High-performance Routing at the Nanometer Scale

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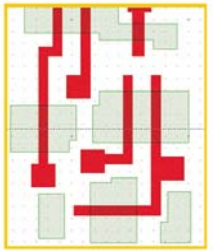
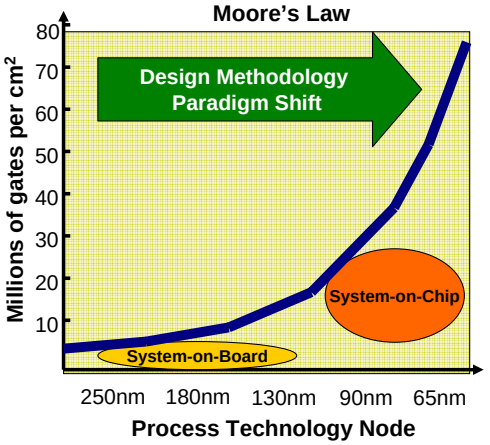
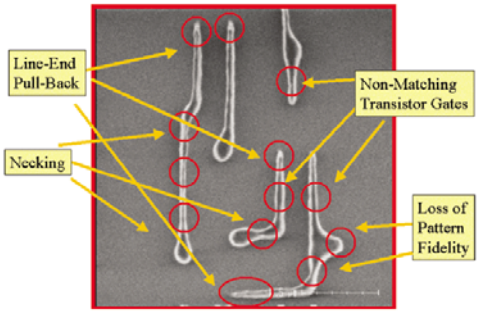
Technology Trends and Challenges

- Device density grows exponentially
- Physical effects more pronounced

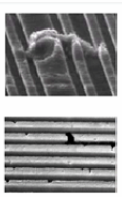


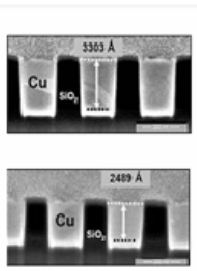


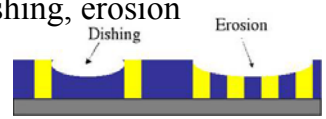


Key Physical Effects

- 180nm – wire delay comparable to gate delay
- 130nm – noise due to crosstalk
- 90nm
  - Difficulty in printing features
    - Numerous design rules introduced in routing
    - Time consuming optical proximity correction (OPC)
  - Across the die variability
  - Significant delay due to coupling capacitance
  - Leakage power
- 65nm and beyond
  - CMP : uneven wire density leads to dishing, erosion
  - Random defects, yield issues
  - Power variability







Problems with Traditional Flow

- Point tools
  - Little or no interaction
- Oversimplified objectives
  - Poorly estimate real objectives
- Delayed yield optimization
  - Consensus: yield should be optimized by *routers*
  - Cadence: *entire PD flow* must account for yield
- Numerous design iterations
  - Greater time to market ⇒ revenue loss

EE Times:
In the Eye of the DFM/DFY Storm
We Haven't Survived 65 nm - We're Just in the Eye of the Storm!
Mitch Heins, Pyxis Technology
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PRINT THIS STORY

"Summary: The Solution is in the Routing"

Introduction
The phrase "eye of the storm" refers to the relatively calm center of a hurricane, where winds are light and the skies are only slightly cloudy, or even clear. If the eye of the hurricane passes over during the daytime, one might see sunny skies and even enjoy a rise in temperature. Observers sometimes

Our Strategy

- Identify simple but effective algorithms for routing
  - Start with global routing (easier)
- Develop flexible open-source infrastructure that will support algorithm extensions
- Identify DFM-related objectives & constraints relevant to global and detail routing
- Incorporate DFM concerns into routing

Our Contributions So Far

- FGR – "Fairly Good Router" (ICCAD `07)
  - Routing based on Lagrange Multipliers
  - Extend A*-search to reshape net topology
- Best known results on ISPD'98 & ISPD'07 routing benchmark suites
- Extended empirical evaluation
  - Steiner trees vs. MSTs for net decomposition
  - Layer assignment for multi-layer routing

