The Coming of Age of (Academic) Global Routing

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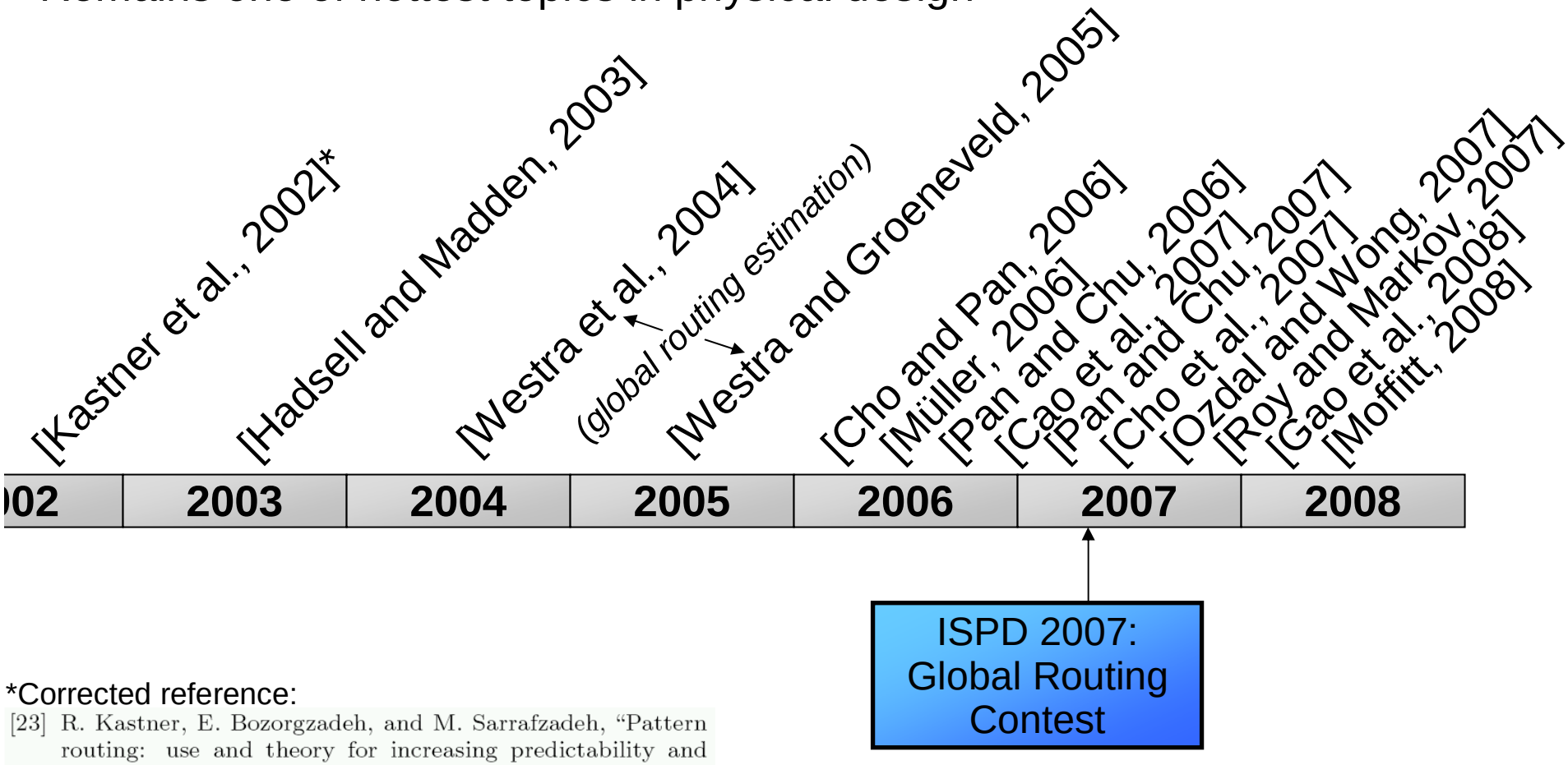
Color copy of paper available @
`http://www.eecs.umich.edu/~mmoffitt/papers/moffitt_ispd2008.pdf`

