A Hierarchical Bin-Based Legalizer for Standard-Cell Designs with Minimal Disturbance

Yu-Min Lee, Tsung-You Wu, and Po-Yi Chiang

Department of Electrical Engineering
National Chiao Tung University

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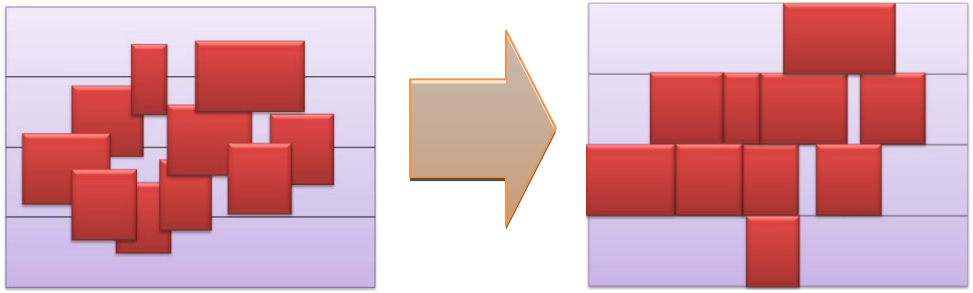
Outline

- Introduction
- Literature Overview
- Legalization Approach
- Experimental Results
- Conclusion

Introduction
- Legalization for Standard-Cell Based Design

- Given a global placement with millions of standard cell circuits
- Each standard cell can be represented as a rectangle
  - Every rectangle has the equal height, but different width

- The goal of legalization is to eliminate overlaps by disturbing cells as little as possible into row structure



Un-legalized placement Legalized placement

Legalized placement
- **Overlap-free**
- **Cells are aligned to row structure**

Introduction
- Cell Movement Estimation

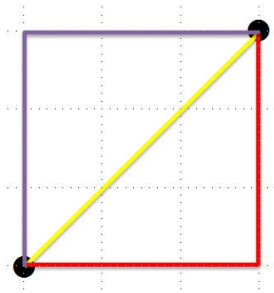
- Given n cells, two well-known cost functions can be used to estimate the movement during legalization.
  - Quadratic movement

$$\sum_{i=1}^{n}(p_x^i - q_x^i)^2 + (p_y^i - q_y^i)^2$$

$$\begin{cases} (p_x^i, p_y^i): \text{ the global placemnet position of cell } i \\ (q_x^i, q_y^i): \text{ the legalized position of cell } i \end{cases}$$

  - Manhattan distance movement

$$\sum_{i=1}^{n}\left(\left|p_x^i - q_x^i\right| + \left|p_y^i - q_y^i\right|\right)$$



Manhattan distance movement is **more practical** movement estimation than quadratic movement.

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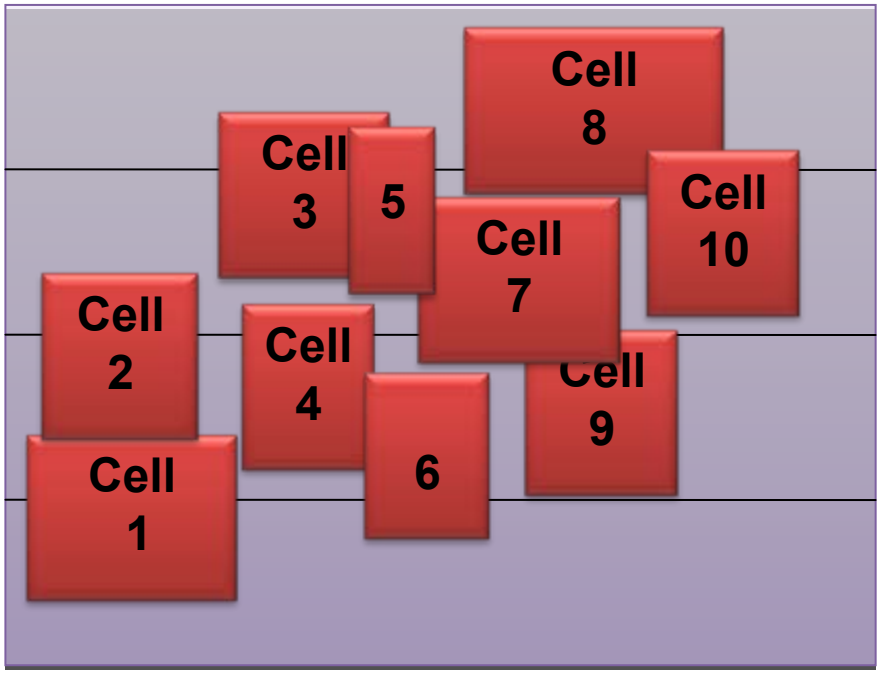
Existing Works

- **Dynamic Programming-Based**
  - Single-row optimization [Kahng et al., ASPDAC'99, Brenner et al., DATE'00]
  - Multiple-row optimization [Agnihotri et al., ICCAD'03]
- **Flow and Diffusion-Based** [Brenner et al., ISPD'04, Ren et al., DAC'05, Luo et al., ASPDAC'08]
  - Use either a minimum cost flow formulation or diffusion to spread cells from high density region to low density region
- **Computational-Geometry-Based** [Luo et al., ICCAD'05]
- **Ordering Preserved in *x*-coordinate**
  - Tetris [Hill, Patent 2002]: legalize cells one by one with fixed-legalized-cell position
  - Abacus [Spindler et al., ISPD'08]: legalize cells one by one with movable-legalized cell position

