Density Gradient Minimization with Coupling-Constrained Dummy Fill for CMP Control

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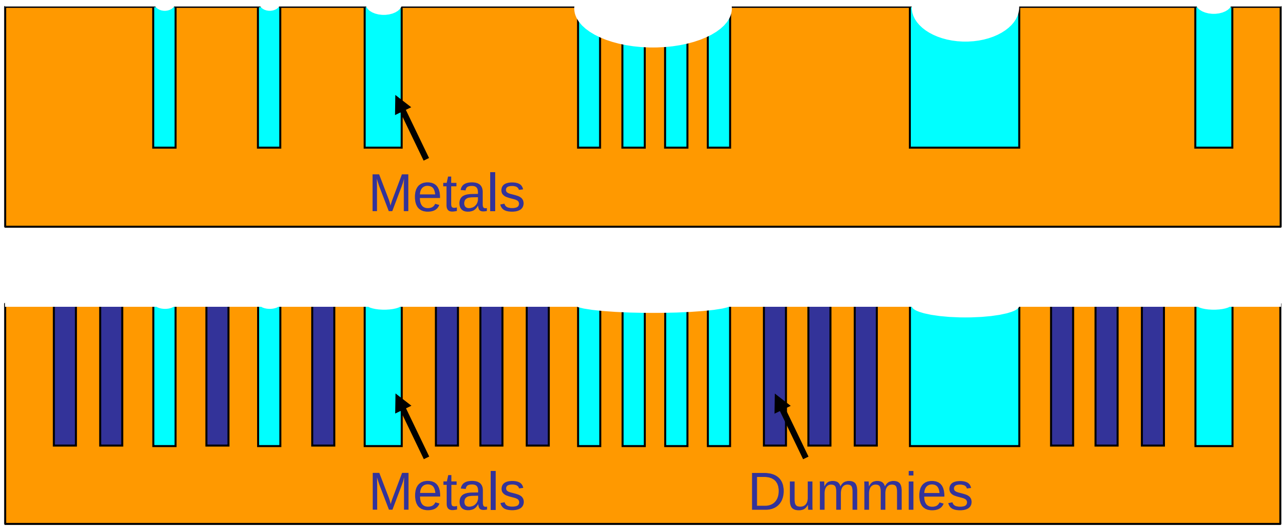
Outline

- Introduction
- Definition of Density Gradient
- Previous Work
- Multilevel Gradient Driven Dummy Fill Algorithm
- Experimental Results
- Conclusion and Future Work

Introduction

- Dummy fill is a general method to achieve layout uniformity before CMP (chemical-mechanical polishing)



- Objectives for dummy fill:
  - minimize induced **coupling capacitance** of dummies
  - minimize **dummy counts**
  - minimize **density gradient** of metal density

Density Gradient

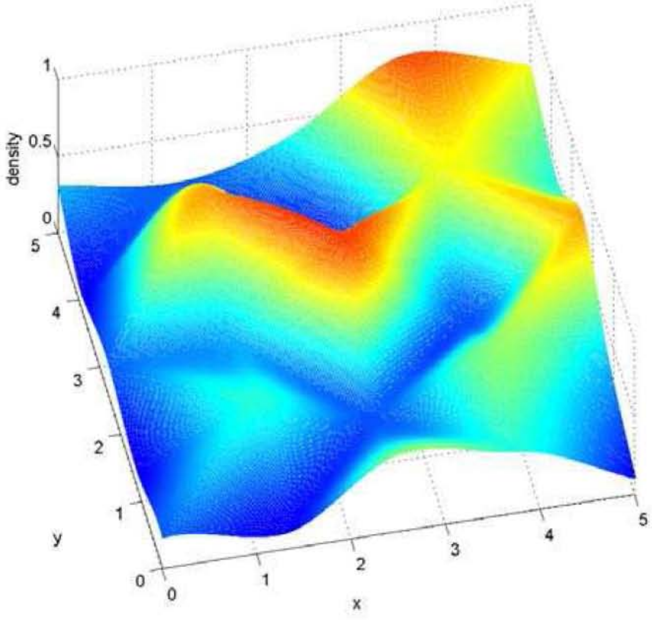
- Gradient
  - means the rate of change of the function value in the direction of maximum change.
  - is generally used in solving optimization problem, such as the conjugate gradient method and the gradient descent method.

- Density gradient of a tile
  - is the maximum density difference between this tile and the adjacent tiles.

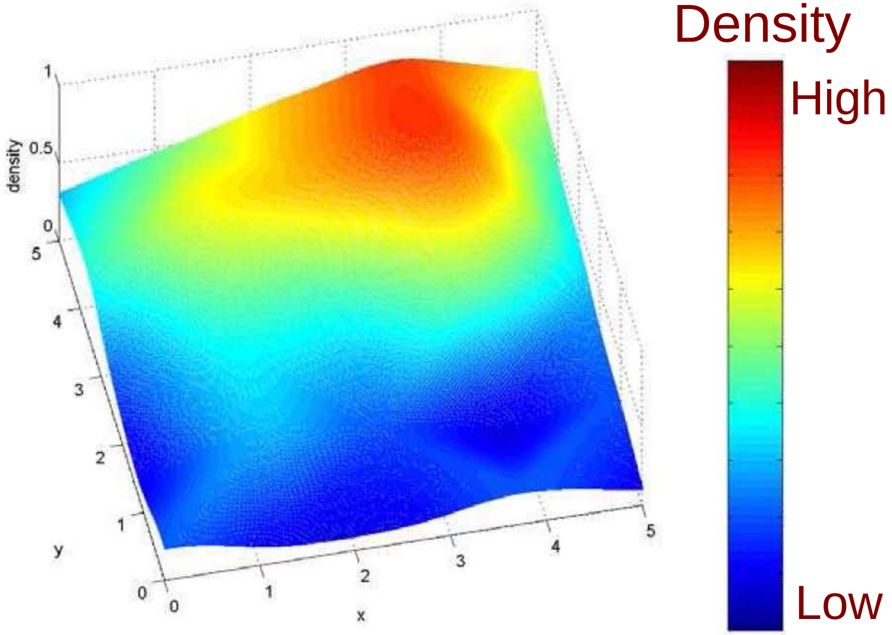
- Our work is the first work in the literature that simultaneously considers **coupling constraints**, **dummy counts**, and **density gradient**

Density Variation vs. Density Gradient

- Density gradient is different from density variation, but both of them would affect the post-CMP thickness.



density variation = 0.0523
density gradient = 0.7



density variation = 0.0523
density gradient = 0.4

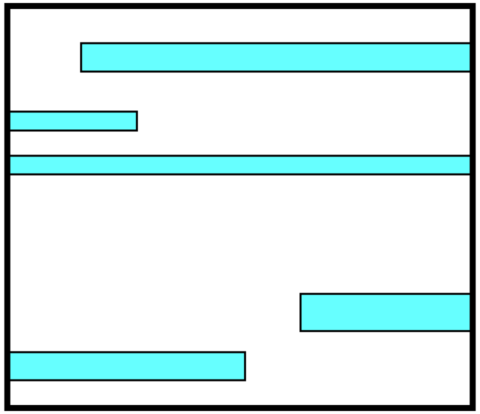
Considering density variation is not sufficient!

