Multiple-Layer Multiple-Patterning Aware Placement Refinement for Mixed-Cell-Height Designs

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Outline

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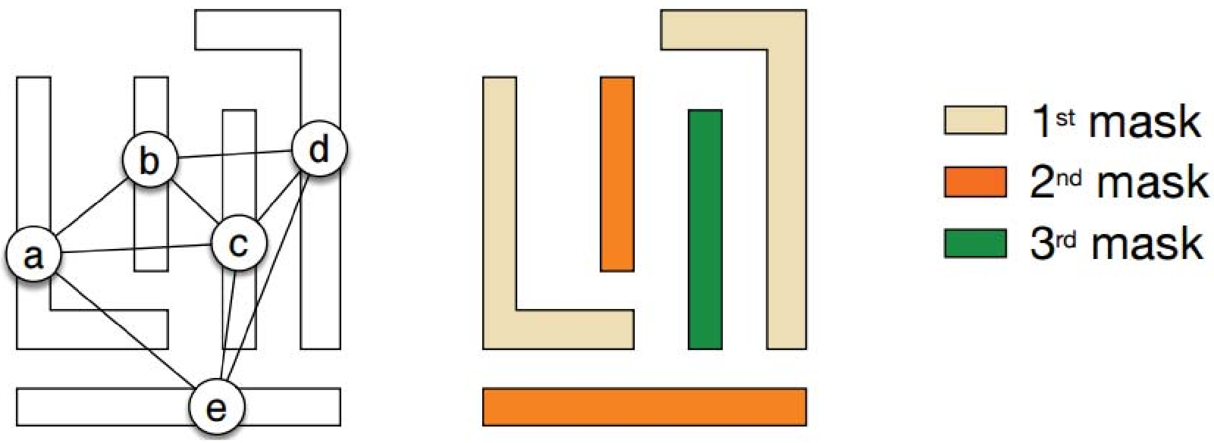
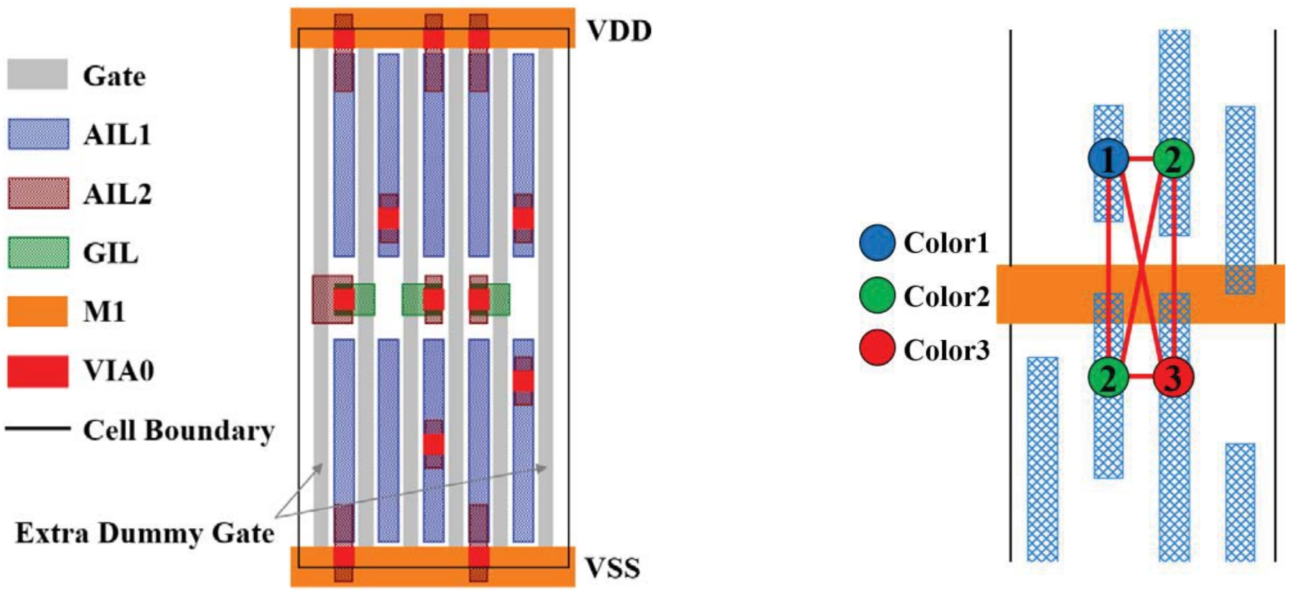
Multiple Patterning Lithography (MPL)

- With the use of MPL, the circuit patterns are partitioned into several different masks, whereby the pattern density in each mask decreases and the resolution is improved.
- Layout decomposition is a fundamental problem for MPL.



