SD Codes: Erasure Codes Designed for How Storage Systems Really Fail

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Liberation Codes
Rotated RS Codes
Jerasure

Mario Blaum
(IBM Almaden)

EVENODD Codes
Blaum-Roth Codes
Generalized EO & RDP
PMDS

Jim Hafner
IBM Almaden

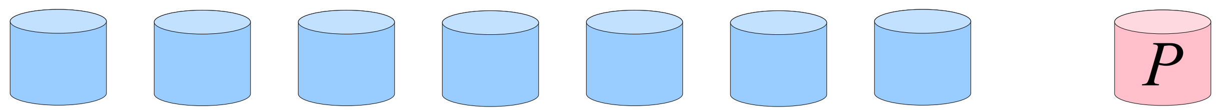
WEAVER Codes
HoVer Codes
REO Engine

Erasure Codes are Everywhere

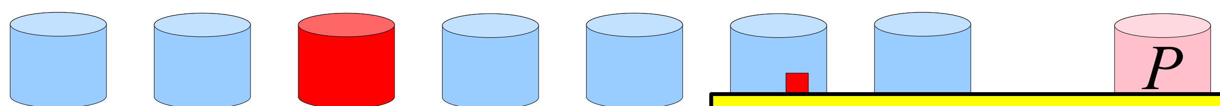
- Commercial systems:
  - From IBM, Microsoft, HP, Netapp, Panasas, EMC, Cleversafe, Amazon, etc...
- Non Commercial Systems:
  - HAIL, Tahoe-LAFS, Pergamum, POTSHARDS, Oceanstore, NC-Cloud, Hydra, etc...
- All employ erasure codes that tolerate more than one disk failure.

The RAID-6 Disconnect

Let's start with a RAID-5 system composed of *n* disks.

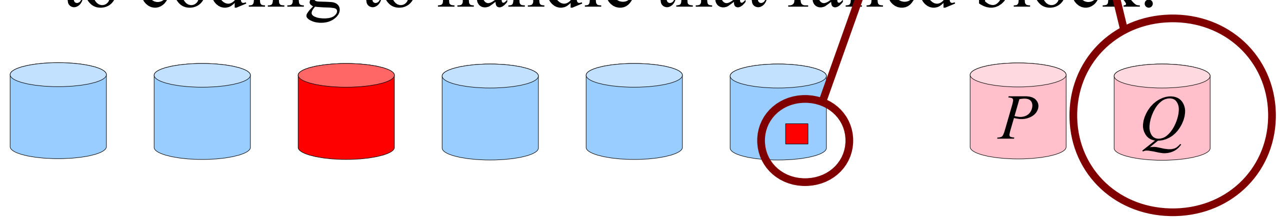


The catastrophic failure mode is a disk failure combined with a latent sector failure.



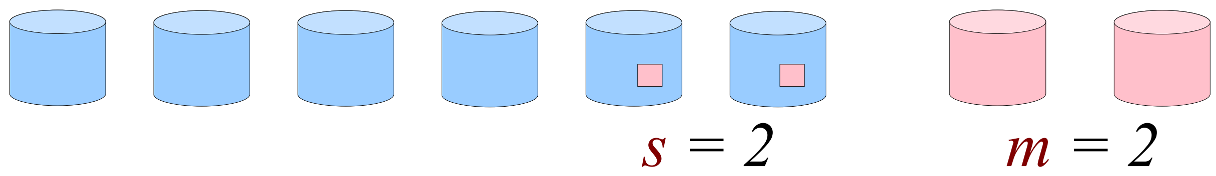
This seems wasteful.

The RAID-6 solution dedicates an entire extra disk to coding to handle that failed block.

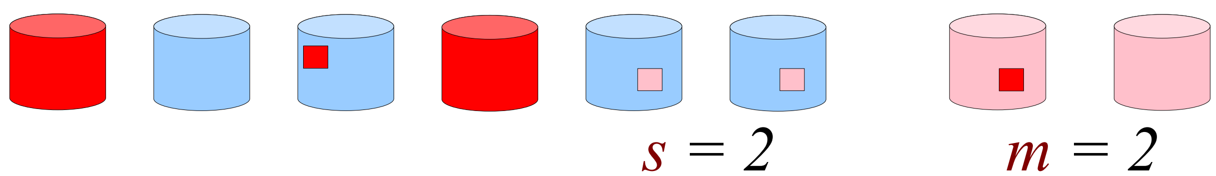


The SD Code Methodology

Dedicate *m* disks and *s* sectors per stripe to coding.

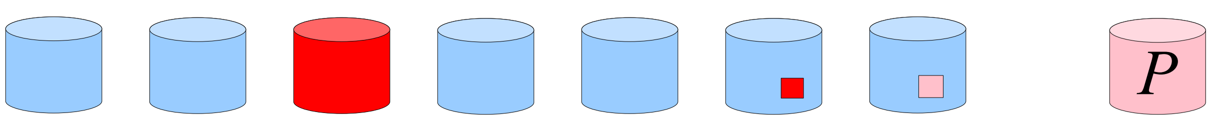


Tolerates the failure of any *m* disks and *s* sectors.



Thus, storage costs match failure modes.

Fixes the RAID-6 disconnect (*m=1, s=1*):

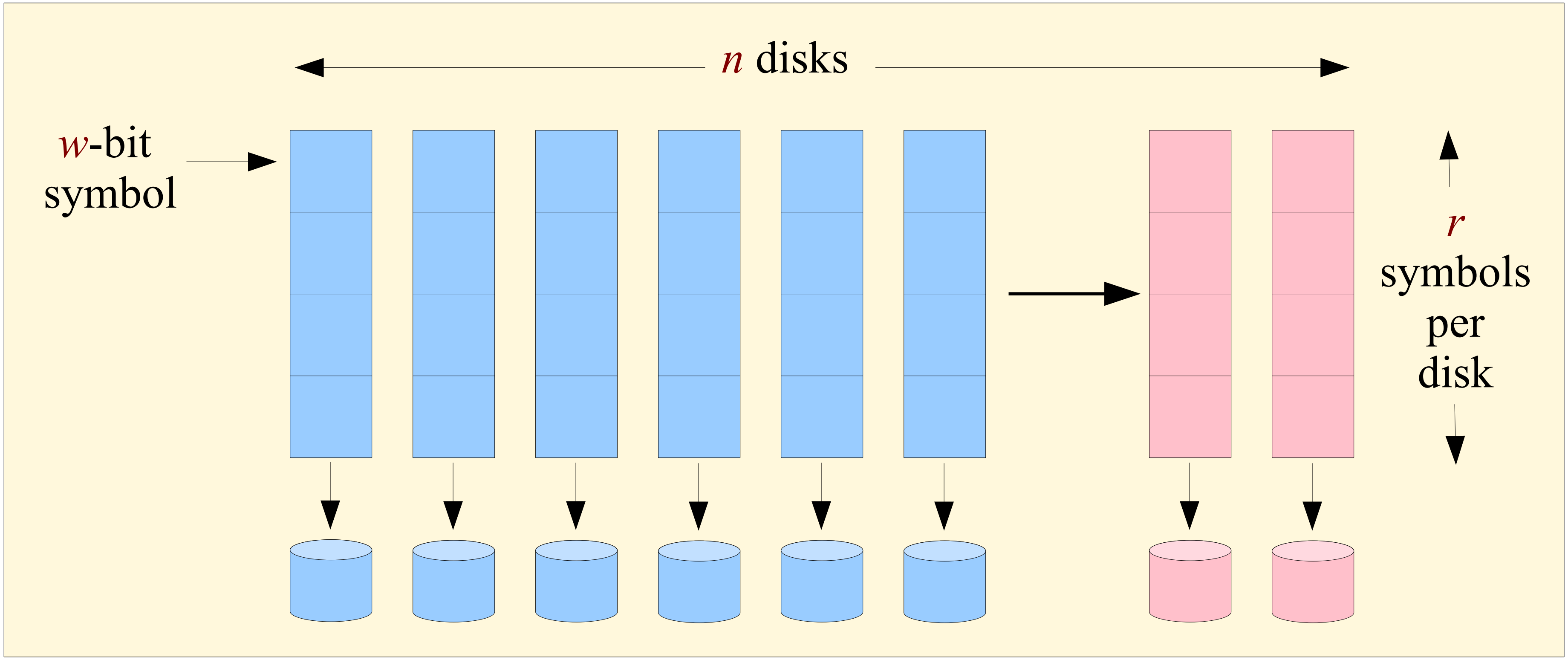


In This Talk

- Detail the SD methodology in FAST language.
  - How it works.
  - Constructions.
  - Performance (theoretical & actual).
  - Open source support.
  - Related work.

