FAST'19

Fast Erasure Coding for Data Storage: A Comprehensive Study of the Acceleration Techniques

Tianli Zhou & Chao Tian
Texas A&M University

Contents

- Motivation
- Background and Review

- Evaluating Individual Techniques
- Find the Best Strategy under Optimized Bitmatrix
- Proposed Coding Procedure and Evaluation

- Conclusion

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Data Reliability

Data Reliability

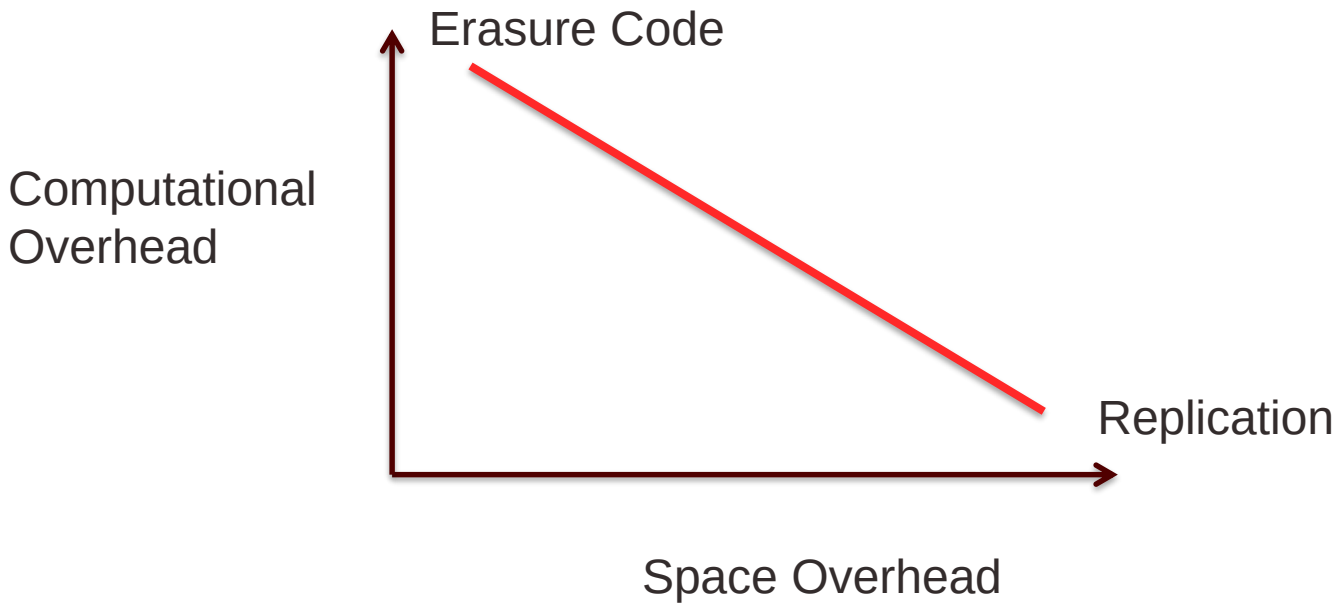
- Disaster happens

Data Reliability

- Disaster happens

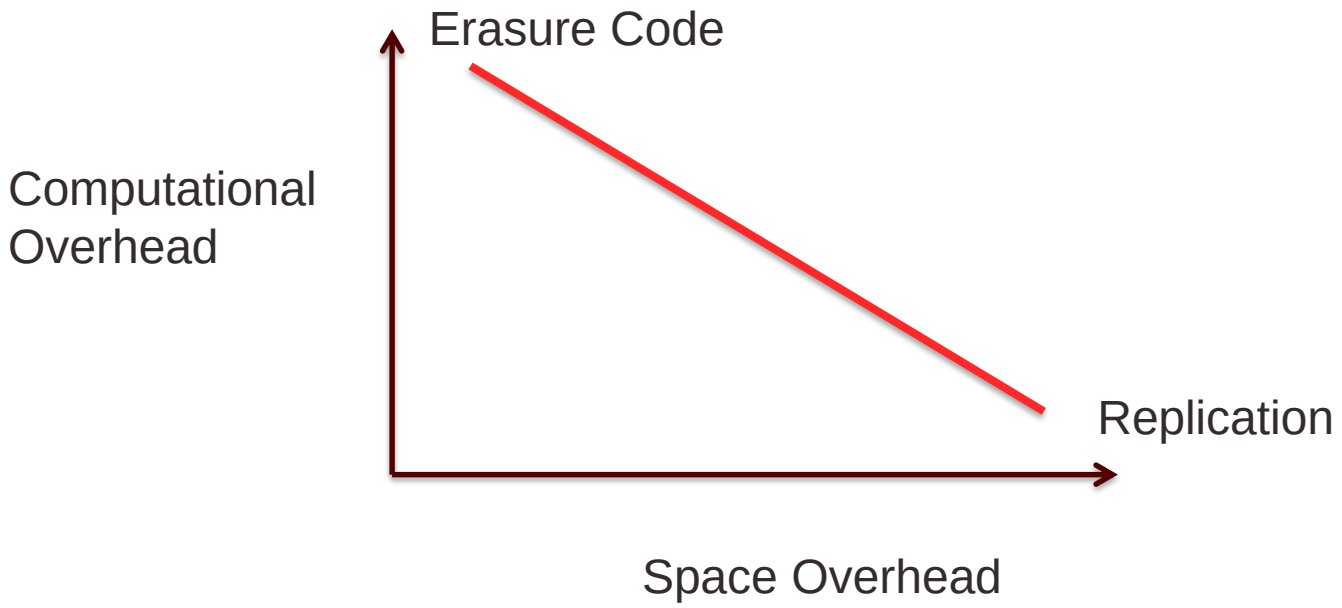
- Disk failure
- Server malfunction
- and more….

Replication - Erasure Code



Replication - Erasure Code

- Minimum space overhead
- Much more computational load
- Erasure code relies on Galois Field (finite field) ops



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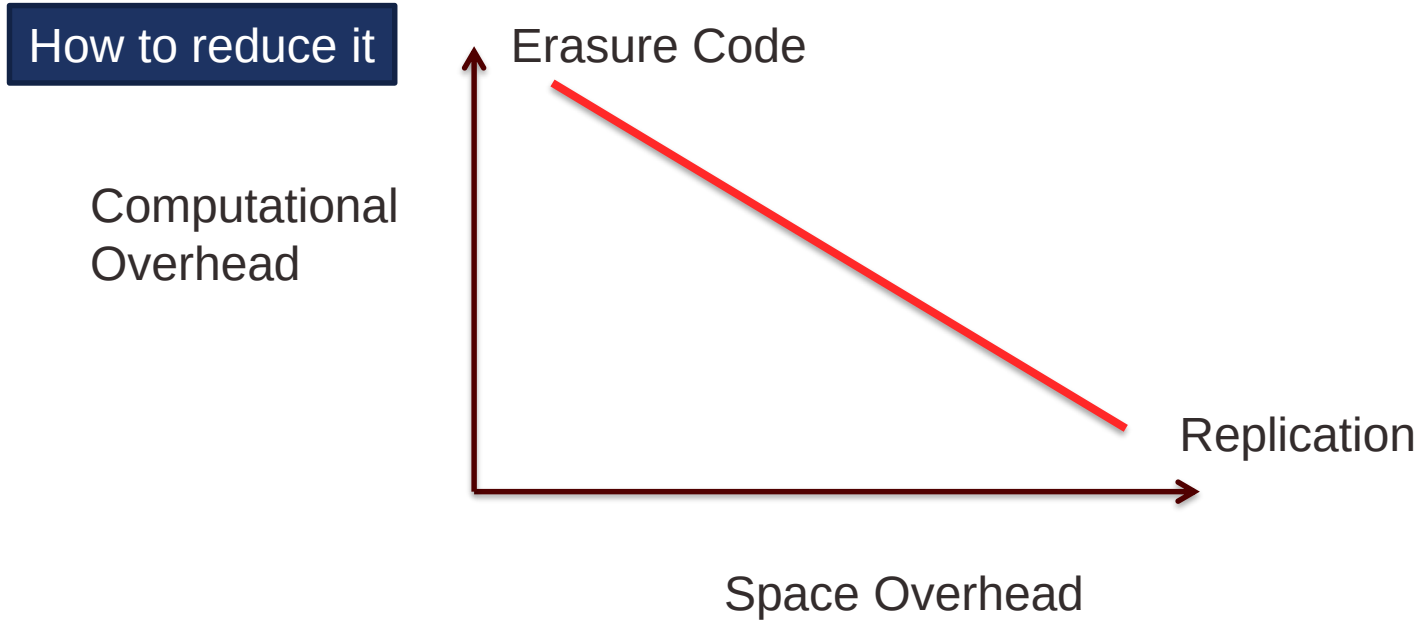


Acceleration Techniques

Optimize Coding Matrix

Schedule Computing Order

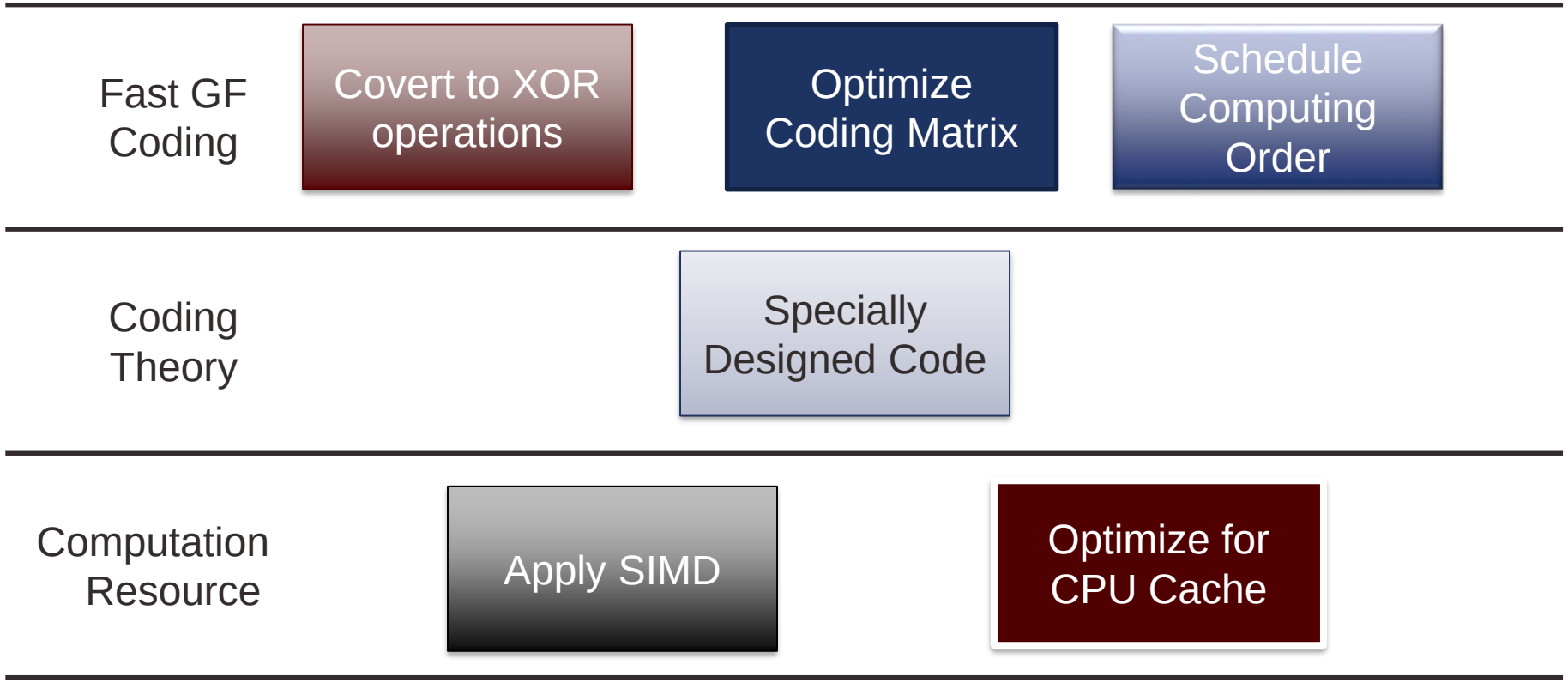
Covert to XOR operations

Apply SIMD

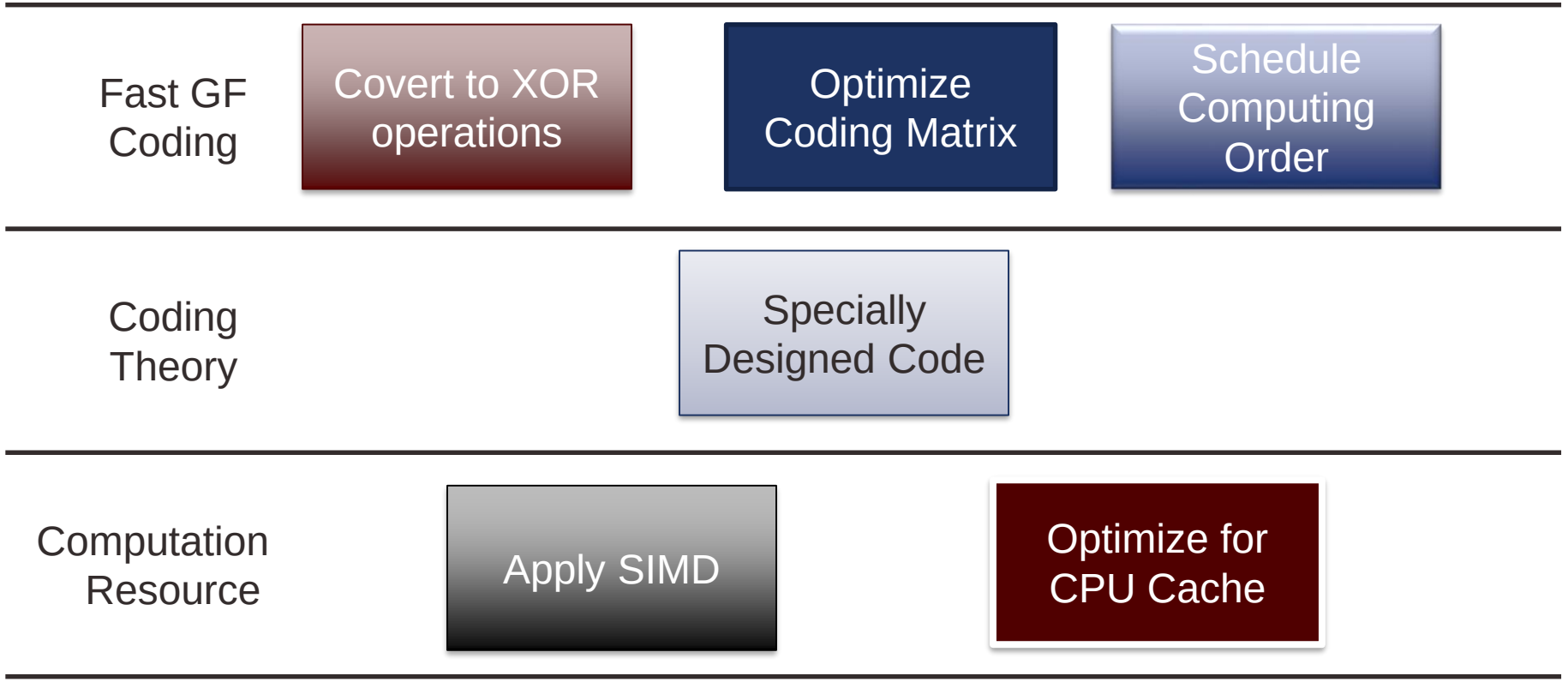
Specially Designed Code

Optimize for CPU Cache

Acceleration Techniques



Acceleration Techniques



?

Question to Answer

- Most effective technique(s)?
- Utilize together?
- Components to be optimized?

- Problem is still important
  - Reduce energy consumption
  - Virtualized environment
  - Mobile / embedded system
  - Future I/O technology

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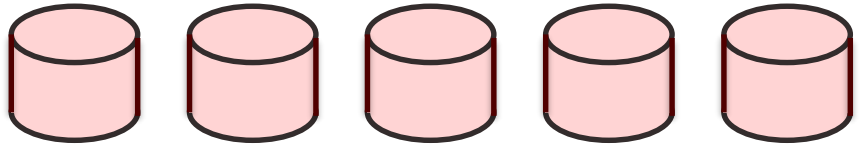
Erasure Code

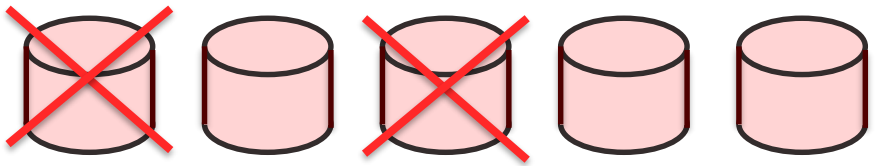
storage nodes



Store coded data to multiple nodes

Erasure Code

storage nodes



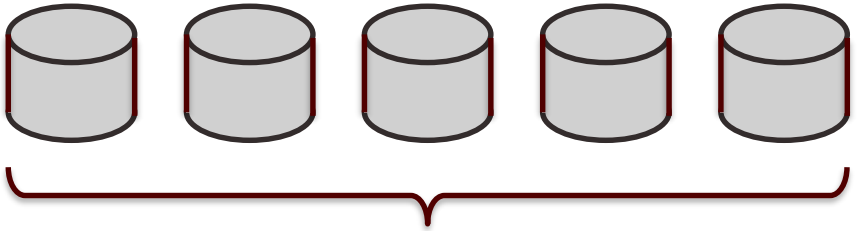
Recover even nodes failures happen

Erasure Code

$k=3$
segments

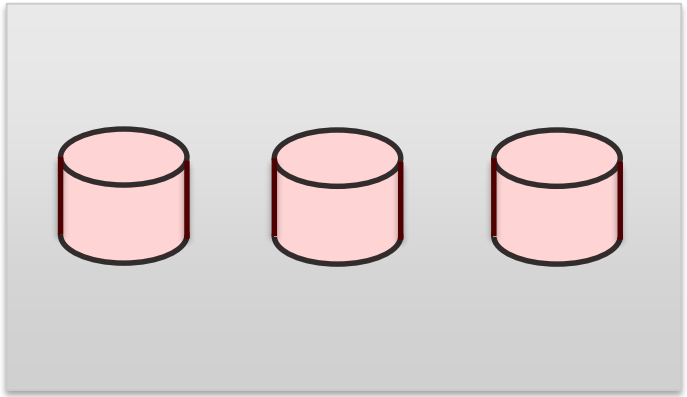
Encode

storage nodes



$n=5$
coded nodes

Erasure Code



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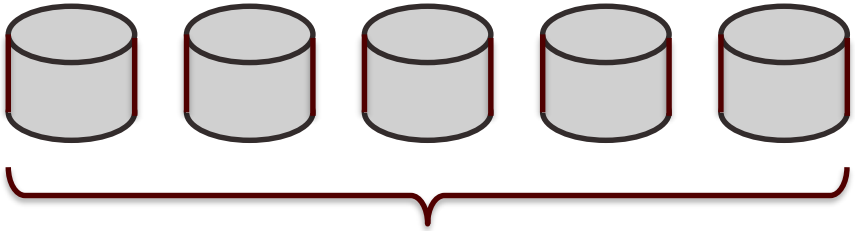

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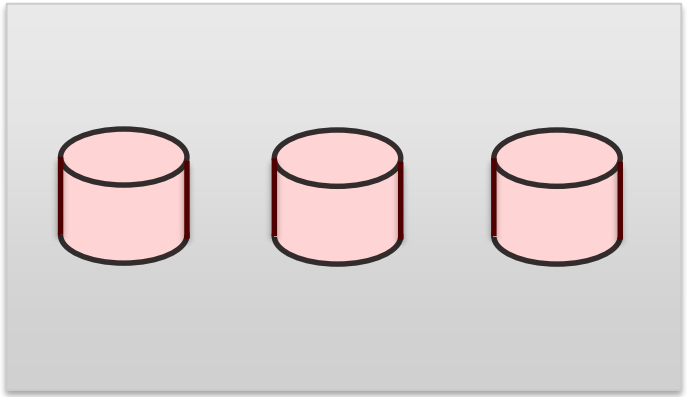

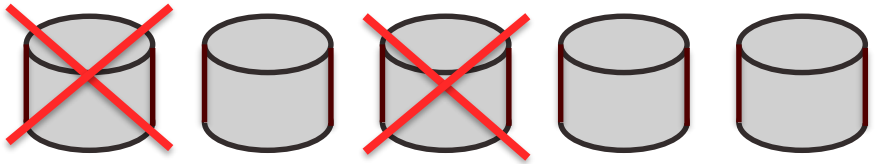

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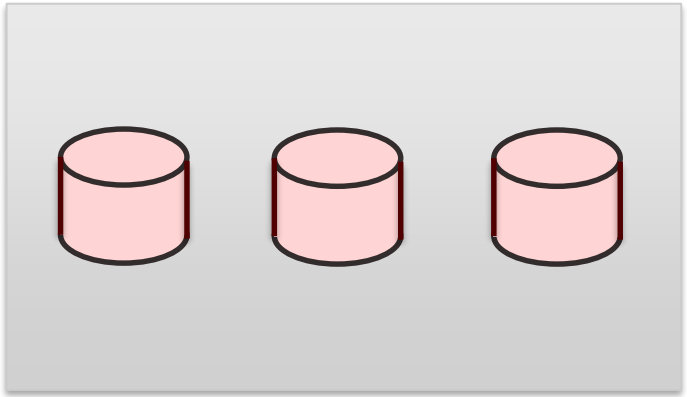
MDS code: recover data from any k surviving nodes

Erasure Code



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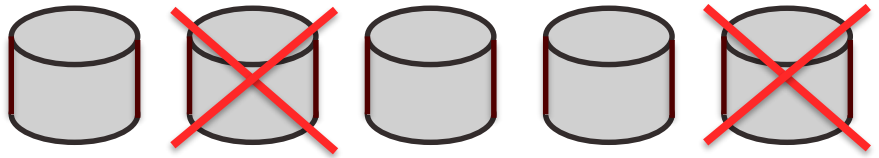

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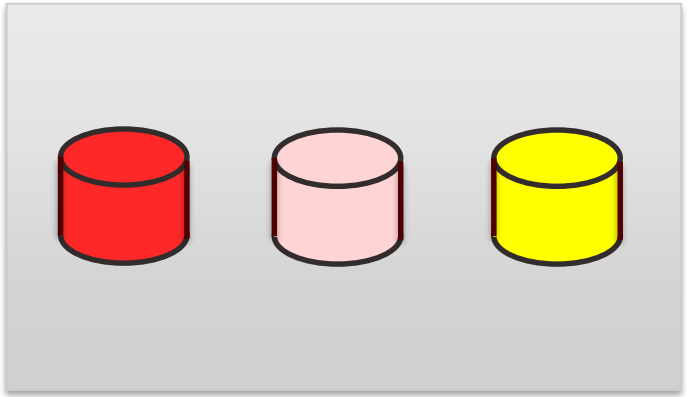

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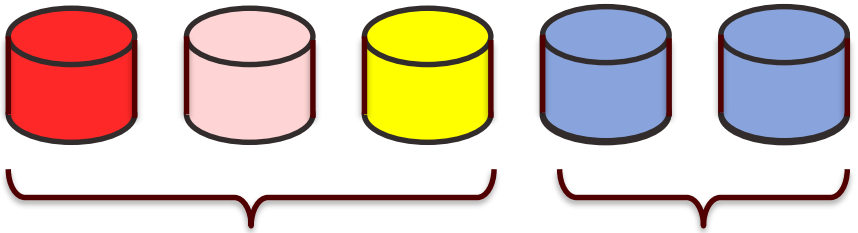
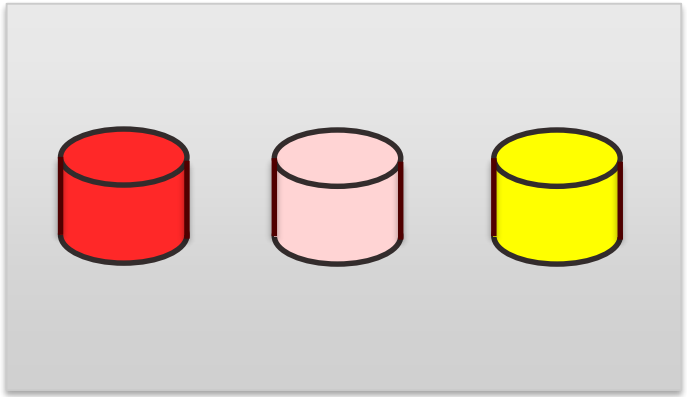


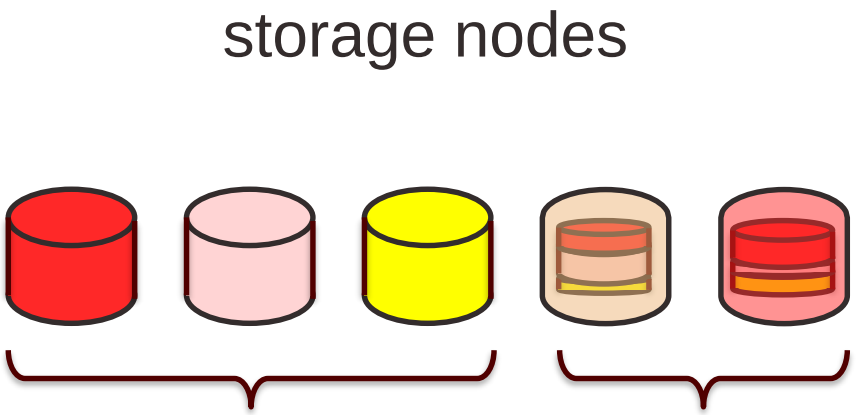
$k=3$
segments

$k=3$
systematic nodes

$m=2$
parity nodes

Erasure Code





$k=3$
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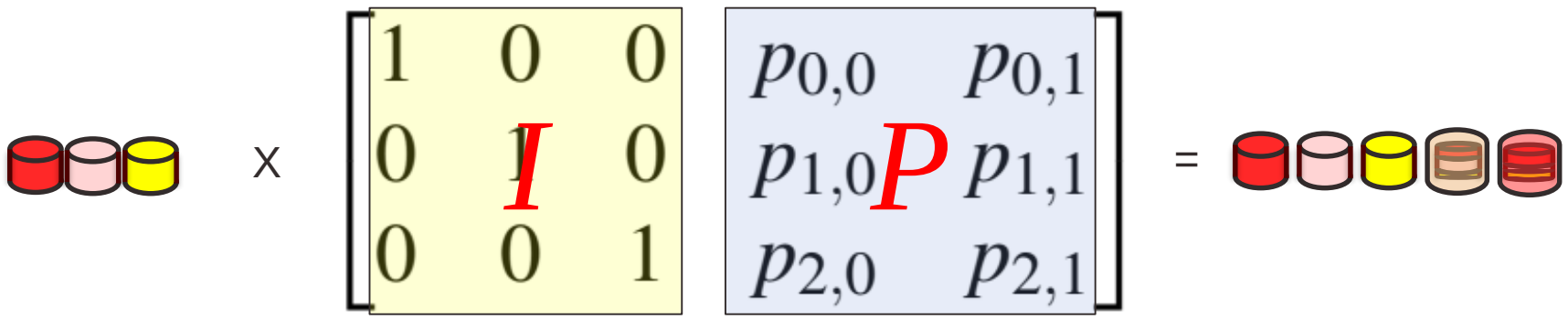
Encoding

- Matrix multiplication on finite field



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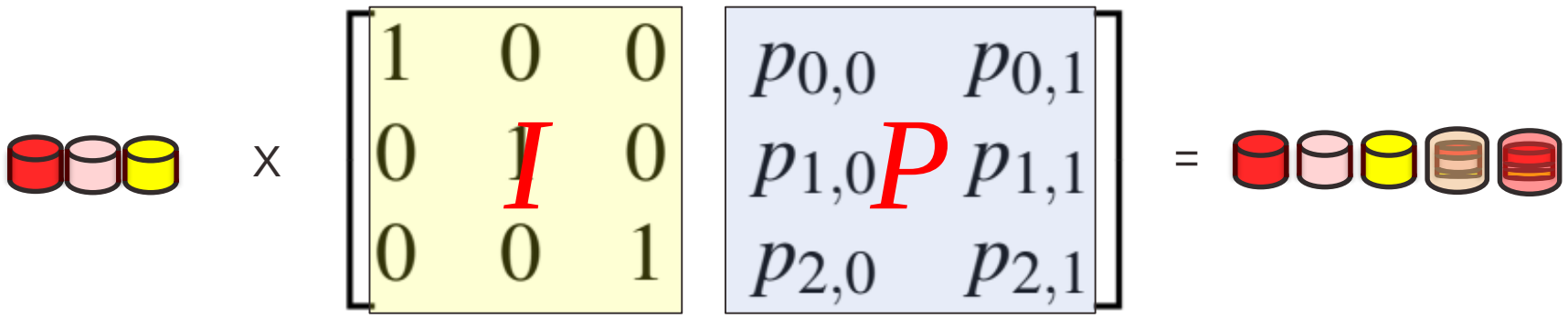

All elements and ops in $GF(2^w)$

Galois Field (GF)
Finite field

Decoding

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_{0,0} & p_{0,1} \\ p_{1,0} & p_{1,1} \\ p_{2,0} & p_{2,1} \end{bmatrix}$$

Decoding

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Decoding

- Submatrix corresponding to surviving data

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_{0,0} & p_{0,1} \\ p_{1,0} & p_{1,1} \\ p_{2,0} & p_{2,1} \end{bmatrix}$$

$$\left[\begin{array}{c|cc} 0 & p_{0,0} & p_{0,1} \\ 0 & p_{1,0} & p_{1,1} \\ 1 & p_{2,0} & p_{2,1} \end{array}\right]$$

Decoding

- Submatrix corresponding to surviving data
- Invert

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} I \qquad \begin{bmatrix} p_{0,0} & p_{0,1} \\ p_{1,0} & p_{1,1} \\ p_{2,0} & p_{2,1} \end{bmatrix} P$$

$$\left[\begin{array}{c|cc} 0 & p_{0,0} & p_{0,1} \\ 0 & p_{1,0} & p_{1,1} \\ 1 & p_{2,0} & p_{2,1} \end{array}\right]^{-1}$$

Decoding

- Submatrix corresponding to surviving data
- Invert
- Multiplication

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad I$$

$$\begin{bmatrix} p_{0,0} & p_{0,1} \\ p_{1,0} & p_{1,1} \\ p_{2,0} & p_{2,1} \end{bmatrix} \quad P$$

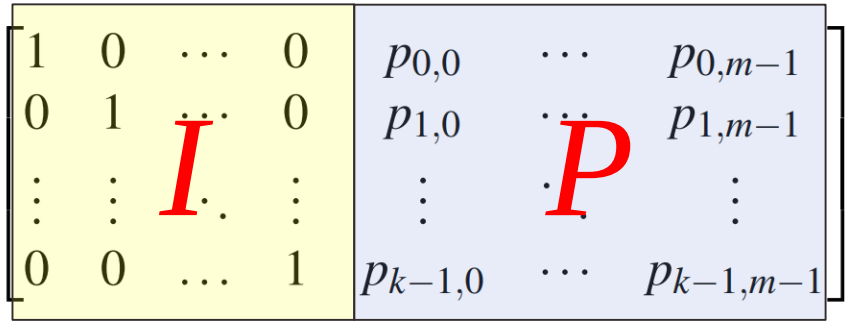
x

$$\begin{bmatrix} 0 & p_{0,0} & p_{0,1} \\ 0 & p_{1,0} & p_{1,1} \\ 1 & p_{2,0} & p_{2,1} \end{bmatrix}^{-1}$$