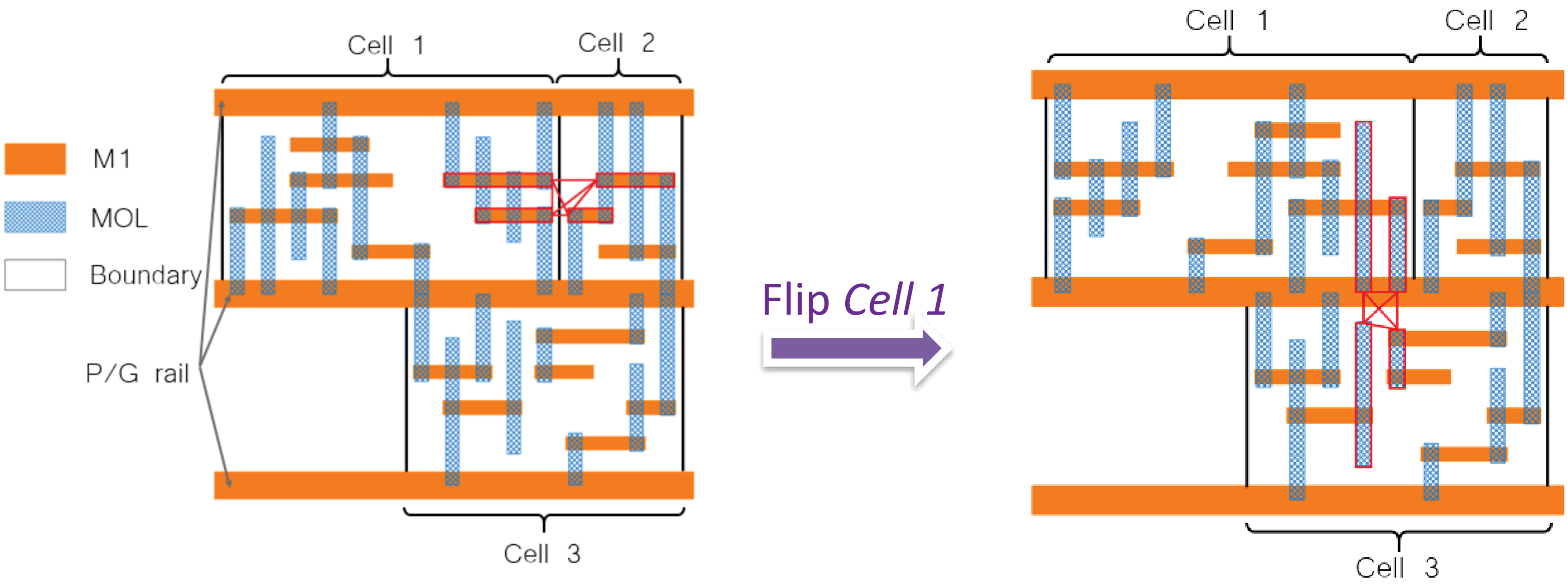
Middle-of-Line (MOL) Structure

- The cell structure with multiple layers is adopted to improve the intra-cell routability at advanced technology nodes.
- Features in MOL layers may introduce inter-row conflicts.



Conflict Interplay among Layers

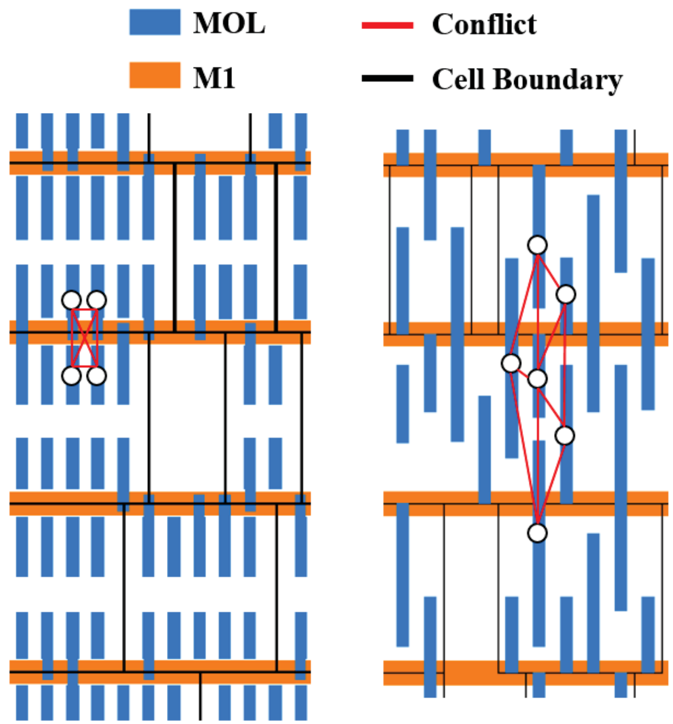
- For a multiple-layer MPL problem, a refinement method that solves conflicts for a layer may lead to the occurrence of new conflicts in another layer.



Major Differences from Prior Work

- Prior work [TCAD17]: TPL aware placement refinement
  - Single-row height cells
  - Layout decomposition
    - M1 layer + an MOL layer

- Our work:
  - A mix of single-row height and multiple-row height cells
  - Layout decomposition
    - Multiple MPL layers



(a) (b)

[TCAD17]: Y. Lin, B. Yu, B. Xu, and D. Z. Pan, “Triple patterning aware detailed placement toward zero cross-row middle-of-line conflict,” IEEE TCAD, 2017.