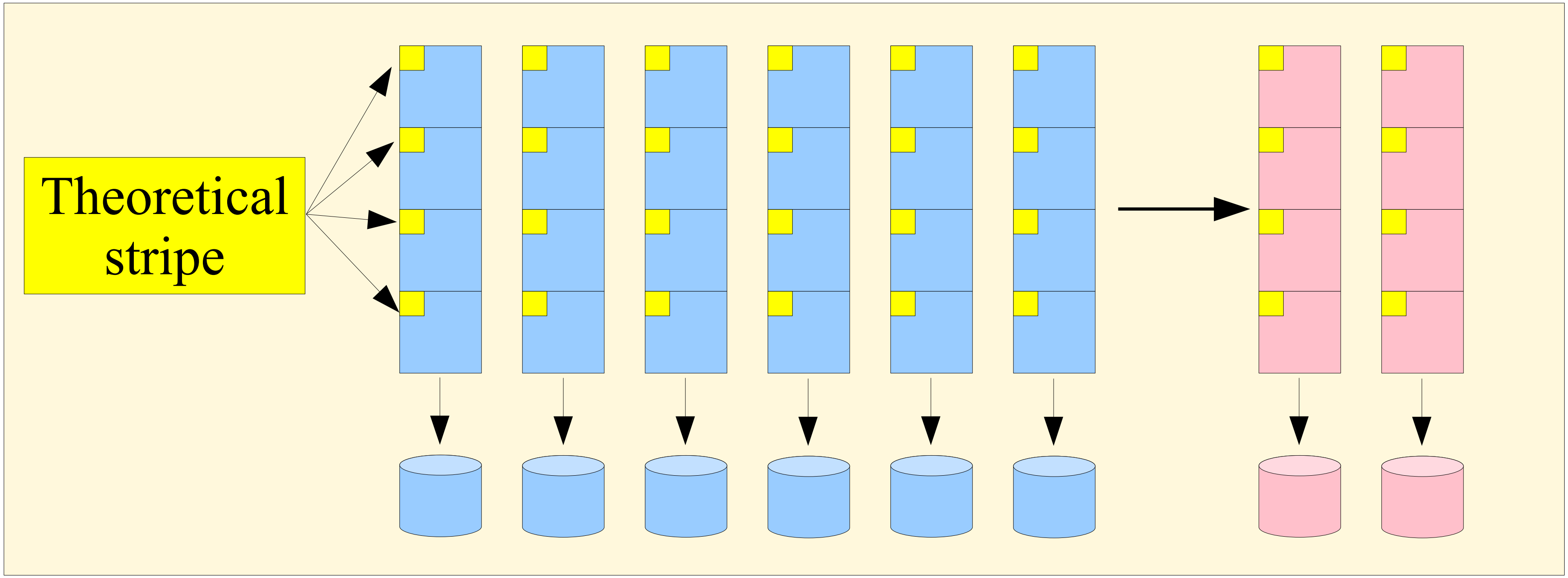
Two Views of a "Stripe"

- The Theoretical View:
  - Disks hold *w*-bit symbols rather than sectors.
  - Precisely: *r* symbols from each of *n* disks:



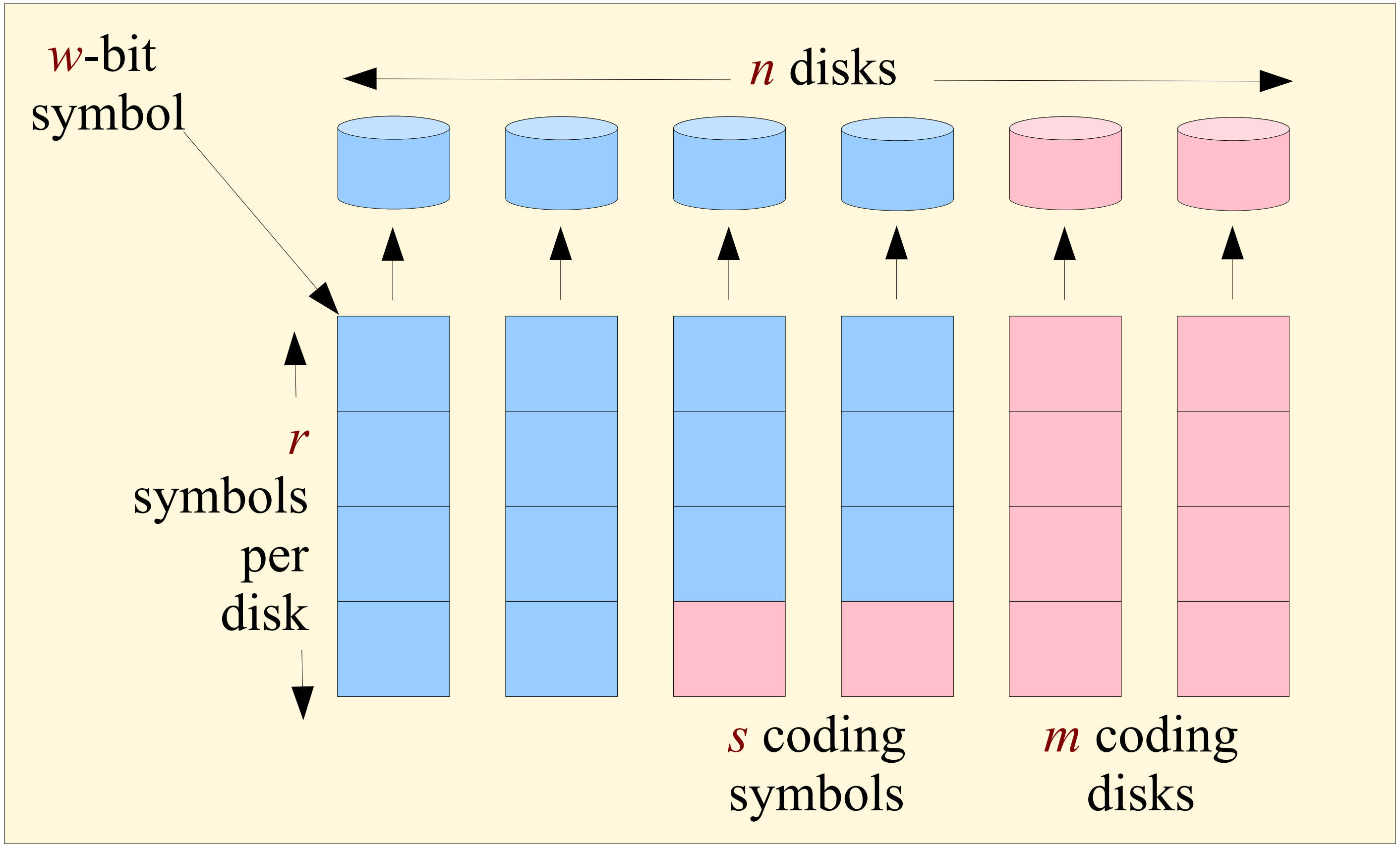
Two Views of a "Stripe"

- The Systems View:
  - Disks hold sectors/blocks rather than symbols.
  - Groups together theoretical stripes for performance.



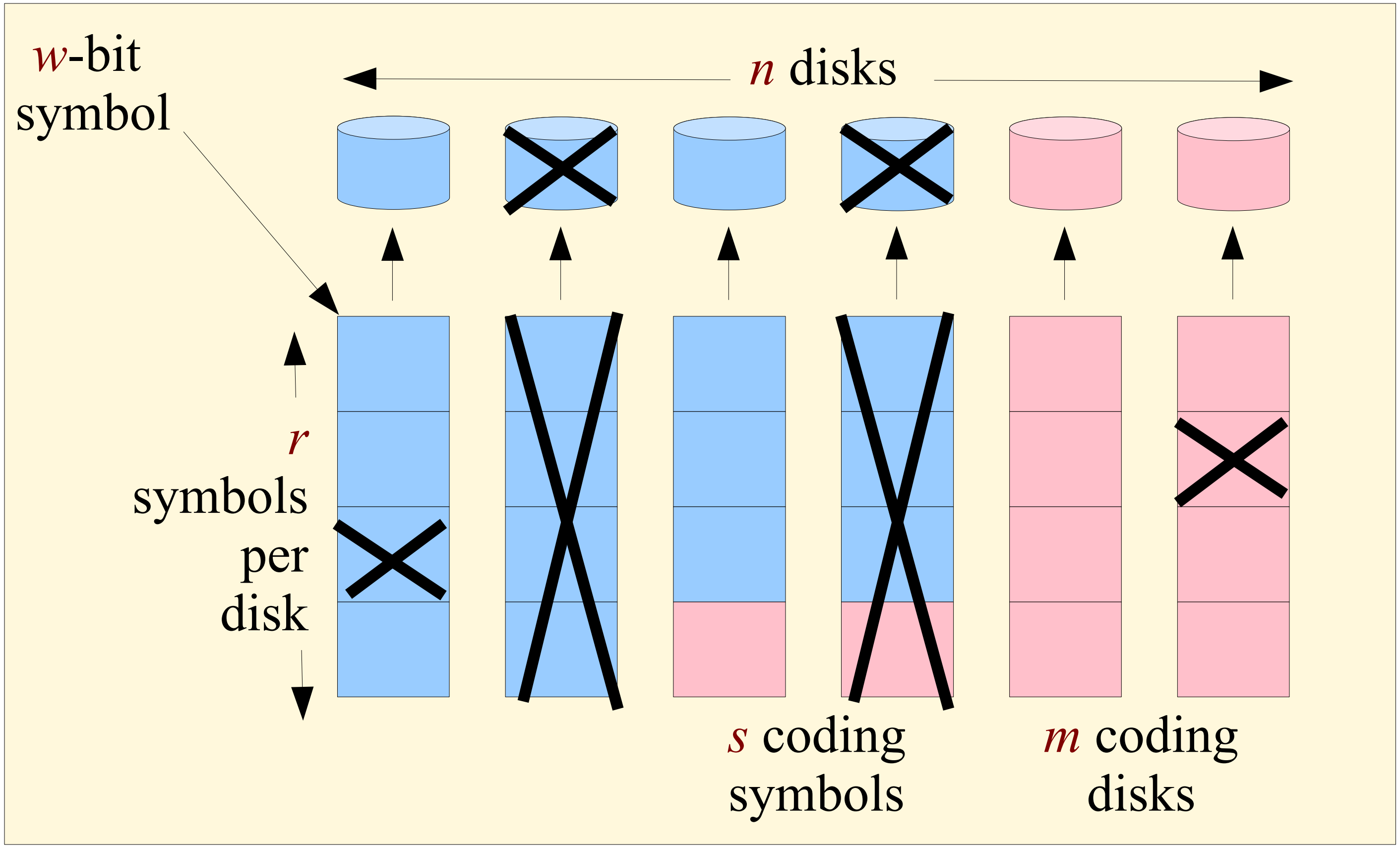
Presentation of SD Codes

- Uses the Theoretical view to define the code.
- With the understanding that you map it to the systems view when you implement it.



