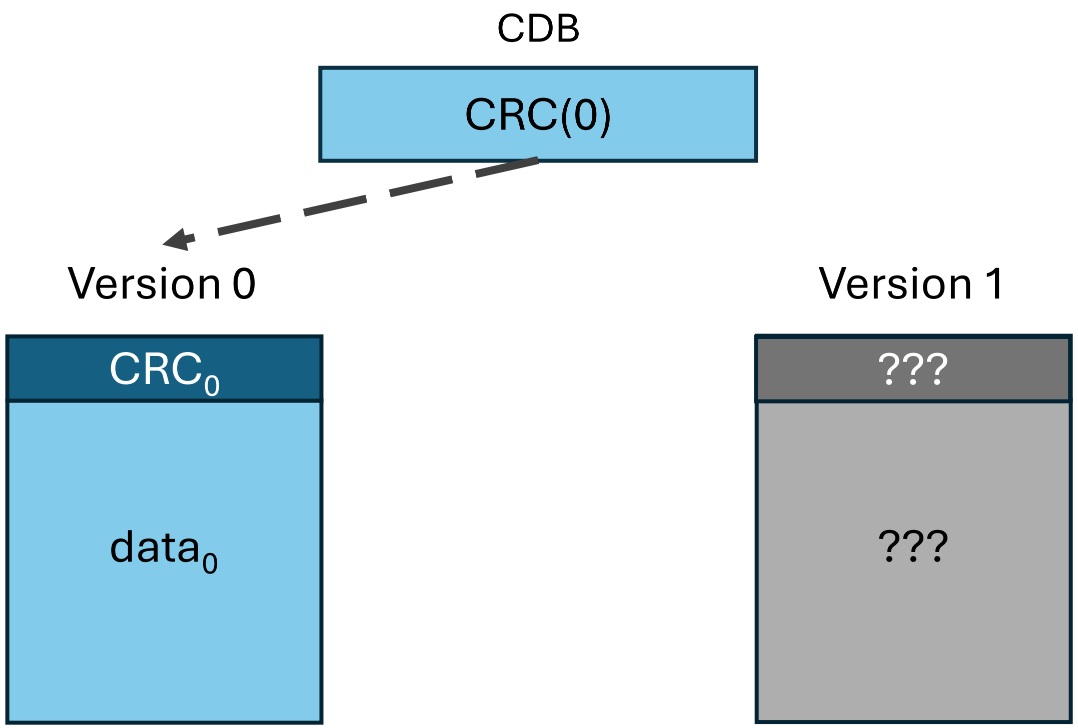

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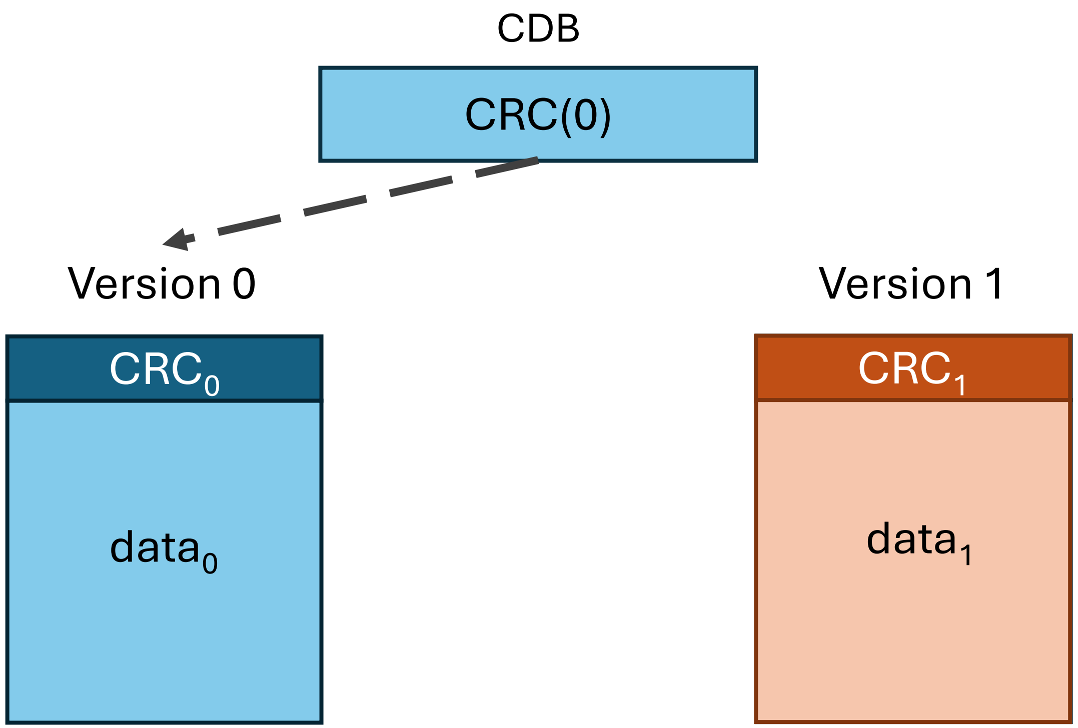

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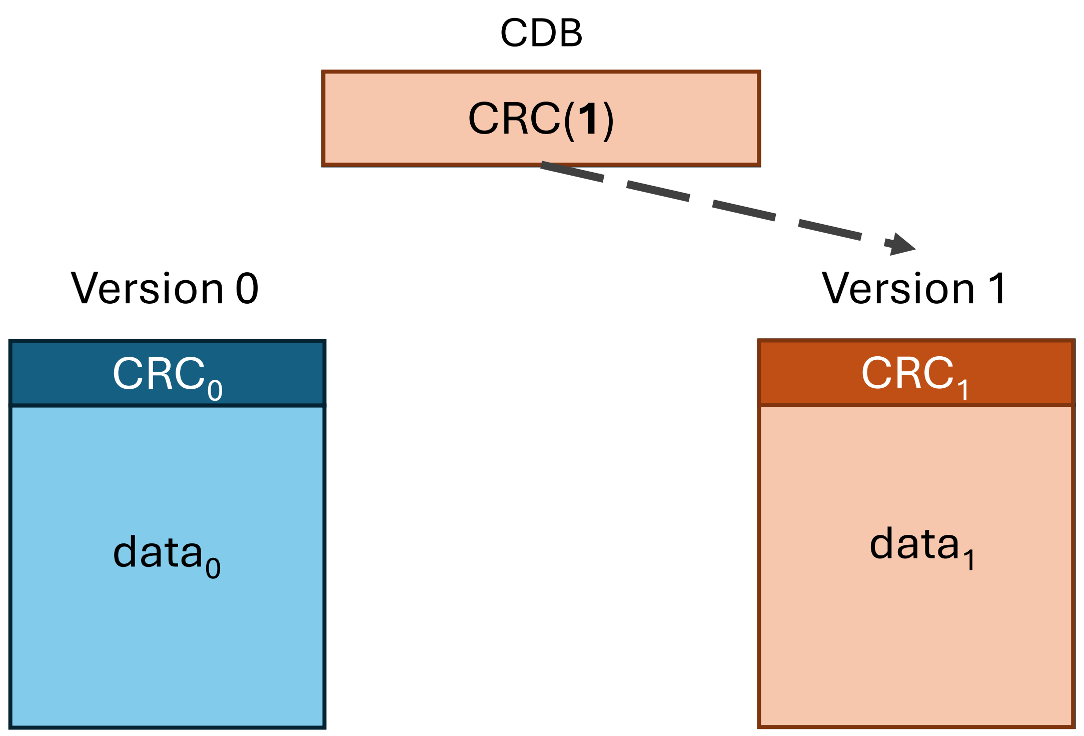

