Linear-time Mixed-Cell-Height Legalization for Minimizing Maximum Displacement

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Outline

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1 / Introduction

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3 / Experimental Results

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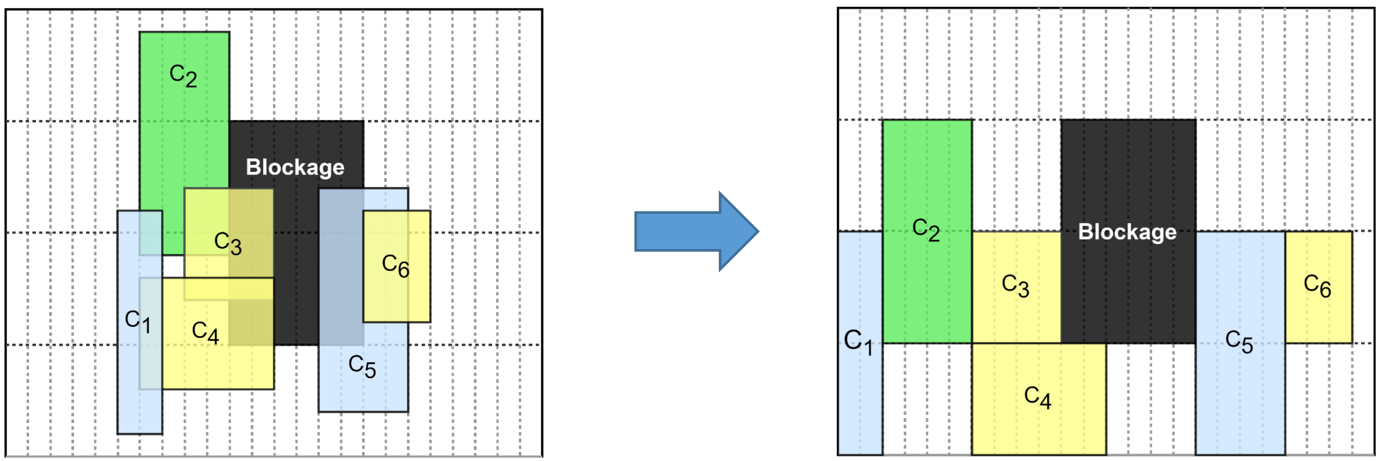
Introduction

- Mixed-cell-height circuit
  - Fast-growing complexity and shrinking number of intra-cell routing tracks in advanced technology nodes.
  - Complex / large driving cells can be designed as multiple-row height.
  - Simple cells are still designed as single-row-height structure.
  - This resulted in challenges on the legalization stage.

