STAIR Codes: A General Family of Erasure Codes for Tolerating Device and Sector Failures in Practical Storage Systems

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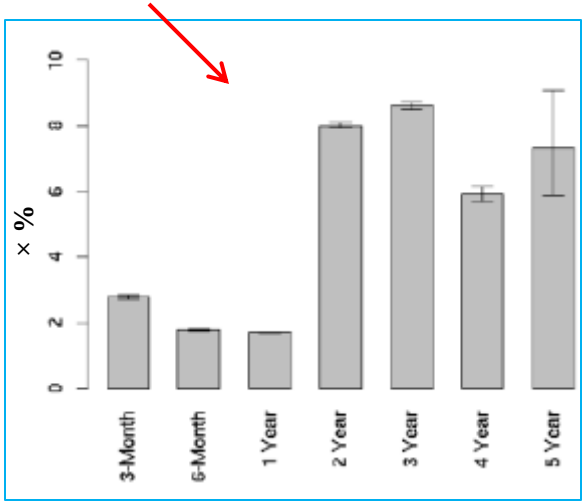
FAST '14

Device and Sector Failures

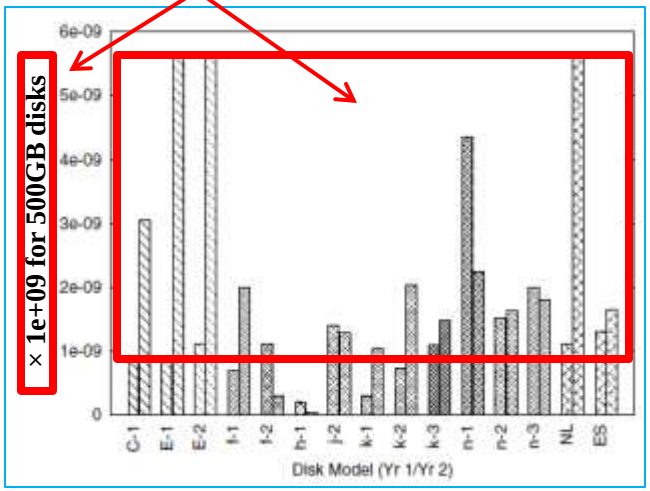
- Storage systems susceptible to both device and sector failures
  - *Device failure*: data loss in an entire device
  - *Sector failure*: data loss in a sector

(a) Annual disk failure rate: 1~10%



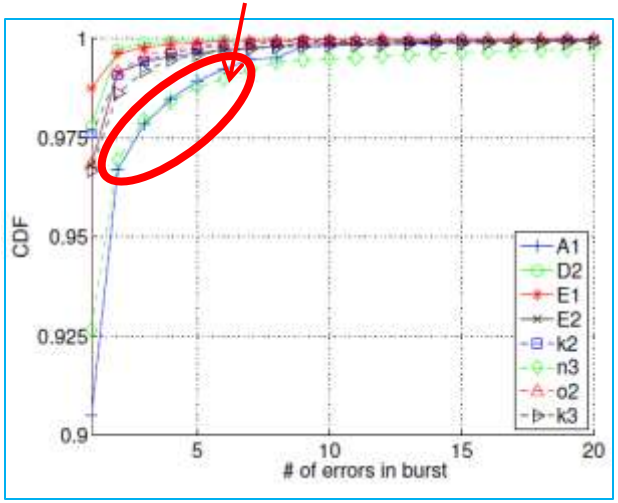
Annual disk failure rate
[Pinheiro et al., FAST'07]

(b) Sector failures can be more frequent than disk failures



Annual sector failure rate
[Bairavasundaram et al., SIGMETRICS '07]

(c) Sector failure bursts can be long (> 5)



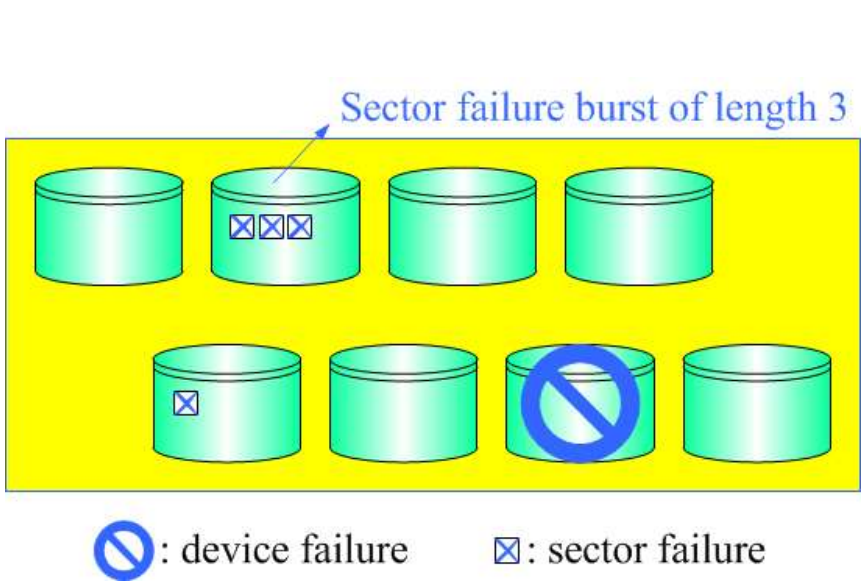
Burstiness of sector failures
[Schroeder et al., FAST '10]

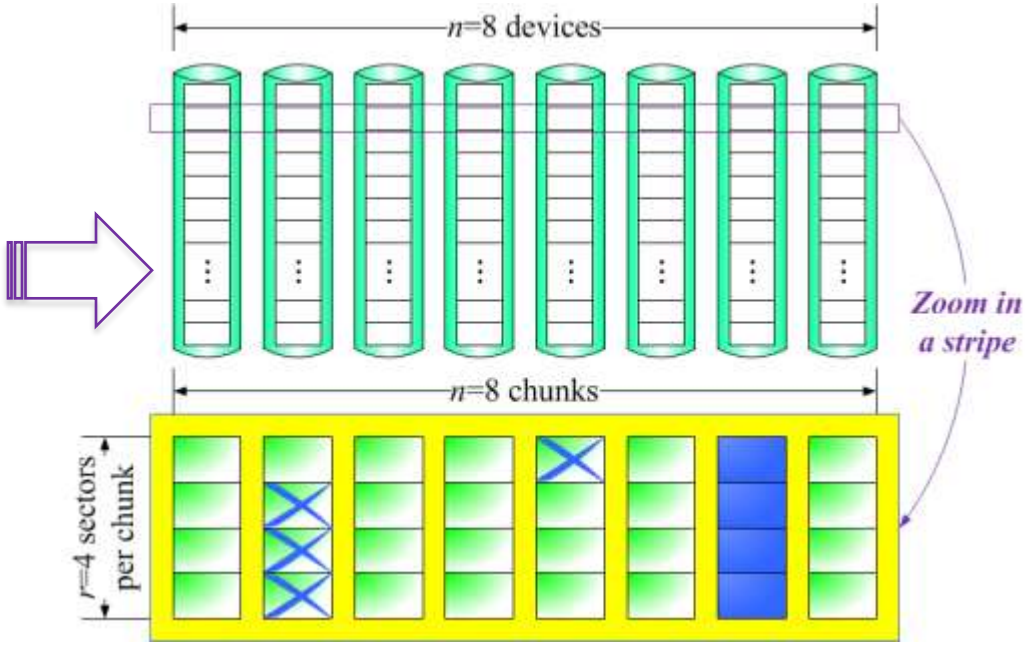
Erasure Coding

- **Erasure coding**: adds redundancy to data
- ***(N,K)* systematic MDS codes**
  - Encodes K data pieces to create N-K *parity* pieces
  - Stripes the N pieces across disks
  - Any K out of N pieces can recover original K data pieces and the N-K parity pieces → fault tolerance
- Three erasure coding schemes:
  - Traditional RAID and erasure codes (e.g., Reed-Solomon codes)
  - Intra-Device Redundancy (IDR)
  - Sector-Disk (SD) codes

Mixed Failure Scenario

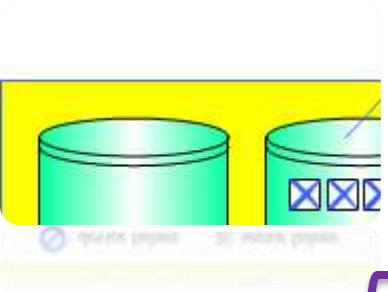
- Consider an example failure scenario with
  - $m=1$ entirely failed device, and
  - $m'=2$ partially failed devices with **1** and **3** sector failures

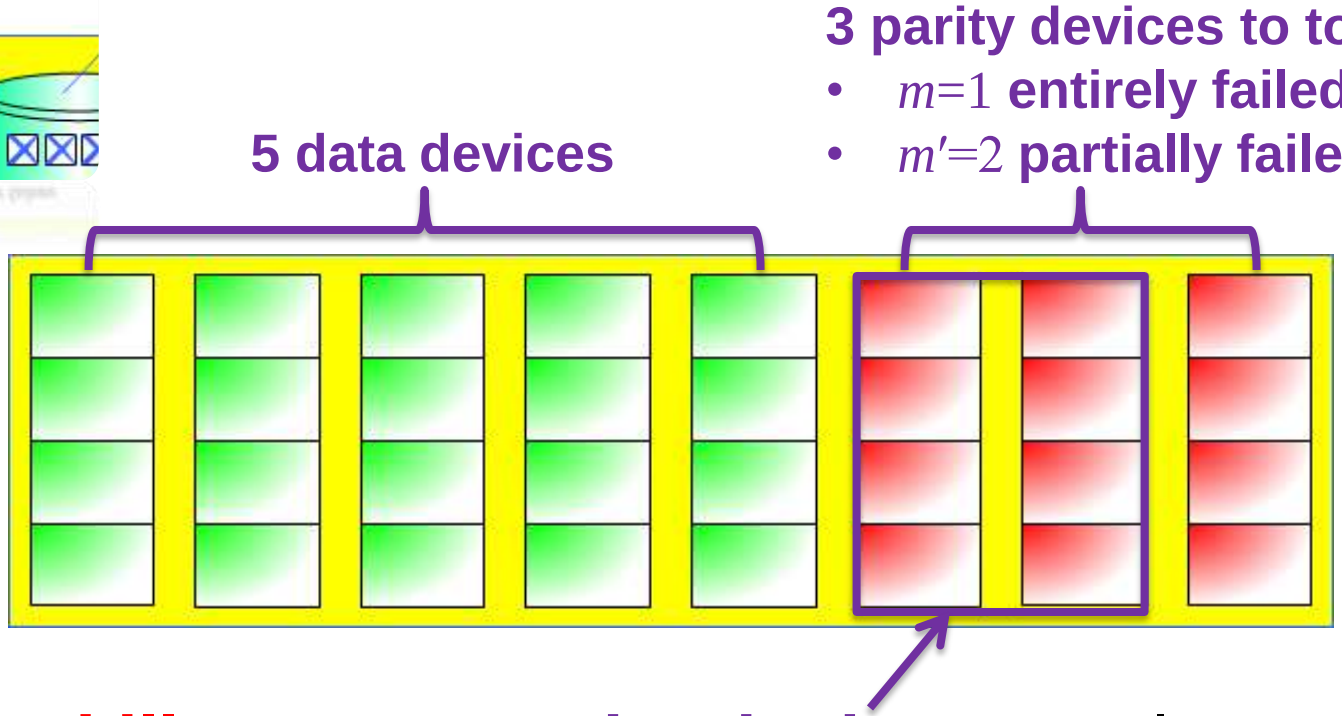




Question: ***How can we efficiently tolerate such a mixed failure scenario via erasure coding?***

Traditional RAID and Erasure Codes

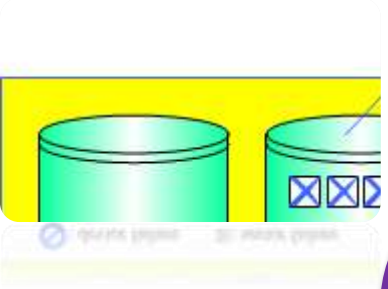


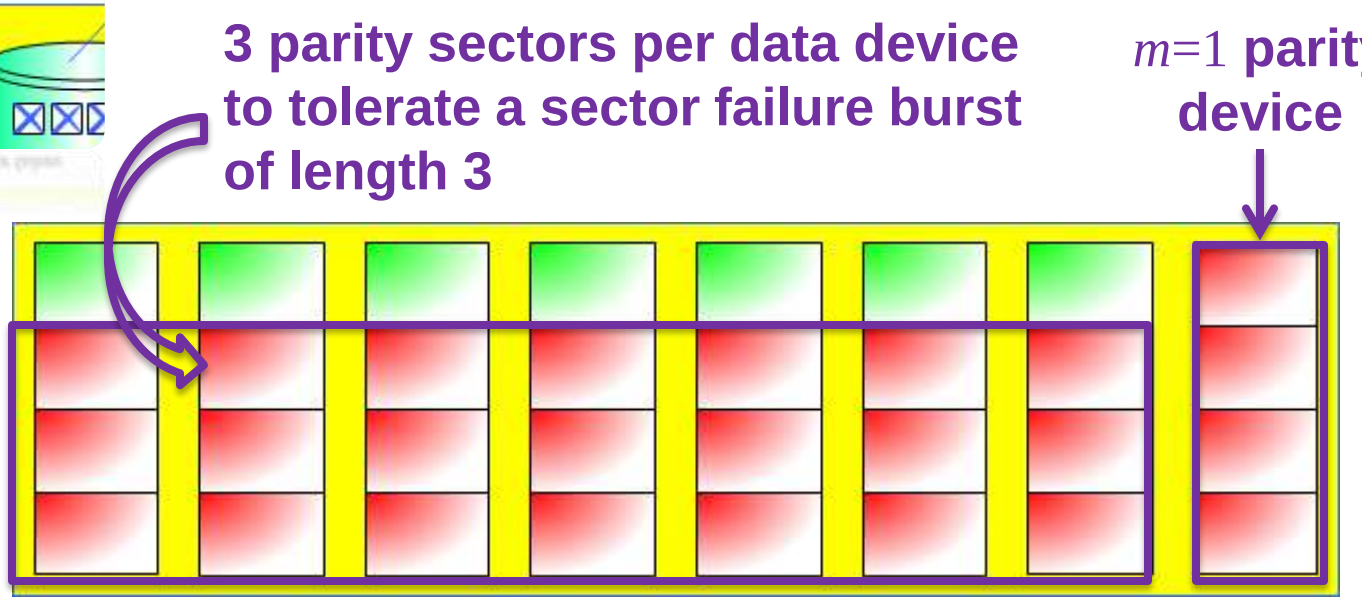


- **Overkill** to use **2 parity devices** to tolerate m'=2 partially failed devices
  - Device-level tolerance only