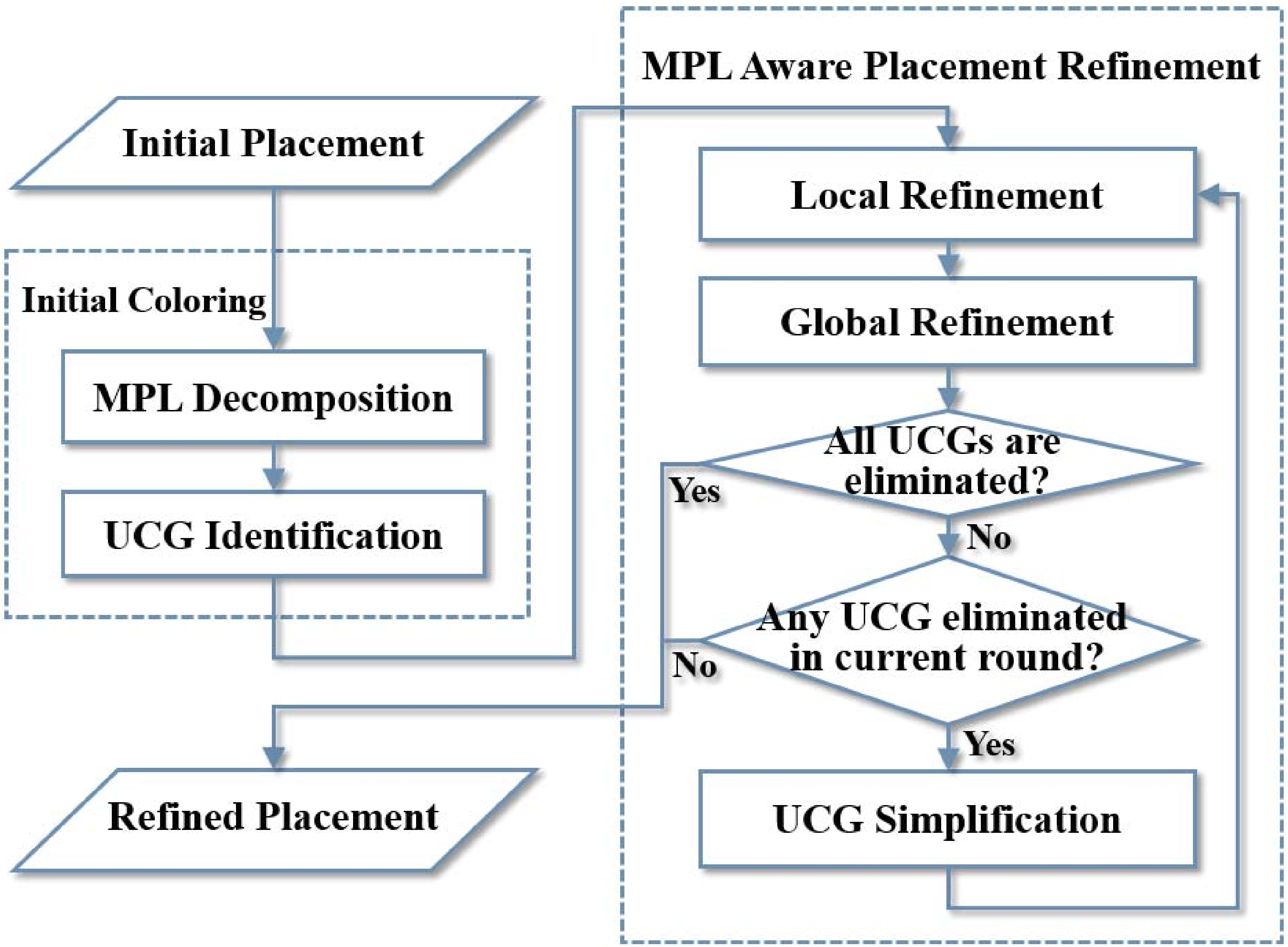
Contributions

- We develop a placement refinement methodology to overcome multiple-layer MPL issue for mixed-cell-height designs.
- A concept of uncolored cell group (UCG) is introduced to facilitate the effective elimination of coloring conflicts.
- Our methodology complements prior work to tackle the other cases.

Problem Formulation

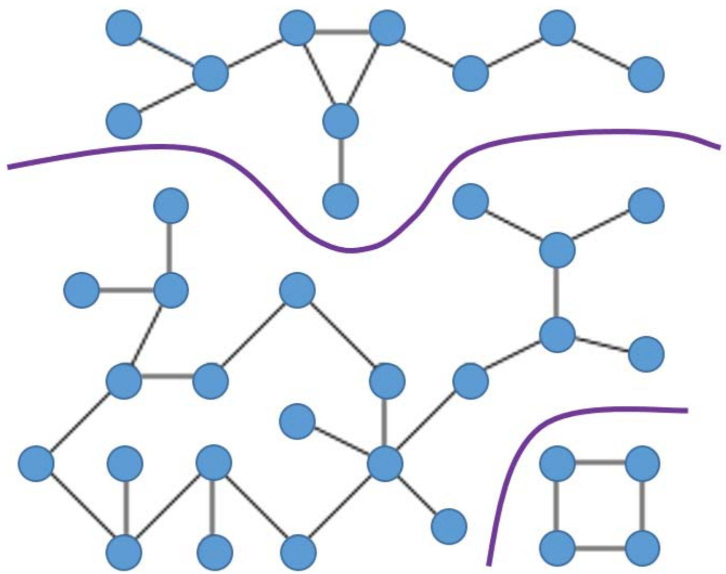
- Input:
  - A legal placement with single-row/multiple-row height cells
  - A minimum coloring spacing rule for each MPL layer (where different layers may have different requirements on the number of masks)
- Output:
  - A legal placement within the given placement region
  - A layout decomposition without any stitch for each MPL layer
- Objective:
  - To minimize the total cell displacement
  - To minimize the number of coloring conflicts

Overall Flow of Our Methodology

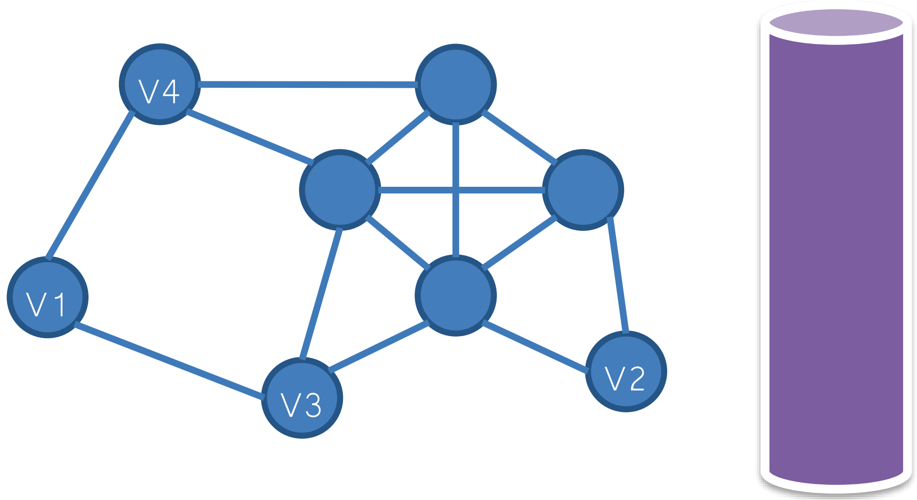


Connected Component Computation

- Connected component computation partitions the graph into several connected components.