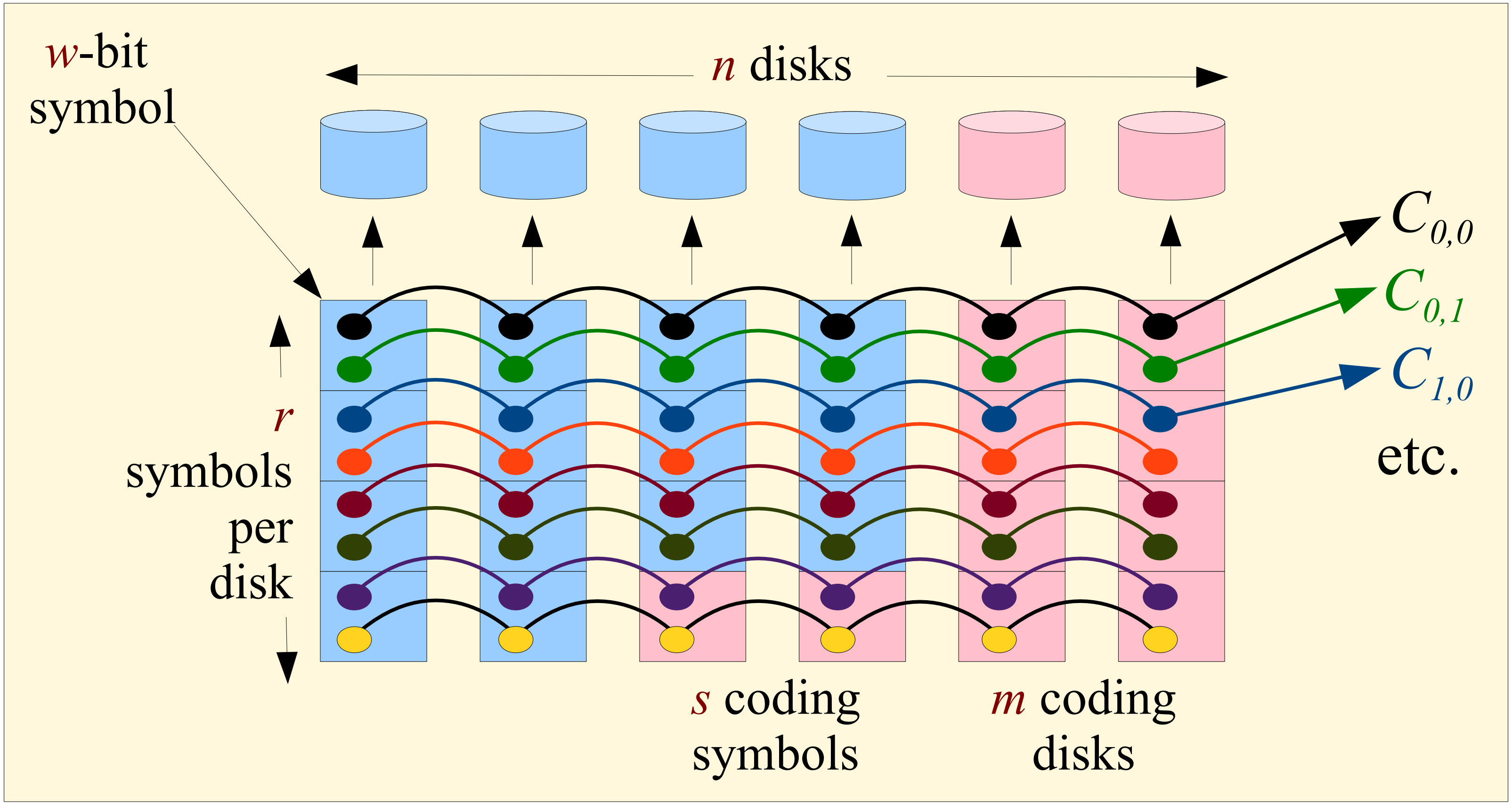
Presentation of SD Codes

- The goal is to tolerate any *m* disk failures, coupled with any additional *s* block failures.



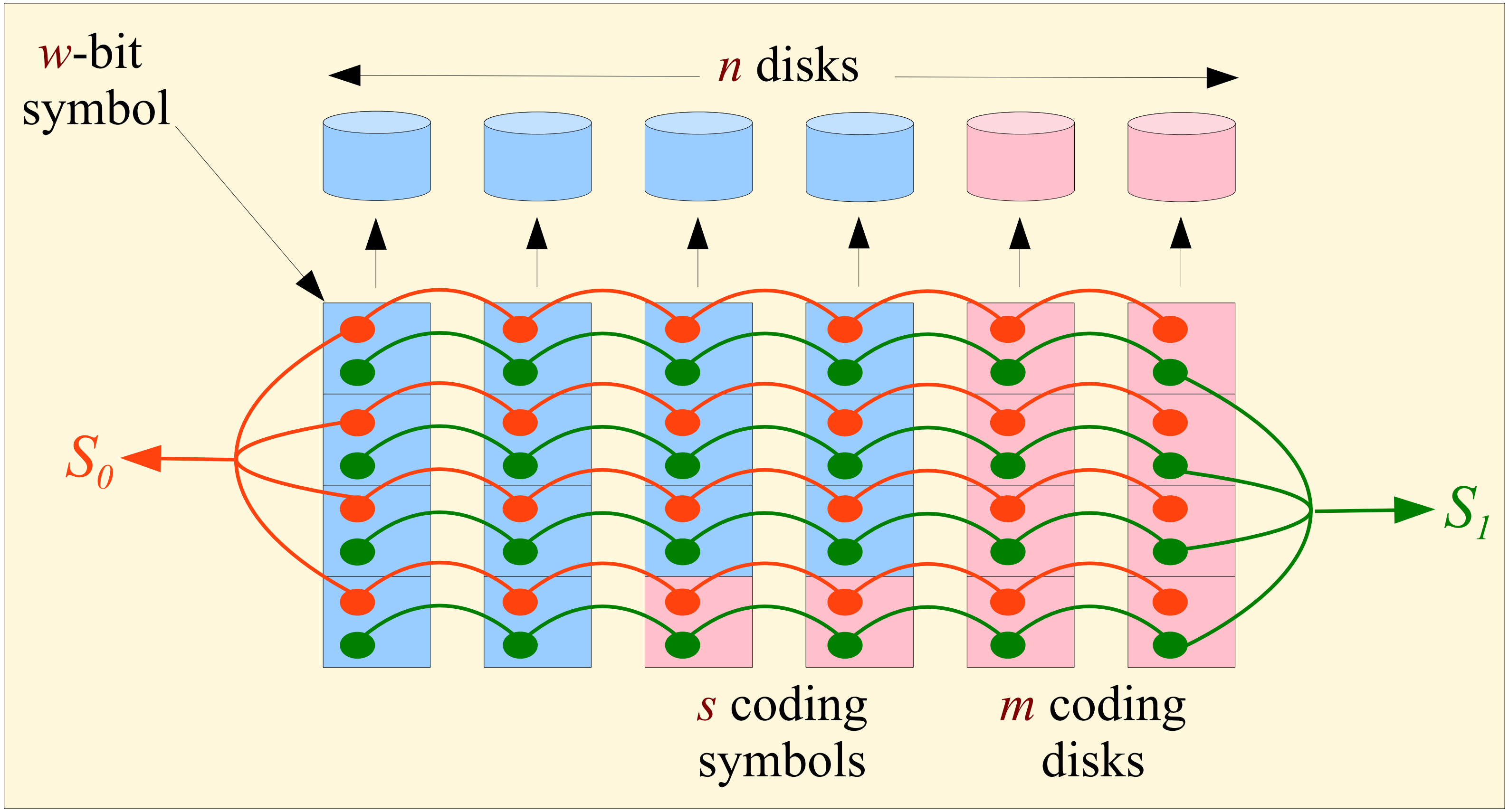
Code Definition

- There are *mr* separate coding equations that involve only rows of the stripes: $C_{i,j}$



Code Definition

- Plus *s* more equations that involve all of the symbols in the stripe: S_x



Code Def nition

- All arithmetic is in a Galois Field *GF(2^w)*
  - Just like Reed-Solomon coding
  - Open source libraries (See Friday's Talk)
  - Larger *w* are slower.
  - But larger *w* yield more codes with the SD property.
- Each equation governed by a different coefficient a_i.