Previous Work

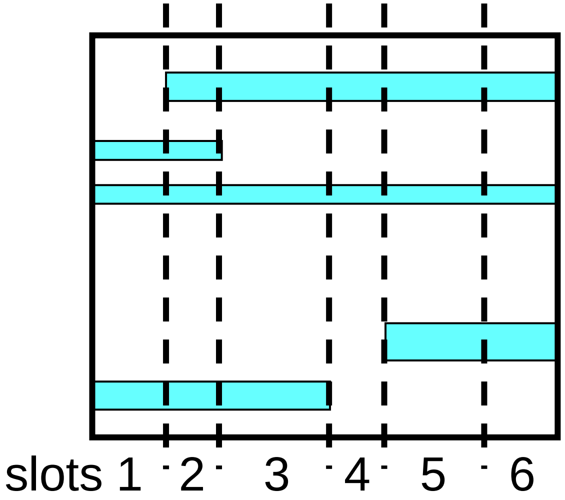
- Highlighted the importance of density variation
  - Chen *et al.*, “Closing the Smoothness and Uniformity Gap in Area Fill Synthesis,” *ISPD’02*.
- Considered wire density control during routing
  - Li *et al.*, “Multilevel Full-Chip Routing with Testability and Yield Enhancement,” *TCAD’07*
  - Chen *et al.*, “A Novel Wire-Density-Driven Full-Chip Routing System for CMP Variation Control,” *TCAD’09*
- Formed a tradeoff between excessive coupling and lithography cost
  - Deng *et al.*, “Coupling-Aware Dummy Metal Insertion for Lithography,” *ASPDAC’07*.
- Found the maximum dummy insertion regions with no coupling violation
  - Xiang *et al.*, “Fast Dummy-Fill Density Analysis With Coupling Constraints,” *TCAD’08*.

Previous Work: Coupling-Constrained Dummy Fill

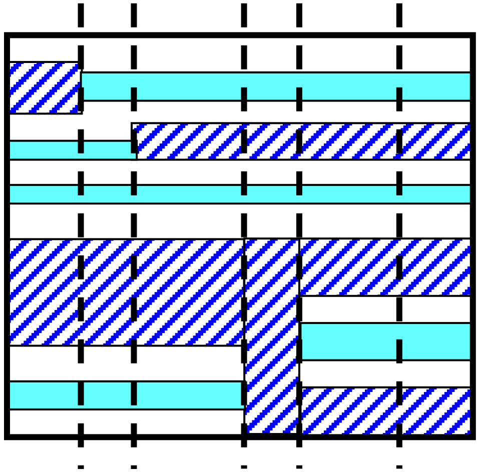
- CDF Algorithm presented in [Xiang *et al.* TCAD'08]



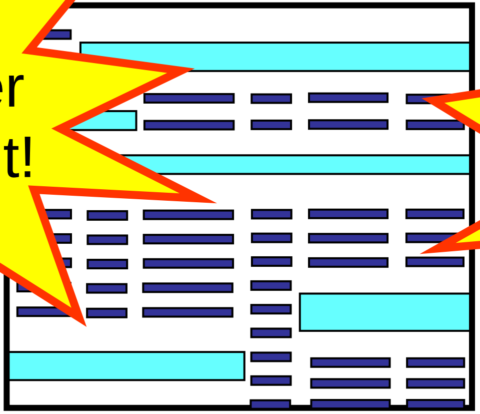
A layout



Slot partition by endpoints of segments



Coupling-free fill regions identification for each slot



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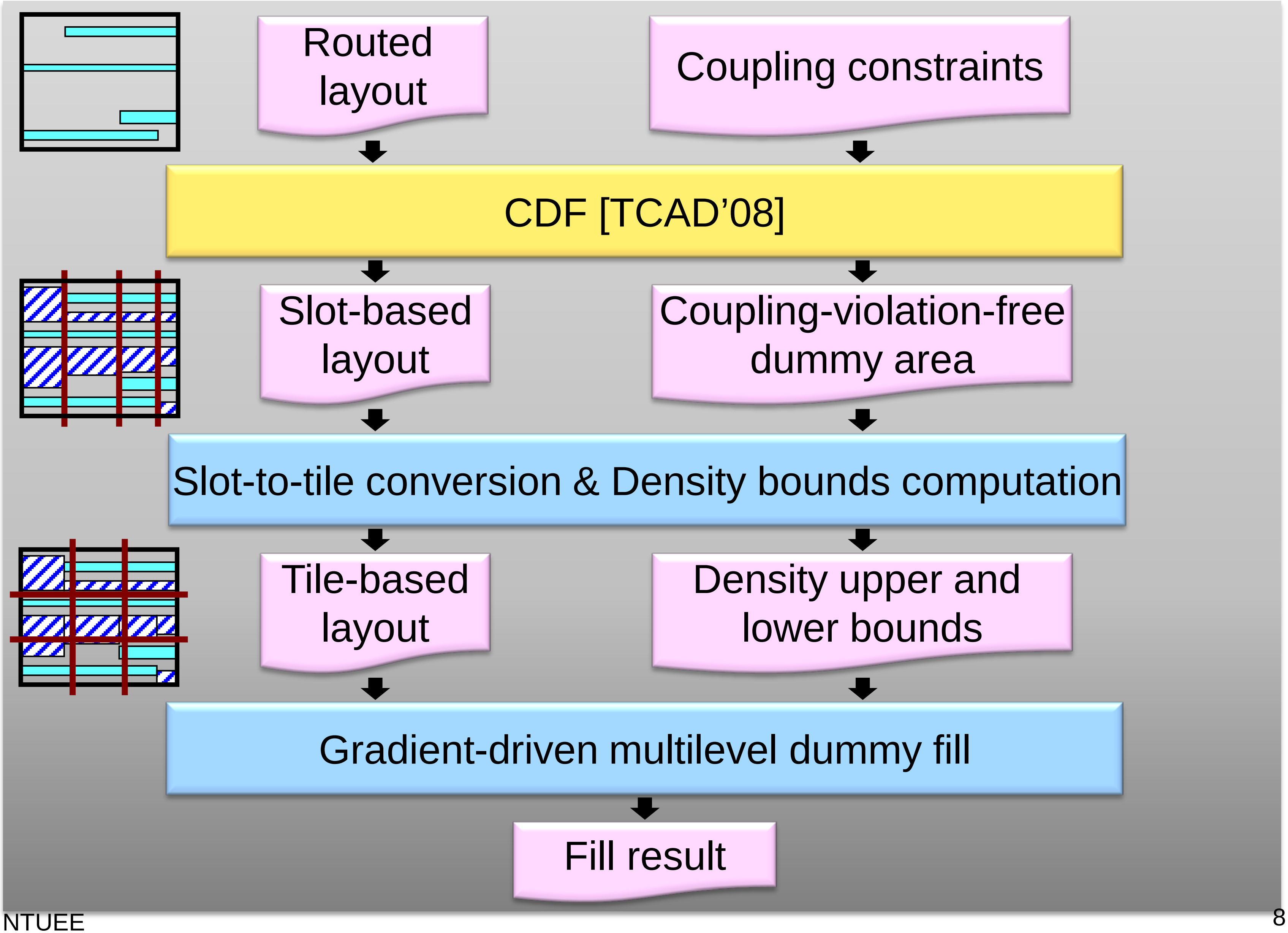
Did not consider density gradient!