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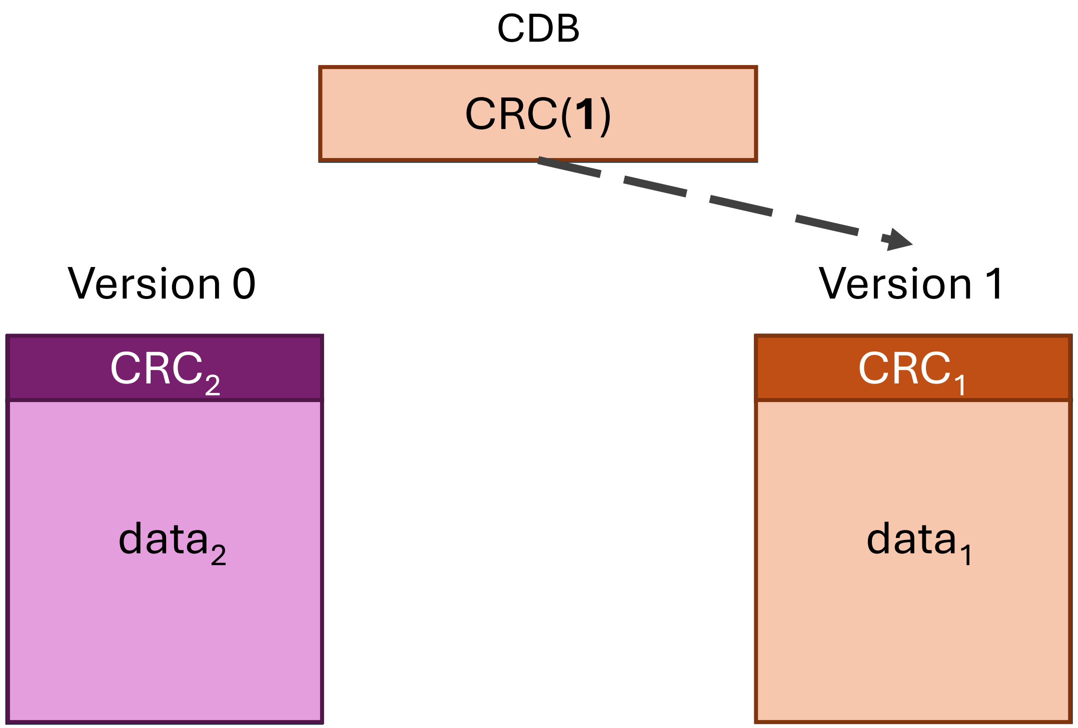

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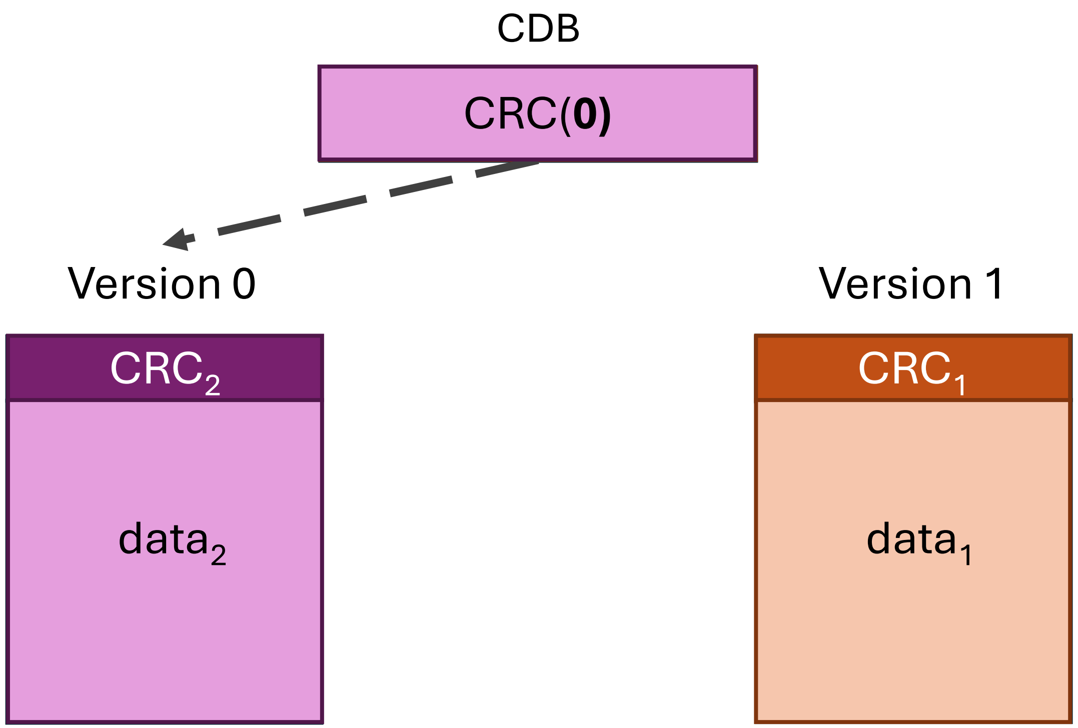

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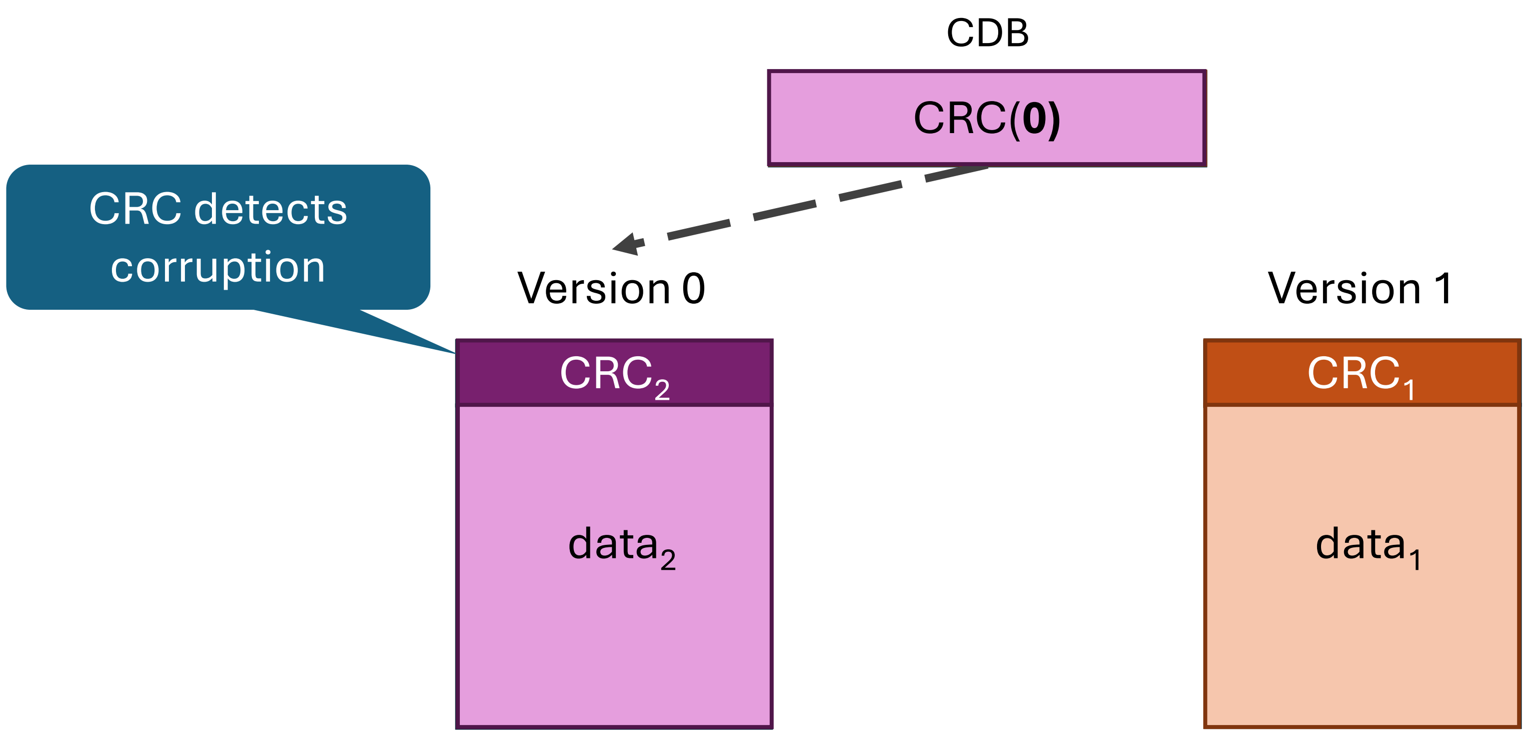