Example: $n=6,\ m=2,\ s=2,\ r=4,\ a_i = 2^i$

Each $C_{i,j}$ equation is the sum of exactly n terms, partitioned by rows.

$$1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \;\circleddash\!\!\rightarrow 0 \qquad C_{0,0}$$

$$1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \;\circleddash\!\!\rightarrow 0 \qquad C_{1,0}$$

$$1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \;\circleddash\!\!\rightarrow 0 \qquad C_{2,0}$$

$$1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \oplus 1 \;\circleddash\!\!\rightarrow 0 \qquad C_{3,0}$$

$$1 \oplus 2 \oplus 2^2 \oplus 2^3 \oplus 2^4 \oplus 2^5 \;\circleddash\!\!\rightarrow 0 \qquad C_{0,1}$$

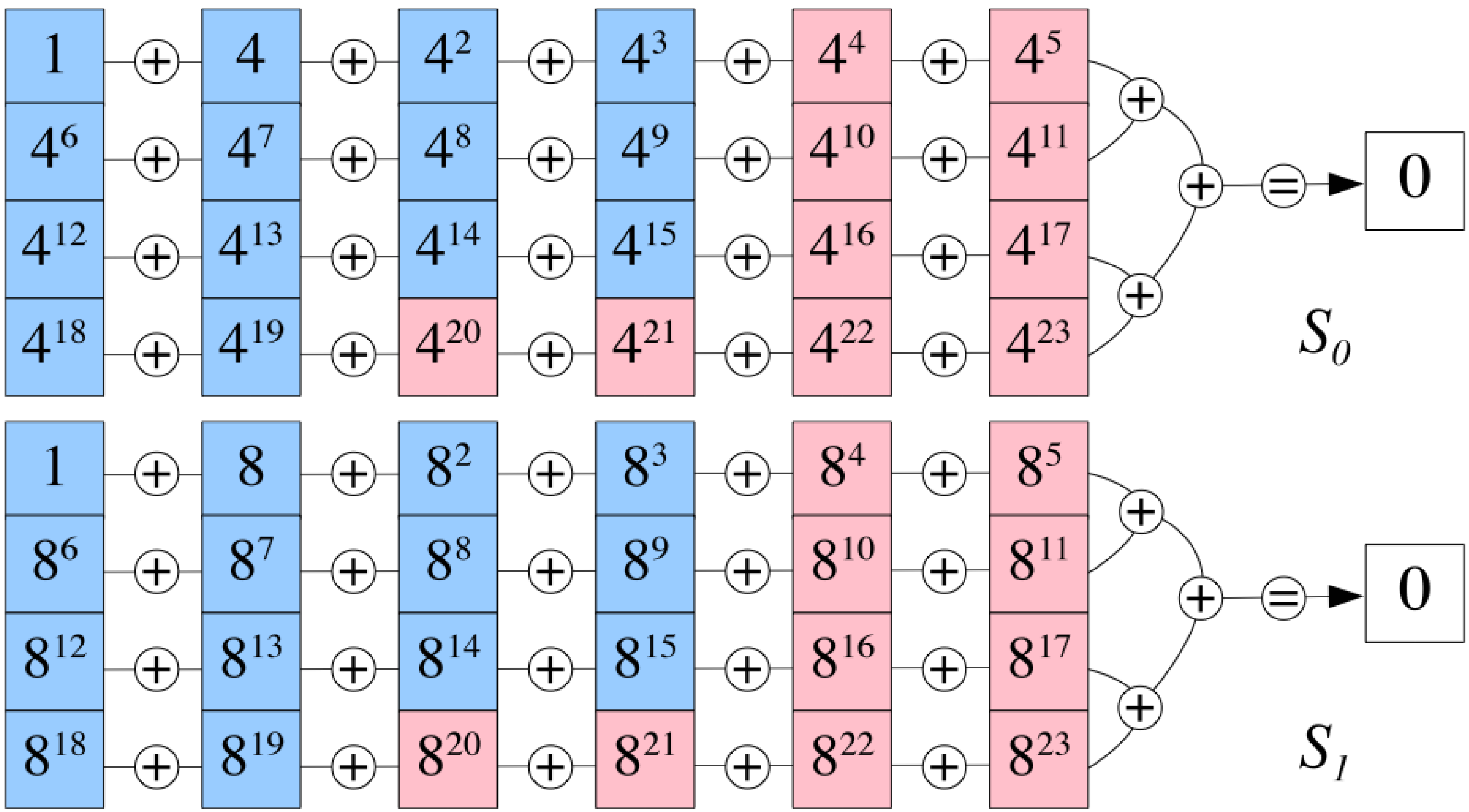
$$2^6 \oplus 2^7 \oplus 2^8 \oplus 2^9 \oplus 2^{10} \oplus 2^{11} \;\circleddash\!\!\rightarrow 0 \qquad C_{1,1}$$

$$2^{12} \oplus 2^{13} \oplus 2^{14} \oplus 2^{15} \oplus 2^{16} \oplus 2^{17} \;\circleddash\!\!\rightarrow 0 \qquad C_{2,1}$$

$$2^{18} \oplus 2^{19} \oplus 2^{20} \oplus 2^{21} \oplus 2^{22} \oplus 2^{23} \;\circleddash\!\!\rightarrow 0 \qquad C_{3,1}$$

Example: $n=6,\ m=2,\ s=2,\ r=4,\ a_i = 2^i$

Each S_x equation is the sum of all *nr* terms.



Decoding

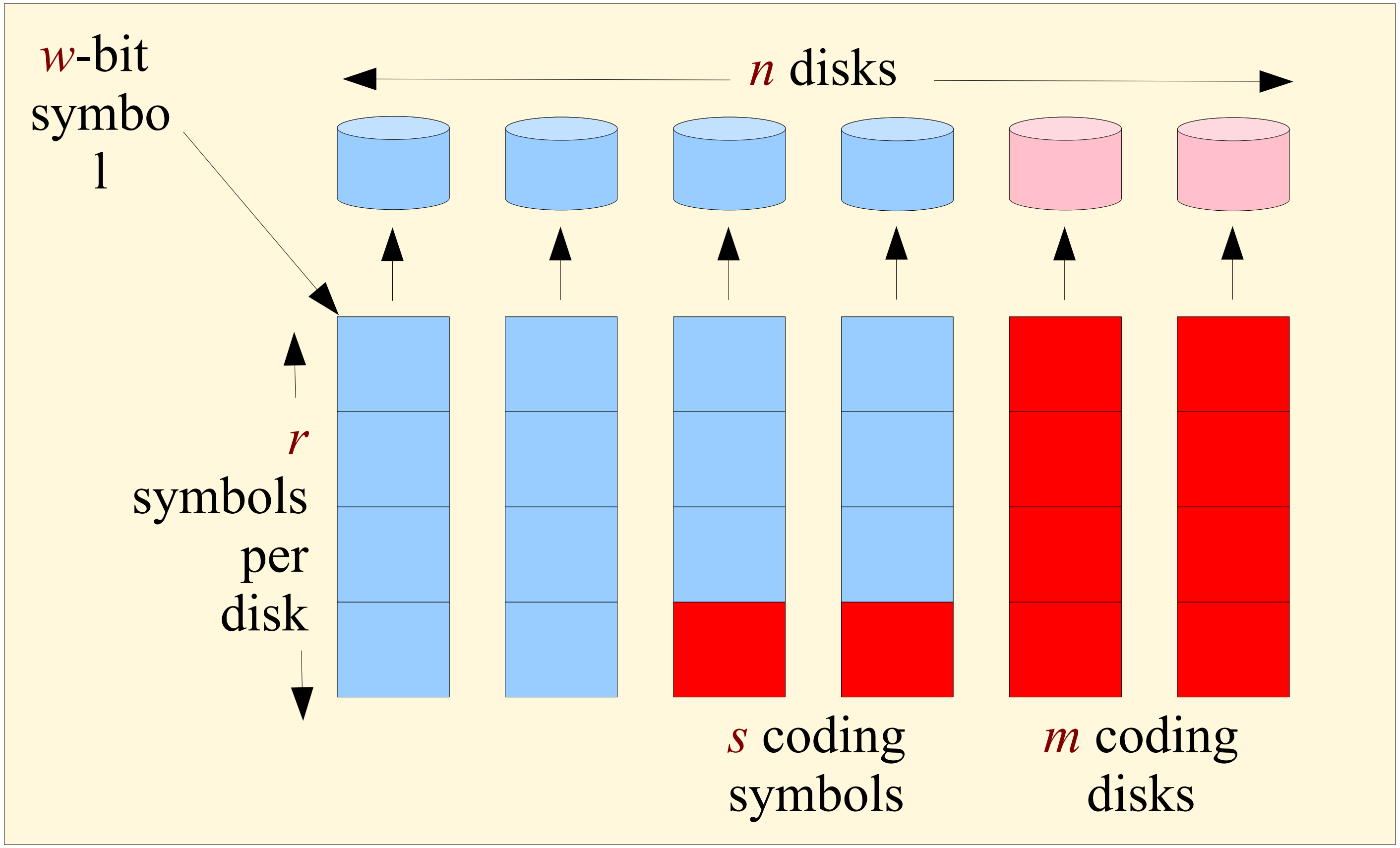
- Recall that there are *mr+s* equations.
- When *m* disks and *s* sectors fail, you lose *mr+s* symbols in the stripe.
- That gives you:

mr+s equations with *mr+s* unknowns.