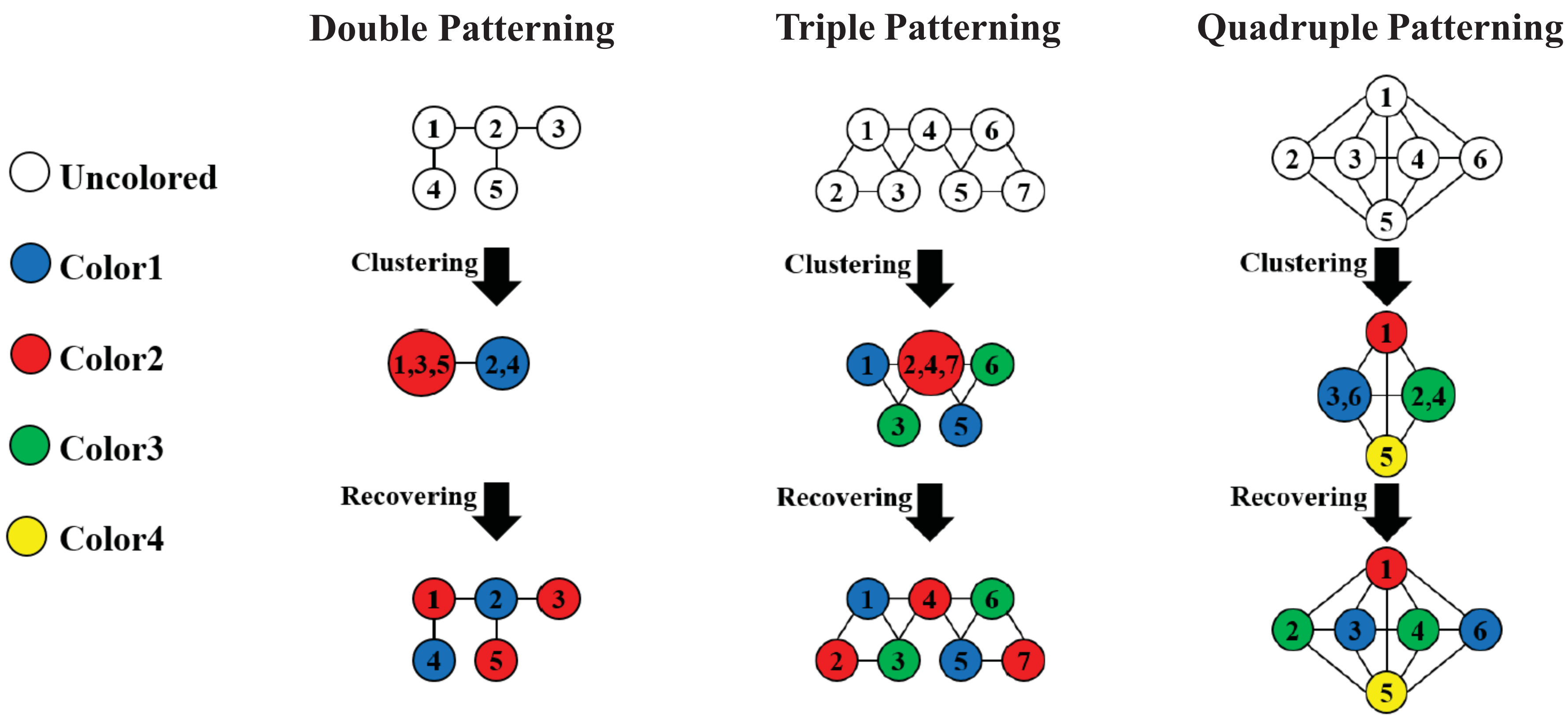


Vertex Removal

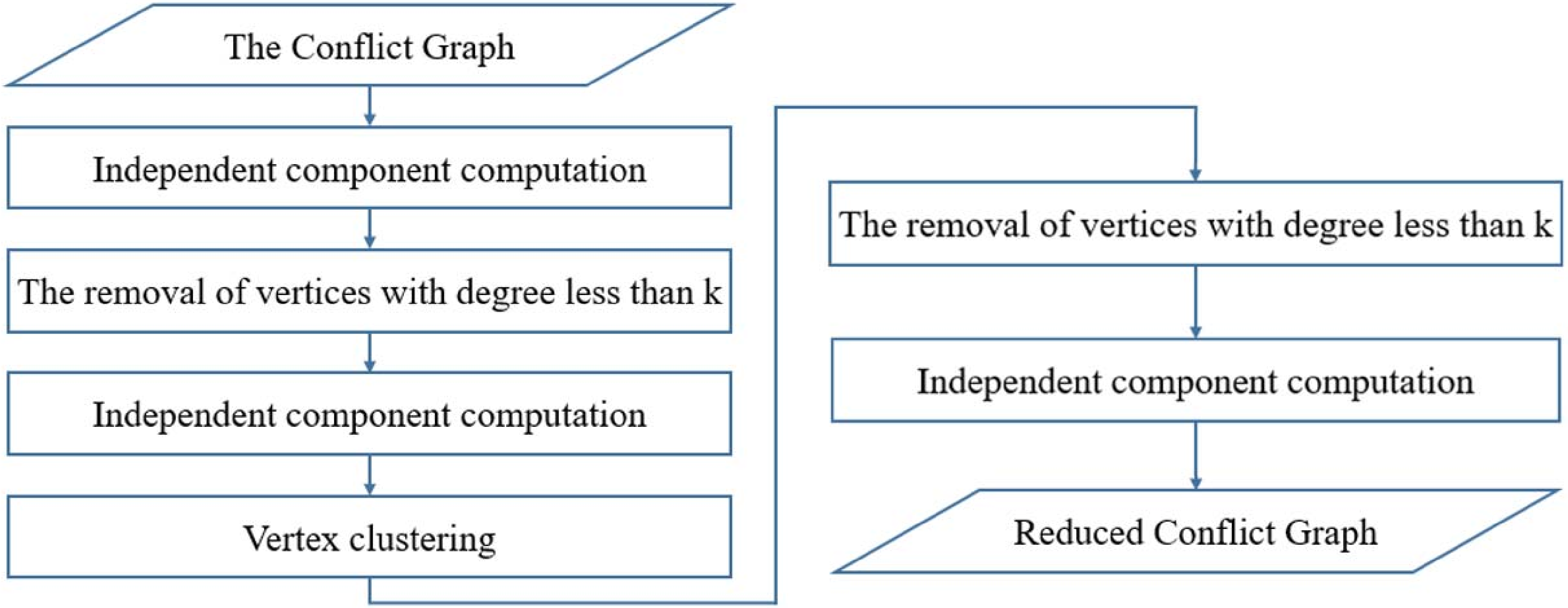


* k (number of colors) is set to 3 in this example.