=

Cauchy Reed-Solomon Codes

- Direct assign P to Cauchy matrix



Cauchy Reed-Solomon Codes

$$X = (x_1, \ldots, x_k) \qquad Y = (y_1, \ldots, y_m)$$

$$C = \begin{bmatrix} \frac{1}{x_1 + y_1} & \frac{1}{x_1 + y_2} & \cdots & \frac{1}{x_1 + y_m} \\ \frac{1}{x_2 + y_1} & \frac{1}{x_2 + y_2} & \cdots & \frac{1}{x_2 + y_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{x_k + y_1} & \frac{1}{x_k + y_2} & \cdots & \frac{1}{x_k + y_m} \end{bmatrix}$$

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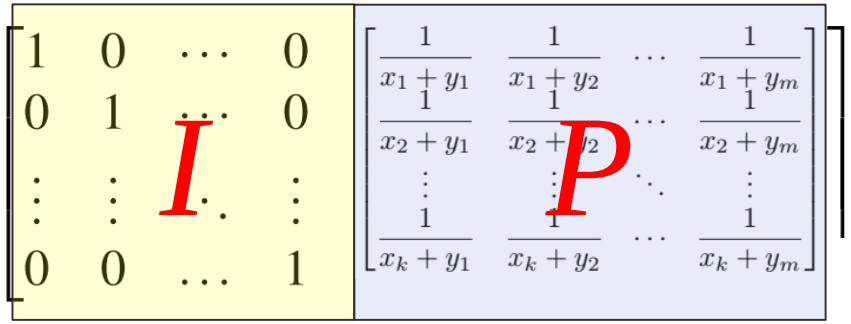
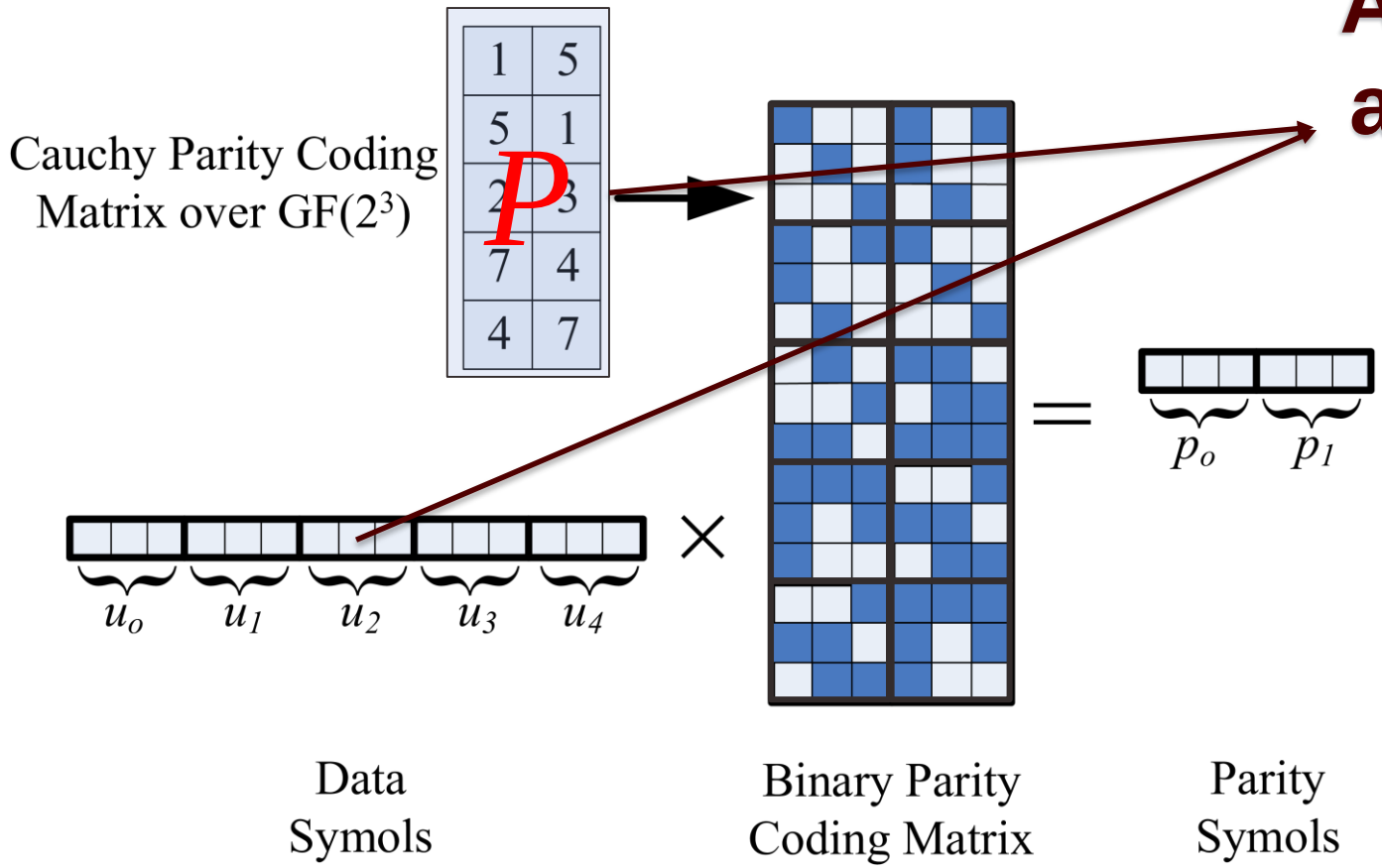


Fast GF Ops – Binary Representation

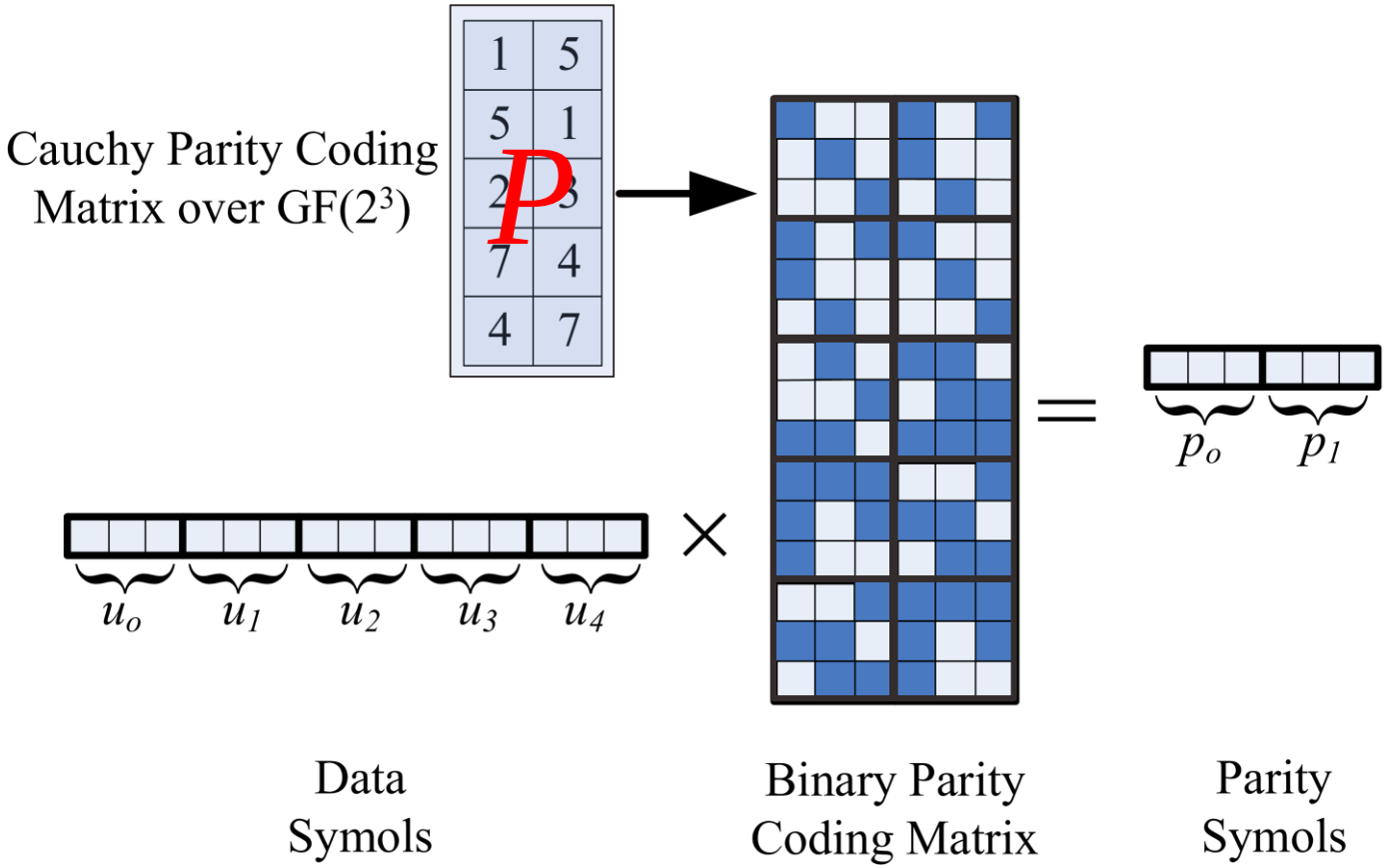
- Binary representation of GF elements



All coefficients and messages are in $GF(2^w)$

Fast GF Ops – Binary Representation

- Message bit-vector representation



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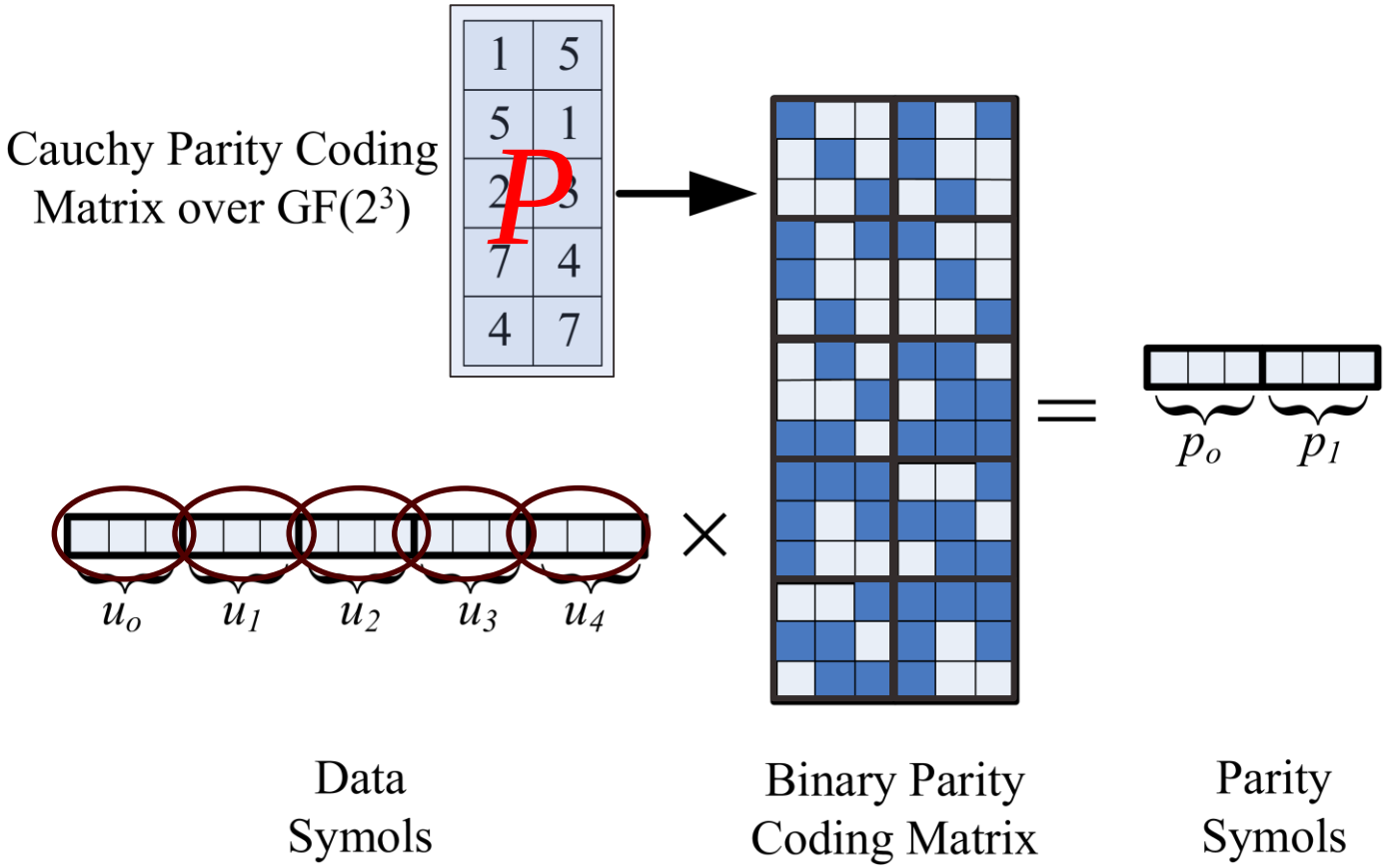

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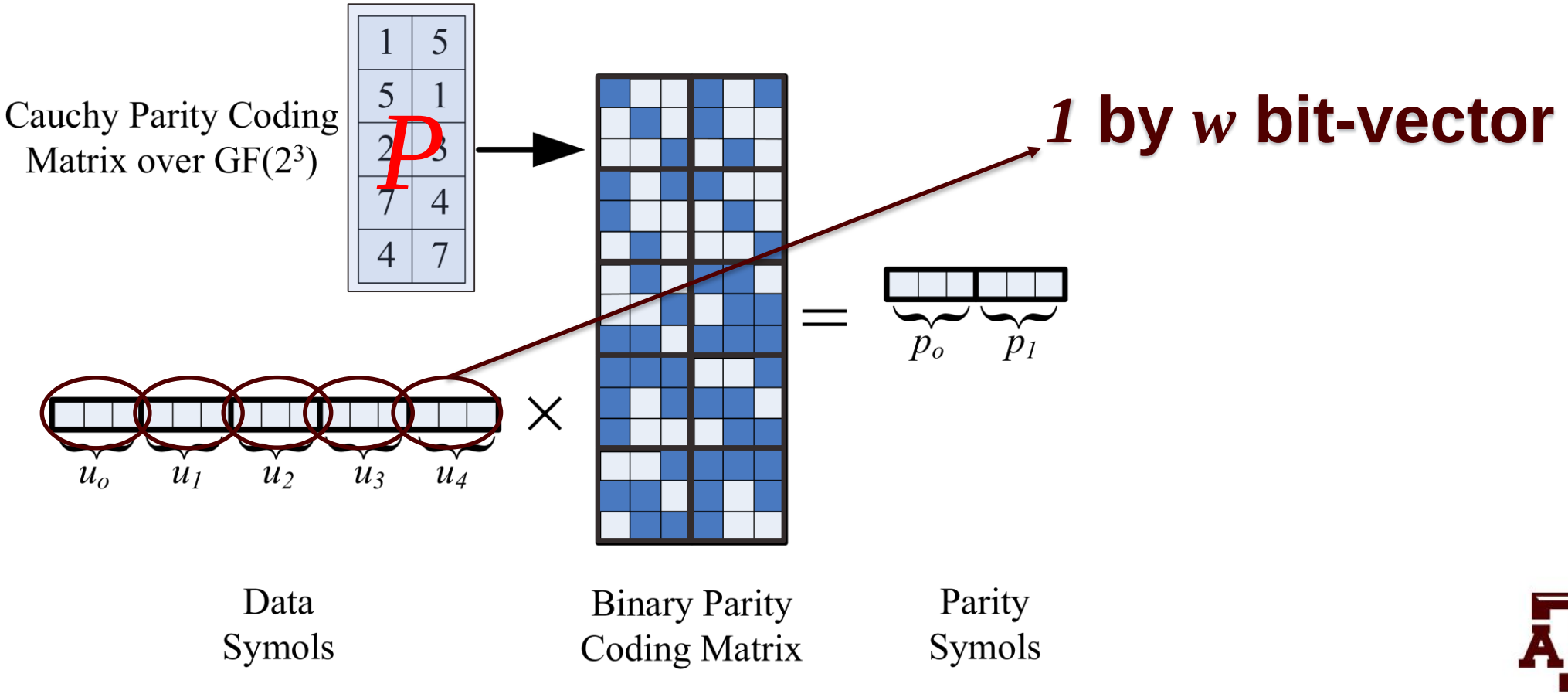

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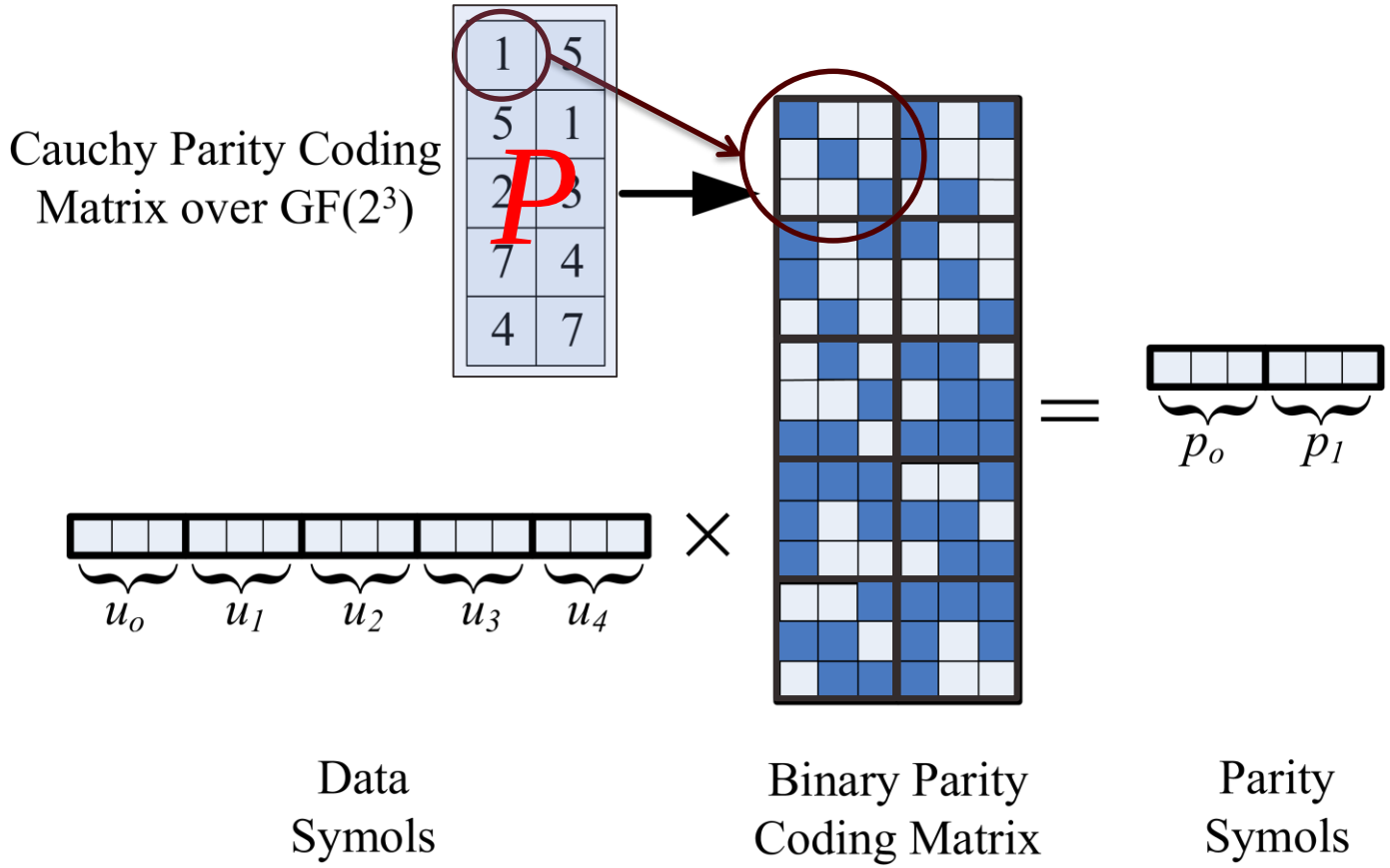

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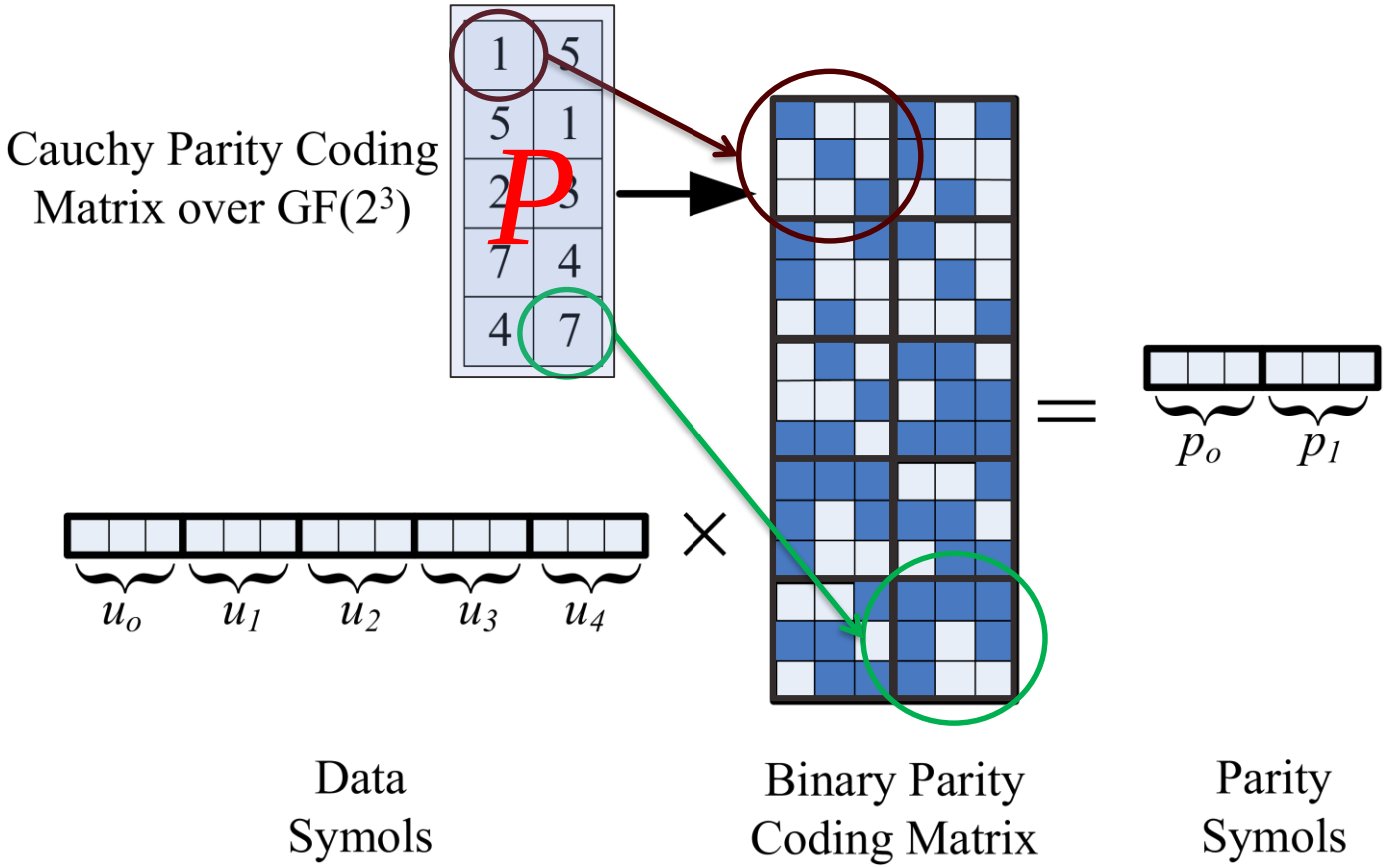

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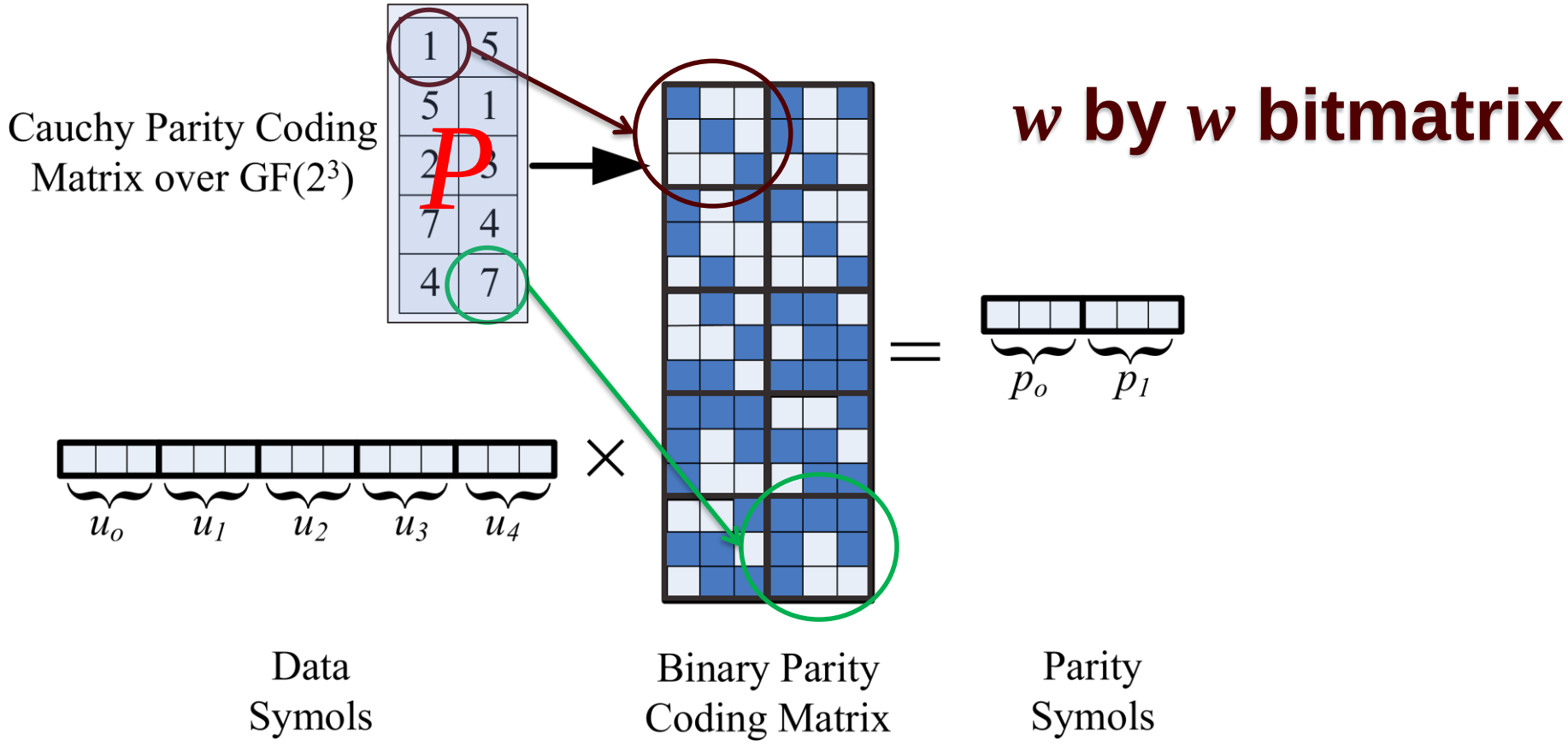
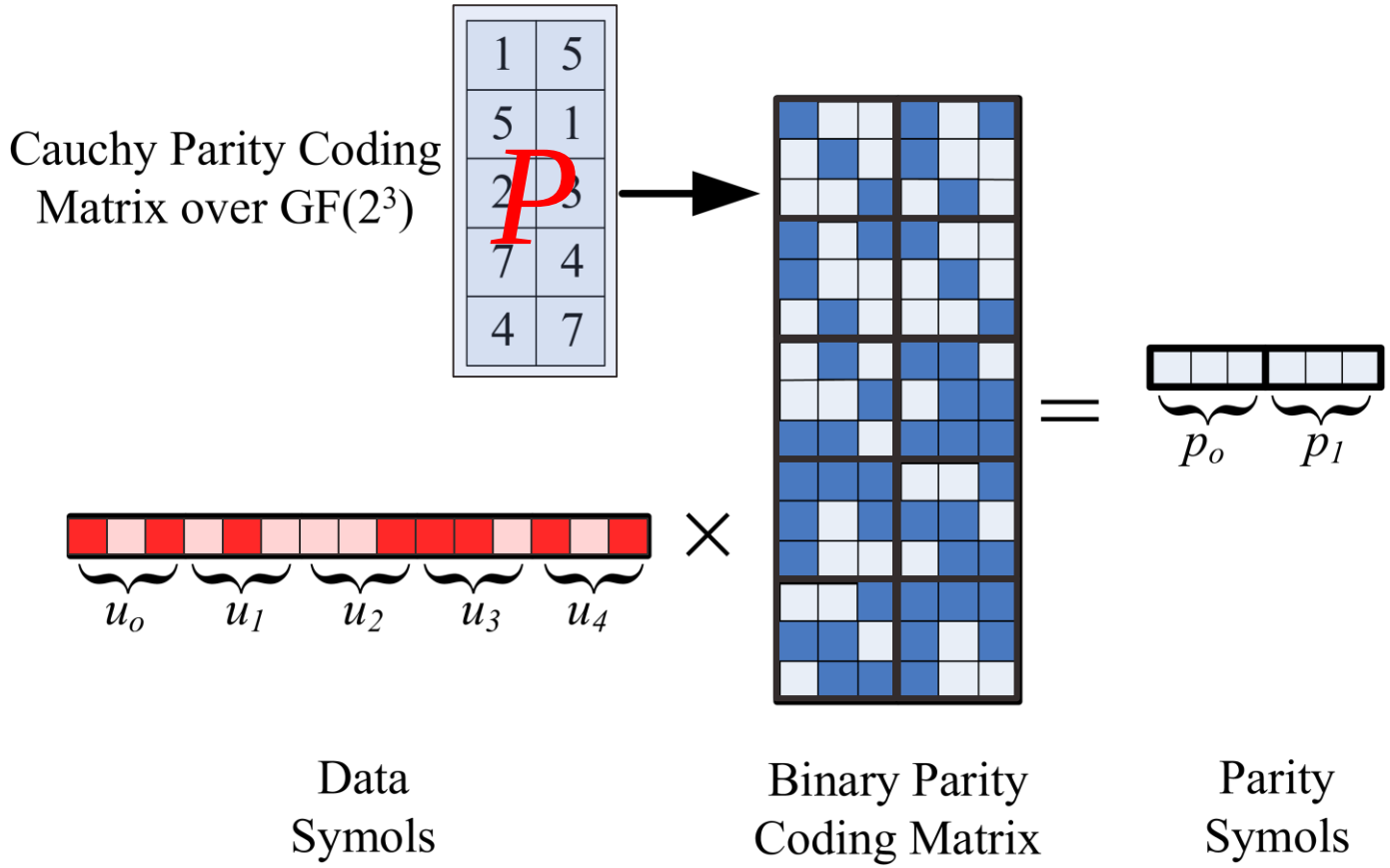


