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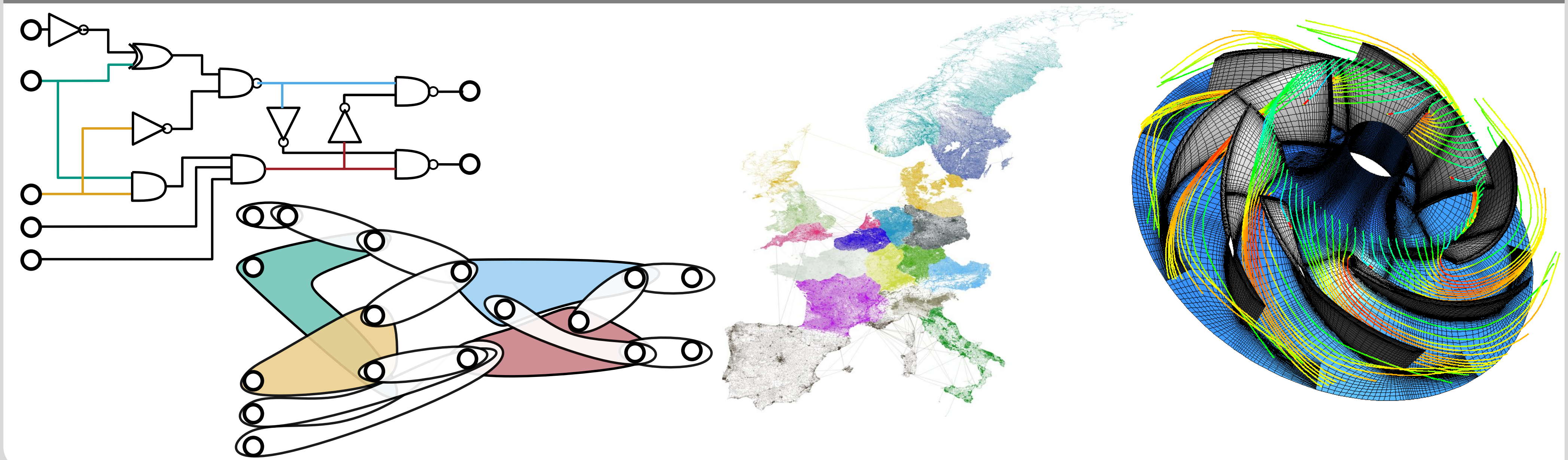
High Quality Hypergraph Partitioning

Algorithms II · January 28, 2019
Sebastian Schlag

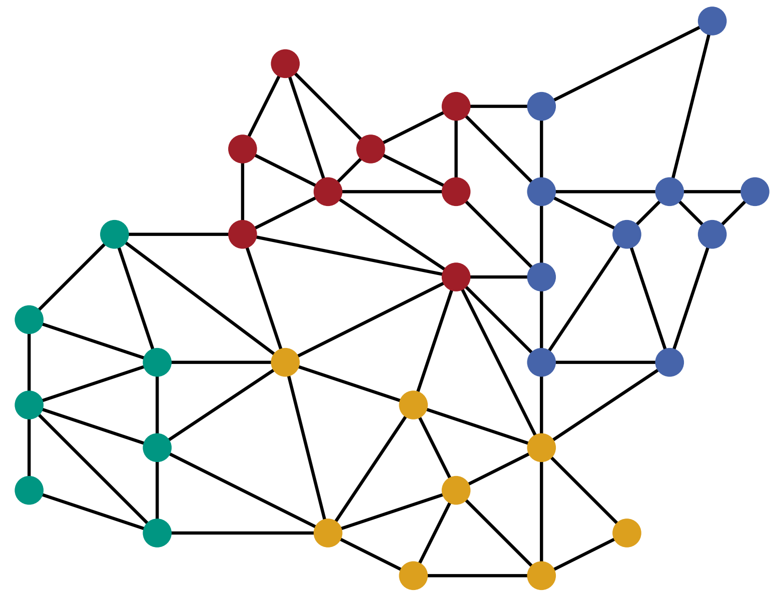
INSTITUTE OF THEORETICAL INFORMATICS · ALGORITHMICS GROUP



Graphs and Hypergraphs

Graph $G = (V, E)$

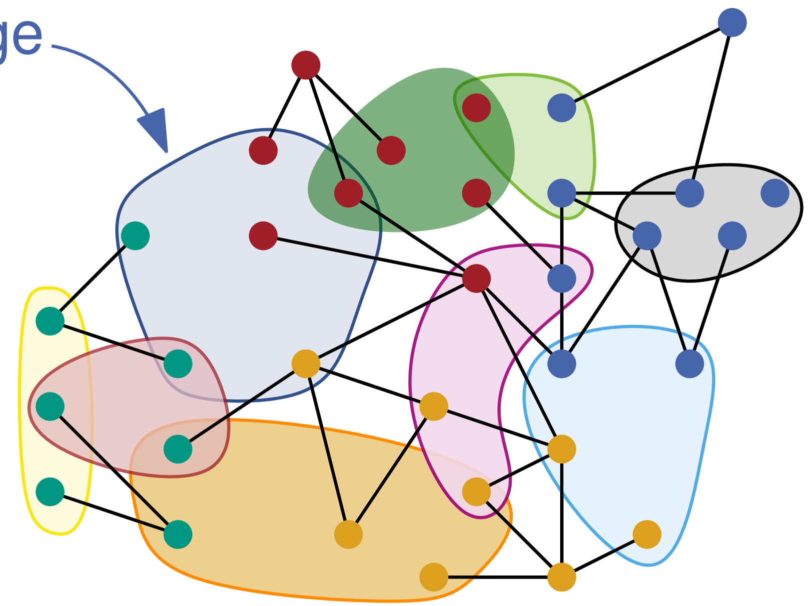
vertices → V edges → E



- Models **relationships** between **objects**
- Dyadic (**2-ary**) relationships

Hypergraph $H = (V, E)$

hyperedge



- Generalization of a graph
  $\Rightarrow$ hyperedges connect ≥ 2 nodes
- Arbitrary (**d-ary**) relationships
- Edge set $E \subseteq \mathcal{P}(V) \setminus \emptyset$

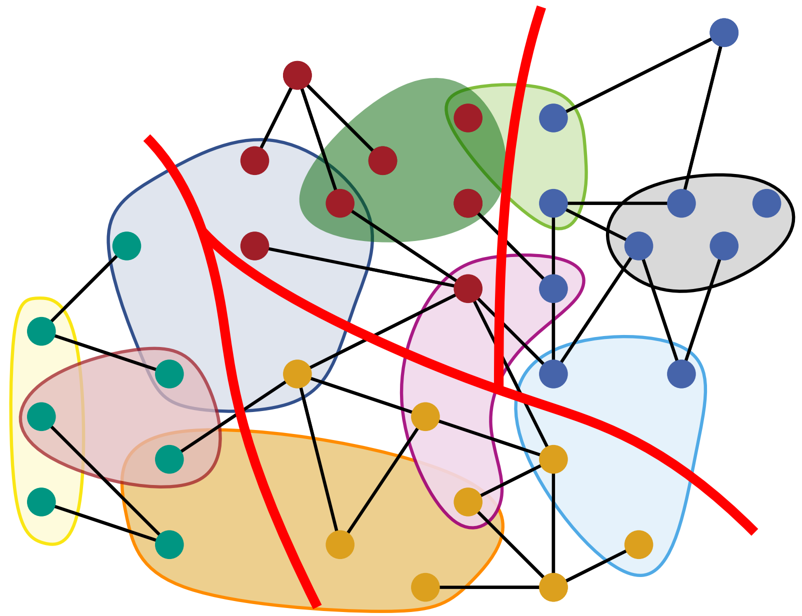
ε-Balanced Hypergraph Partitioning

Partition hypergraph $H = (V, E, c : V \to \mathbb{R}_{>0}, \omega : E \to \mathbb{R}_{>0})$ into **k** disjoint blocks $\Pi = \{V_1, \ldots, V_k\}$ such that

- Blocks V_i are **roughly equal-sized**:

$$c(V_i) \leq (1 + \varepsilon) \left\lceil \frac{c(V)}{k} \right\rceil$$

- **Objective** function on hyperedges is **minimized**



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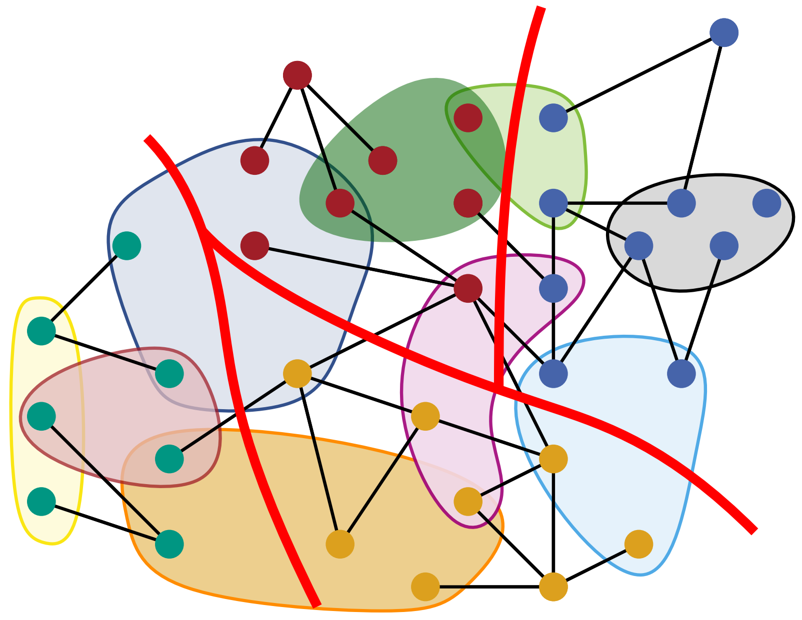

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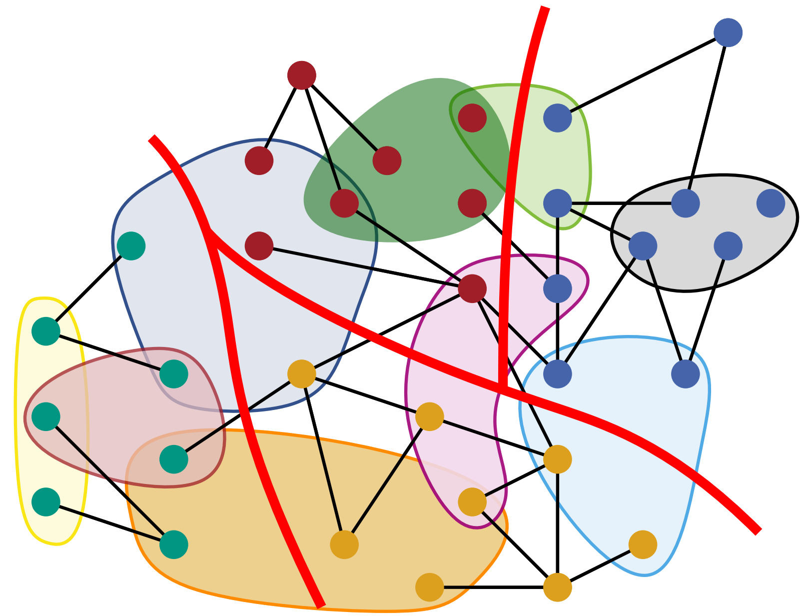

Common Objectives:

- cut: $\sum_{e \in \text{Cut}} \omega(e)$

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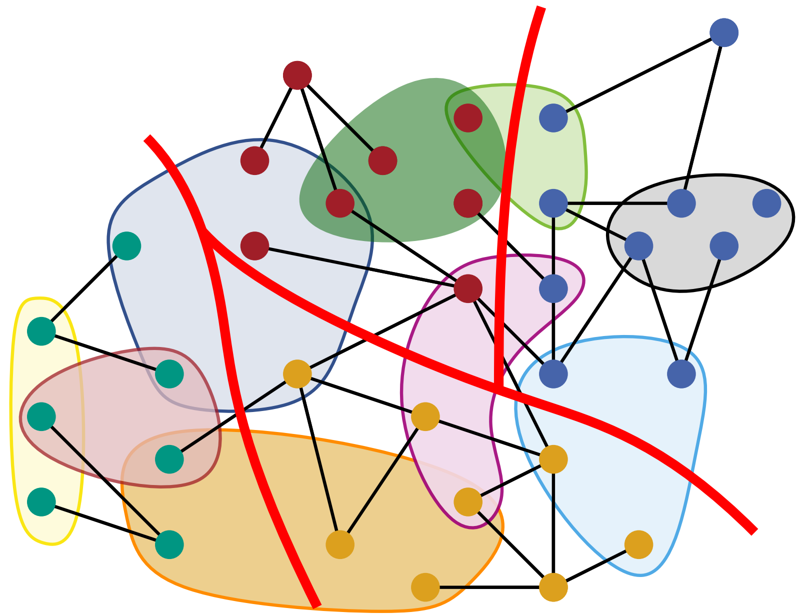
- Connectivity: $\sum_{e \in \text{cut}} (\lambda - 1)\, \omega(e)$



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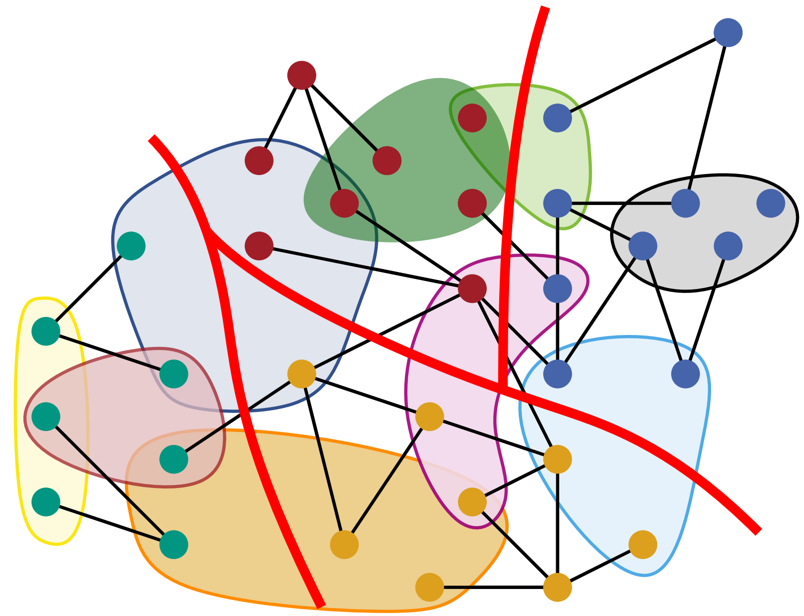
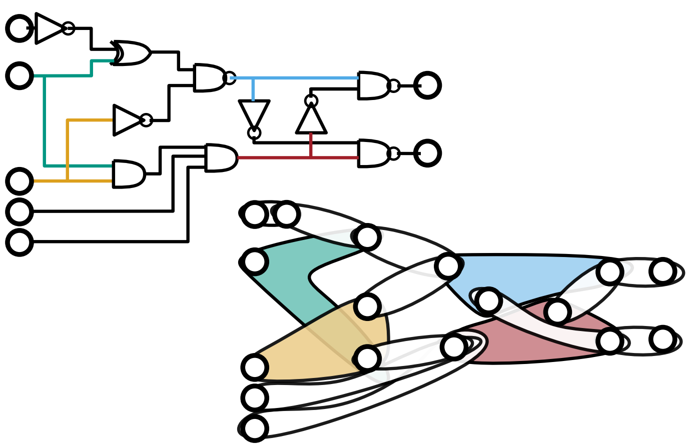
 # blocks connected by *e*



Applications



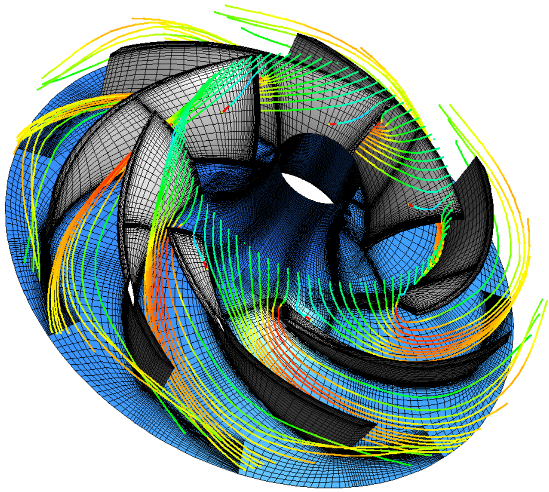
VLSI Design

Warehouse Optimization

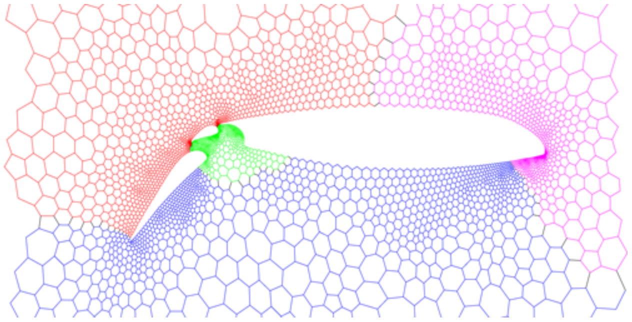
[Martin Grandjean, via Wikimedia Commons]

Complex Networks

Route Planning



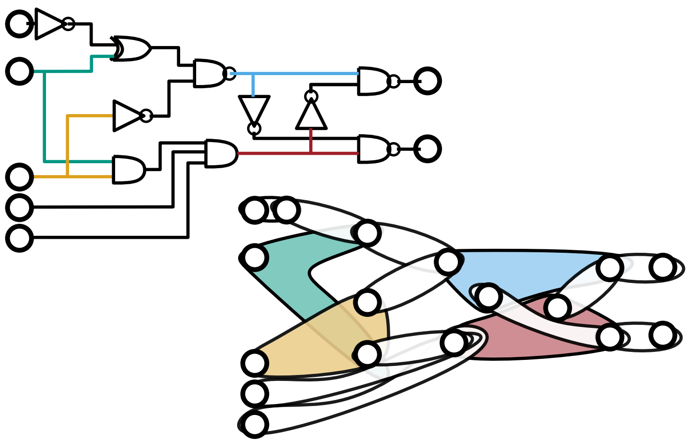
Simulation



$$\mathbf{R}^{n \times n} \ni Ax = b \in \mathbf{R}^n$$

Scientific Computing

Applications



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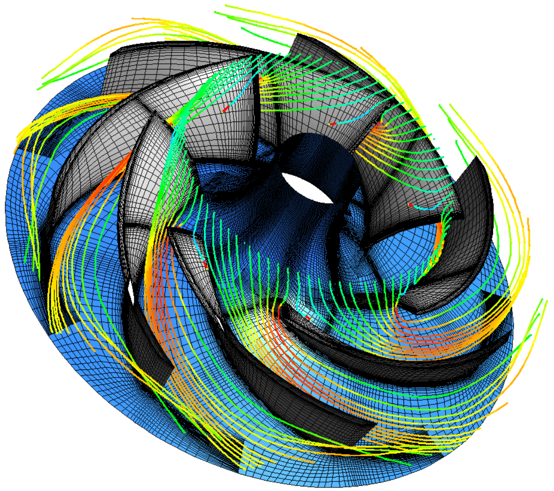