A Brief Timeline of "Modern" Global Routing

Original formulation proposed over quarter-century ago *[Nair et al., DAC 1982]*

Remains one of hottest topics in physical design



*Corrected reference:

[23] R. Kastner, E. Bozorgzadeh, and M. Sarrafzadeh, "Pattern routing: use and theory for increasing predictability and avoiding coupling," in *TCAD*, vol. 21, no. 7, pp. 777–790, 2002.

ISPD 2007 Routing Contest: Logistics

(from last year's contest overview)

- Open contest primarily for academic community
  - **17 teams registered; 11 final entries**
  - **8 new global routing benchmarks released**
  - **Benchmarks derived from ISPD 2005/2006 placement solutions**
- Contestants had ~ 2 weeks to run their global router on benchmarks
- Quality metrics
  - **Primary criteria: minimize overflows**
  - **Secondary criteria: minimize wirelength**
  - **No CPU time limits**

ISPD 2007 Routing Contest: Benchmarks

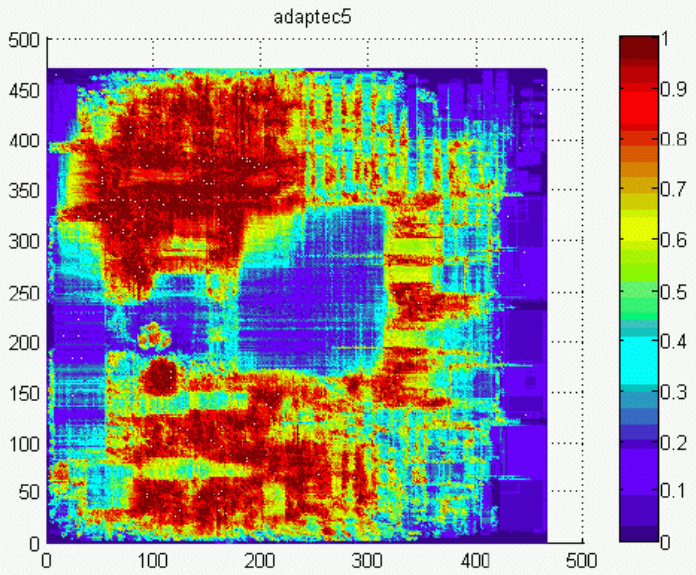
name	nets	grids	v. cap	h. cap
adaptec1	219794	324 × 324	70	70
adaptec2	260159	424 × 424	80	80
adaptec3	466295	774 × 779	62	62
adaptec4	515304	774 × 779	62	62
adaptec5	867411	465 × 468	110	110
newblue1	331663	399 × 399	62	62
newblue2	463213	557 × 463	110	110
newblue3	551667	973 × 1256	80	80

- Community in desperate need of these
  - **Previous ISPD ’98 benchmarks have 10x less nets, 75x less g-cells, are flat, and (as of `07) are trivially routable**
  - **Artificial reduction of capacity can make those harder, but not nearly as relevant as true modern designs**

ISPD 2007 Routing Contest: An Example

adaptec5.mfar50.3d.50.20.100.gr

	Total OV	Max OV	WL
BoxRouter	0	0	298.08
MaizeRouter	2	2	305.32
FGR	2480	2	264.58
FastRouter	9894	76	707.86
NTHU-R(3)	20632	10	504.97
FlexRouter	21802	26	336.09
Bockenem	98950	20	575.76
NTU2-R(13)	120602	16	718.64
NTU1-R(9)	208804	48	556.45



ISPD 2007 Routing Contest: Final Rankings

3D Track

Place	Router
1st	MaizeRouter
2nd	BoxRouter 2.0
3rd	FGR
4th	FastRoute
5th	NTHU-R(3)
6th	FlexRouter
7th	Bockenem
8th	NTU1-R(9)
9th	NTU2-R(13)