Fast GF Ops – Binary Representation

- Matrix multiplication on GF -> XORs



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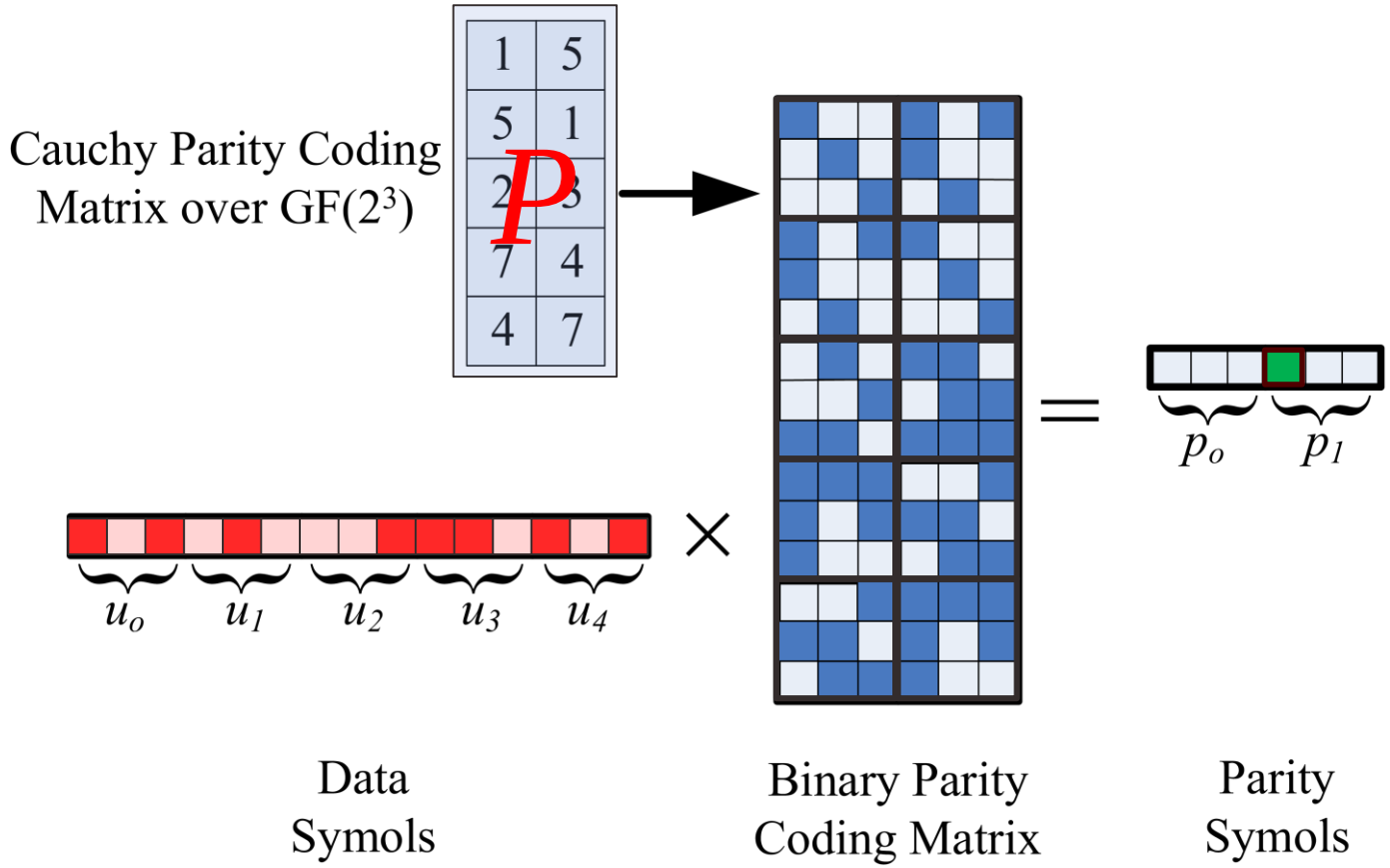

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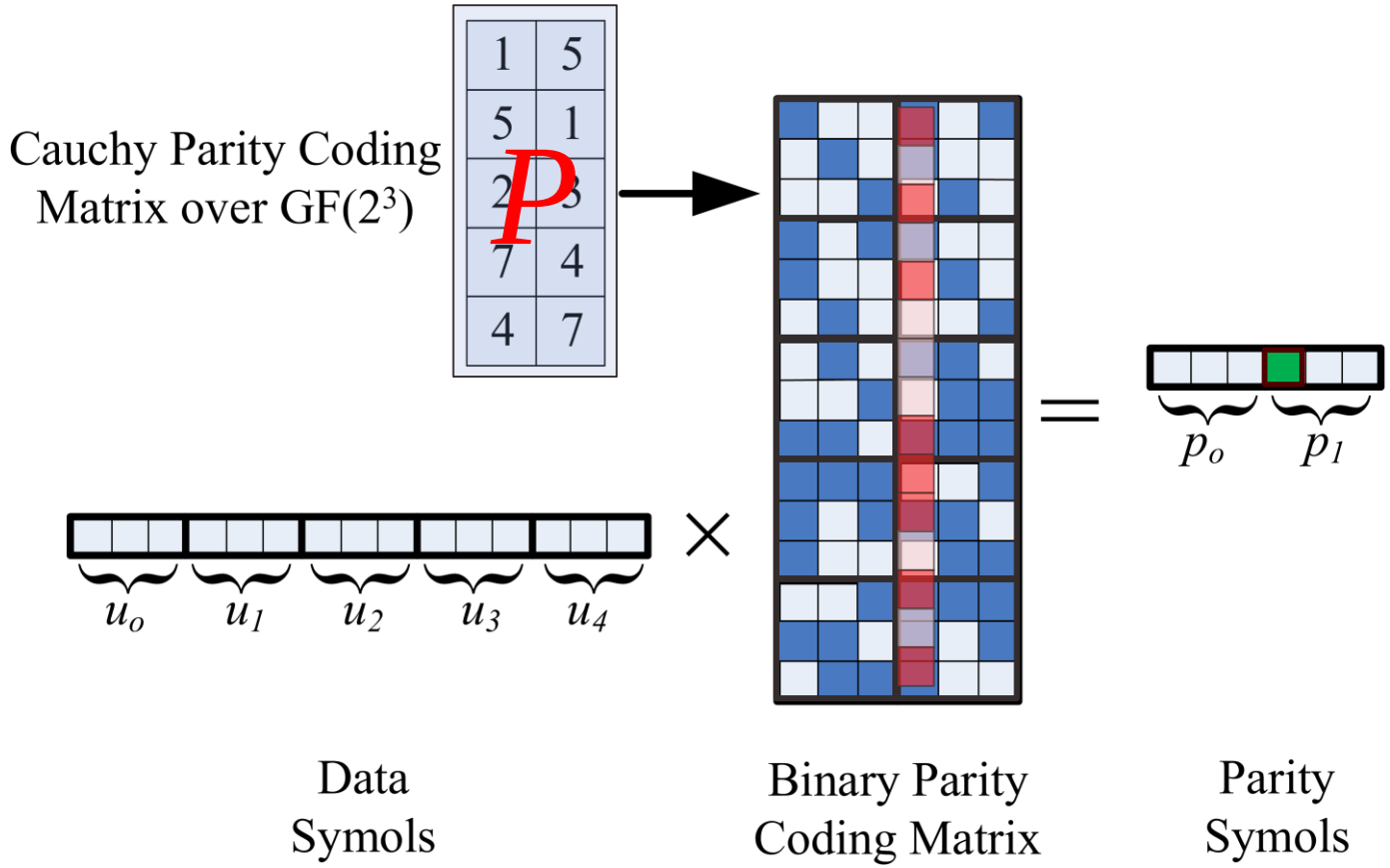

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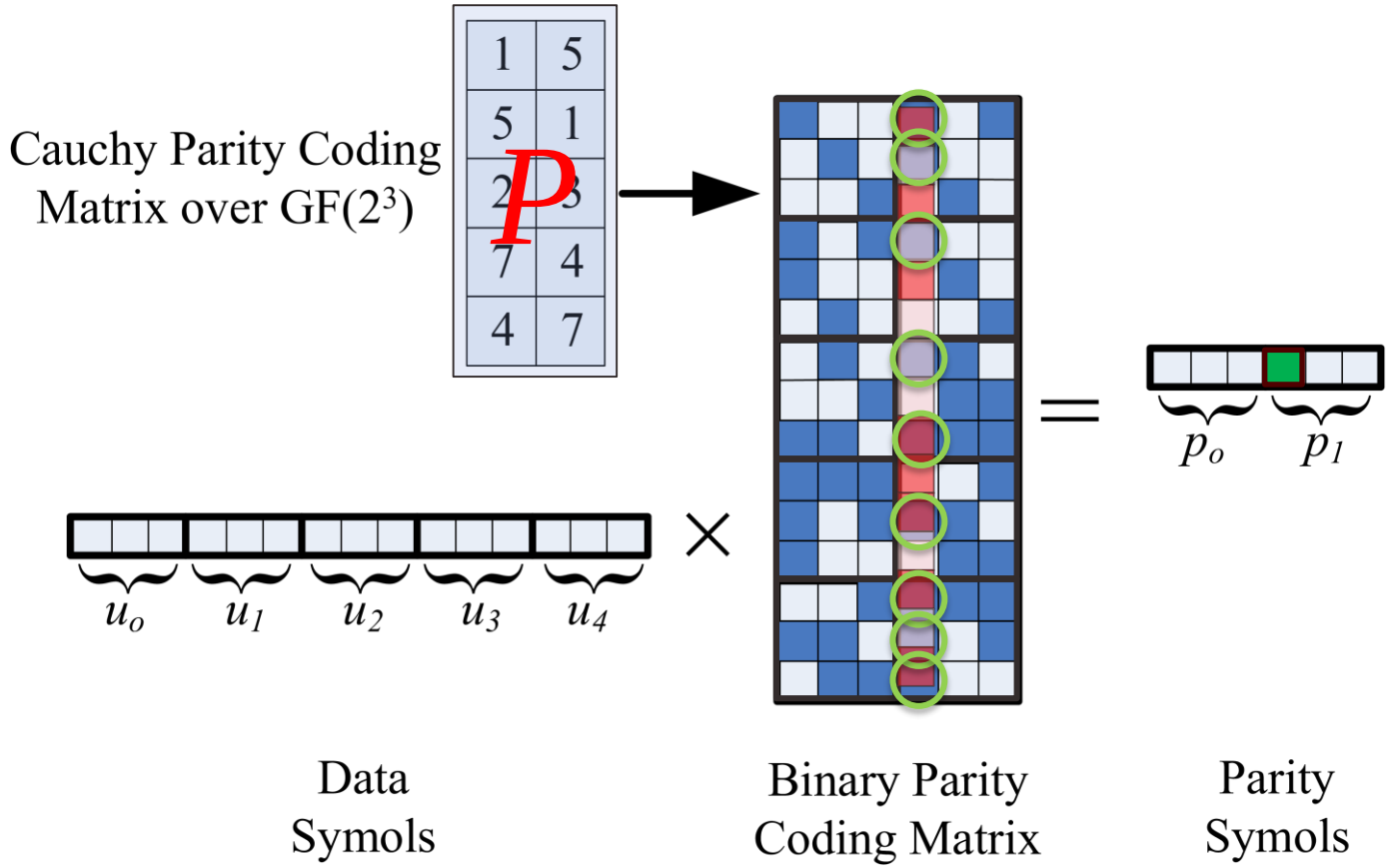

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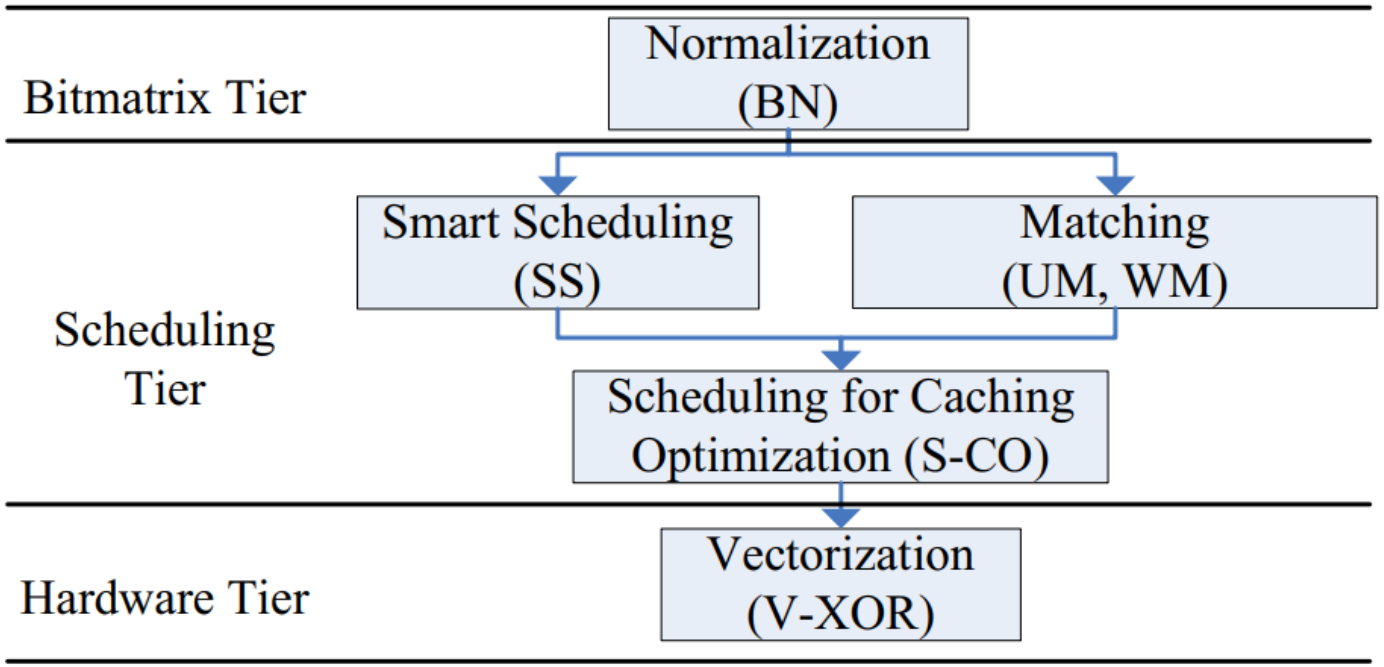
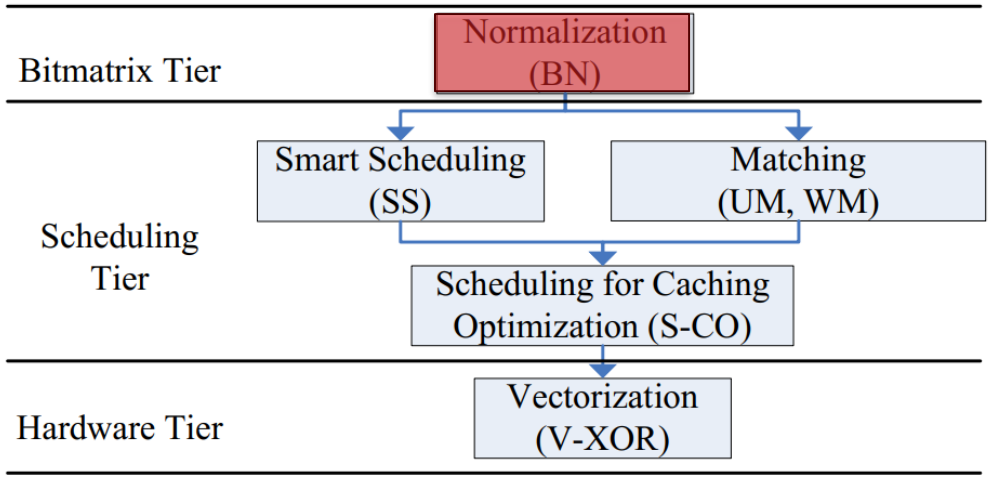
Techniques Tiers



Bitmatrix Normalization (BN)

- Normalize by each element, find less bit 1s



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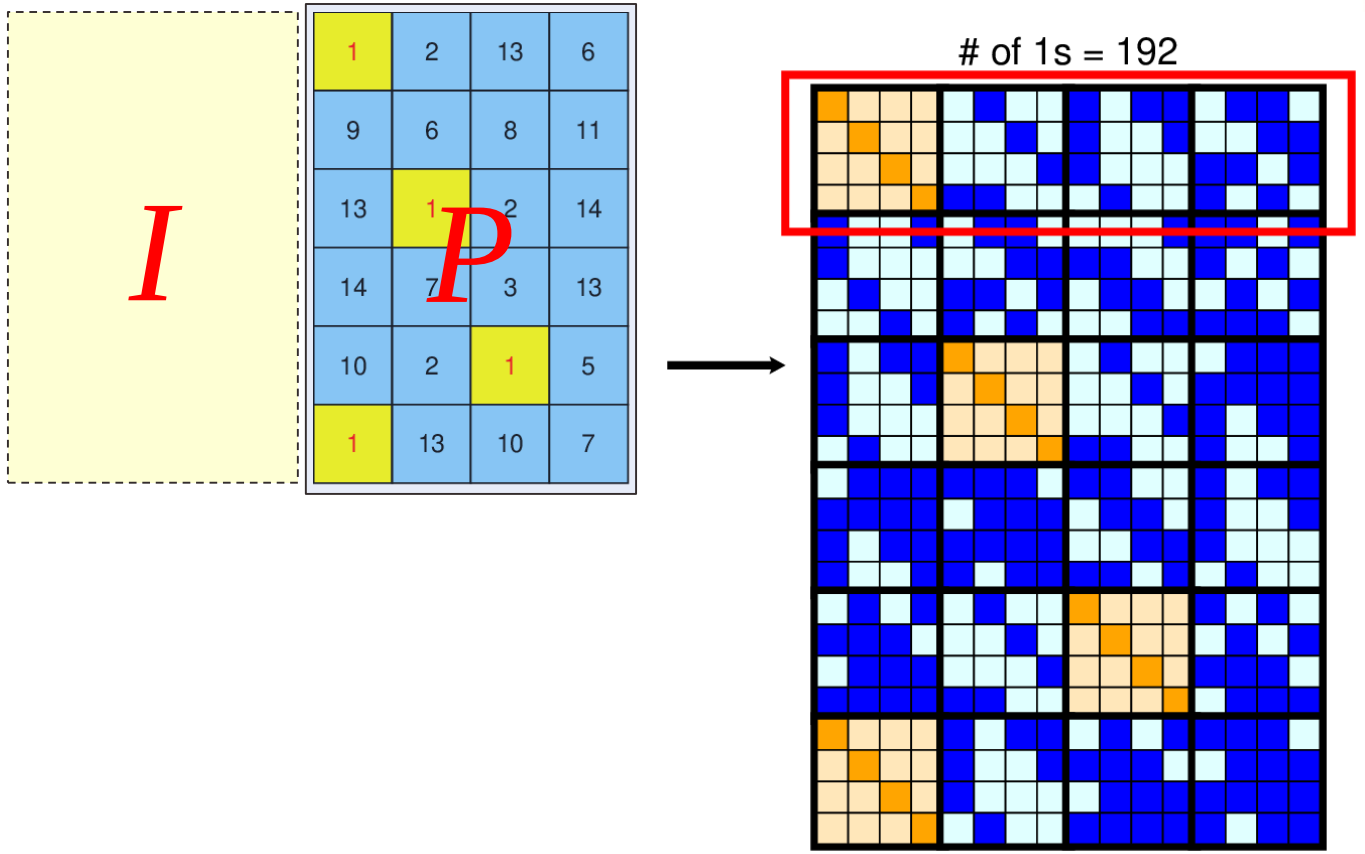

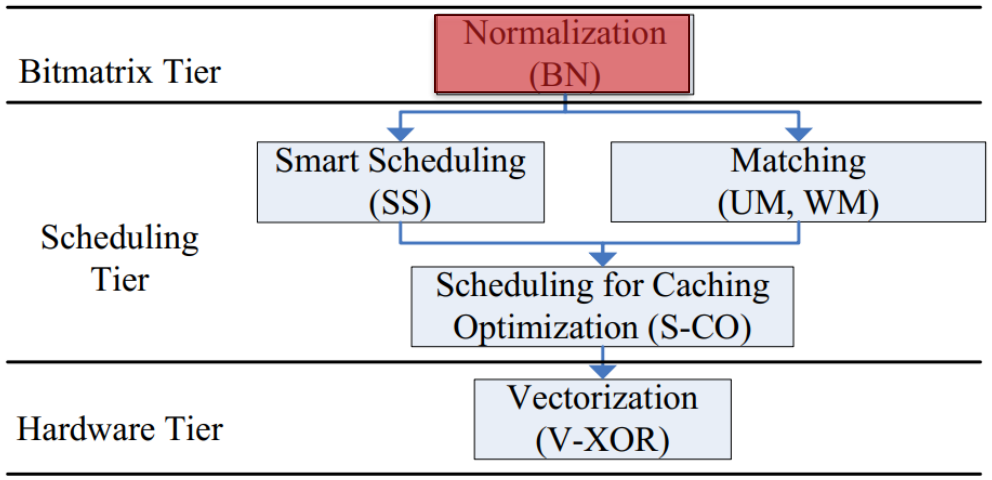

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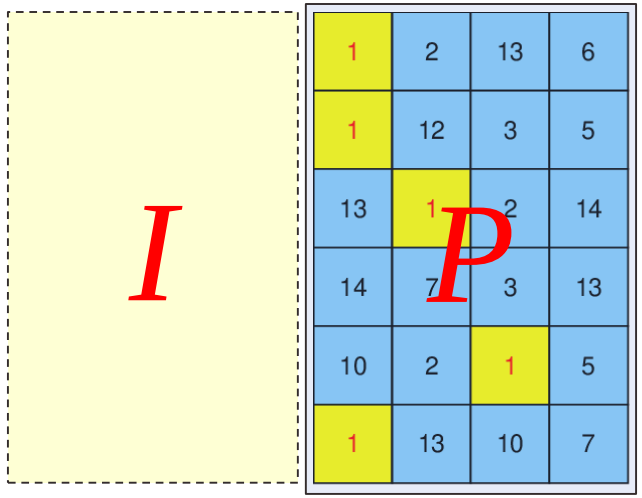

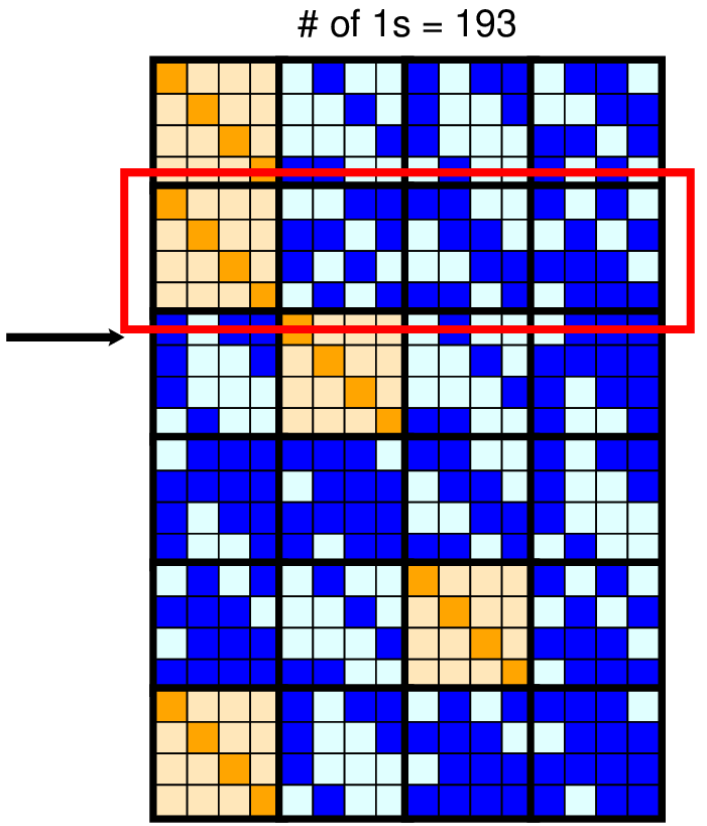

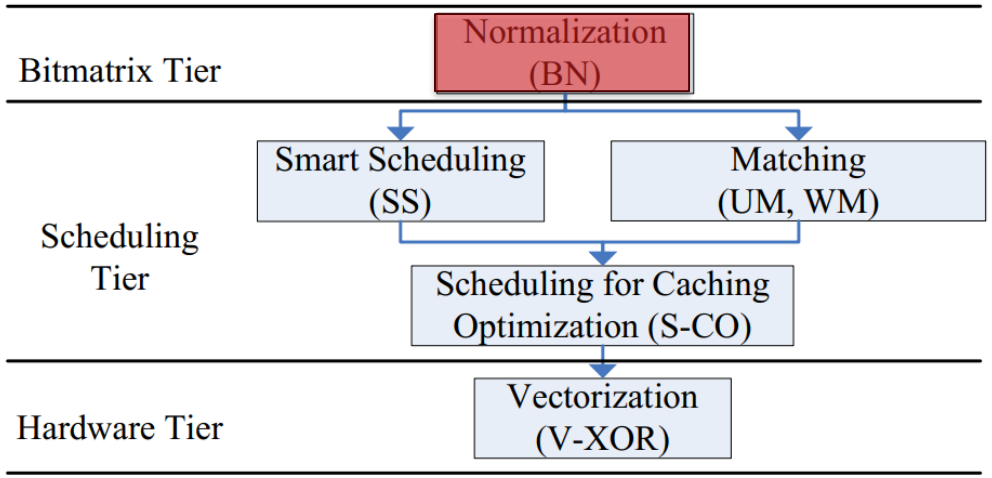

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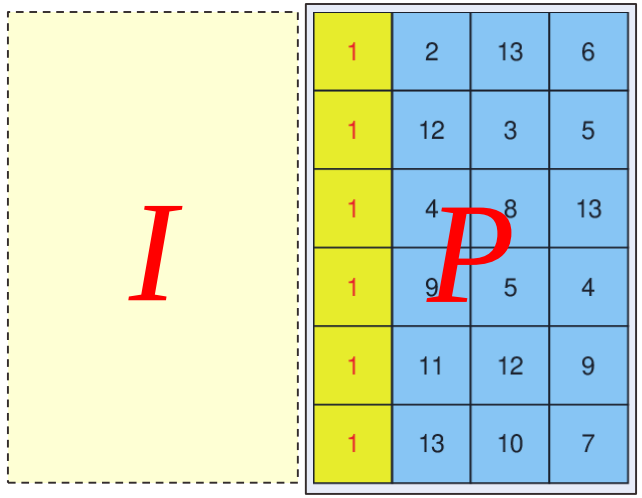

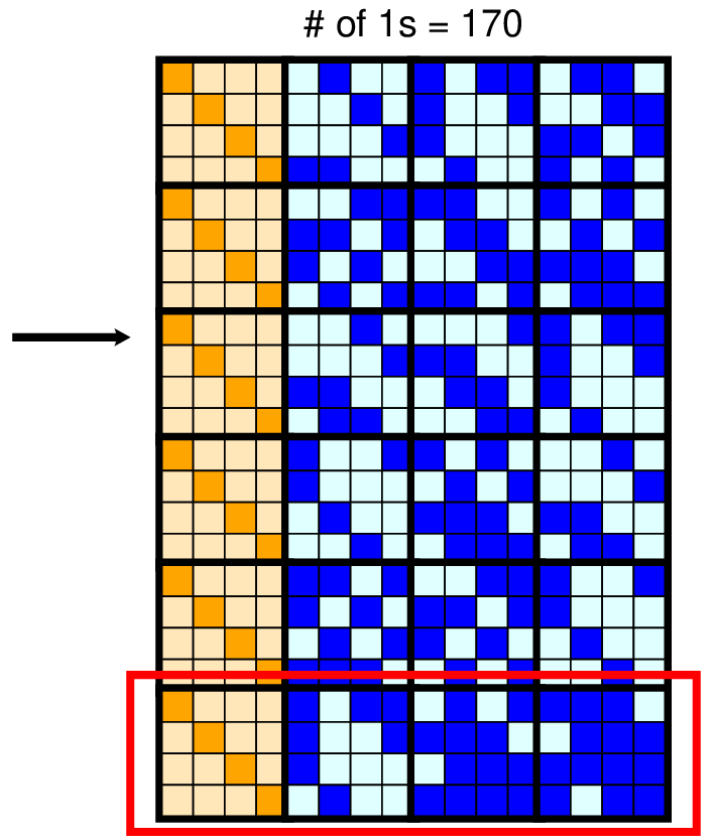

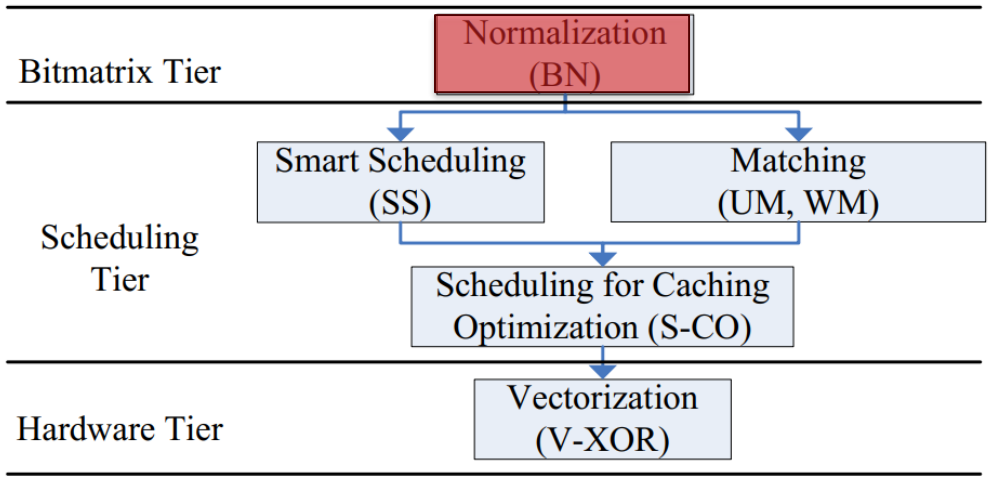

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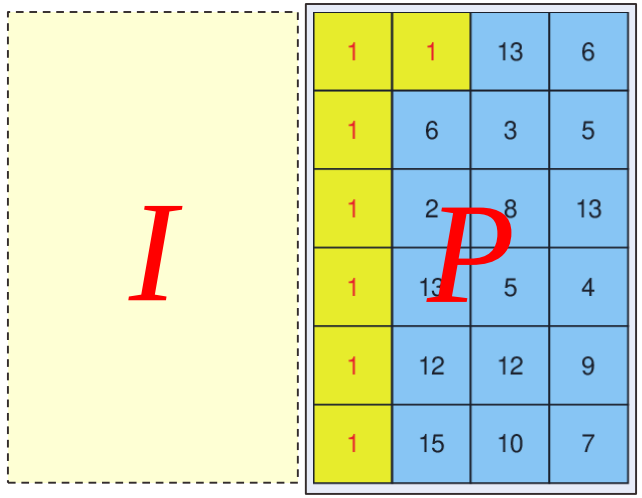