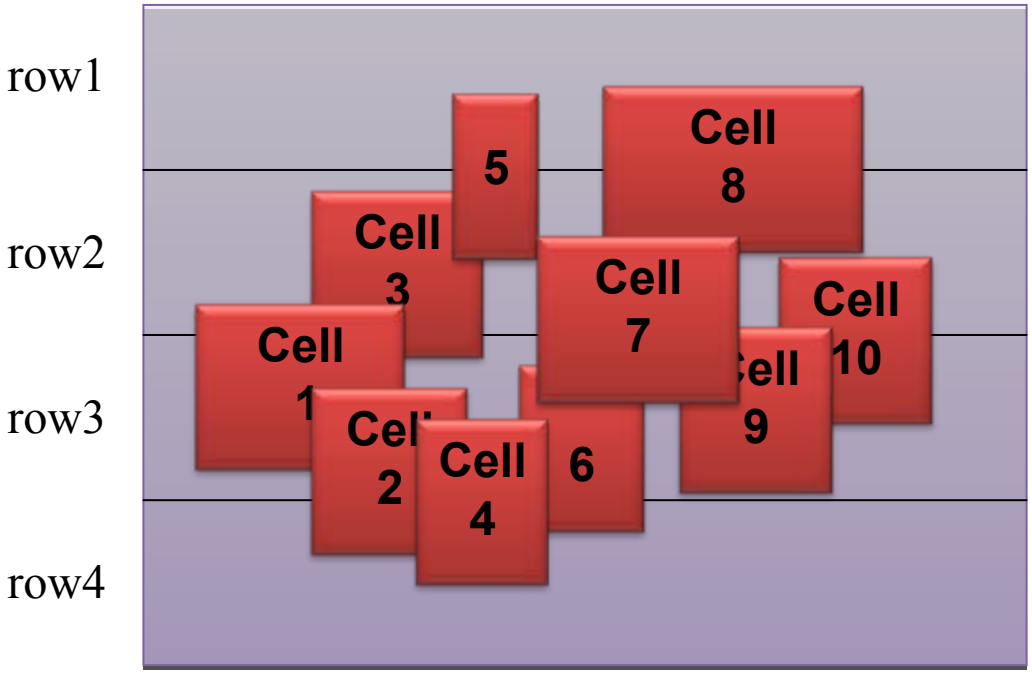
Tetris Overview

- A greedy cell movement approach.
- Cells are processed one by one from the order based on the *x*-coordinates of cells.
- Once a cell has been legalized, it will not be moved anymore.



Abacus Overview

- Use quadratic movement function to estimate the movement
- Use similar technique like Tetris, but move legalized cells.
- Use dynamic refresh to place the cells for minimizing the total movement in one row.
- Search all rows in a chip and use quadratic programming to insert a lowest cost cell for minimizing the movement.



Features of Proposed Legalizer - HiBinLegalizer

- We develop an efficient legalization approach with Manhattan distance movement cost function.
- **Bin Merged Procedure:** To limit the movable scope of each cell, two shapes of integrated bins are developed.
- **Legalization Framework:** The approach places cells in the row having the lowest cost; moreover, it preserves the relative order of cells in each row.
- **Legalization Core (LegCore):** It refreshes the positions of legalized cells during legalization; i.e., the approach preserves the best position for cells instantly.
- **Weighted Sum of Distances Solver (WSoDS):** The solver minimizes the Manhattan distance movement of total cells between global placement and legalization by median concept.

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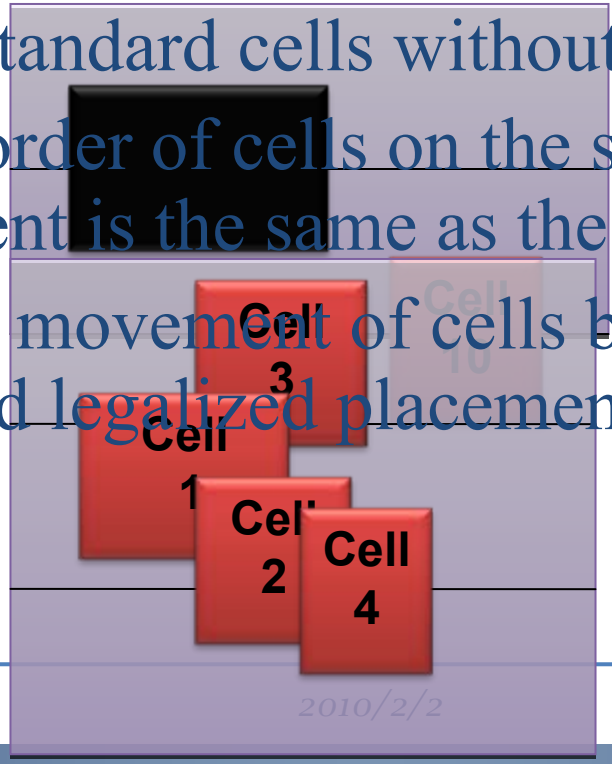
Problem Formulation