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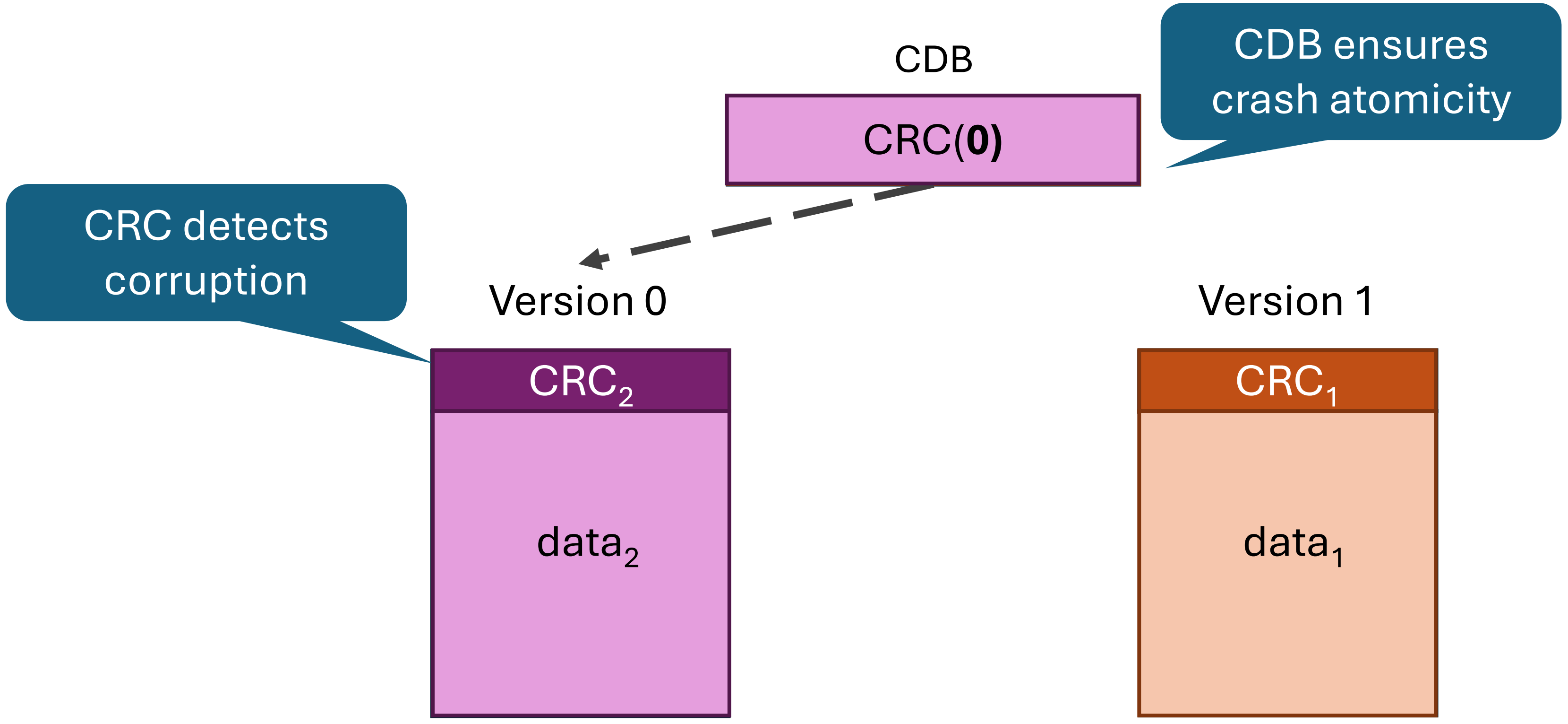

Using properties of CRC algorithms

CRC algorithms are engineered to *always* detect a certain number c of flipped bits! (Koopman 2024)

We can definitively prove the absence of up to c bits of corruption

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Depends on length of byte sequence; always ≥ 1

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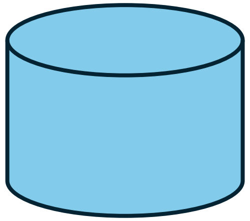
We can definitively prove the absence of up to c bits of corruption

CRC check fails if and only if $[1, c]$ bits are corrupted

New corruption model



storage
device

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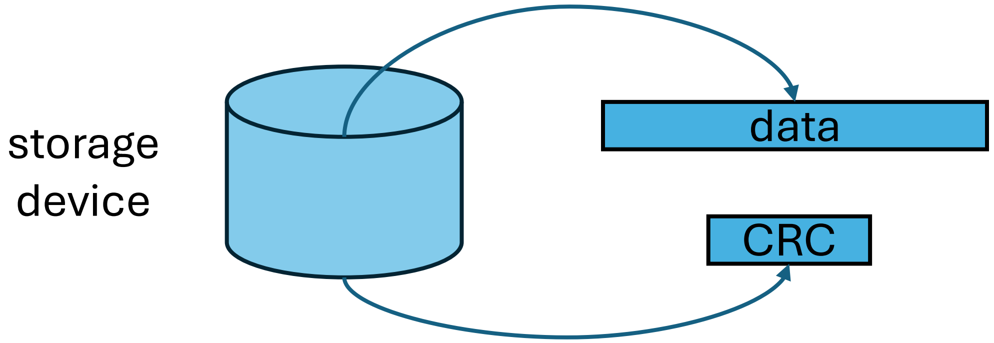

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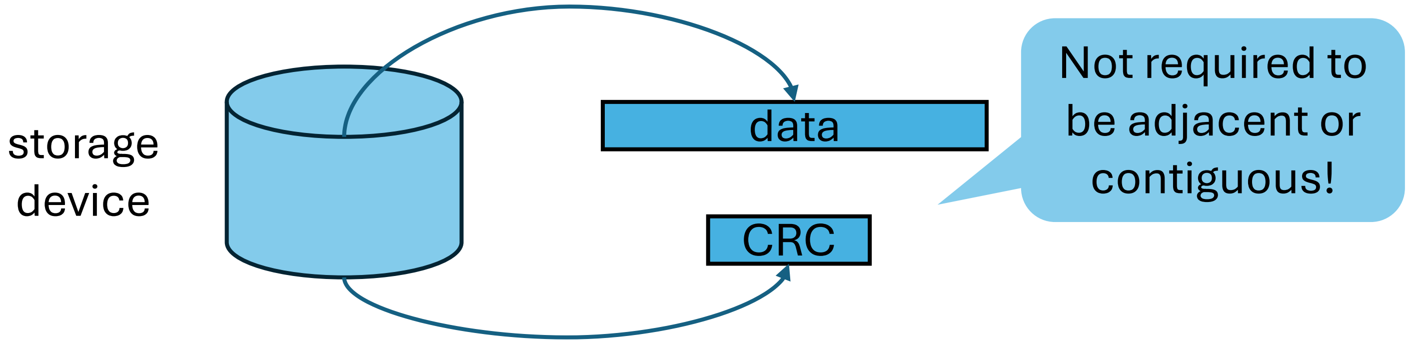