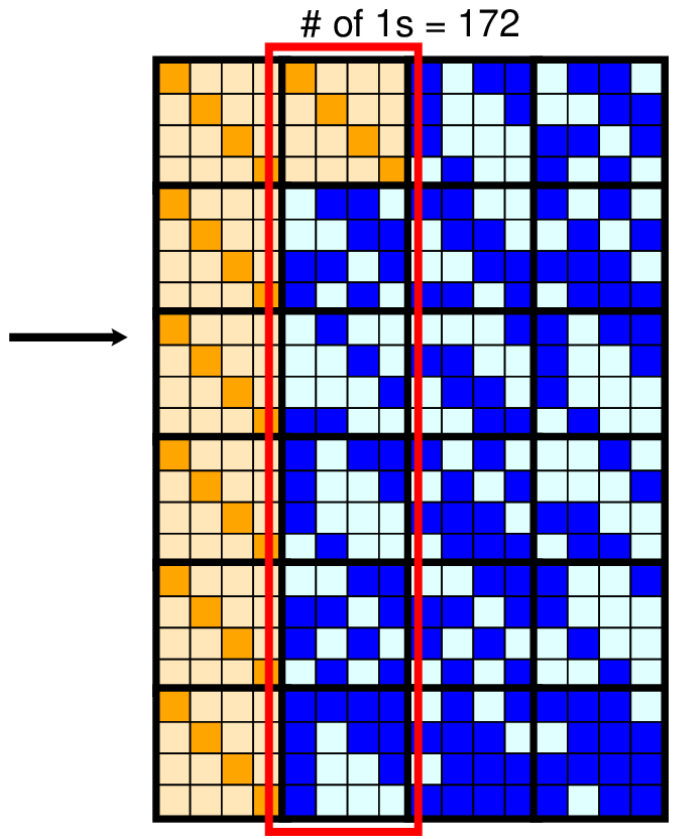

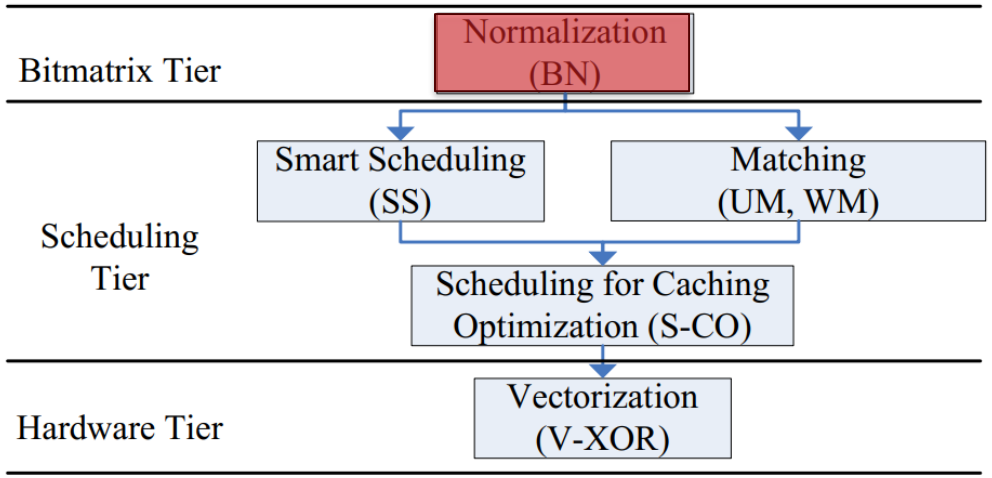

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Bitmatrix Normalization (BN)

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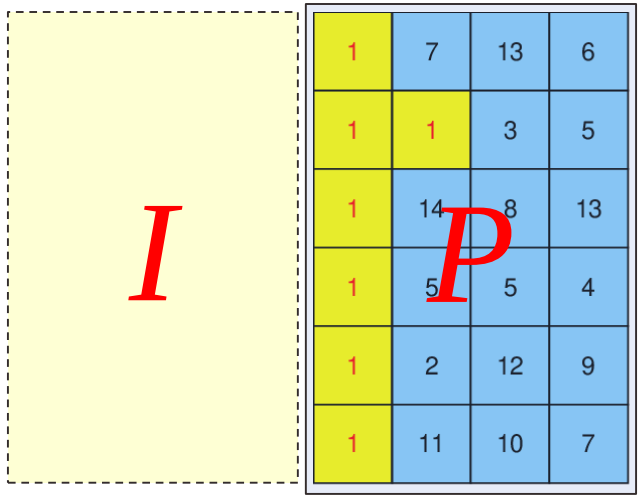

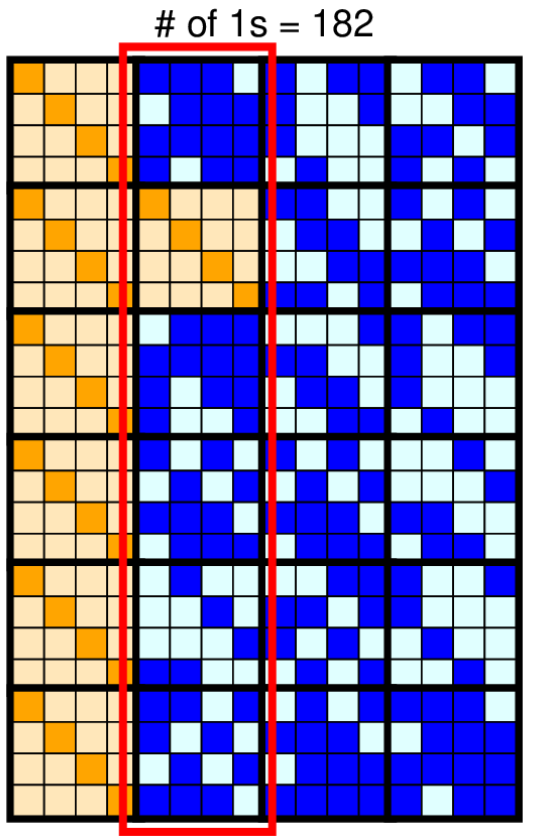

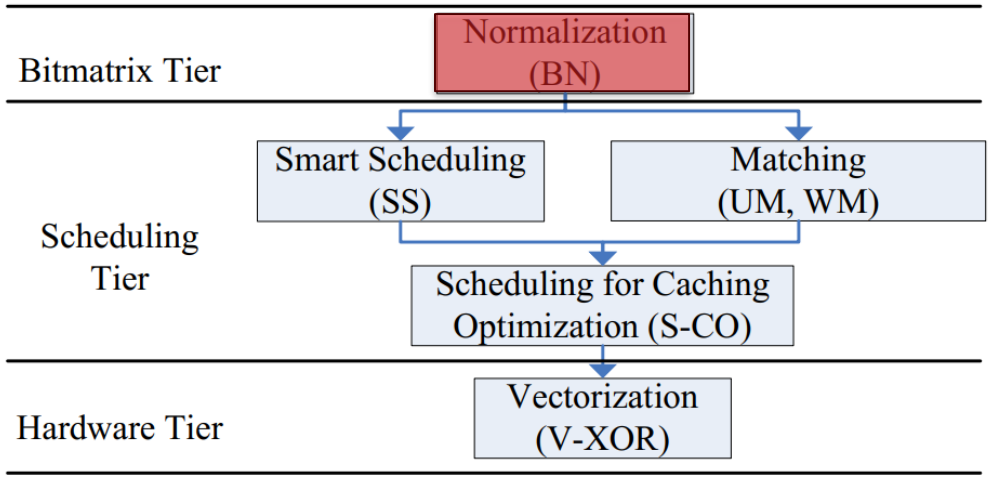

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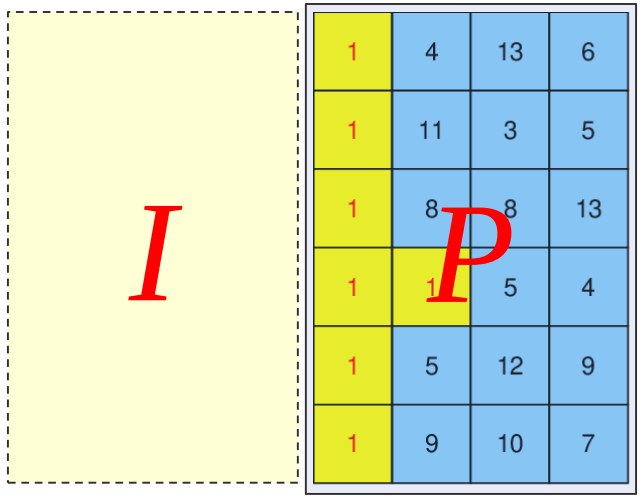

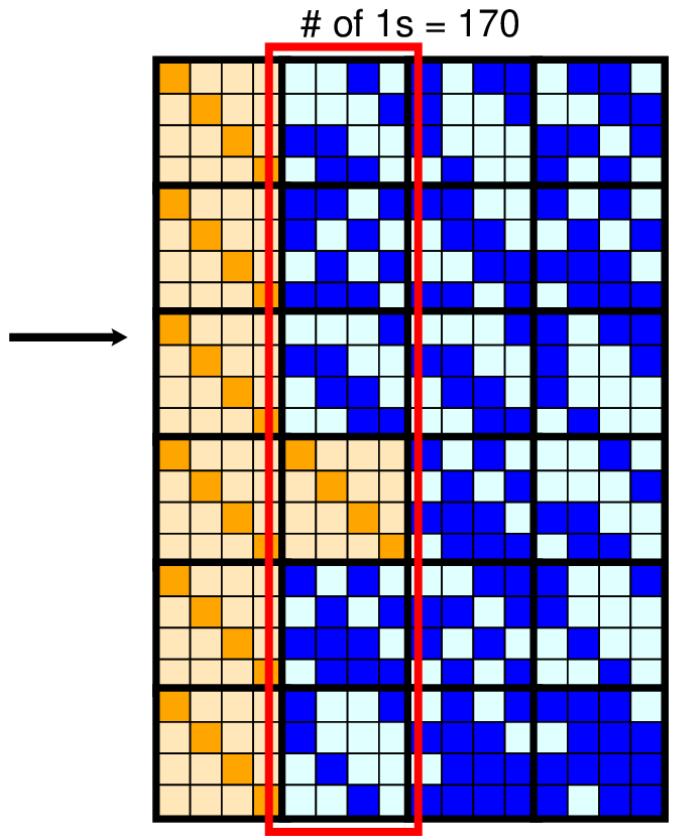

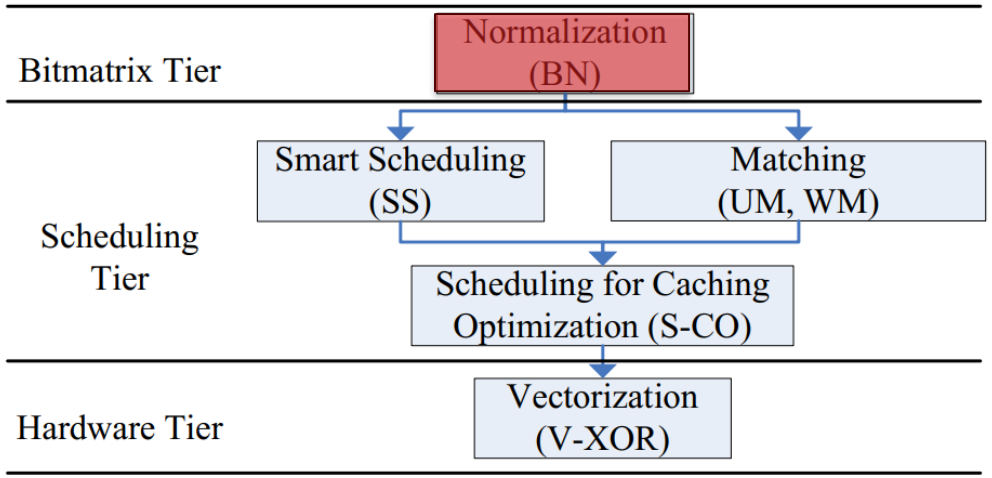

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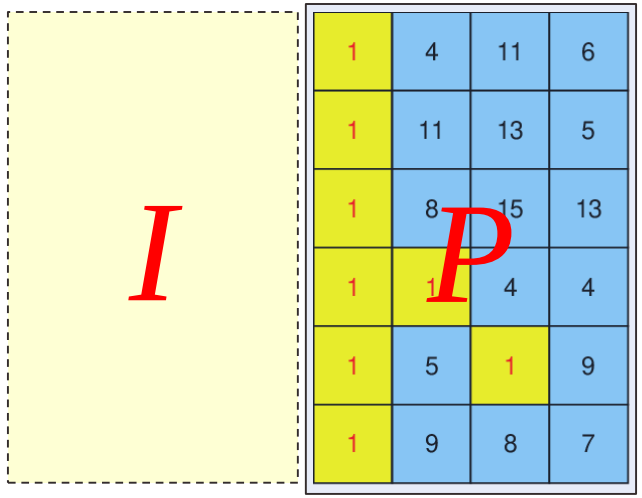

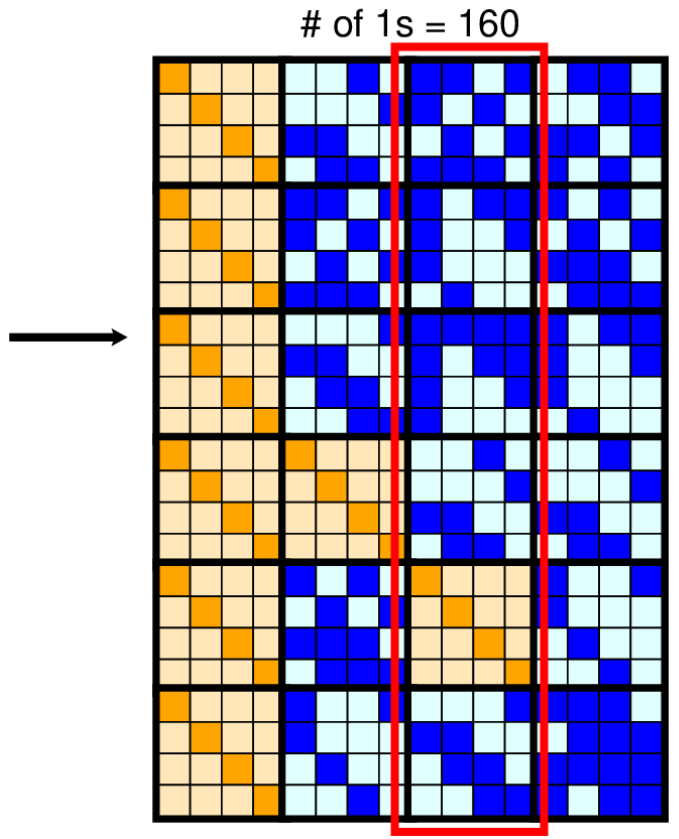

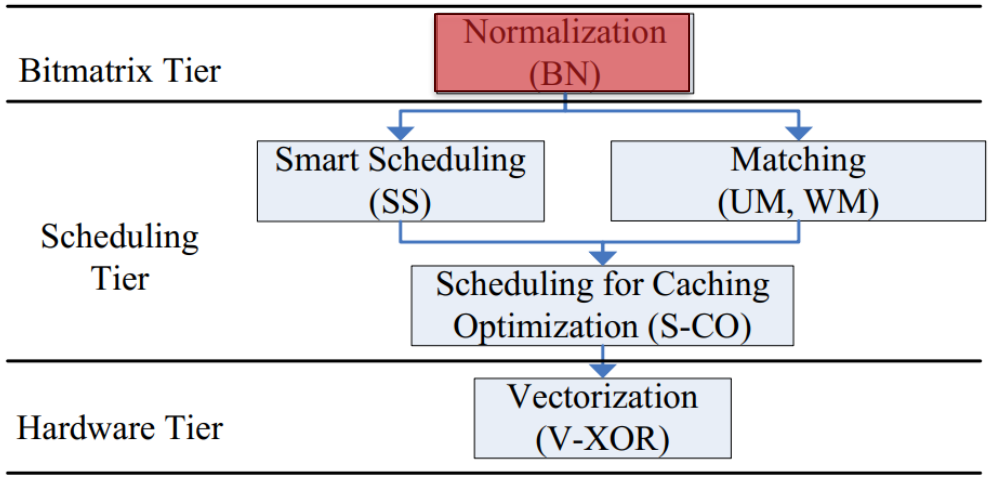

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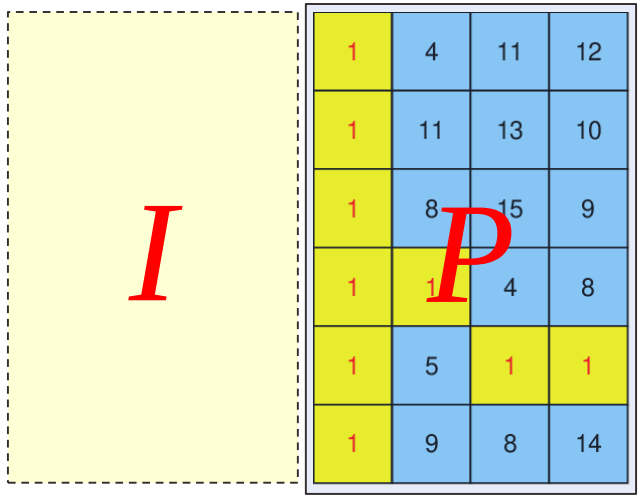

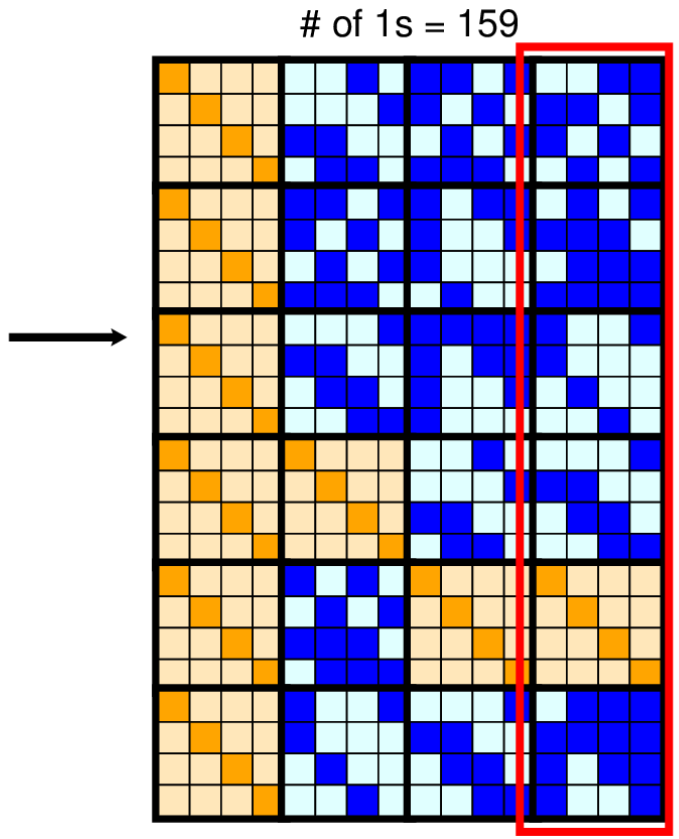

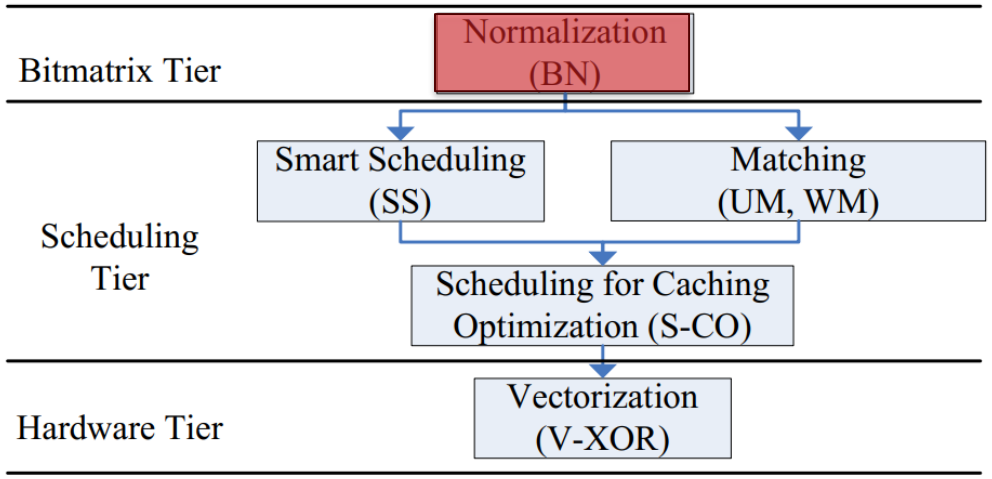

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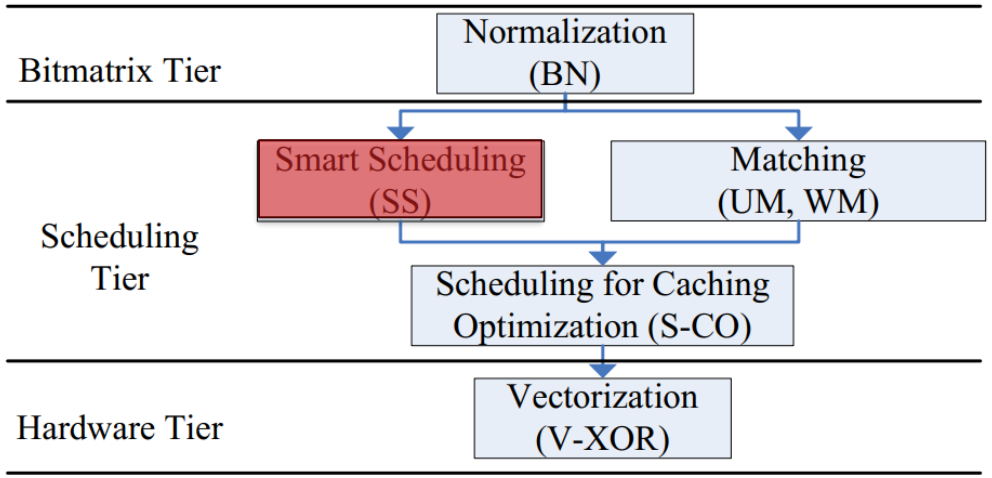
Smart Scheduling (SS)

- Utilize both message and computed parities



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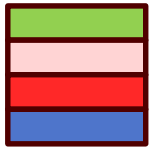

3 XORs

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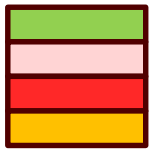

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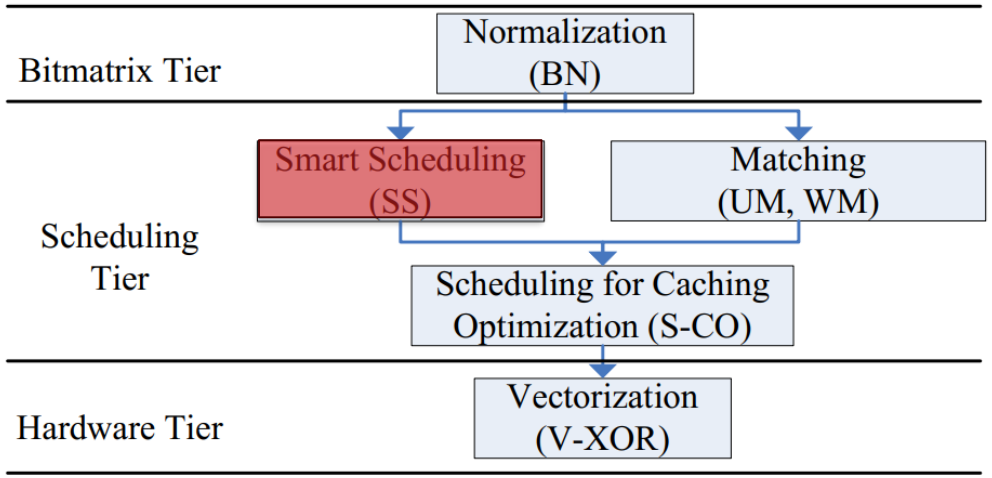

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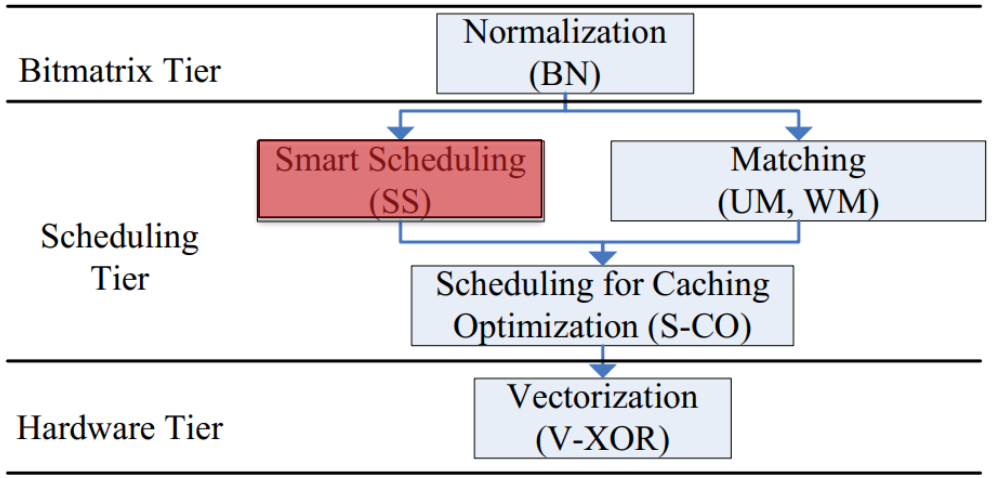

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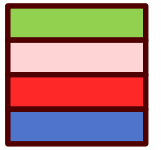

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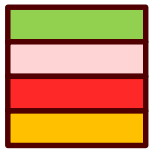

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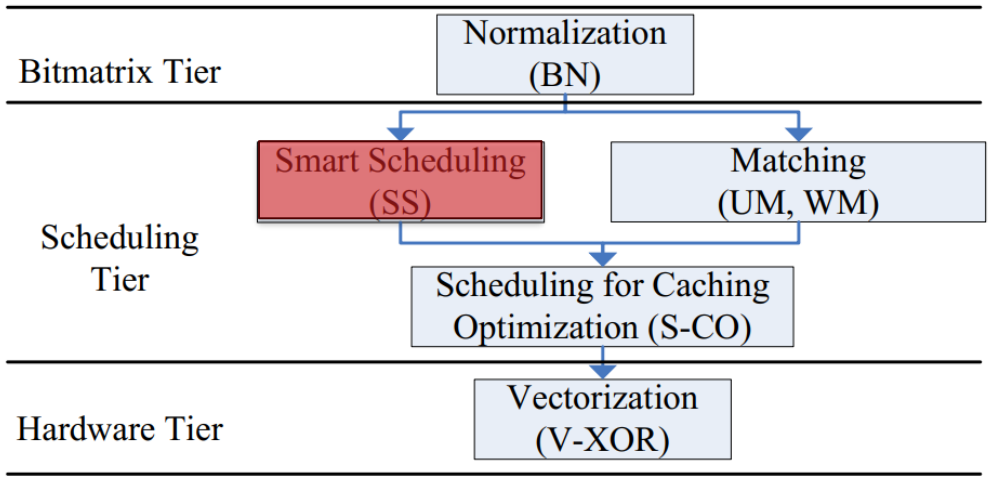

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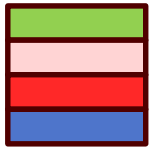

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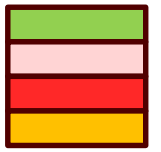

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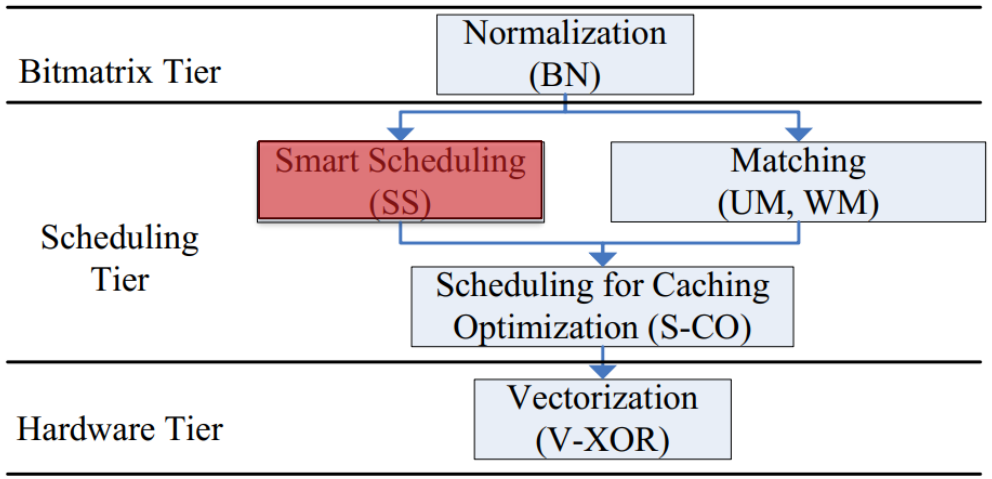

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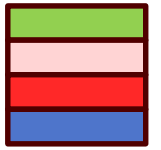

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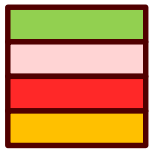

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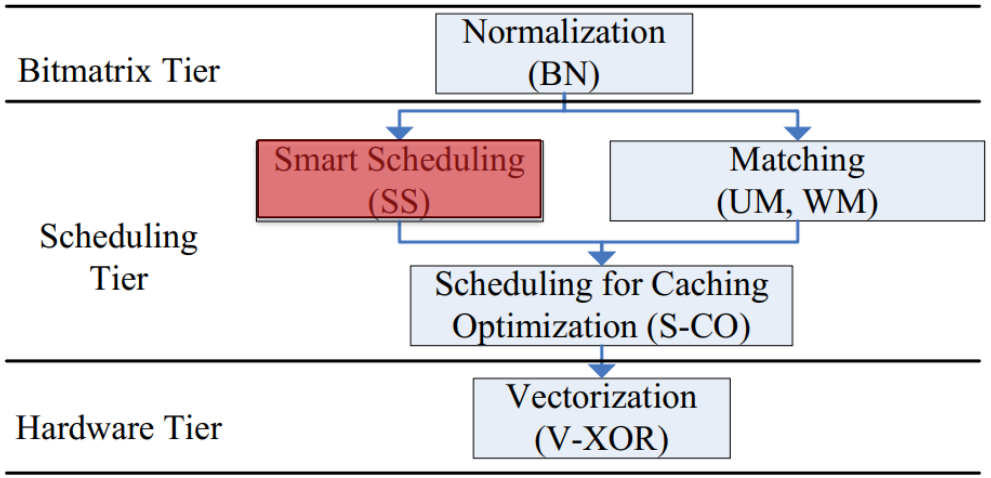

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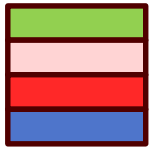

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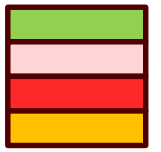

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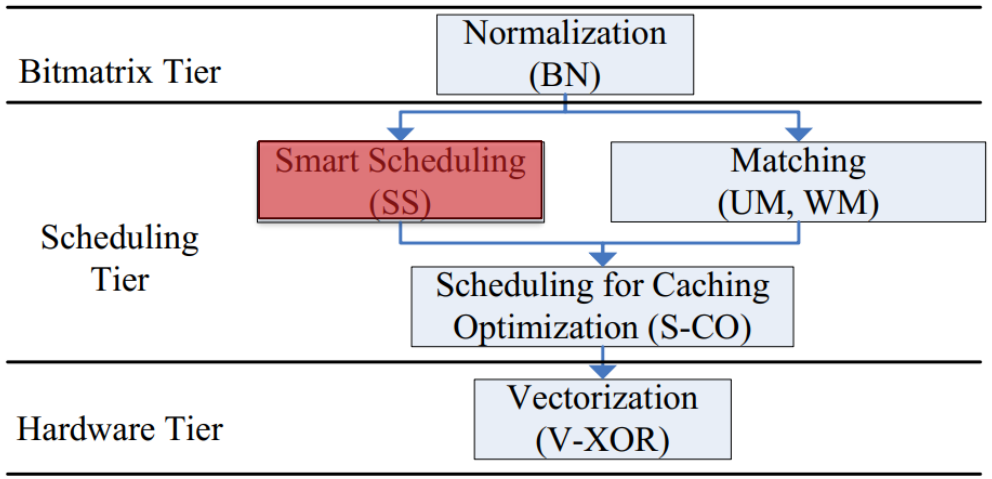

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Matching (UM, WM)