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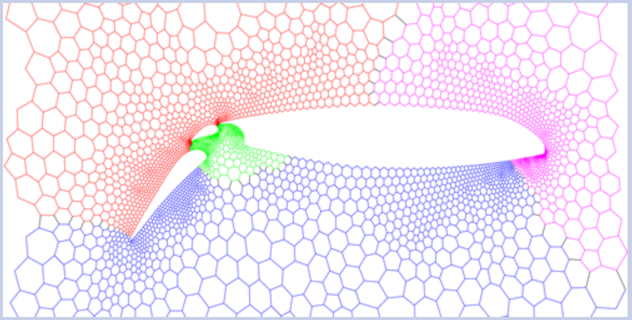


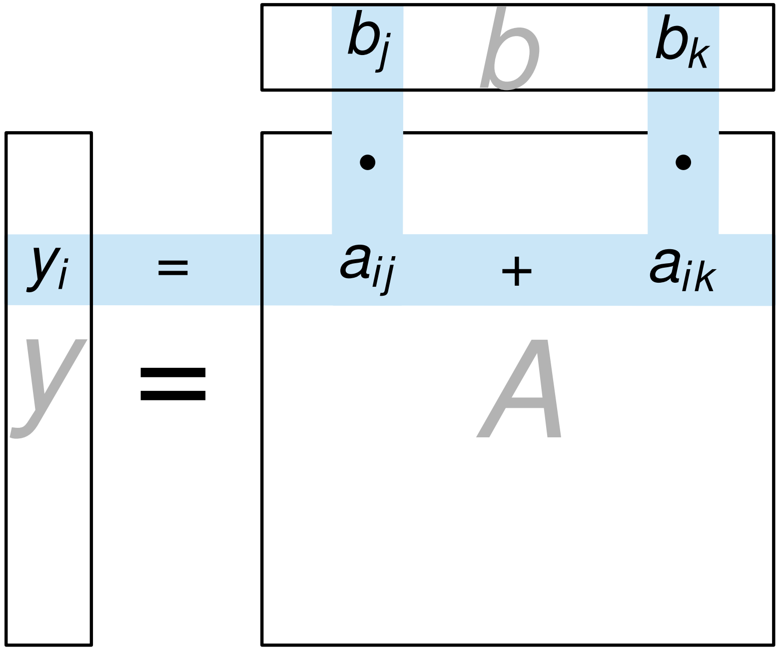
$$\mathbb{R}^{n\times n} \ni Ax = b \in \mathbb{R}^n$$

Scientific Computing

Parallel Sparse-Matrix Vector Product (SpM×V)

[Catalyürek,Aykanat]

$$y = A\,b$$



Setting:

- Repeated SpM×V on supercomputer
- A is large ⇒ distribute on multiple nodes
- Symmetric partitioning ⇒ y & b divided conformally with A

Parallel Sparse-Matrix Vector Product (SpM×V)

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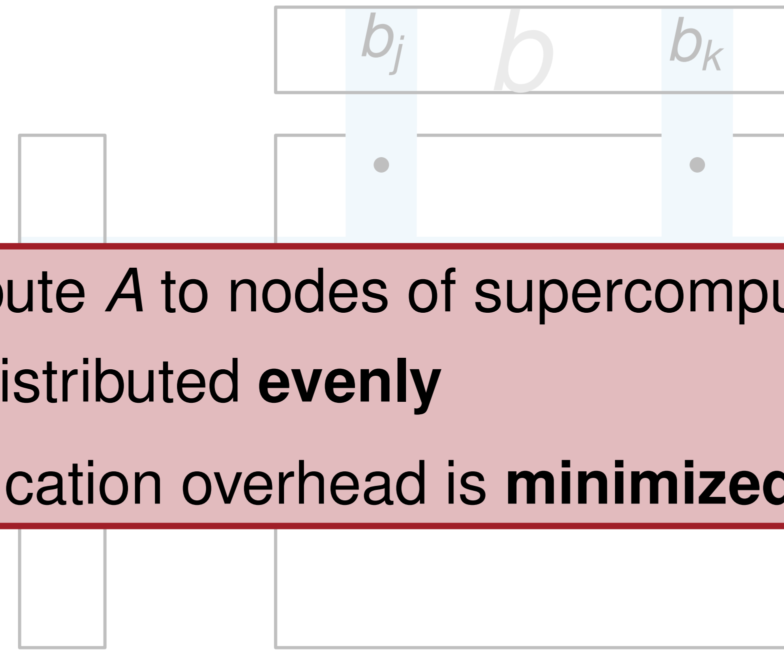

Task: distribute A to nodes of supercomputer such that

- work is distributed **evenly**
- communication overhead is **minimized**

Setting:

- Repeated SpM×V on supercomputer
- A is large $\Rightarrow$ distribute on multiple nodes
- Symmetric partitioning $\Rightarrow$ y & b divided conformally with A

Naive Approach: Rowwise Decomposition

$A \in \mathbf{R}^{16 \times 16}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	b	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
1	*x*									*x*						
2		*x*			*x*							*x*				
3			*x*			*x*										
4				*x*							*x*					
5	*x*				*x*								*x*			
6					*x*	*x*										
7		*x*			*x*		*x*		*x*							
8				*x*				*x*			*x*					
9									*x*			*x*			*x*	
10	*x*						*x*			*x*			*x*			
11			*x*								*x*	*x*		*x*		
12											*x*	*x*				*x*
13					*x*		*x*						*x*			
14					*x*	*x*						*x*		*x*		
15									*x*						*x*	
16				*x*				*x*								*x*

Naive Approach: Rowwise Decomposition

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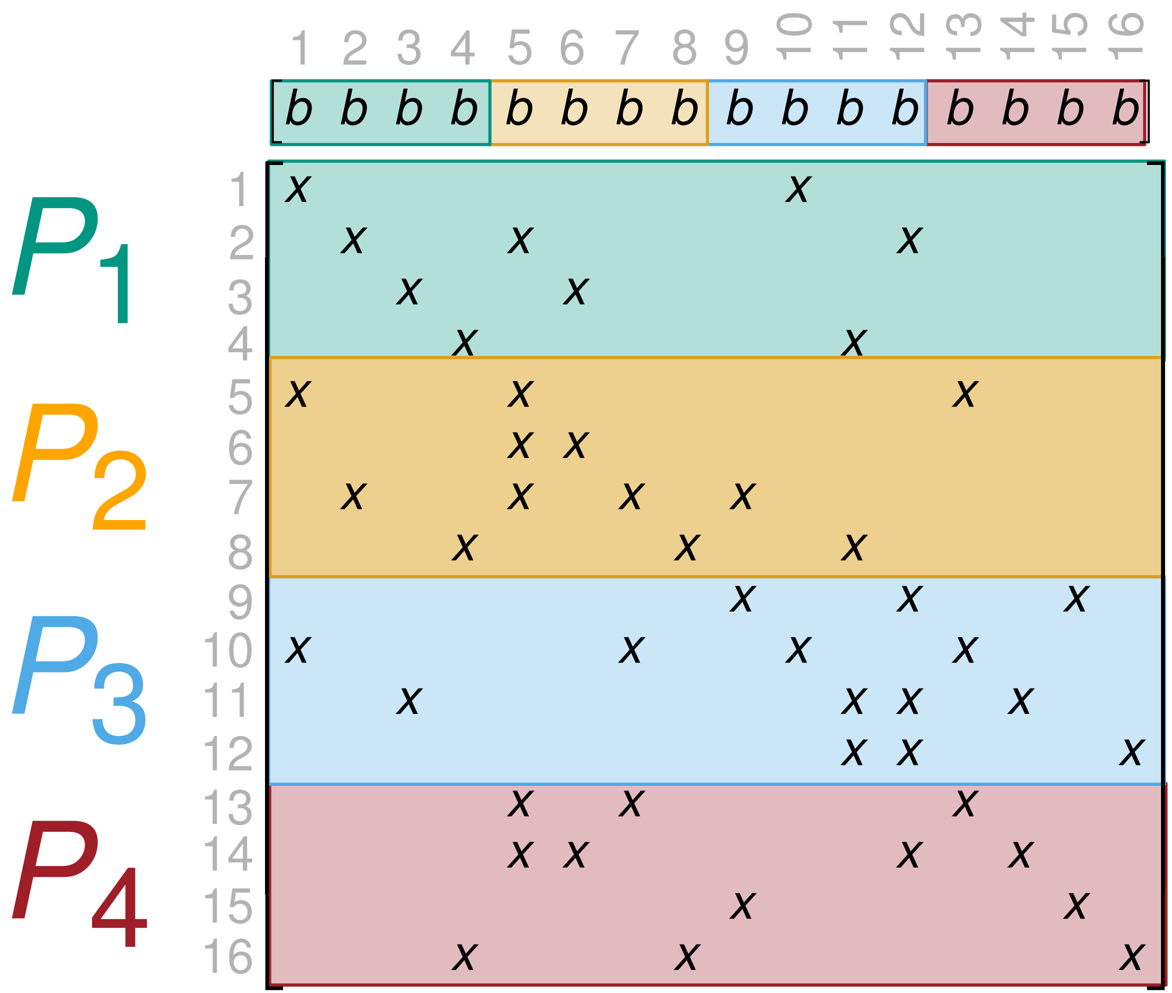

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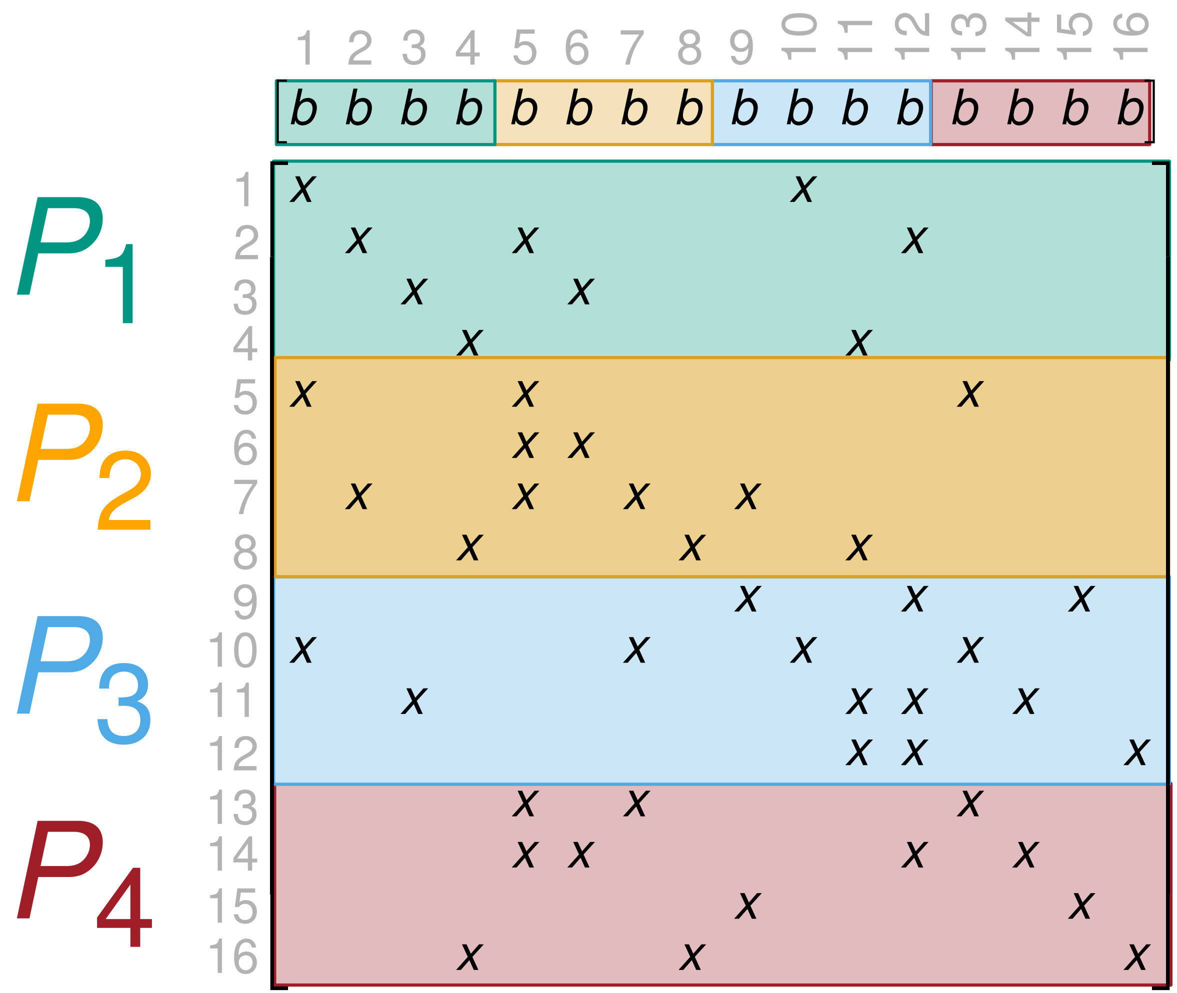

Load Balancing?

$\Rightarrow 9$

$\Rightarrow 12$

$\Rightarrow 14$

$\Rightarrow 12$

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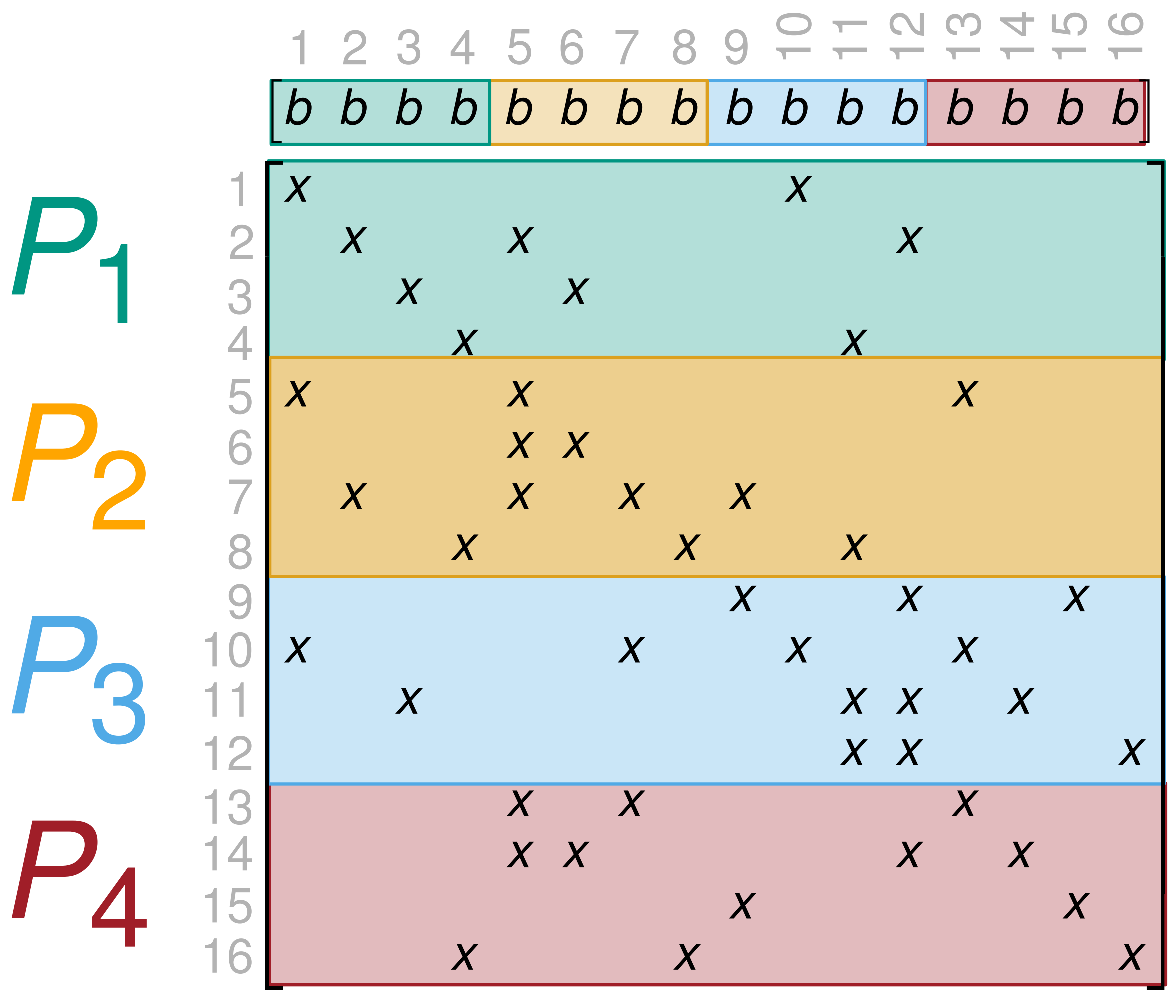

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Commuication Volume?