Used too many dummies!

Our Algorithm Flow



Routed layout

Coupling constraints

CDF [TCAD'08]

Slot-based layout

Coupling-violation-free dummy area

Slot-to-tile conversion & Density bounds computation

Tile-based layout

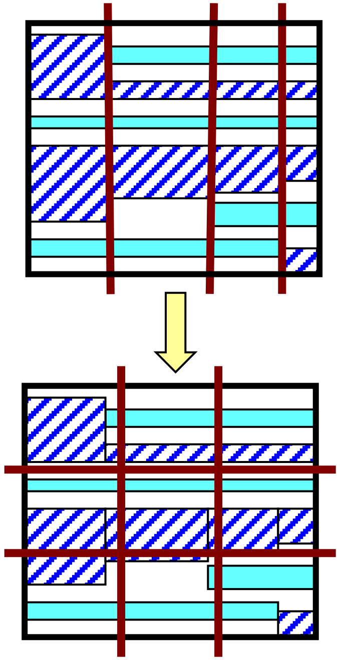
Density upper and lower bounds

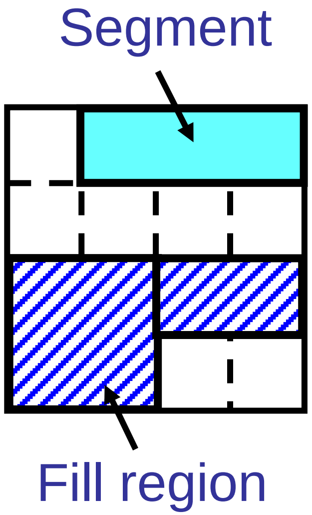
Gradient-driven multilevel dummy fill

Fill result

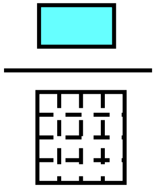
Slot-to-Tile Conversion and Density Bounds Computation

- Convert slot-based layout to tile-based layout
- Compute tile density bounds in each tile satisfying both coupling and foundry density rules

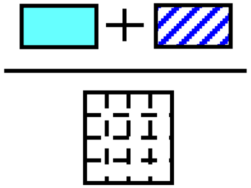




Lower bound B_l =



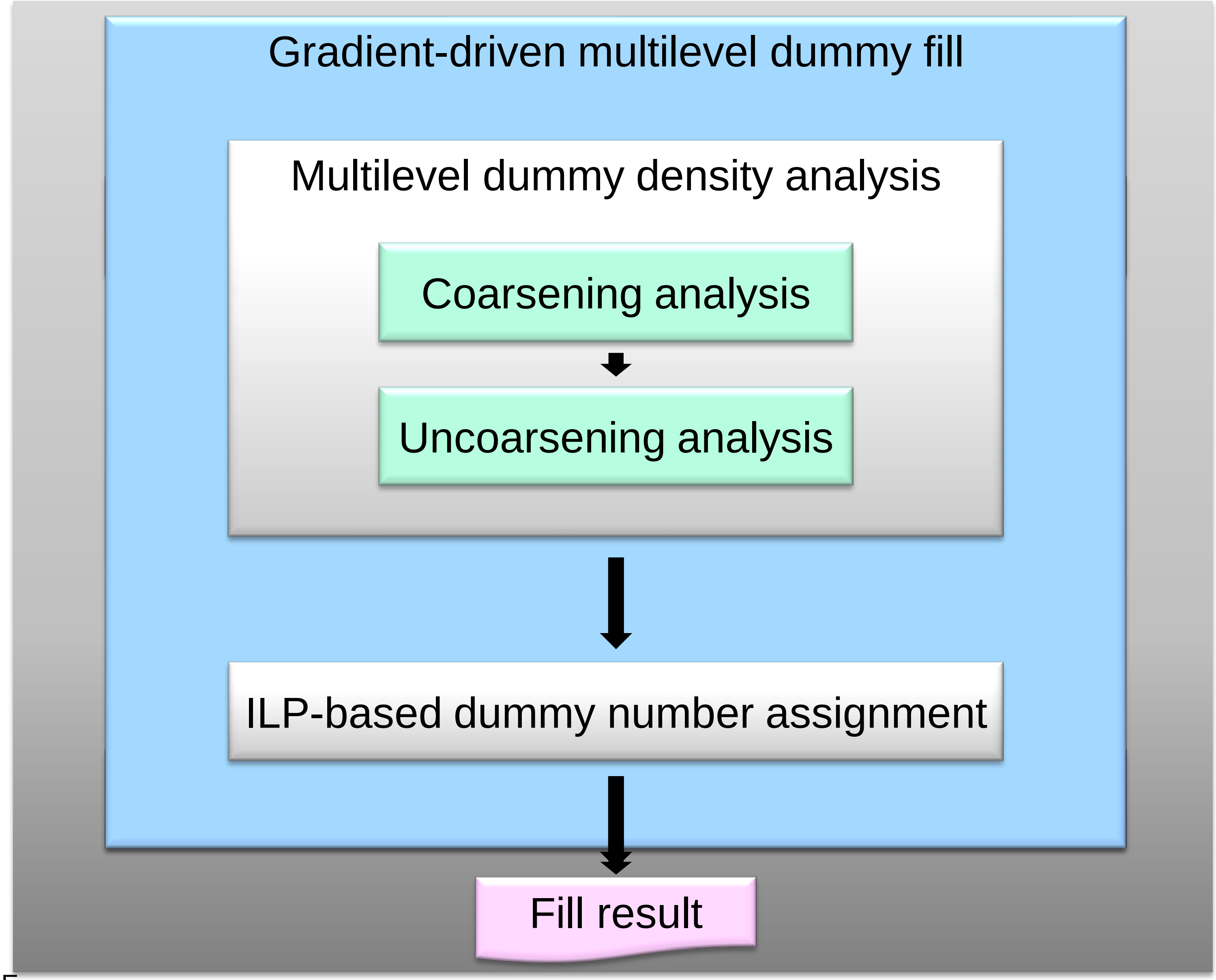
Upper bound B_u =



Further adjust the bounds according to foundry density rules

(B_l, B_u) guarantees no coupling and density rule violations in the following stages