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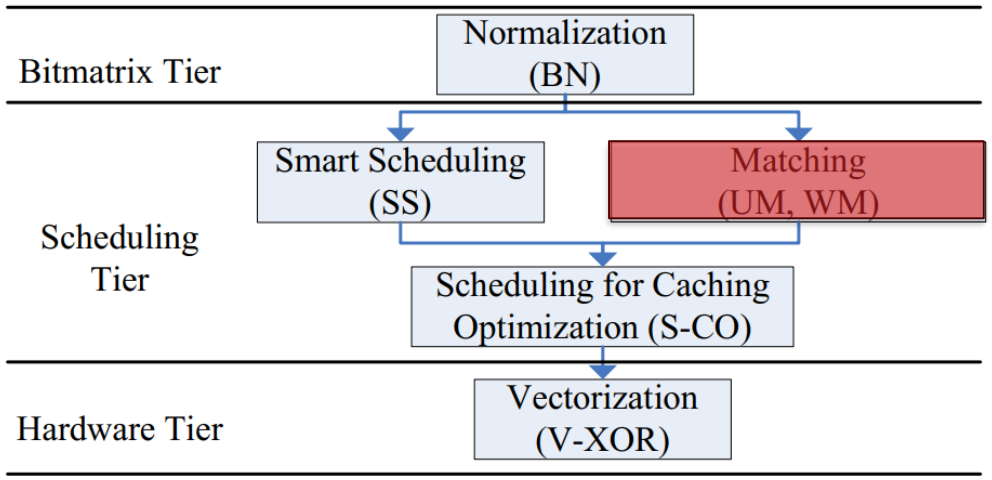

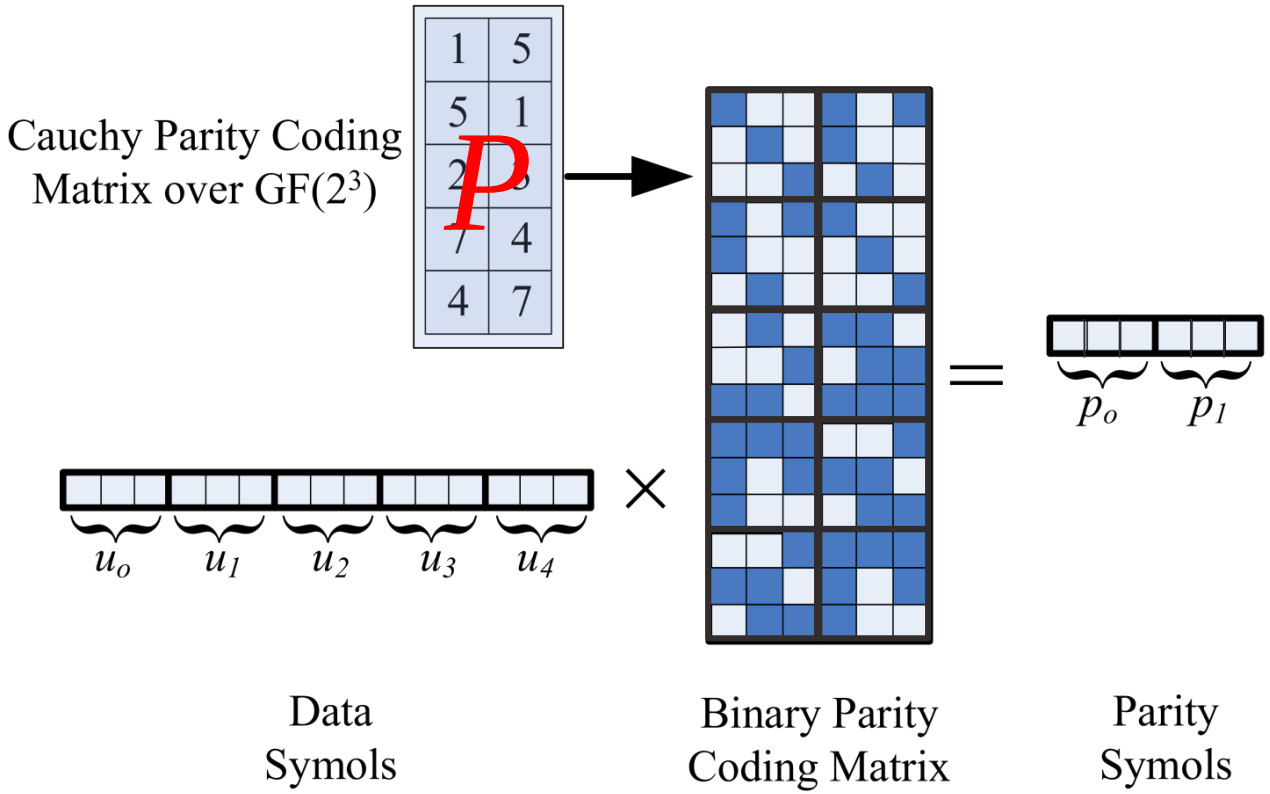

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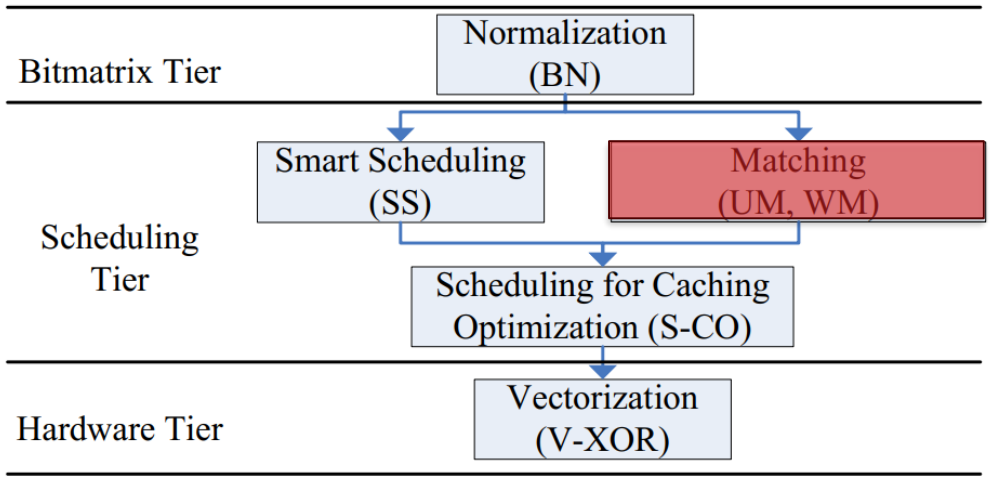

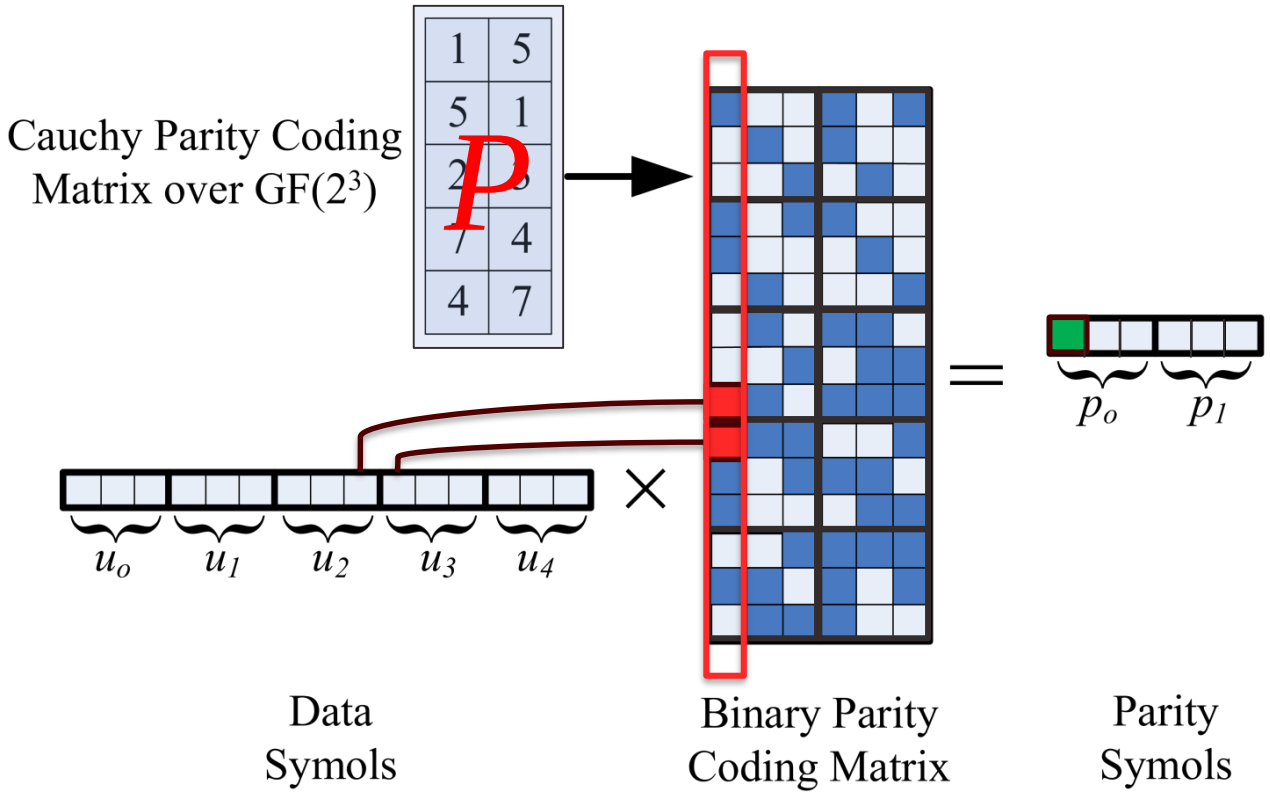

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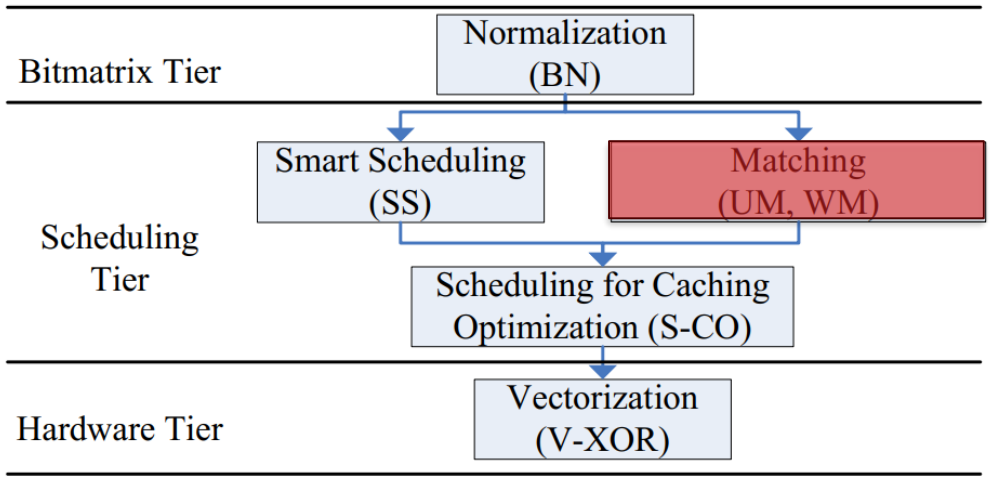

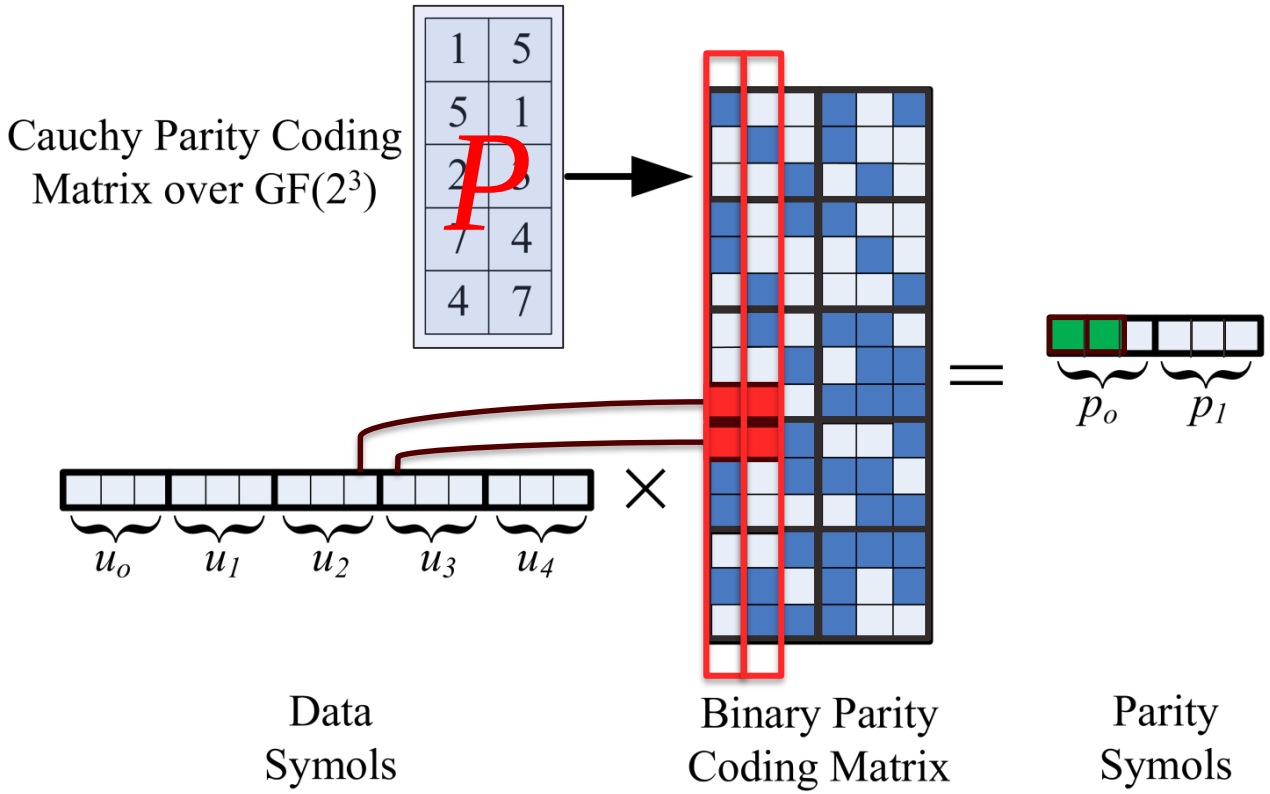

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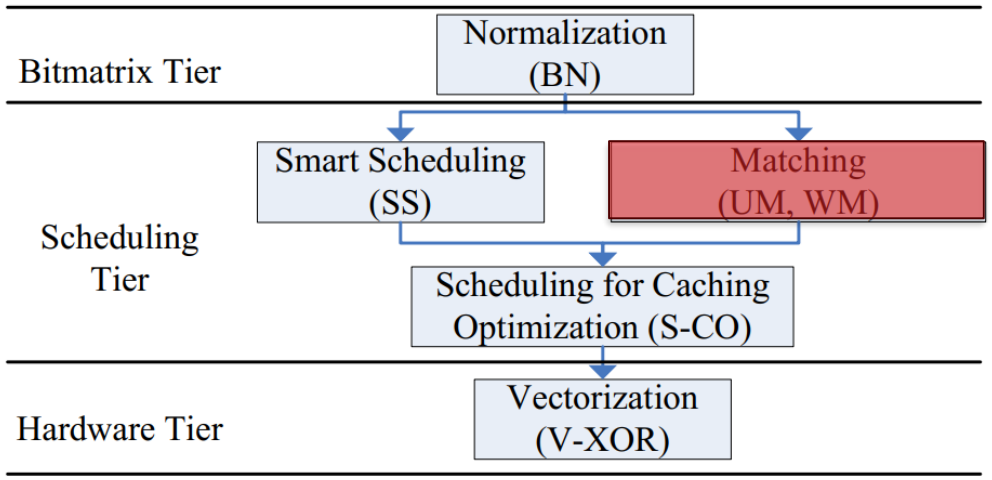

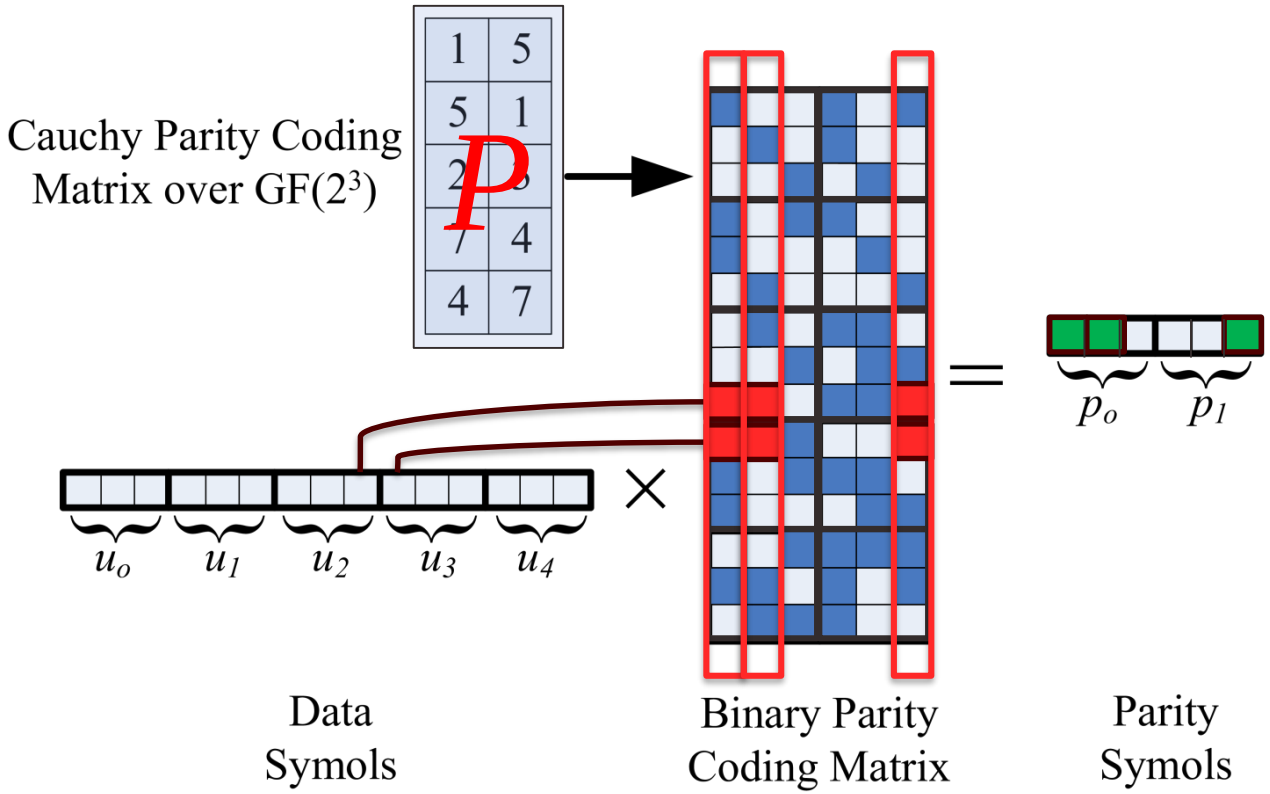

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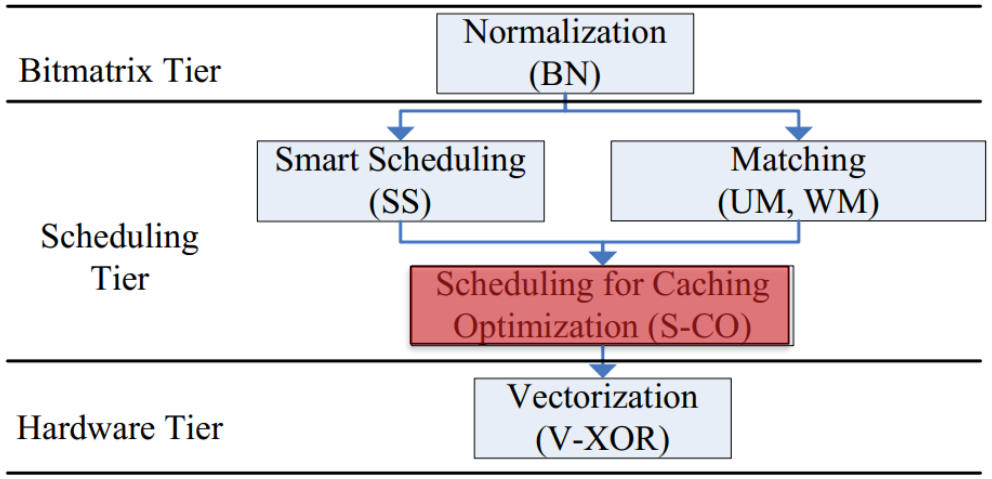

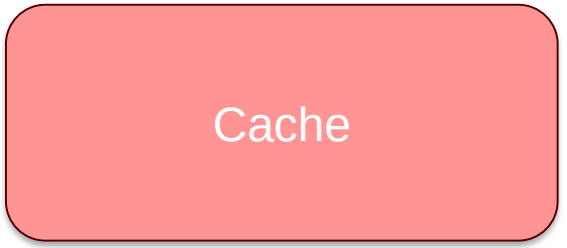

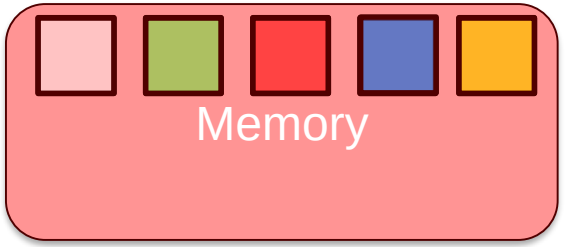

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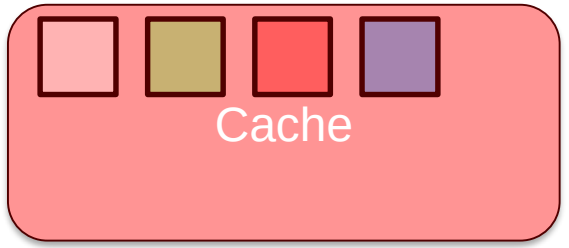

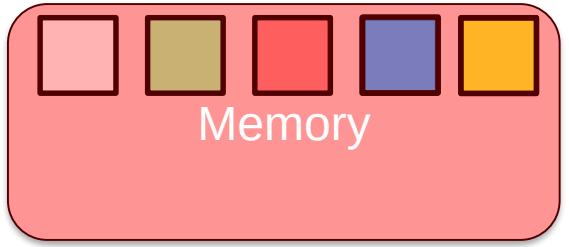

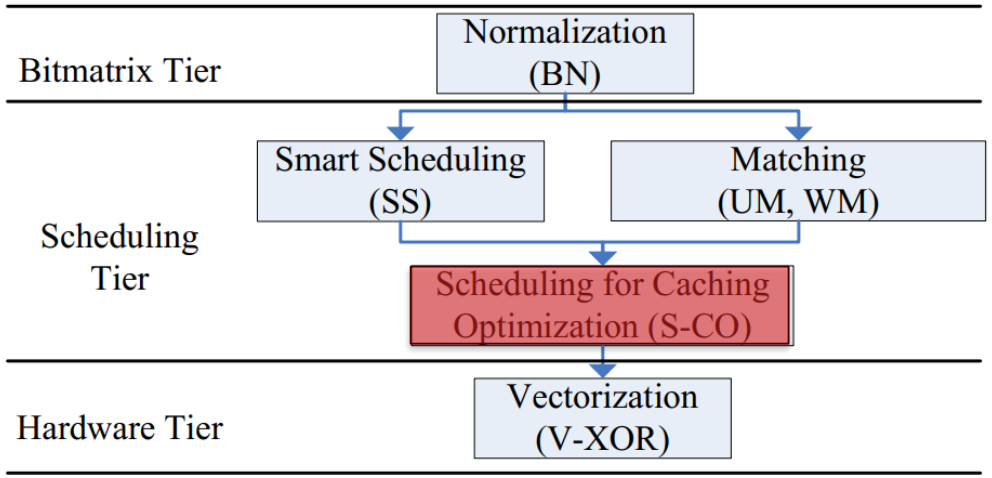

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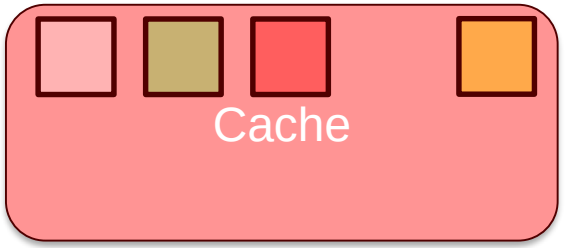

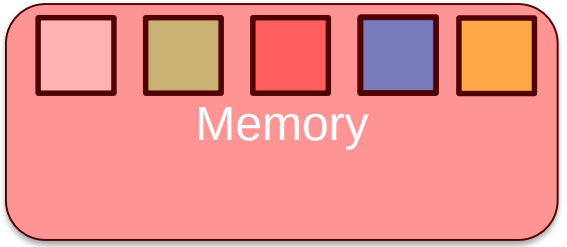

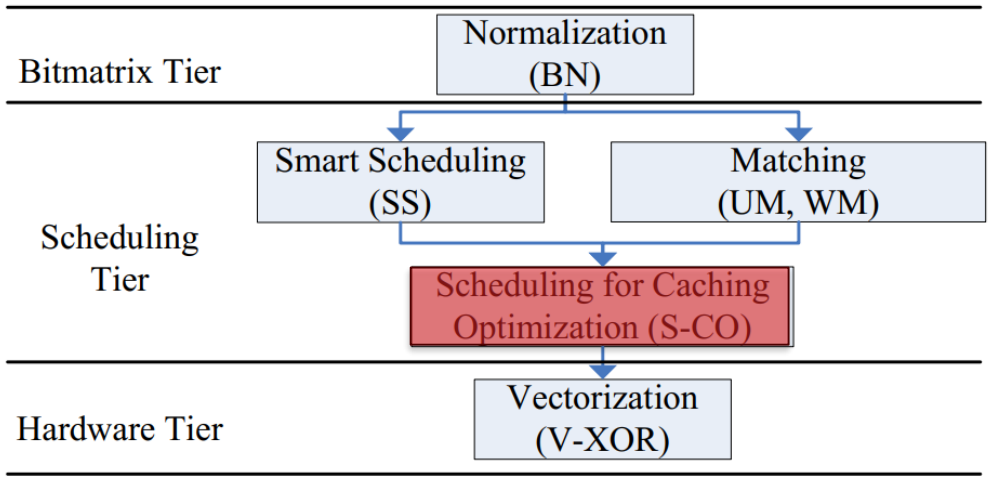

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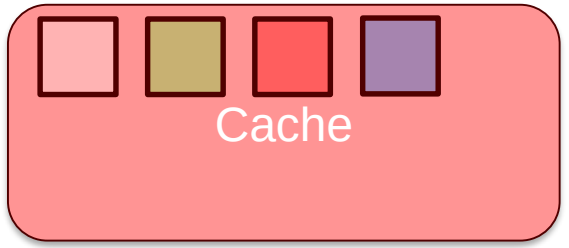

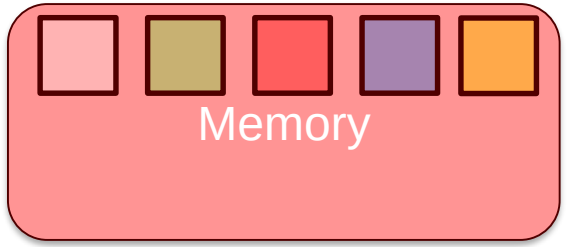

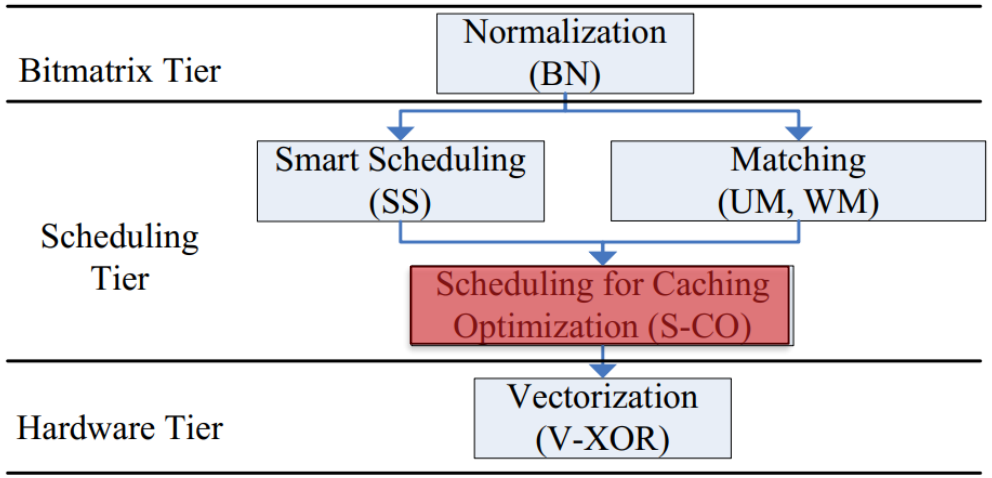

Jianqiang Luo, Mochan Shrestha, Lihao Xu, and James S. Plank. Efficient encoding schedules for XOR-based erasure codes. IEEE Transactions on Computers, 63(9):2259–2272, 2014.