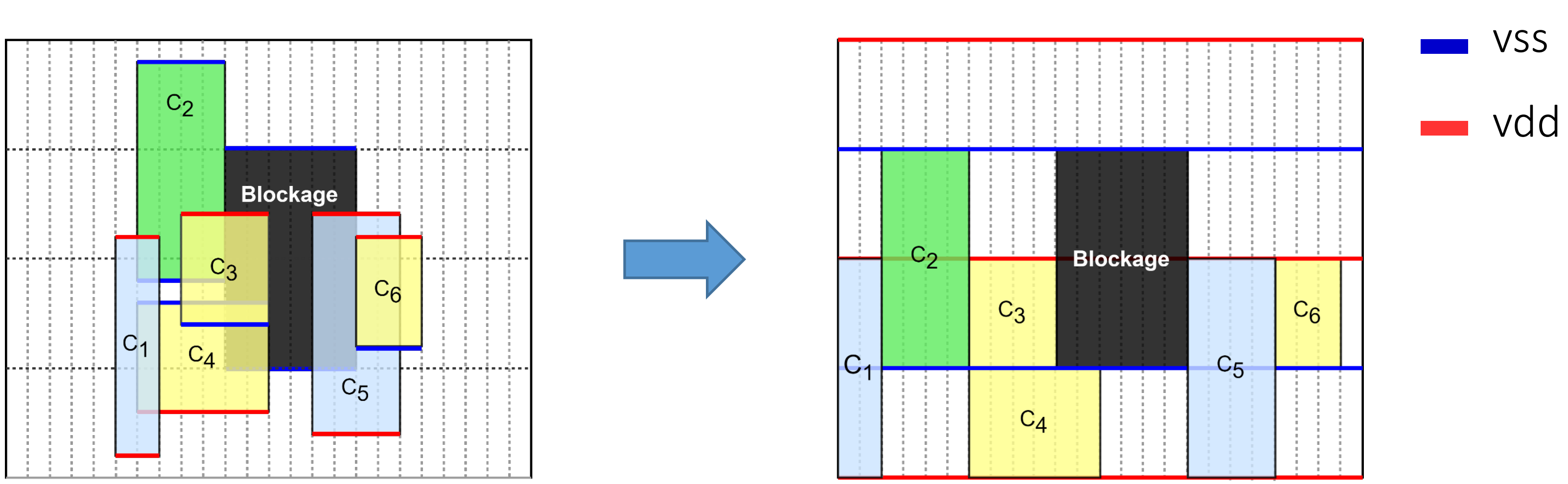
Introduction

- Legalization
  - Remove cell overlapping and align them to the placement sites on rows.
  - The result has a significant impact on later stages in the VLSI design flow.
  - Should optimize both average and maximum displacement to preserve the quality of the global placement.



Introduction

- Challenges regarding multiple-row height cells
  - Each row of a design cannot be considered independently anymore. (e.g. we can no longer utilize traditional legalizers, i.e. Abacus, Tetris.)
  - Should take care of power-rail alignment.
    - Odd-row-height cells can be flipped horizontally to satisfy the constraint.
    - Even-row-height cells should be placed in every other row with proper power rails.