- Use standard algebra to solve.
- (We went over this in yesterday's tutorial.)

Encoding

- It's just a special case of decoding.
- For that reason, the location of the coding symbols is really arbitrary.



SD Code Constructions

- Given *n, m, s* and *r*.
- Our goal is to find *m+s* coefficients a_i such that every combination of *m* disk and *s* sector failures may be tolerated in $GF(2^w)$, where:
  - *w* = 8 is preferred (because it's fastest),
  - Then *w* = 16,
  - Then *w* = 32.

SD Code Constructions

- When $a_i = 2^i$, we have some theory, which allows us to test a stricter, PMDS condition.
  - We call this the "Main Construction."
- Otherwise, we simply test all failure scenarios.

$$\binom{n}{m}\binom{r(n-m)}{s} \text{ of these.}$$

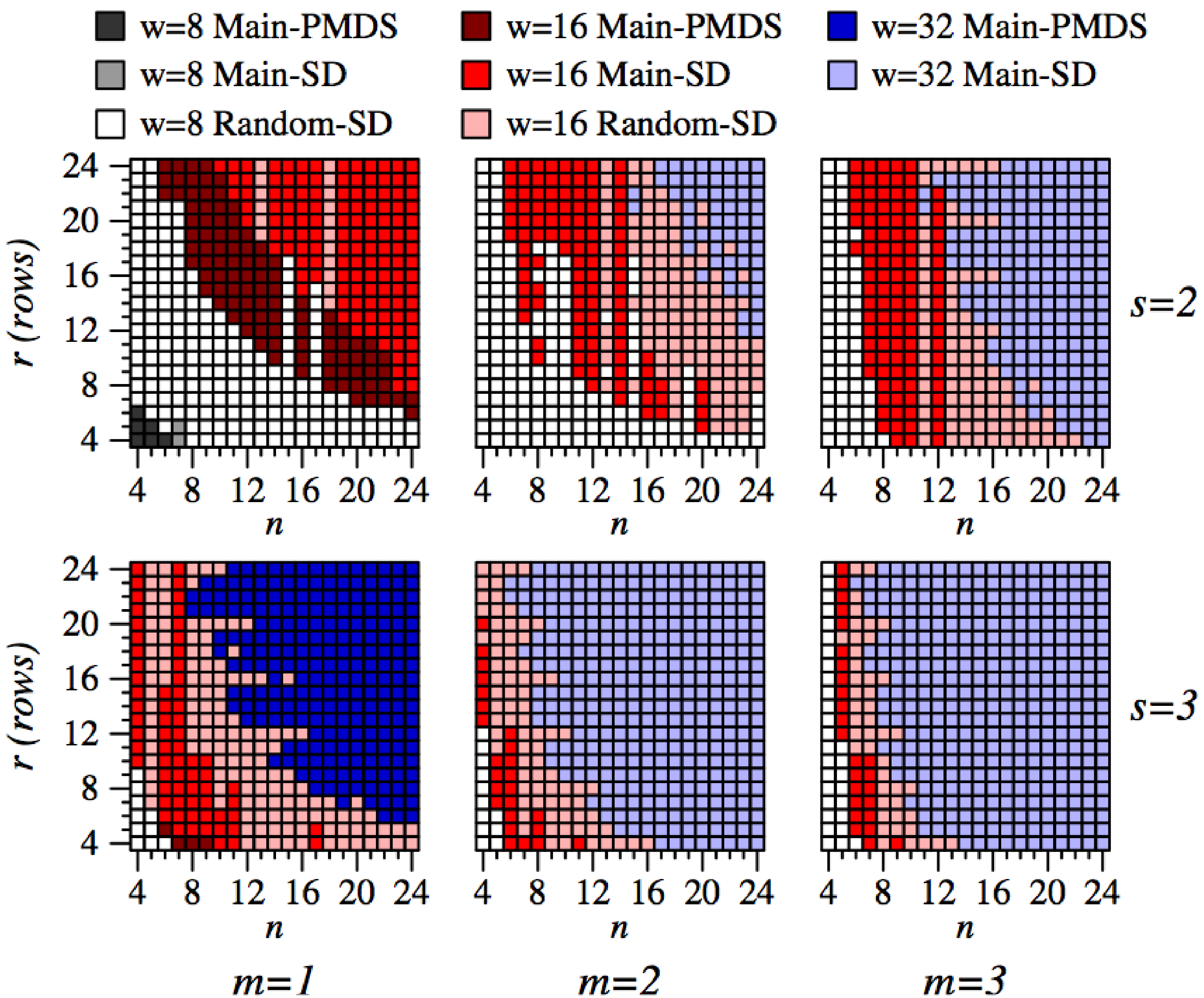
- Do it with brute-force enumeration.
  - (I made it a lab in my CS302 Algorithms course)

SD Code Constructions

- When $m = 1$ and $s = 1$, the main construction is PMDS (therefore SD) when $n \le 2^w$.
  - This is the RAID-6 replacement.
  - $w = 8$ handles 256-disk systems.
- When $m > 1$ and $s = 1$, the main construction is PMDS (therefore SD) when $nr \le 2^w$.

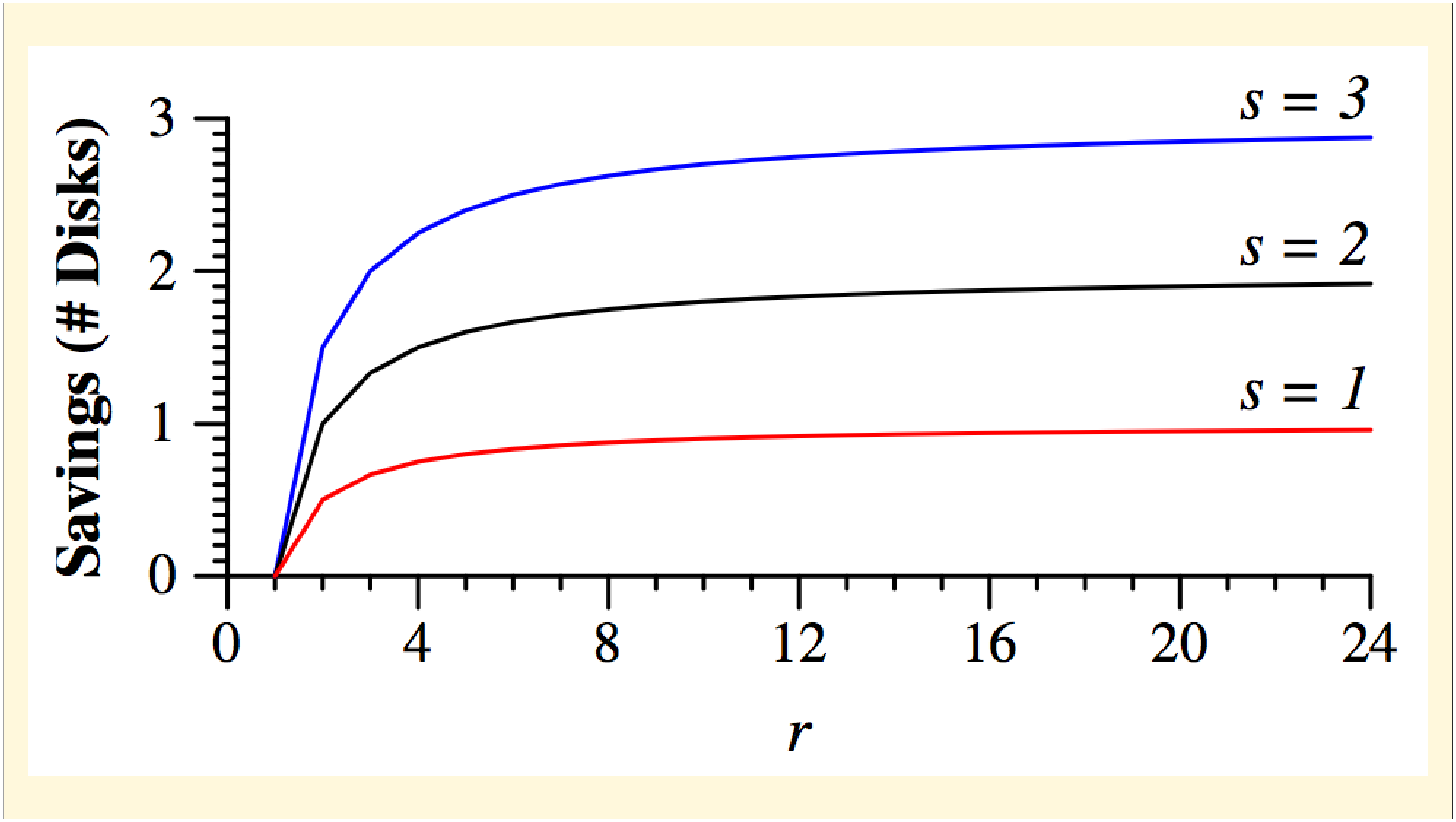
Otherwise...

They exist, but not in any general form.