Input

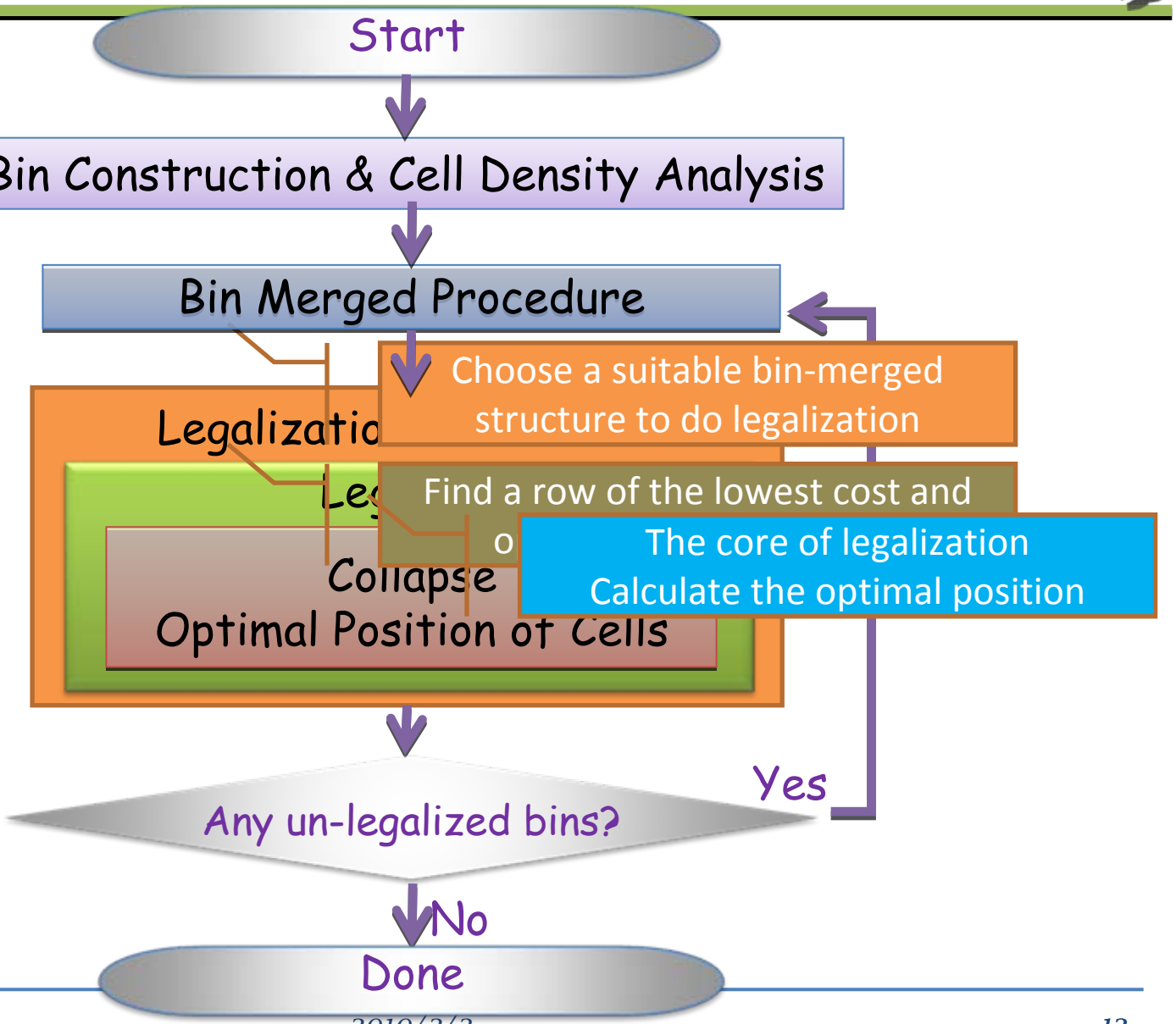
- Given a chip design and cell information with a global placement result.

Goal

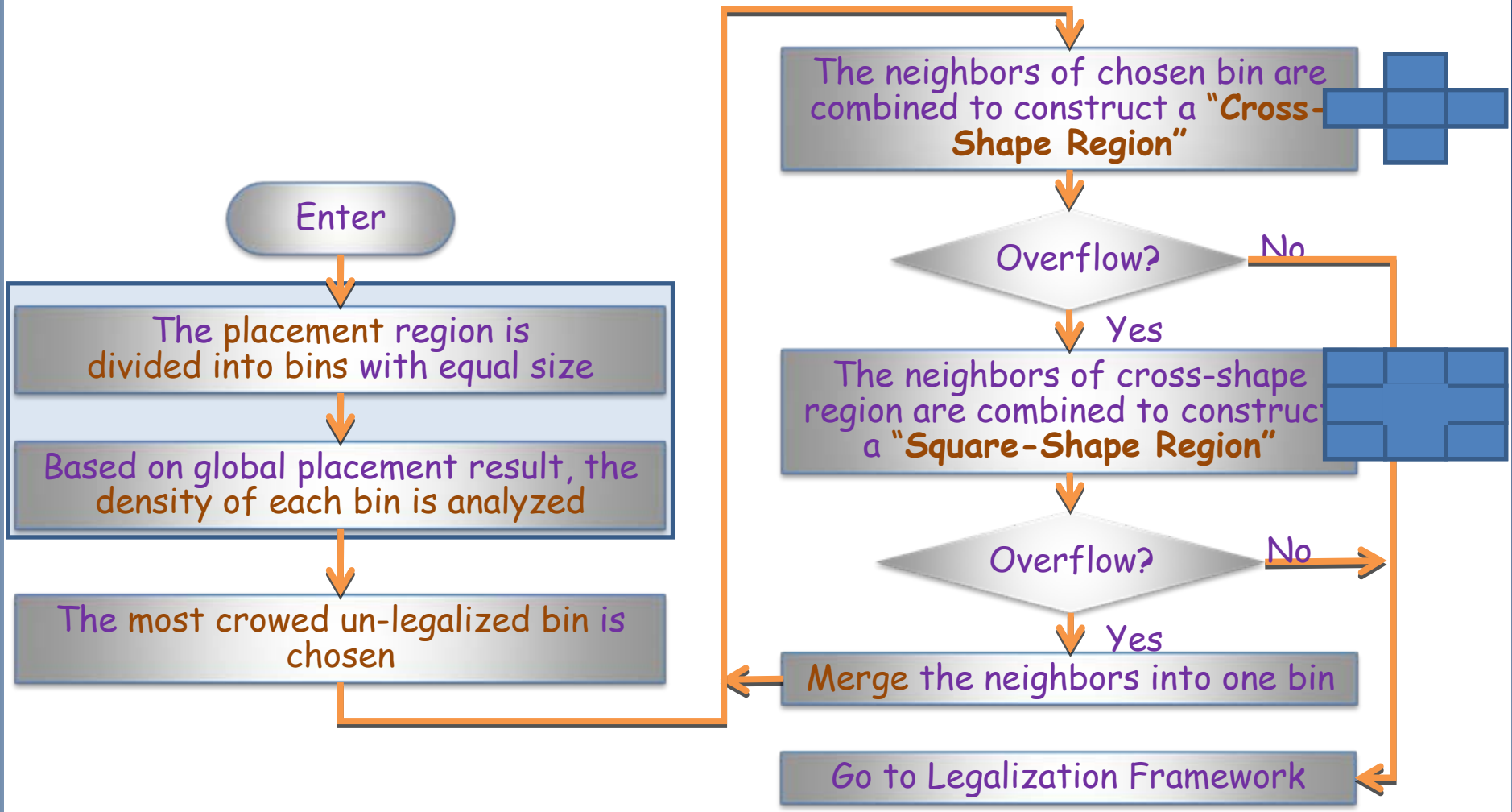
- Align all standard cells to feasible rows.
- Legalize all standard cells without overlap.
- The relative order of cells on the same row in the legal placement is the same as the global placement.
- Minimize the movement of cells between global placement and legalized placement.