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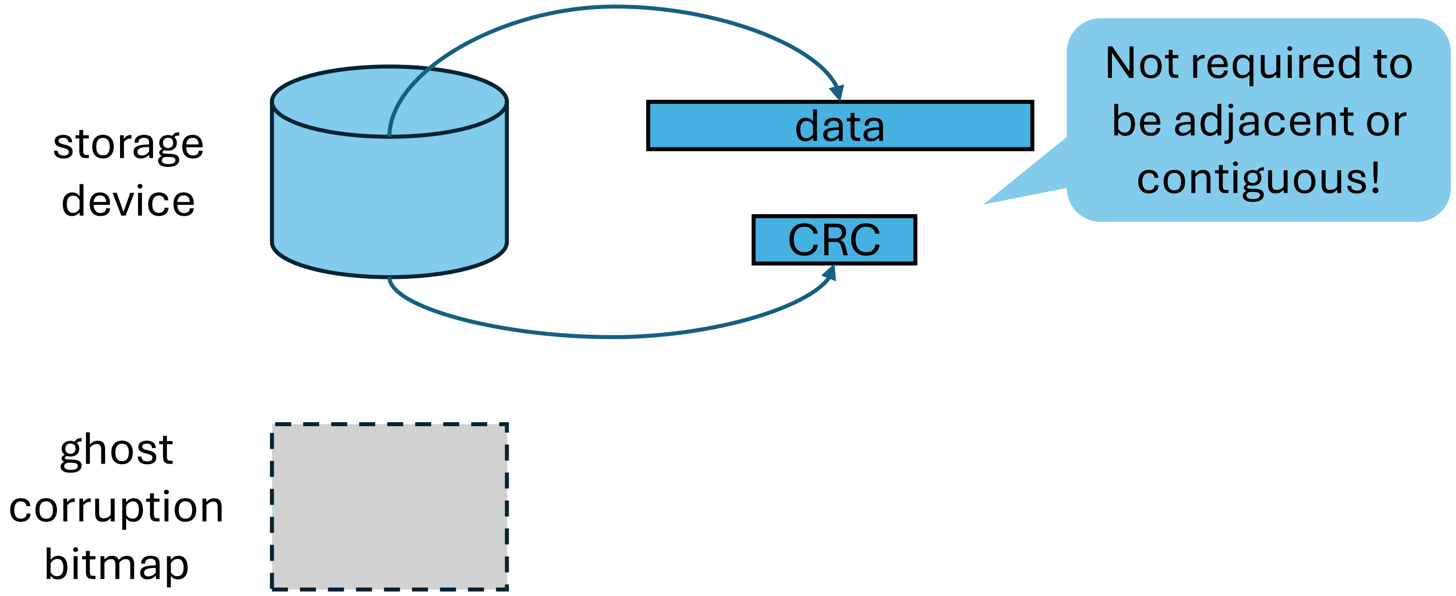

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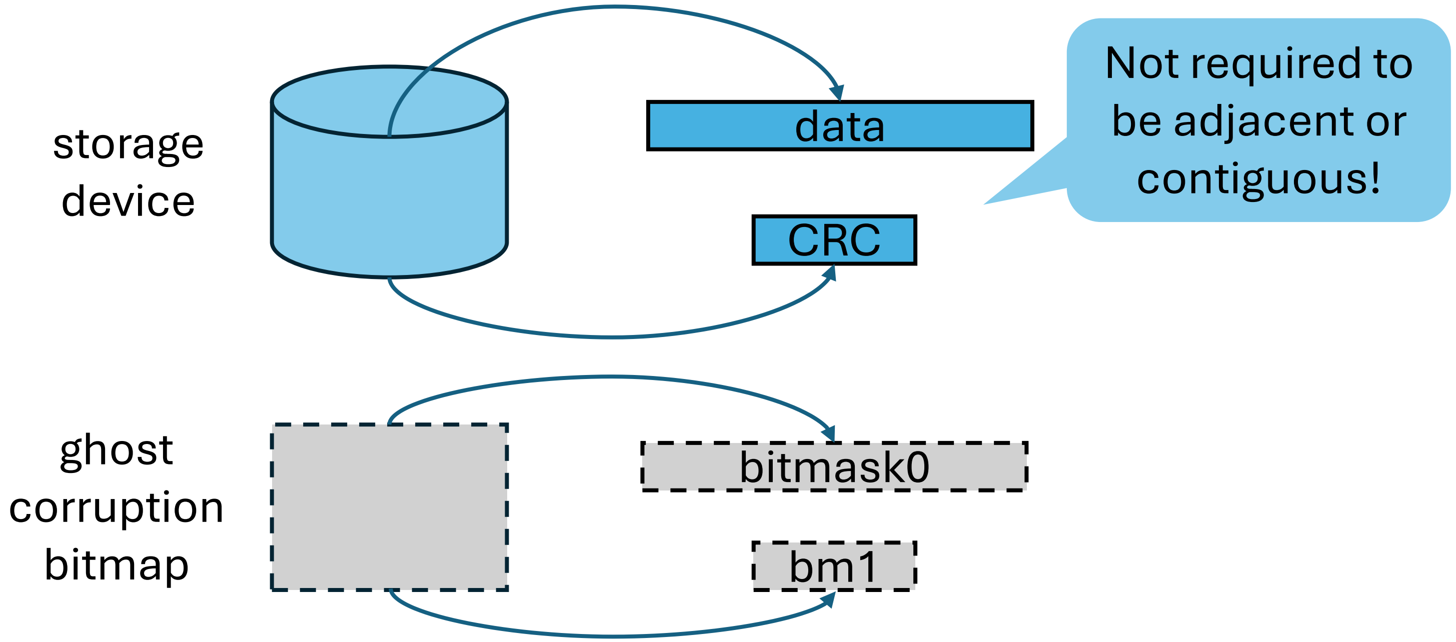

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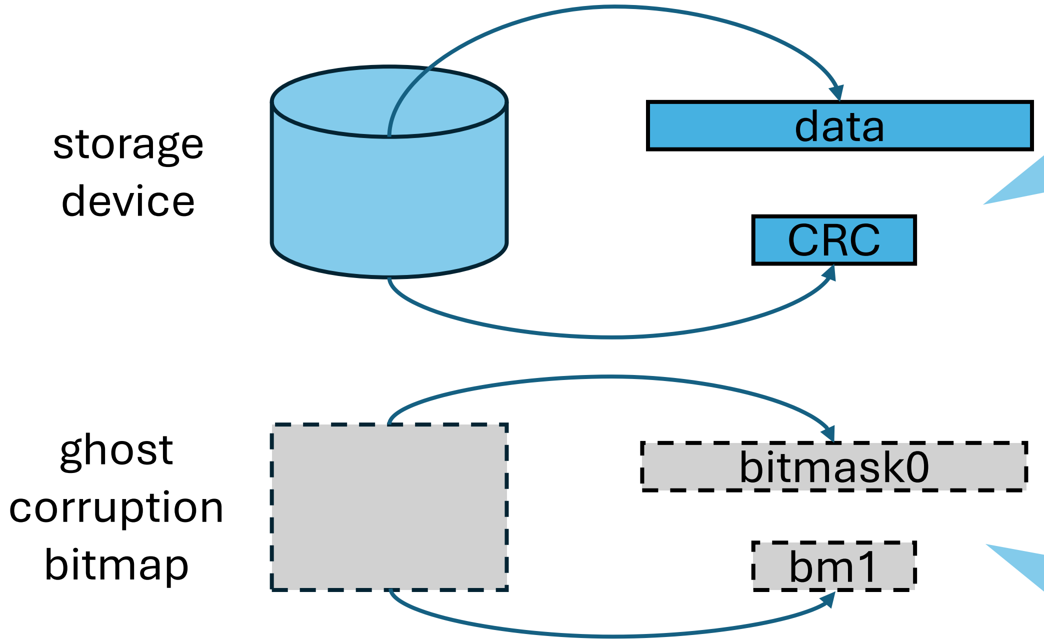

Not required to be adjacent or contiguous!