Gradient-Driven Dummy Fill Flow



Gradient-driven multilevel dummy fill

Multilevel dummy density analysis

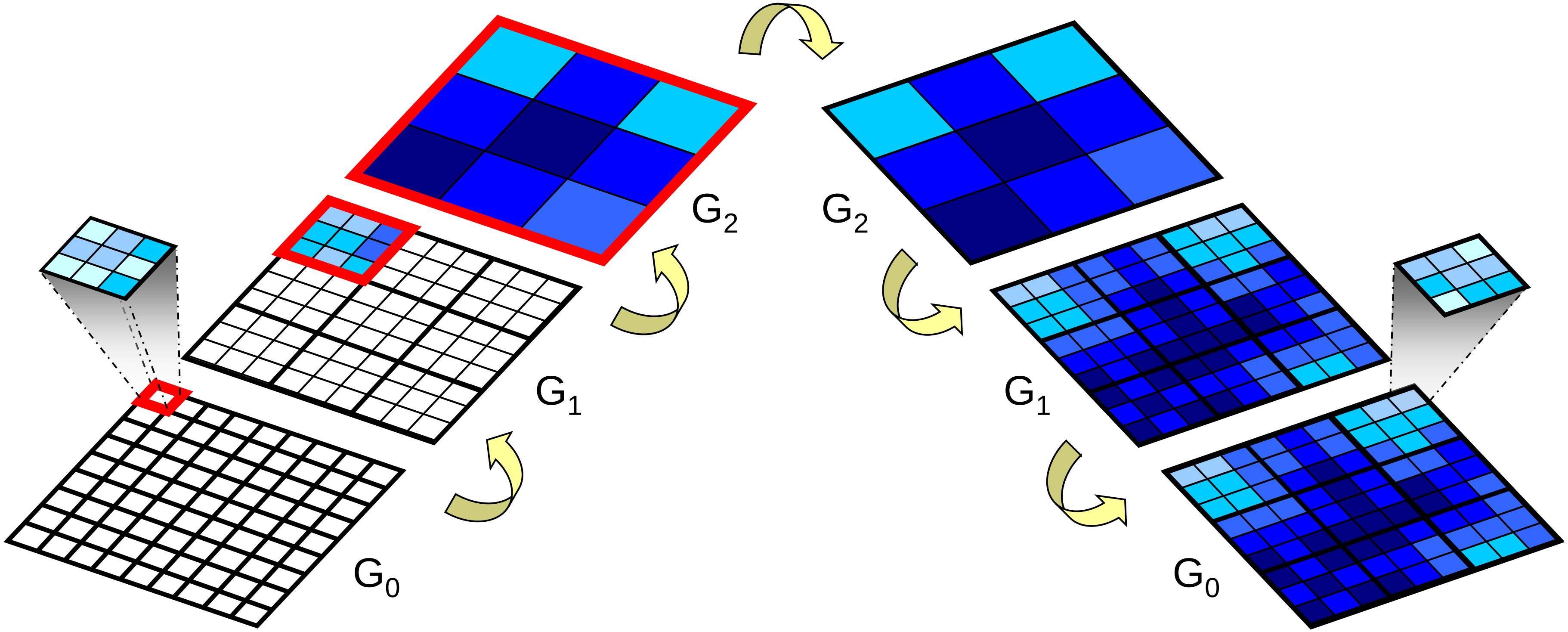
Coarsening analysis

Uncoarsening analysis

ILP-based dummy number assignment

Fill result

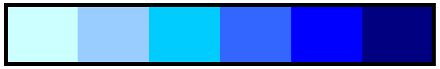
Multilevel Dummy Density Analysis



Coarsening

(1) Gradient minimization
by Gaussian smoothing
(2) Density bounds update
level by level

Metal Density



Uncoarsening

(1) Density extraction
(2) ILP-based dummy
number assignment

Coarsening: Gradient Minimization

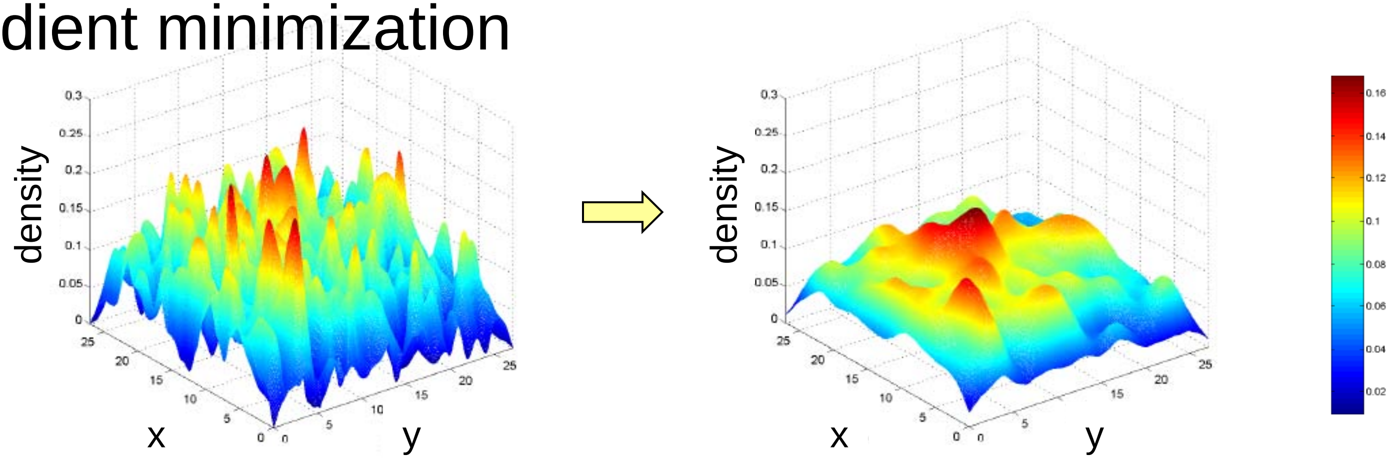
- Gaussian smoothing at tile $(\hat{x},\hat{y}) = \sum D_c(x,y)g(x,y)$
  - $D_c(x,y)$: original density
  - $g(x,y)$: weighting function = $\frac{1}{2\pi\sigma^2}\exp\left(-\frac{(x-\hat{x})^2+(y-\hat{y})^2}{2\sigma^2}\right)$

0.1	0.4	0.1	0.2	0.3
0.2	0.4	0.4	0.3	0.2
0.3	0.3	0.2	0.2	0.1
0.1	0.1	0.2	0.1	0.3
0.2	0.2	0.4	0.3	0.4