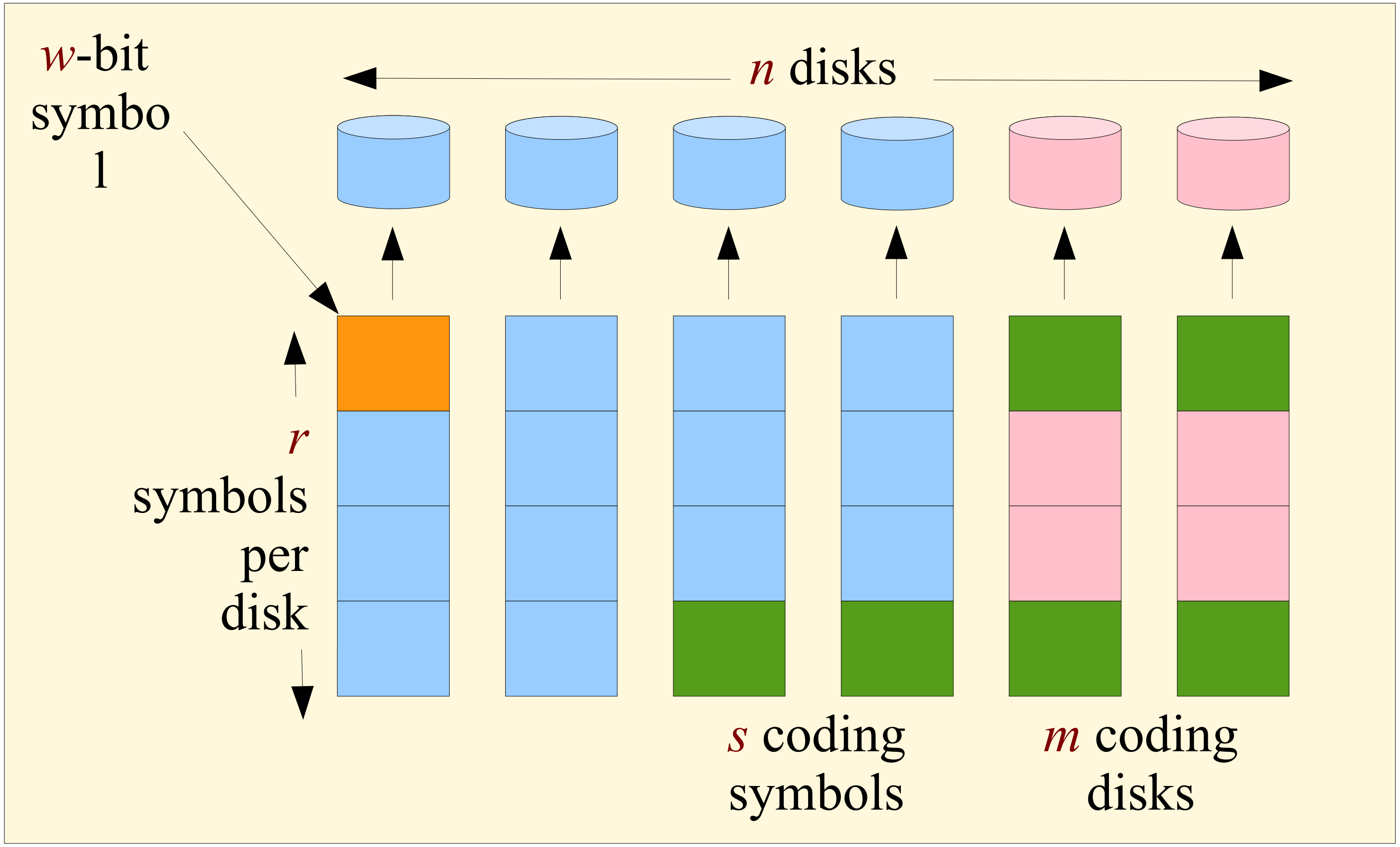
Properties: Storage Overhead

- Pretty obvious, but also pretty drastic.



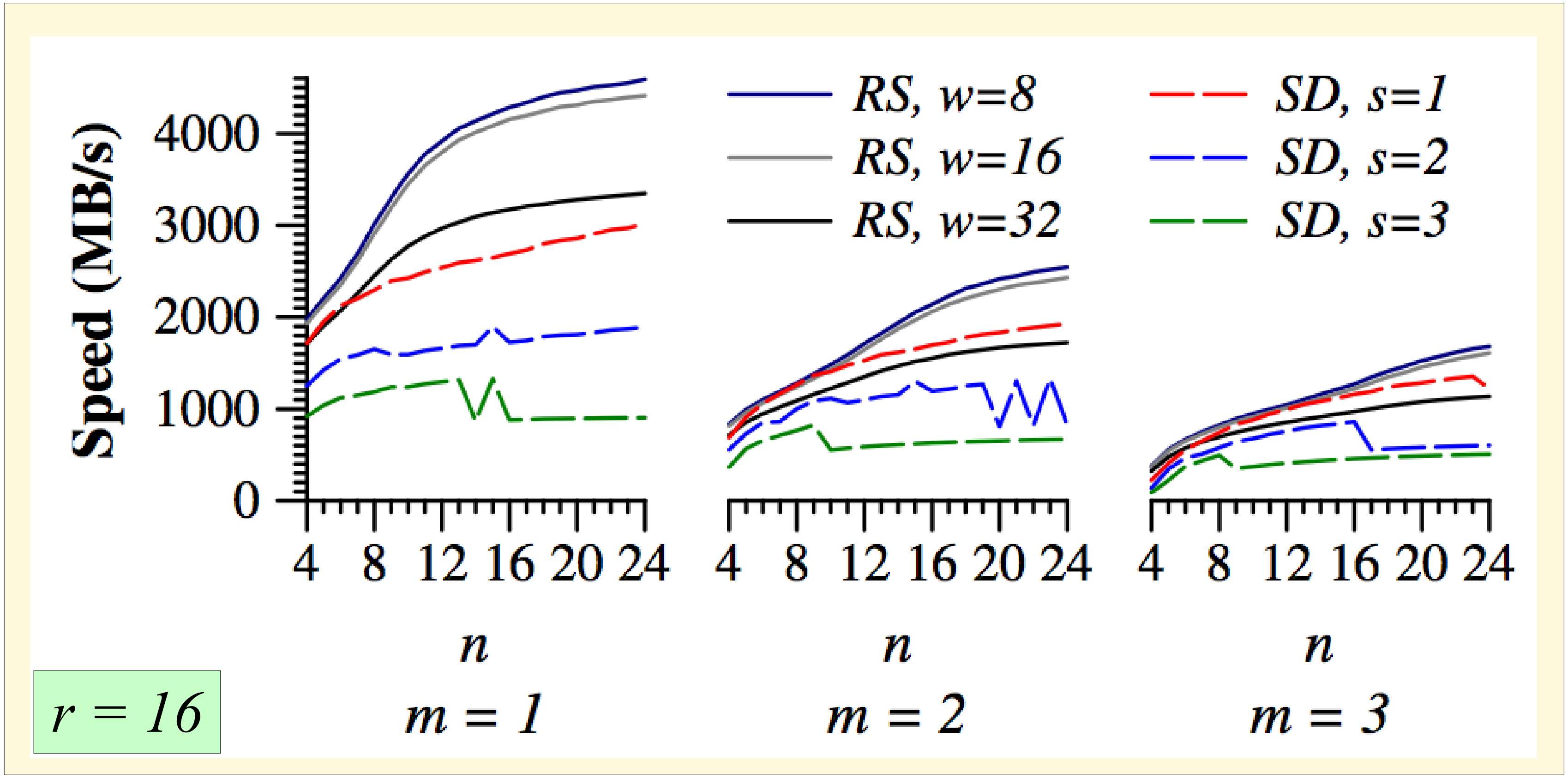
Properties: Update Penalty

- Roughly *2m+s* – not too good.
- Applicable to cloud/log-based systems.