CRC algorithms are engineered to detect up to c bit errors

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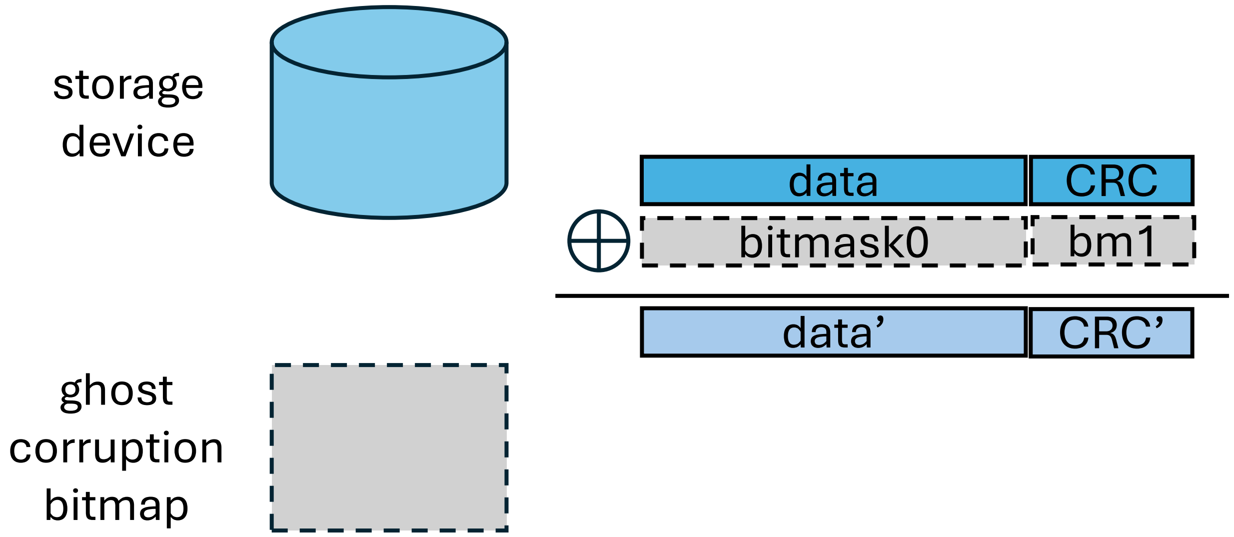

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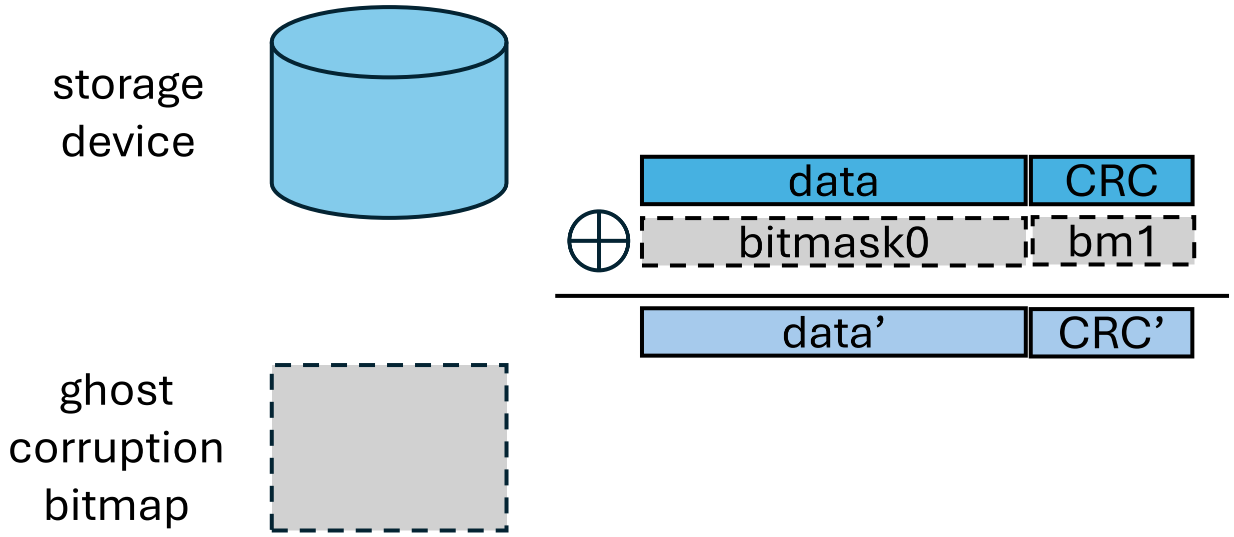

If bitmask contains $[1, c]$ bit flips, then CRC' does *not* match data'

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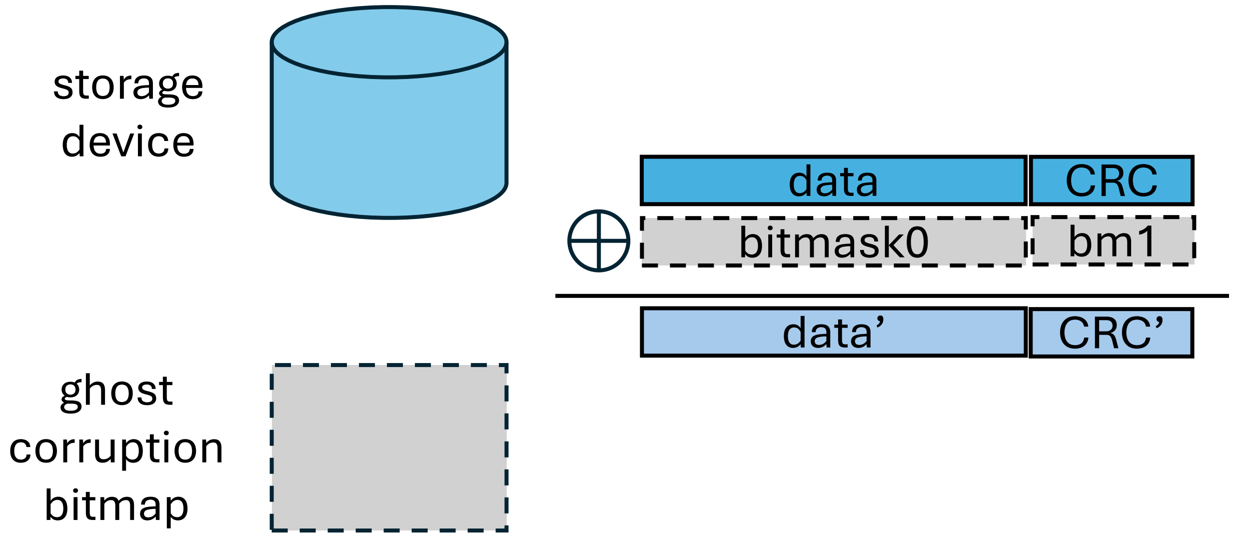

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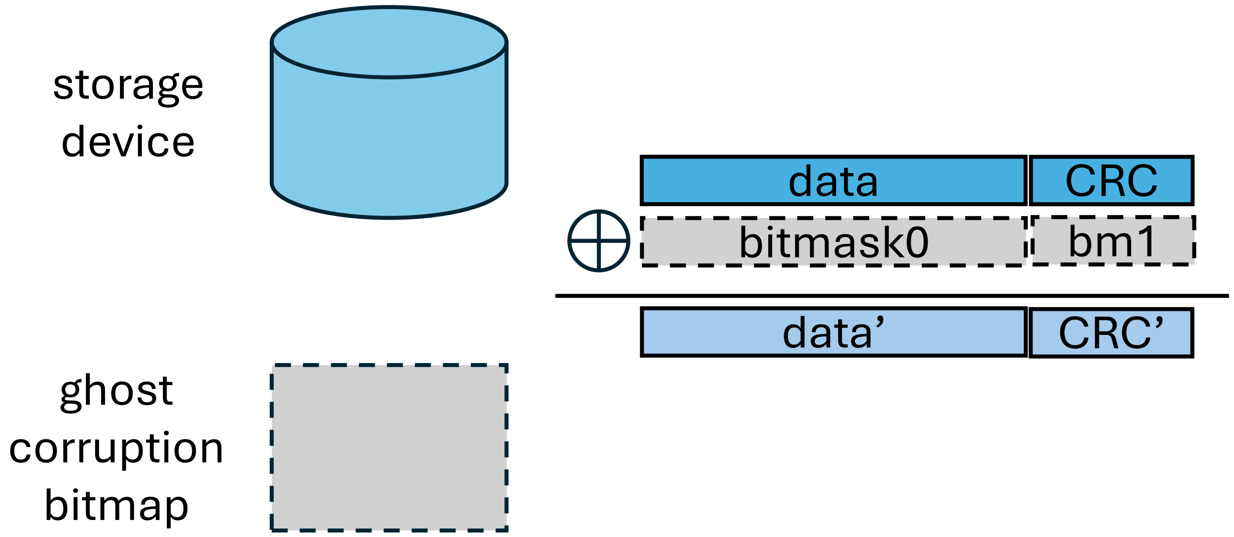

