3D-Flow: Flow-based Standard Cell Legalization for 3D ICs

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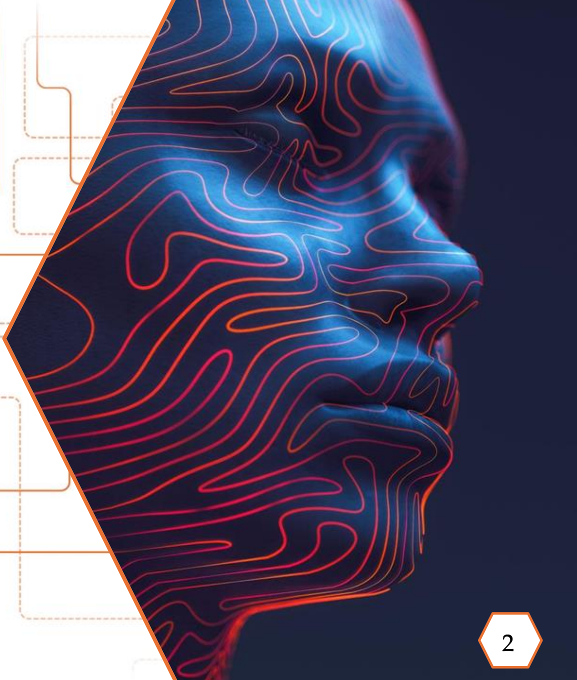

Introduction

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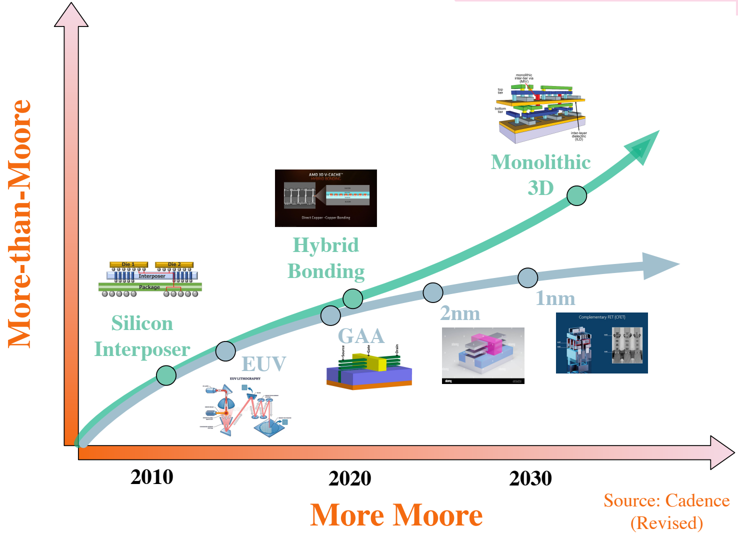
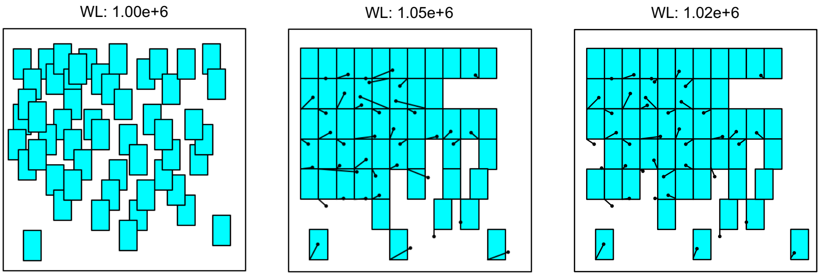
More Moore and More-than-Moore



Source: Cadence (Revised)

Placement Legalization

- Standard cells must be aligned to placement rows and sites without overlapping.
- Minimize average and maximum cell displacement.