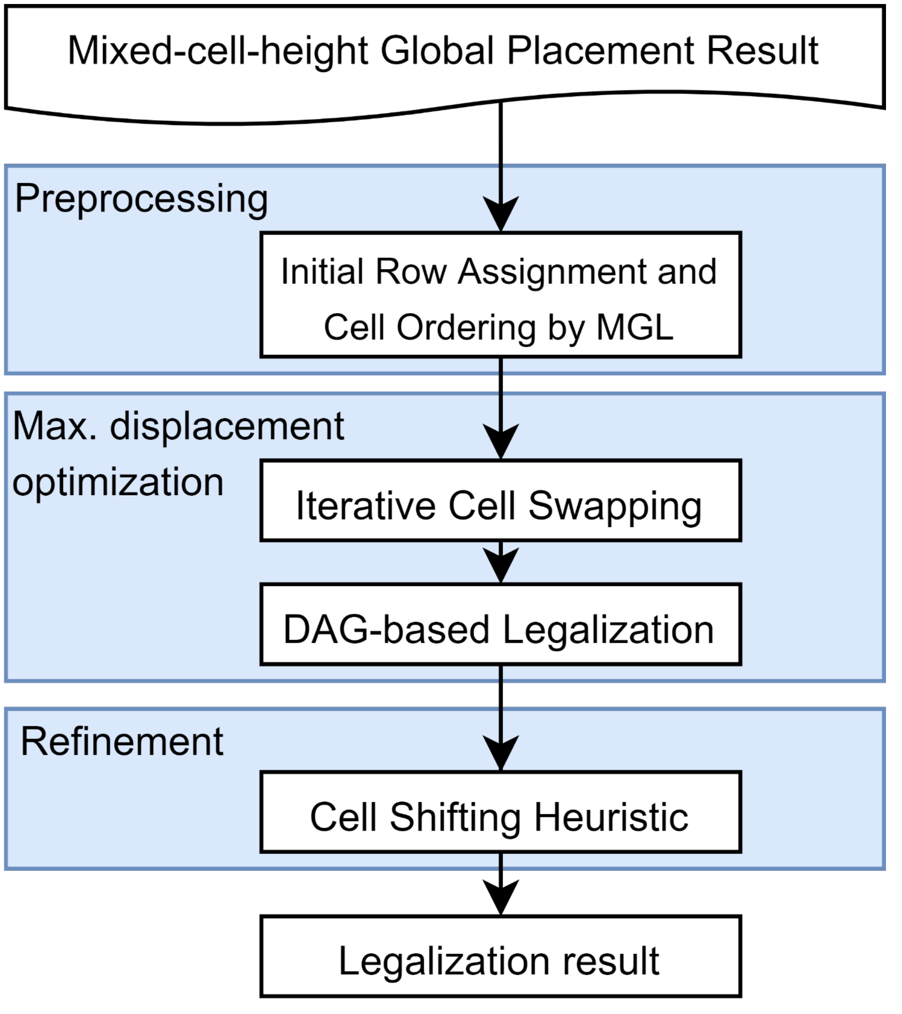


Problem Formulation

- Input:
  - A global placement, where there are cells of multiple-row height.
- Output:
  - A legalized placement, with maximum and total displacement minimized.
- Such that:
  - Cells must be placed inside the layout region.
  - Cells must not overlap with one another or with the preplaced macros.
  - Cells must be located at placement sites on the rows.
  - Cells must be placed in rows with proper P/G rail alignment.

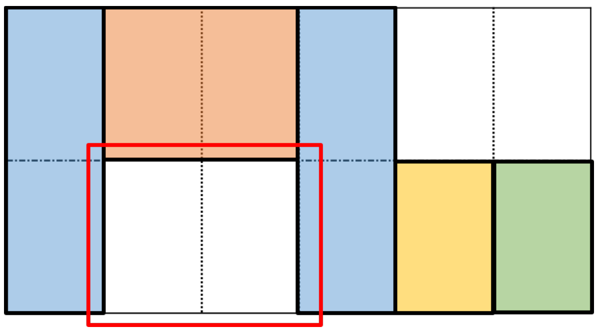
Outline

Overall Flow



Preprocessing

- To find a good initial cell ordering and row assignment.
- Following the cell ordering of global placement tended to create a lot of dead space.
  - The dead spaces will affect both placement feasibility and optimality.



[4] Haocheng Li, Wing-Kai Chow, Gengjie Chen, Bei Yu, and Evangeline F.Y. Young. 2021. Pin-Accessible Legalization for Mixed-Cell-Height Circuits.

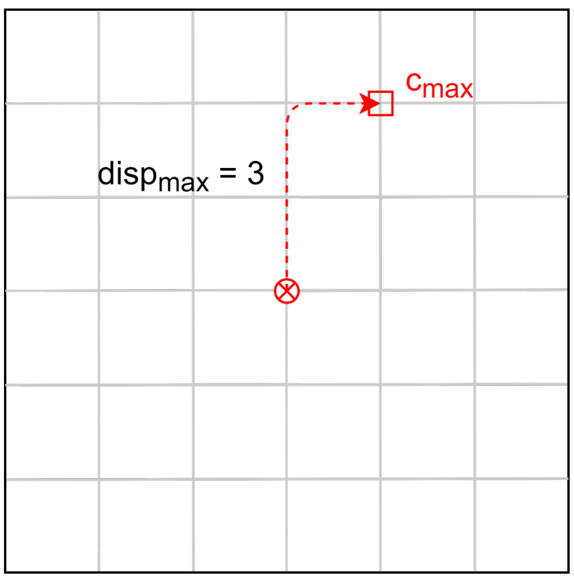
Preprocessing

- Obtain initial row assignment and ordering of cells using multi-row global legalization(MGL) from [4].
  - It ensures that legalization under this initial row assignment and cell ordering is feasible.
  - There exists a high quality legalized placement in terms of total cell displacement under this initial row assignment and cell ordering.

[4] Haocheng Li, Wing-Kai Chow, Gengjie Chen, Bei Yu, and Evangeline F.Y. Young. 2021. Pin-Accessible Legalization for Mixed-Cell-Height Circuits.