2D Track

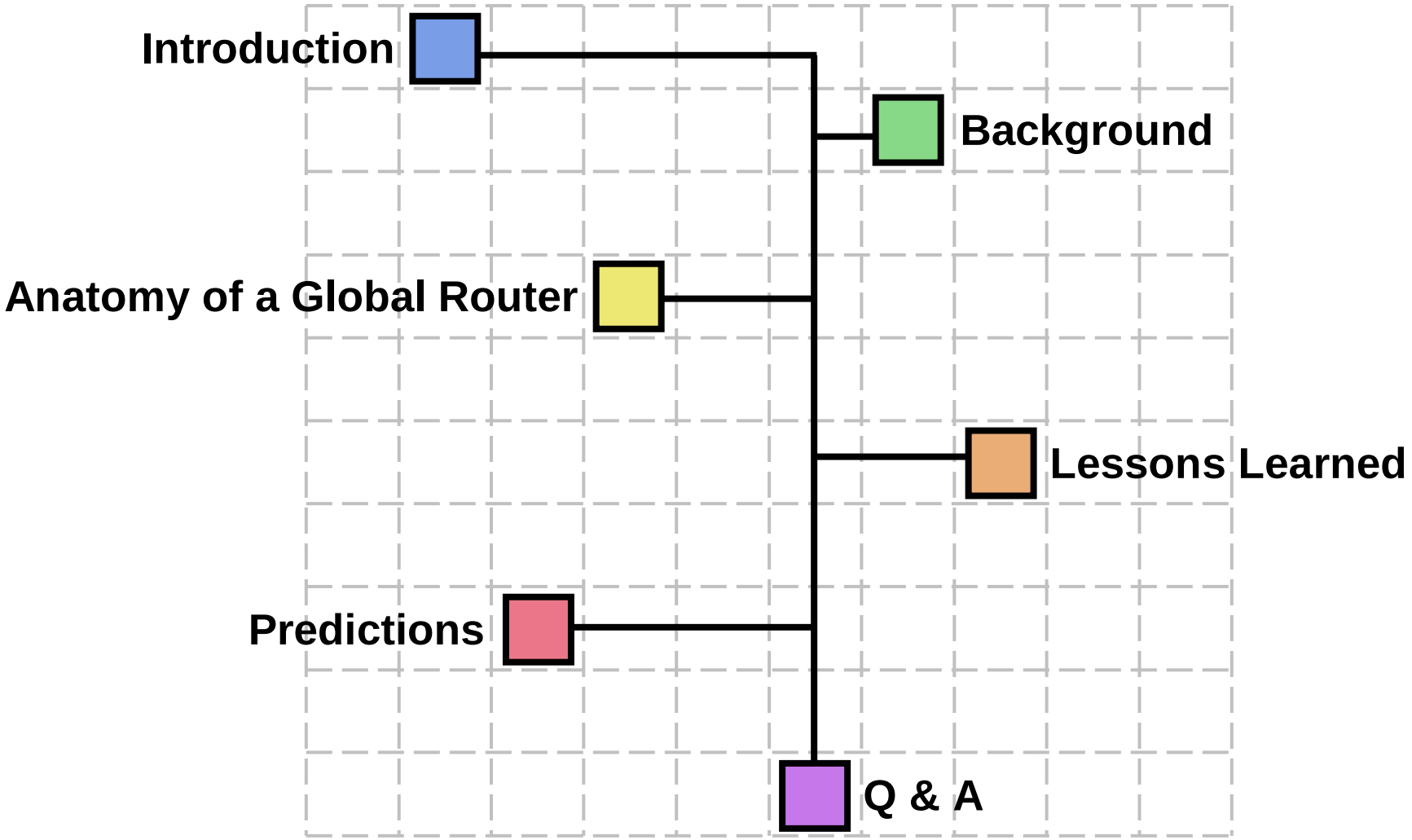
Place	Router
1st	FGR
2nd	MaizeRouter
3rd	BoxRouter 2.0
4th	FastRoute
5th	NTHU-R(3)
6th	Bockenem
7th	NTCU-R(10)
8th	FlexRouter
9th	NTU2-R(13)