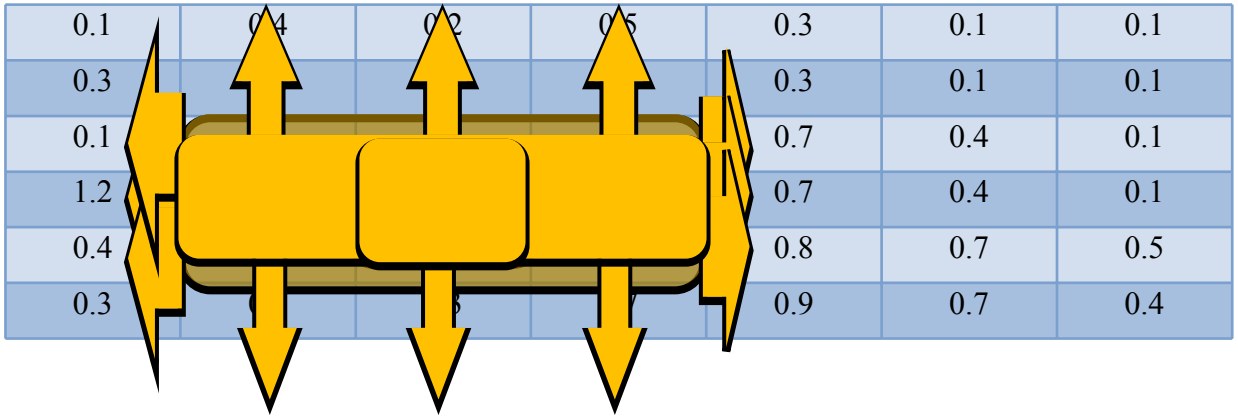
Flow Chart of HiBinLegalizer



Bin Merged Procedure



Example for Bin Merged Procedure

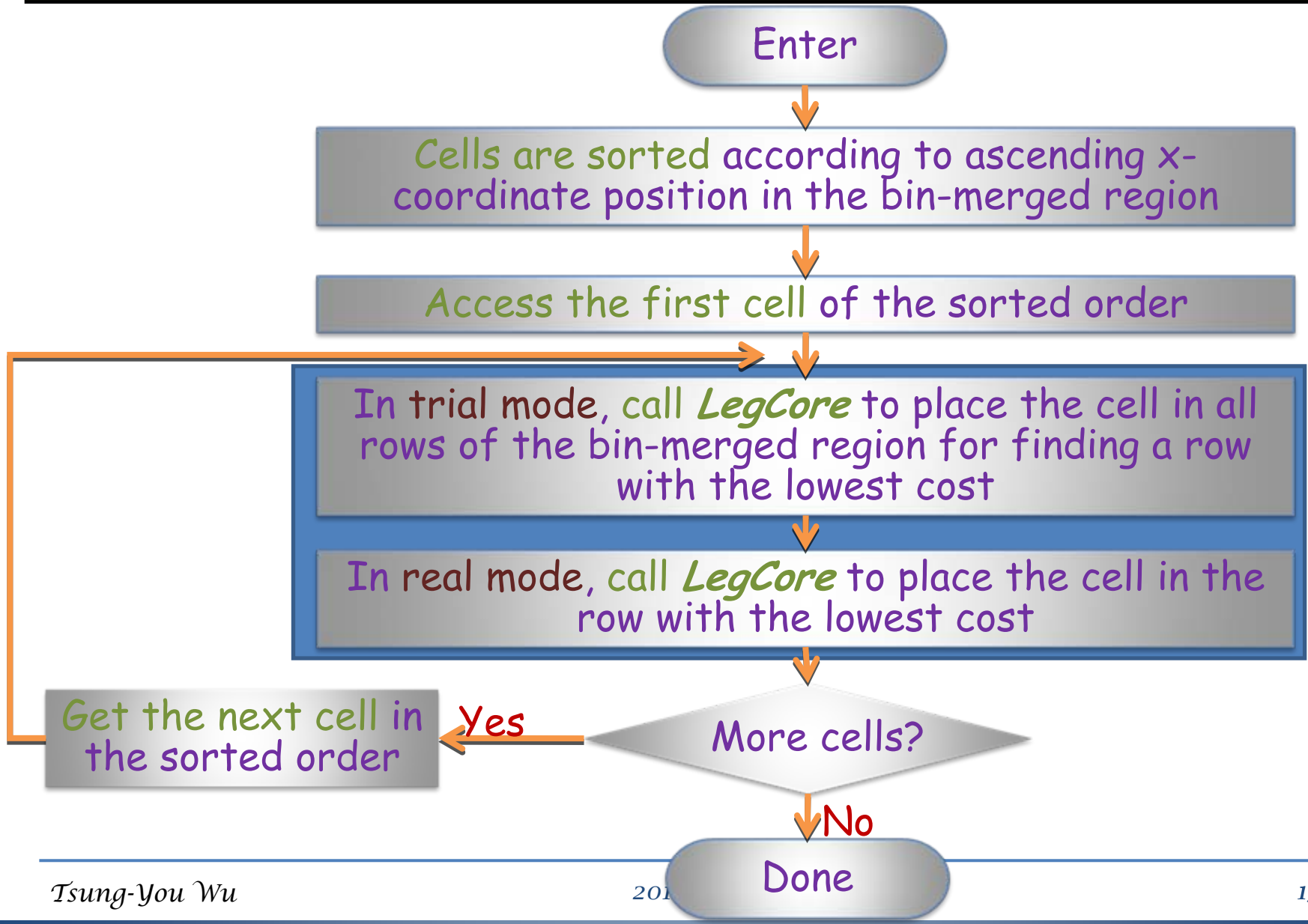


- The most crowed un-legalized bin is chosen.
- Use the ***cross-shape region*** to legalize cells in the shelter region.