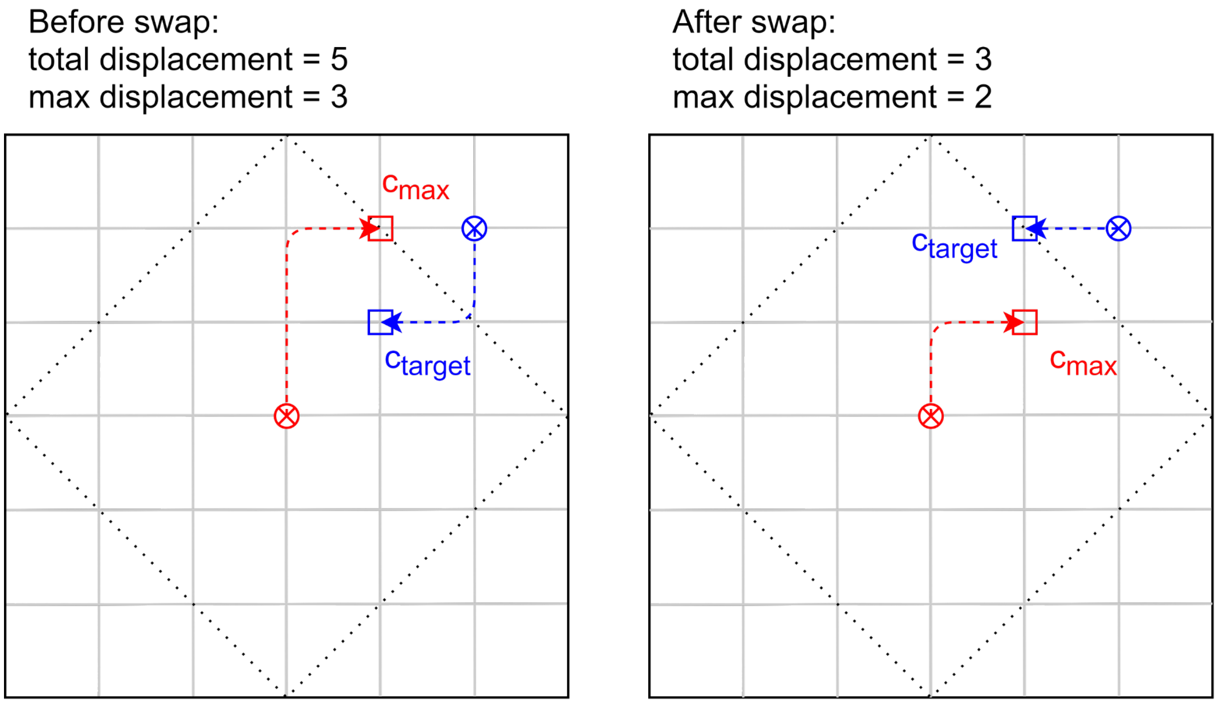
Iterative Cell Swapping

- To minimize maximum displacement.
- In each iteration:
    1. Locate the maximum displacement cell c_{max} (displacement=$disp_{max}$)



Iterative Cell Swapping

- In each iteration:
  2. Pick a target cell c_{target} within $disp_{max}$ from the GP position of c_{max}.
     - Such that swapping c_{max} and c_{target} will reduce the maximum displacement and will not increase the total displacement.
     - We prefer a target cell c_{target} with dimension as close to c_{max} as possible.