See paper for:

- Reasoning about corruption on byte-addressable storage
- New primitive for CRC management on PM

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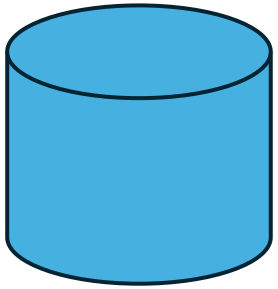

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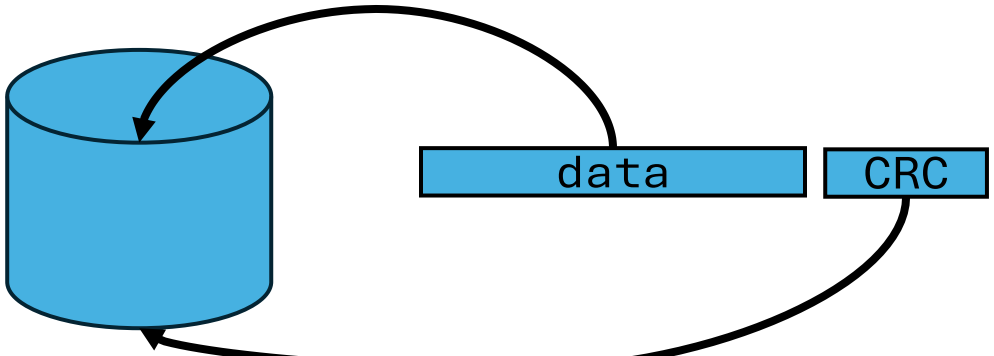

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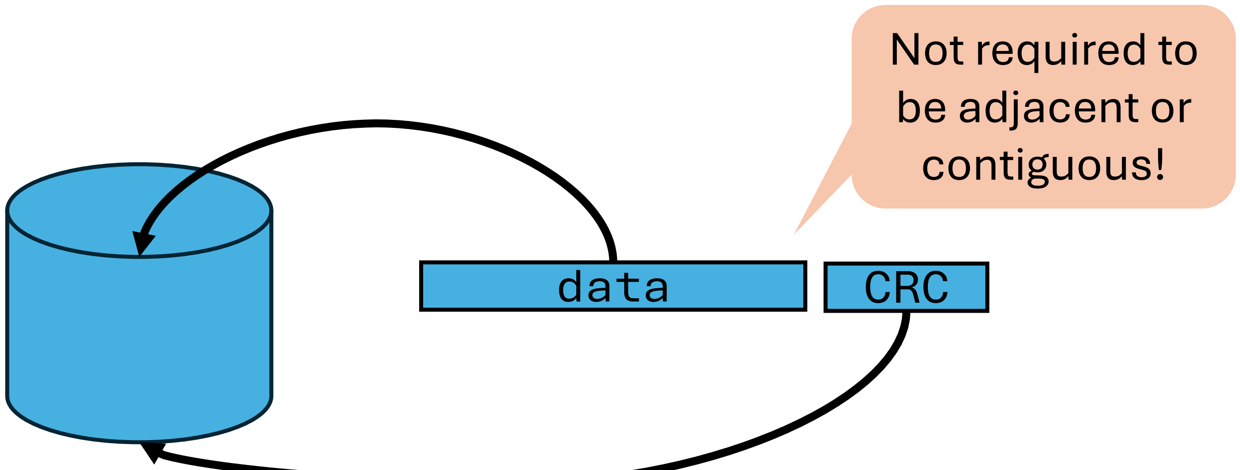

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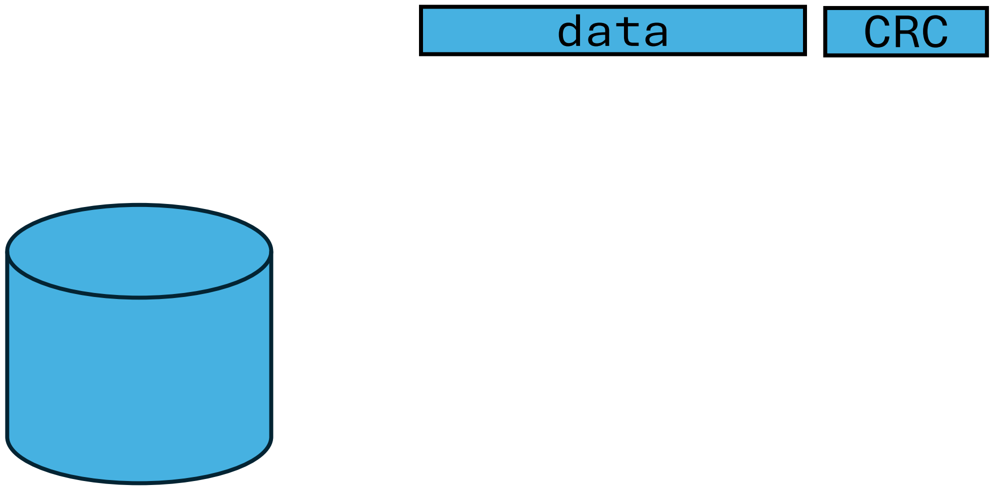

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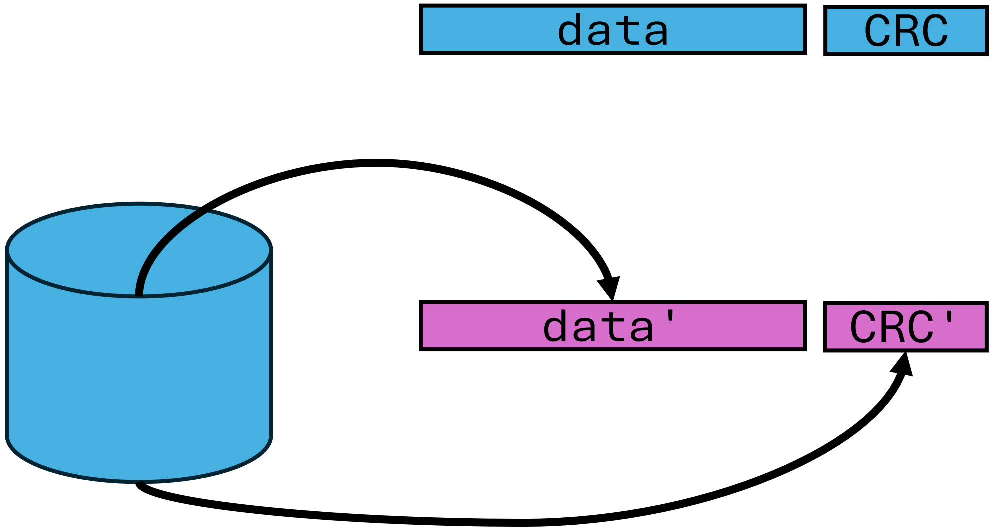