Intra-Device Redundancy (IDR)

[*Dholakia et al., TOS 2008*]



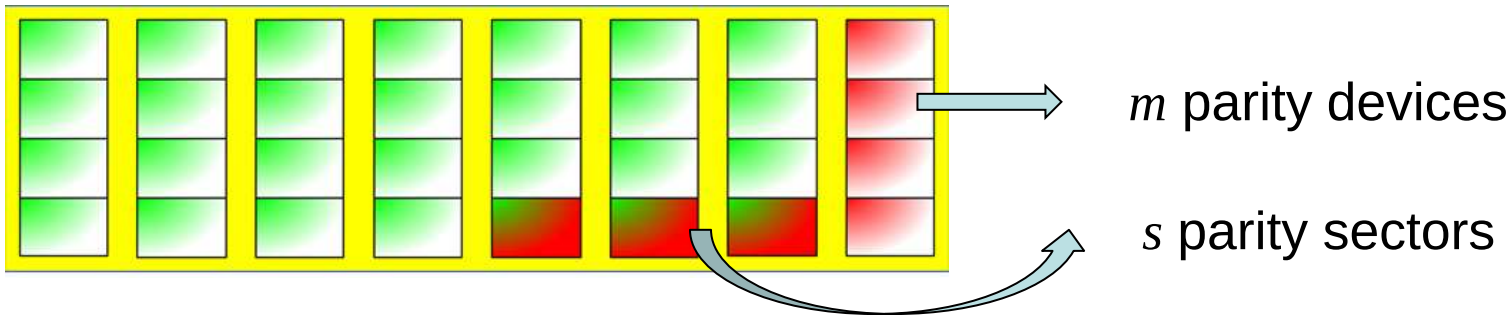


- Still **overkill** to add parity sectors per data device

Sector-Disk (SD) Codes

[*Plank et al., FAST '13, TOS'14*]

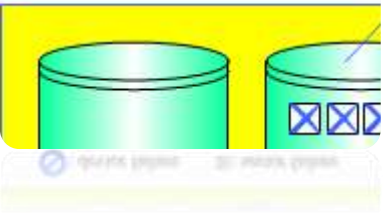
- Simultaneously tolerate
  - m entirely failed devices
  - s failed sectors (per stripe) in partially failed devices
- Construction currently limited to $s \leq 3$

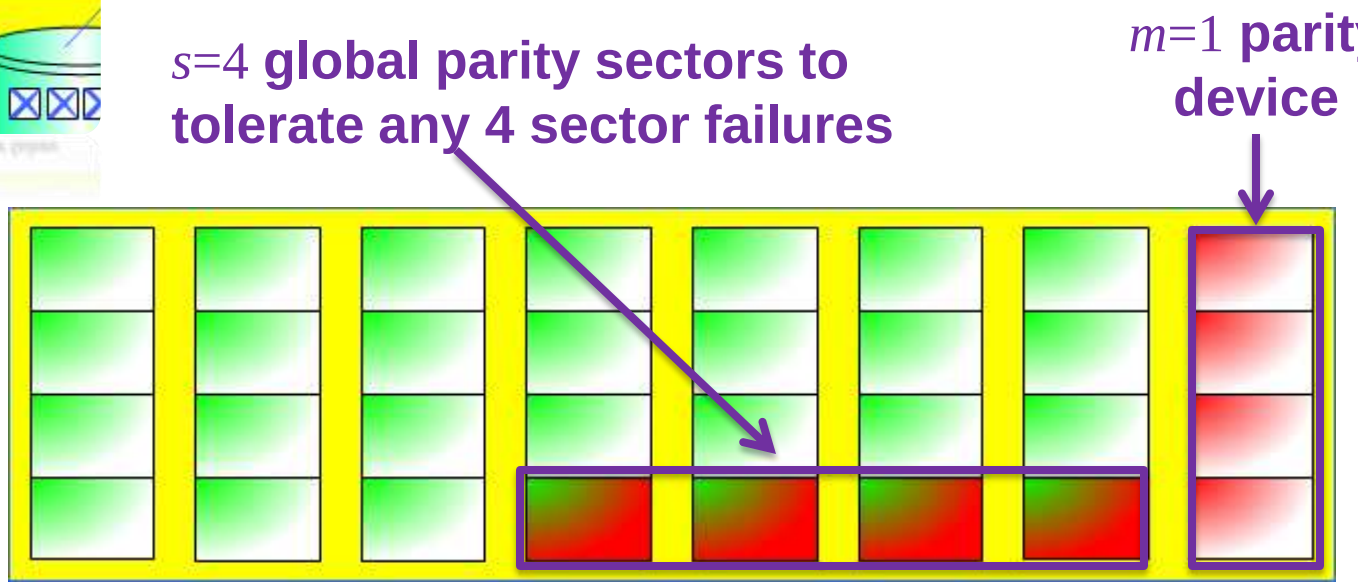


- How to tolerate our mixed failure scenario?
  - $m=1$ entirely failed device, and
  - $m'=2$ partially failed devices with **1** and **3** sector failures

Sector-Disk (SD) Codes

[*Plank et al., FAST '13, TOS'14*]

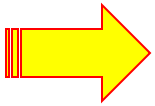




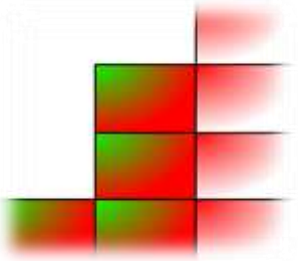
- Such an SD code is **unavailable**

Our Work

- Construct a **general, space-efficient** family of erasure codes to tolerate both device and sector failures
  - **a) General**: without any restriction on
    - *size of a storage array,*
    - *number of tolerable device failures, or*
    - *number of tolerable sector failures*
  - **b) Space-efficient**:
    - number of global parity sectors = number of sector failures (like SD codes)



STAIR Codes



Key Ideas of STAIR Codes

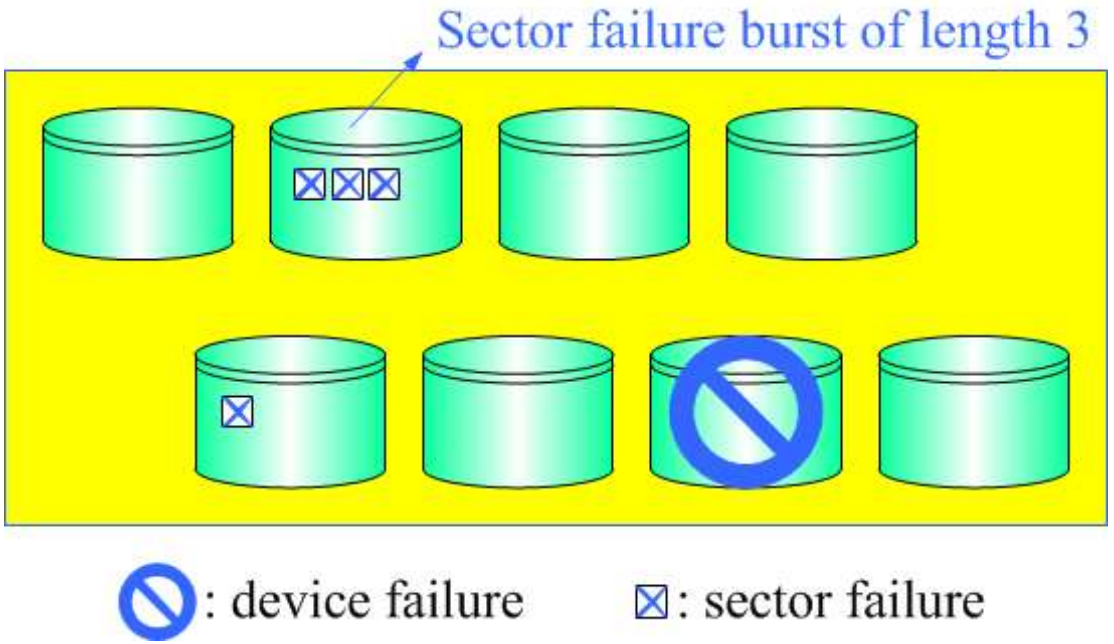
- Sector failure coverage vector $\mathbf{e}$
  - Defines a pattern of how sector failures occur, rather than how many sector failures would occur
- Code structure based on two encoding phases
  - Each phase builds on an MDS code
- Two encoding methods: upstairs and downstairs encoding
  - Reuse computed parity results in encoding
  - Provide complementary performance gains

Sector Failure Coverage Vector

- SD codes define s
  - Tolerate any combination of s sector failures per stripe
  - Currently limited to $s \leq 3$

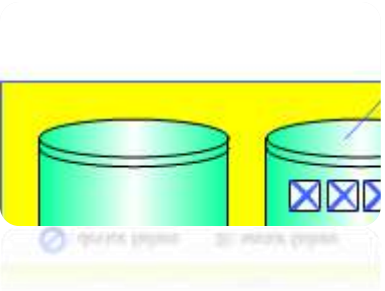
- STAIR codes define sector failure coverage vector
  $\mathbf{e} = (e_0, e_1, e_2, \ldots, e_{m'-1})$
  - Bounds # of partially failed devices m'
  - Bounds # of sector failures per device e_l $(0 \leq l \leq m' - 1)$
    - $\sum e_l = s$
  - Rationale: sector failures come in small bursts
    → Can define small m' and reasonable size e_l for bursts

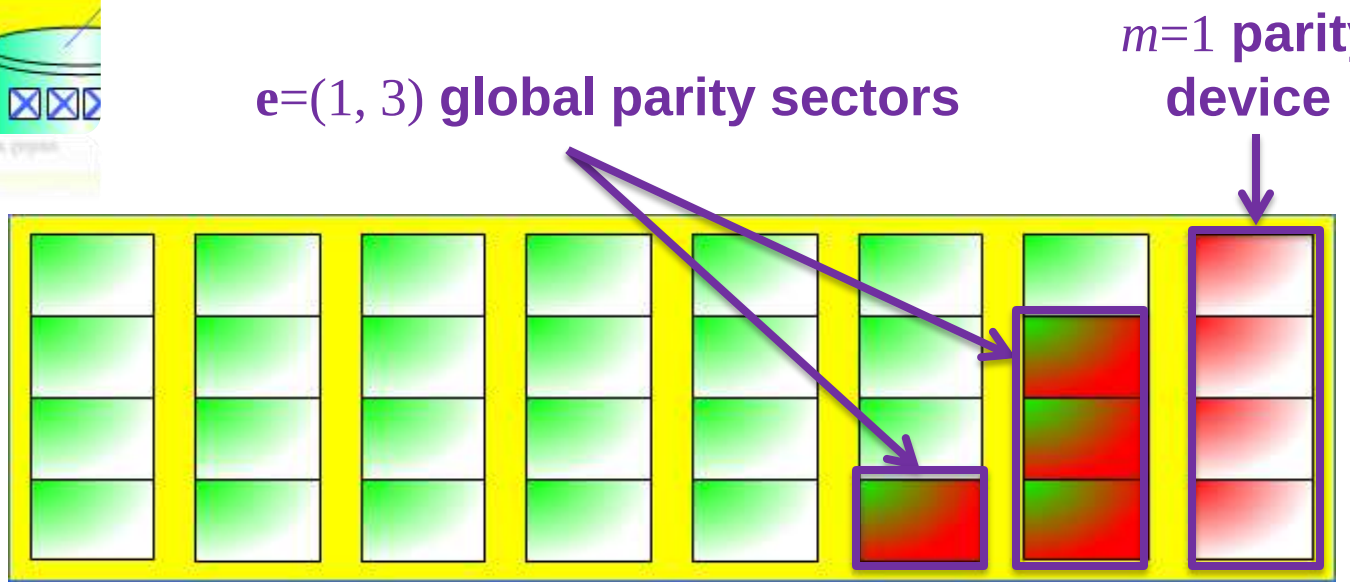
Sector Failure Coverage Vector



- Set **e**=(1, 3):
  - At most **2** devices (aside entirely failed devices) have sector failures
    - One device has at most **3** sector failures, and
    - Another one has at most **1** sector failure