Vectorization

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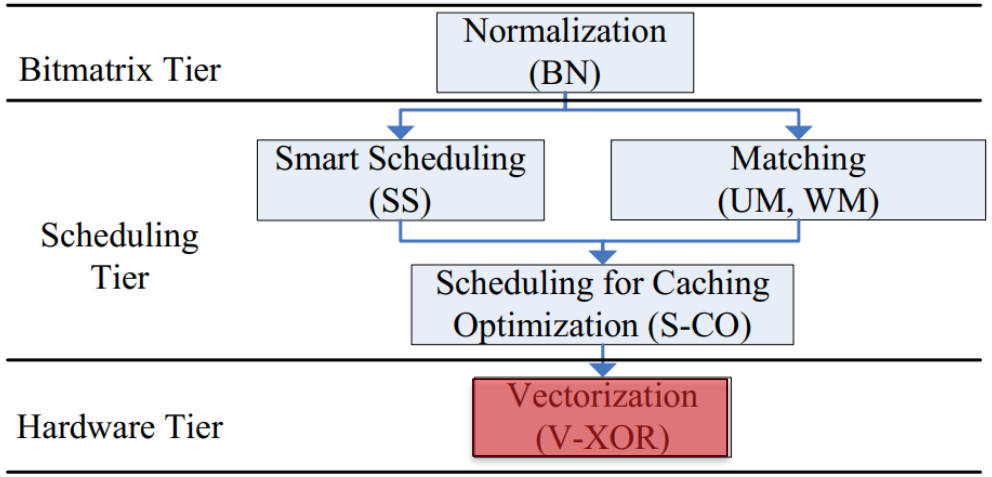
  - AVX2: 256 bits
  - AVX512: 512 bits



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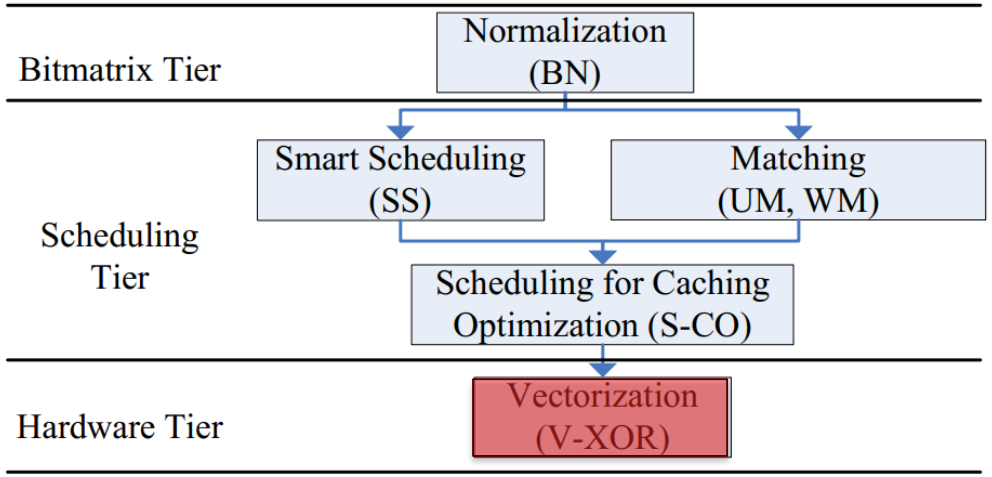

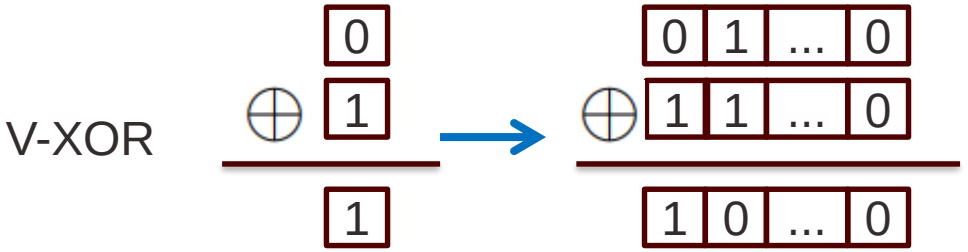

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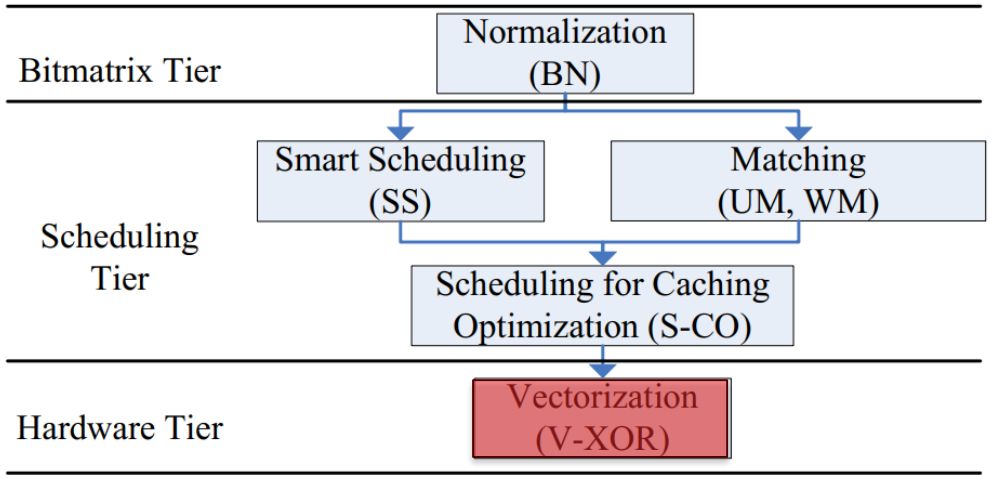

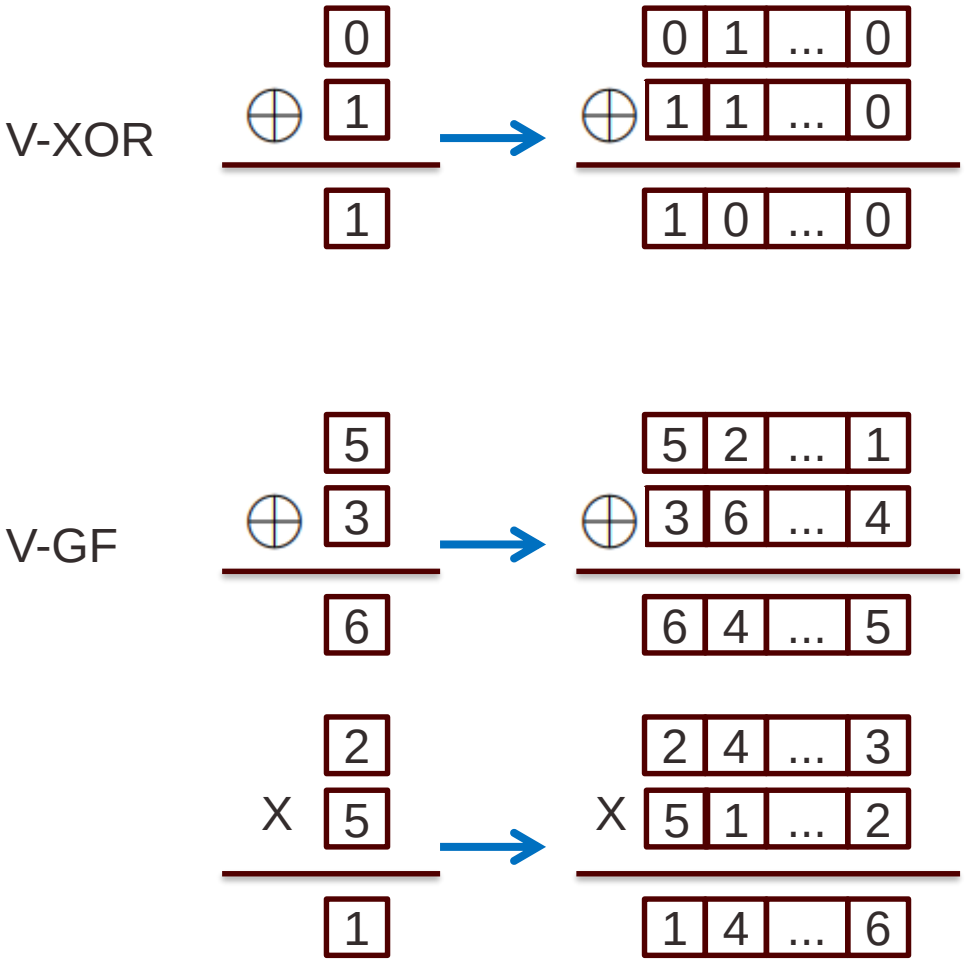

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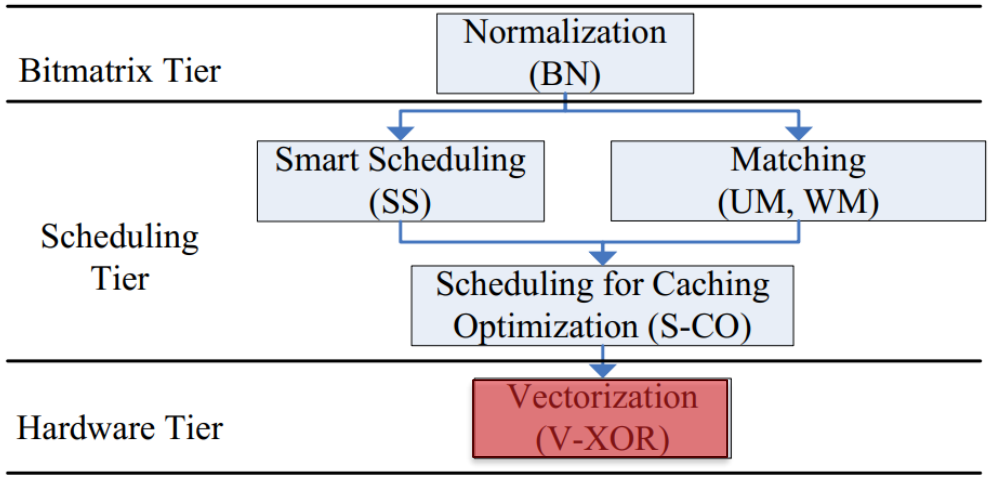

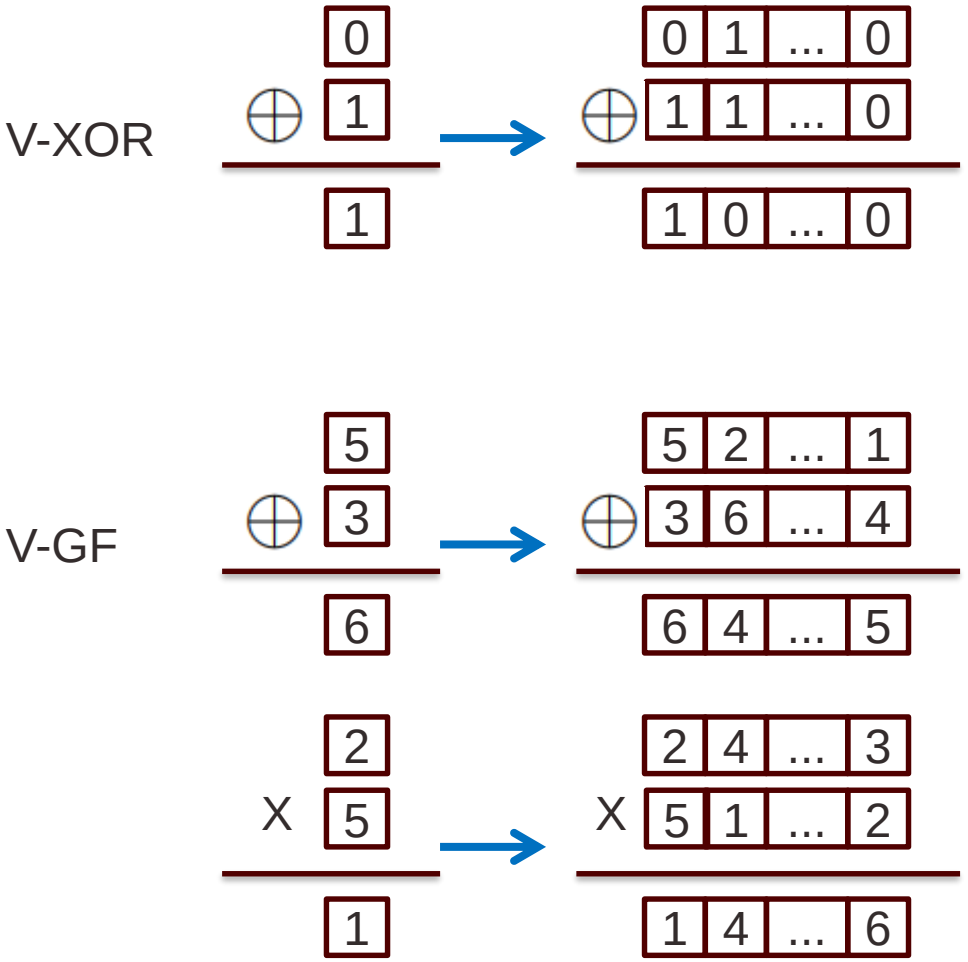

Jerasure 2.0

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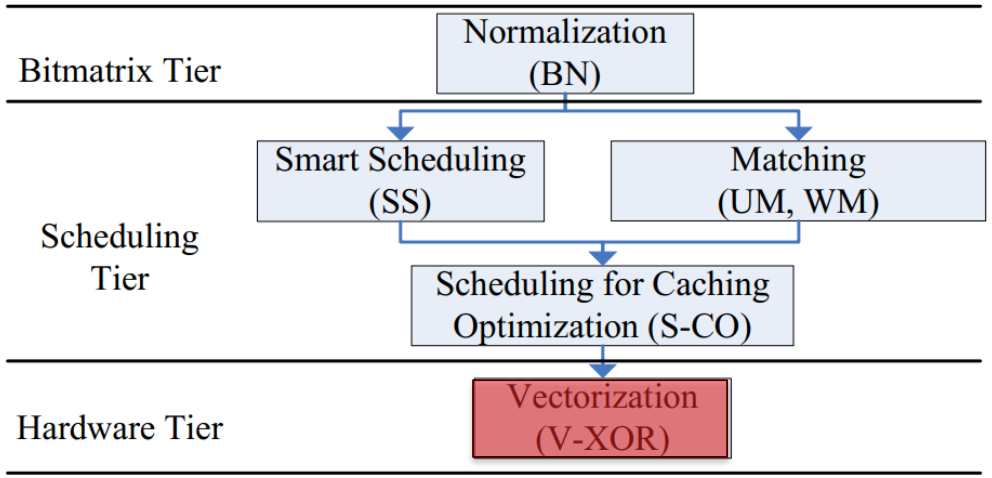

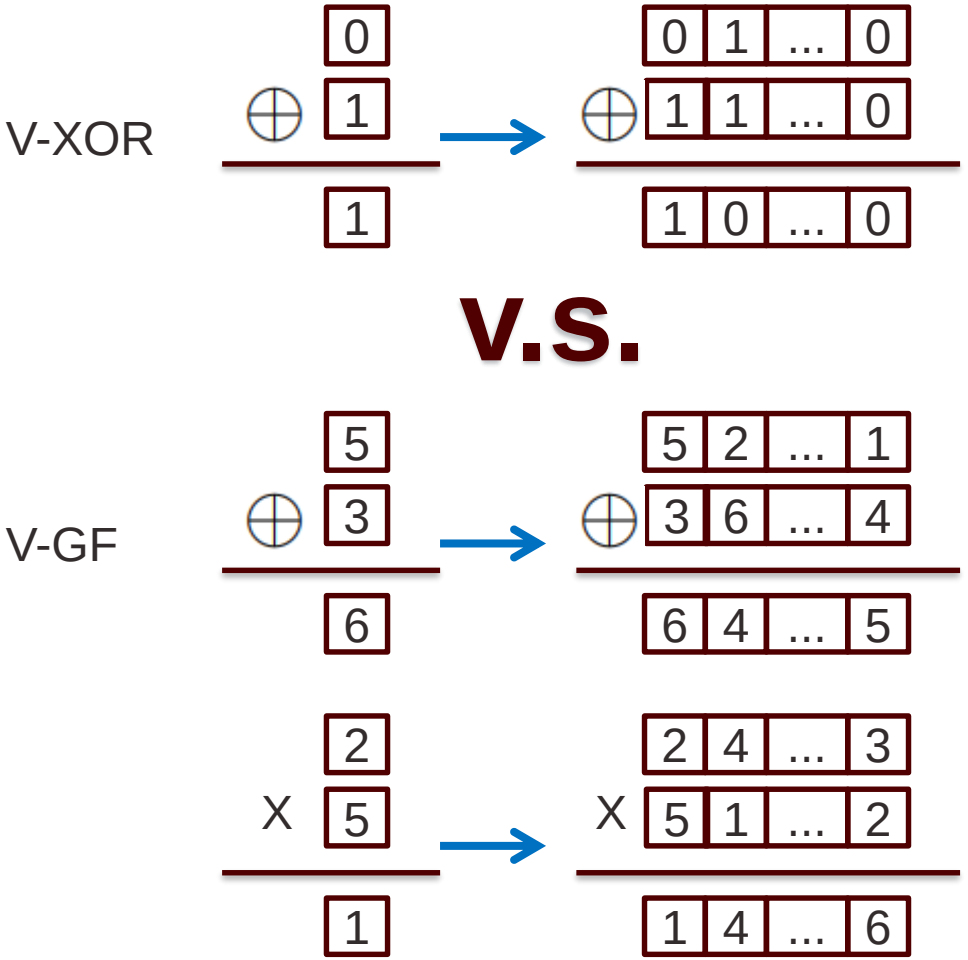

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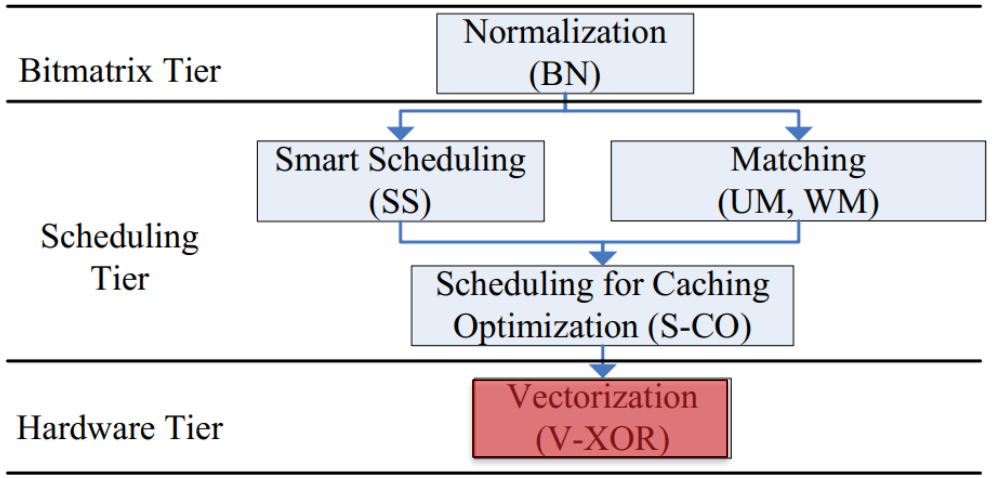
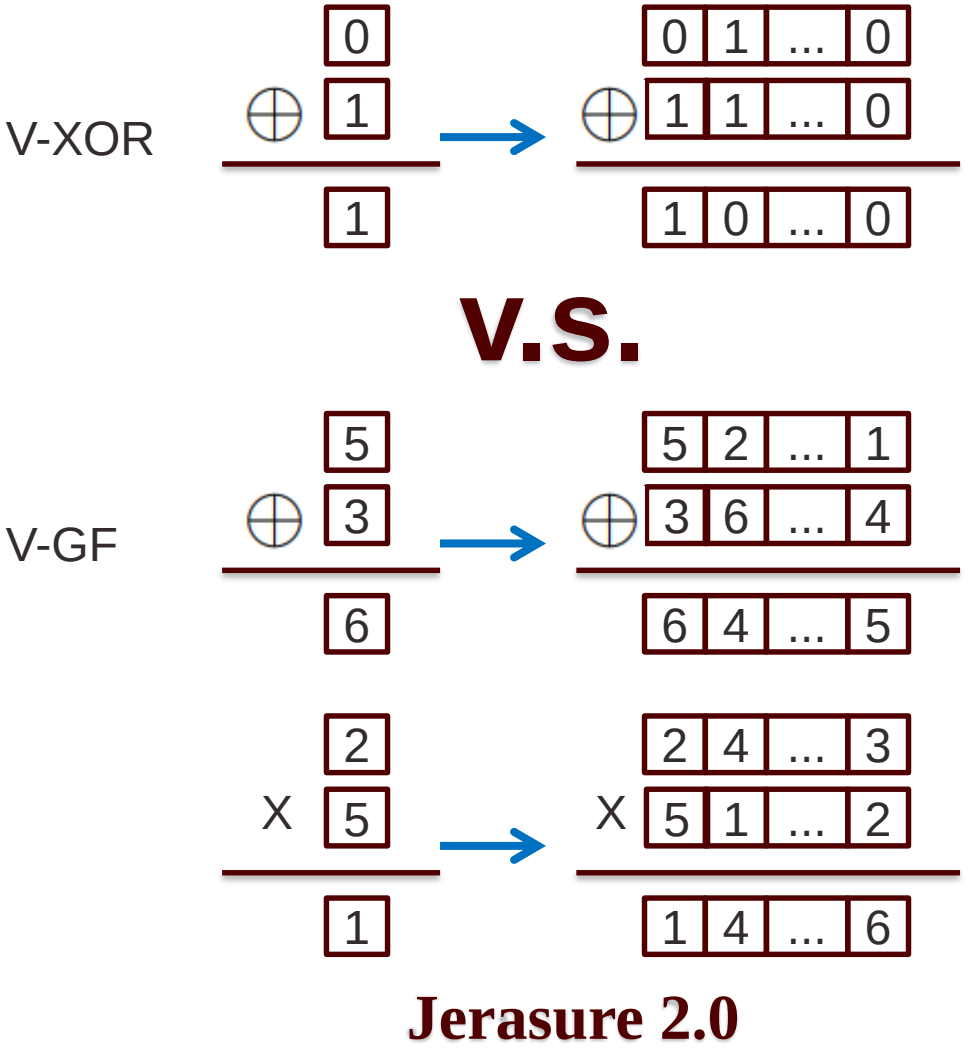




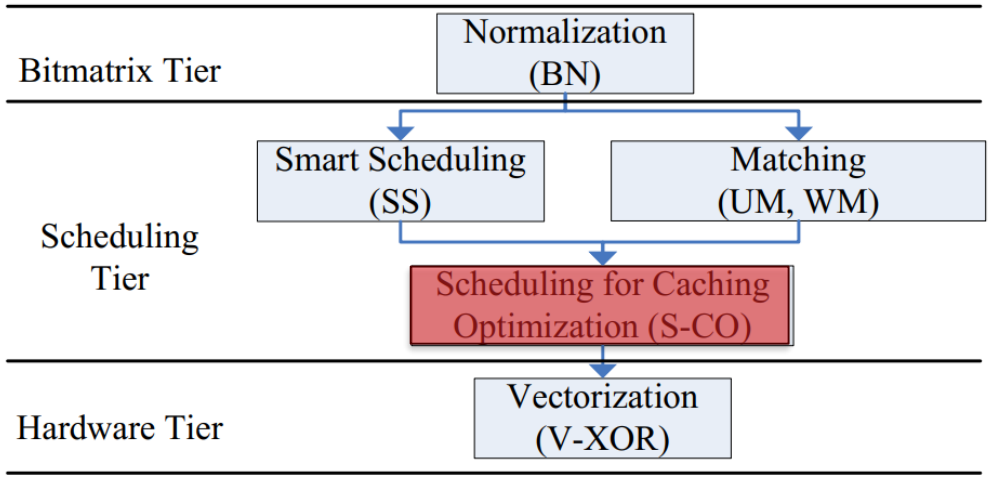
Jerasure 2.0

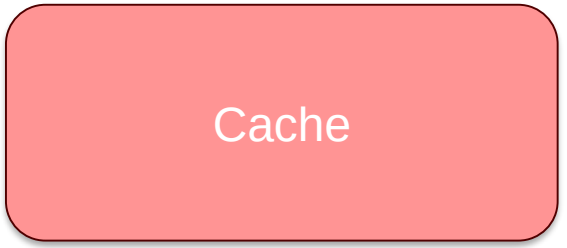
Scheduling - Cache Optimization (S-CO)

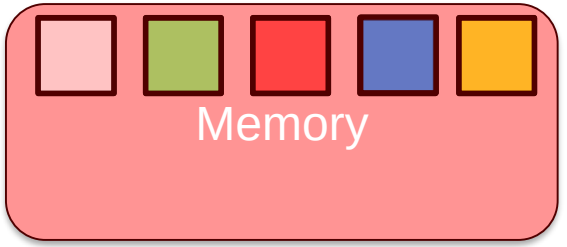
- Reduce cache miss penalty

$$p_0 = u_0 \oplus u_2 \oplus u_3 \oplus u_4$$

$$p_1 = u_0 \oplus u_2 \oplus u_3 \oplus u_5$$







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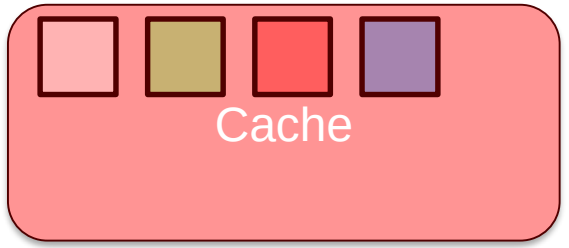
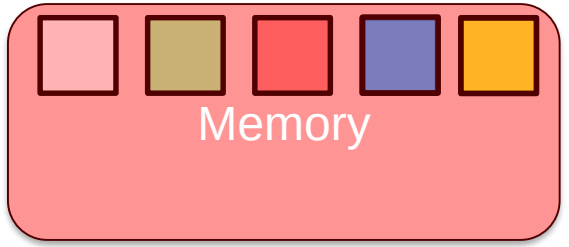
$u_0 \rightarrow p_0, p_1, p_{2\ldots}$

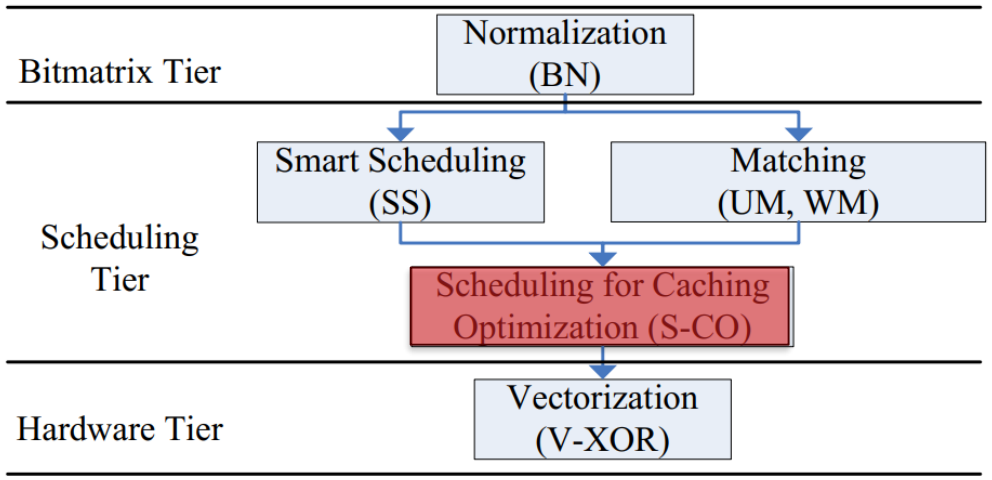
$u_1 \rightarrow p_2, p_3, p_{5\ldots}$

$u_2 \rightarrow p_0, p_1, p_{4\ldots}$

$u_3 \rightarrow p_2, p_6, p_{8\ldots}$







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Question to Answer

- Most effective technique(s)?
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Individual Techniques

Table 1: Performance improvements by individual techniques

(n,k,w)	The number of XOR's in the baseline code	Reduction in the number of XOR's				Throughput increase	
		BN	SS	UM	WM	S-CO	V-XOR
(8,6,4)	104	42.31%	17.31%	31.73%	31.73%	2.14%	98.44%
(8,6,8)	362	53.31%	33.70%	34.53%	34.81%	0.52%	126.36%
(9,6,4)	152	32.89%	19.74%	32.89%	32.89%	3.54%	90.48%
(9,6,8)	549	44.63%	29.14%	38.25%	38.25%	4.51%	152.87%
(10,6,4)	200	27.50%	22.00%	36.00%	36.00%	0.60%	91.30%
(10,6,8)	736	40.90%	28.80%	38.59%	38.59%	1.23%	130.71%
(12,8,4)	256	23.44%	23.44%	35.94%	35.94%	9.21%	118.26%
(12,8,8)	1028	36.38%	24.81%	39.79%	39.79%	0.10%	156.88%
(16,10,4)	496	18.95%	21.77%	37.70%	37.70%	8.28%	138.93%
(16,10,8)	1920	30.16%	21.98%	40.89%	40.89%	5.00%	179.00%
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Individual Techniques

XOR-based Vectorization

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Bitmatrix Normalization

Unweighted Matching

Weighted Matching

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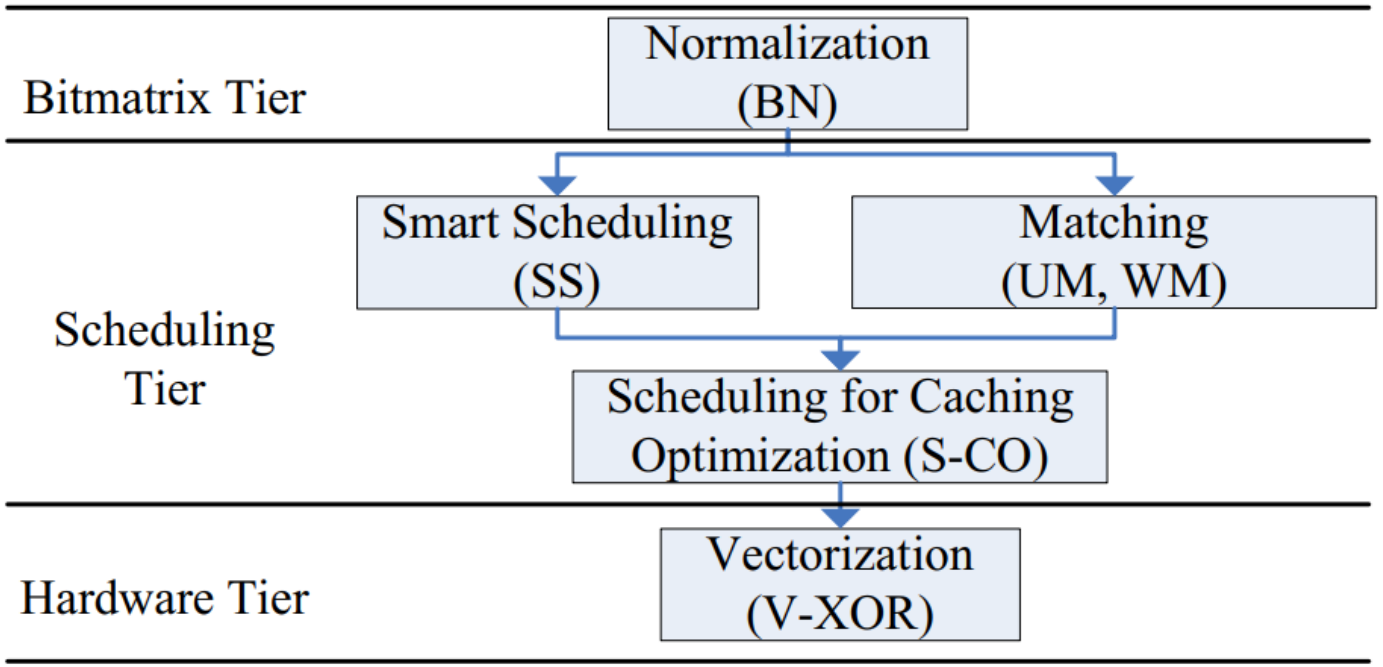

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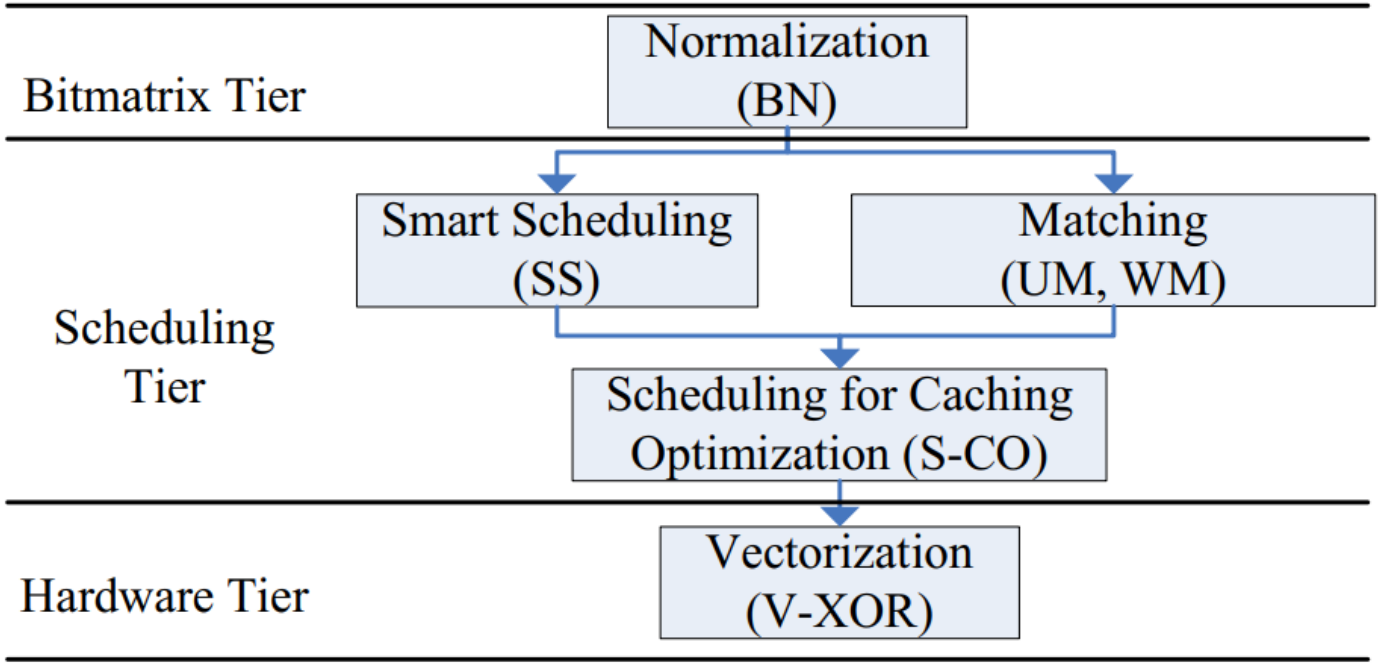