- **Winners far less important than ideas…**

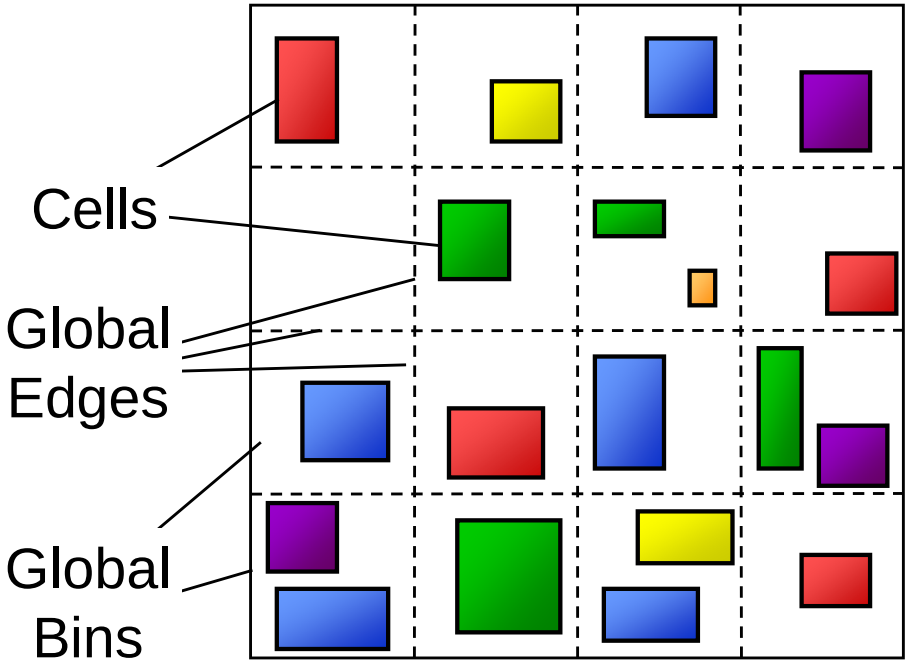
Global Routing's "Coming of Age"

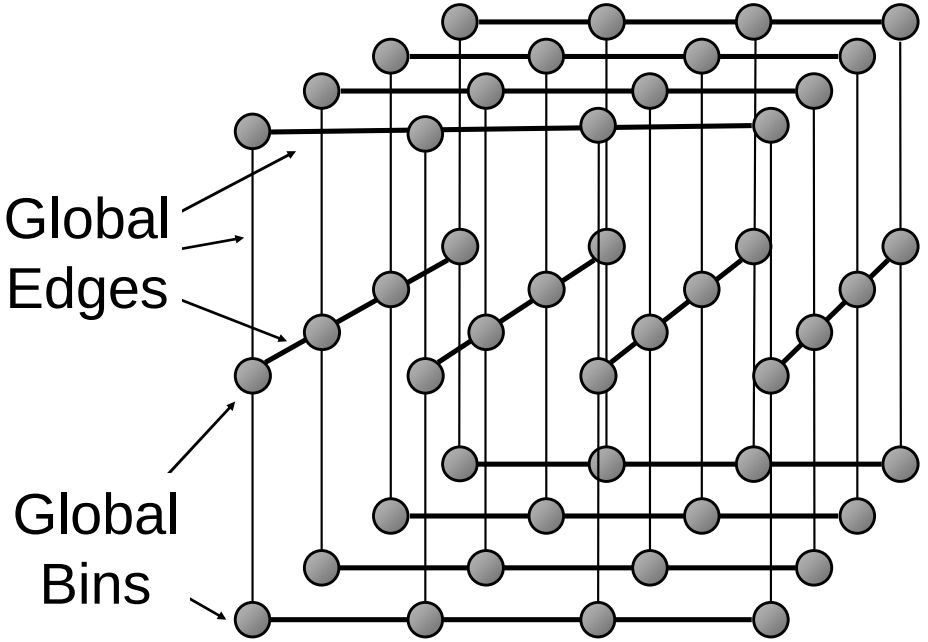
- **Reviews of global routing to date**
  - "*A survey on multi-net global routing for integrated circuits*" [Hu and Sapatnekar, 2001]
  - "*Electronic Design Automation for Integrated Circuits Handbook (Chapter 8, Routing)*" [Scheffer et al., 2006]
- **Over past year, community has witnessed emergence of new "conventional wisdom"**
- **Our objectives:**
  - Address key similarities / differences / common themes
  - Touch on lessons learned
  - Extrapolate predictions from current trends in the field