Parity Layout

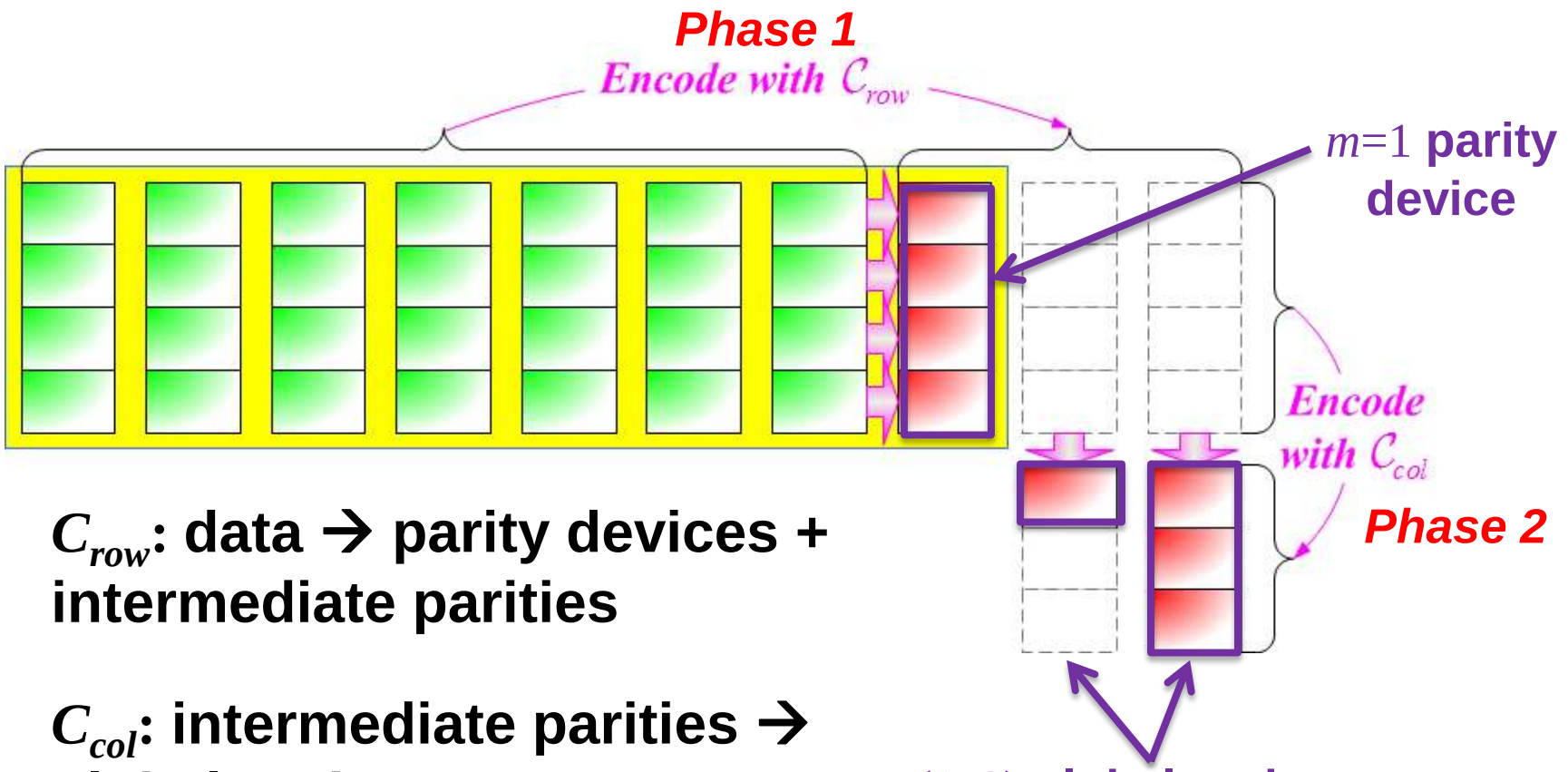




- **Q:** How to generate the **e**=(1, 3) global parity sectors and the m=1 parity device?

- **A:** Use two MDS codes C_{row} and C_{col}

Two Encoding Phases

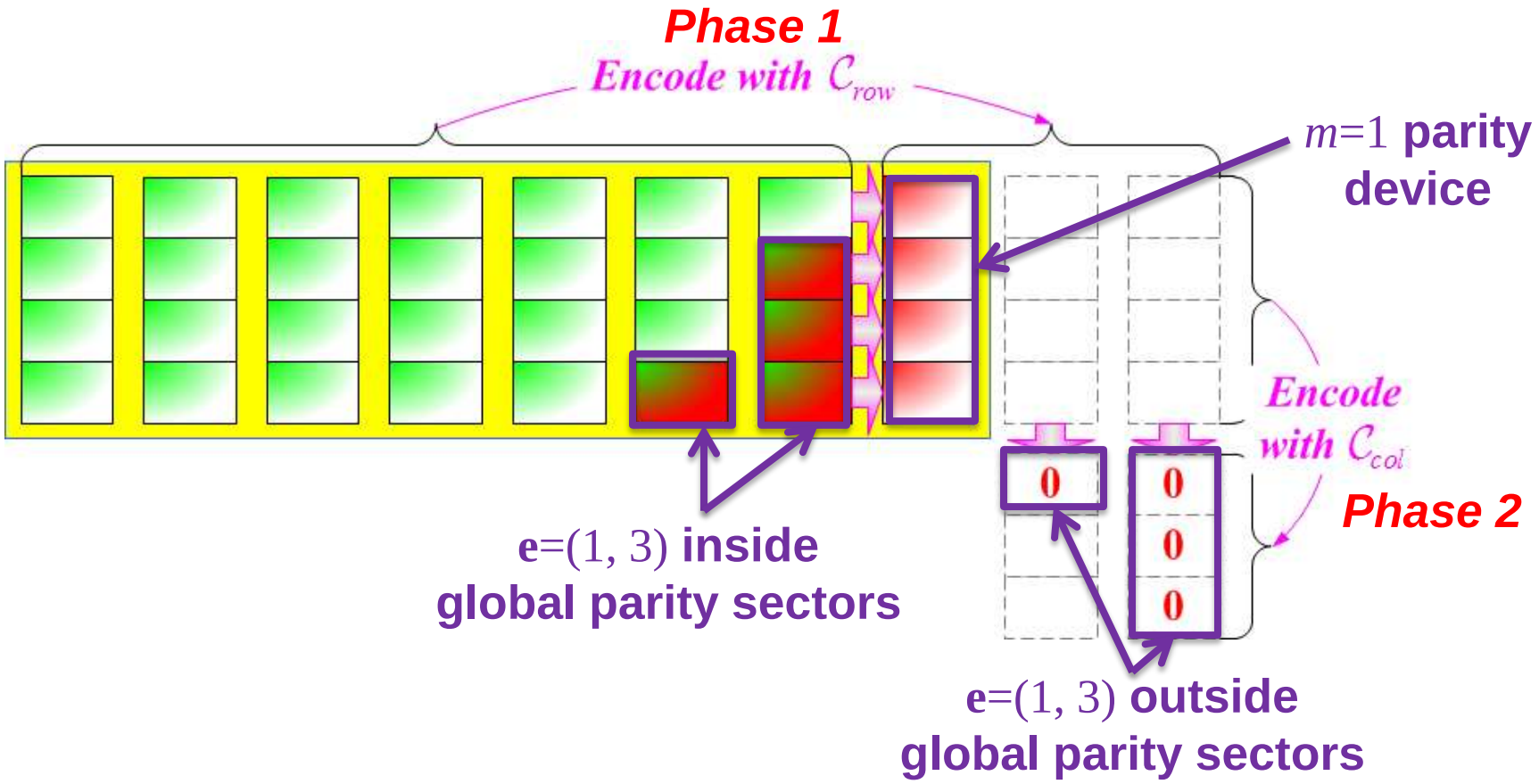


C_{row}: data → parity devices + intermediate parities

C_{col}: intermediate parities → global parity sectors

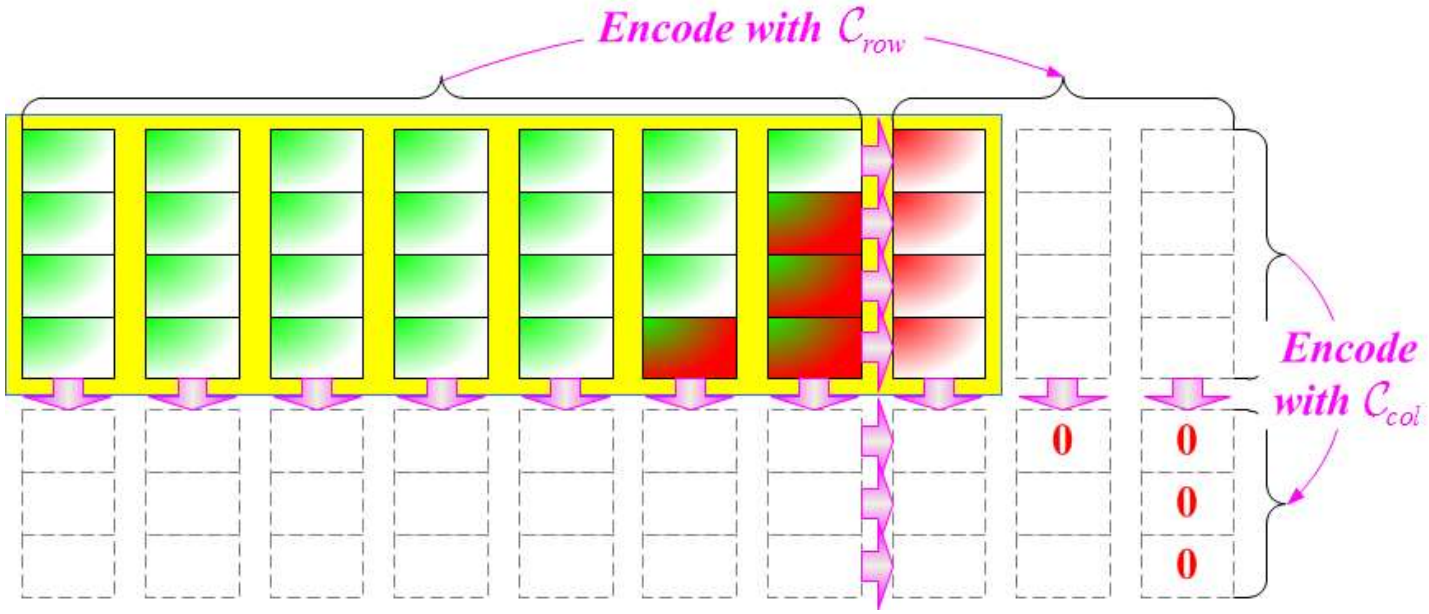
***Q:** How to keep the global parity sectors inside a stripe?*

Two Encoding Phases



- ***A:*** set outside global parity sectors as **zeroes**; reconstruct inside global parity sectors

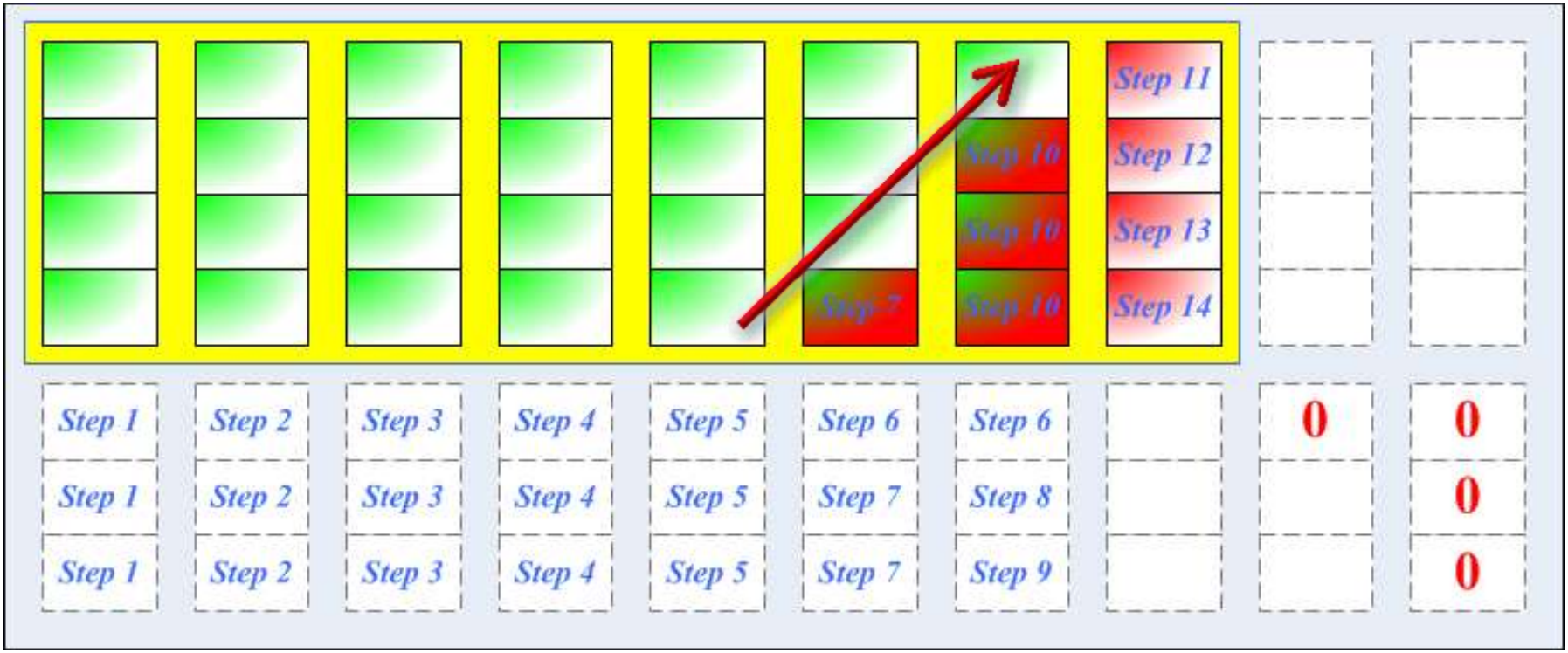
Augmented Rows



- Q: How do we compute inside parity sectors?
  - A: Augment a stripe
- Encode each column with C_{col} to form **augmented rows**
  - Generate virtual parities in augmented rows
- Each augmented row is a codeword of C_{row}

Upstairs Encoding

- Idea: Generate parities in upstairs direction



- Can be generalized as **upstairs decoding** for recovering failures

Upstairs Encoding

- Detailed steps:

C_{row}: (10,7) code **C_{col}: (7,4) code**

Upstairs Encoding

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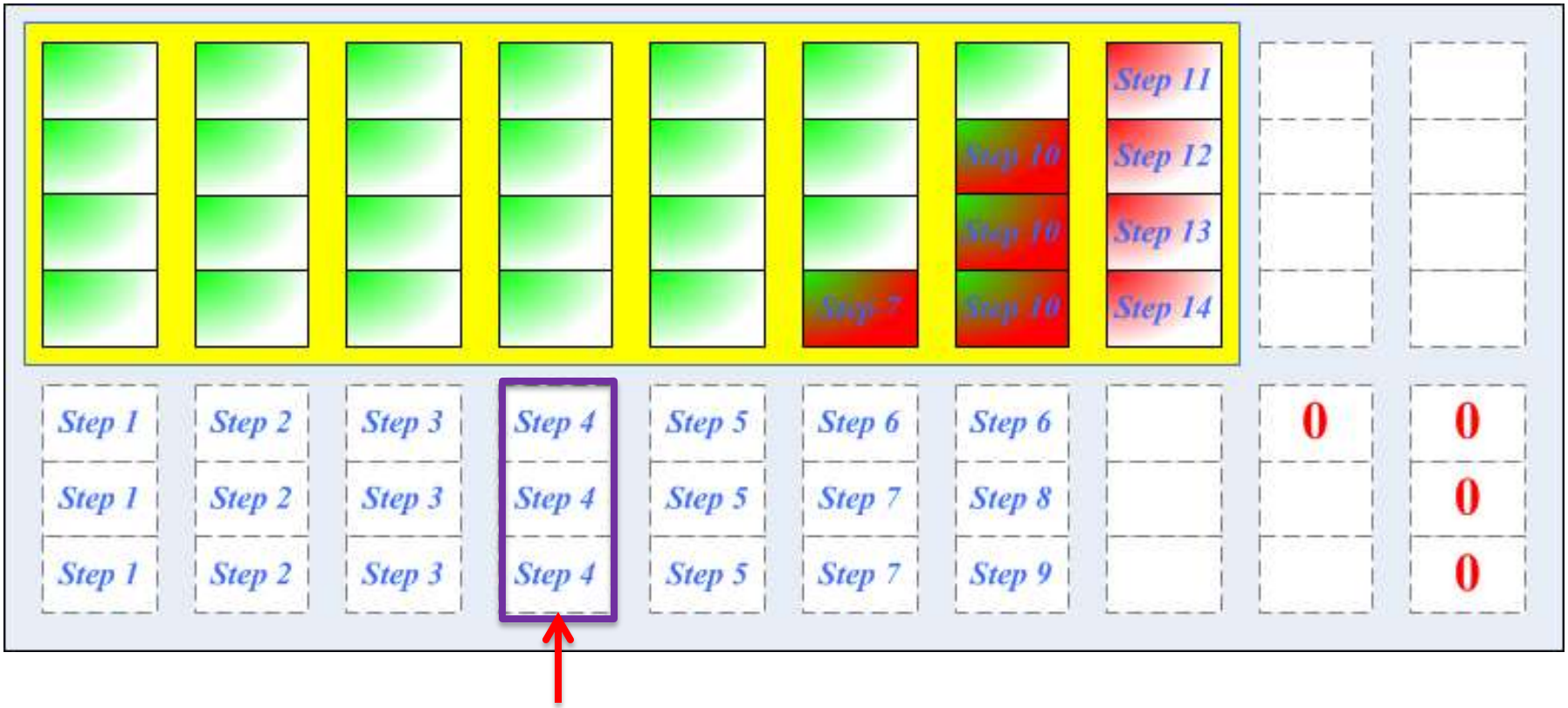

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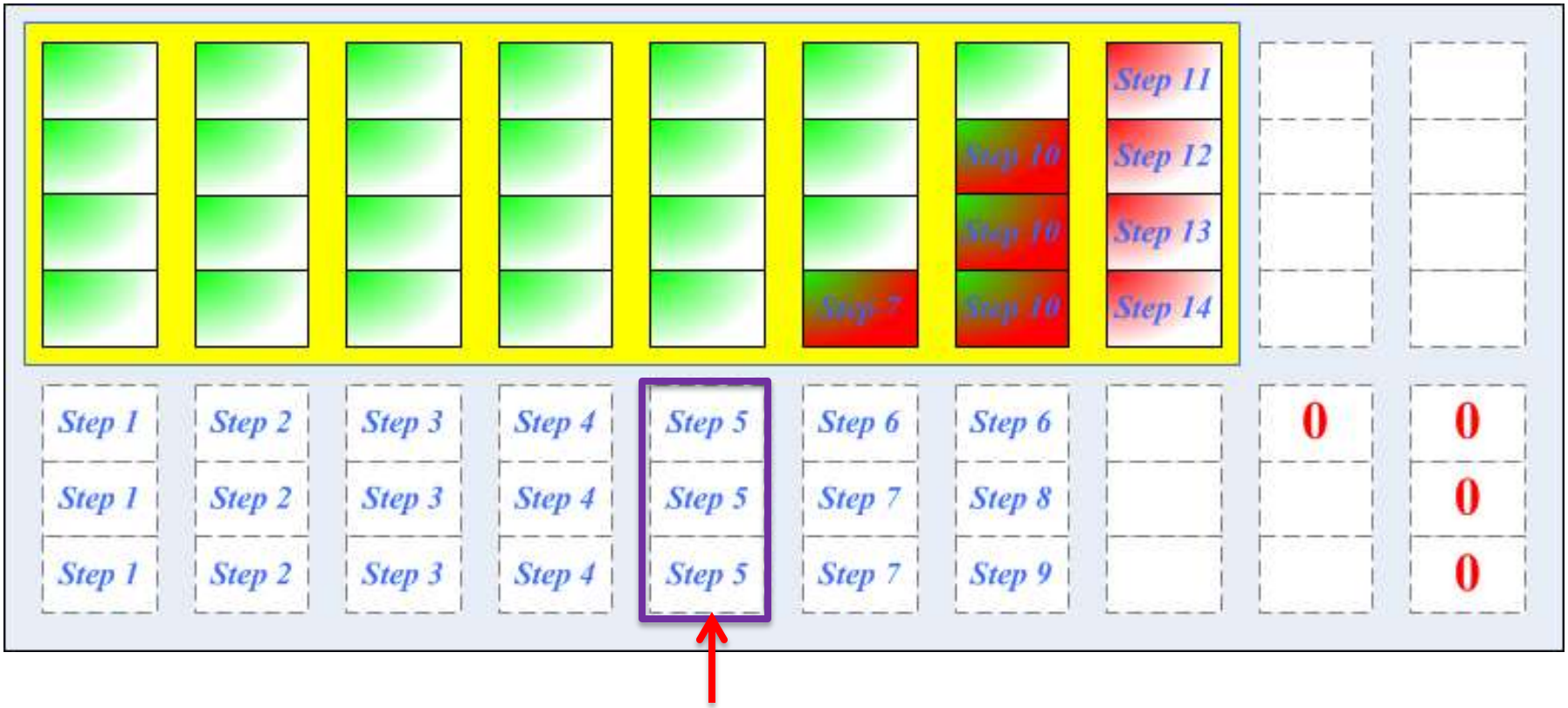

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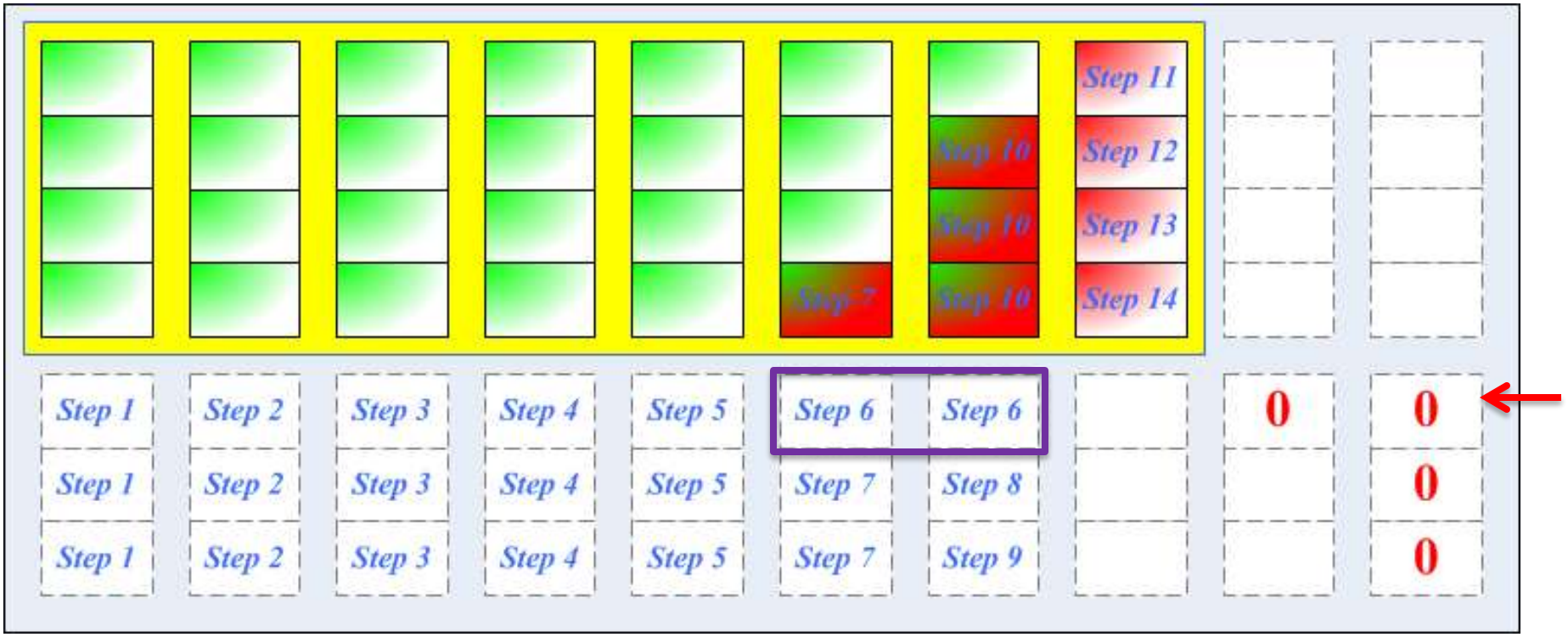

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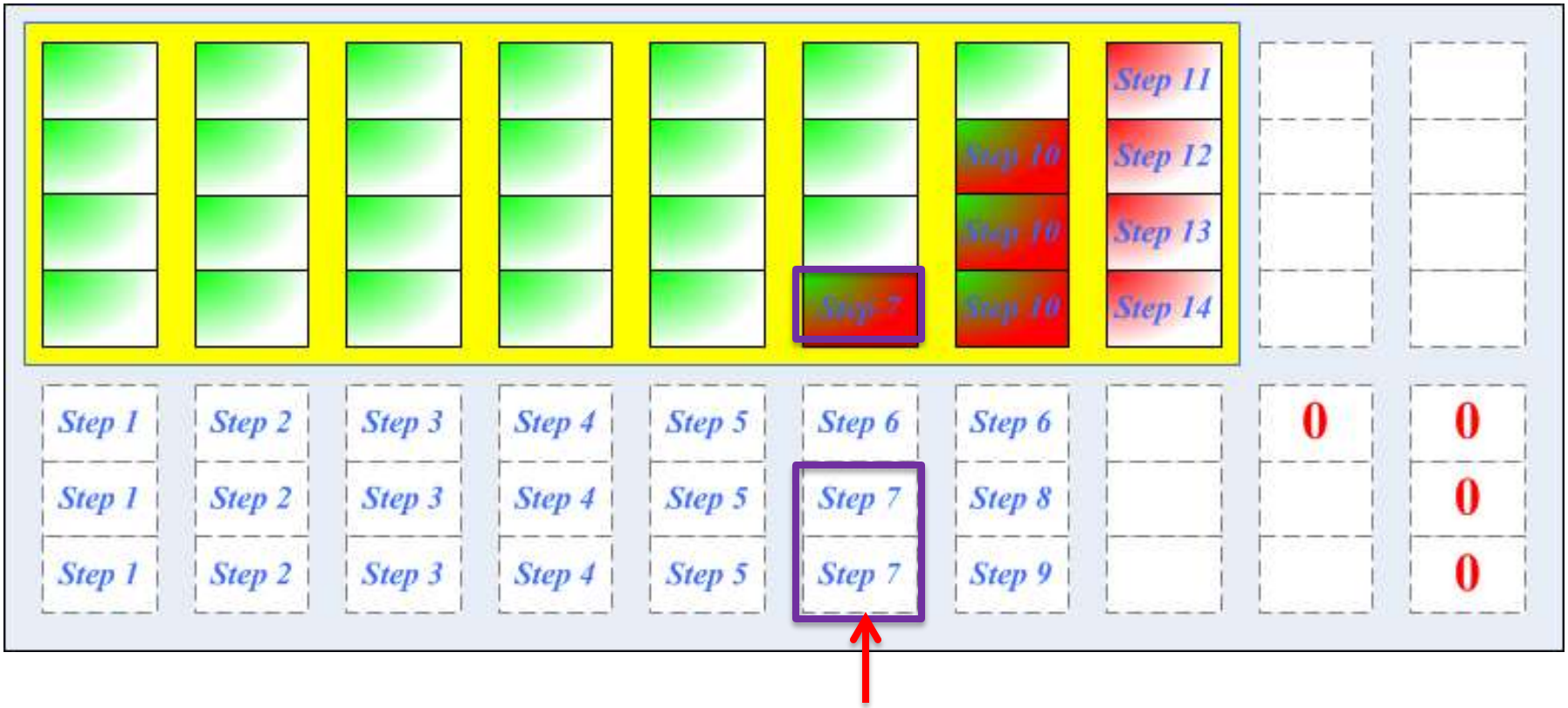