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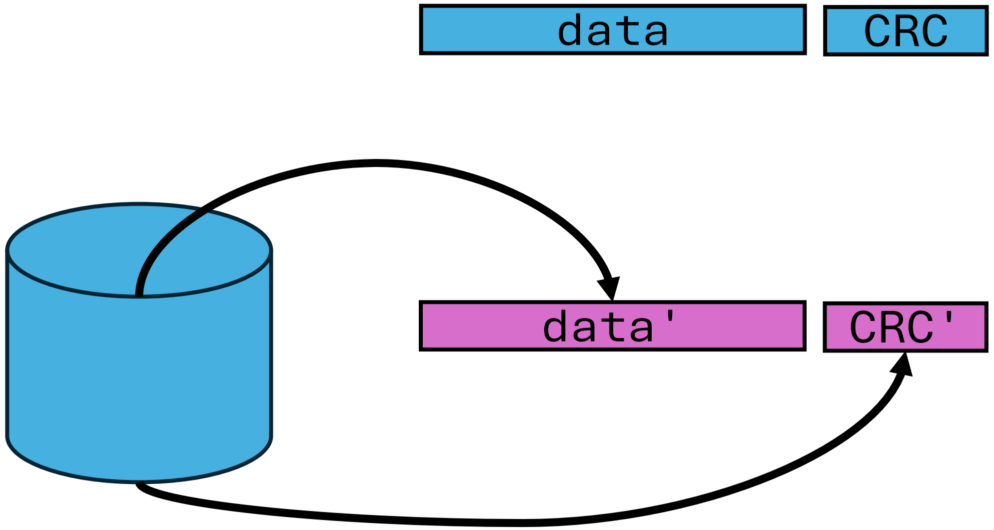
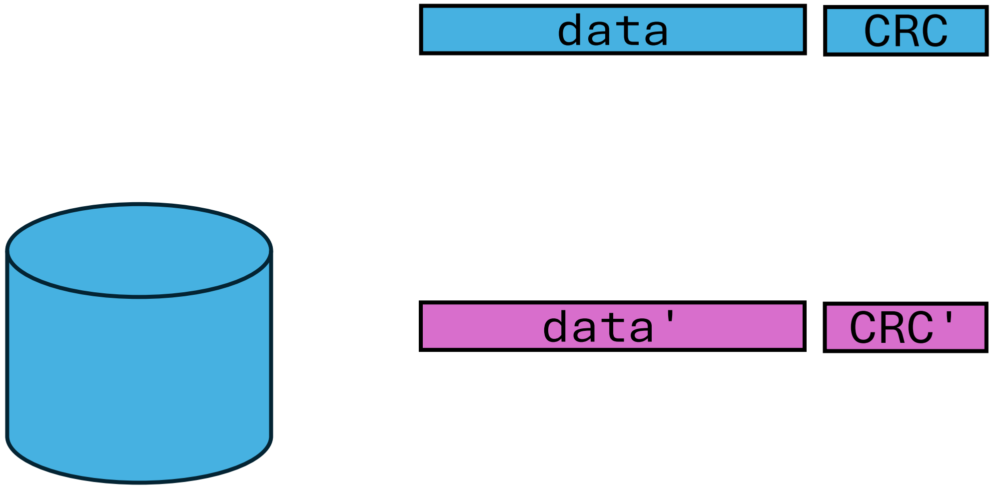


How are `data`/`data'` and `CRC`/`CRC'` related? How do we reason about this relationship?

New corruption model



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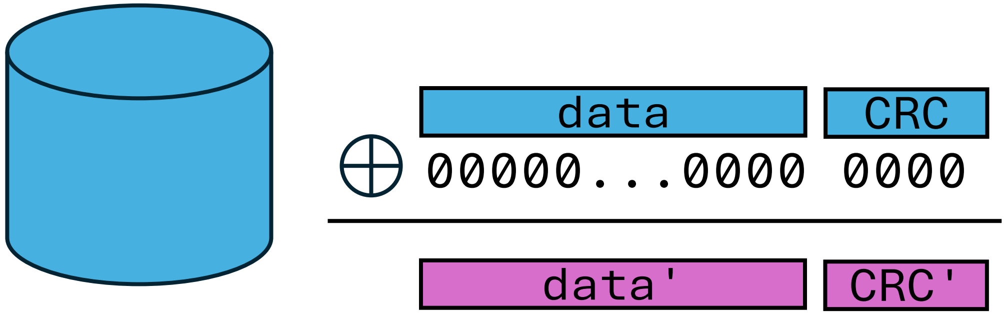

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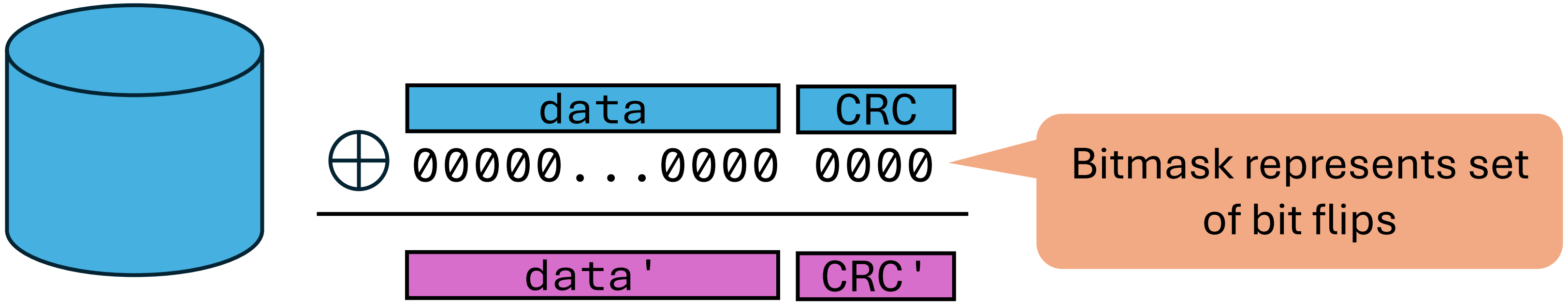

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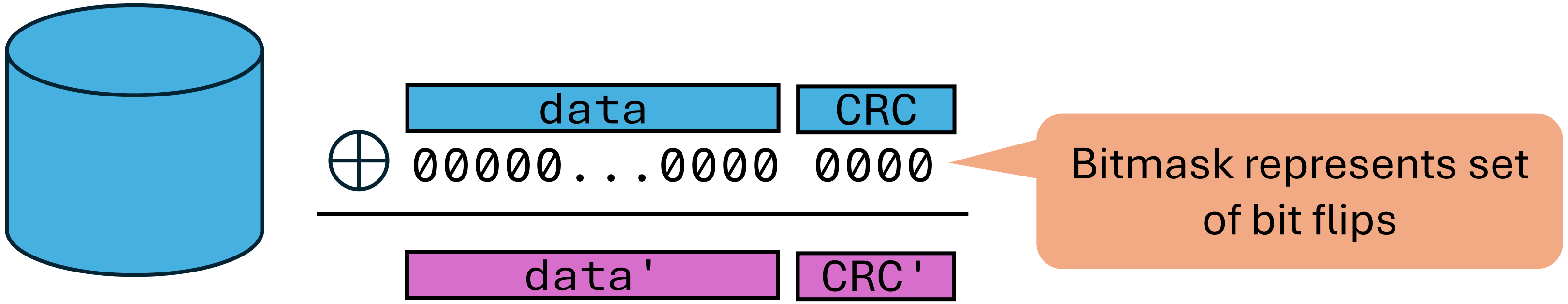
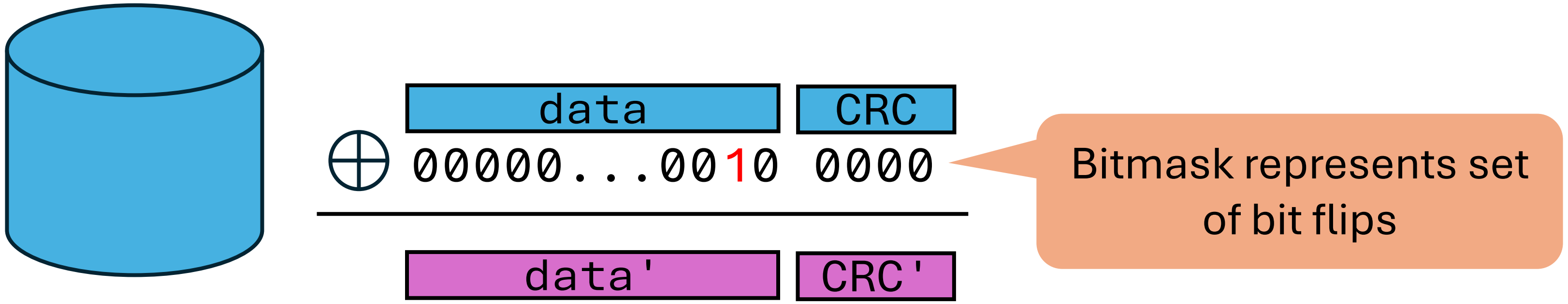


Guarantees:

- No bit flips ==> `CRC' == crc(data')`

New corruption model

How are `data`/`data'` and `CRC`/`CRC'` related? How do we reason about this relationship?