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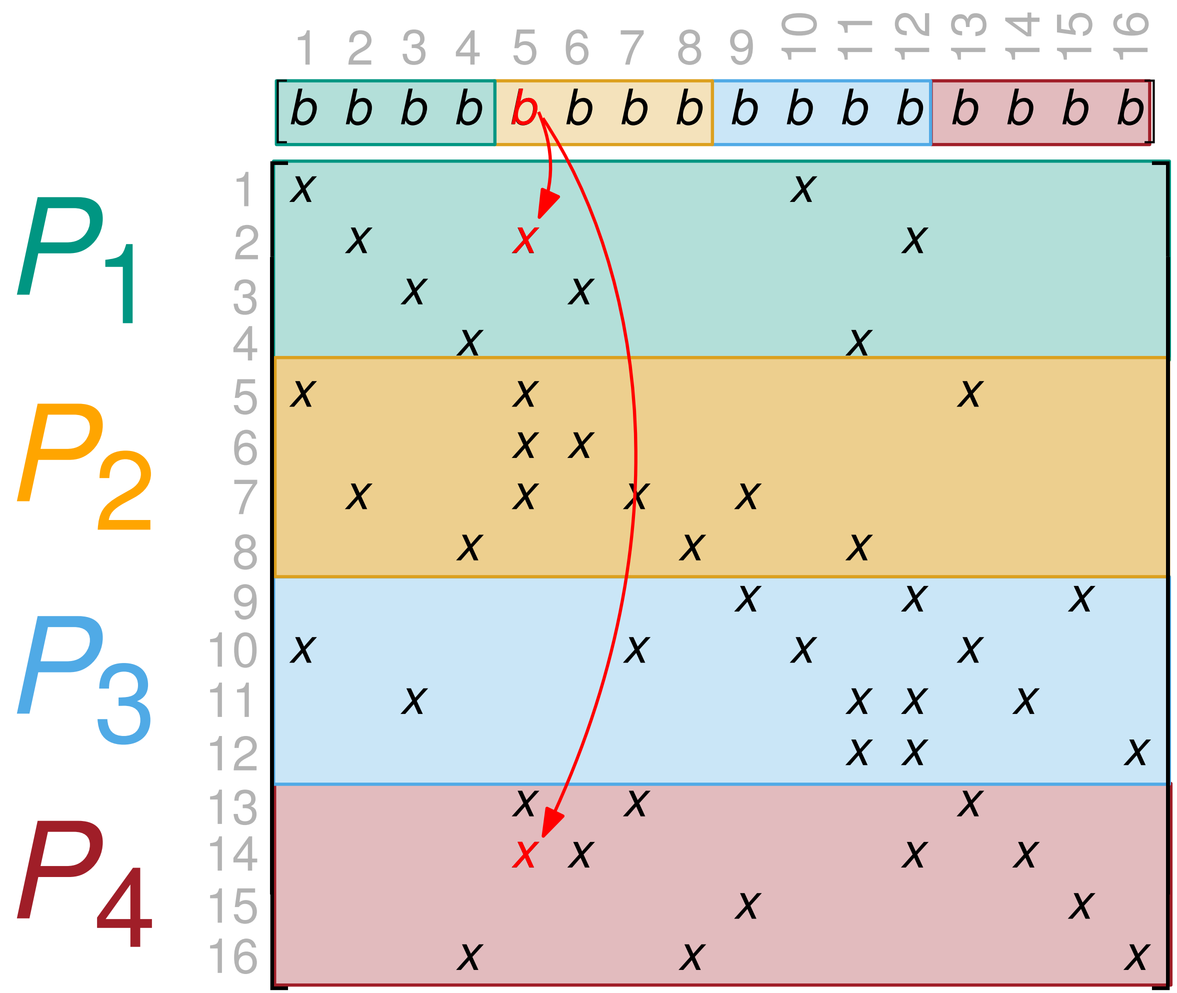

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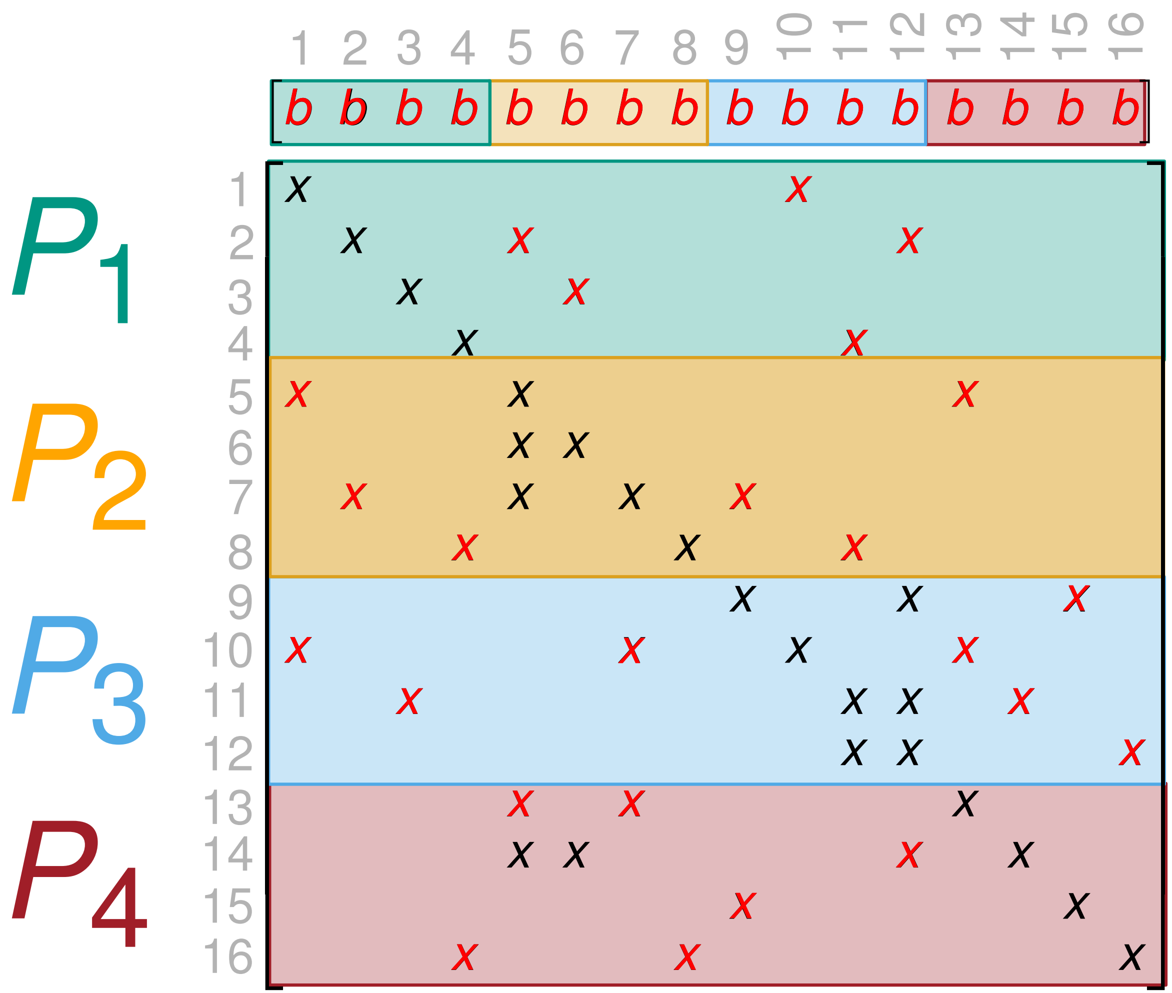

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Commuication Volume? $\Rightarrow$ 24 entries!

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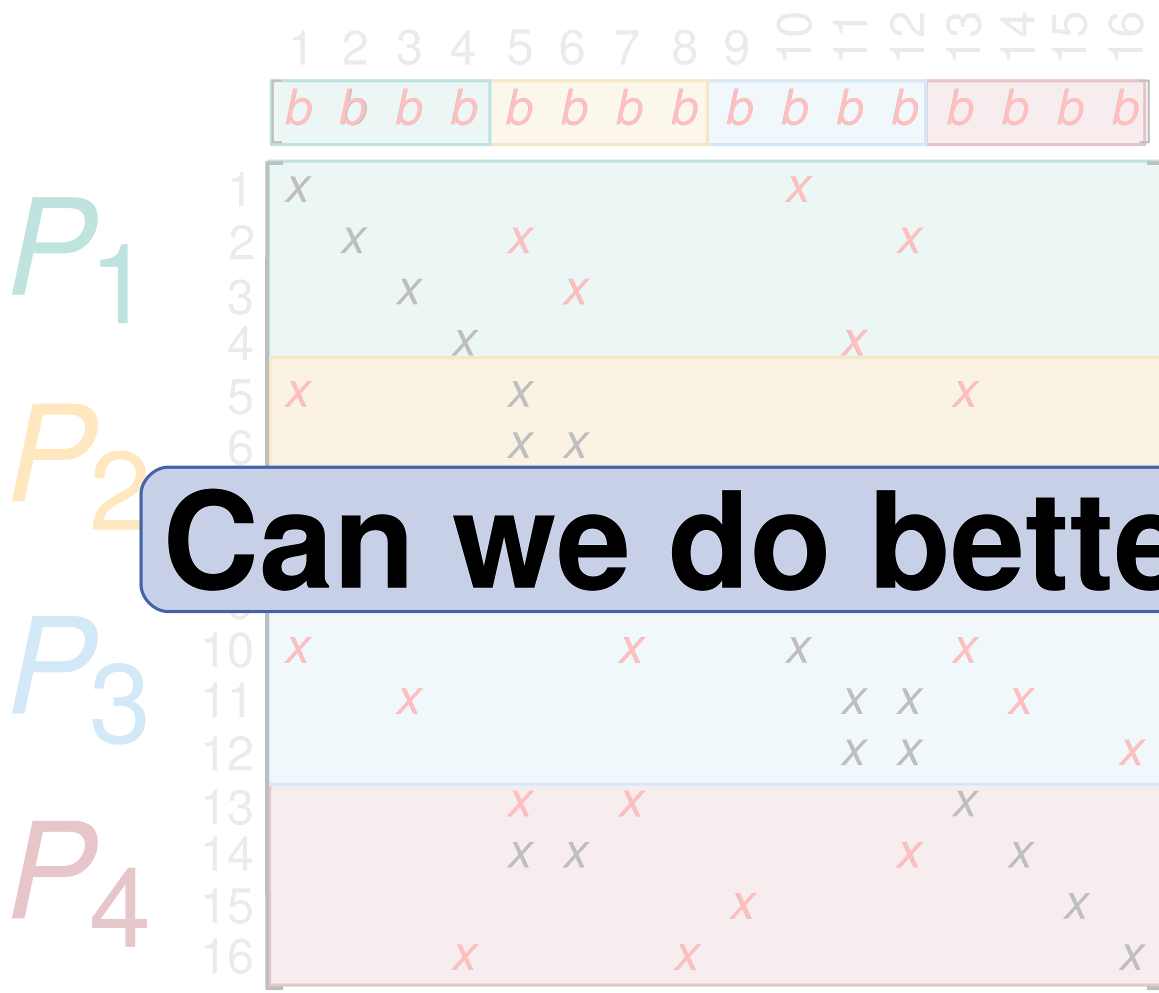

Load Balancing?

$\Rightarrow$ 9

$\Rightarrow$ 12

$\Rightarrow$ 14

$\Rightarrow$ 12

Can we do better?

Commuication Volume? $\Rightarrow$ 24 entries!

From SpM×V to Hypergraph Partitioning

$A \in \mathbb{R}^{16\times16} \Rightarrow H = (V_R, E_C)$

- One vertex per row:
  $\Rightarrow V_R = \{v_1, v_2, \ldots, v_{16}\}$
- One hyperedge per column:
  $\Rightarrow E_C = \{e_1, e_2, \ldots, e_{16}\}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
1	x									x						
2		x			x							x				
3			x			x										
4				x							x					
5	x				x								x			
6					x	x										
7		x			x		x		x							
8				x				x			x					
9									x			x			x	
10	x						x			x			x			
11			x								x	x		x		
12											x	x				x
13					x		x						x			
14					x	x						x		x		
15									x						x	
16				x				x								x

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$v_i \in V_R$:

- Inner product of row *i* with *b*
- $\Rightarrow c(v_i) := \#$ nonzeros

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
1	x									x						
2		x			x							x				
3			x			x										
4				x							x					
5	x				x								x			
6					x	x										
7		x			x		x		x							
8				x				x			x					
v_9 9									x			x			x	
10	x						x			x			x			
11			x								x	x		x		
12											x	x				x
13					x		x						x			
14					x	x						x		x		
15									x						x	
16				x				x								x

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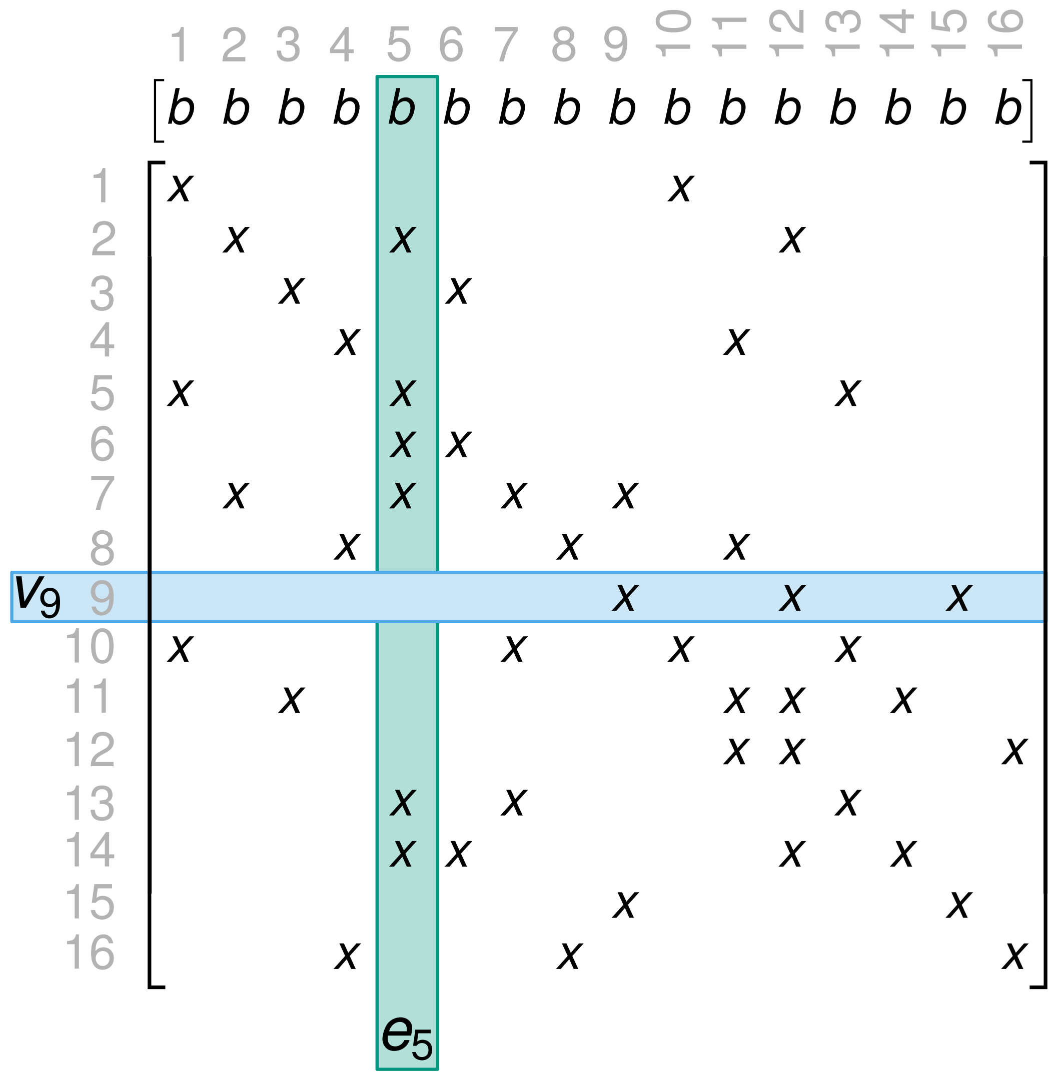
$e_j \in E_C$:

- Set of vertices that need b_j



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$v_i \in$

- In
- $\Rightarrow c(v_i) :=$ # nonzeros

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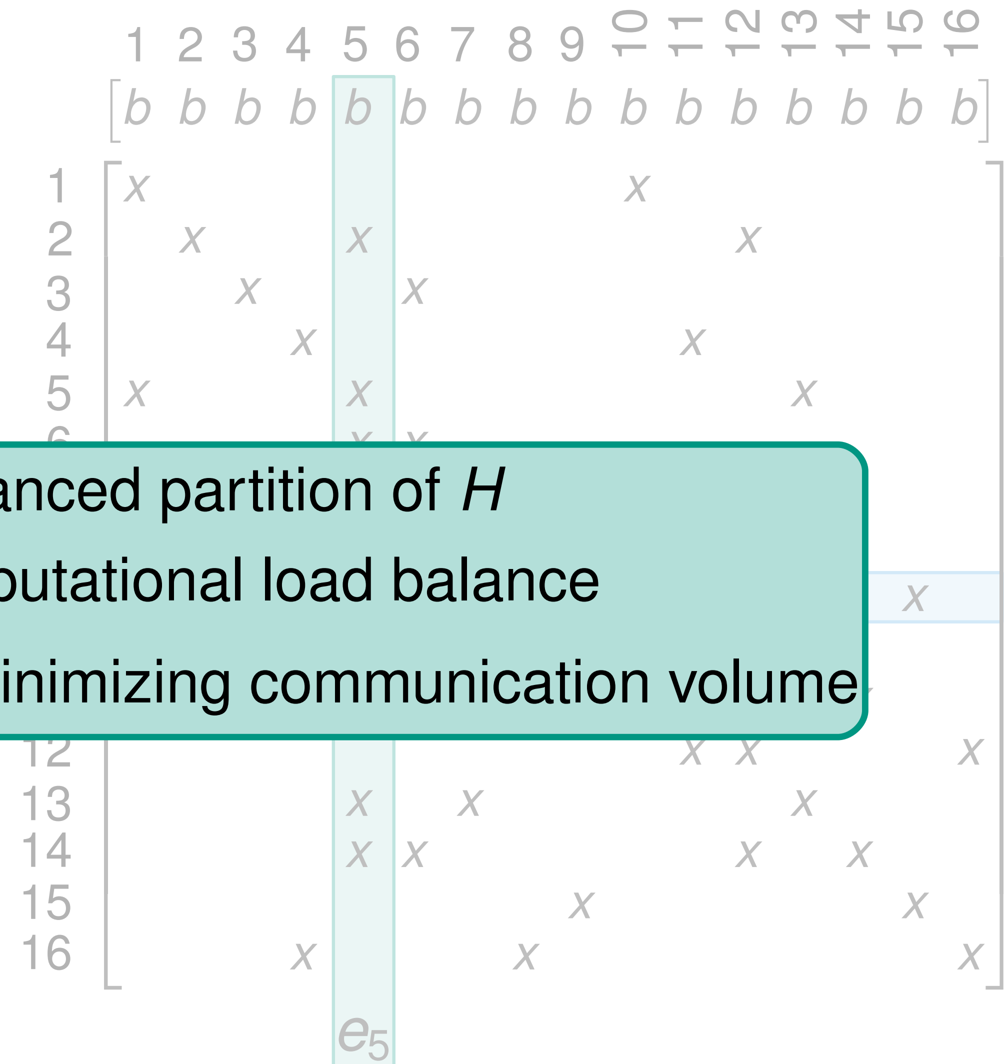
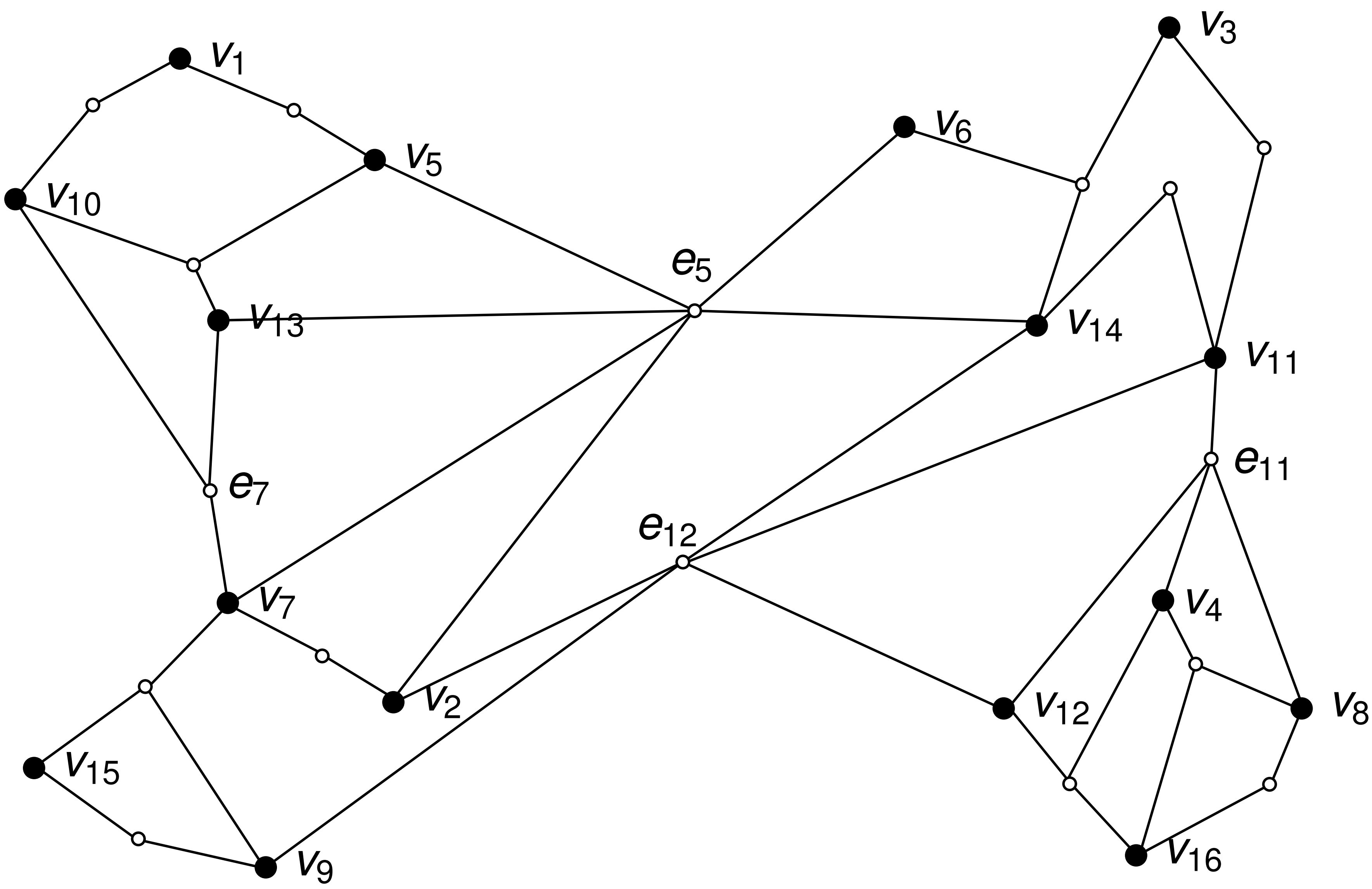