Iterative Cell Swapping

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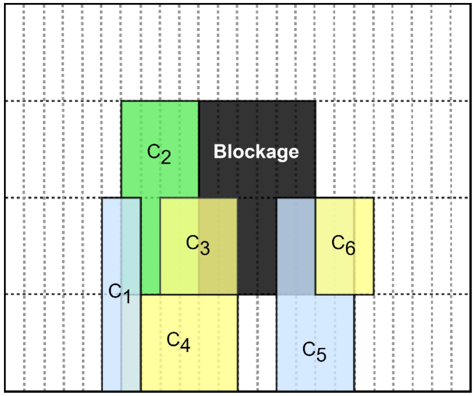
- In each iteration:
  1. Locate the maximum displacement cell c_{max} (displacement=$disp_{max}$)
  2. Pick a target cell c_{target} within $disp_{max}$ from the GP position of c_{max}.
     - Such that swapping c_{max} and c_{target} will reduce the maximum displacement and will not increase the total displacement.
     - We prefer a target cell c_{target} with dimension as close to c_{max} as possible.
- Check if the new placement after each swapping operation is still legalizable.
  - If not, revoke the last cell swap and proceed to next step.

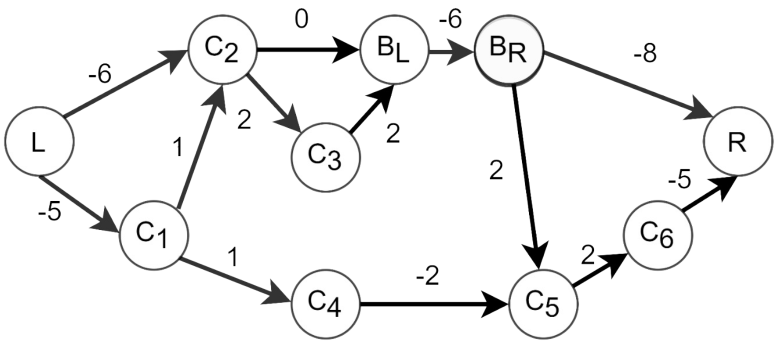
DAG-Based Legalization

- To minimize maximum displacement under fixed row assignment and cell ordering.
- We will build a DAG, and use it to facilitate the dynamic-programming-based computation of each cell’s shift amount.
  - It is guaranteed to have optimal maximum displacement after applying the calculated shift amount to each cell.

DAG-Based Legalization

- Build DAG G:
  - $\forall edge$: $(i,j) \in G$, cell j (c_j) is immediately on the right of cell i (c_i) .
  - For every edge (i,j), edge length = $s_{ij} = w_i - (\hat{x_j} - \hat{x_i})$
- Define deficit s_{ij}:
  - If $(\mathrm{i},\mathrm{j}) \in G$, $s_{ij} = w_i - (\hat{x_j} - \hat{x_i})$
  - Else, $s_{ij} = w_{ij}^* - (\hat{x_j} - \hat{x_i})$
    p_{ij}^* is the path from c_i to c_j in G with the largest total cell width and w_{ij}^* is the total width of all cells in p_{ij}^*.