1. Global placement 2. Legalization 3. Detailed Placement

Legalization Methods

Category

- **Greedy Search:** Sequentially moving cells to the nearest free locations [US Patent'02][1] [ISPD'08][2].
- **Mathematical Optimization:** network flow formulation with concurrent cell movement [DAC'10][3] [TCAD'13][4].

Legalization as a Minimum-Cost Flow Problem

- Divide the layout into bins V and construct the flow network $G(V, E)$. Let $c \in \Gamma(v)$ denote a cell c in a bin v.
- Let $S = \{v \mid v \in V, \text{sup}(v) > 0\}$ as source bins, and $T = \{v \mid v \in V, \text{dem}(v) > 0\}$ as sink bins. Let $R = V - S - T$ denote the remaining bins.

$$
\begin{aligned}
\min \quad & \sum_{(u,v)\in E} \sum_{c\in\Gamma(u)} \text{cost}_{u,v,c} a_{u,v,c} \\
\text{s.t.} \quad & \sum_{u\in V} \sum_{c\in\Gamma(v)} w_c a_{v,u,c} - \sum_{u\in V} \sum_{c\in\Gamma(u)} w_c a_{u,v,c} \geq \text{sup}(v), \quad && \forall v \in S \\
& \sum_{u\in V} \sum_{c\in\Gamma(u)} w_c a_{u,v,c} - \sum_{u\in V} \sum_{c\in\Gamma(v)} w_c a_{v,u,c} \leq \text{dem}(v), \quad && \forall v \in T \\
& \sum_{u\in V} \sum_{c\in\Gamma(u)} w_c a_{u,v,c} - \sum_{u\in V} \sum_{c\in\Gamma(v)} w_c a_{v,u,c} = 0, \quad && \forall v \in R \\
& a_{u,v,c} \in \{0, 1\}, \quad \forall (u, v) \in E, \forall c \in \Gamma(u),
\end{aligned}
\tag{1}
$$

3D-Flow

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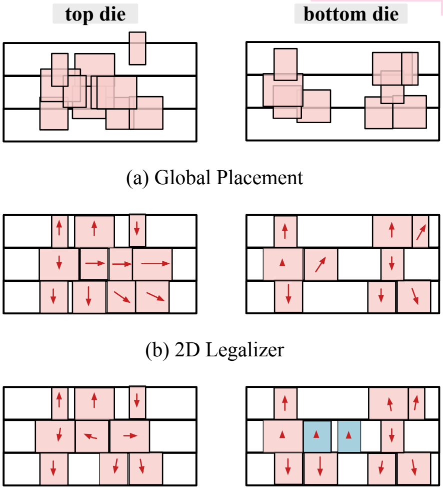
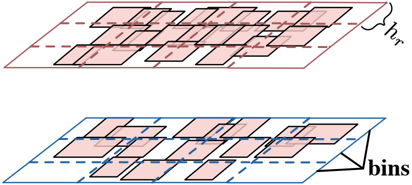
Motivation

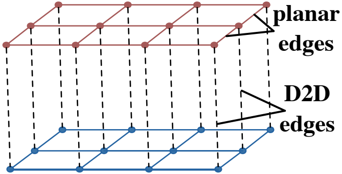


(c) 3D-Flow Legalizer

3D Flow Network Construction



Initial Bin Assignment



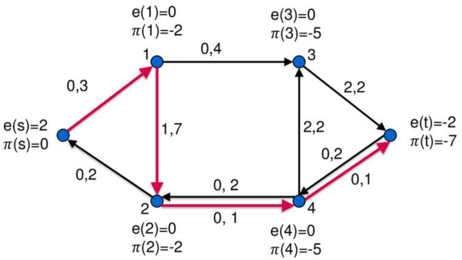
3D Grid Graph

- Fractional cells $\gamma = (c_\gamma, \rho_\gamma)$, where $c_\gamma = c$ and $\rho_\gamma \in (0, 1]$, and $\sum_{\gamma: c_\gamma = c} \rho_\gamma = 1$ for any cell c.
- For a bin v, let $\text{cap}(v) = w_v$ represent capacity. Total width of fractional cells in bin v is $w_{\Gamma(v)} = \sum_{\gamma \in \Gamma(v)} w_{c_\gamma} \times \rho_\gamma$.