Solution: ε-balanced partition of H

- Balanced partition ⇝ computational load balance
- Small $(\lambda - 1)$-cutsize ⇝ minimizing communication volume

From SpM×V to Hypergraph Partitioning



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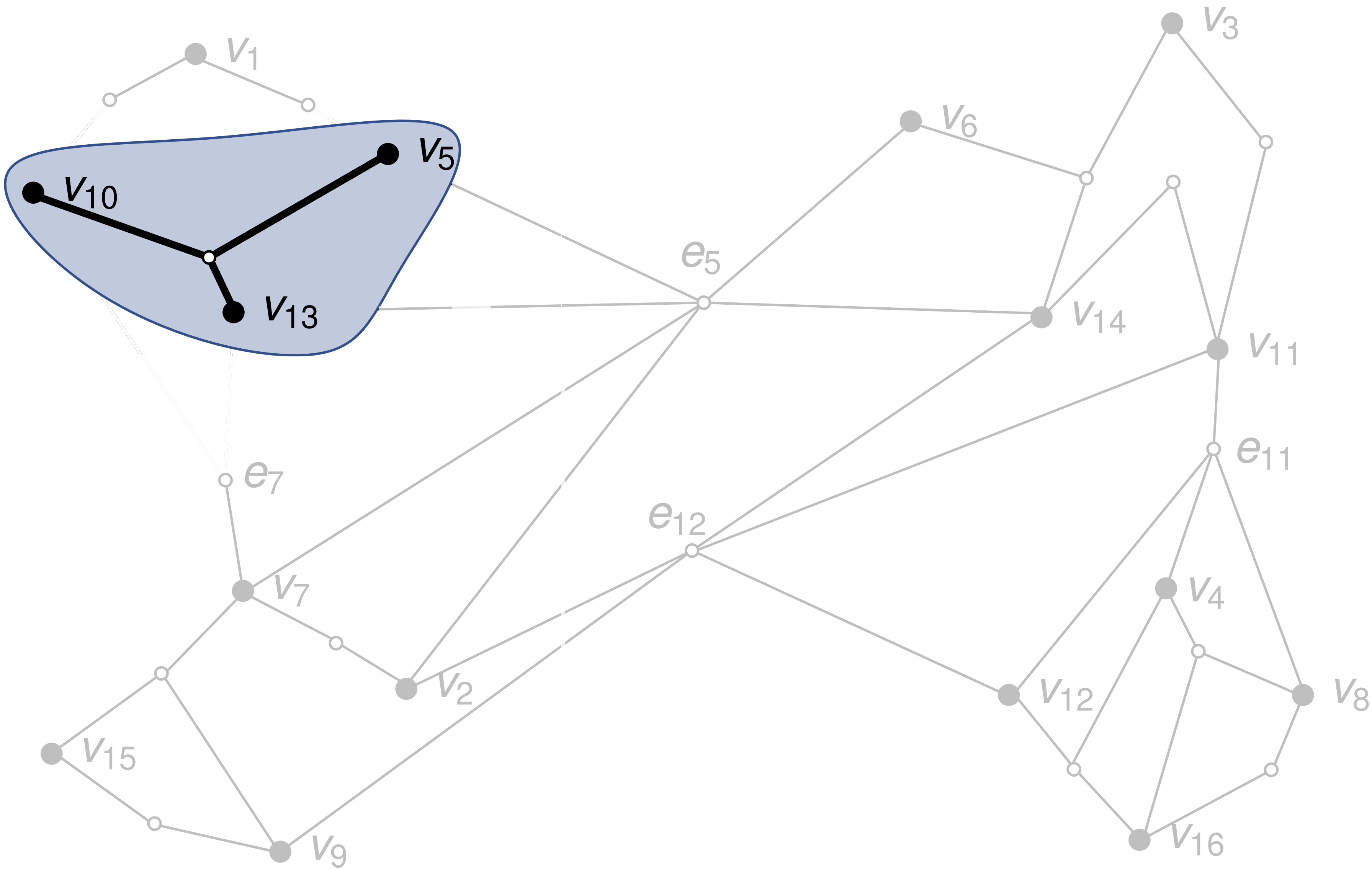

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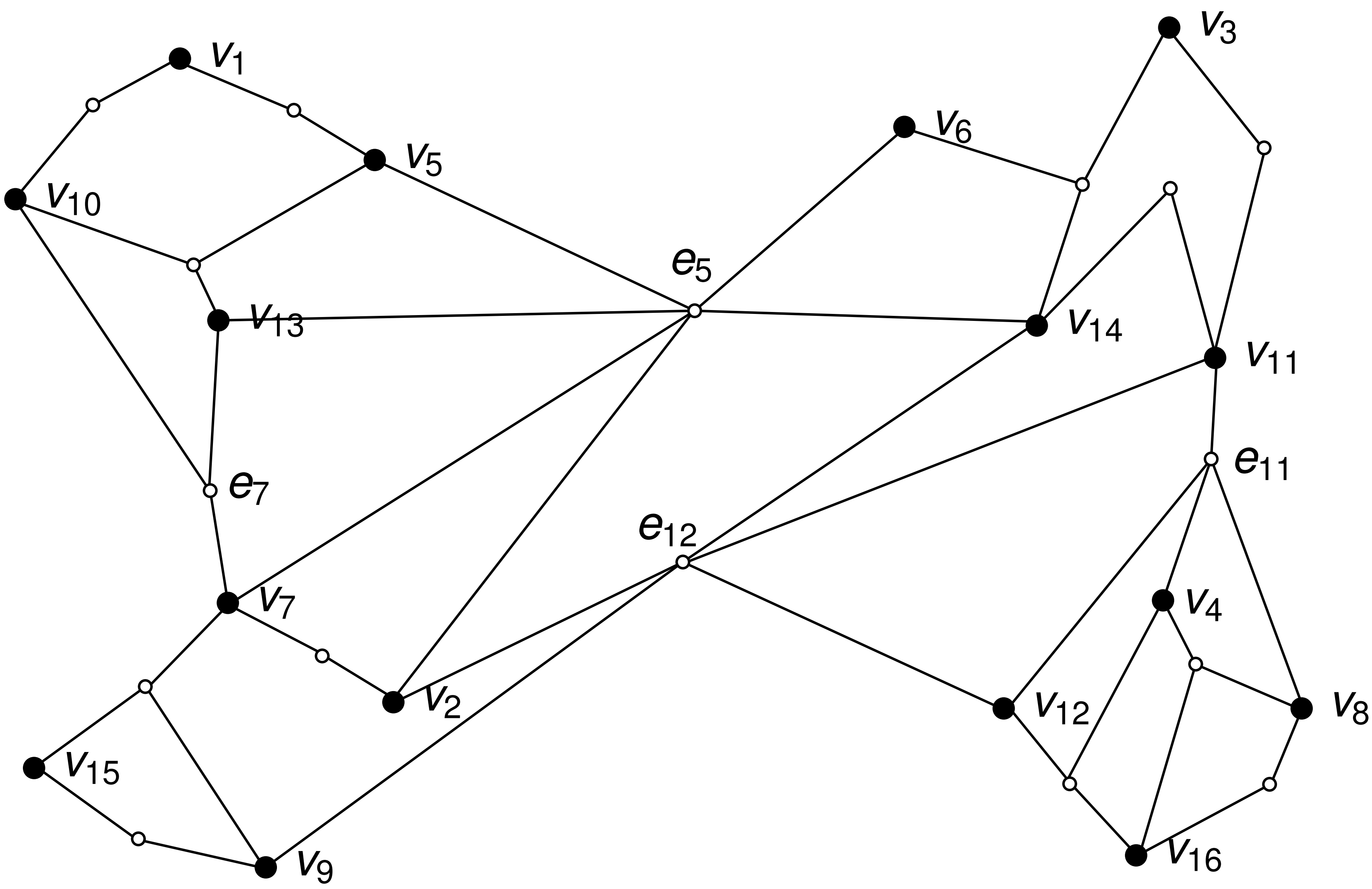

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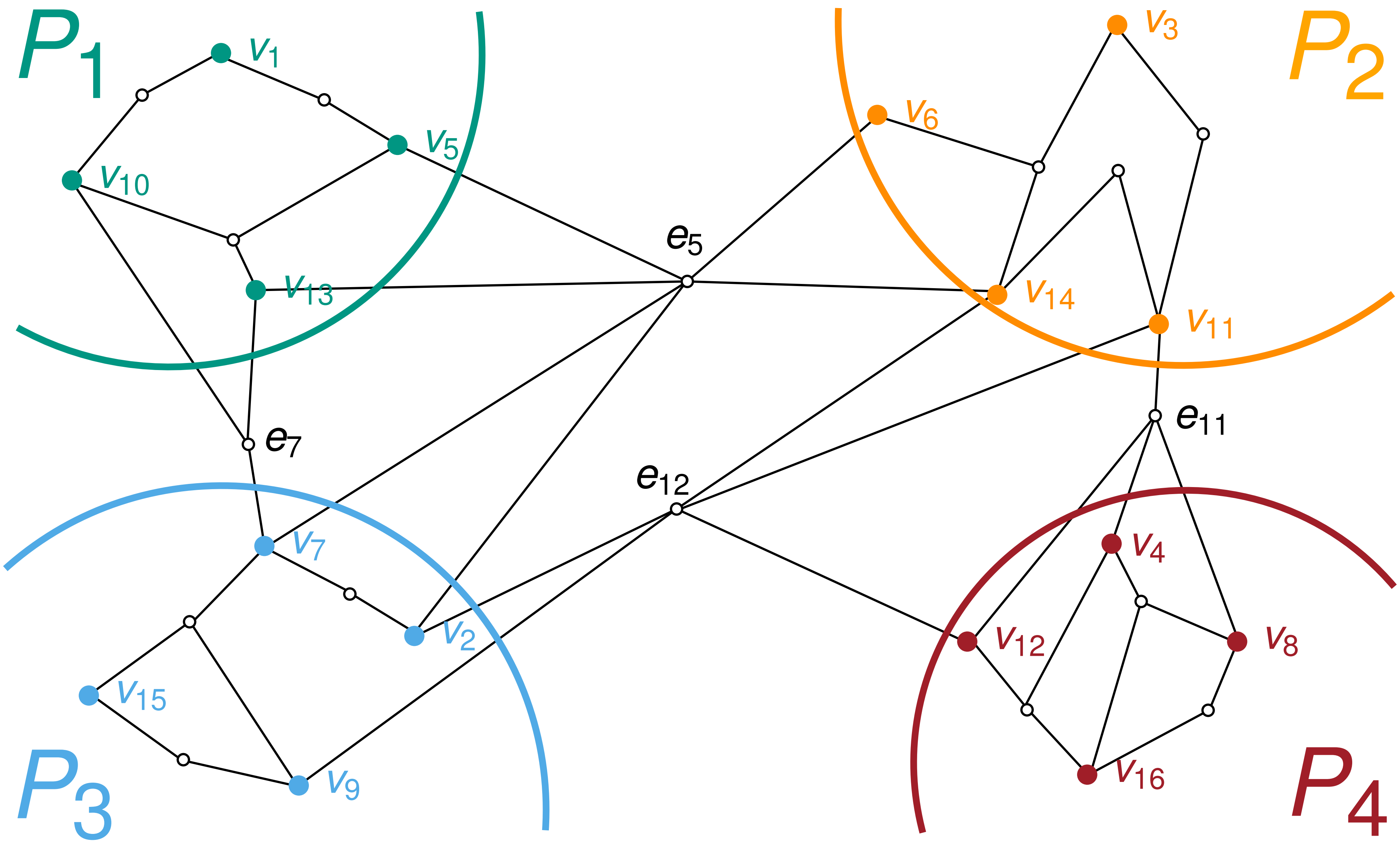

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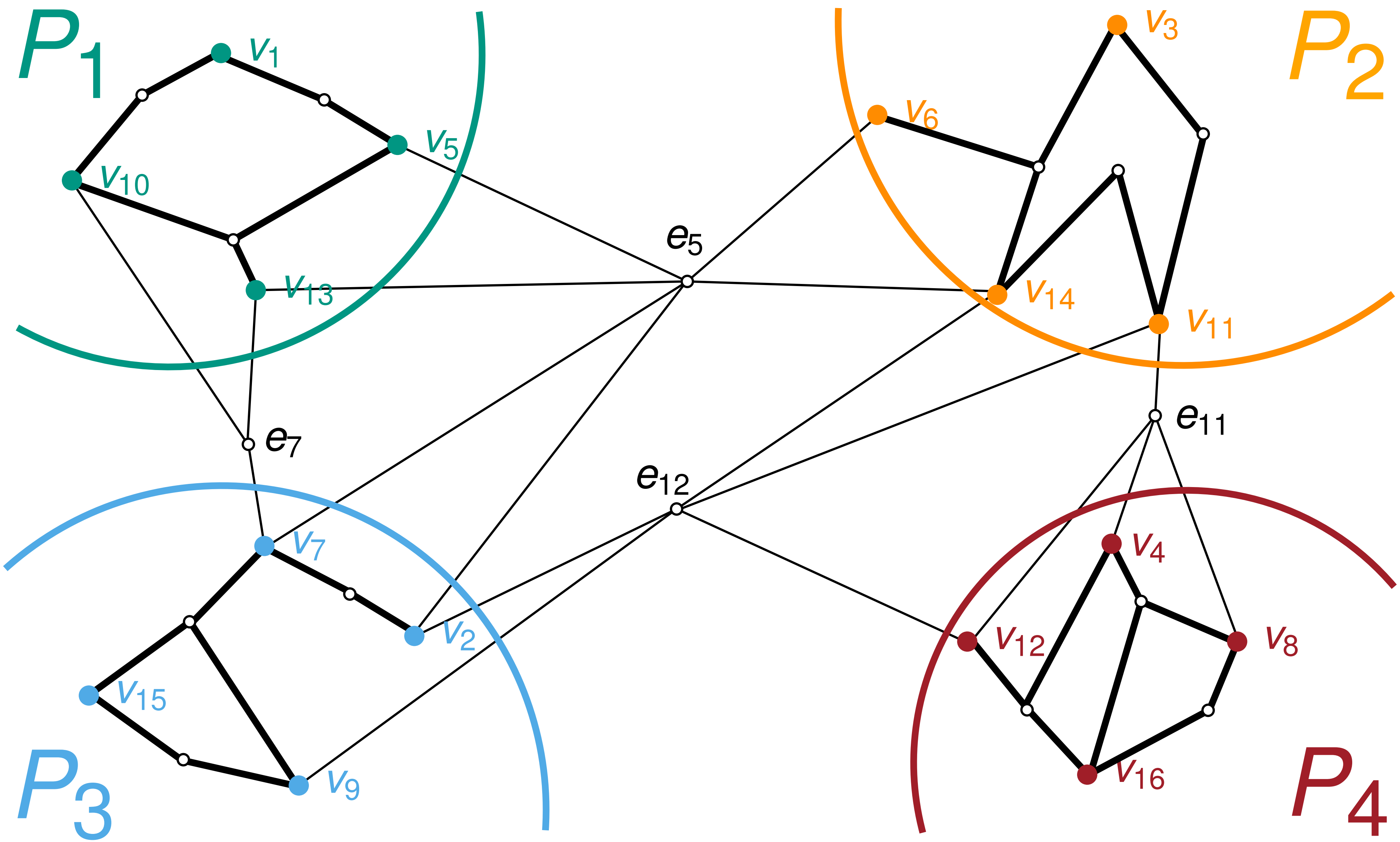