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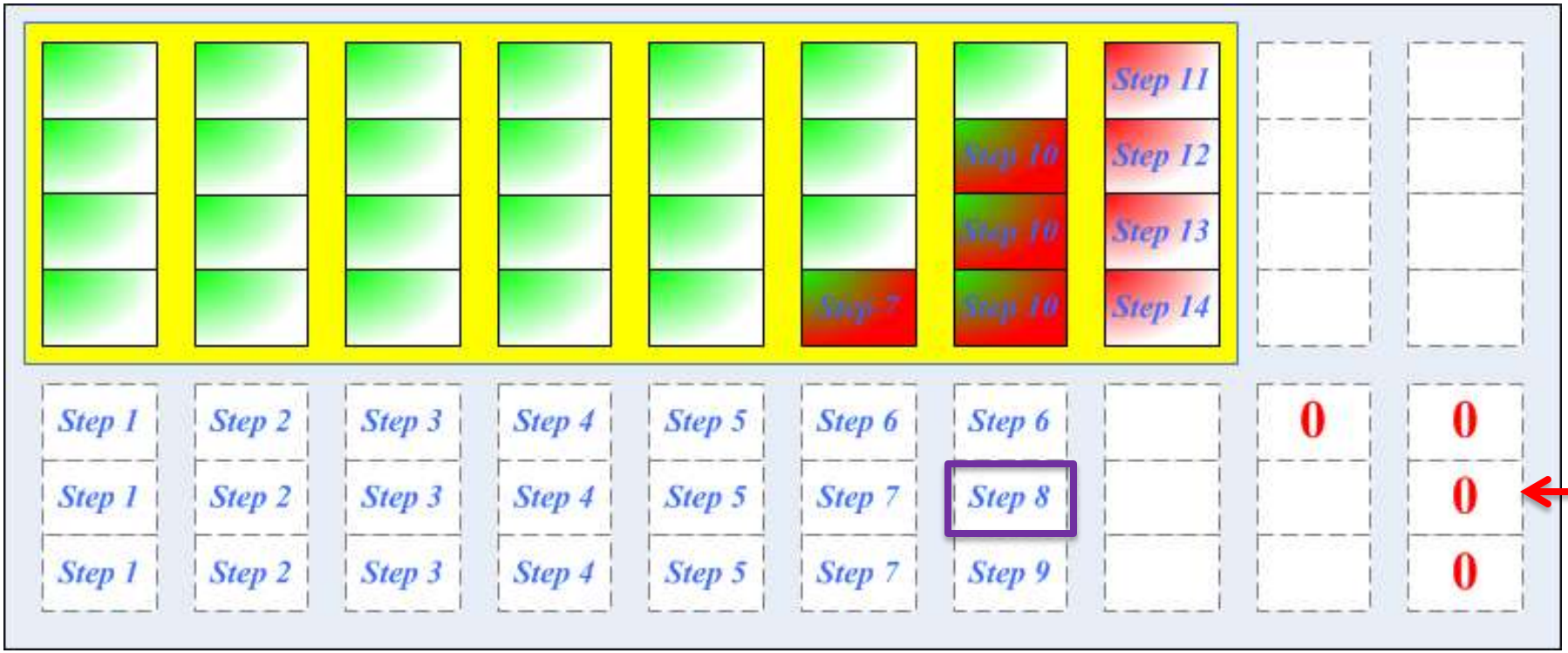

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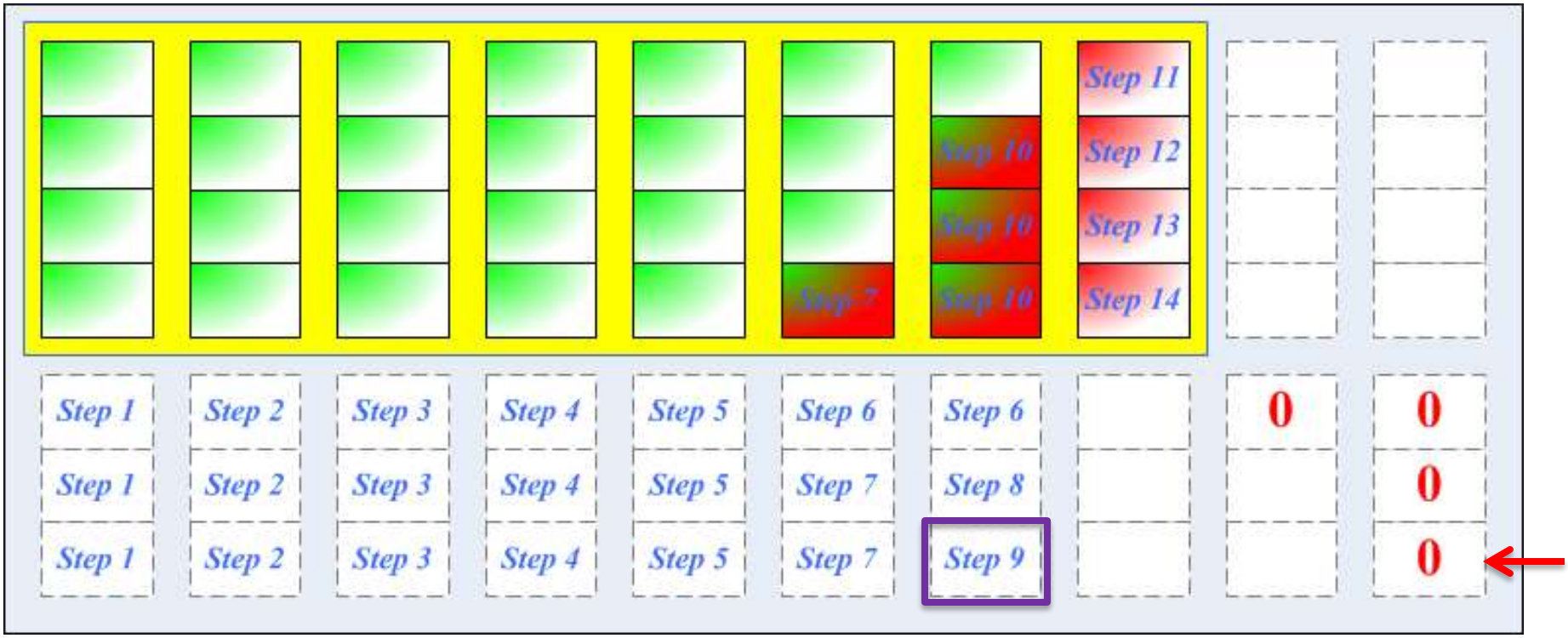

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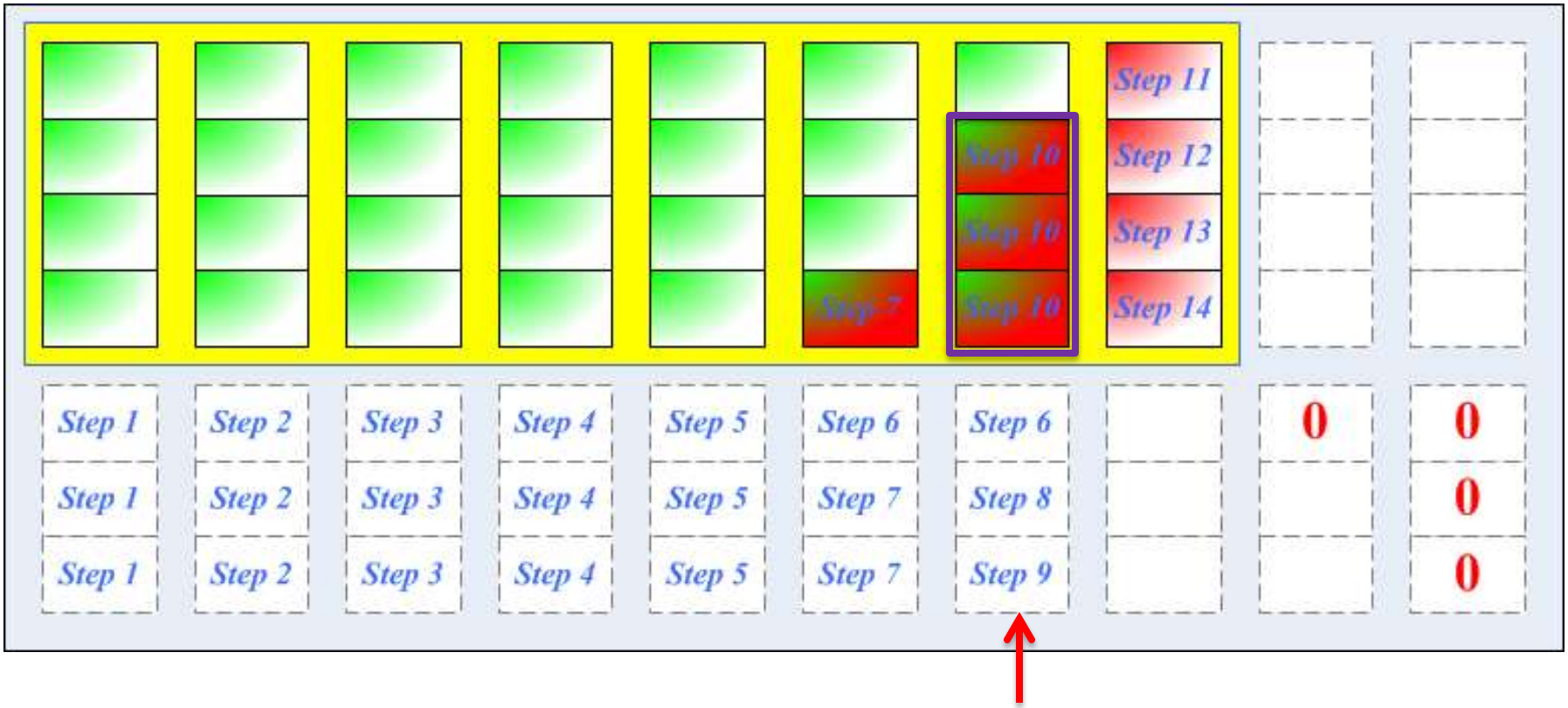

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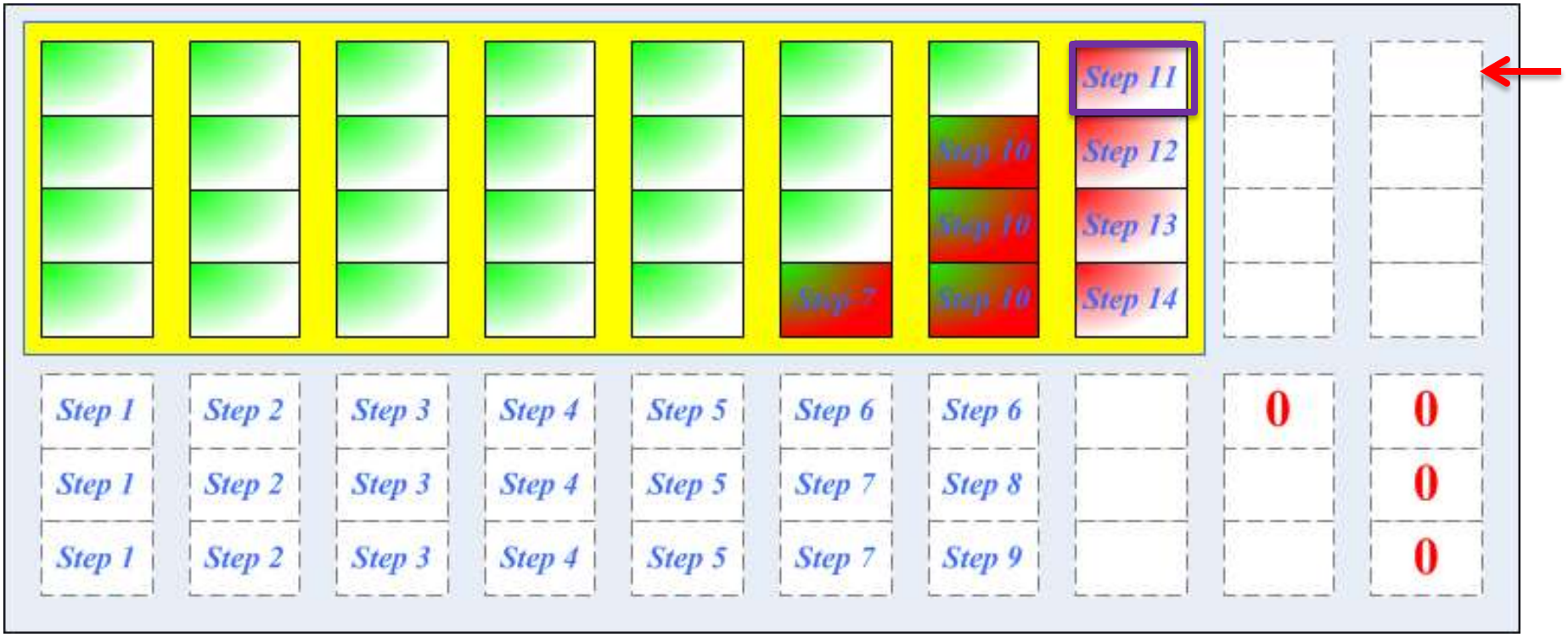

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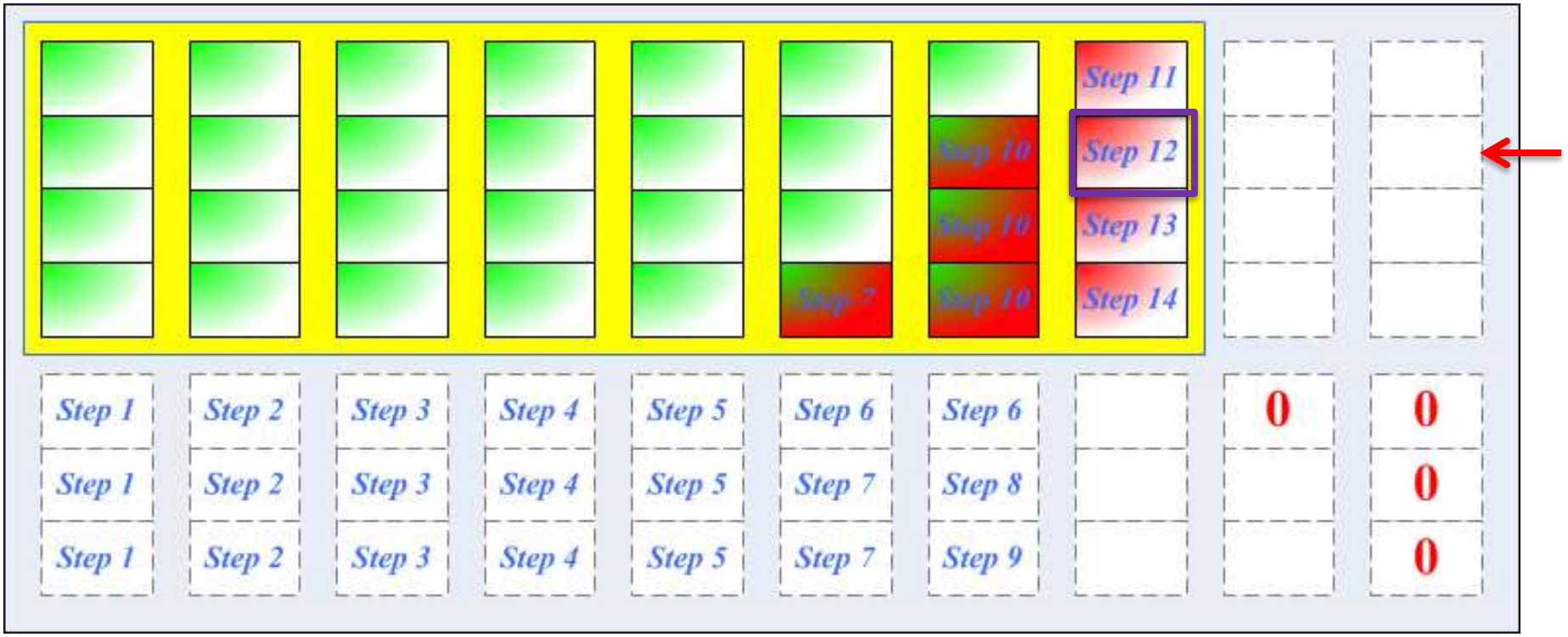