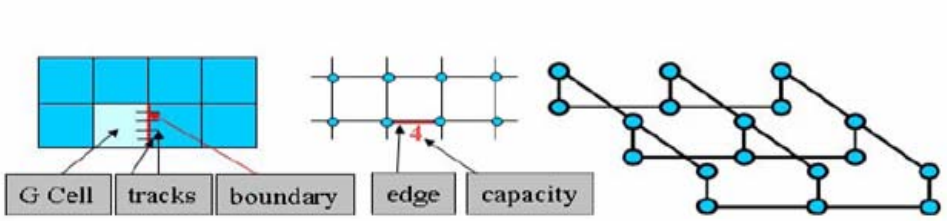
Review: Lagrange Relaxation

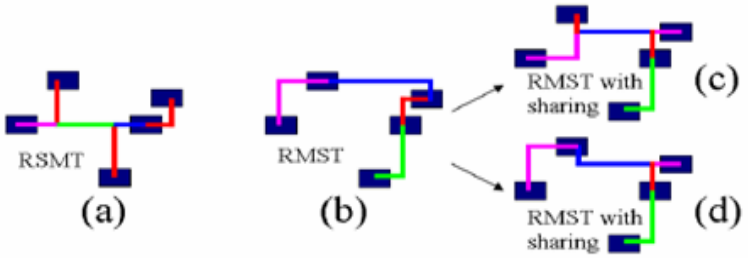
- Start with: *optimization problem with constraints*
- Convert constraints to penalties
- Add penalties to original objective
  - New variable for each penalty: *Lagrange multiplier*
- Optimizing new objective solves original problem
  - New problem is easier to solve
  - Continuous case
    - Solve with Newton's method, steepest decent, etc.
  - Discrete case
    - Iterative techniques such as RRR

Analogy

- Land prices in downtown
  - Many businesses want offices in downtown (competition)
  - Some businesses could move further
- Solution: auction
  - Start with initial price & solicit bids
  - Increase price until only one bidder remains
- Rationale: **encourage efficient use of land**

Review of Global Routing





Discrete Lagrange Multipliers (DLM) in Routing

Total Wirelength

$$\min_{\mathbf{x}\in X} W(\mathbf{x})$$

$$\text{subject to } C_e(\mathbf{x}) = 0, \quad 1 \le e \le n$$

Net Routed Length

Capacity Violations

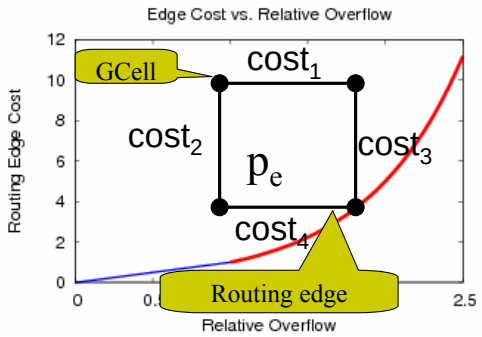
$$W(\mathbf{x}) = \sum_{i=1}^{m} R_i(\mathbf{x}) = \sum_{e=1}^{n} B_e(\mathbf{x}) = \sum_{e=1}^{n} \left(\sum_{\text{net } i \text{ uses } e} b_e \right)$$

$$F(\mathbf{x}, \lambda) = \sum_{e=1}^{n} (B_e(\mathbf{x}) + \lambda_e C_e(\mathbf{x}))$$

DLM Formulation

$$F(\mathbf{x}, \lambda) = \sum_{e=1}^{n} (B_e(\mathbf{x}) + \lambda_e C_e(\mathbf{x}))$$

- Cost per routing edge: $cost_e = b_e + h_e \cdot p_e$
  - b_e : base edge cost
  - h_e : historical congestion cost
    - Incremented for congested edges <u>at each iteration</u>
  - p_e : current congestion penalty
- Key diff w.r.t. NCR
  - $NCRcost_e = h_e (b_e + p_e)$
- Use A*-search to route

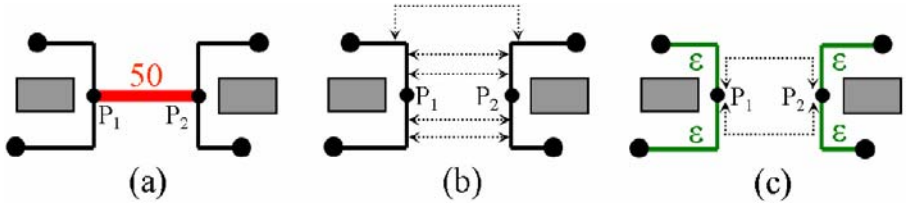


Multi-pin Nets

- Maze search connects pin pairs
  - Nets with 3 or more pins must be decomposed
- Standard decomposition methods
  - Steiner tree
    - If optimal, shortest possible wirelength
  - Minimum spanning tree
    - Up to 50% more wirelength than Steiner
    - Simple construction: easy to consider congestion
- We compare both options
  - Steiner trees lead to fewer routing segments, more vias