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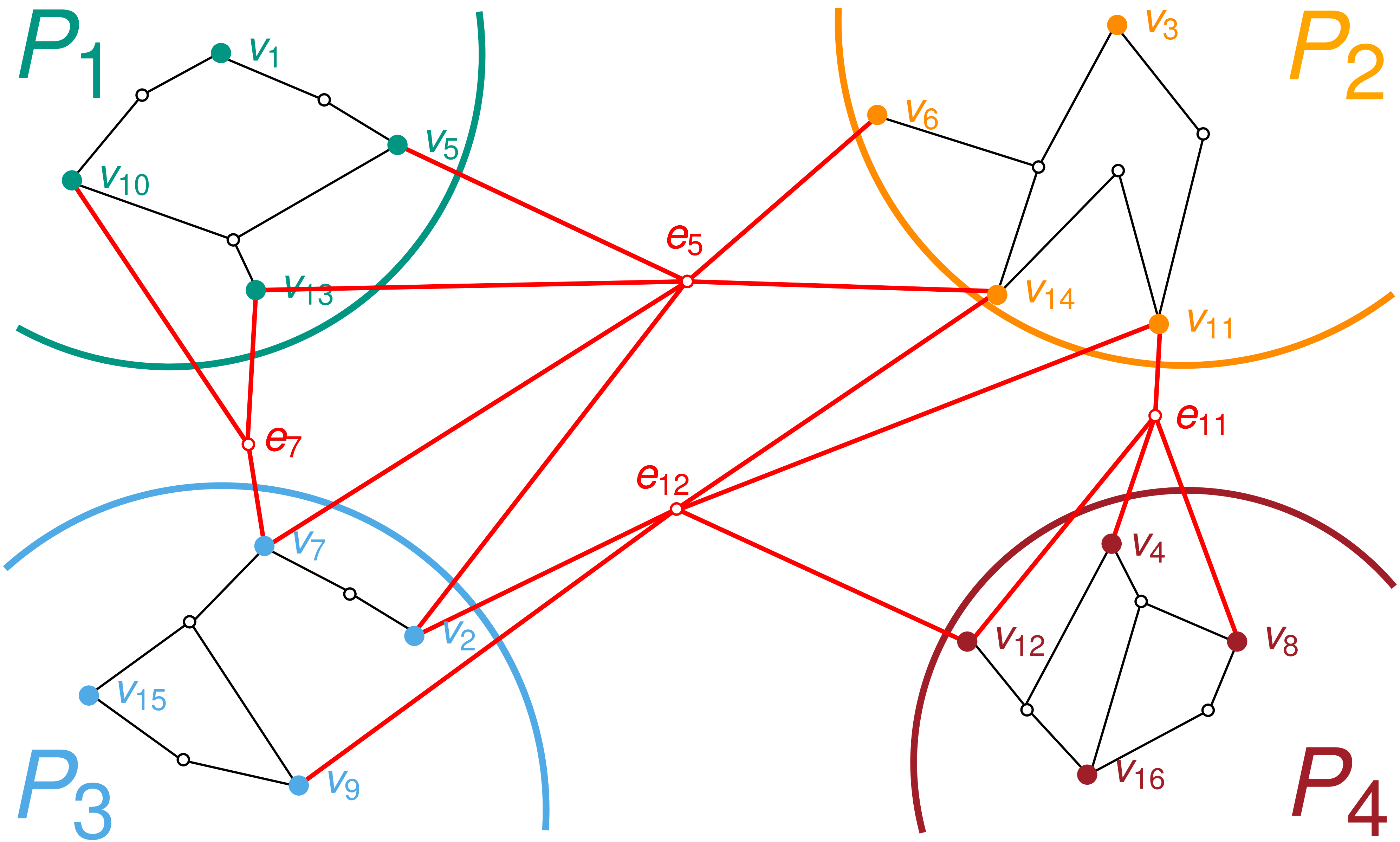

From Hypergraph Partitioning to SpM×V

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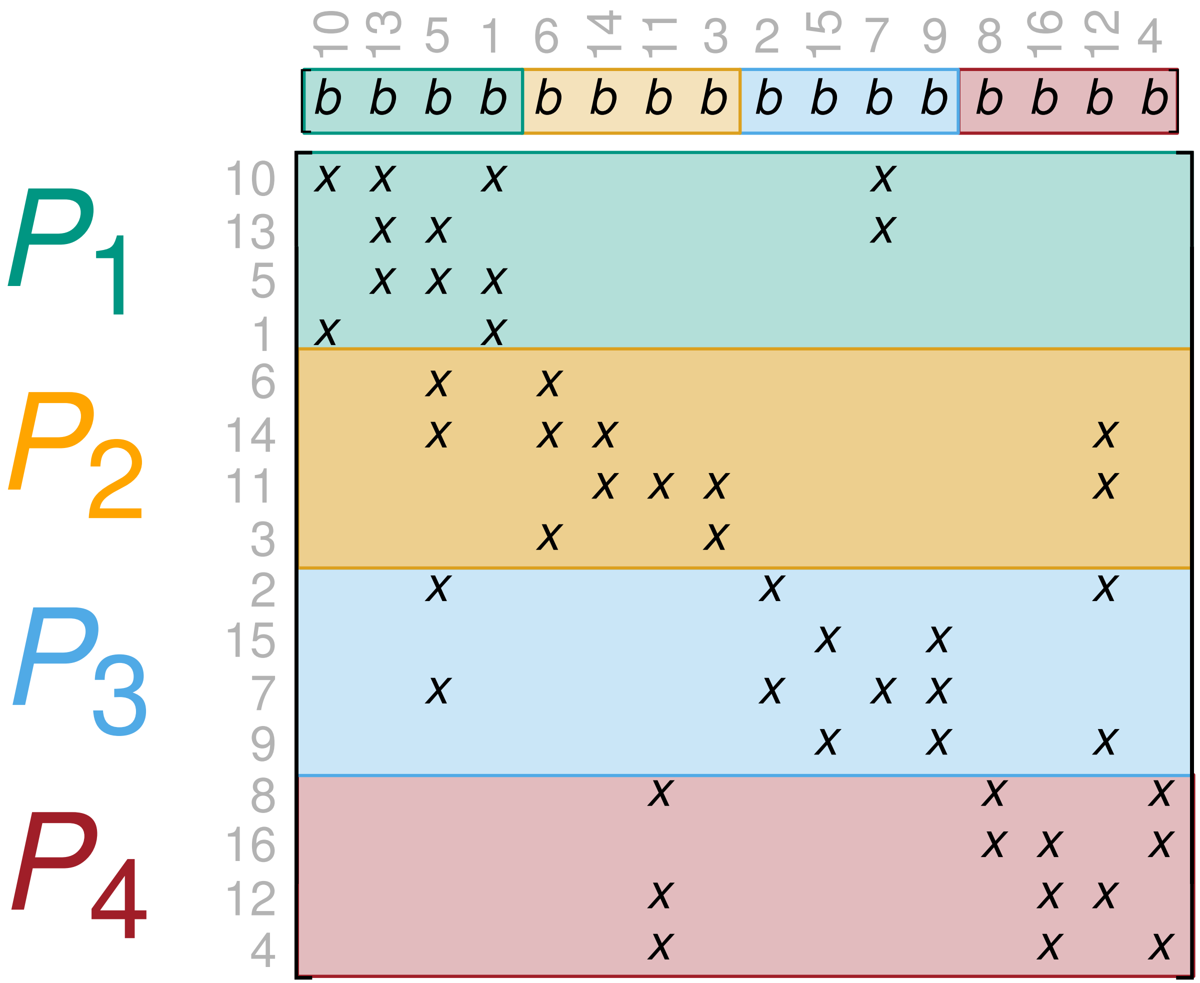
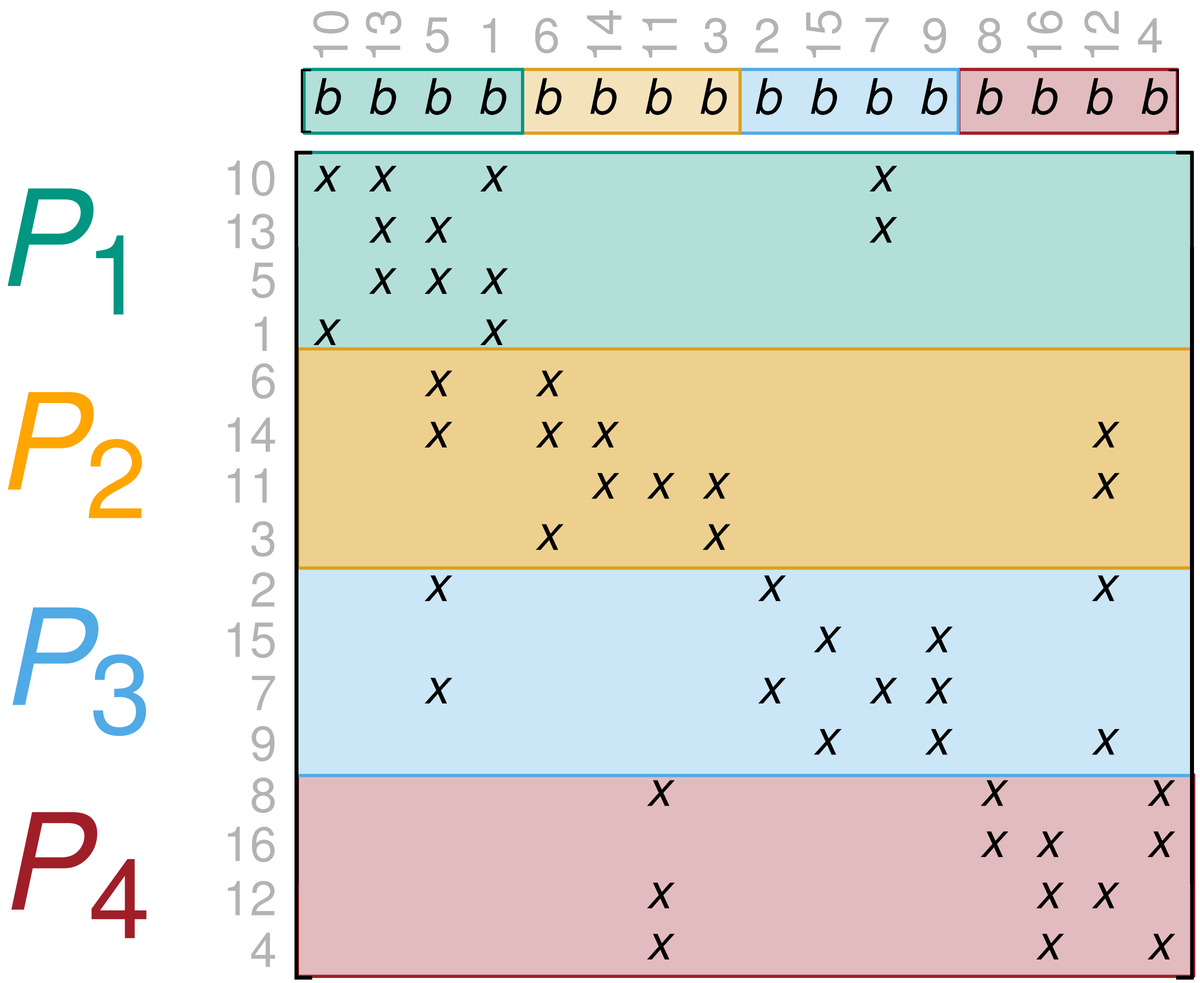
		10	13	5	1	6	14	11	3	2	15	7	9	8	16	12	4
		b	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
P_1	10	*x*	*x*		*x*							*x*					
	13		*x*	*x*								*x*					
	5		*x*	*x*	*x*												
	1	*x*			*x*												
P_2	6			*x*		*x*											
	14			*x*		*x*	*x*									*x*	
	11						*x*	*x*	*x*							*x*	
	3					*x*			*x*								
P_3	2			*x*						*x*						*x*	
	15										*x*		*x*				
	7			*x*						*x*		*x*	*x*				
	9										*x*		*x*			*x*	
P_4	8							*x*						*x*			*x*
	16													*x*	*x*		*x*
	12							*x*							*x*	*x*	
	4							*x*							*x*		*x*

From Hypergraph Partitioning to SpM×V



Load Balancing?

From Hypergraph Partitioning to SpM $\times$ V



Load Balancing?

$\Rightarrow$ 12

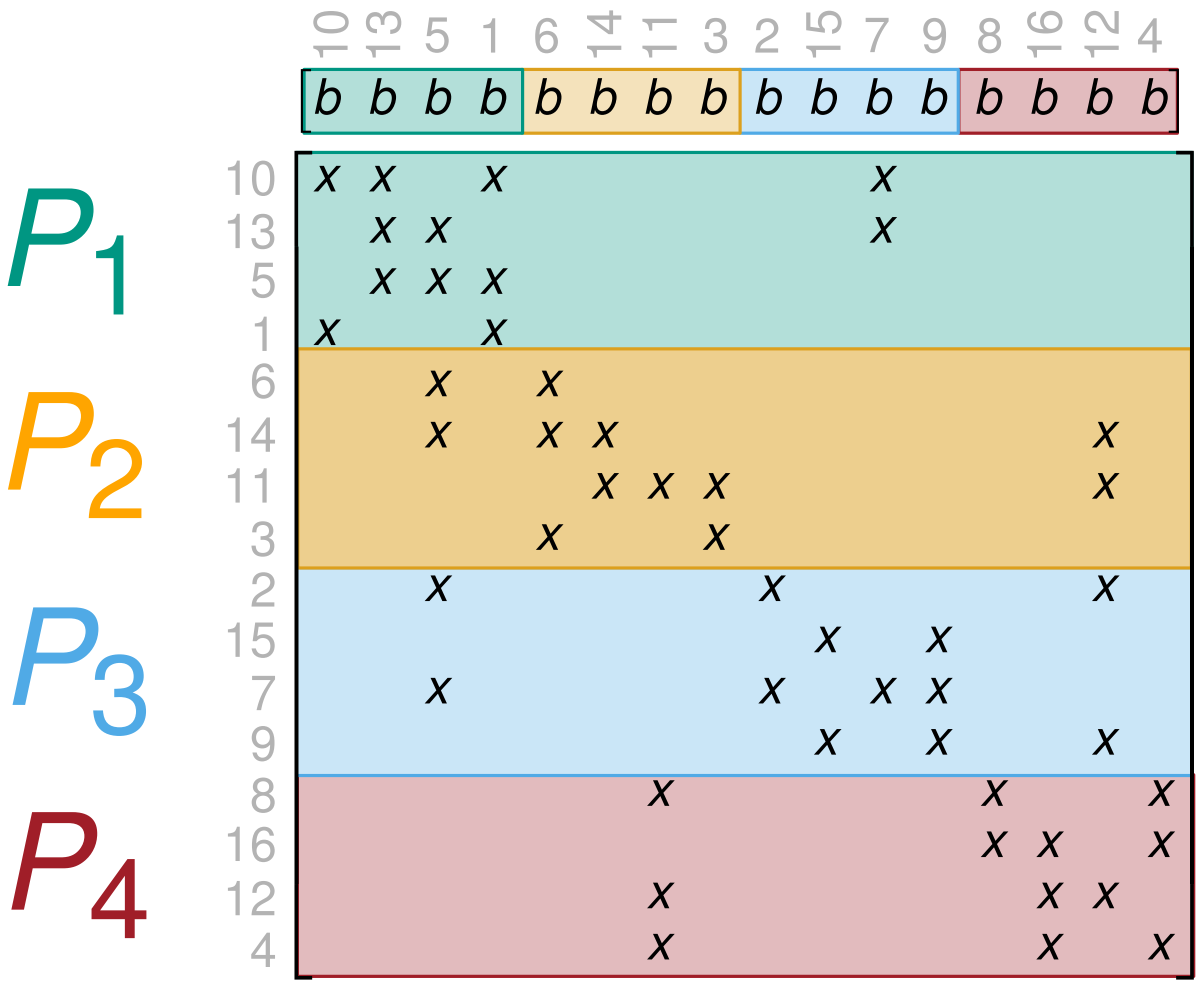
$\Rightarrow$ 12

$\Rightarrow$ 12

$\Rightarrow$ 12

From Hypergraph Partitioning to SpM$\times$V

Where are the cut-hyperedges?



Load Balancing?

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$\Rightarrow$ 12

Commuication Volume?

From Hypergraph Partitioning to SpM×V

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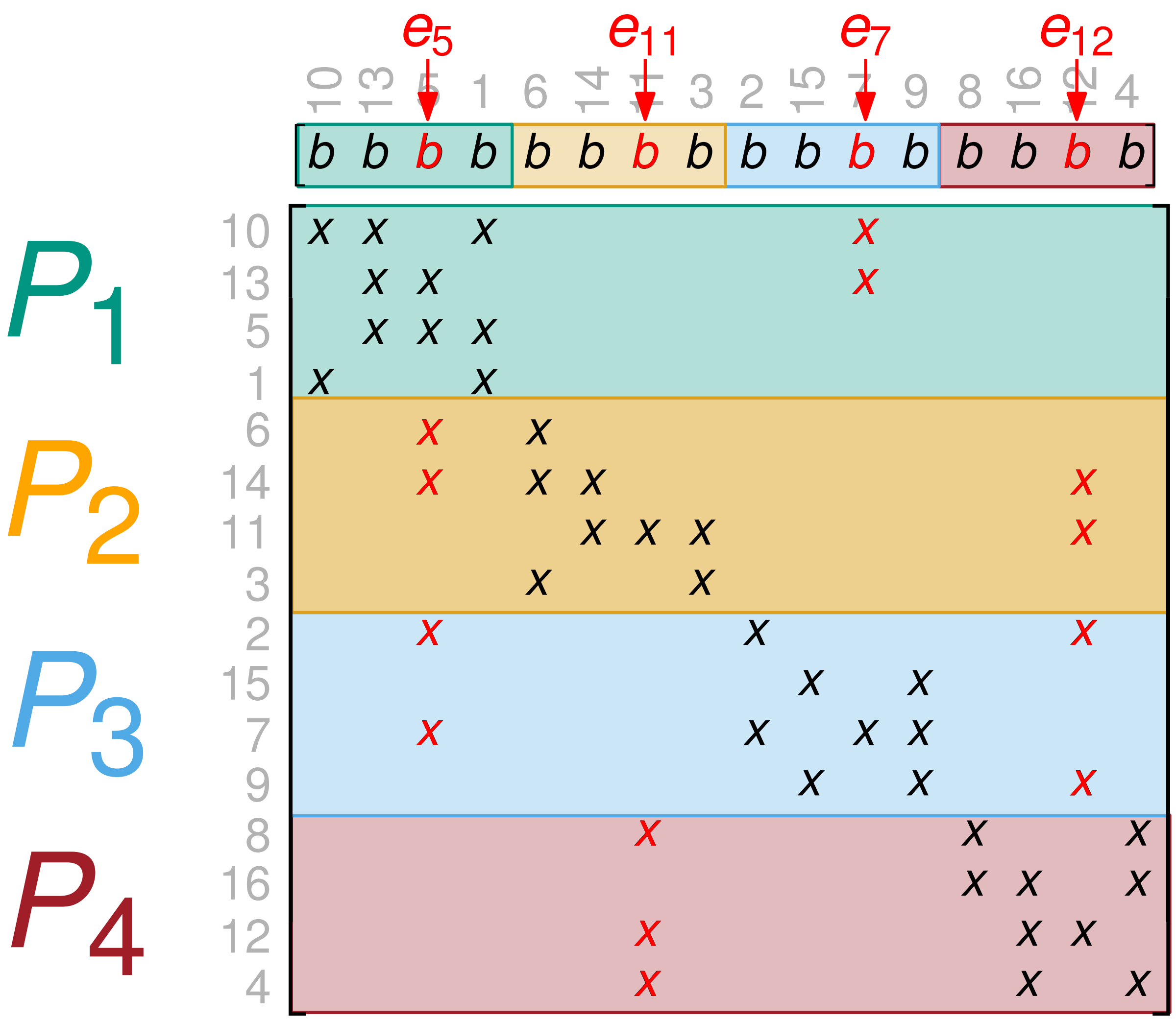

Load Balancing?