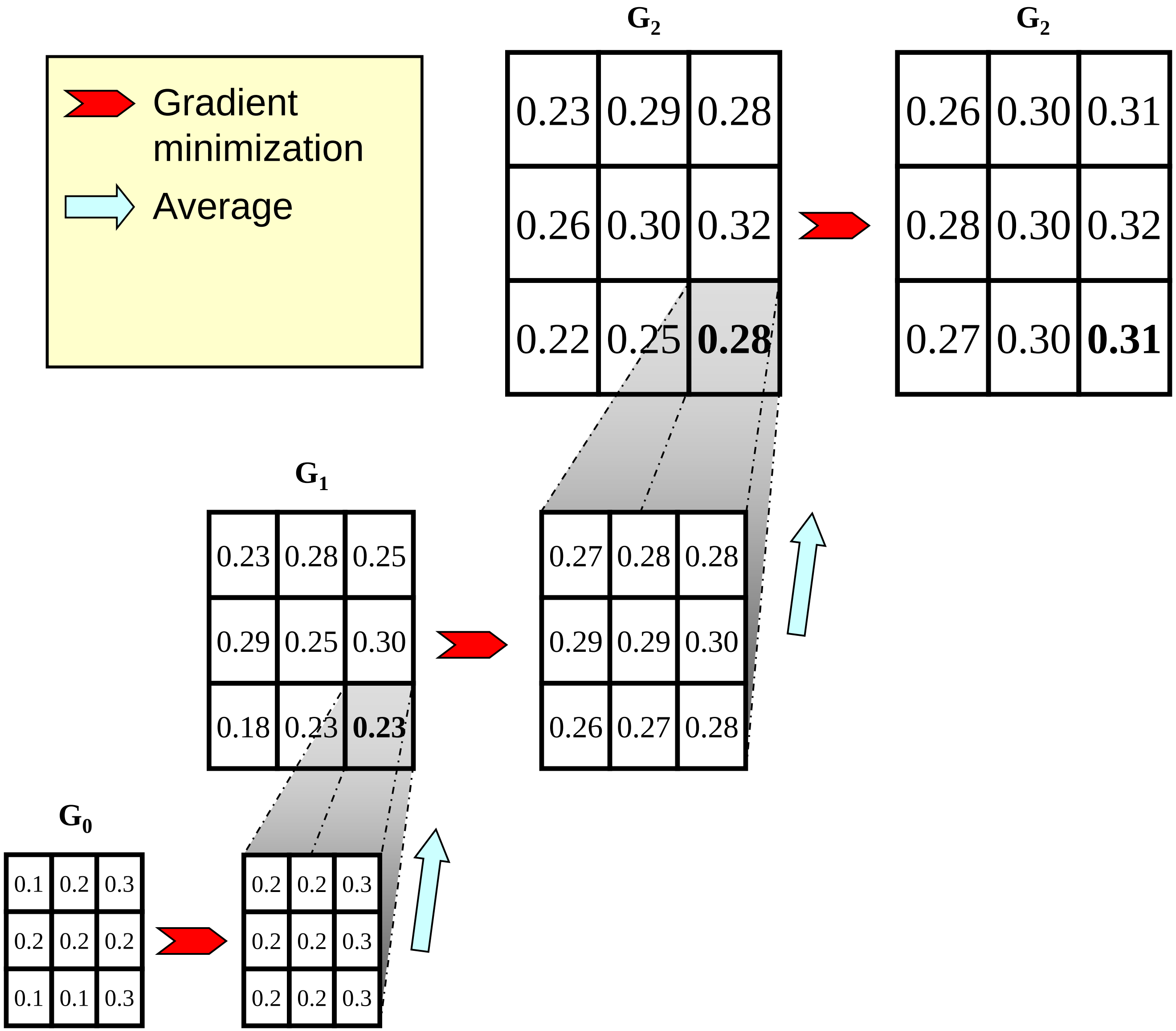
→ Gaussian smoothing (σ=1.0) →

0.25	0.36	0.20	0.21	0.28
0.27	0.36	0.35	0.28	0.26
0.24	0.25	0.24	0.20	0.18
0.17	0.19	0.23	0.19	0.27
0.22	0.25	0.35	0.27	0.34