Topology Restructuring in Maze Search

- Static decompositions cannot react to congestion
  - Steiner points may become congested
- We reshape the tree during rerouting
  - Steiner points will change
  - Initial MSTs will become Steiner trees
- Modify routing edge weights in A*
  - Previously-used segments cost ε, a small value



2-d vs. Multi-layer Routing

- Maze routing can handle arbitrary grids
  - No theoretical limits on number of layers
  - Practically, only 2 layers are needed: H & V
- To route multi-layer as 2-d:
  - Combine H & V capacities for each GCell
  - Route along the induced 2-d grid
  - Convert the 2-d soln. by layer assignment
- 2-d routing + layer assignment faster, more successful
  - When multi-layer succeeds, better soln. quality

Summary of Empirical Results

- **ISPD'98 benchmarks** (no vias)
  - 12k - 64k nets, 64x64 - 256x64 GCells, 1 layer
  - Violation free (unmatched in literature)
  - 2.7% better WL than FastRoute
  - 3.6% better WL than BoxRouter, 35% less runtime
- **ISPD'07 contest benchmarks**
  - 220k - 860k nets, 324x324 - 973x1256 GCells
  - 2-d : 2 layers, 3-d : 6 layers
  - 8.4% better WL than MaizeRouter (1st 3-d, 2nd 2-d)
  - 9.9% better WL than BoxRouter (2nd 3-d, 3rd 2-d)

Results for ISPD'98 benchmarks

- Comparison to published results for BoxRouter and FastRoute 2.0
- FGR is 35% faster than BoxRouter

Bench-mark	BoxRouter ovfl	BoxRouter WL	FastRoute 2.0 ovfl	FastRoute 2.0 WL	FGR ovfl	FGR WL	vs. Box-Router	vs. Fast-Route 2.0
ibm01	**102**	65588	**31**	68489	0	**63332**	-3.44%	-7.53%
ibm02	**33**	178759	0	178868	0	**168918**	-5.51%	-5.56%
ibm03	0	151299	0	150393	0	**146412**	-3.23%	-2.65%
ibm04	**309**	173289	**64**	175037	0	**167101**	-3.57%	-4.53%
ibm05	0	409747	–	–	0	**409739**	-0.00%	–
ibm06	0	282325	0	284935	0	**277608**	-1.67%	-2.57%
ibm07	**53**	378876	0	375185	0	**366180**	-3.35%	-2.40%
ibm08	0	415025	0	411703	0	**404714**	-2.48%	-1.70%
ibm09	0	418615	**3**	424949	0	**413053**	-1.33%	-2.80%
ibm10	0	593186	0	595622	0	**578795**	-2.43%	-2.83%
Average							**-2.71%**	**-3.64%**

ISPD'07 Contest Benchmarks

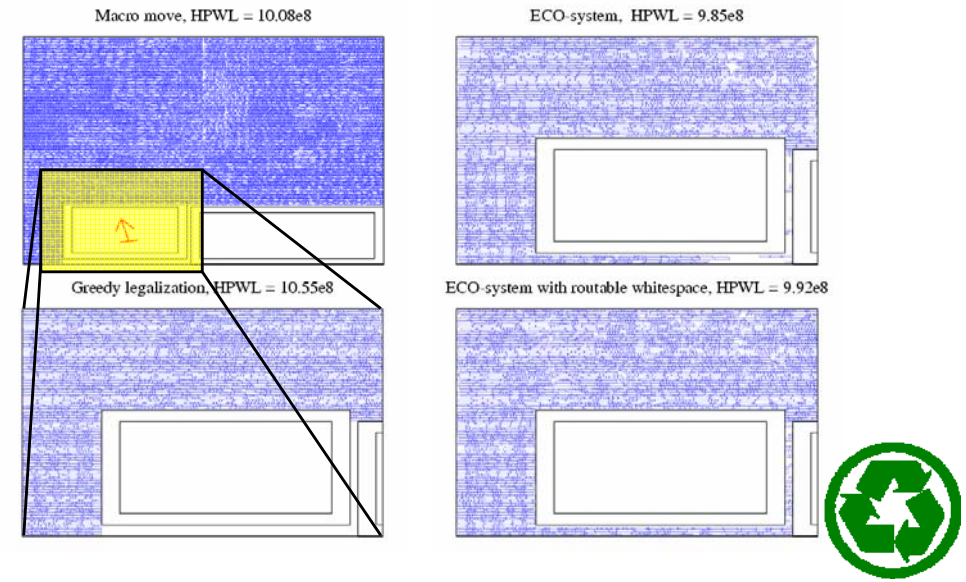
- Best competition: BoxRouter & MaizeRouter