⇒ 12

⇒ 12

⇒ 12

⇒ 12

Commuication Volume? ⇒ 6 entries!

How does Hypergraph Partitioning work?

How does

Bad News:

- Hypergraph Partitioning is $\mathbf{NP}$-hard
- Even finding good approximate solutions for graphs is $\mathbf{NP}$-hard

work?

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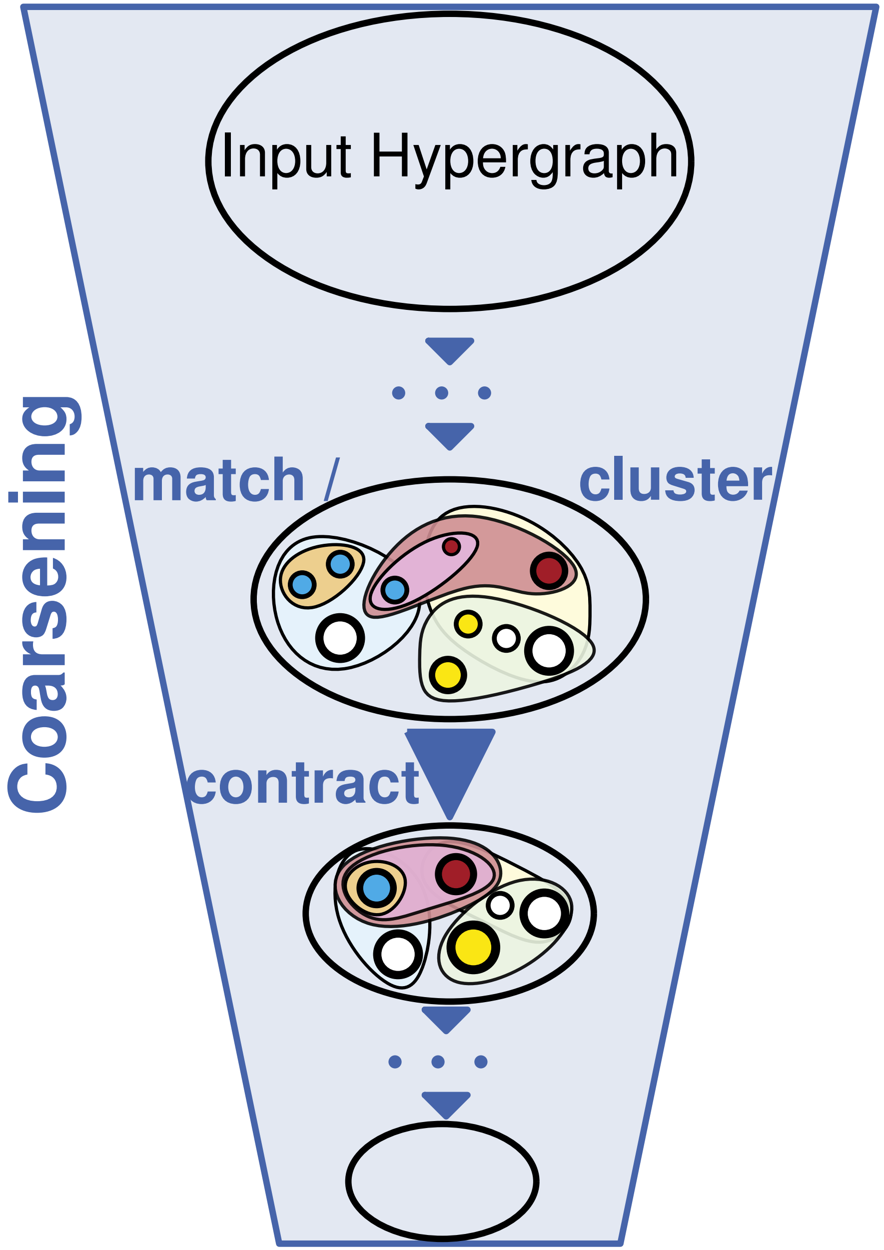
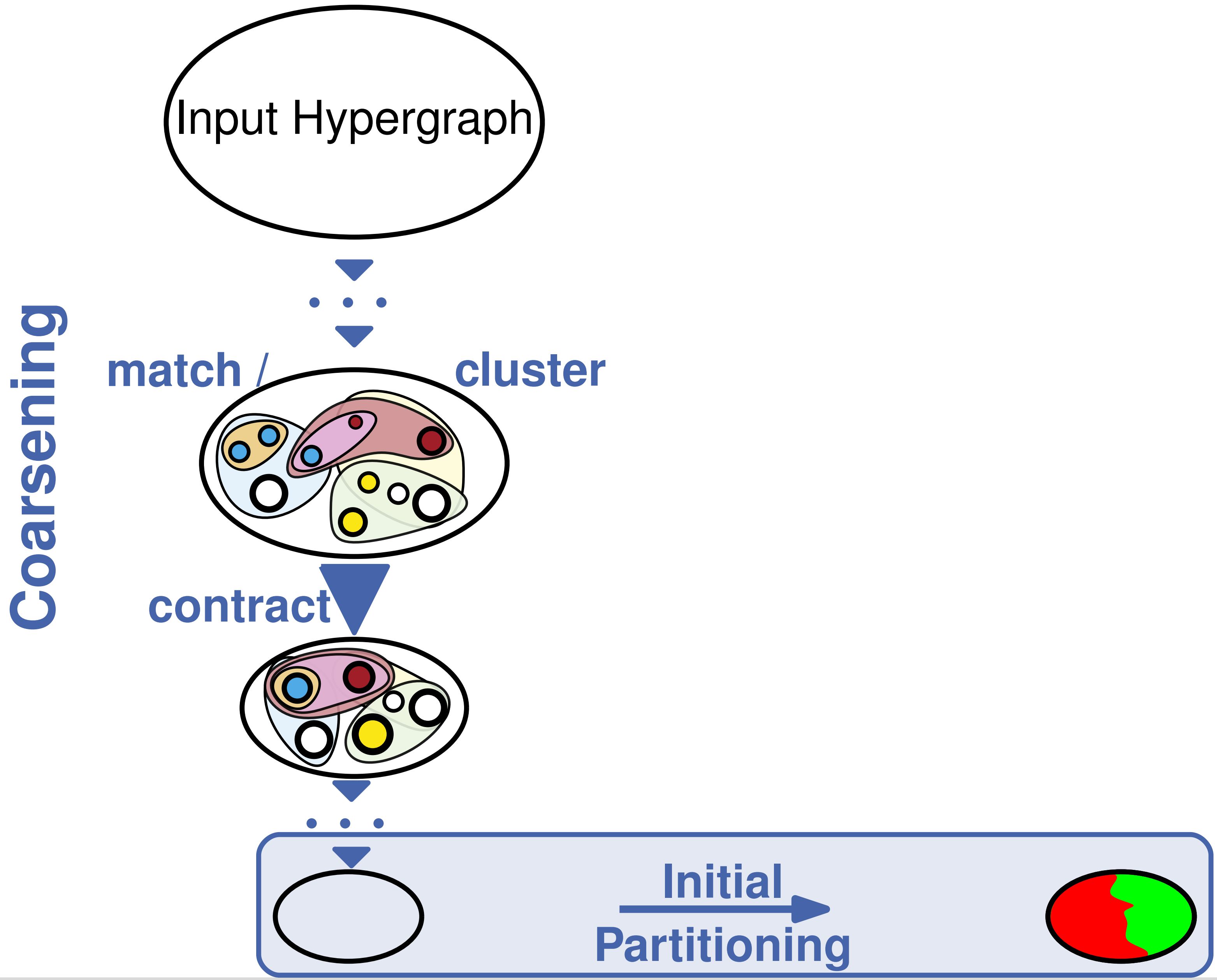
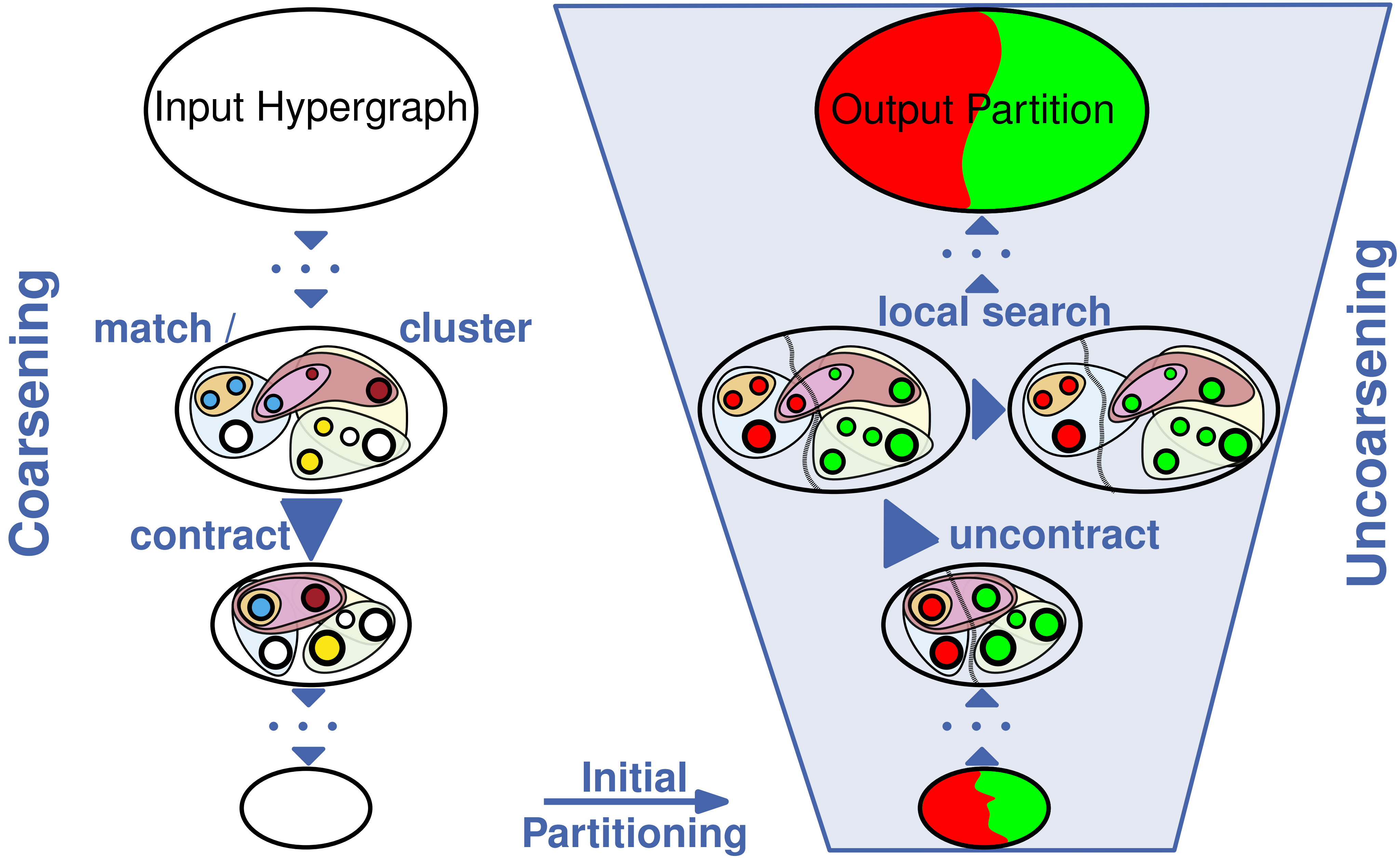
Successful Heuristic: Multilevel Paradigm



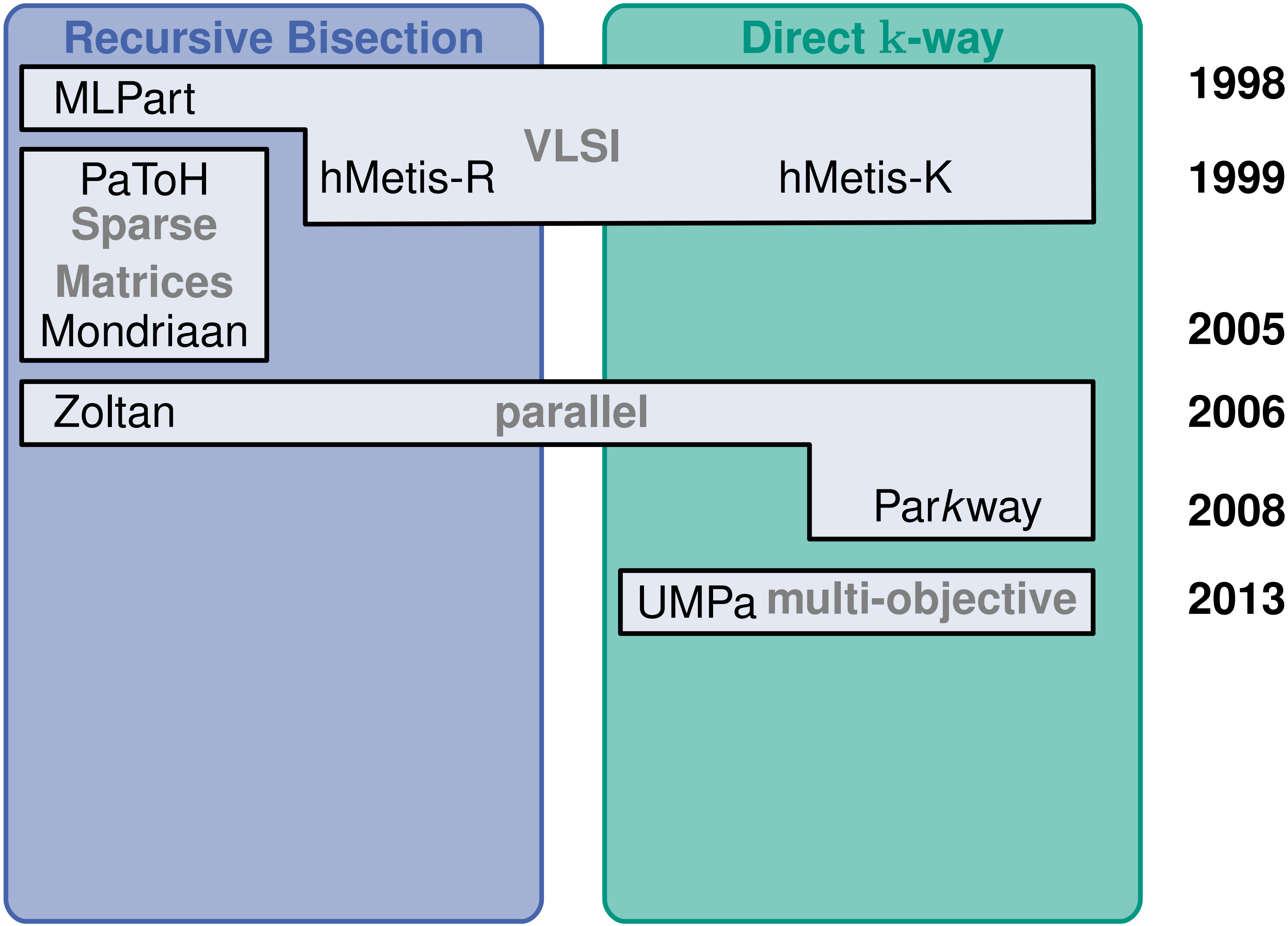
Successful Heuristic: Multilevel Paradigm