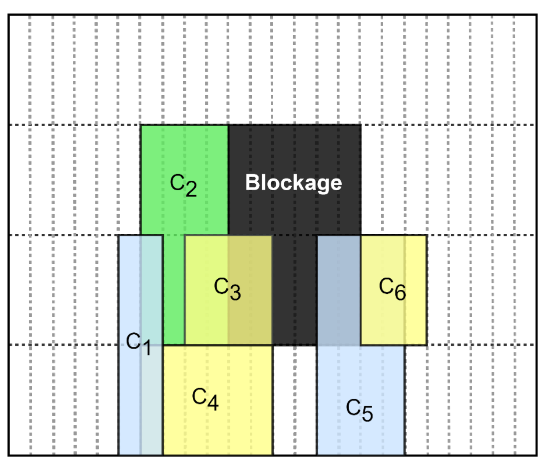


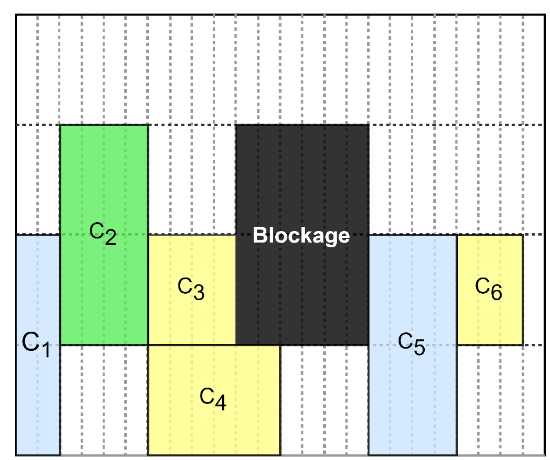


DAG-Based Legalization

- $\Delta y_i{}^{+} = |y_i - \widehat{y_i}|$
- $\rho_i = \max_{k}(\Delta y_i{}^{+} + s_{ki})$
- $\theta_i = \max_{j}(s_{ij} + \Delta y_i{}^{+})$
- $l_i = \max_{k \in F}(s_{ki} + \Delta y_i{}^{+})$
- $r_i = \max_{j \in F}(\Delta y_i{}^{+} + s_{ij})$
- $$\Delta x_i = \begin{cases} l_i - \Delta y_i^{+} & if\, l_i - \Delta y_i^{+} > \mu_i \\ -r_i + \Delta y_i^{+} & if\, -r_i + \Delta y_i^{+} < \mu_i \\ \mu_i & otherwise \end{cases}$$

i	w_i	Δy_i^{+}	ρ_i	θ_i	l_i	r_i	$l_i - \Delta y_i{}^{+}$	$-r_i + \Delta y_i{}^{+}$	$\mu_i = \lceil(\rho_i - \theta_i)/2\rceil$
1	2	1	1	5	-4	6	-5	-5*	-2
2	4	4	4	4	0	8	-4	-4*	0
3	4	2	6	2	0	4	-2	-2*	2
4	6	3	3	3	-1	-2	-4	5	0*
5	4	2	4	3	4	-1	2*	3	1
6	3	1	6	1	5	-4	4*	5	3





Cell Shifting Heuristic

- To minimize total displacement under fixed row assignment and cell ordering.
- After running the DAG-based legalization
  - We get the cell positions for optimal maximum displacement under the given row assignment and cell ordering.
  - Many cells are still movable without harming the optimal maximum displacement.
- The basic idea of this stage is as follows:
  - Make cell clusters, and horizontally shift each cluster to minimize the total displacement.
  - Uncluster all cells, and horizontally shift each cell to reduce its displacement.

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Experimental Results

- Benchmark information

Benchmarks	% cell types				#Macros	Util. (%)
	1xH	2xH	3xH	4xH		
des_perf_1	100.0	0.00	0.00	0.00	0	90.64
des_perf_a_md1	95.66	4.34	0.00	0.00	4	55.11
des_perf_a_md2	96.99	1.00	1.00	1.00	4	55.92
des_perf_b_md1	94.80	5.20	0.00	0.00	0	54.98
des_perf_b_md2	90.47	6.02	2.01	1.50	0	64.69
edit_dist_1_md1	90.31	6.12	2.04	1.53	0	67.47
edit_dist_a_md2	90.31	6.12	2.04	1.53	6	59.42
edit_dist_a_md3	93.88	2.04	2.04	2.04	6	57.22
fft_2_md2	89.62	6.56	2.18	1.64	0	83.12
fft_a_md2	89.57	6.59	2.19	1.65	6	32.41
fft_a_md3	93.42	2.19	2.19	2.19	6	31.24
pci_bridge32_a_md1	90.39	6.07	2.02	1.52	4	49.57
pci_bridge32_a_md2	85.51	7.08	4.04	3.37	4	57.72
pci_bridge32_b_md1	90.38	6.07	2.02	1.52	6	28.68
pci_bridge32_b_md2	97.97	1.01	1.01	1.01	6	19.72
pci_bridge32_b_md3	94.94	1.01	2.02	2.02	6	23.98