Bench-mark		Best of BoxRouter and MaizeRouter Overflow total	Overflow max	Cost (e5)	Router	FGR Overflow total	Overflow max	Cost (e5)	vs. Best
adaptec	#1 2-d	0	0	58.84	Box	0	0	**54.44**	-7.48%
	#1 3-d	0	0	99.61	Maize	0	0	**88.45**	-11.20%
	#2 2-d	0	0	55.69	Box	0	0	**52.30**	-6.09%
	#2 3-d	0	0	98.12	Maize	0	0	**89.89**	-8.39%
	#3 2-d	0	0	137.75	Maize	0	0	**130.89**	-4.98%
	#3 3-d	0	0	214.08	Maize	0	0	**199.66**	-6.74%
	#4 2-d	0	0	128.45	Maize	0	0	**125.00**	-2.69%
	#4 3-d	0	0	194.38	Maize	0	0	**179.36***	-7.73%
	#5 2-d	0	0	164.32	Box	0	0	**152.13**	-7.42%
	#5 3-d	0	0	298.08	Box	0	0	**259.98**	-12.78%
newblue	#1 2-d	400	2	51.13	Box	526	4	**47.42**	-7.26%
	#1 3-d	400	2	101.83	Box	514	2	**94.26**	-7.43%
	#2 2-d	0	0	79.64	Maize	0	0	**76.51**	-3.93%
	#2 3-d	0	0	139.66	Maize	0	0	**129.40***	-7.35%
	#3 2-d	32588	1236	114.63	Maize	39908	1120	**109.23**	-4.71%
	#3 3-d	32840	1058	184.40	Maize	39828	374	**173.71**	-5.80%
Average									**-7.03%**

Applications of Our Algorithms & SW

- Incremental routing
- Detail routing
- Integrated place-and-route
- DFM-aware global and detail routing
- An open-source RTL-to-GDSII tool-chain

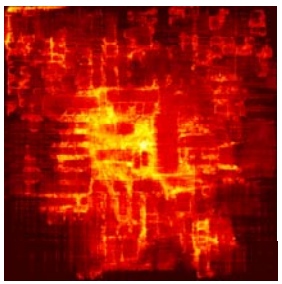
Illustration: ECO Placement



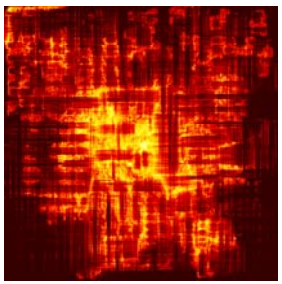
Integrated Place-and-Route

- FGR initial routing
  - Many times faster than full routing
  - Congestion and WL very similar to final solution
- Use these maps in **ROOSTER** (our placer)

FGR initial routing

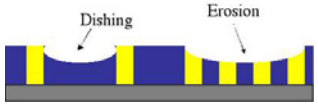


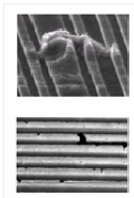
FGR final routing



Yield- and Manufacturability-driven Routing

- Model-based routing
- Minimization of vias
  - Major source of timing, variability problems
  - Doubling often needed to improve yield
- Density constraints
  - Affect capacitance, crosstalk, CMP





Open-source Tool-chain

- From CANDE 2005 predictions for 2010
  - An open-source RTL-to-GDSII tool-chain will be available
- Currently available tools
  - Synthesis & technology mapping (ABC, OAGear)
  - Verification (MiniSAT, CUDD, OAGear)
  - ATPG (ATALANTA)
  - Partitioning, floorplanning & placement (UMPack)
- Missing
  - Full-chip routing
  - Clock-tree synthesis

Summary

- Routing is key to DFM
  - Must be flexible to accommodate DFM concerns
  - Must use simple algorithms
- FGR framework – Lagrange multipliers
  - Unmatched solution quality
  - Extensions for yield and manufacturability
- Integrated P&R
- DFM-aware routing
- Open source tools – FGR release @ICCAD`07

References

- J. A. Roy and I. L. Markov, "High-performance Routing at the Nanometer Scale", ICCAD 2007
- J. A. Roy and I. L. Markov, "ECO-system: Embracing the Change in Placement", to appear in *IEEE Trans. on CAD*, 2008
- J. A. Roy and I. L. Markov, "Seeing the Forest and the Trees: Steiner Wirelength Optimization in Placement", *IEEE Trans. on CAD*, vol. 26 no. 4, pp. 632-644, April 2007