Successful Heuristic: Multilevel Paradigm



Taxonomy of Hypergraph Partitioning Tools



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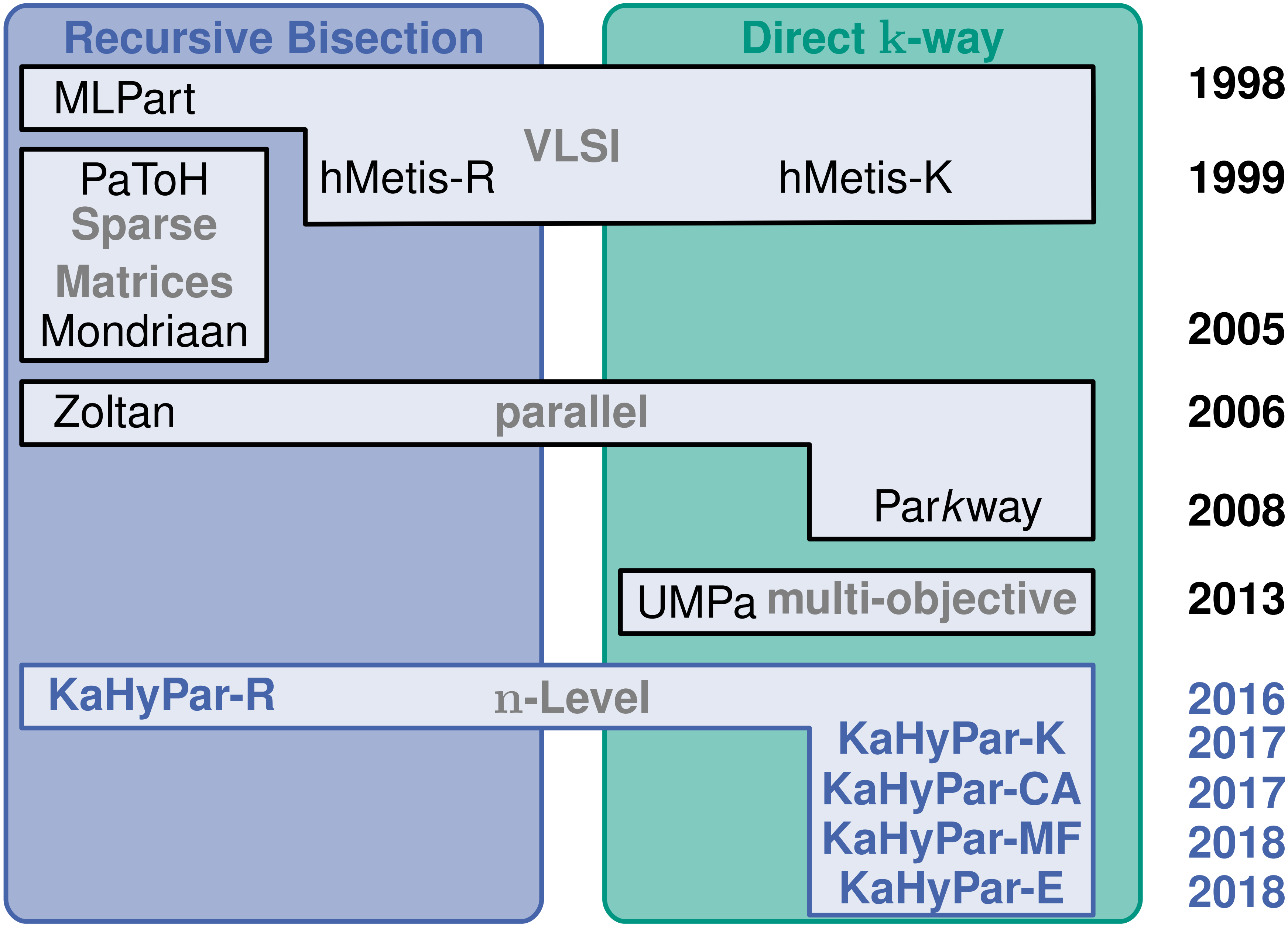
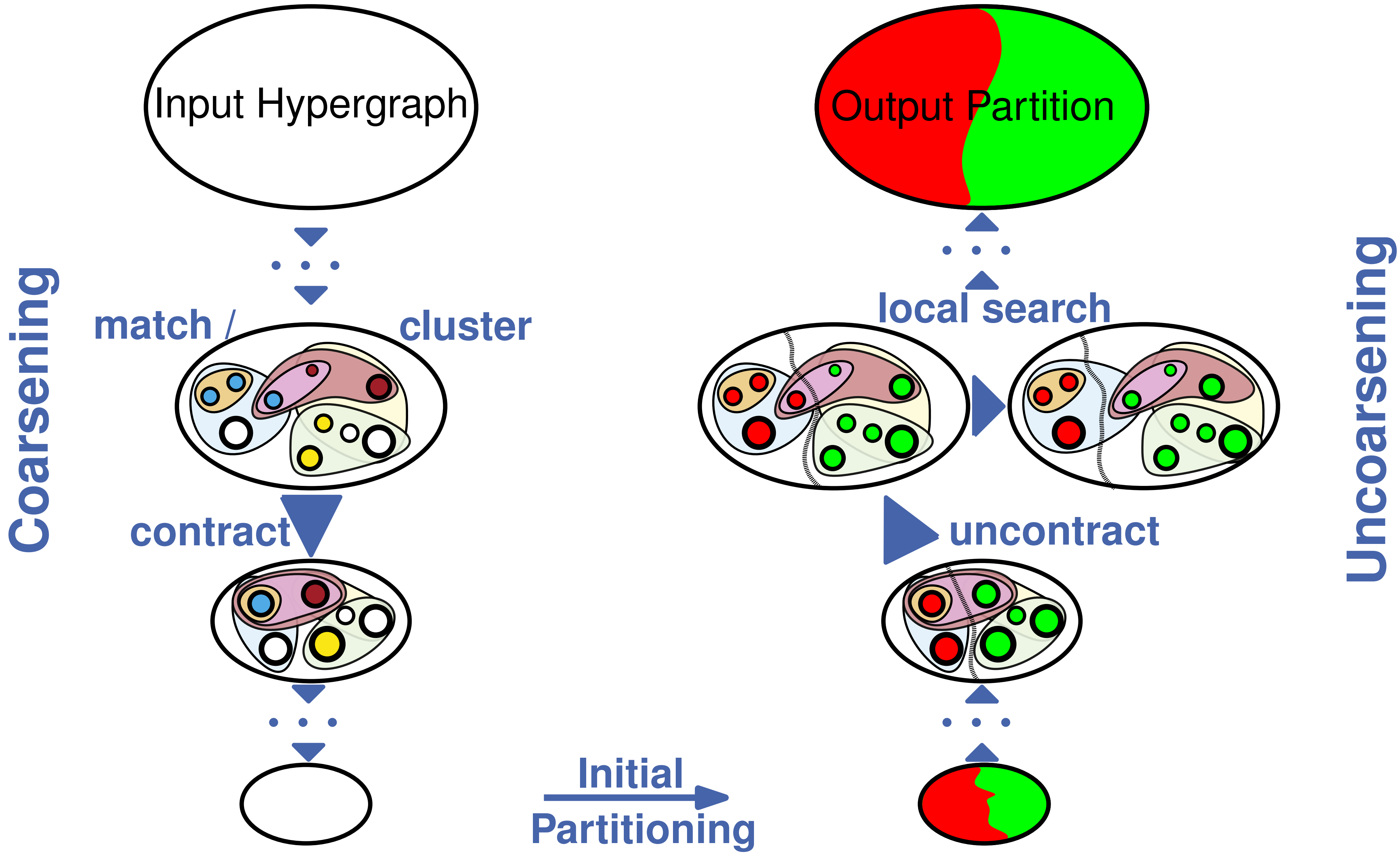
Taxonomy of Hypergraph Partitioning Tools



Why Yet Another Multilevel Algorithm?



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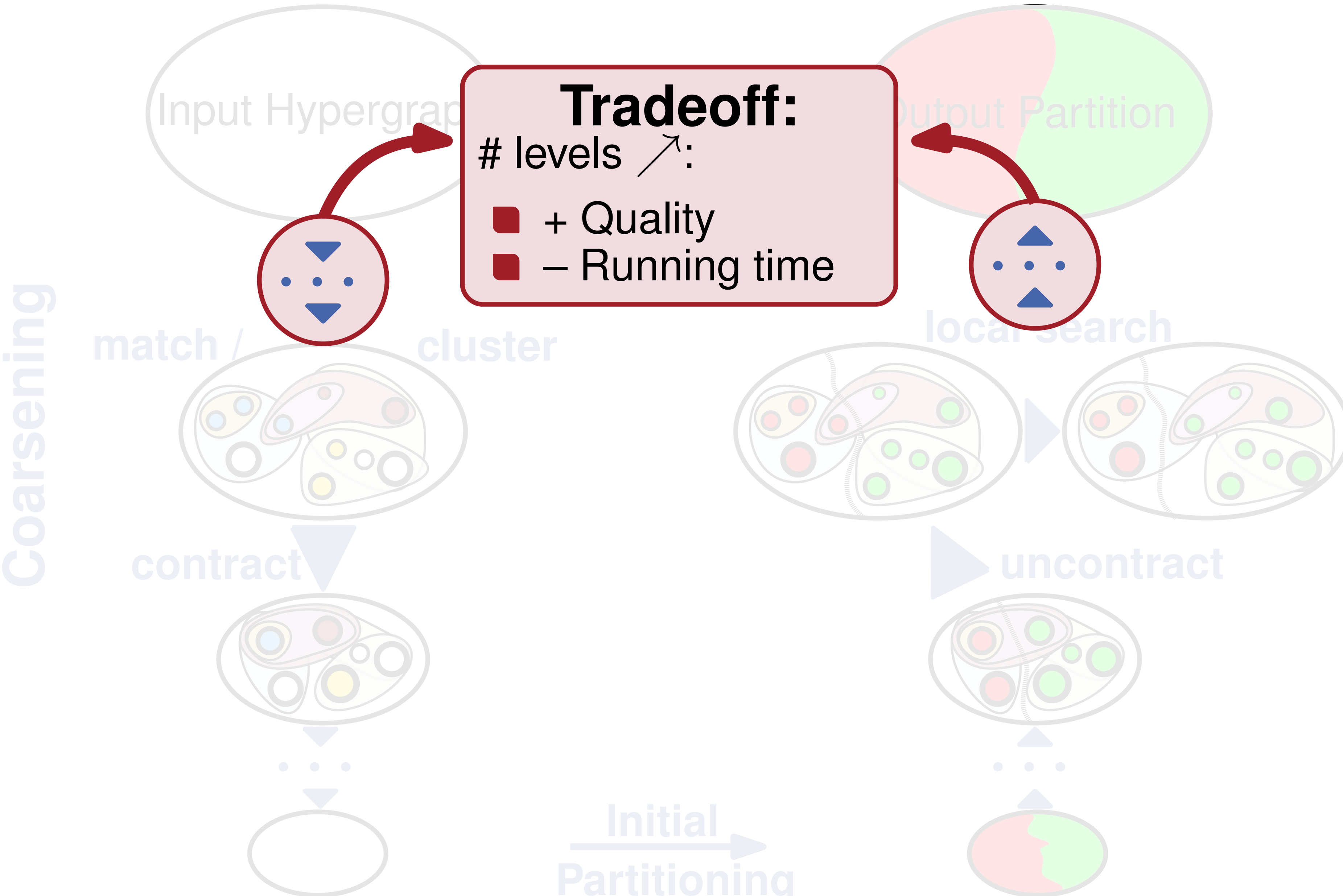
Why Yet Another Multilevel Algorithm?

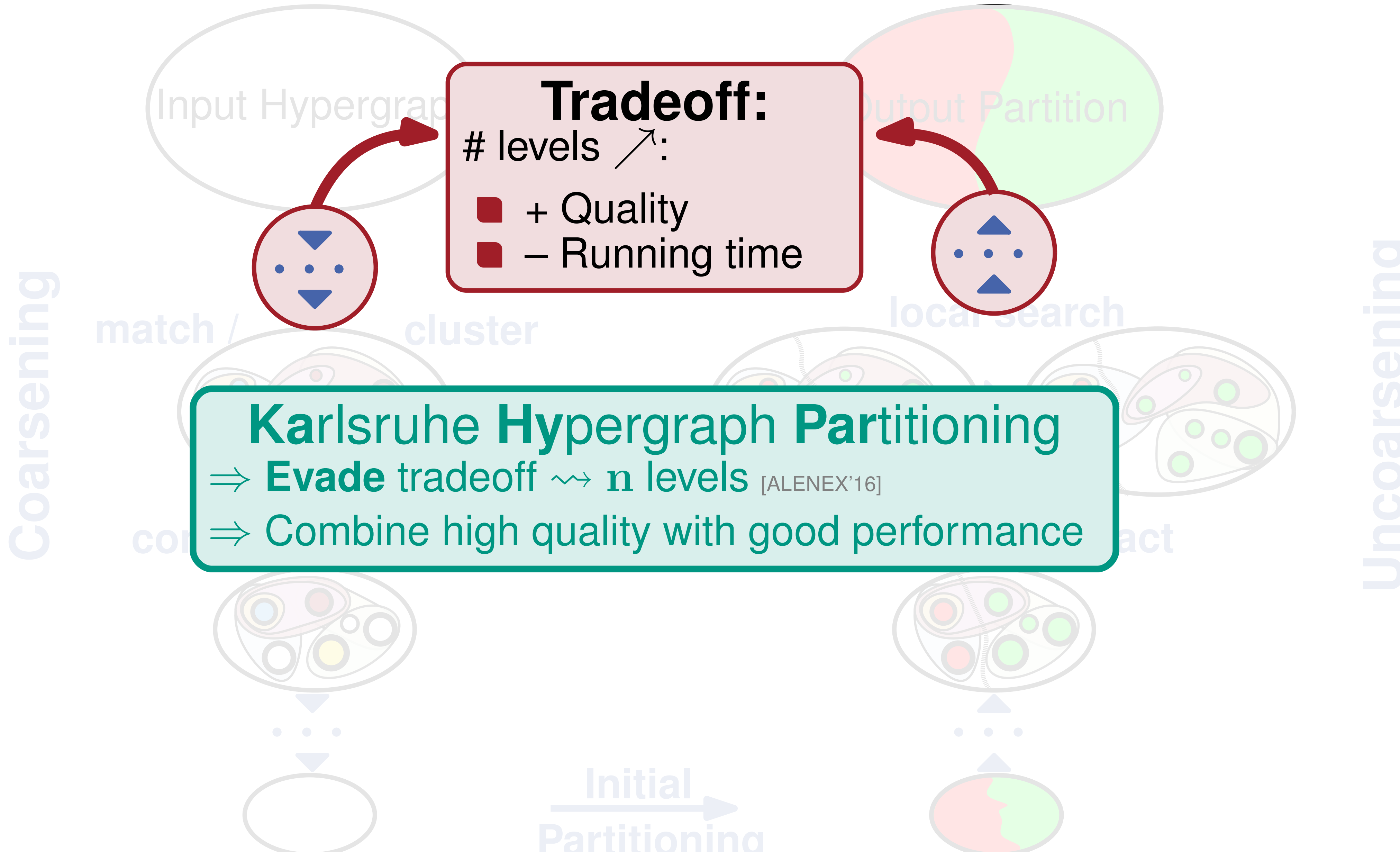


Tradeoff:

levels ↗:

- + Quality
- – Running time

Why Yet Another Multilevel Algorithm?



Tradeoff:

\# levels $\nearrow$:

- + Quality
- – Running time

Karlsruhe **Hy**pergraph **Par**titioning

$\Rightarrow$ **Evade** tradeoff $\rightsquigarrow$ $\mathbf{n}$ levels [ALENEX'16]

$\Rightarrow$ Combine high quality with good performance

KaHyPar: Novel Algorithmic Ingredients

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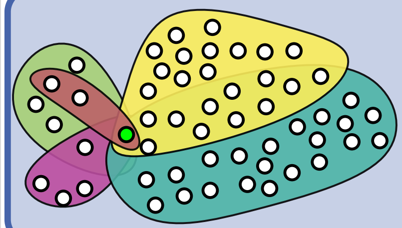
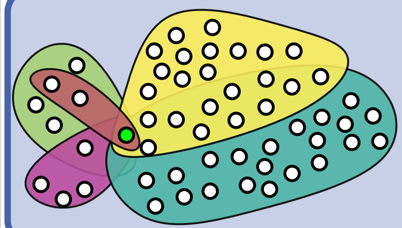


Min-Hash Based Sparsification

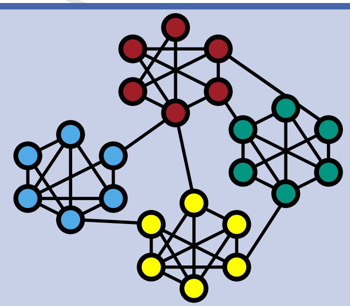
[ALENEX'17]

KaHyPar: Novel Algorithmic Ingredients



Min-Hash Based Sparsification

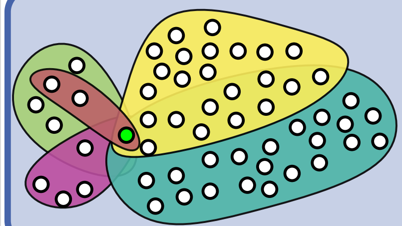
[ALENEX'17]



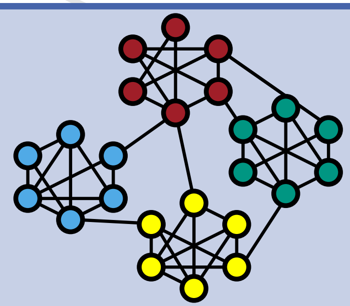
Community-Aware Coarsening

[SEA'17]

KaHyPar: Novel Algorithmic Ingredients



Min-Hash Based Sparsification
[ALENEX'17]



Community-Aware Coarsening
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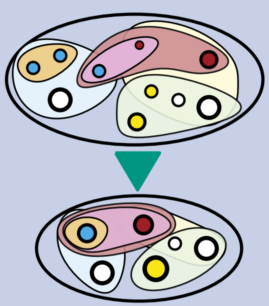
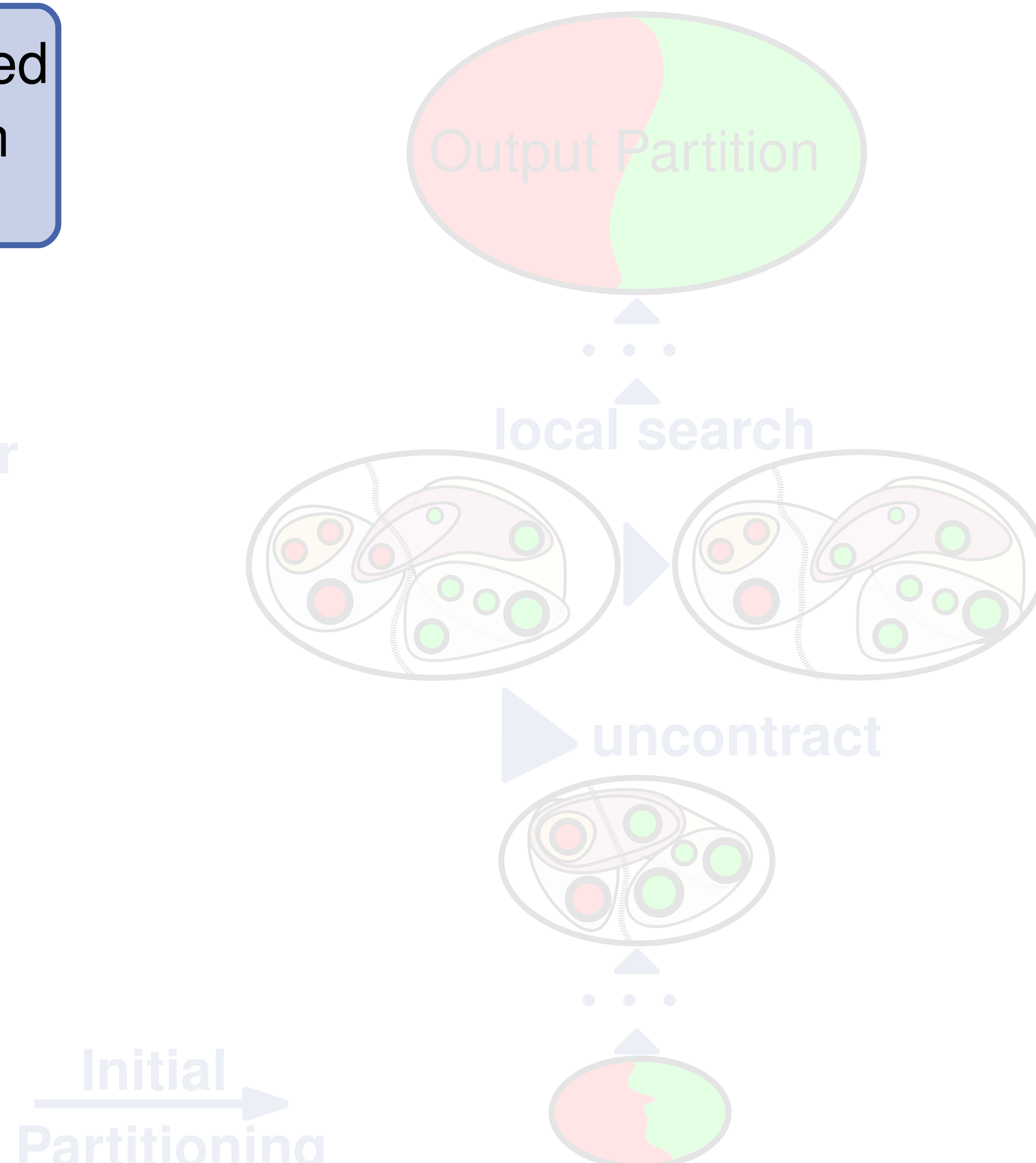