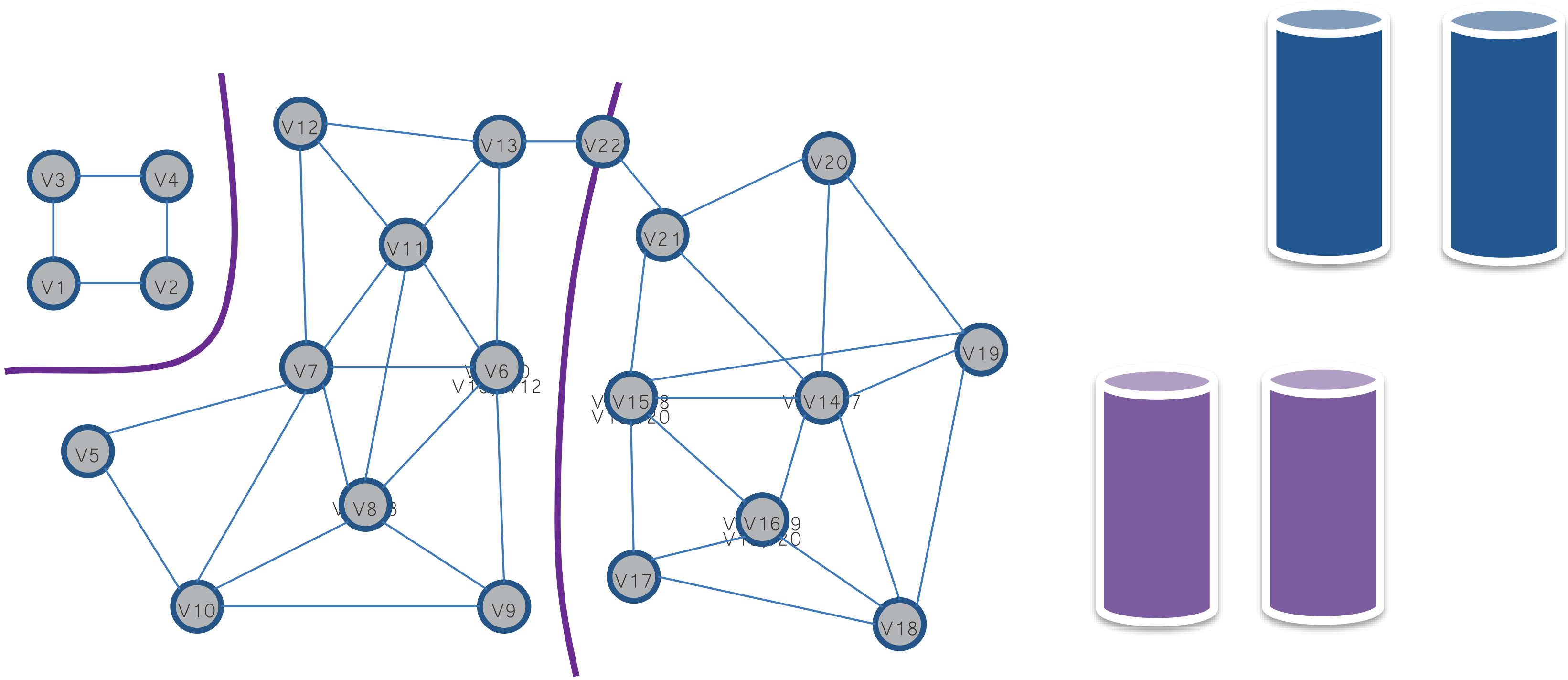
Vertex Clustering



Flow of Graph Reduction



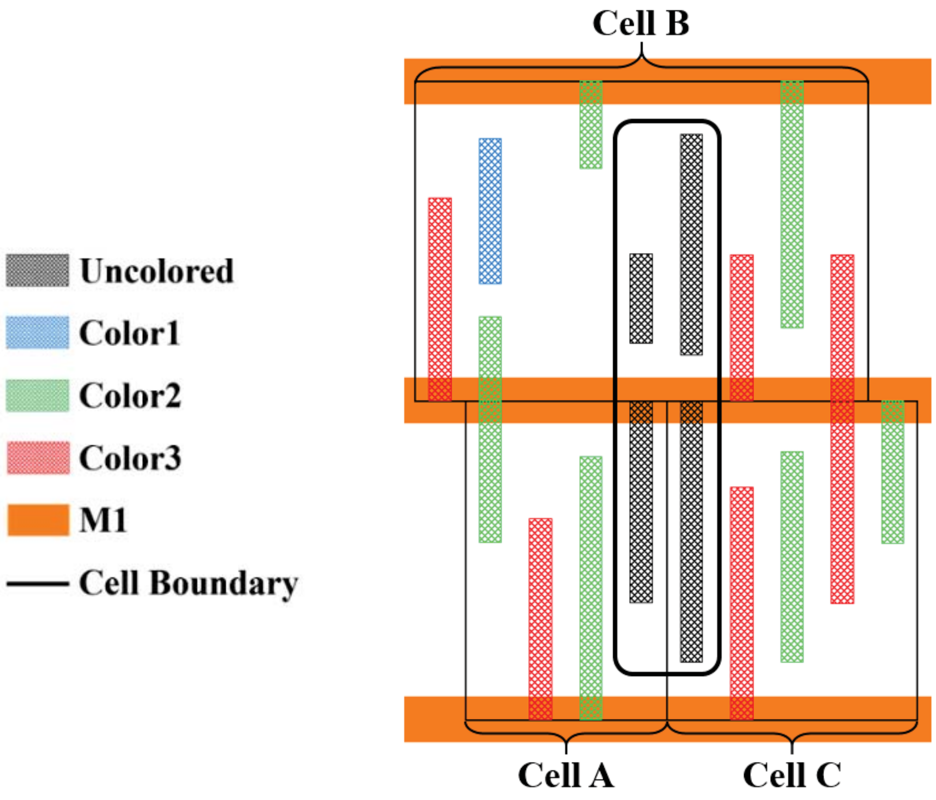
Vertex Coloring



* *k* is set to 3 in this example.