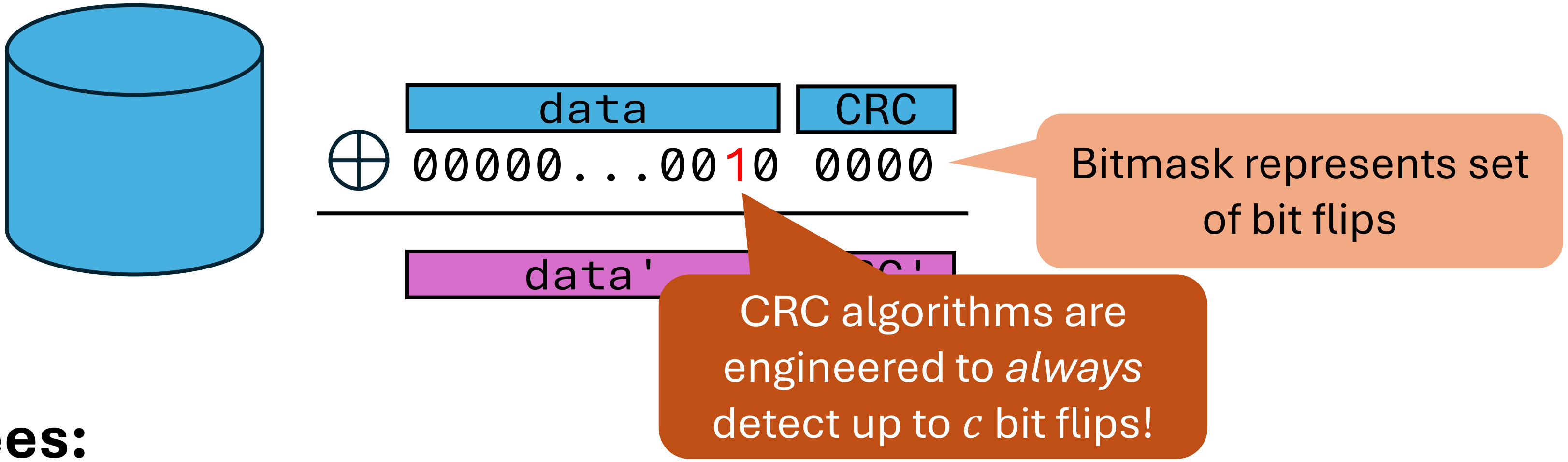


Guarantees:

- No bit flips ==> `CRC' == crc(data')`

New corruption model

How are `data`/`data'` and `CRC`/`CRC'` related? How do we reason about this relationship?



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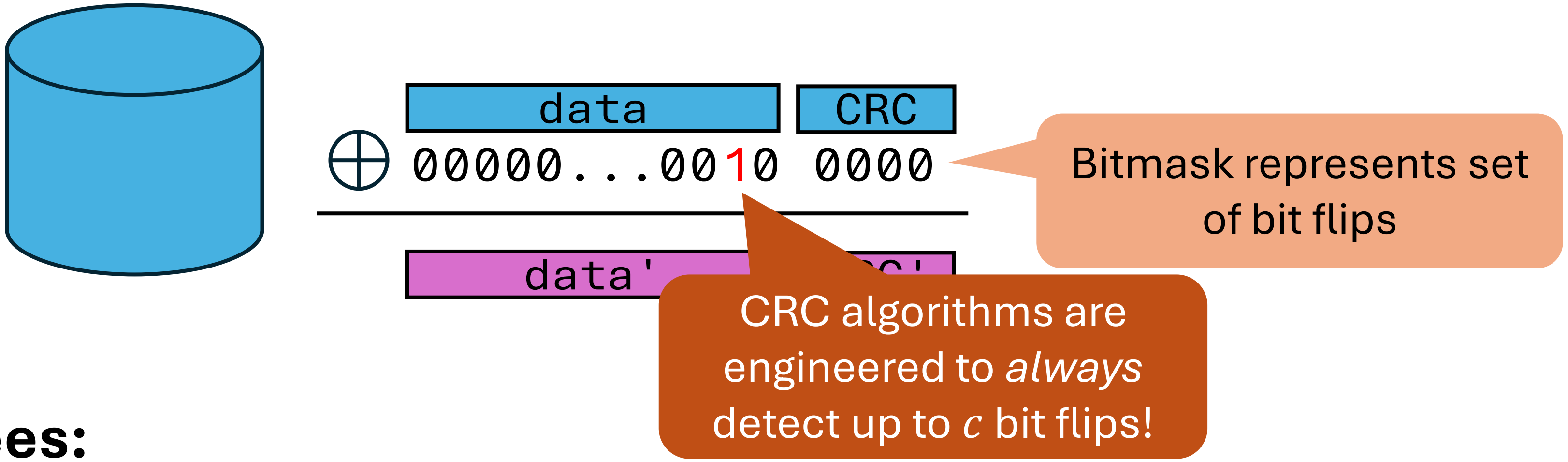
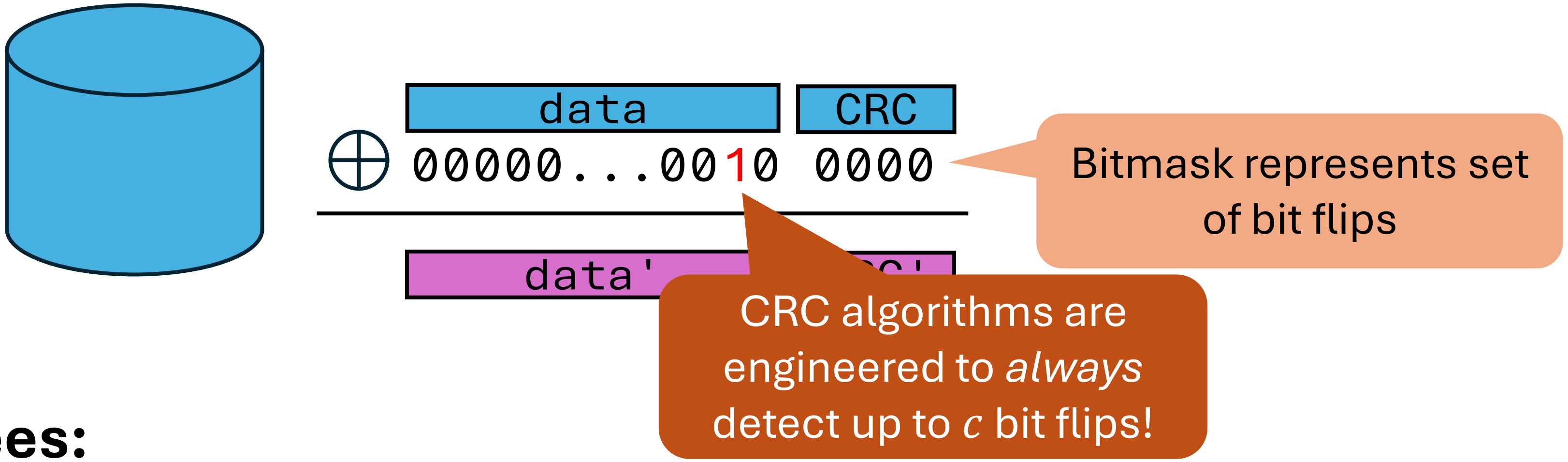


Guarantees:

- No bit flips ==> `CRC' == crc(data')`
- $1 \leq$ Population count of bitmask $\leq c$ ==> `CRC' != crc(data')`

New corruption model

How are `data`/`data'` and `CRC`/`CRC'` related? How do we reason about this relationship?



Guarantees:

- No bit flips ==> `CRC' == crc(data')`
- $1 \leq$ Population count of bitmask $\leq c$ ==> `CRC' != crc(data')`

Assuming $\leq c$ bit flips, CRC check proves whether data has been corrupted!