Fast *n*-Level Coarsening
[ALENEX'16,ALENEX'17]



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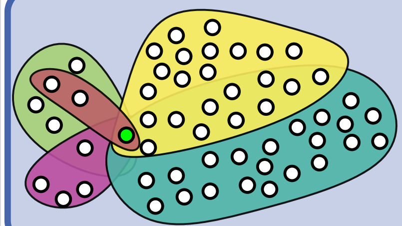
KaHyPar: Novel Algorithmic Ingredients



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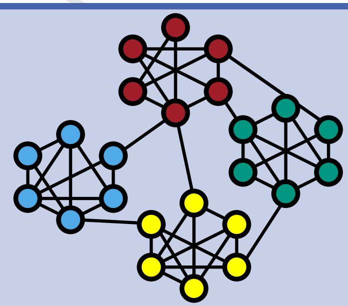
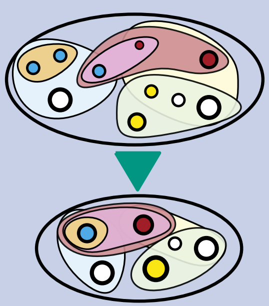


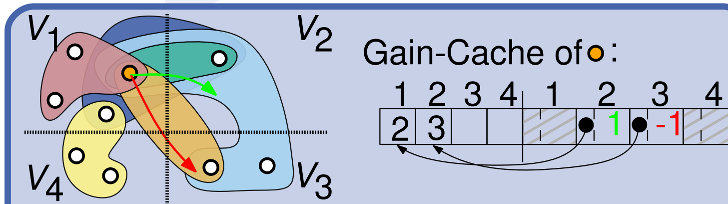
Community-Aware Coarsening

[SEA'17]



Fast *n*-Level Coarsening

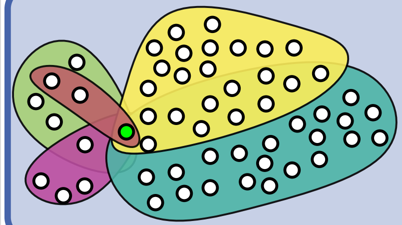
[ALENEX'16,ALENEX'17]



Engineered *k*-way FM

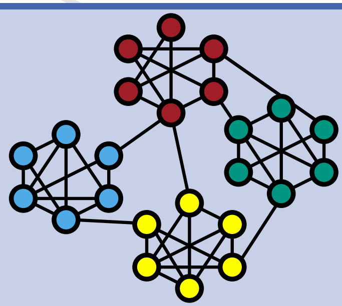
[ALENEX'17]

KaHyPar: Novel Algorithmic Ingredients



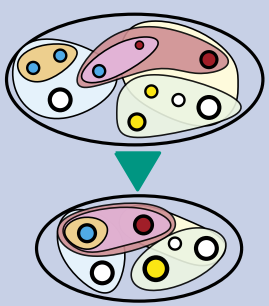
Min-Hash Based Sparsification

[ALENEX'17]



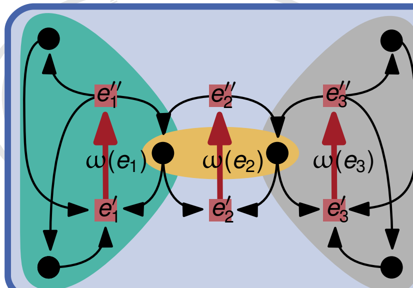
Community-Aware Coarsening

[SEA'17]



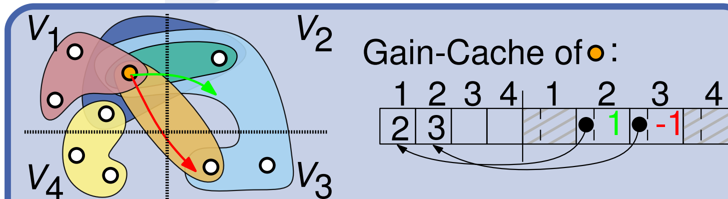
Fast n-Level Coarsening

[ALENEX'16,ALENEX'17]



Max-Flow Min-Cut Refinement

[SEA'18]



Engineered k-way FM

[ALENEX'17]

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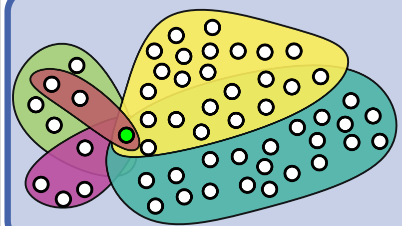
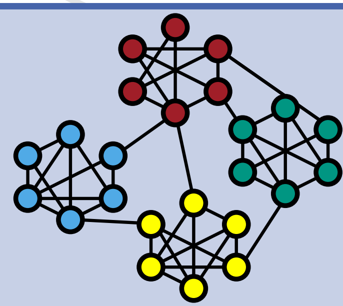
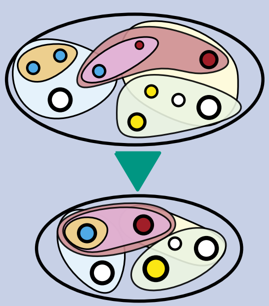
KaHyPar: Novel Algorithmic Ingredients



Min-Hash Based Sparsification
[ALENEX'17]



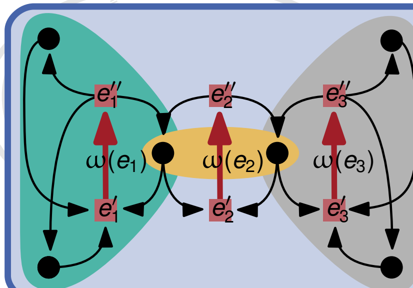
Community-Aware Coarsening
[SEA'17]



Fast n-Level Coarsening
[ALENEX'16,ALENEX'17]

$$\text{Algorithm } A \leftarrow \begin{cases} \text{Config } \mathcal{C}_1 \\ \text{Config } \mathcal{C}_2 \end{cases}$$

Algorithm Configuration
[Öhl, Bachelor's Thesis]



Max-Flow Min-Cut Refinement
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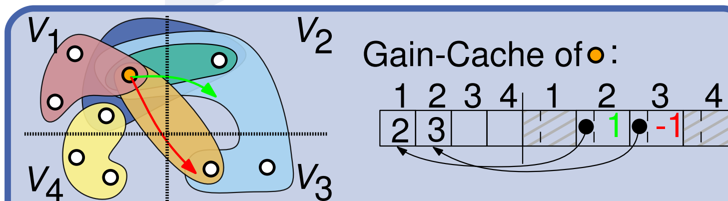
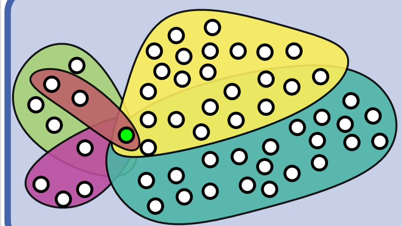


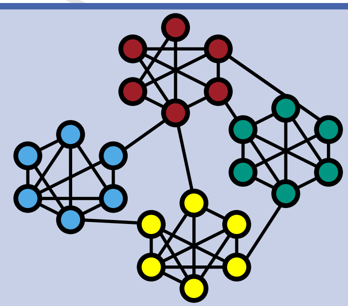
Engineered k-way FM
[ALENEX'17]

KaHyPar: Novel Algorithmic Ingredients



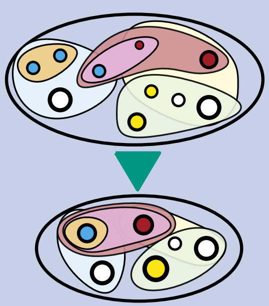
Min-Hash Based Sparsification

[ALENEX'17]



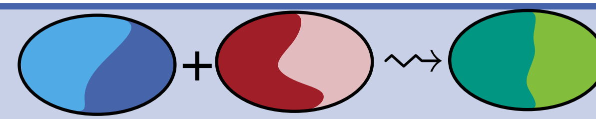
Community-Aware Coarsening

[SEA'17]



Fast n-Level Coarsening

[ALENEX'16,ALENEX'17]



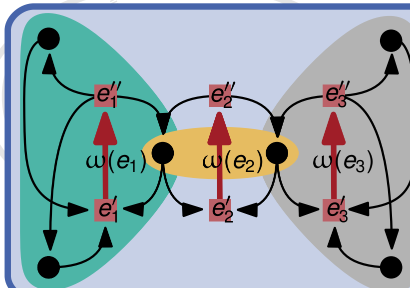
Memetic Multilevel Algorithm

[GECCO'18]

$$\text{Algorithm } A \leftarrow \begin{cases} \text{Config } \mathcal{C}_1 \\ \text{Config } \mathcal{C}_2 \end{cases}$$

Algorithm Configuration

[Öhl, Bachelor's Thesis]



Max-Flow Min-Cut Refinement

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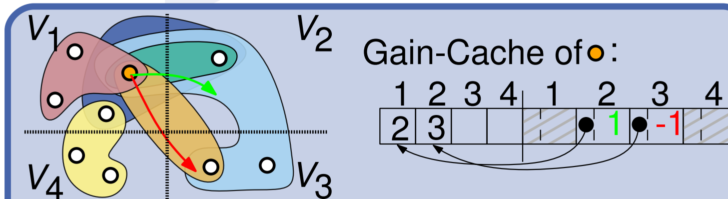

Engineered k-way FM

[ALENEX'17]

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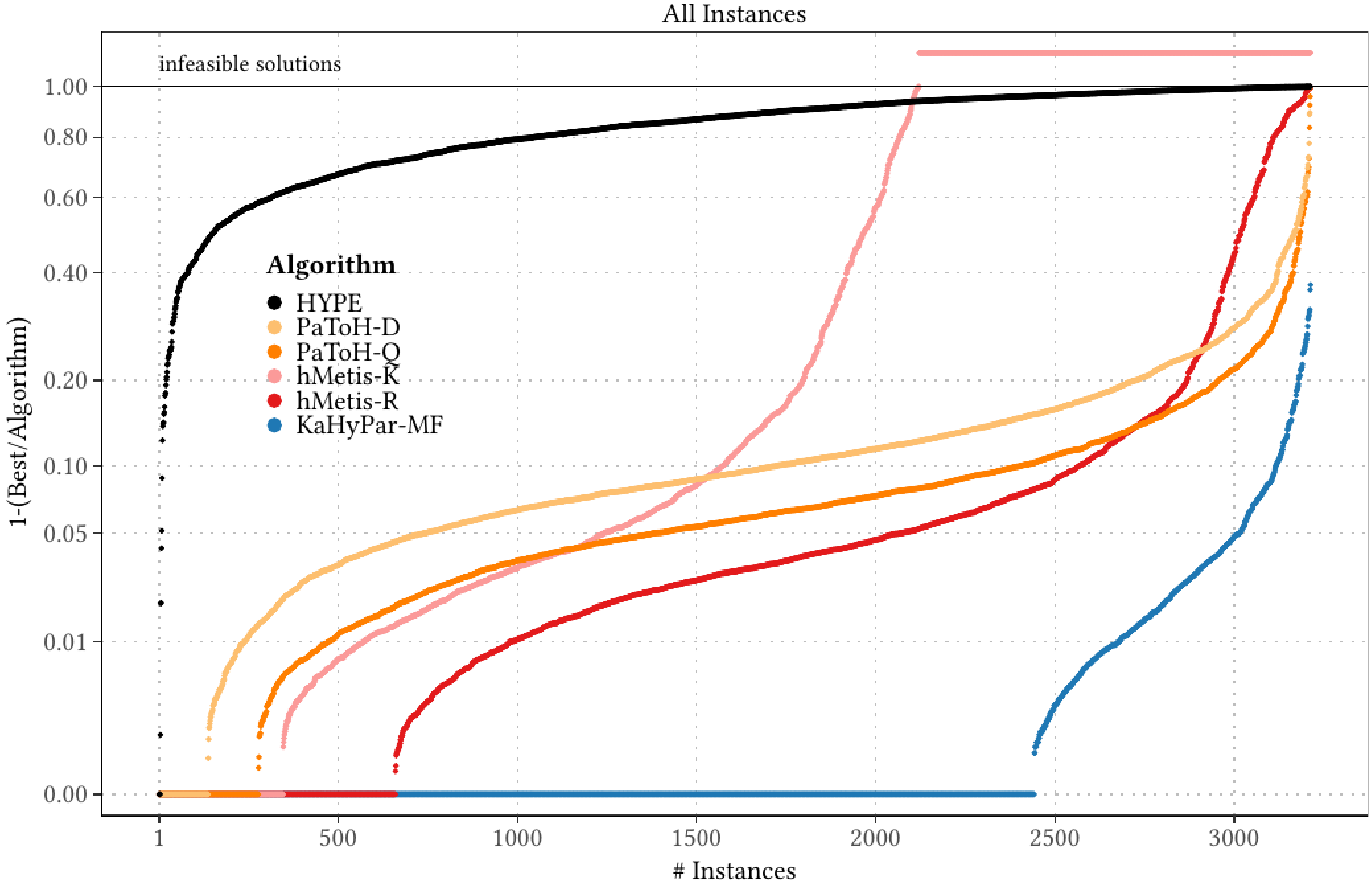
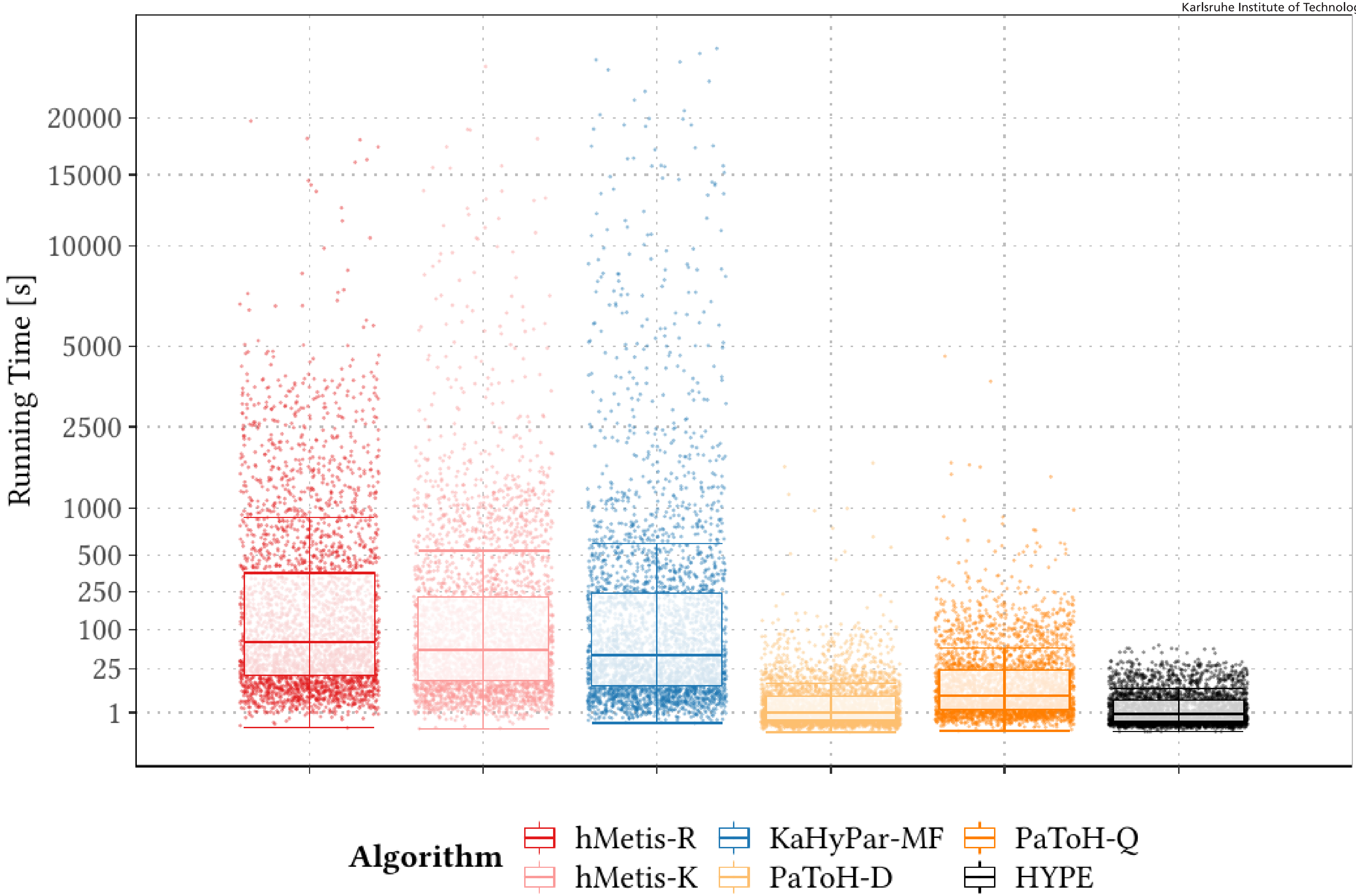
Latest Experimental Results - Quality



Latest Experimental Results - Running Time



KaHyPar - Karlsruhe Hypergraph Partitioning

- *n*-Level Partitioning Framework
- Objectives:
  - Cut
  - Connectivity $(\lambda - 1)$
- Partitioning Modes:
  - Recursive bisection
  - Direct *k*-way
- Advanced Features:
  - Evolutionary algorithm
  - Flow-based refinement
  - Advanced local search algorithms
- `http://www.kahypar.org`