- Merge the neighbors to construct a ***square-shape region*** to legalize cells
- Iterate it until the cell density is below a pre-defined threshold!

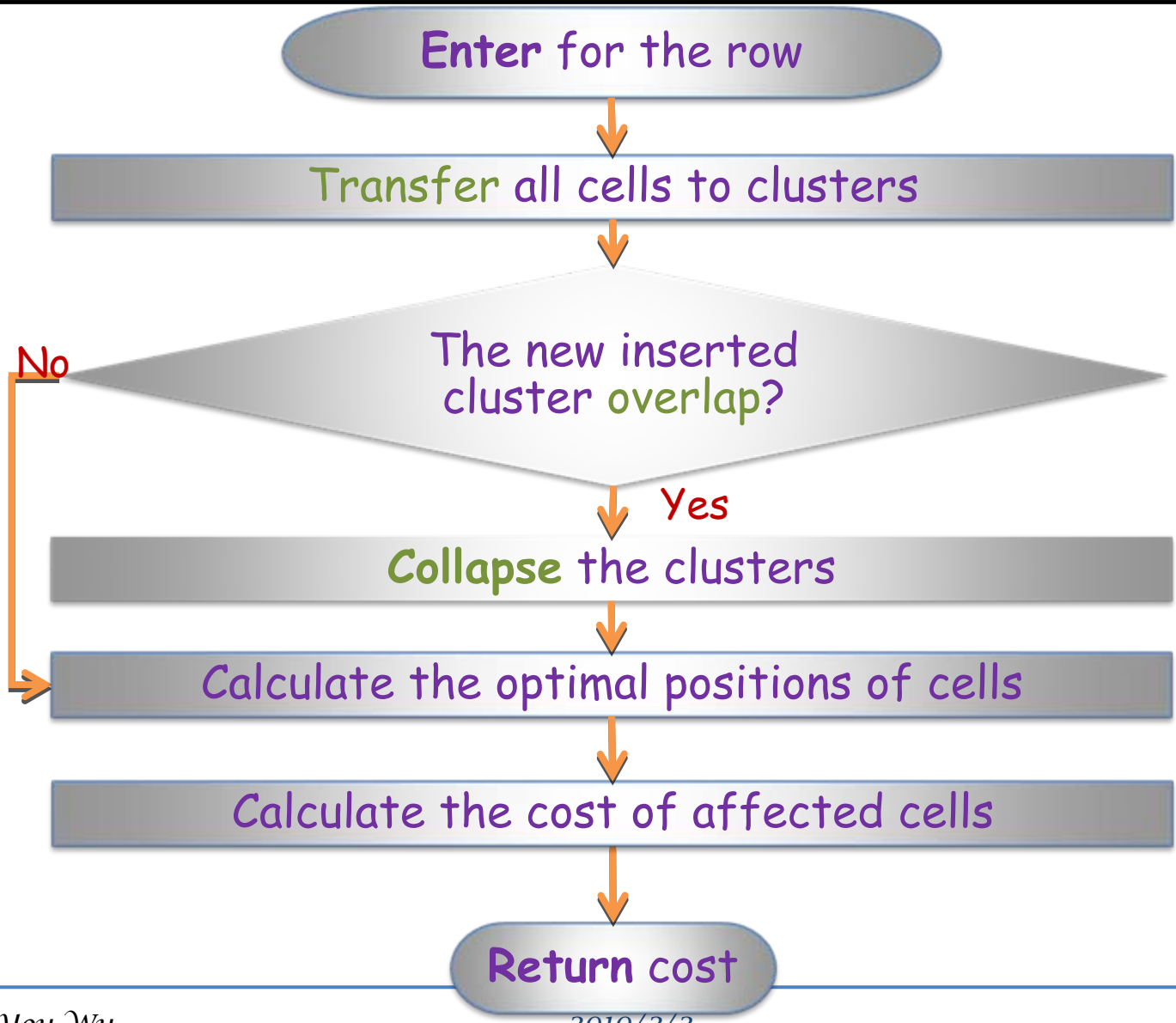
Why we use bin-merged structure?