Outline of Talk



Global Routing: Problem Formulation





- **Fundamental problem in VLSI**
  - Little more than afterthought many years ago [Alpert et al., `07]
  - Rapidly becoming a bottleneck in the physical design flow

Global Routing: Basic Algorithms

- **Maze Routing**
  - Optimal for 2-pin nets and any monotonic cost function
  - Commonly considered “brute force” approach
- **Pattern Routing [Kastner et al., 2002]**
  - Explores ‘L’ and ‘Z’ shapes to improve efficiency
- **Ripup-and-Reroute**
  - Iteratively selects nets to tear down and reconstruct
- **Multicommodity Flows [Albrecht, 2001]**
  - Viewed by many as “exotic”, although not fundamentally dissimilar than Ripup-and-Reroute

Global Routing: Full Routing Engines

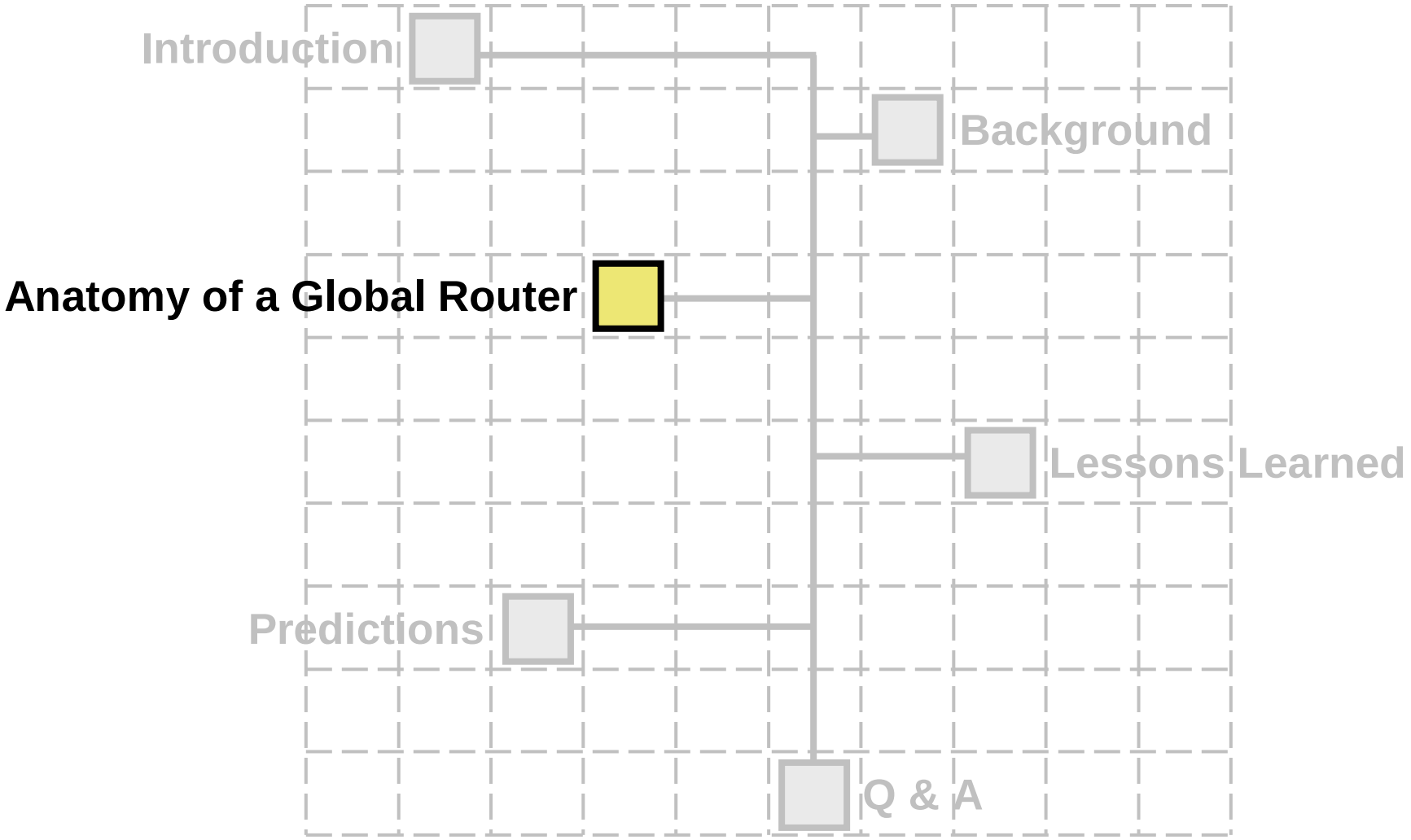
- **Labyrinth [Kastner et al., 2002]** … predictable / pattern routing
- **Chi [Hadsell and Maddel, 2003]** … R&R with congestion amplification
- **FastRoute [Pan and Chu, 2006] and FastRoute 2.0 [Pan and Chu, 2007]** … edge shifting, multi-source multi-sink
- **DpRouter [Cao et al., `07]** … dynamic pattern routing and segment-move technique
- **BoxRouter [Cho and Pan, 2006] and BoxRouter 2.0 [Cho et al., 2007]** … ILP formulation, box expansion, historical cost functions