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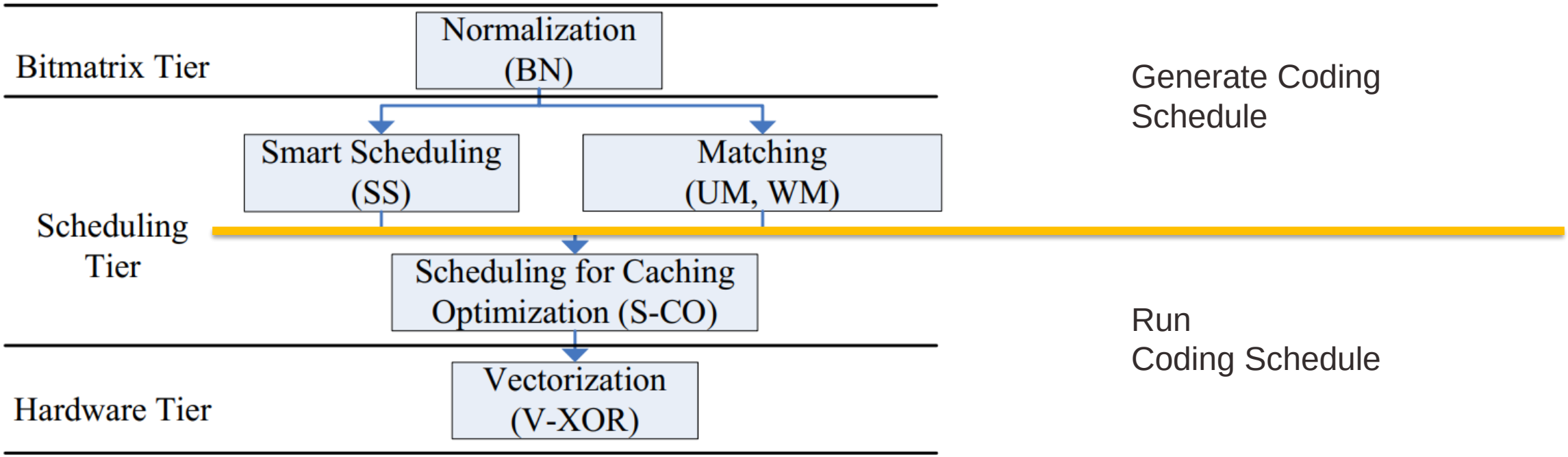

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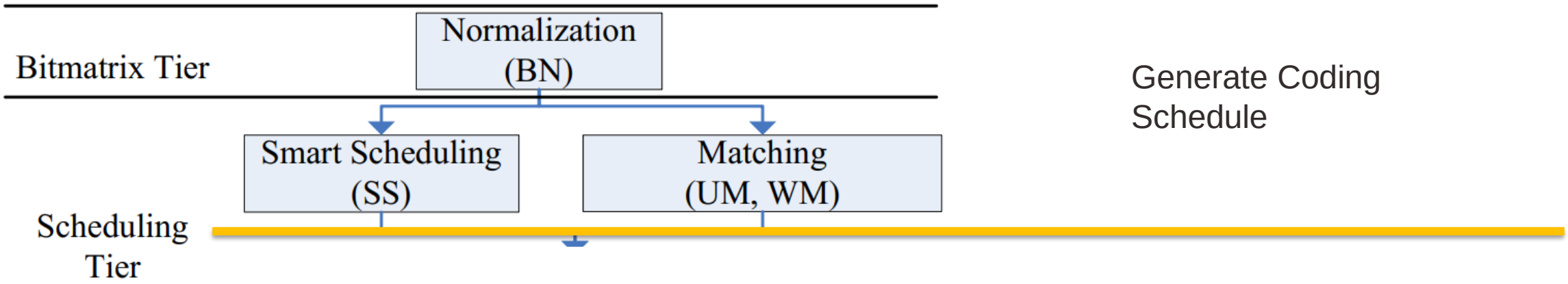

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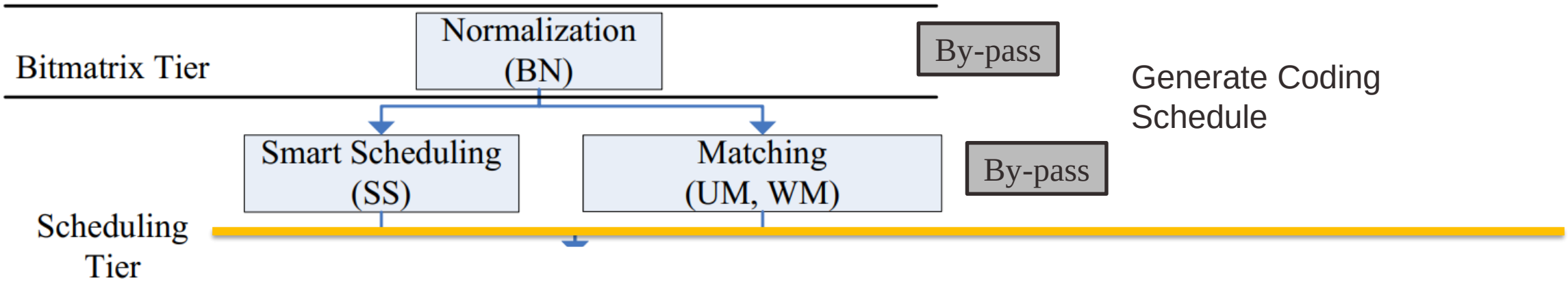

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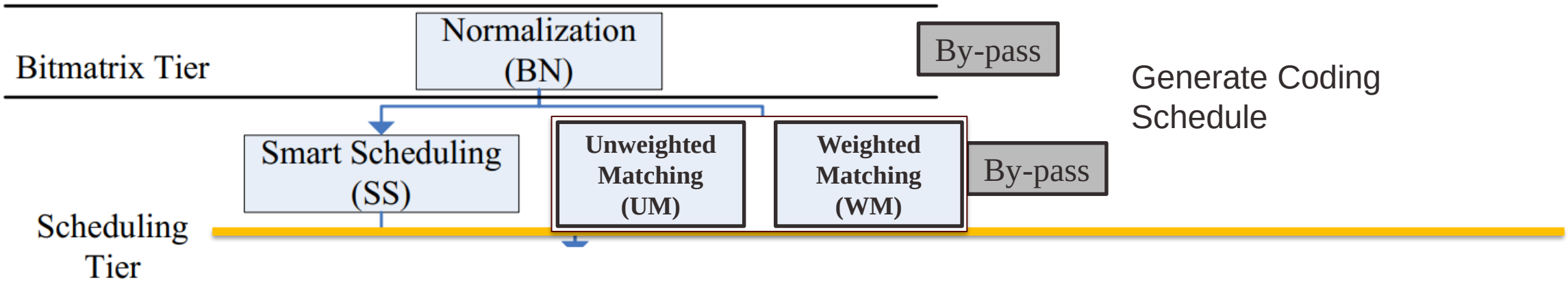

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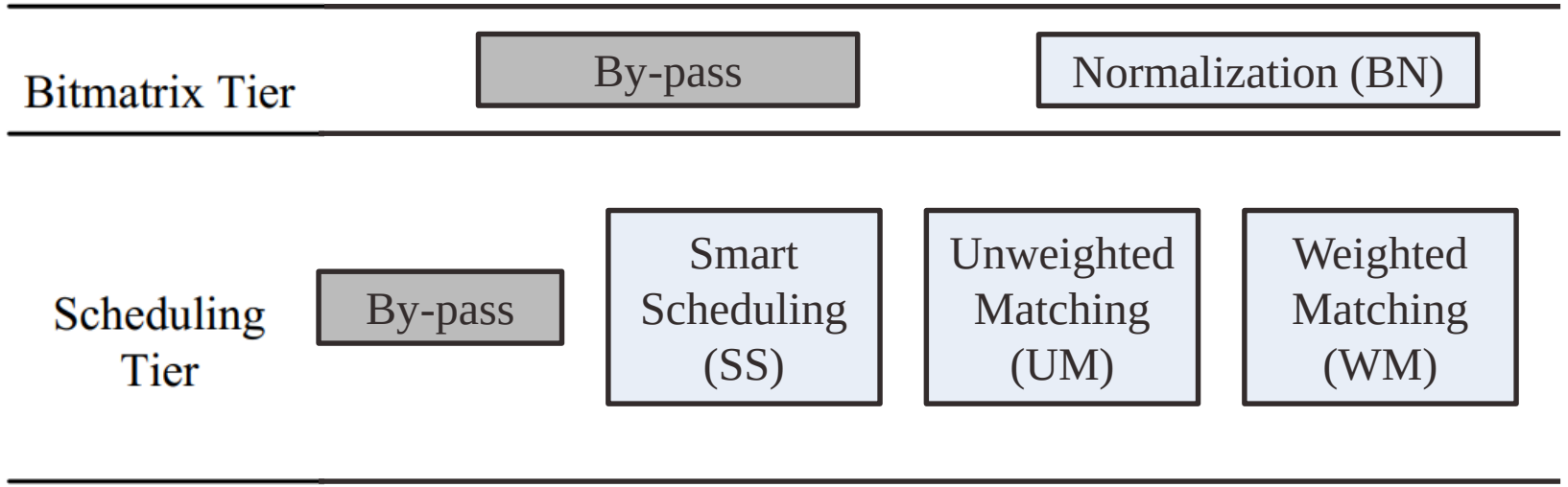
Combinations (i,j)-strategy



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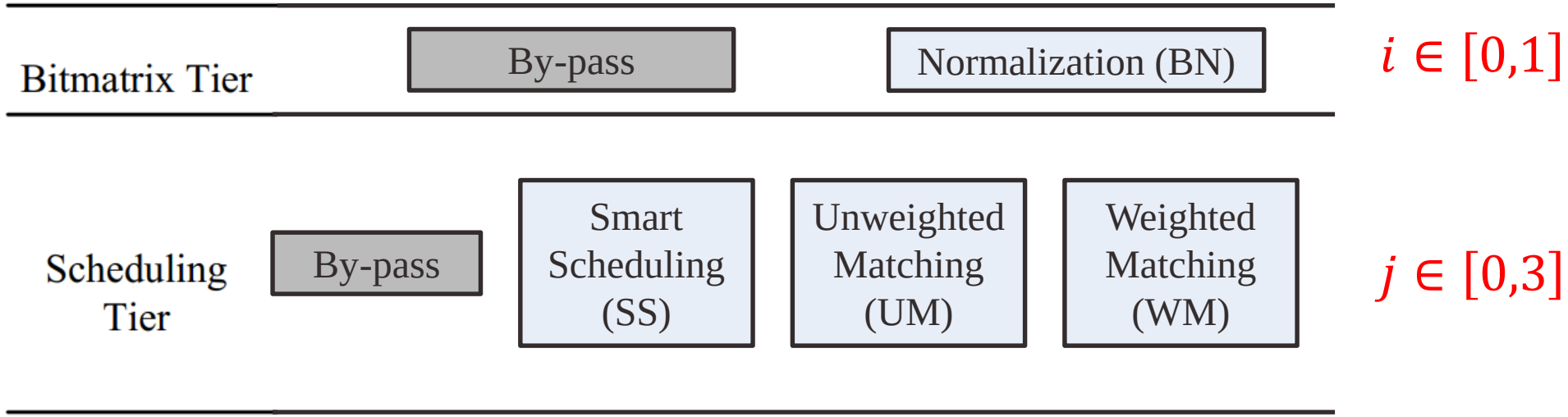
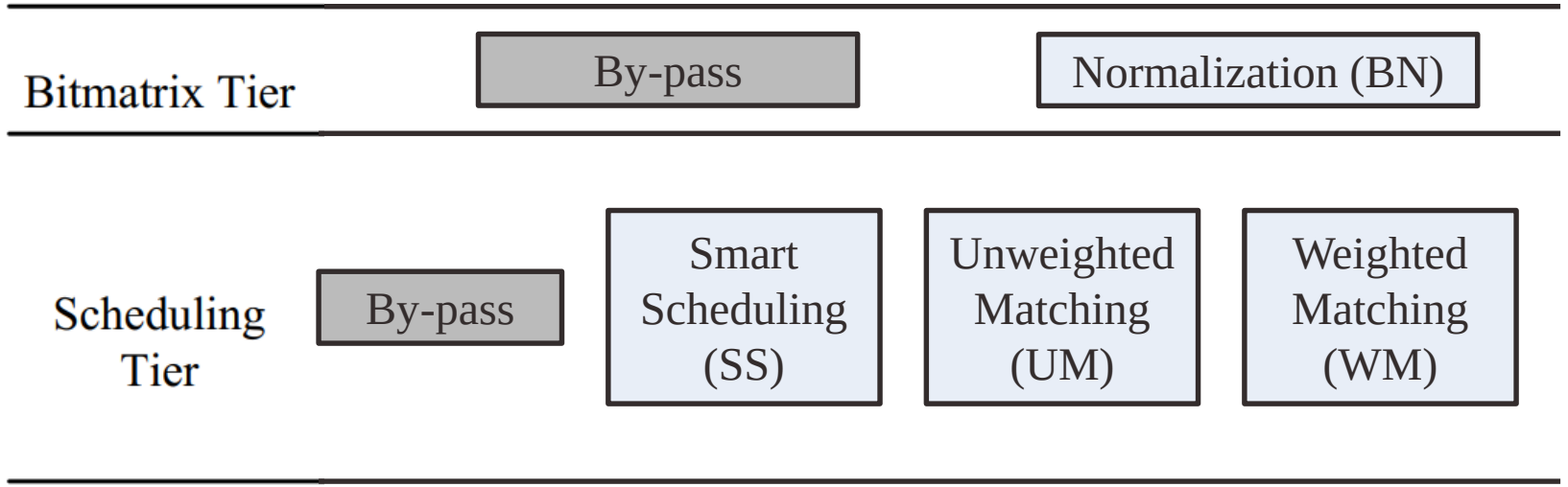


$i \in [0,1]$

$j \in [0,3]$

Combinations (i,j)-strategy

Example: strategy-(1,1)



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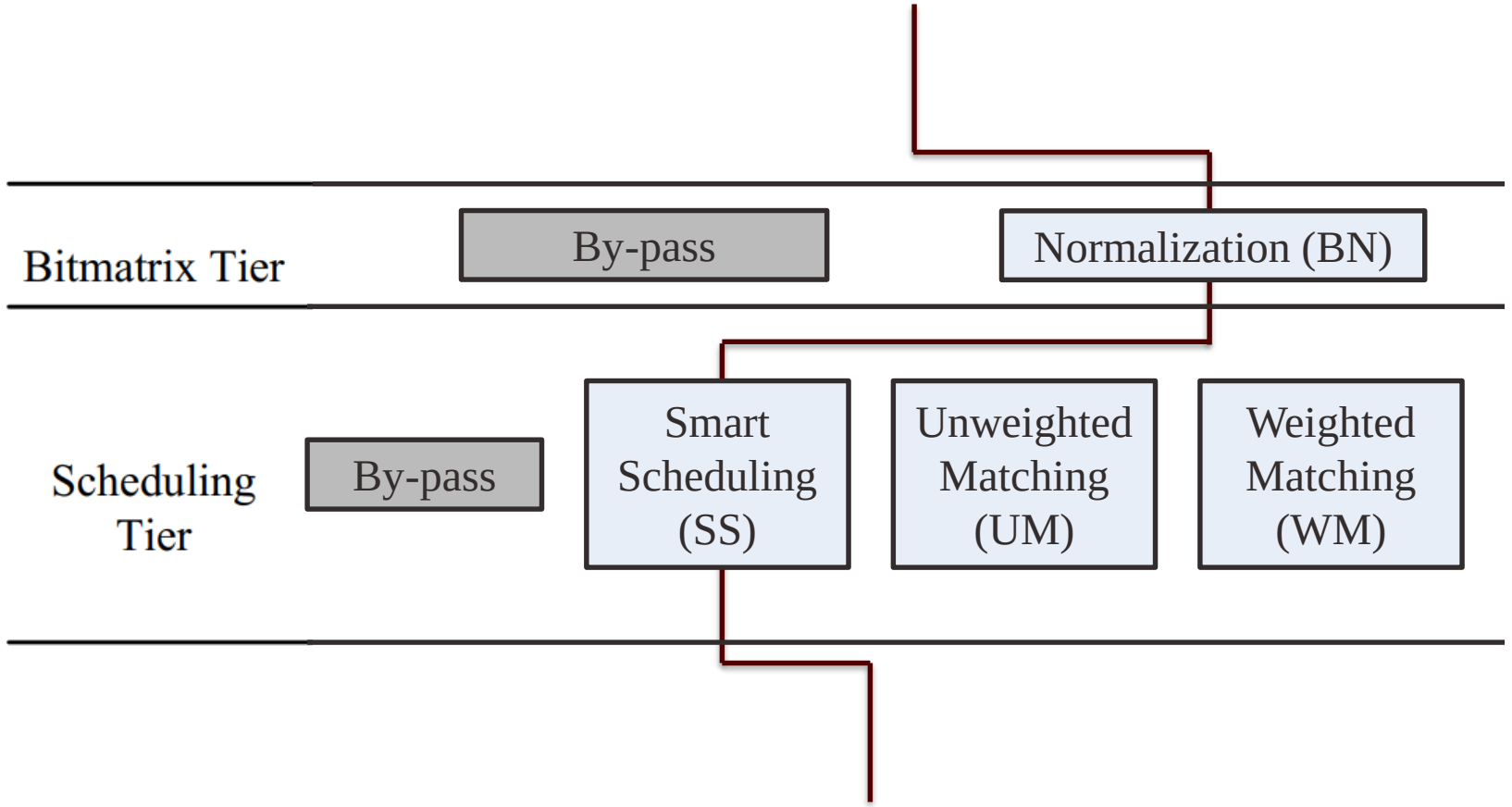

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Contents

- Motivation
- Background and Review

- Evaluating Individual Techniques
- Find the Best Strategy under Optimized Bitmatrix
- Proposed Coding Procedure and Evaluation

- Conclusion

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Choice of Cauchy Matrix

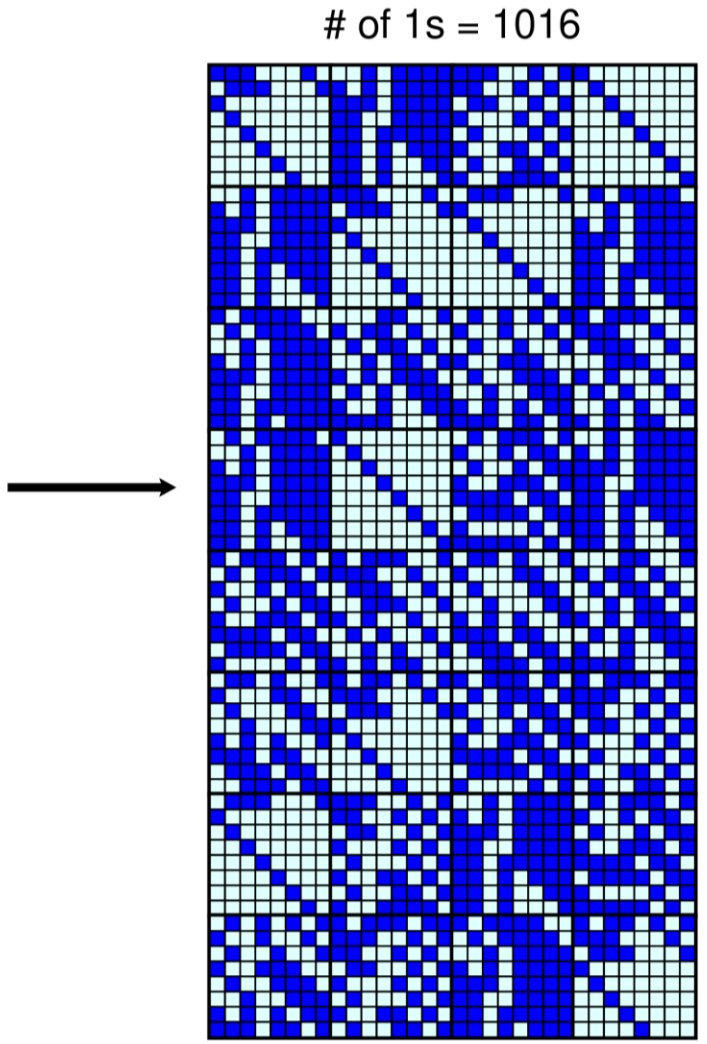
- Different X,Y array yields different Cauchy Matrix

Choice of Cauchy Matrix

- Different *X*,*Y* array yields different Cauchy Matrix

X = 6 1 7 3
Y = 2 5 10 0 8 9 4 11

71	244	167	1
244	71	142	122
61	152	170	157
122	1	186	244
93	157	150	152
150	173	93	221
142	167	244	186
170	221	61	173

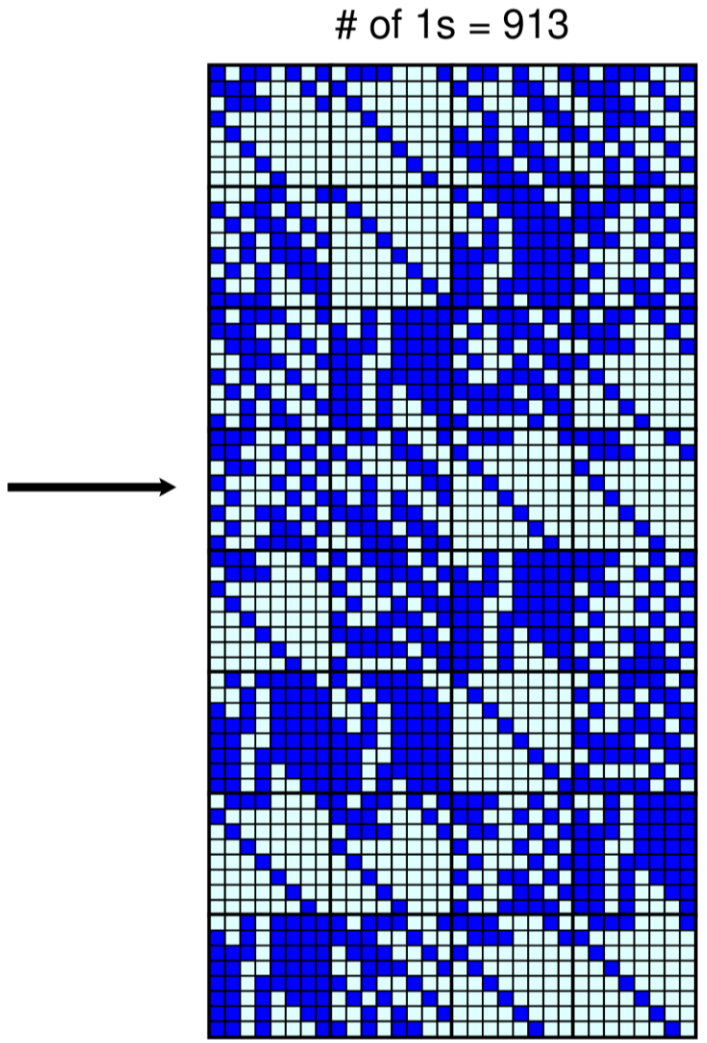


Choice of Cauchy Matrix

- Different *X*,*Y* array yields different Cauchy Matrix

X = 1 11 6 0
Y = 9 10 8 4 5 7 3 2

173	142	150	157
152	1	61	221
157	244	93	173
167	150	142	71
71	93	244	167
122	61	1	186
142	173	167	244
244	157	71	142



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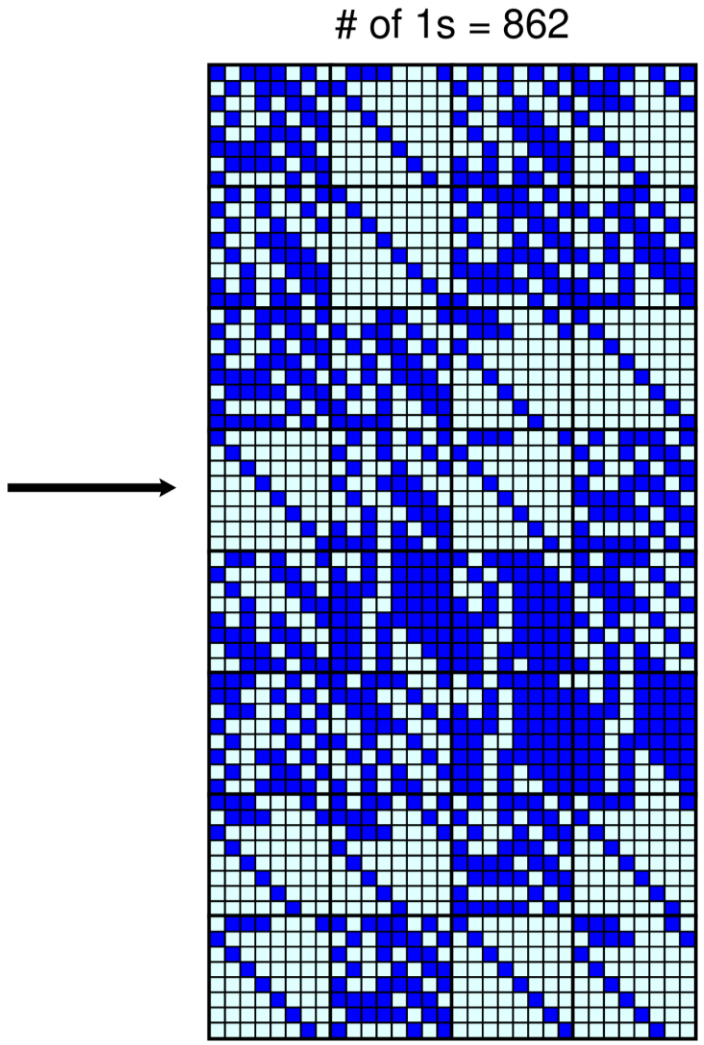
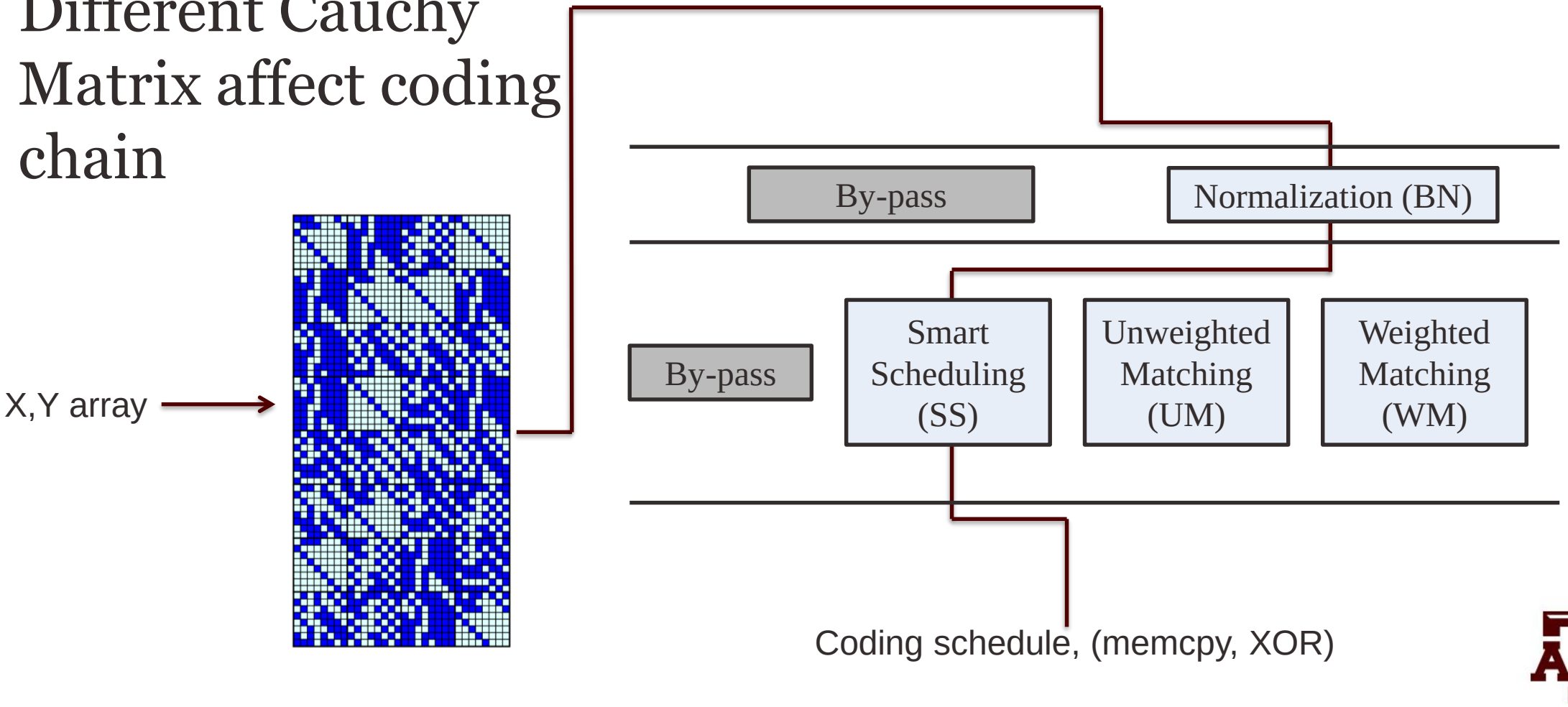
142	93	1	71



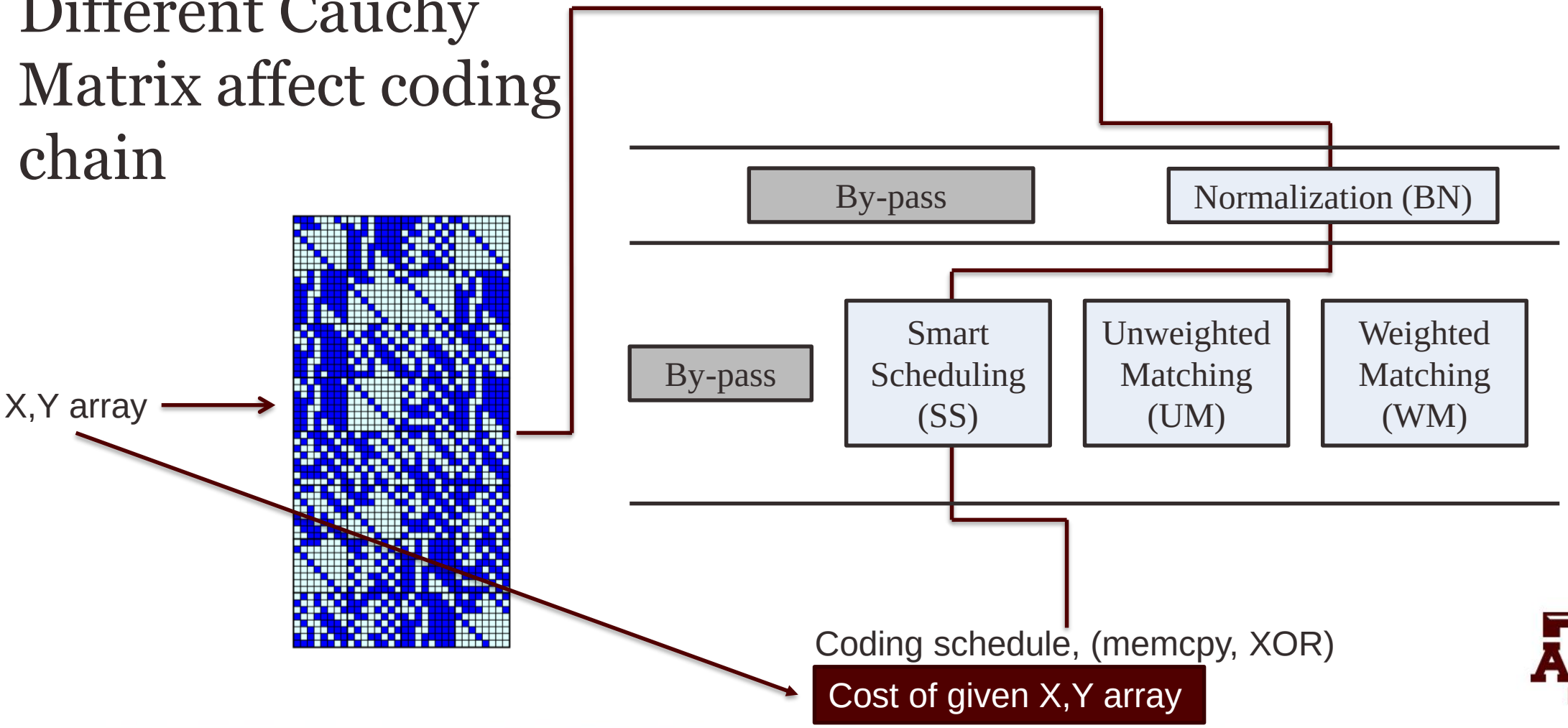
Choice of Cauchy Matrix

- Different Cauchy Matrix affect coding chain



Choice of Cauchy Matrix

- Different Cauchy Matrix affect coding chain



Bitmatrix Optimization

- Individual bitmatrix optimization for all (i,j)-strategies
- Simulated Annealing and Genetic Algorithm
- # of operations as cost