*Bin-merged structure can **restrict the movement of cells** and the **wirelength** in the congested bin efficiently.*

Legalization Framework



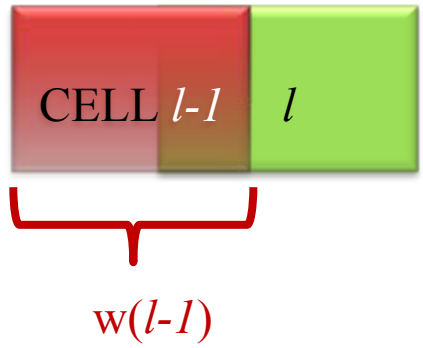
Legalization Core (LegCore)



The Optimal Position by Weighted Sum of Distances Solver (WSoDS) (1/3)

- We preserve the relative cell orders in *x*-coordinate.
  - The relative order of cells on the same row in the legal placement is the same as the global placement.
- Before legalization, two consecutive cells *l-1* and *l* are overlapped; hence,

$$x(l) - x(l-1) \le w(l-1)$$



$x(l)$: the original *x*-coordinate position of cell *l*

$w(l)$: the width of cell *l*

$x'(l)$: the *x*-coordinate position of legalized cell *l*

N_r : total number of cells in one cluster

- After legalization
  - It can be shown that to minimize $\sum_{k=1}^{N_r} e(l)\left|x'(l) - x(l)\right|^p$ ($p>0$), the legalized cells must be **abutted**. In other words

$$\text{optimal } x'(l) = x'(1) + \sum_{k=1}^{l-1} w(k); \quad \text{for } l = 2,\ldots,N_r$$

The Optimal Position by WSoDS with Manhattan Distance (p=1) (2/3)

- The Weighted Sum of Distances Solver with Manhattan distance is constructed as follows.

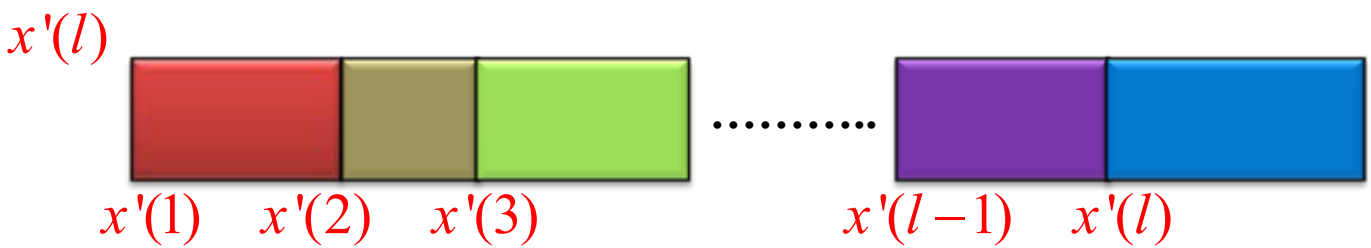
$$\textbf{minimize} \quad \sum_{k=1}^{N_r} |x'(l) - x(l)| = |r_1| + \cdots + |r_l| + \cdots + |r_{N_r}|,$$

$$\textbf{s.t.} \quad x'(l) - x(l) \geq w(l-1); \quad 2 \leq l \leq N_r$$

- Here, $|r_l|$ for the optimal $x'(l)$ can be written as

$$|r_l| = \left| x'(1) + \sum_{k=1}^{l-1} w(k) - x(l) \right|; \quad \text{(the movement of cell } l\text{)}$$

$$-\Delta x_l \triangleq -\left(x(l) - \sum_{k=1}^{l-1} w(k) \right)$$



The Optimal Position by WSoDS with Manhattan Distance (p=1) (3/3)

- The problem can be rewritten as follows with only one unknown variable $x'(1)$.

$$\textbf{minimize} \sum_{k=1}^{N_r} \left| x'(l) - x(l) \right| = \textbf{minimize} \sum_{k=1}^{N_r} \left| x'(1) - \Delta x(l) \right|$$

- The problem can be solved by the median concept.
  - Calculate $\Delta x_l = x(l) - \sum_{k=1}^{l-1} w(l)$ for each cell l
  - Sort the sequence $\left\{ \Delta x_l \right\}_{l=1}^{N_r}$ into $\left\{ \Delta x_l^{'} \right\}_{l=1}^{N_r}$
  - The median is