- Gaussian smoothing opens up a new direction for gradient minimization



Coarsening: Density Analysis



- ➤ Gradient minimization
- ⇨ Average

G_0

0.1	0.2	0.3
0.2	0.2	0.2
0.1	0.1	0.3

0.2	0.2	0.3
0.2	0.2	0.3
0.2	0.2	0.3

G_1

0.23	0.28	0.25
0.29	0.25	0.30
0.18	0.23	**0.23**

0.27	0.28	0.28
0.29	0.29	0.30
0.26	0.27	0.28

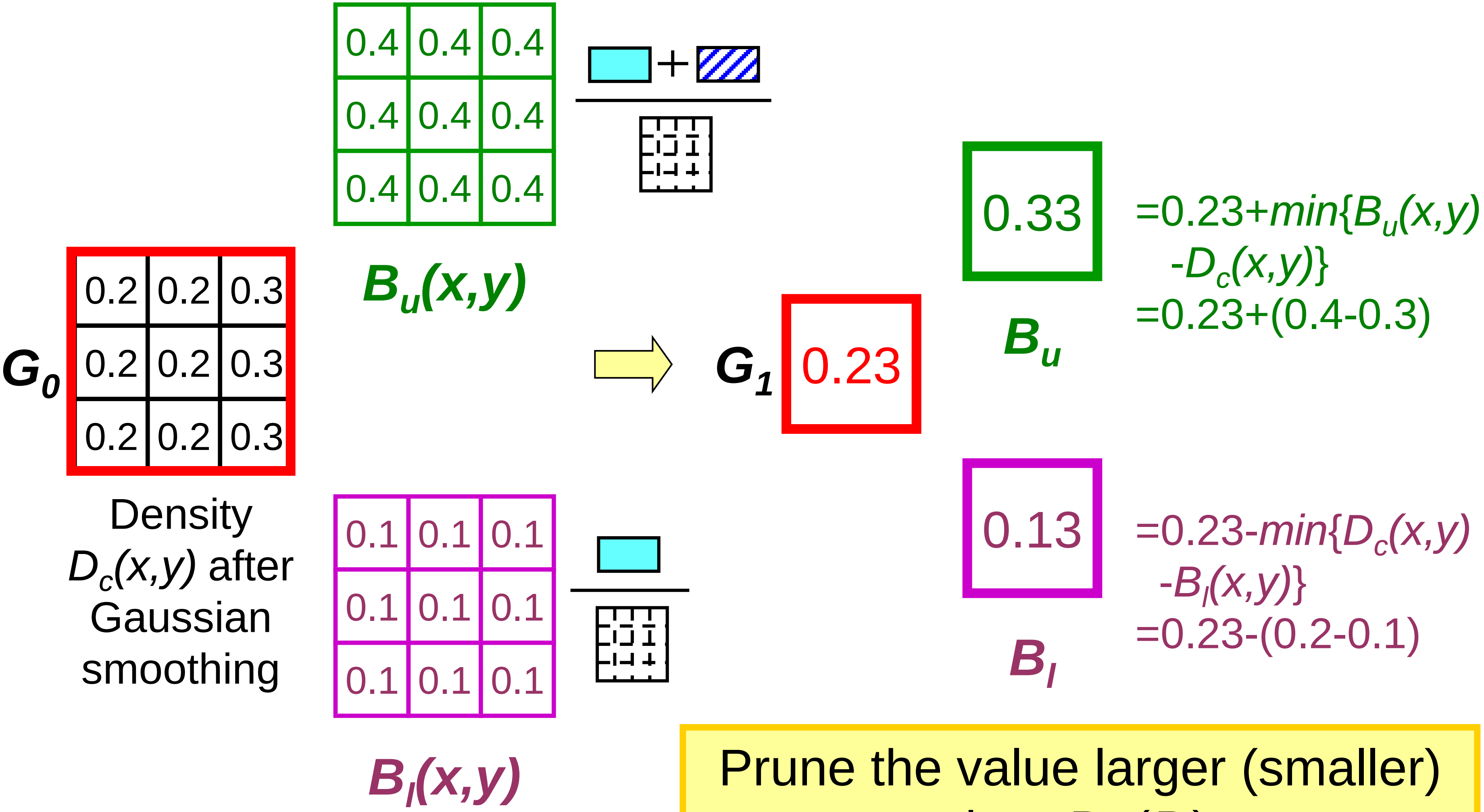
G_2

0.23	0.29	0.28
0.26	0.30	0.32
0.22	0.25	**0.28**

G_2

0.26	0.30	0.31
0.28	0.30	0.32
0.27	0.30	**0.31**

Coarsening: Tile Density Bounds Update



G_0

0.2	0.2	0.3
0.2	0.2	0.3
0.2	0.2	0.3

Density $D_c(x,y)$ after Gaussian smoothing

0.4	0.4	0.4
0.4	0.4	0.4
0.4	0.4	0.4

$B_u(x,y)$

0.1	0.1	0.1
0.1	0.1	0.1
0.1	0.1	0.1

$B_l(x,y)$

G_1 0.23

B_u 0.33

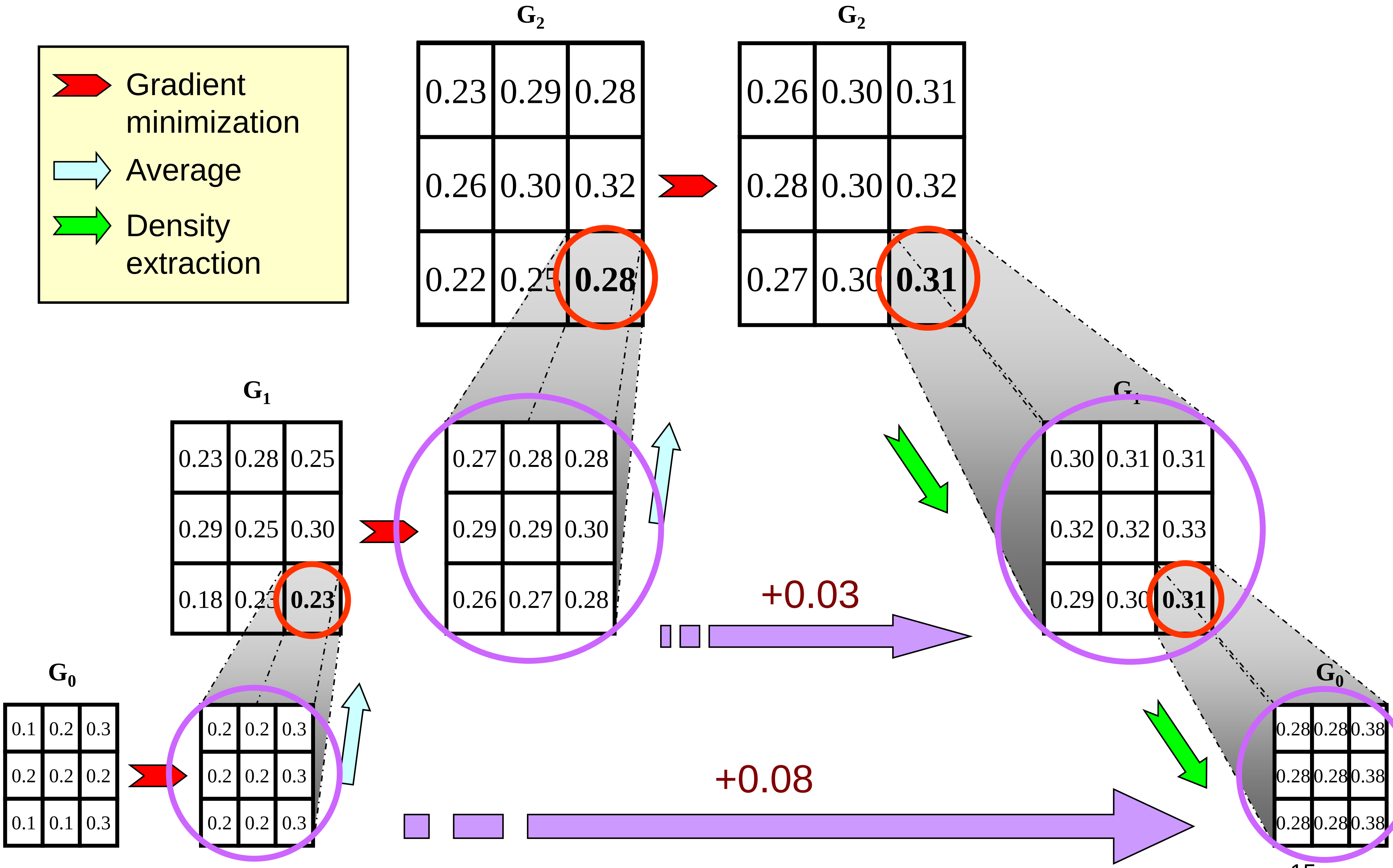
$=0.23+\min\{B_u(x,y)-D_c(x,y)\}$
$=0.23+(0.4-0.3)$

B_l 0.13

$=0.23-\min\{D_c(x,y)-B_l(x,y)\}$
$=0.23-(0.2-0.1)$

Prune the value larger (smaller) than B_u (B_l)