$$\text{sup}(v) = \max\{0, w_{\Gamma(v)} - w_v\}, \quad (2)$$

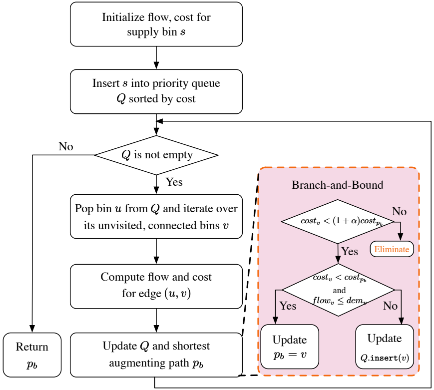
$$\text{dem}(v) = \max\{0, w_v - w_{\Gamma(v)}\}. \quad (3)$$

Successive Shortest Path Algorithm [OR'90][5]

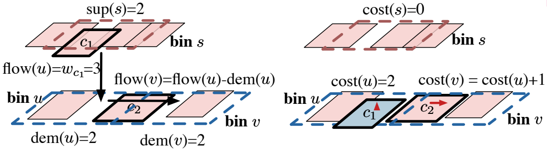


- No negative cost cycle. Using Dijkstra's algorithm with reduced cost $cost_{u,v} \leftarrow cost_{u,v} + \pi_u - \pi_v$ to find the augmenting path.
- Our displacement cost can be negative. $D_c(v) = |x_c - x'_c| + |y_c - y'_c|$, $\mathrm{cost}_{u,v,c} = D_c(v) - D_c(u)$; Dijkstra is time-consuming for 3D grid graph.

Augmentation with Branch-and-Bound

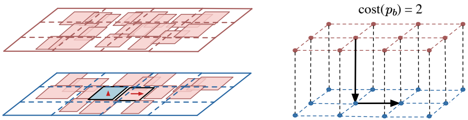


Algorithm Flow

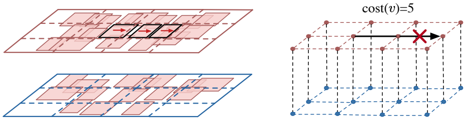


(a) Candidate Path

(b) Cell Movement

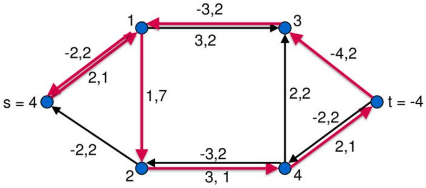


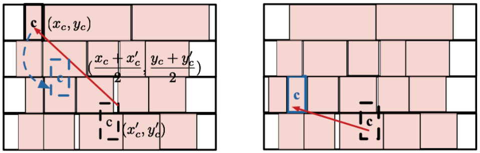
(a) Shortest Augmenting Path



(b) Eliminated Branch

Post-Optimization with Cycle-Canceling [JACM'89][6]





(a) Negative Cycle (b) Reduced Displacement

- After the flow-based legalization, row-based placement algorithm [ISPD'08][2] is used to remove overlap within bins.
- We construct negative cycles by moving cells with large displacement toward their initial positions. We select the cells with displacement $D_c > \max\{5h_r, \frac{D_{\max}}{2}\}$.

Experimental Results

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Experimental Setup

Table: The statistics of ICCAD 2022 contest benchmarks.

ICCAD 2022	#Cells	#Macros	#Nets	h_r^+	h_r^-
case2	2735	0	2644	176	252
case2h	2735	0	2644	252	252
case3	44764	0	44360	115	115
case3h	44764	0	44360	92	115
case4	220845	0	220071	92	115
case4h	220845	0	220071	103	115

Table: The statistics of ICCAD 2023 contest benchmarks.