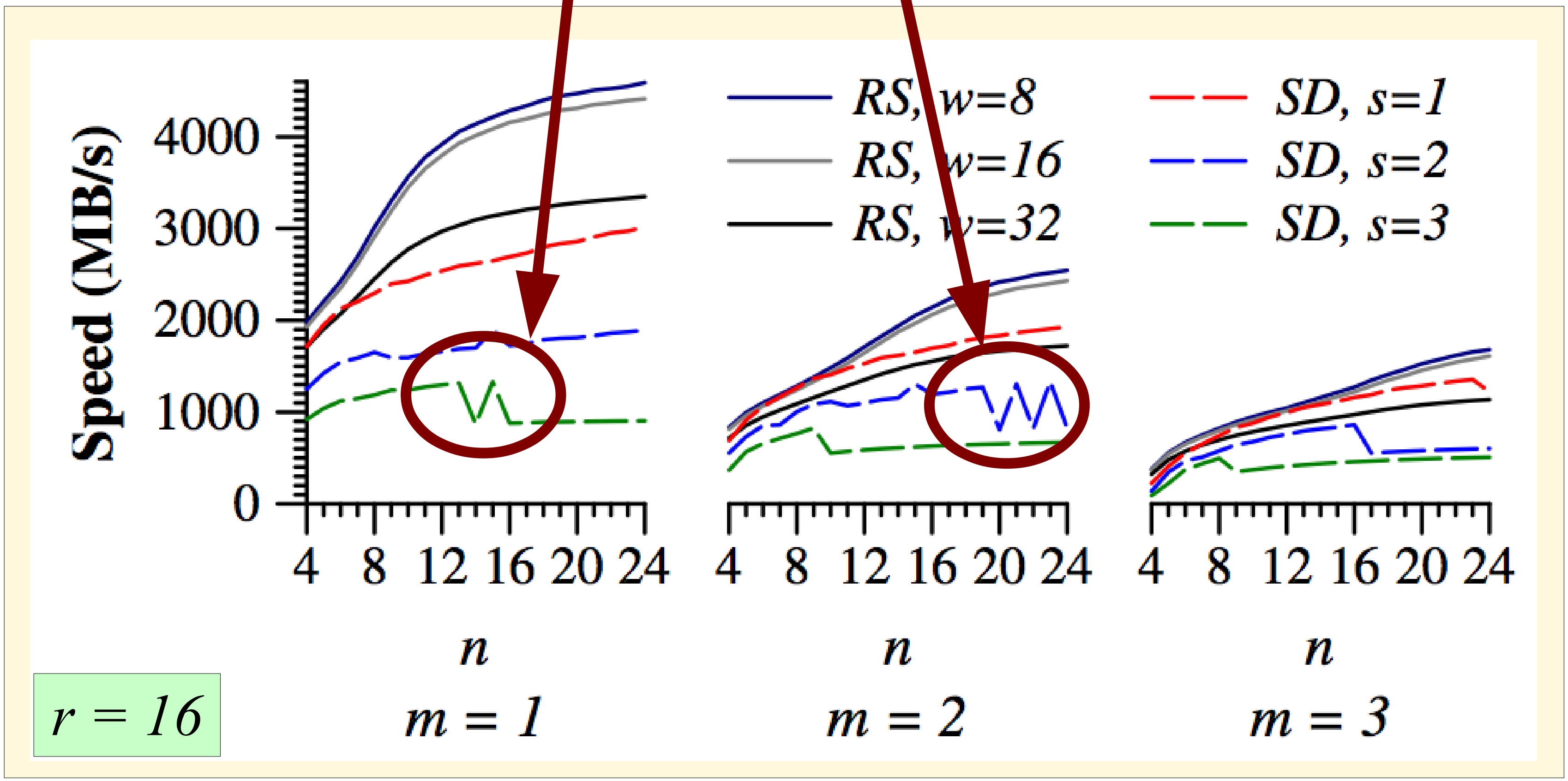
Properties: Encoding Speed

- 32M stripes. Intel Core i7, 3.02 GHz.
- Using SSE for GF Arithmetic (Friday)



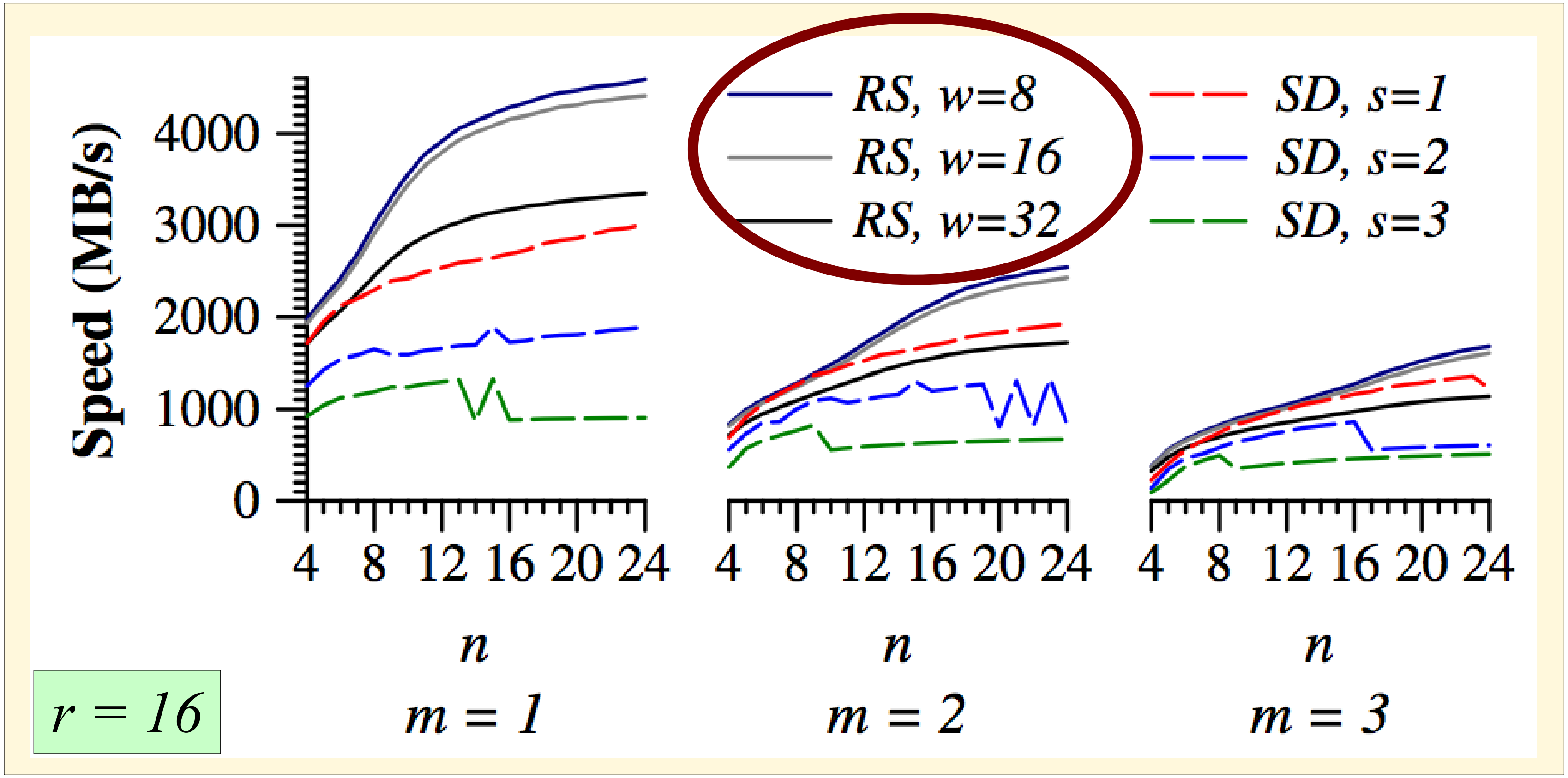
Properties: Encoding Speed

Jagged lines are when you switch between values of *w*.



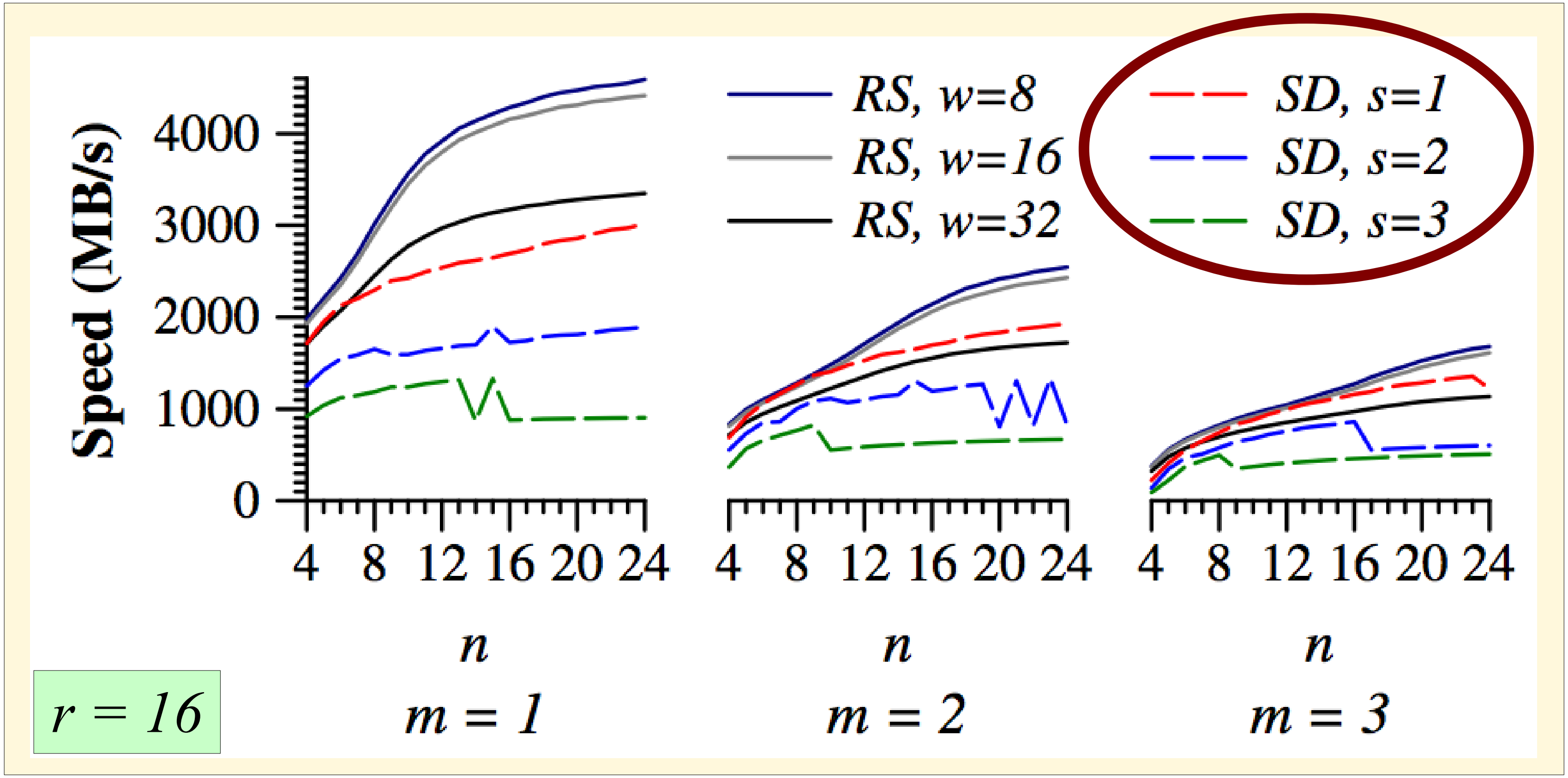
Properties: Decoding Speed

Up to *m* failures per row equals Reed-Solomon Speed



Properties: Decoding Speed

For maximum failures, decoding speed equals encoding speed.