Uncoarsening: Density Extraction



G2

0.23	0.29	0.28
0.26	0.30	0.32
0.22	0.25	**0.28**

G2

0.26	0.30	0.31
0.28	0.30	0.32
0.27	0.30	**0.31**

G1

0.23	0.28	0.25
0.29	0.25	0.30
0.18	0.23	**0.23**

0.27	0.28	0.28
0.29	0.29	0.30
0.26	0.27	0.28

G1

0.30	0.31	0.31
0.32	0.32	0.33
0.29	0.30	**0.31**

G0

0.1	0.2	0.3
0.2	0.2	0.2
0.1	0.1	0.3

0.2	0.2	0.3
0.2	0.2	0.3
0.2	0.2	0.3

G0

0.28	0.28	0.38
0.28	0.28	0.38
0.28	0.28	0.38

ILP-based Dummy Number Assignment

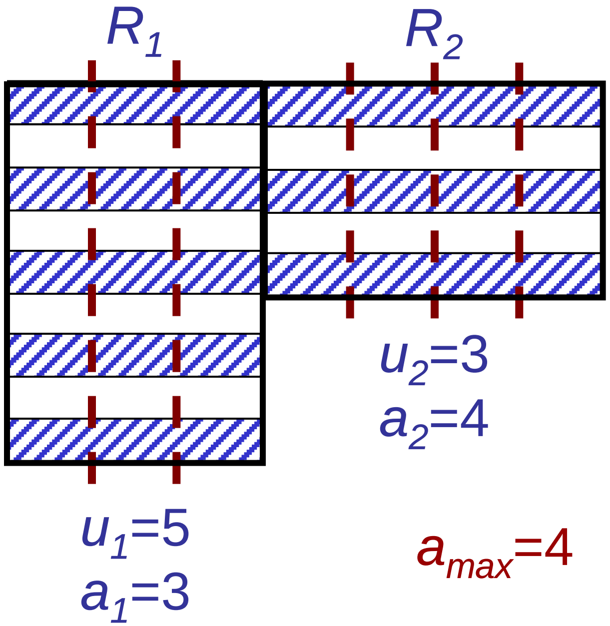
- Optimally insert minimal # of dummies to satisfy the desirable tile density d_d in a tile
- For the tile with n fill regions $R_1, \ldots, R_n$,

$$\text{minimize} \quad \sum_{i=1}^{n} r_i$$

$$\text{subject to} \quad d_d a - \frac{1}{2} a_{\max} \le \sum_{i=1}^{n} a_i r_i \le d_d a + \frac{1}{2} a_{\max}$$

$$r_i \le u_i, i = 1, \ldots, n$$

r_i: # of dummies in R_i
d_d: dummy density of tile
a: tile area
a_i: area of one dummy in R_i
a_{max}: max $\{a_i\}$
u_i: max # of dummies in R_i



Experimental Setting

- Programming language: C++
- Workstation: 2.0 GHz AMD-64 with 8GB memory
- ILP solver: lp_solve
- Parameters
  - Window size=3 × 3
  - Gaussian smoothing: σ=1.0
  - Foundry density lower and upper bounds: 20% and 60%
- Test cases: MCNC and industrial Faraday benchmarks
- Comparison with the CDFm algorithm [modified from CDF algorithm, TCAD'08] for all layers and layer 1
  - CDF algorithm: tries to insert as many dummies as possible
  - CDFm algorithm: also honors the density lower and upper bound rules

Benchmarks

- Routing results from Chen *et al.*, ICCAD'07

Circuit	**Size (μm×μm)**	**#Layer**	**#Segment**	**#Level**	**Wire Density**		
					Avg.	**Max**	**Std.**
Mcc1	45000×39000	4	6199	4	9.85%	47.80%	9.46%
Mcc2	152400×152400	4	34371	4	10.80%	54.50%	9.90%
Struct	4903×4904	3	10692	4	0.71%	5.19%	0.88%
Primary1	7522×4988	3	6889	4	0.54%	9.10%	0.94%
Primary2	10438×6488	3	28513	4	1.23%	10.10%	1.39%
S5378	435×239	3	9816	3	8.68%	30.30%	5.60%
S9234	404×225	3	8462	3	7.43%	30.80%	5.80%
S13207	660×365	3	21891	3	8.98%	28.90%	5.53%
S15850	705×389	3	25699	3	9.76%	30.00%	5.04%
S38417	1144×619	3	64045	3	8.32%	32.10%	4.87%
S38584	1295×672	3	85931	3	9.37%	28.40%	4.55%
Dma	408.4×408.4	6	98018	5	15.60%	71.40%	16.30%
Dsp1	706.0×706.0	6	169867	5	10.70%	55.10%	13.40%
Dsp2	642.8×642.8	6	159525	5	11.00%	60.50%	13.20%
Risc1	1003.6×1003.6	6	237862	5	8.74%	58.10%	12.90%
Risc2	959.6×959.6	6	240978	5	8.82%	50.60%	11.90%

Runtime and Inserted Dummy Counts

- Inserted dummy count is only 19% compared with CDF algorithm

- Timing overhead is only 19%

Circuit	CDF		Ours	
	#Dummy	Time (s)	#Dummy	Time (s)
Mcc1	1,262,298	160	163,821	171
Mcc2	20,117,831	7249	4,282,218	7292
Struct	9,004,650	45	159,457	72
Primary1	7,102,170	32	188,771	53
Primary2	24,897,686	428	360,221	490
S5378	269,916	21	53,527	22
S9234	230,220	14	58,230	17
S13207	657,861	73	141,723	76
S15850	721,317	99	155,336	103
S38417	2,100,467	330	248,582	337
S38584	2,460,061	518	277,747	526
Dma	1,457,877	67	321,635	101
Dsp1	3,648,742	290	1,012,893	330
Dsp2	2,815,009	189	778,375	231
Risc1	9,071,800	252	3,208,787	312
Risc2	7,235,118	396	2,626,317	446
Comp.	**1.00**	**1.00**	**0.19**	**1.19**

Statistics of Metal Density (MCNC)

- The average density gradient are reduced by 70% and 59% among all layers and of layer 1, respectively

Circuit	**CDF Analysis Algorithm**						**Ours**					
	Density Gradient among Layers			**Density Gradient of Layer 1**			**Density Gradient among Layers**			**Density Gradient of Layer 1**		
	Avg.	**Max**	**Std.**	**Avg.**	**Max**	**Std.**	**Avg.**	**Max**	**Std.**	**Avg.**	**Max**	**Std.**
Mcc1	7.14%	35.81%	5.87%	5.28%	12.53%	12.31%	1.59%	14.42%	1.80%	1.81%	11.73%	3.62%
Mcc2	4.40%	14.67%	2.39%	3.53%	8.16%	5.07%	2.23%	16.84%	2.54%	2.80%	12.07%	5.21%
Struct	1.41%	5.75%	1.34%	0.56%	5.67%	2.74%	0.16%	0.33%	0.07%	0.19%	0.33%	0.13%
Primary1	2.38%	13.09%	2.54%	1.61%	10.34%	4.60%	0.14%	0.32%	0.08%	0.17%	0.32%	0.15%
Primary2	1.22%	3.97%	0.97%	0.20%	1.25%	2.44%	0.12%	0.25%	0.05%	0.14%	0.25%	0.10%
S5378	5.38%	15.88%	2.53%	5.38%	12.85%	4.37%	1.99%	10.00%	0.96%	2.18%	5.36%	1.70%
S9234	6.31%	20.79%	3.18%	6.27%	14.01%	5.52%	2.02%	8.67%	1.11%	2.25%	4.26%	1.96%
S13207	4.19%	14.62%	1.98%	3.54%	9.24%	3.61%	1.53%	7.54%	0.91%	1.49%	5.52%	1.59%
S15850	4.13%	12.50%	1.92%	3.64%	8.81%	3.43%	1.38%	9.90%	0.79%	1.36%	2.41%	1.38%
S38417	2.91%	9.32%	1.42%	2.28%	6.67%	2.68%	0.93%	9.97%	0.85%	0.89%	1.53%	1.47%
S38584	2.80%	8.97%	1.29%	2.41%	7.08%	2.34%	0.79%	8.24%	0.68%	0.79%	1.38%	1.18%
Comp.	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.30**	**0.56**	**0.39**	**0.41**	**0.47**	**0.38**