ICCAD 2023	#Cells	#Macros	#Nets	h_r^+	h_r^-
case2	13901	6	19547	33	33
case2h1	13901	6	19547	33	48
case2h2	13901	6	19547	33	48
case3	124231	34	164429	33	48
case3h	124231	34	164429	36	48
case4	740211	32	758860	92	115
case4h	740211	32	758860	55	69

- We conduct experiments on ICCAD 2022 and 2023 contest benchmarks. We use SOTA true-3D placers [TCAD'23][7] [TCAD'24][8] to generate the global placement results.
- **Baselines:** Tetris [US Patent'02][1], Abacus [ISPD'08][2], and BonnPlaceLegal [TCAD'13][4].

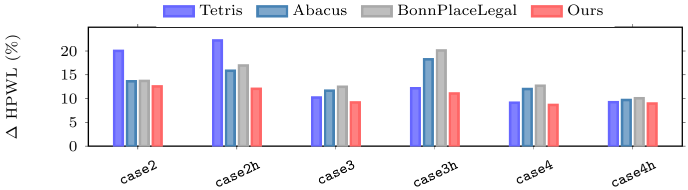
Experimental Results

ICCAD 2022	Tetris			Abacus			BonnPlaceLegal			Ours		
	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT
case2	0.801	7.27	0.23	0.522	3.05	0.24	0.511	2.91	0.26	**0.503**	**2.77**	0.27
case2h	1.091	5.77	0.22	0.593	4.34	0.24	0.610	4.80	0.24	**0.511**	**2.97**	0.25
case3	0.929	13.40	1.15	0.705	5.81	1.35	0.727	6.13	2.70	**0.660**	**4.53**	1.54
case3h	1.162	8.30	1.19	0.938	9.47	1.44	0.986	7.95	6.28	**0.750**	**4.61**	1.73
case4	1.775	12.83	6.79	1.383	16.81	10.98	1.428	15.13	72.93	**1.174**	**11.25**	9.69
case4h	1.622	27.59	6.75	1.161	14.96	9.96	1.186	11.94	53.68	**1.100**	**8.14**	10.36
Average	1.613	2.31	**0.76**	1.125	1.54	0.95	1.153	1.43	3.34	**1.000**	**1.00**	1.00

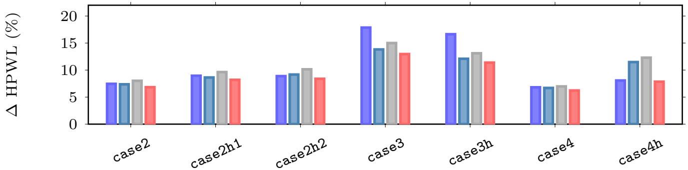
ICCAD 2023	Tetris			Abacus			BonnPlaceLegal			Ours		
	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT	Avg. Disp.	Max. Disp.	RT
case2	3.029	13.27	0.50	2.199	11.33	0.61	2.308	11.50	2.49	**2.109**	**9.09**	0.64
case2h1	3.609	50.28	0.57	2.509	35.28	0.68	2.668	36.85	4.80	**2.433**	**27.03**	0.74
case2h2	3.709	46.29	0.55	2.673	39.26	0.71	2.828	34.11	5.19	**2.518**	**27.73**	0.74
case3	3.612	195.31	3.07	2.475	136.25	4.52	2.615	131.96	59.83	**2.442**	**70.82**	4.46
case3h	3.041	141.31	2.89	2.266	119.31	4.21	2.370	109.11	69.99	**2.204**	**99.05**	5.74
case4	1.349	127.69	22.86	1.000	17.32	37.79	1.023	15.32	264.23	**0.920**	**13.77**	39.13
case4h	1.709	128.19	23.75	1.432	78.55	47.02	1.492	77.71	315.26	**1.130**	**54.31**	37.73
Average	1.461	2.97	**0.69**	1.076	1.40	1.00	1.127	1.34	8.89	**1.000**	**1.00**	1.00

- **13**% and **43**% less average and maximum displacement on standard-cell-only benchmarks.
- **8**% and **34**% less average and maximum displacement on mixed-size benchmarks.