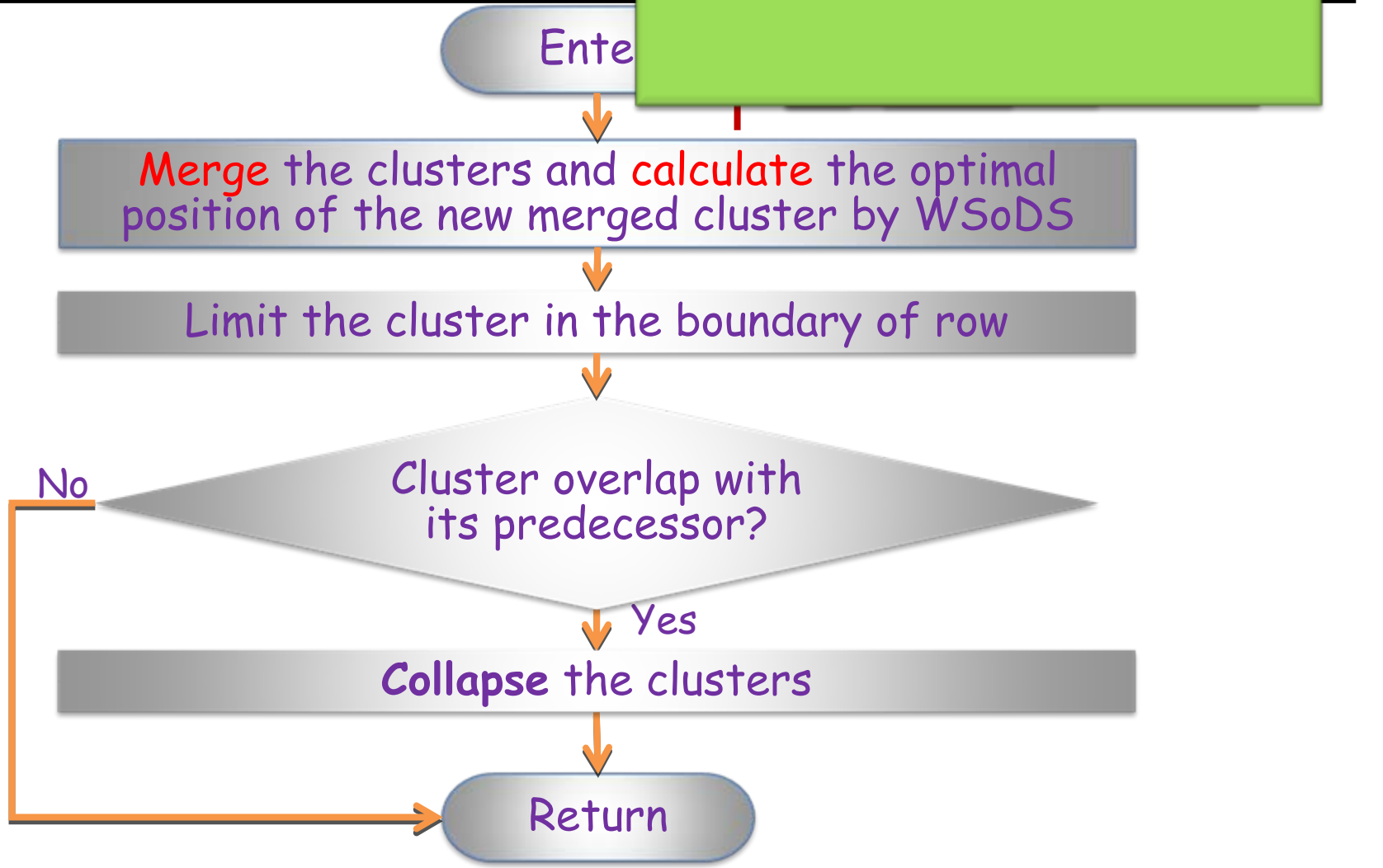
$$Q_{1/2}\left(\left\{ \Delta x_l^{'} \right\}_{l=1}^{N_r} \right) = \begin{cases} \Delta x_{(l+1)/2}^{'}, & \text{if } N_r \text{ is odd} \\ \frac{1}{2}\left(\Delta x_{l/2}^{'} + \Delta x_{l/2+1}^{'} \right), & \text{if } N_r \text{ is even} \end{cases}$$

  - Choose $Q_{1/2}\left(\left\{ \Delta x_l^{'} \right\}_{l=1}^{N_r} \right)$ as the x-coordinate position of the first cell $x'(1)$ of the cluster, and the optimal position for each cell can be obtained quickly.

$|x-1|+|x-2|+|x-3|+|x-4|+|x-5|$

Let $Q_{1/2}$ be 3

Collapse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Merge the clusters and calculate the optimal position of the new merged cluster by WSoDS
Limit the cluster in the boundary of row
Cluster overlap with its predecessor?
No
Yes
Collapse the clusters
Return

Runtime Complexity of HiBinLegalizer

- A global placement with N cells and M rows
- The chip is divided into total $B = B_x \times B_y$ bins, and assume that $B_x = B_y = (B)^{1/2}$
- The number of rows is extended to $M \times (B)^{1/2}$
- Assume that $N_r \approx N / (M\sqrt{B})$ cells in each one of these extended rows in average.
- We can conclude that

The Runtime Complexity $\approx O\left(N^2 / B\right)$

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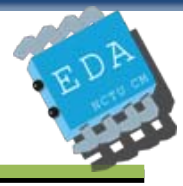
Experimental Results
- Setting