[no_opt by SA by GA], # of ops in schedule

(i,j)	$(n,k,w)=(8,6,4)$			$(n,k,w)=(9,6,4)$			$(n,k,w)=(10,6,4)$			$(n,k,w)=(12,8,4)$			$(n,k,w)=(16,10,4)$		
(0,0)	112	**77**	**77**	164	122	**117**	216	173	**162**	272	**232**	**232**	520	**462**	464
(0,1)	94	70	**68**	134	102	**100**	172	137	**134**	212	190	**188**	412	**368**	**368**
(0,2)	90	72	**68**	127	103	**101**	164	134	**132**	204	186	**180**	376	**344**	345
(0,3)	90	72	**68**	127	102	**101**	164	**132**	**132**	204	184	**182**	376	**343**	345
(1,0)	68	**58**	**58**	114	99	**98**	161	142	**141**	212	**198**	**198**	426	**419**	**419**
(1,1)	64	**58**	**58**	99	90	**89**	138	**120**	**120**	189	174	**171**	365	**352**	**352**
(1,2)	64	58	**57**	98	**87**	**87**	133	**118**	**118**	176	165	**164**	326	317	**316**
(1,3)	64	58	**57**	98	90	**87**	132	**118**	**118**	175	**164**	**164**	326	**316**	**316**

(i,j)	$(n,k,w)=(8,6,8)$			$(n,k,w)=(9,6,8)$			$(n,k,w)=(10,6,8)$			$(n,k,w)=(12,8,8)$			$(n,k,w)=(16,10,8)$		
(0,0)	378	291	**247**	573	467	**425**	768	611	**582**	1060	880	**841**	1968	1685	**1681**
(0,1)	256	234	**225**	413	393	**349**	556	518	**479**	805	740	**684**	1546	1432	**1374**
(0,2)	286	227	**217**	408	346	**321**	532	474	**450**	726	636	**591**	1304	1180	**1170**
(0,3)	286	216	**197**	408	357	**329**	532	460	**450**	726	636	**627**	1304	1180	**1170**
(1,0)	185	151	**142**	328	286	**262**	467	434	**419**	686	613	**563**	1389	1293	**1246**
(1,1)	164	155	**133**	285	270	**230**	411	383	**371**	593	557	**544**	1264	1184	**1133**
(1,2)	167	143	**134**	272	244	**225**	377	343	**335**	520	487	**462**	998	951	**922**
(1,3)	167	144	**130**	273	249	**233**	377	**337**	**337**	520	473	**467**	995	941	**932**

[no_opt by SA by GA], # of ops in schedule

(i,j)	$(n,k,w)=(8,6,4)$			$(n,k,w)=(9,6,4)$			$(n,k,w)=(10,6,4)$			$(n,k,w)=(12,8,4)$			$(n,k,w)=(16,10,4)$		
(0,0)	112	**77**	**77**	164	122	**117**	216	173	**162**	272	**232**	**232**	520	**462**	464
(0,1)	94	70	**68**	134	102	**100**	172	137	**134**	212	190	**188**	412	**368**	**368**
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(1,0)	68	**58**	**58**	114	99	**98**	161	142	**141**	212	**198**	**198**	426	**419**	**419**
(1,1)	64	**58**	**58**	99	90	**89**	138	**120**	**120**	189	174	**171**	365	**352**	**352**
(1,2)	64	58	**57**	98	**87**	**87**	133	**118**	**118**	176	165	**164**	326	317	**316**
(1,3)	64	58	**57**	98	90	**87**	132	**118**	**118**	175	**164**	**164**	326	**316**	**316**

(i,j)	$(n,k,w)=(8,6,8)$			$(n,k,w)=(9,6,8)$			$(n,k,w)=(10,6,8)$			$(n,k,w)=(12,8,8)$			$(n,k,w)=(16,10,8)$		
(0,0)	378	291	**247**	573	467	**425**	768	611	**582**	1060	880	**841**	1968	1685	**1681**
(0,1)	256	234	**225**	413	393	**349**	556	518	**479**	805	740	**684**	1546	1432	**1374**
(0,2)	286	227	**217**	408	346	**321**	532	474	**450**	726	636	**591**	1304	1180	**1170**
(0,3)	286	216	**197**	408	357	**329**	532	460	**450**	726	636	**627**	1304	1180	**1170**
(1,0)	185	151	**142**	328	286	**262**	467	434	**419**	686	613	**563**	1389	1293	**1246**
(1,1)	164	155	**133**	285	270	**230**	411	383	**371**	593	557	**544**	1264	1184	**1133**
(1,2)	167	143	**134**	272	244	**225**	377	343	**335**	520	487	**462**	998	951	**922**
(1,3)	167	144	**130**	273	249	**233**	377	**337**	**337**	520	473	**467**	995	941	**932**

[no_opt by SA by GA], # of ops in schedule

(i,j)	$(n,k,w)=(8,6,4)$			$(n,k,w)=(9,6,4)$			$(n,k,w)=(10,6,4)$			$(n,k,w)=(12,8,4)$			$(n,k,w)=(16,10,4)$		
(0,0)	112	**77**	**77**	164	122	**117**	216	173	**162**	272	**232**	**232**	520	**462**	464
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(1,1)	64	**58**	**58**	99	90	**89**	138	**120**	**120**	189	174	**171**	365	**352**	**352**
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(1,3)	64	58	**57**	98	90	**87**	132	**118**	**118**	175	**164**	**164**	326	**316**	**316**

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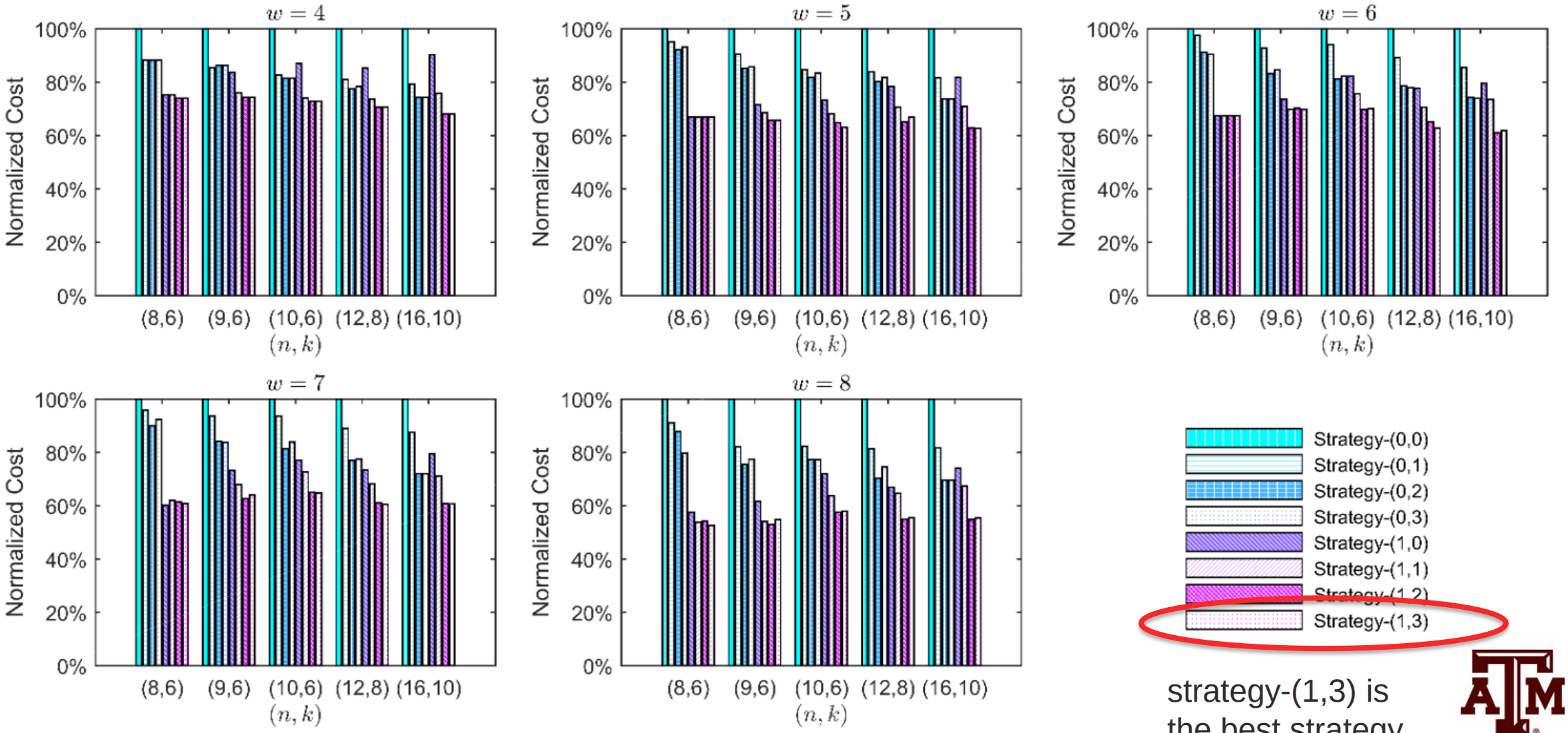
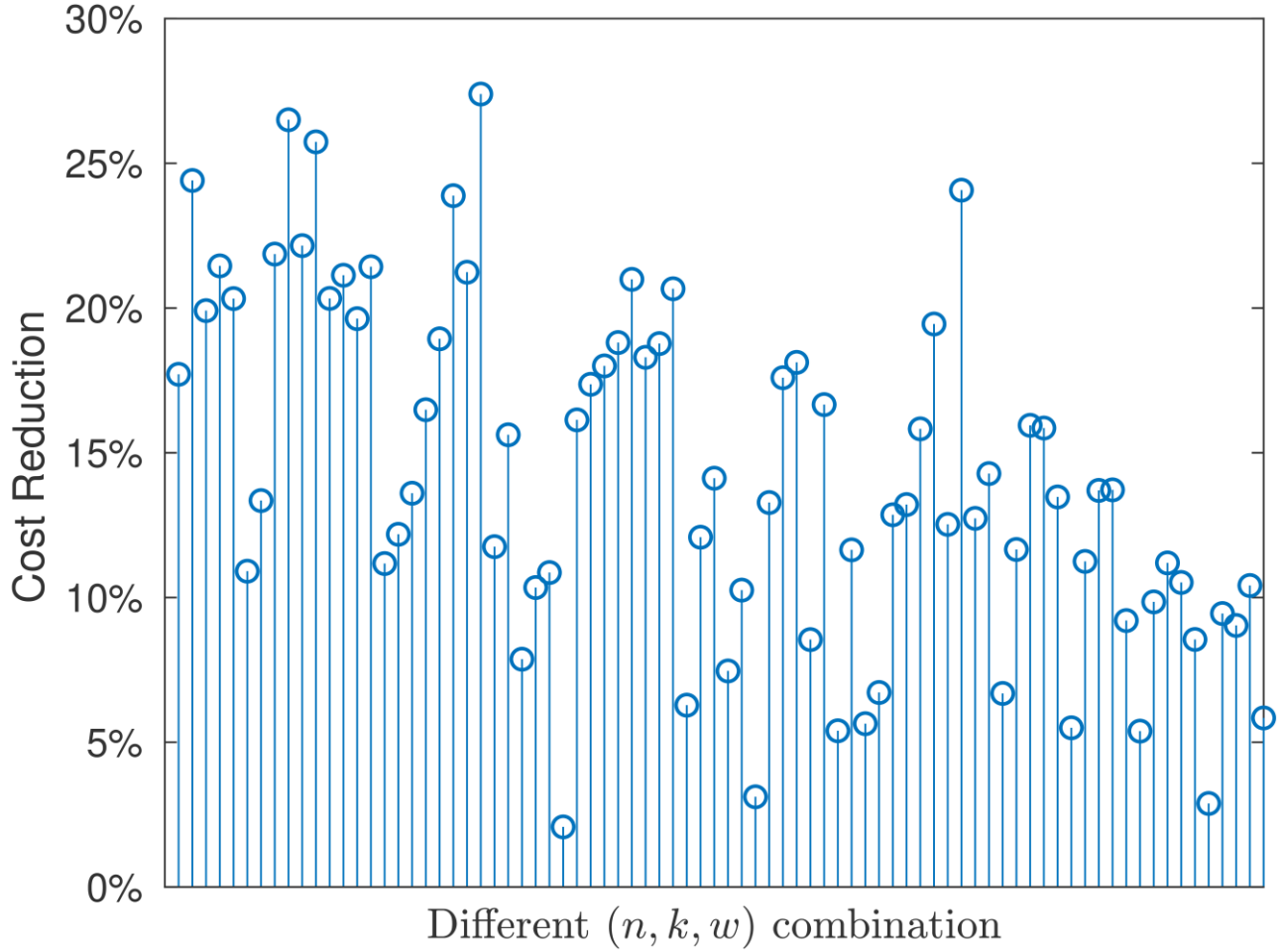
Strategies-(i,j) with Optimized Bitmatrices



strategy-(1,3) is the best strategy

Optimized Bitmatrix Reduced Costs



Cost Function Improvement

- Memcpy is 1.5x faster than XOR
- Cost functions:
  - Total # of XORs in schedule
  - Total # of ops in schedule
  - Weighted sum of ops in schedule

Table 4: Encoding throughput (GB/s) using bitmatrices obtained by the genetic algorithm under different cost functions

(n,k,w)	Cost Function		
	# of XOR	# of XOR and copying	Weighted
(8,6,4)	4.64	4.66	**4.68**
(8,6,8)	4.30	**4.35**	4.32
(9,6,4)	3.72	3.73	**3.80**
(9,6,8)	3.28	3.28	**3.44**
(10,6,4)	2.33	2.51	**2.52**
(10,6,8)	1.99	1.97	**2.11**
(12,8,4)	2.96	3.11	**3.16**
(12,8,8)	2.54	2.56	**2.58**
(16,10,4)	2.29	2.29	**2.32**
(16,10,8)	1.71	1.72	**1.74**

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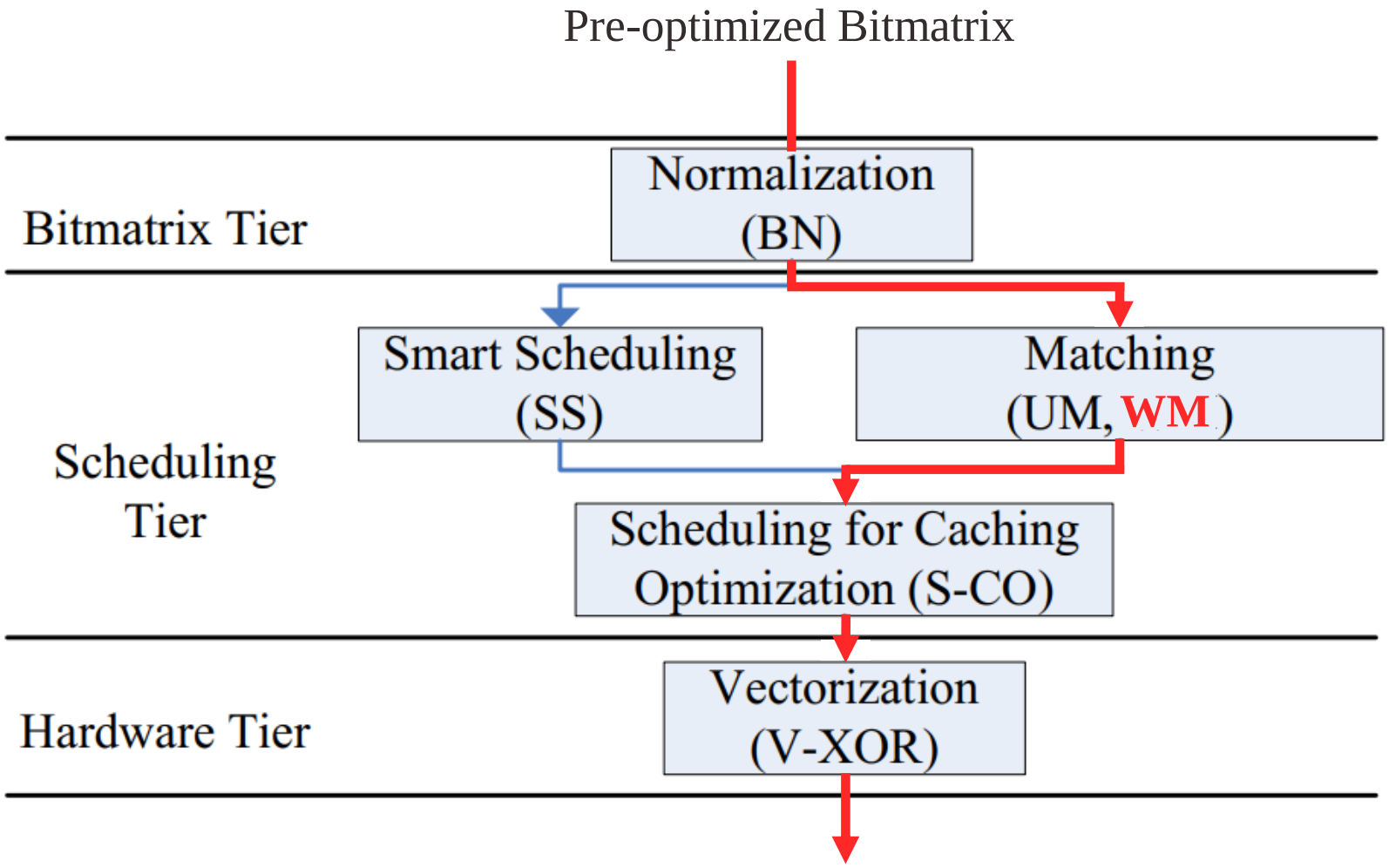
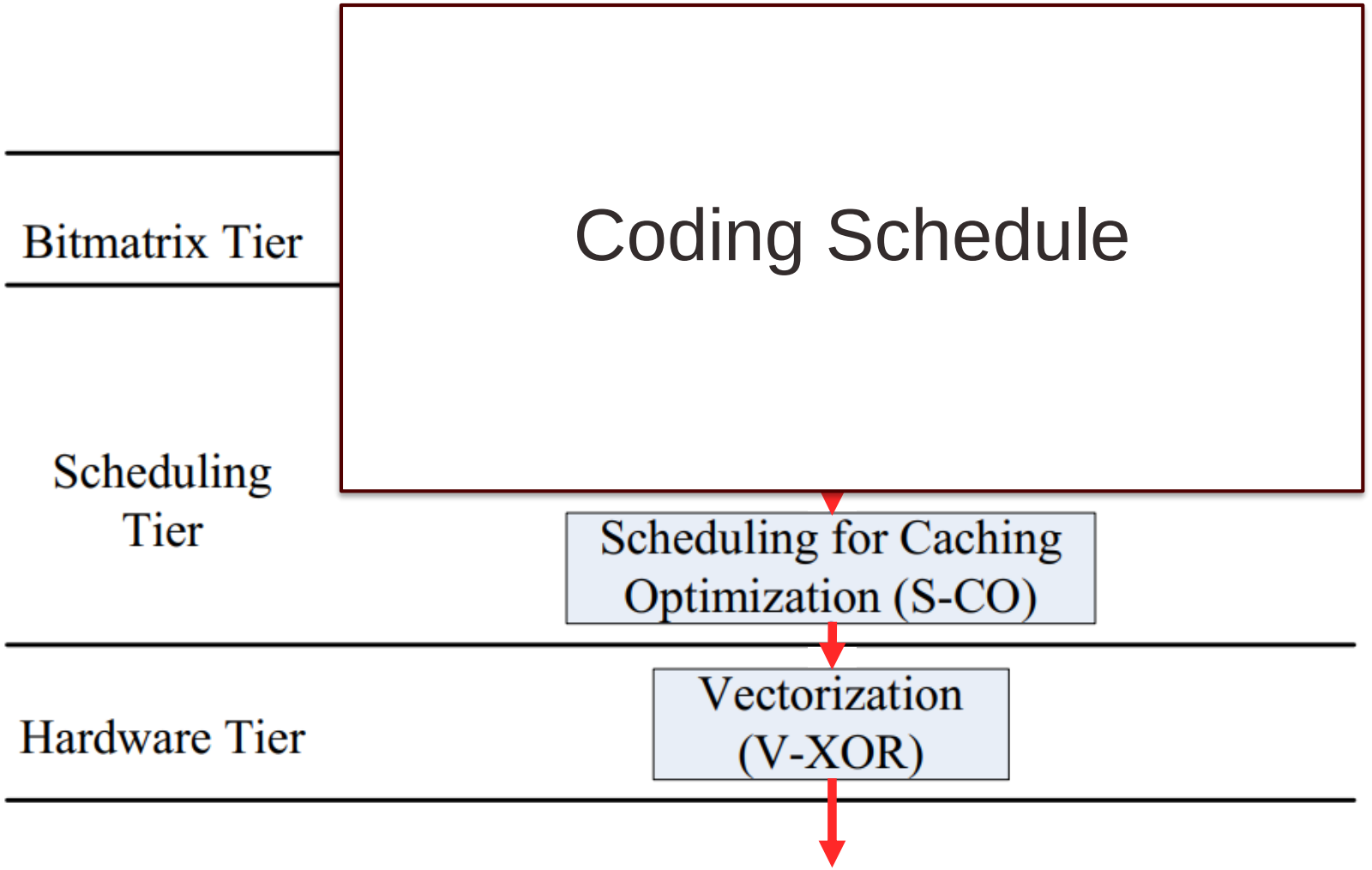
- Conclusion

Proposed Coding Procedure



Proposed Coding Procedure



Testing Setup

- Ryzen 1700X @ 3.4Ghz (8C/16T)
- 16GB DDR4
- Ubuntu 18.04 64-bit, GCC 7.3.0

- Jerasure 1.2A/ Jerasure 2.0:
  - XOR-based Cauchy RS code (BN, SS applied)
  - GF-based RS code
  - Raid-6
- Other codes:
  - EVENODD
  - RDP
  - STAR

Encoding v.s. Efficient RS/CRS code

Table 5: Encoding throughput (GB/s) for methods that allow general *(n, k)* parameters and $w = 8$

(n,k)	Proposed	Vectorized XOR-based CRS code	Vectorized GF-based RS code [16]
(7,5)	4.64	**4.73**	2.52
(8,6)	5.21	**5.22**	2.70
(9,7)	5.32	**5.45**	2.74
(10,8)	5.36	**5.59**	2.77
(12,10)	5.72	**5.88**	2.81
(8,5)	**3.19**	2.75	1.76
(9,6)	**3.49**	2.84	1.77
(10,7)	**3.67**	2.79	1.80
(11,8)	**3.72**	2.92	1.82
(13,10)	**3.82**	3.10	1.84
(10,6)	**2.55**	2.15	1.31
(11,7)	**2.75**	2.17	1.32
(12,8)	**2.86**	2.20	1.35
(14,10)	**2.86**	2.19	1.40
(15,10)	**2.30**	1.79	1.11
(16,10)	**1.96**	1.48	0.92

Outperform vectorized XOR-based CRS code for $m>2$

Encoding v.s. Efficient RS/CRS code

Table 5: Encoding throughput (GB/s) for methods that allow general *(n, k)* parameters and $w = 8$

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(15,10)	**2.30**	1.79	1.11
(16,10)	**1.96**	1.48	0.92

Outperform vectorized XOR-based CRS code for $m>2$

Outperform vectorized GF-based RS code with big margin (~ 2x faster)

Encoding v.s. Three Parities Codes

Table 6: Encoding throughputs (GB/s): Three parities

(n,k,w)	Proposed	Vectorized XOR-based CRS code	STAR code [8]	Quantcast QFS [13]
(8,5,4)	**3.59**	3.25	2.97	2.92
(8,5,8)	**3.19**	2.75	2.97	2.92
(9,6,4)	3.52	**3.72**	3.42	3.04
(9,6,8)	**3.49**	2.84	3.42	3.04
(10,7,4)	**4.15**	3.86	3.76	3.25
(10,7,8)	3.67	2.79	**3.76**	3.25
(11,8,4)	**4.36**	4.13	3.94	3.27
(11,8,8)	3.72	2.92	**3.94**	3.27
(13,10,4)	**4.51**	4.08	4.37	3.41
(13,10,8)	3.82	3.10	**4.37**	3.41

Similar or better performance than specially designed codes

Encoding v.s. Two Parities Codes

Table 7: Encoding throughputs (GB/s): Two parities

(n,k,w)	Proposed	Vectorized XOR-based CRS code	Vectorized Raid-6	EVEN ODD [2]	RDP [6]
(7,5,4)	**5.16**	4.85	n/a	4.28	4.37
(7,5,8)	4.64	**4.73**	2.18	4.28	4.37
(8,6,4)	4.67	**5.22**	n/a	4.83	4.95
(8,6,8)	5.21	**5.22**	2.15	4.83	4.95
(9,7,4)	**5.77**	5.59	n/a	5.20	5.32
(9,7,8)	5.32	**5.45**	2.16	5.20	5.32
(10,8,4)	**5.90**	5.23	n/a	5.50	5.69
(10,8,8)	5.36	5.59	2.17	5.50	**5.69**
(12,10,4)	6.23	6.00	n/a	6.02	**6.24**
(12,10,8)	5.72	5.88	2.17	6.02	**6.24**

Similar or better performance than specially designed codes

Overall Encoding Improvement

Reference codes or methods	Improvement by proposed code
General (n,k) Codes	
GF-based RS code w/o vectorization	552.27%
XOR-based CRS code w/o vectorization	53.65%
Vectorized GF-based RS code [16]	99.82%
Vectorized XOR-based CRS code	14.98%
Three Parities Codes	
STAR [8]	5.59%
Quancast-QFS [13]	21.68%
Two Parities Codes	
Raid-6 w/o vectorization	206.88%
Vectorized Raid-6	142.07%
RDP [6]	5.85%
EVENODD [2]	8.79%

Decoding

Decoding

- Direct read in most cases

Decoding

- Direct read in most cases
- Degraded read (decoding) only if **systematic** nodes fail

Decoding

- Direct read in most cases
- Degraded read (decoding) only if **systematic** nodes fail
  - Single disk failure rate : 1%
  - In (10,6) erasure code storage system
    - 1 systematic node failure: ~ 0.055
    - 2 systematic node failure: ~ 0.0014
    - 3 systematic node failure: ~ 1.8×10^{-5}
    - 4 systematic node failure: ~ 1.4×10^{-7}

Decoding

- Direct read in most cases
- Degraded read (decoding) only if **systematic** nodes fail
  - Single disk failure rate : 1%
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    - 1 systematic node failure: ~ 0.055
    - 2 systematic node failure: ~ 0.0014
    - 3 systematic node failure: ~ 1.8×10^{-5}
    - 4 systematic node failure: ~ 1.4×10^{-7}
- Decoding performance should be viewed as secondary importance

Decoding Throughput

Table 9: Decoding throughput (GB/s) for methods that allow general (n,k) parameters and $w = 8$

(n,k)	Proposed	Vectorized XOR-based CRS code	Vectorized GF-based RS code [16]
(7,5)	3.87	**4.56**	2.58
(8,6)	**5.45**	4.86	2.67
(9,7)	4.46	**5.06**	2.70
(10,8)	4.89	**5.11**	2.75
(12,10)	4.45	**5.52**	2.79
(8,5)	**3.04**	2.11	1.71
(9,6)	**2.94**	2.20	1.74
(10,7)	**3.28**	2.29	1.76
(11,8)	**3.08**	2.31	1.71
(13,10)	**3.21**	2.37	1.88
(10,6)	**2.38**	1.80	1.31
(11,7)	**2.35**	1.85	1.32
(12,8)	**2.54**	1.87	1.33
(14,10)	**2.47**	1.89	1.38
(15,10)	**2.00**	1.48	1.09
(16,10)	**1.77**	1.30	0.91

Table 10: Decoding throughputs (GB/s): Three parities

(n,k,w)	Proposed	Vectorized XOR-based CRS code	STAR code [8]	Quantcast QFS [13]
(8,5,4)	**4.28**	3.08	3.20	1.77
(8,5,8)	**3.04**	2.11	3.20	1.77
(9,6,4)	**4.13**	3.41	3.23	1.74
(9,6,8)	**2.94**	2.20	3.23	1.74
(10,7,4)	**4.55**	3.53	3.52	1.77
(10,7,8)	**3.28**	2.29	3.52	1.77
(11,8,4)	**4.70**	3.78	3.13	1.68
(11,8,8)	**3.08**	2.31	3.13	1.68
(13,10,4)	**4.86**	3.71	3.50	1.71
(13,10,8)	3.21	2.37	**3.50**	1.71

Table 11: Decoding throughputs (GB/s): Two parities

(n,k,w)	Proposed	Vectorized XOR-based CRS code	Vectorized Raid-6	EVEN ODD [2]	RDP [6]
(7,5,4)	5.52	4.85	n/a	6.66	**7.28**
(7,5,8)	3.87	4.65	2.64	6.66	**7.28**
(8,6,4)	5.43	5.14	n/a	7.42	**8.00**
(8,6,8)	5.45	4.86	2.67	7.42	**8.00**
(9,7,4)	6.03	5.37	n/a	7.65	**8.13**
(9,7,8)	4.46	5.06	2.73	7.65	**8.13**
(10,8,4)	5.88	5.73	n/a	7.93	**8.44**
(10,8,8)	4.89	5.11	2.77	7.93	**8.44**
(12,10,4)	6.23	5.89	n/a	7.49	**9.10**
(12,10,8)	4.45	5.52	2.81	7.49	**9.10**

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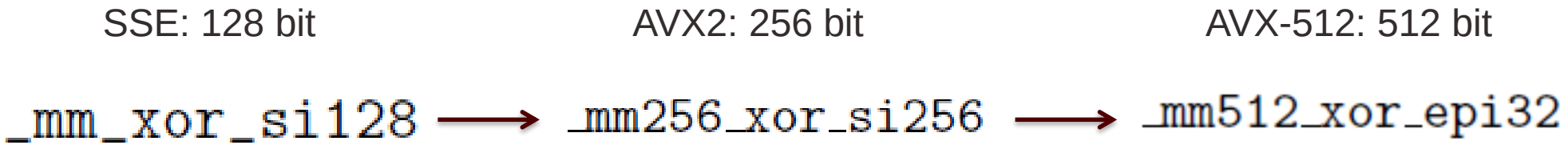
Conclusion

- Comprehensive study of acceleration techniques
- Combine existing techniques and jointly optimize the bitmatrix
- Proposed approach outperforms most existing approaches in encoding throughput.

Conclusion : Key Finding

- Vectorization at XOR-level is much better choice than vectorization of finite field operations
  - Higher throughput (~ 2x faster)
  - Easy migration to newer SIMD ISA



Thank you!

Questions?

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Chao Tian: chao.tian@tamu.edu

Source code:

https://bitbucket.org/zhoutl1106/zerasure.git

https://github.com/zhoutl1106/zerasure.git