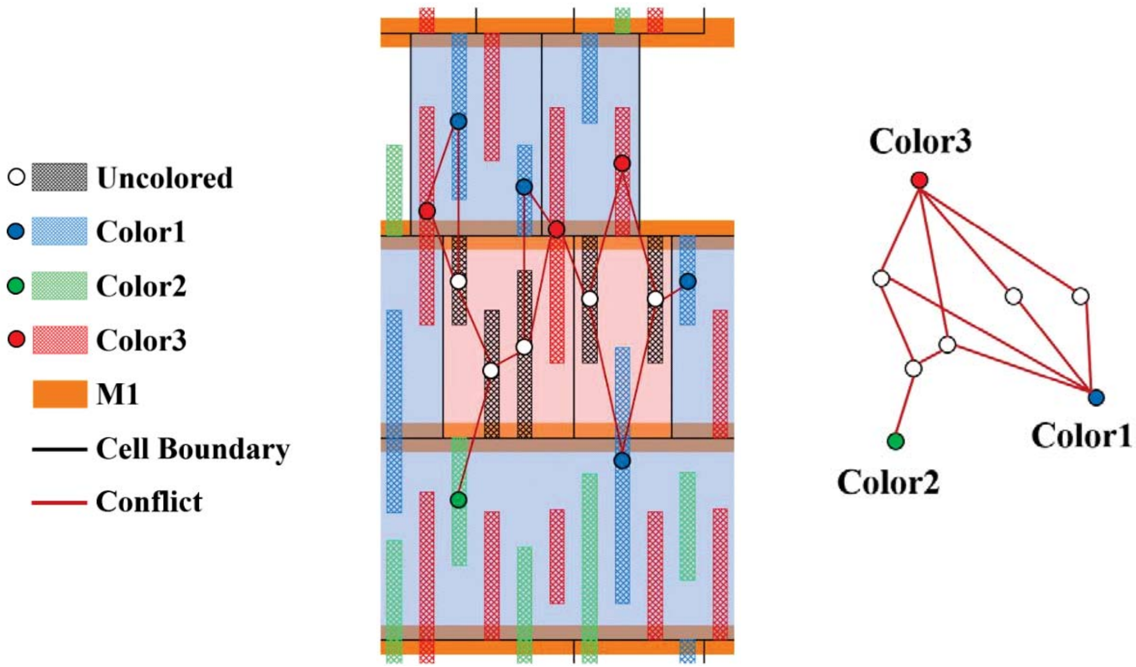
UCG Identification

- The set of cells that contain these uncolored features is called an uncolored cell group (UCG).
- After the initial coloring phase, all UCGs are identified.



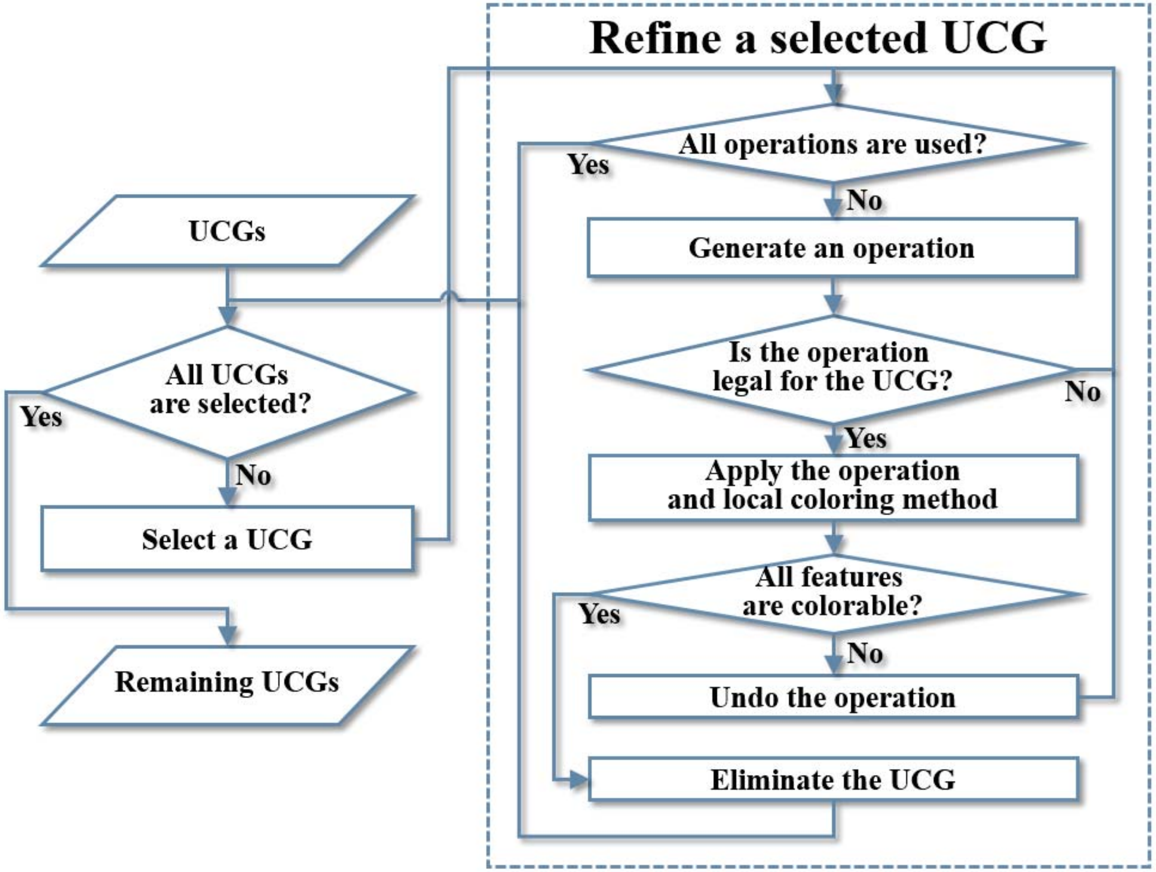
Local Coloring Method

- We construct a local conflict graph for all features in the refined UCG
- The additional *k* virtual vertices representing the features with the given *k* colors in nearby cells.