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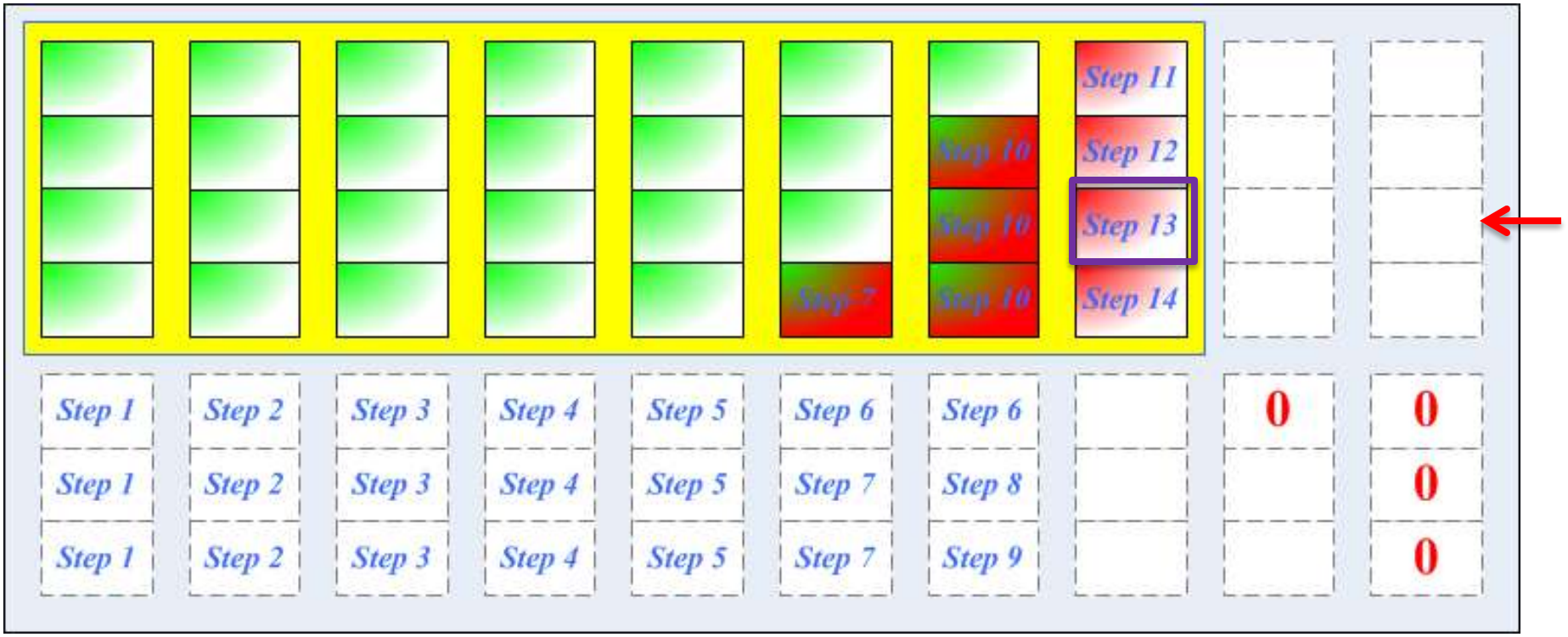

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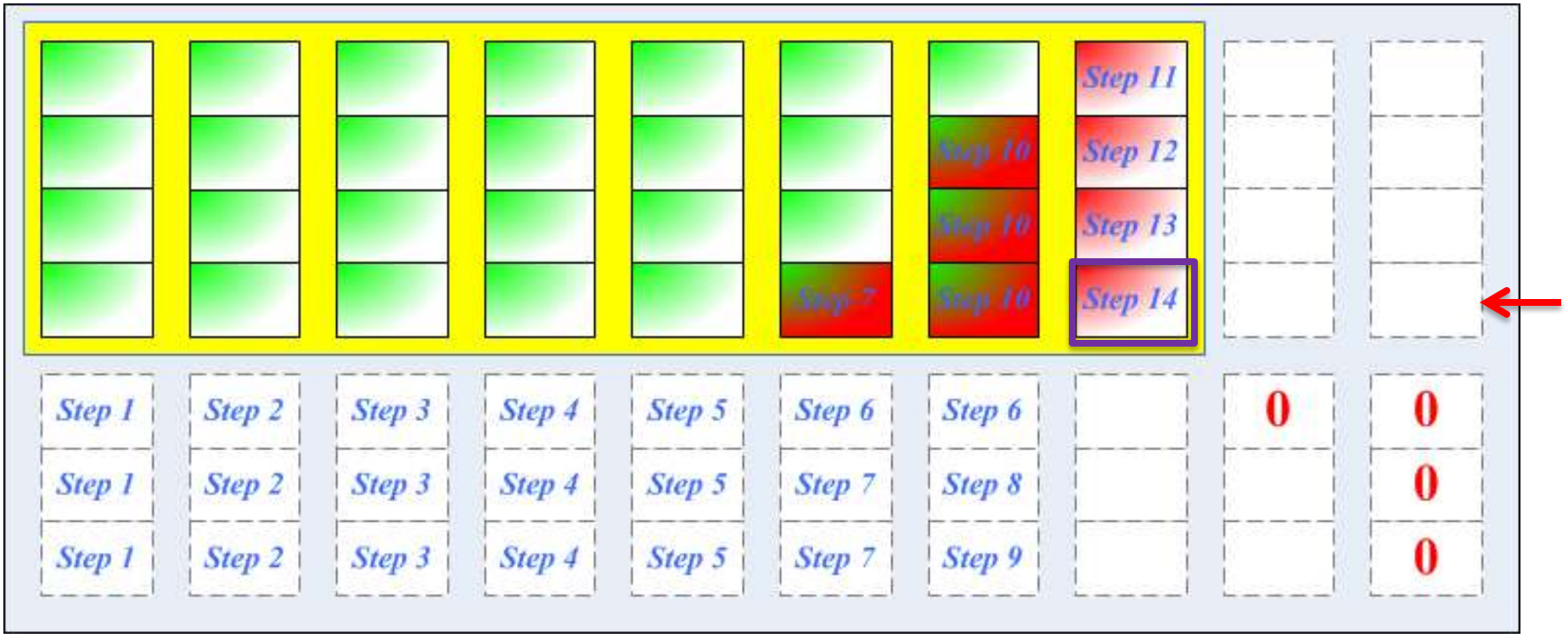
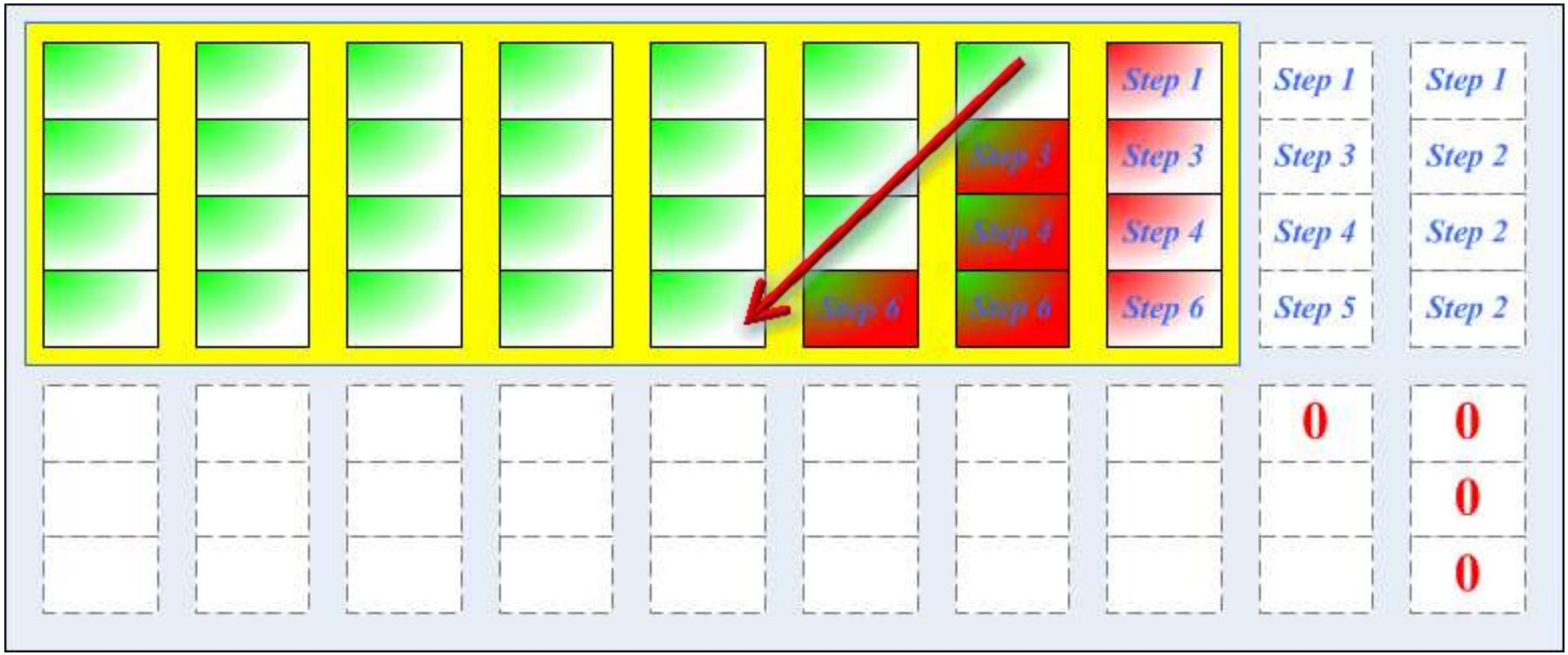


Notes: parity computations reuse previously computed parities

Downstairs Encoding

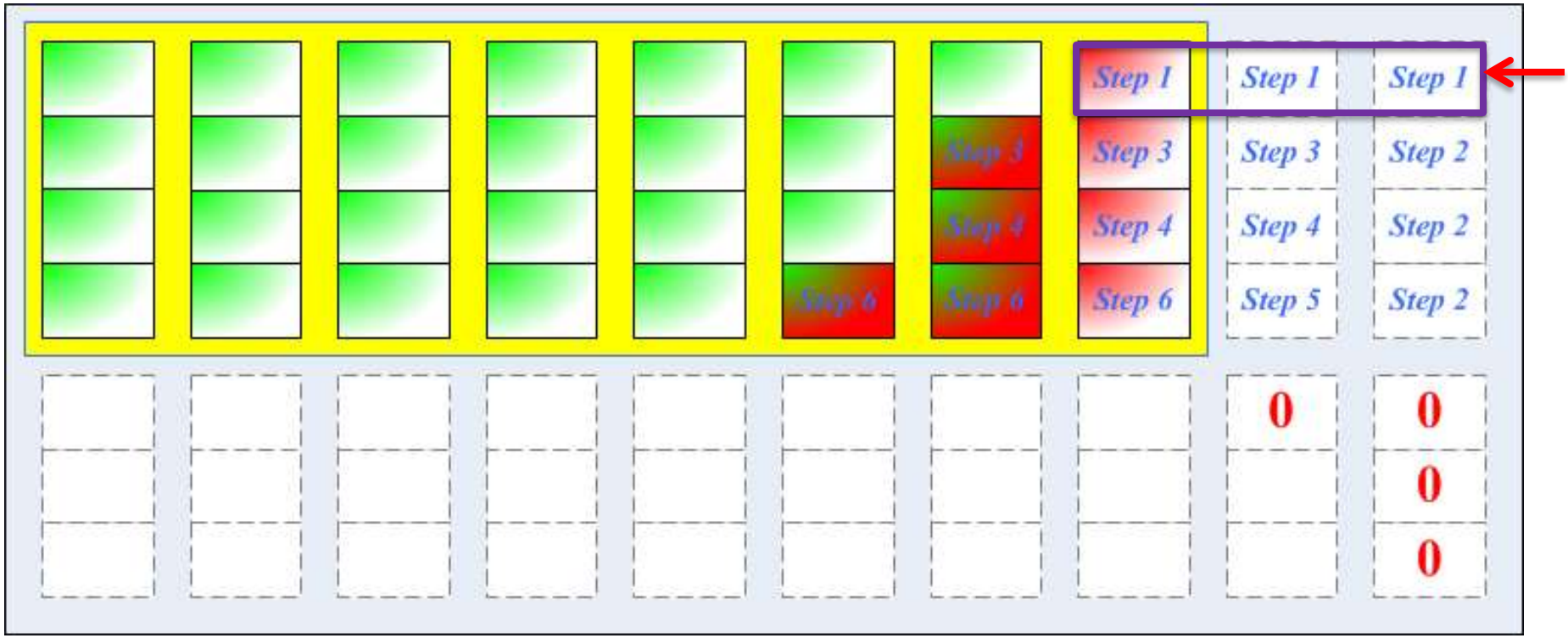
- Another idea: Generate parities in downstairs direction



- **Cannot** be generalized for decoding

Downstairs Encoding

- Detailed steps:



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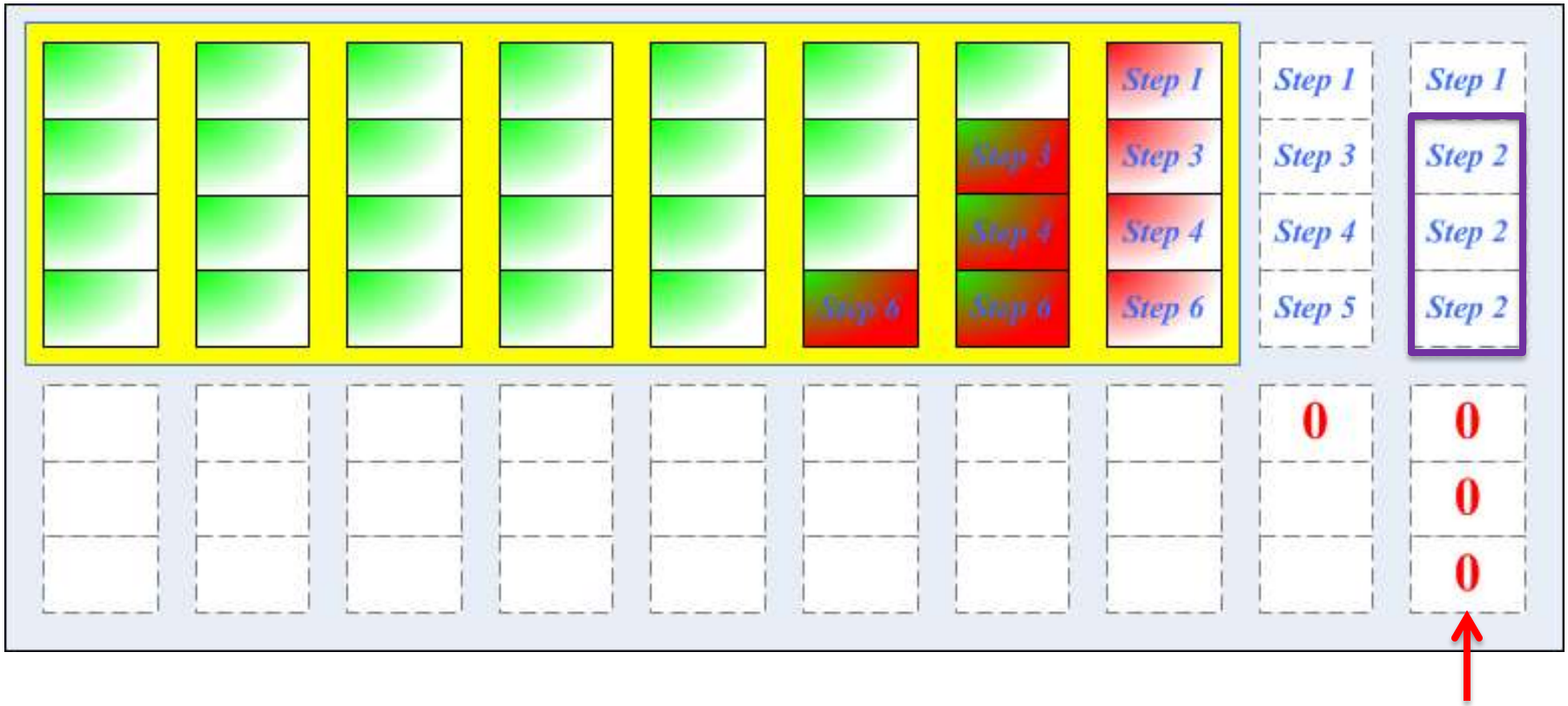

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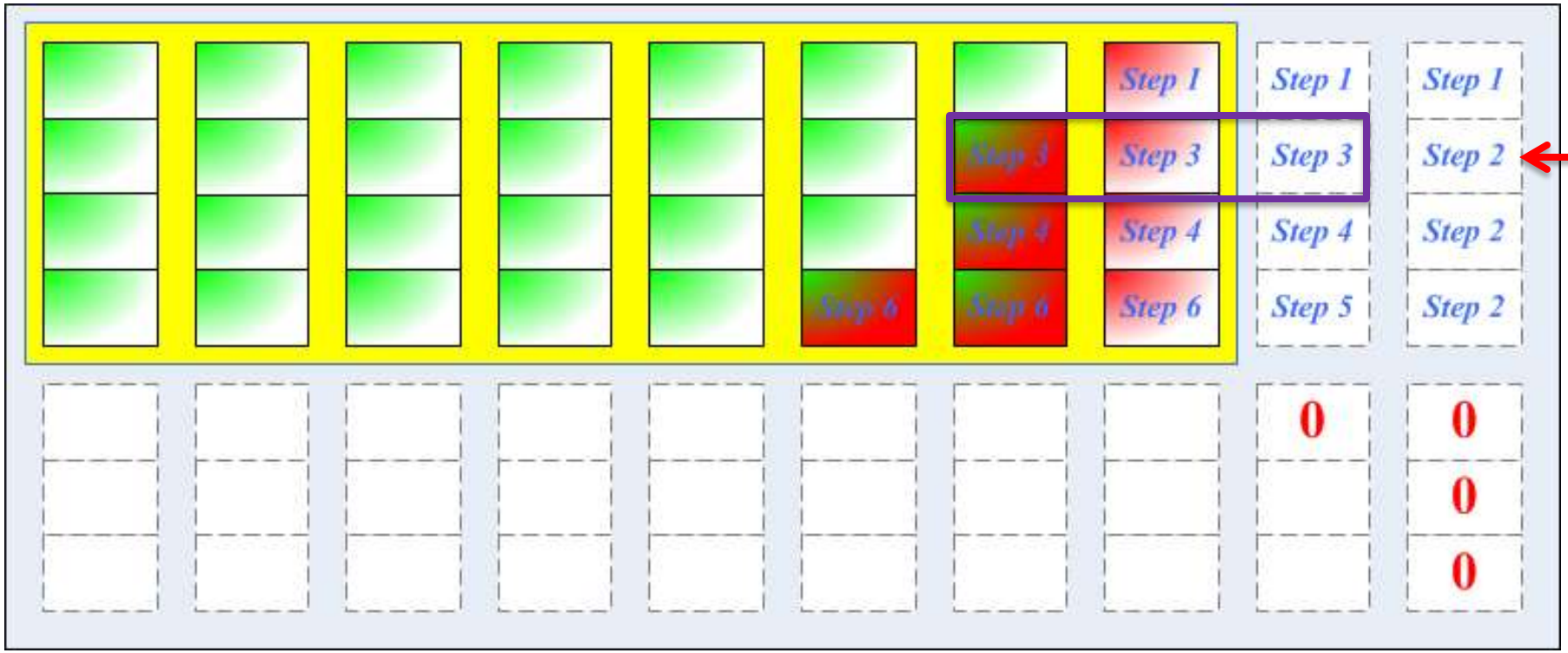

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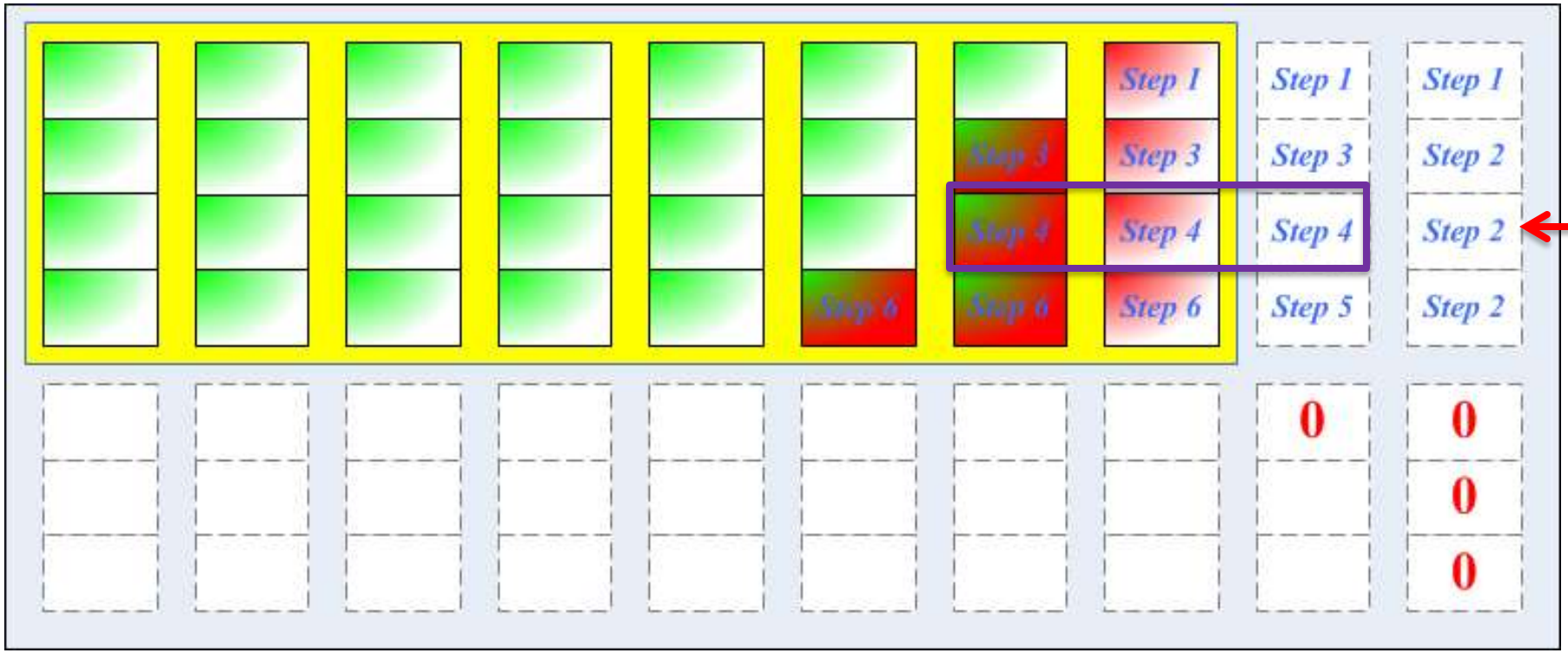

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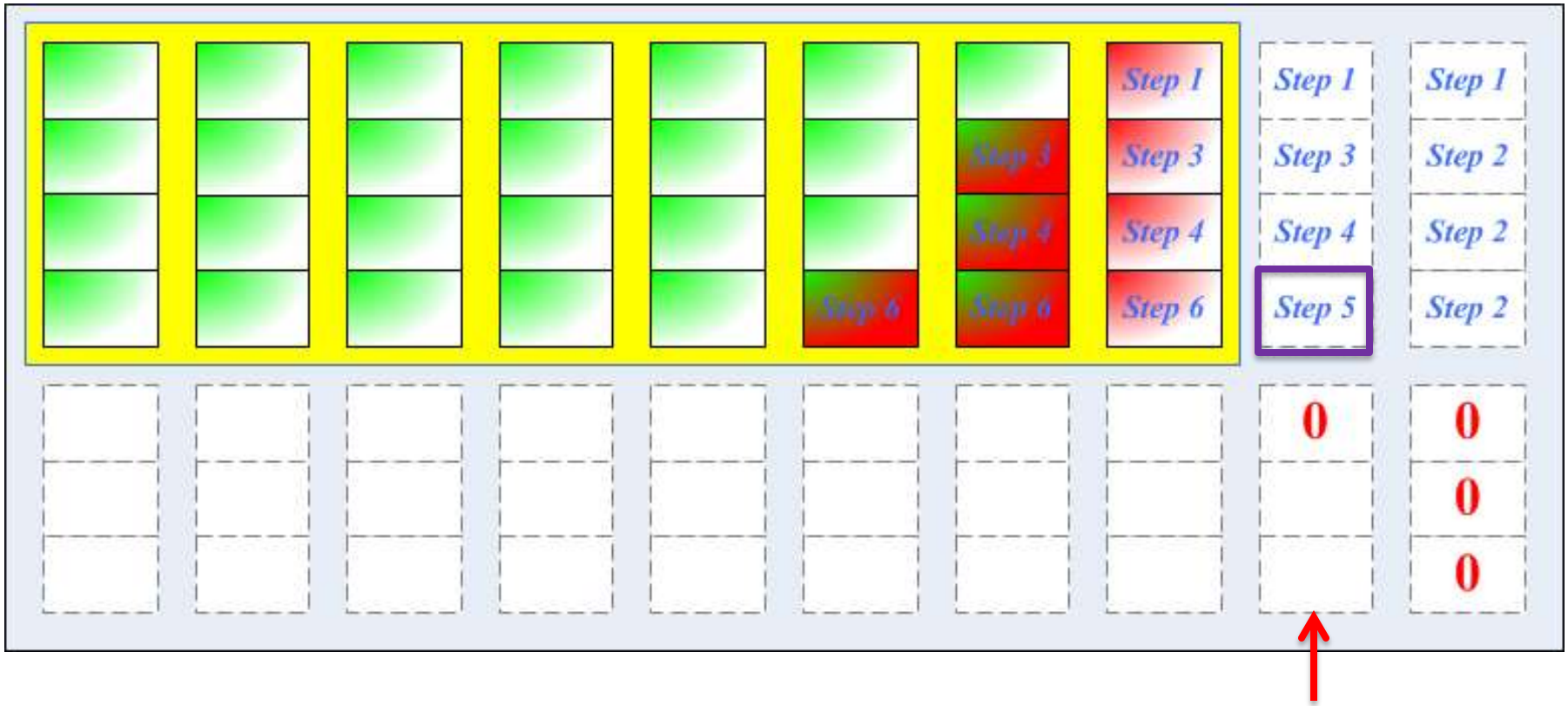