Experimental Results



(a) Δ HPWL (%) increase on ICCAD 2022 benchmarks.

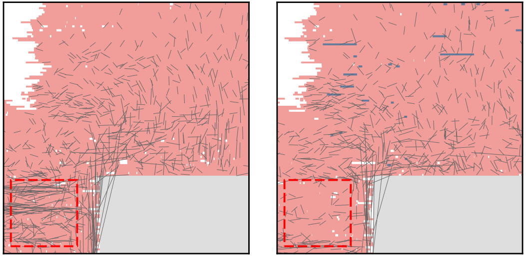


(b) Δ HPWL (%) increase on ICCAD 2023 benchmarks.

Ablation Study on Die-to-Die Cell Movement

Table: Comparison on the legalization results for our 3D-Flow legalizer with and without die-to-die (D2D) cell movement.

ICCAD 2023	w/o. D2D		Ours		
	Avg. Disp.	Max. Disp.	Avg. Disp.	Max. Disp.	#Move
case2	2.197	11.33	**2.109**	**9.09**	35
case2h1	2.506	35.28	**2.433**	**27.03**	46
case2h2	2.711	32.10	**2.518**	**27.73**	54
case3	2.582	98.98	**2.442**	**70.82**	493
case3h	2.229	107.84	**2.204**	**99.05**	373
case4	0.931	15.32	**0.920**	**13.77**	2479
case4h	1.358	54.33	**1.130**	**54.31**	2081
Average	1.068	1.19	**1.000**	**1.00**	-



(c) w/o. D2D cell movement

(d) Our 3D-Flow Legalizer

By moving only a few cells vertically, our legalizer finds white space for other cells to minimize displacement in a global view.

Conclusion and Future Direction

- The 3D-Flow legalizer effectively utilizes vertical stacking to determine legal positions for cells, achieving minimal displacement with a global perspective.
- Experimental results demonstrate that the 3D-Flow legalizer reduces displacement while maintaining competitive runtime performance.
- Future directions include leveraging vertical stacking for detailed placement, routability-driven 3D placement, clock tree synthesis . . .

References I

[1] Dwight Hill. *Method and system for high speed detailed placement of cells within an integrated circuit design*. US Patent 6,370,673. 2002.

[2] Peter Spindler, Ulf Schlichtmann, and Frank M Johannes. "Abacus: Fast legalization of standard cell circuits with minimal movement". In: *Proc. ISPD*. 2008, pp. 47–53.

[3] Minsik Cho et al. "History-based VLSI legalization using network flow". In: *Proc. DAC*. 2010, pp. 286–291.

[4] Ulrich Brenner. "BonnPlace legalization: Minimizing movement by iterative augmentation". In: *IEEE TCAD* 32.8 (2013), pp. 1215–1227.

[5] Andrew V Goldberg and Robert E Tarjan. "Finding minimum-cost circulations by successive approximation". In: *Mathematics of Operations Research* 15.3 (1990), pp. 430–466.

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[6] **Andrew V Goldberg and Robert E Tarjan. "Finding minimum-cost circulations by canceling negative cycles".** In: *Journal of the ACM (JACM)* 36.4 (1989), pp. 873–886.

[7] **Peiyu Liao et al. "Analytical Die-to-Die 3D Placement with Bistratal Wirelength Model and GPU Acceleration".** In: *IEEE TCAD* (2023).

[8] **Yuxuan Zhao et al. "Analytical Heterogeneous Die-to-Die 3D Placement with Macros".** In: *IEEE TCAD* (2024).

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