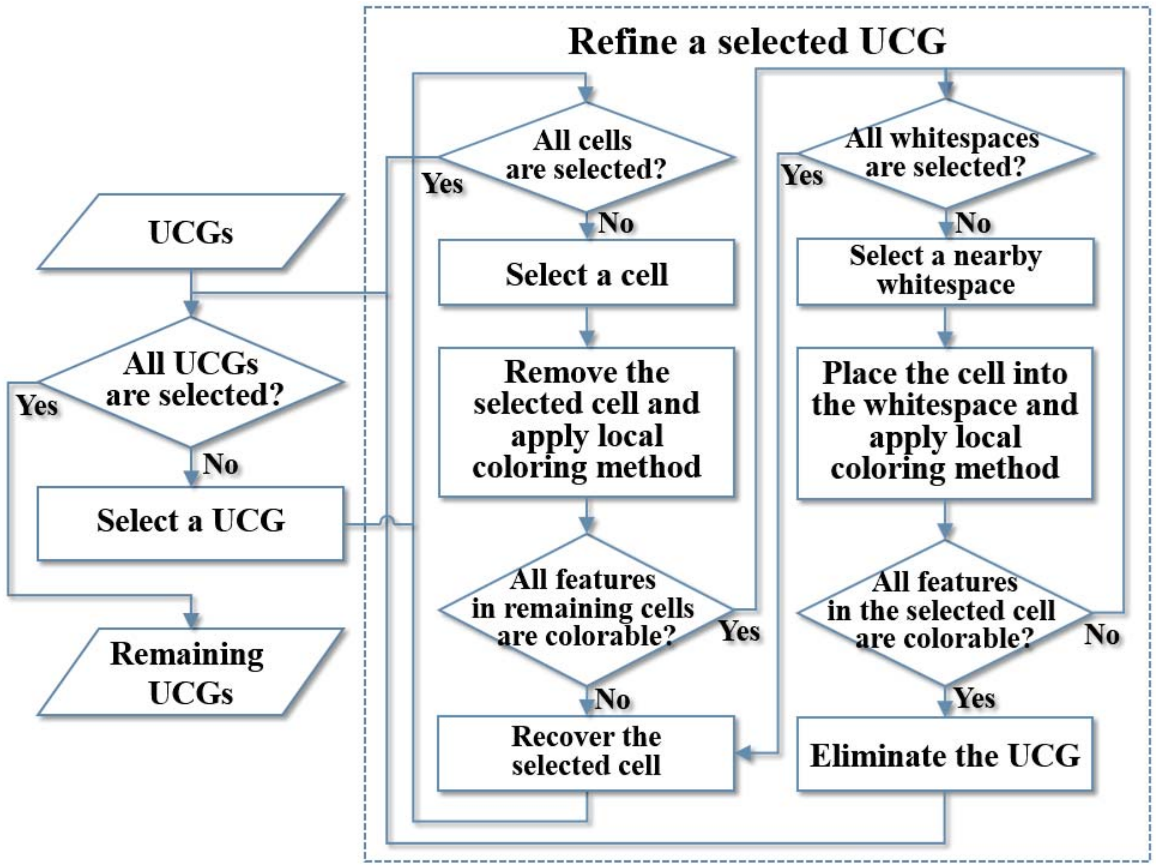
Local Refinement

- A local refinement operation is a combination of cell flipping, cell shifting, and cell swapping
- It is applied only to cells in the targeted UCG.



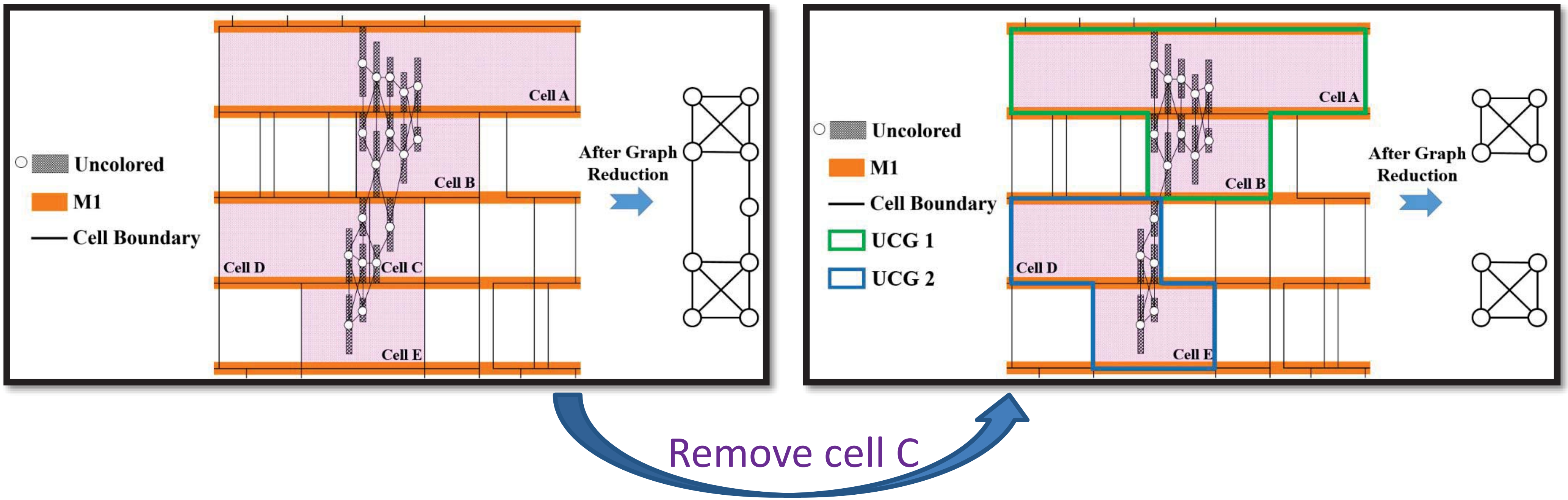
Global Refinement

- If all local refinement operations fail to eliminate a UCG, we consider removing a cell from the UCG.
- We remove and relocate a thinner cell first.



UCG Simplification

- For each remaining UCG, we reduce its conflict graph and split it into smaller ones.