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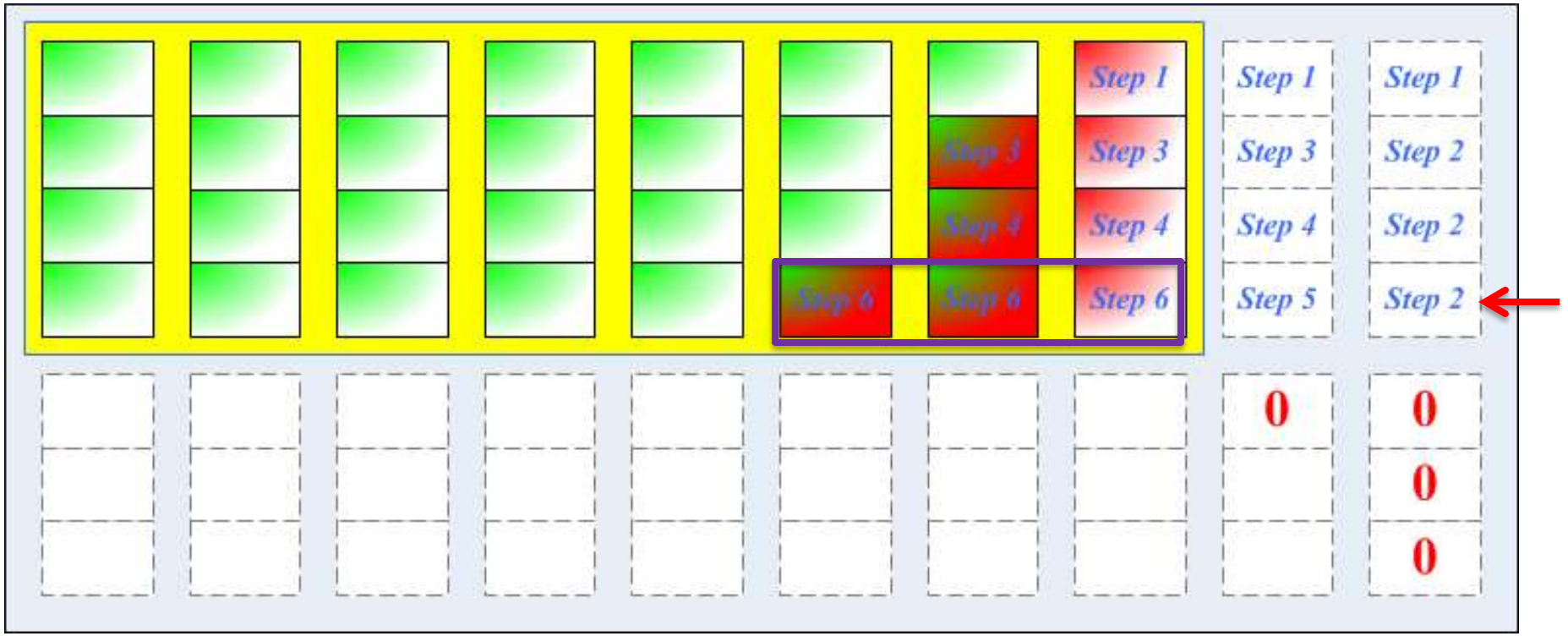
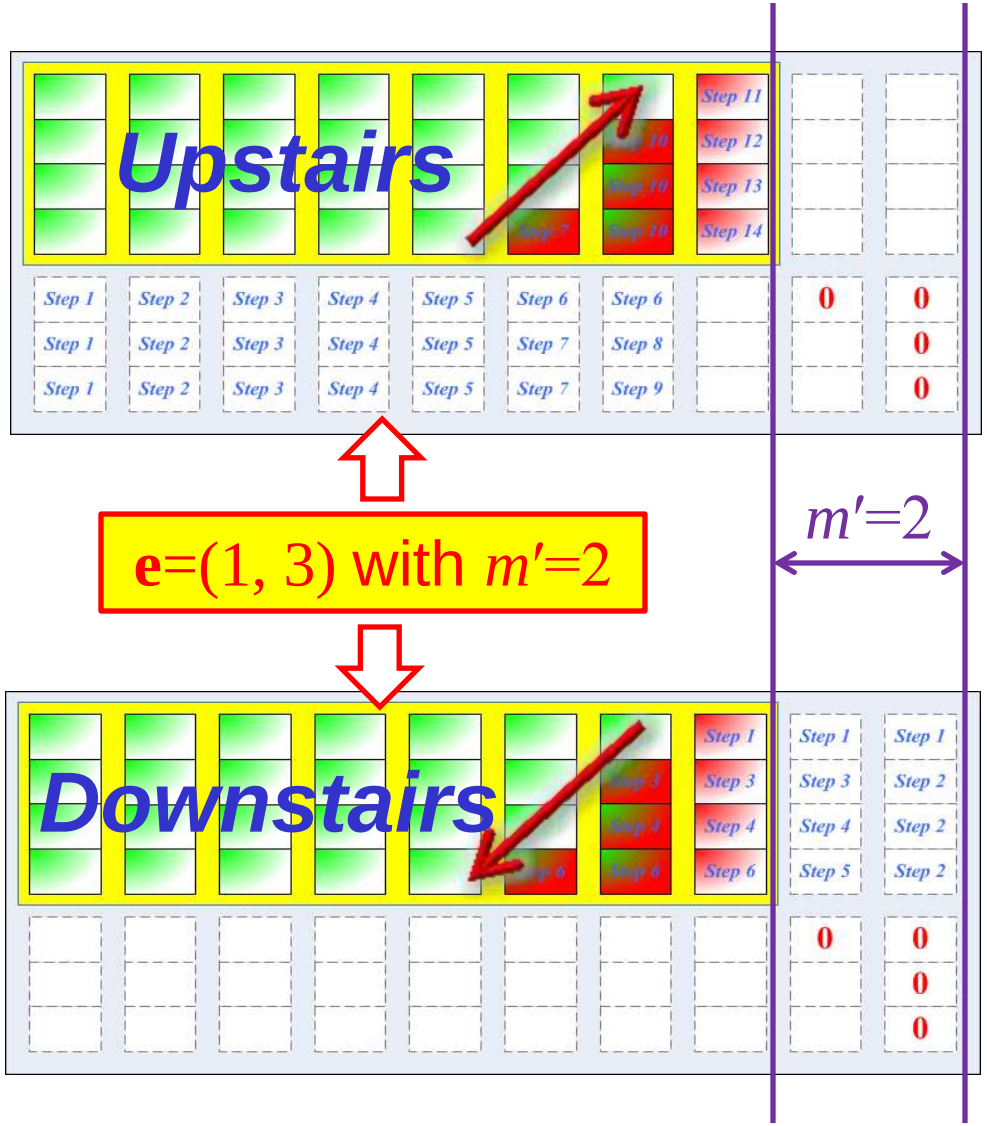


Like upstairs encoding, parity computations reuse previously computed parities

Choosing Encoding Methods



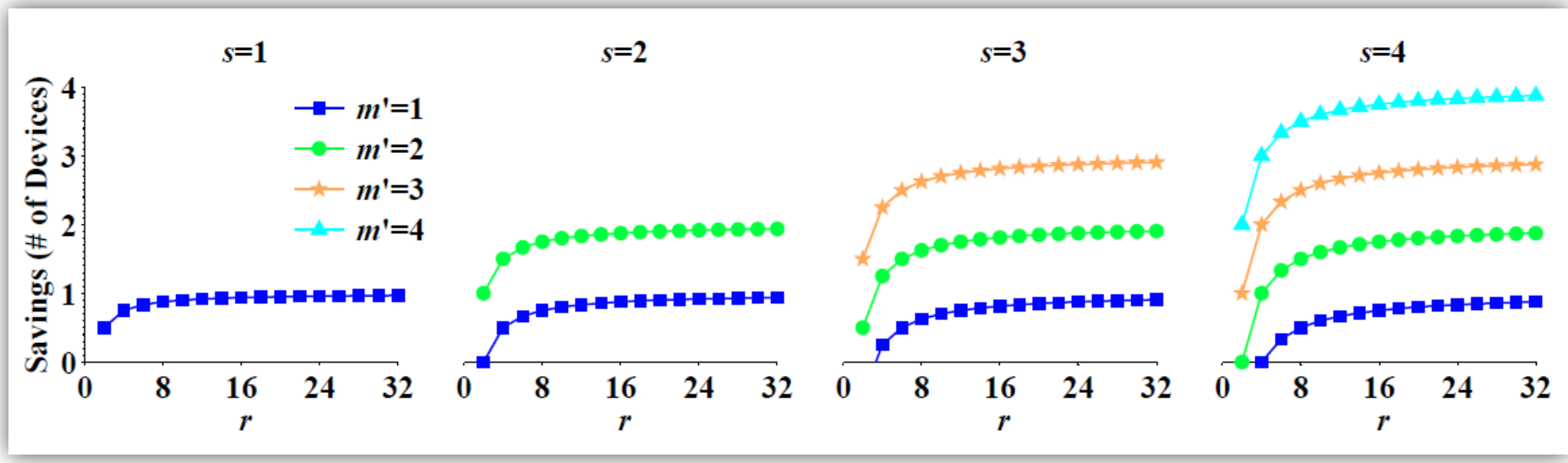
- The two methods are **complementary**
- Intuition:
  - Choose upstairs encoding for large m'
  - Choose downstairs encoding for small m'
- Details in paper

Evaluation

- Implementation
  - Built on libraries Jerasure [Plank, FAST'09] and GF-Complete [Plank, FAST'13]
- Testbed machine:
  - Intel Core i5-3570 CPU 3.40GHz with SSE4.2
- Comparisons with RS codes and SD codes
  - Storage saving
  - Encoding/decoding speeds
  - Update cost

Storage Space Saving

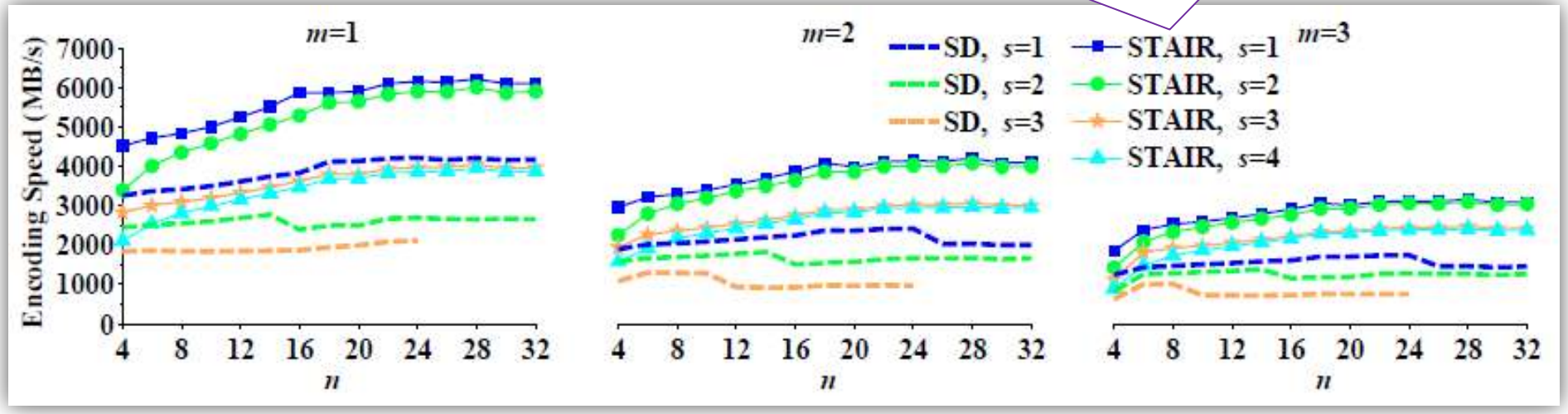
- STAIR codes save $m' - \frac{s}{r}$ devices compared to traditional erasure codes using device-level fault tolerance
  - s = # of tolerable sector failures
  - m' = # of partially failed devices
  - r = chunk size



As r increases, # of devices saved ≈ m'

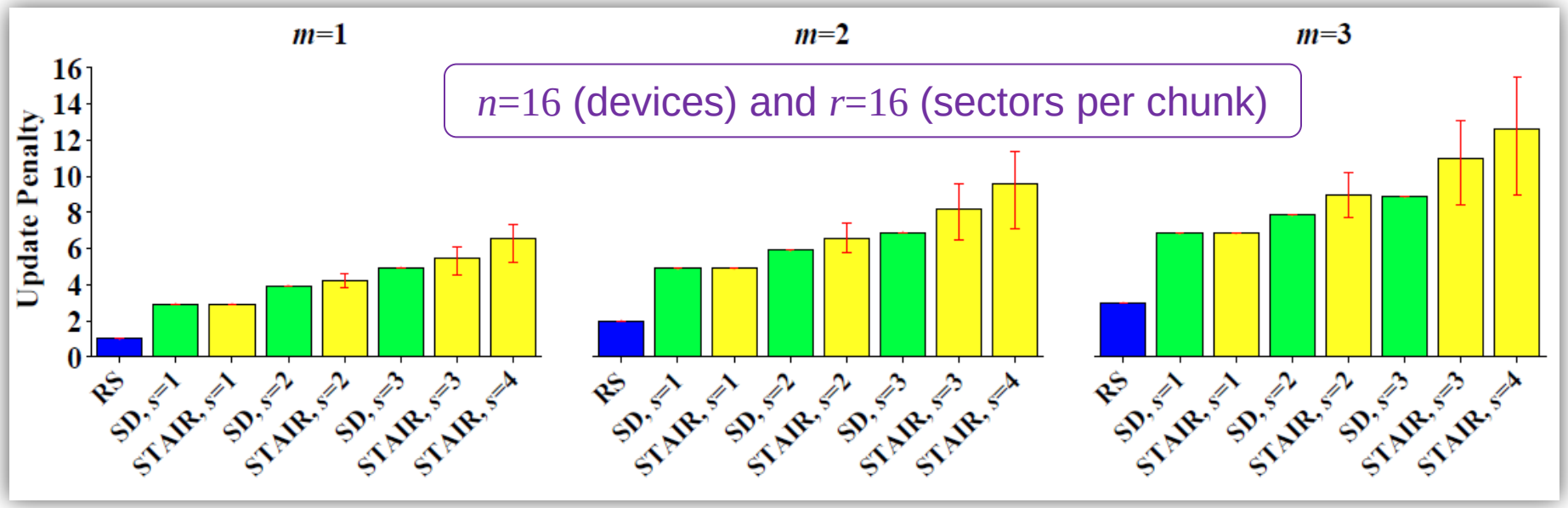
Encoding Speed

n = number of devices
r=16 (sectors per chunk)



- Encoding speed of STAIR codes is on order of **1000MB/s**
- STAIR codes **improve** encoding speed of SD codes **by ~100%**, due to parity reuse
- Similar results for decoding

Update Cost



(Update penalty: average # of updated parity sectors for updating a data sector)

- **Higher update penalty than traditional codes**, due to global parity sectors
- Good for systems with rare updates (e.g., backup) or many full-stripe writes (e.g., SSDs) [*Plank et al., FAST '13, TOS'14*]

Conclusions

- STAIR codes: a general family of erasure codes for tolerating both device and sector failures in a space-efficient manner

- Complementary upstairs encoding and downstairs encoding with improved encoding speed via parity reuse

- Open source STAIR Coding Library (in C):
  - **http://ansrlab.cse.cuhk.edu.hk/software/stair**