Statistics of Metal Density (Faraday)

- The average density gradient are reduced by 40% and 91% among all layers and of layer 1, respectively

Circuit	CDF Analysis Algorithm						Ours					
	Density Gradient among Layers			Density Gradient of Layer 1			Density Gradient among Layers			Density Gradient of Layer 1		
	Avg.	Max	Std.	Avg.	Max	Std.	Avg.	Max	Std.	Avg.	Max	Std.
Dma	3.39%	19.50%	3.30%	1.77%	10.22%	9.01%	2.23%	21.45%	3.10%	0.60%	1.01%	8.57%
Dsp1	2.90%	24.33%	3.69%	2.87%	24.33%	9.03%	1.49%	20.08%	2.50%	0.14%	0.57%	6.95%
Dsp2	2.66%	26.81%	3.62%	2.85%	26.81%	8.88%	1.24%	17.27%	1.97%	0.14%	0.59%	5.53%
Risc1	2.66%	21.15%	3.52%	2.74%	18.79%	8.62%	1.77%	21.15%	3.12%	0.14%	0.40%	8.62%
Risc2	2.98%	26.49%	3.92%	2.67%	17.95%	9.64%	2.02%	26.49%	3.57%	0.15%	0.45%	9.88%
Comp.	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.60**	**0.90**	**0.79**	**0.09**	**0.03**	**0.88**

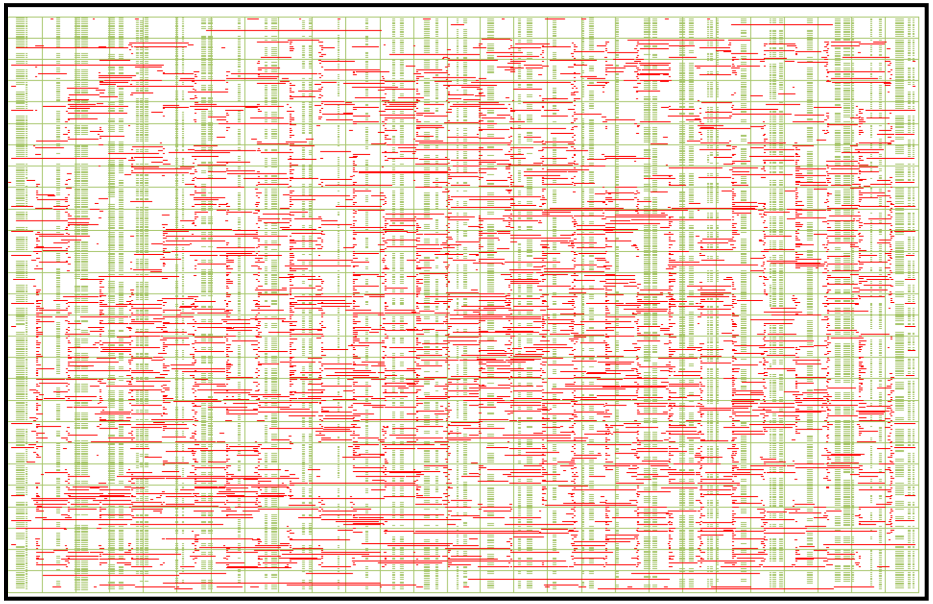
- Overall comparison (MCNC+Faraday)

Circuit	CDF Analysis Algorithm						Ours					
	Density Gradient among Layers			Density Gradient of Layer 1			Density Gradient among Layers			Density Gradient of Layer 1		
	Avg.	Max	Std.	Avg.	Max	Std.	Avg.	Max	Std.	Avg.	Max	Std.
Comp.	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.37**	**0.66**	**0.51**	**0.32**	**0.31**	**0.53**

Comparison of S5378 Layer 1 Filling Results

CDFm algorithm

Metal density = 27.15%
Fill inserted = 100%

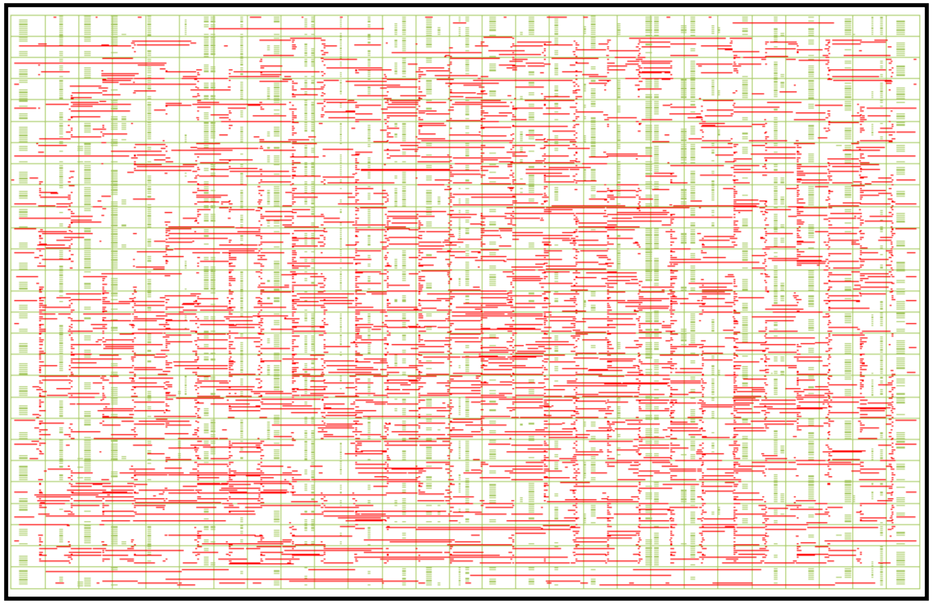


🟥 wires

🟩 fills

Ours

Metal density = 21.97%
Fill inserted = 20%



Conclusions and Future Work

- Presented an effective and efficient dummy fill algorithm considering both gradient minimization and coupling constraints
  - Reduced 63% of density gradient among all layers
  - Saved 91% dummy counts
- Gaussian smoothing is effective for gradient-minimization dummy fill
  - Point out a new research direction on this topic
- Future work: simultaneously gradient and coupling capacitance optimization

Q & A

Thank You!