Experimental Results

Benchmarks	ΔHPWL(%)			Avg. Disp. (sites)			Max Disp. (sites)		
	[4]	[5]	Ours	[4]	[5]	Ours	[4]	[5]	Ours
des_perf_1	5.86	6.66	6.01	6.52	6.97	6.81	42.07	48.95	38.49
des_perf_a_md1	1.65	2.48	1.62	5.60	5.94	5.61	607.30	607.30	607.30
des_perf_a_md2	1.55	2.51	1.53	5.48	5.93	5.50	480.55	403.86	480.55
des_perf_b_md1	1.72	1.52	1.69	4.55	4.77	4.58	42.53	38.45	30.27
des_perf_b_md2	1.51	1.72	1.47	4.95	5.25	4.97	59.39	39.76	30.62
edit_dist_1_md1	1.39	0.14	1.36	5.54	5.79	5.45	58.16	95.45	52.84
edit_dist_a_md2	0.80	1.01	0.79	5.18	5.51	5.16	164.00	164.00	164.00
edit_dist_a_md3	1.30	1.48	1.32	6.92	7.08	7.56	233.00	233.00	233.00
fft_2_md2	13.84	8.78	13.79	7.72	7.54	8.49	54.40	73.6	45.01
fft_a_md2	1.07	0.95	1.04	4.62	4.86	4.58	343.48	345.5	343.48
fft_a_md3	1.11	1.08	1.09	4.35	4.55	4.31	109.62	109.62	109.62
pci_bridge32_a_md1	2.49	3.38	2.45	5.31	5.64	5.30	63.76	63.76	63.76
pci_bridge32_a_md2	3.47	4.38	3.46	6.86	7.14	6.89	121.35	121.35	121.35
pci_bridge32_b_md1	1.73	2.26	1.64	5.58	6.01	5.54	340.30	332.71	332.72
pci_bridge32_b_md2	2.33	2.53	2.30	5.23	5.53	5.20	452.09	430.04	452.09
pci_bridge32_b_md3	2.57	3.17	2.54	5.69	6.1	5.68	476.91	398.57	476.91
Norm. Average	1.01	1.11	1	0.989	1.041	1	1.111	1.112	1

[4] Haocheng Li, Wing-Kai Chow, Gengjie Chen, Bei Yu, and Evangeline F.Y. Young. 2021. Pin-Accessible Legalization for Mixed-Cell-Height Circuits.
[5] Xingquan Li, Jianli Chen, Wenxing Zhu, and Yao-Wen Chang. 2019. Analytical Mixed-Cell-Height Legalization Considering Average and Maximum Movement Minimization.

Experimental Results

- Runtime comparison (measured in seconds)

Benchmarks	MGL	Remaining stages	
		[4]	Ours
des_perf_1	0.915	2.126	0.889
des_perf_a_md1	0.780	0.578	0.429
des_perf_a_md2	0.718	0.735	0.493
des_perf_b_md1	0.450	0.721	1.029
des_perf_b_md2	0.504	0.710	1.234
edit_dist_1_md1	0.495	0.787	1.624
edit_dist_a_md2	0.570	0.768	0.760
edit_dist_a_md3	0.873	1.654	1.310
fft_2_md2	0.133	0.318	0.287
fft_a_md2	0.089	0.122	0.114
fft_a_md3	0.073	0.113	0.107
pci_bridge32_a_md1	0.124	0.174	0.072
pci_bridge32_a_md2	0.144	0.196	0.106
pci_bridge32_b_md1	0.180	0.107	0.097
pci_bridge32_b_md2	0.125	0.193	0.049
pci_bridge32_b_md3	0.130	0.226	0.058
Norm. Average	1	1.607	1

[4] Haocheng Li, Wing-Kai Chow, Gengjie Chen, Bei Yu, and Evangeline F.Y. Young. 2021. Pin-Accessible Legalization for Mixed-Cell-Height Circuits.

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Conclusion

- We proposed a mixed-cell-height legalization approach
  - Optimizes both the total and maximum cell displacement
  - Highly efficient – linear in runtime
  - High quality solutions – 11% smaller maximum displacement compared to the state-of-the-art works with similar average displacement.

Thank You