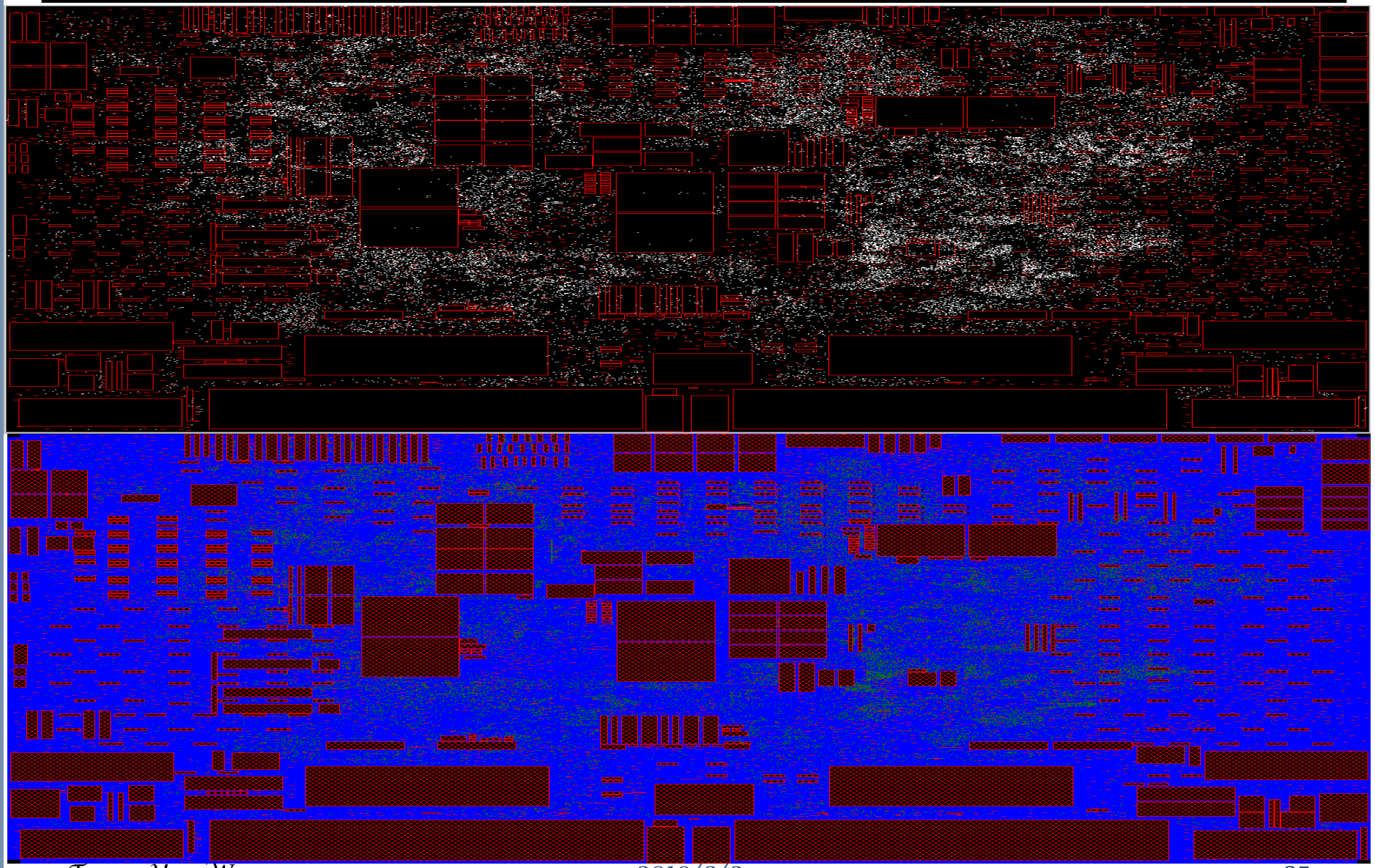
- The developed algorithm is implemented in C++ language and tested on Intel Xeon 5160 3GHz machine with 32GB memory.
- Benchmark
  - ISPD 2005 Placement Contest Benchmark Suite
  - The global placement is constructed by NTUPlace3 which is based on the log-sum-exp model.

Experimental Results
- HiBinLegalizer v.s. Abacus



2005 ISPD Placement Contest Benchmark					HiBinLegalizer					Abacus				
Circuit	Chip Width	Chip Height	#Total Objects	#Mov. Objects	Total Mov. (×e6)	Avg. Mov.	Max. Mov. (×e2)	HPWL (×e6)	Time (s)	Total Mov. (×e6)	Avg. Mov.	Max. Mov. (×e2).	HPWL (×e6)	Time (s)
adaptec1	10692	10680	211447	210904	11.07	0.29	28.10	73.19	10.4	16.80	0.45	86.45	85.61	28.6
adaptec2	14054	14040	255023	254457	28.86	0.85	73.38	86.91	11.1	28.06	0.83	134.46	100.20	33.4
adaptec3	23190	23328	451650	450927	181.48	2.60	110.08	324.52	92.4	355.13	5.08	212.53	696.96	42.9
adaptec4	23190	23328	496045	494716	55.23	0.73	69.18	211.49	45.5	120.07	1.59	218.07	358.11	79.8
bigblue1	10692	10680	278164	277604	18.70	0.44	52.39	88.49	20.8	16.96	0.40	71.60	90.76	70.1
bigblue2	18690	18792	557866	534782	34.55	0.42	37.12	150.78	43.6	56.28	0.68	127.41	202.90	93.7
bigblue4	32190	32328	2177353	2169183	866.74	3.01	145.01	1442.08	789.4	998.14	3.47	288.91	2610.36	1019.5
Comparison					***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.48***	***1.48***	***2.40***	***1.47***	***2.11***

Experimental Results
- Result of Circuit bigblue4



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Conclusion

- An efficiently hierarchical bin-based legalizer -- *HiBinLegalizer*, which minimizes the total movement of cells for minimal disturbance in placement legalization stage, has been presented and applied for standard cell designs.
- The experimental results have shown that *HiBinLegalizer* can efficiently obtain effective legalization results.

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