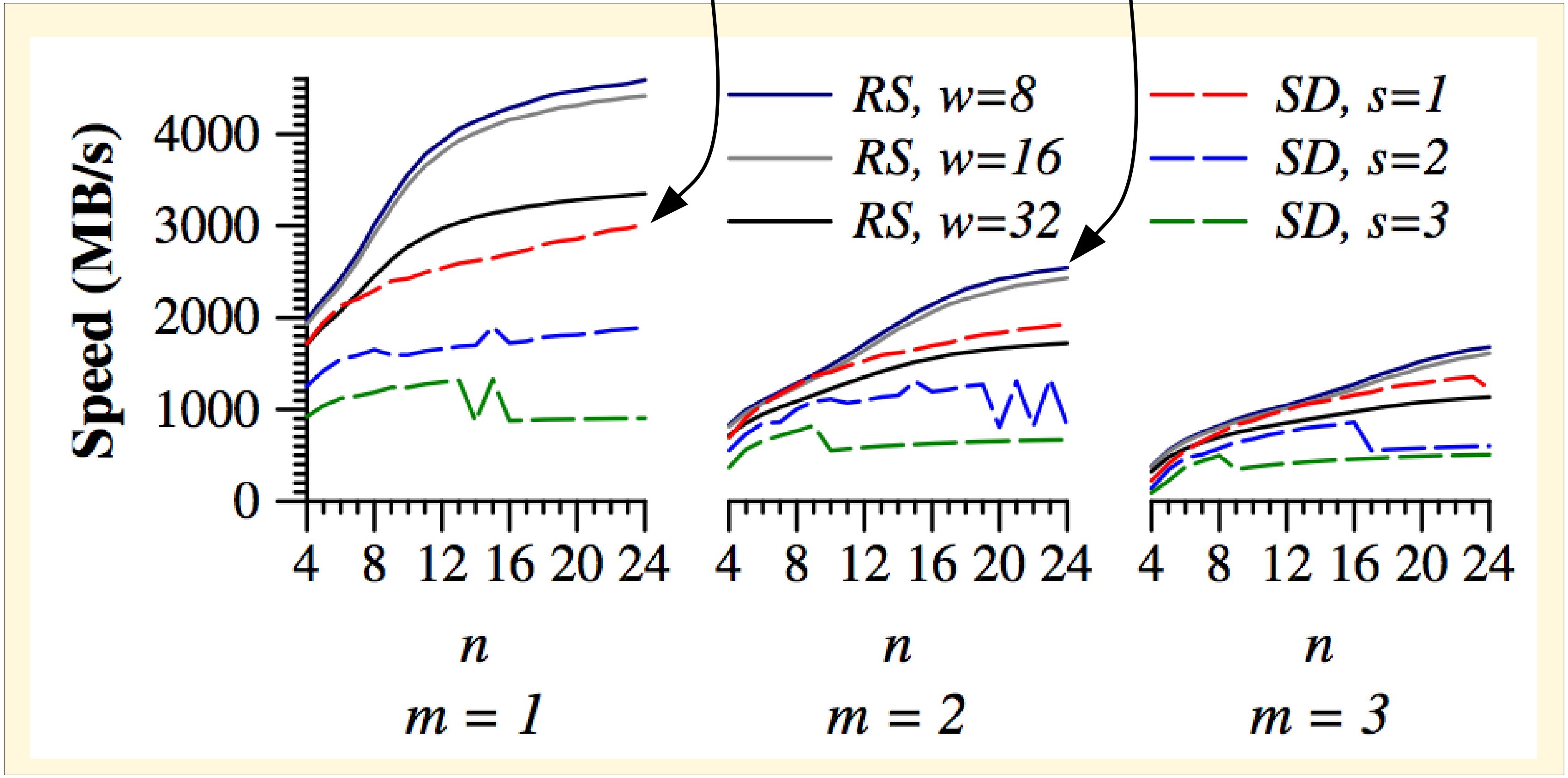


Bottom line

Sure, it's slower than RS coding, but its faster than using extra coding disks.

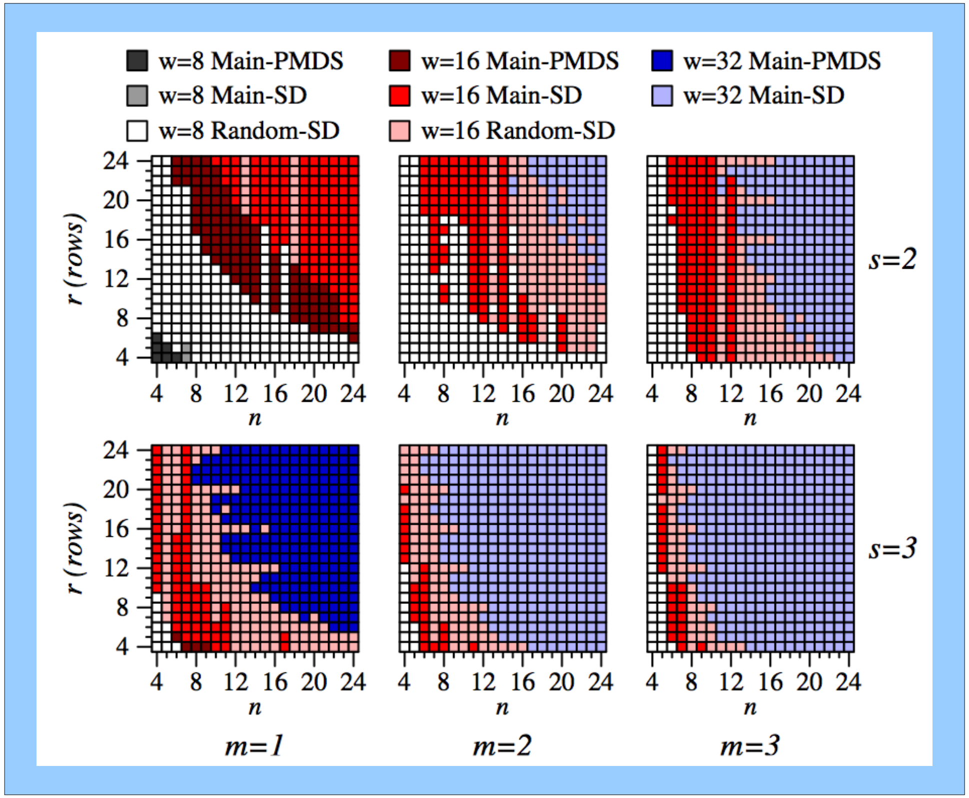
The RAID 6 Replacement

RAID-6



Open Source Code

- SD Programs available from my web site (C).
- Includes encoder/decoder, plus all the constructions from the big yucky picture.
- Fast SSE.
- Doesn't implement RAID – intent is to be a first building block.
- Releasing on Friday.



Related Work

- "Couldn't I just use a *(n,n-m-s)* Reed-Solomon code?"
- Yes, but:
  - Then all coding symbols are functions of all of the data words.
  - Update penalty is all coding blocks.
  - Decoding the common case is expensive.
- "Intradisk Redundancy" [Dholakia, 2009]
  - Reduced failure coverage.

Related Work – Two recent codes

- PMDS Codes
  - IBM
  - *IEEE Transactions on Information Theory, 2013.*
  - Same methodology as SD codes, but with enhanced theory for verifying constructions.

- LRC Codes
  - Microsoft Azure
  - *USENIX ATC 2012.*
  - Intended model is for systems where each block is on a different disk.
  - Current constructions limited to $m = 1$.

Both codes are "maximally recoverable," meaning they tolerate more failure scenarios, with the SD scenario being a subset (Overkill for RAID).

Conclusion

- New erasure-coding methodology to address the failure mode of current storage systems.

- In particular, covers the RAID-6 failure mode without the wasted storage.

- Yes, you've gotta eat some math, but I've got open-source C code that does it all for you.
  - The Galois Field arithmetic.
  - The decoding equations.
  - Constructions for $n, r \leq 24, m, s \leq 3$.

- Performance better than Reed-Solomon substitutes.

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