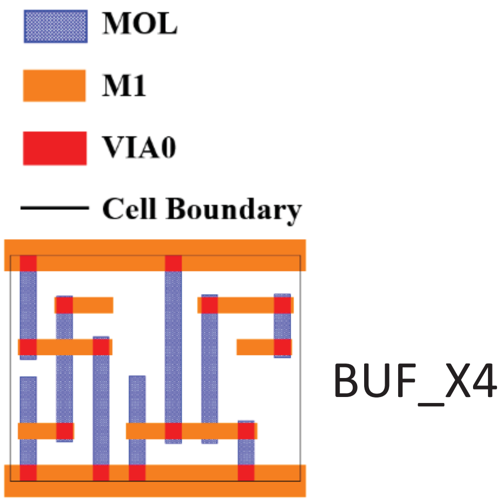


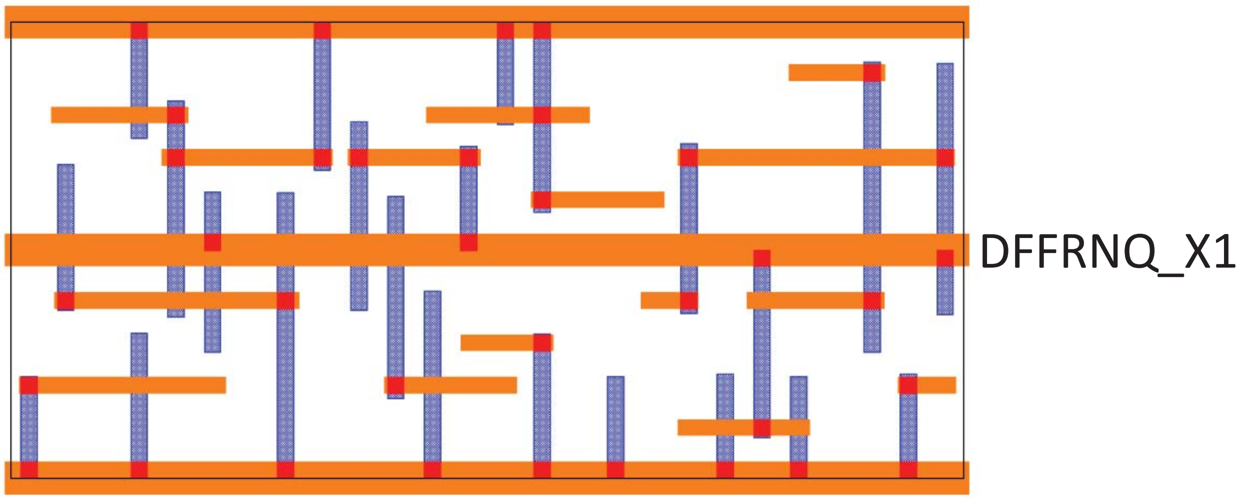
Placement Refinement for Multiple MPL Layers

- While refining a UCG, the refinement operation will be accepted only if all features in each MPL layer of the refined UCG are colorable.
- No new UCG will be generated (unless it is produced in the UCG simplification stage).
- This process guarantees that the number of UCGs will strictly decrease if refinement operations are accepted in each round.

Experiment I: Cell Construction

- We selected some combinational and sequential standard cells from the Nangate 15nm standard cell library, reduced the cell height, and modified their features to make them TPL friendly in the AIL1 layer (re-named as MOL here) , the VIA0 layer, and the M1 layer.
- We also constructed some double-row height standard cells.





Experiment I: Results

- Test cases are from OpenCores with different utilization rates

Design	#Cells	Utilization	#Features (M1/MOL/VIA0)	Initial #Conflicts (M1/MOL/VIA0)	Final #Conflicts (M1/MOL/VIA0)	Avg. Dis (um)	Increased WL	Time (sec)
PNC	982	60%	3521/5989/11125	21 (2/18/1)	0 (0/0/0)	0.008	1.74%	0.68
		70%	3518/5989/11125	16 (4/12/0)	0 (0/0/0)	0.004	0.95%	0.29
		80%	3516/5989/11125	15 (0/15/0)	0 (0/0/0)	0.004	1.26%	0.35
HPDMC	1631	60%	7431/12662/22674	50 (2/14/34)	0 (0/0/0)	0.001	0.69%	1.48
		70%*	7423/12662/22674	69 (2/27/40)	0 (0/0/0)	0.006	1.17%	1.18
		80%	7416/12662/22674	72 (0/25/47)	0 (0/0/0)	0.035	4.30%	1.32
AES	13024	60%	53302/83016/148383	251 (24/66/161)	0 (0/0/0)	0.001	0.28%	6.01
		70%*	53289/83016/148383	293 (29/82/182)	0 (0/0/0)	0.003	0.46%	6.40
		80%	53279/83016/148383	345 (30/107/208)	0 (0/0/0)	0.007	0.72%	4.99
SHA3	68526	60%	216514/321829/626244	294 (0/292/2)	0 (0/0/0)	0.001	0.04%	22.87
		70%*	216500/321829/626244	329 (1/328/0)	0 (0/0/0)	0.004	0.19%	48.60
		80%*	216467/321829/626244	412 (1/408/3)	19 (0/16/3)	0.003	0.15%	155.96
ECG	113900	60%*	448570/734001/1335146	4019 (320/1195/2504)	0 (0/0/0)	0.012	0.97%	469.19
		70%*	448481/734001/1335146	4637 (379/1470/2788)	0 (0/0/0)	0.017	1.36%	541.16
		80%*	448477/734001/1335146	4973 (165/1752/3056)	2 (0/2/0)	0.043	3.42%	1114.7
Avg.						0.010	1.18%	

Experiment II

- Test cases were selected from [TCAD17] with slight modifications of the MOL features of some cell types.
- Each test case was first refined by [TCAD17] to handle the M1 layer and the 4-cliques in the MOL layer.
- Our methodology was invoked as a post-processing approach to eliminate those remaining conflicts as much as possible.
- The pre-coloring method used by [TCAD17] for the M1 layer was modified to only generate candidate coloring solutions without any stitch.

Experiment II: Results

Design	#Cells	Utilization	[TCAD17]		Post-processing by Our Methodology	
			#Conflicts (M1/MOL)	Time (sec)	#Conflicts (M1/MOL)	Time (sec)
alu	2125	70%	18 (0/18)	5.23	0 (0/0)	2.17
		80%	13 (0/13)	5.26	0 (0/0)	2.24
		85%	16 (0/16)	5.53	0 (0/0)	1.94
byp	9116	70%	13 (0/13)	23.06	0 (0/0)	4.62
		80%	8 (0/8)	21.58	0 (0/0)	4.91
		85%	16 (0/16)	23.17	0 (0/0)	4.64
div	6050	70%	1 (0/1)	15.48	0 (0/0)	2.96
		80%	6 (0/6)	15.23	0 (0/0)	3.14
		85%	5 (0/5)	15.29	0 (0/0)	2.9
ecc	1286	70%	3 (0/3)	3.12	0 (0/0)	1.06
		80%	1 (0/1)	3.15	0 (0/0)	1.06
		85%	4 (0/4)	2.52	0 (0/0)	1.18
efc	1956	70%	0 (0/0)	4.48	-	-
		80%	1 (0/1)	4	0 (0/0)	1.44
		85%	2 (0/2)	3.88	0 (0/0)	1.16
ctl	2350	70%	1 (0/1)	5.58	0 (0/0)	1.61
		80%	3 (0/3)	5.44	0 (0/0)	1.79
		85%	3 (0/3)	5.49	0 (0/0)	1.84
top	21251	70%	120 (0/120)	44.71	0 (0/0)	15.36
		80%*	152 (0/152)	39.77	0 (0/0)	37.7
		85%	149 (0/149)	42.14	0 (0/0)	24.13

Conclusion

- A multiple-layer MPL aware placement refinement methodology for mixed-cell-height designs.
- The concept of uncolored cell group (UCG).
- By eliminating UCGs without generating any new coloring conflict around them, the number of UCGs is effectively reduced.
- Our methodology can efficiently eliminate UCGs and reduce coloring conflicts with very small cell displacement.