- **Archer [Ozdal and Wong, 2007]** … spectrum of point-to-point techniques, historical cost functions
- **FGR [Roy and Markov, 2007]** … negotiated-congestion routing, ε-based A*, MST-based initialization
- **MaizeRouter [Moffitt, 2008]** … edge-based operations, garbage collection, interdependent net decomposition
- **NTHU-Route [Gao et al., 2008]** … history-based cost function, adaptive multi-source multi-sink ripup

Global Routing: Feature Matrix

	Labyrinth [23]	*Chi* [17]	*BoxRouter* [11]	Müller [29]	*FastRoute* [33]	*FastRoute* 2.0 [34]	*DpRouter* [5]	*Archer* [32]	*BoxRouter* 2.0 [10]	FGR [36]	MAIZEROUTER [28]	*NTHU-Route* [15]
Pattern routing	✓		✓		✓	✓	✓	✓	✓		✓	✓
Monotonic routing						✓	✓	✓				✓
Maze routing	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
A*-search								✓	✓	✓	✓	
FLUTE dependence			✓		✓	✓	✓	✓	✓		✓	✓
Topo reconstruct.					✓	✓	✓	✓		✓	✓	✓
Incrementality								✓	✓	✓	✓	
Edge "sliding"						✓			✓		✓	
Resource sharing					✓	✓				✓	✓	
ILP or MCF			✓	✓					✓			
Congestion manip.		✓			✓	✓	✓	✓		✓	✓	✓
History-based								✓	✓	✓		✓
Layer assignment				✓				✓	✓	✓	✓	✓
Open source	✓								✓	✓	✓	

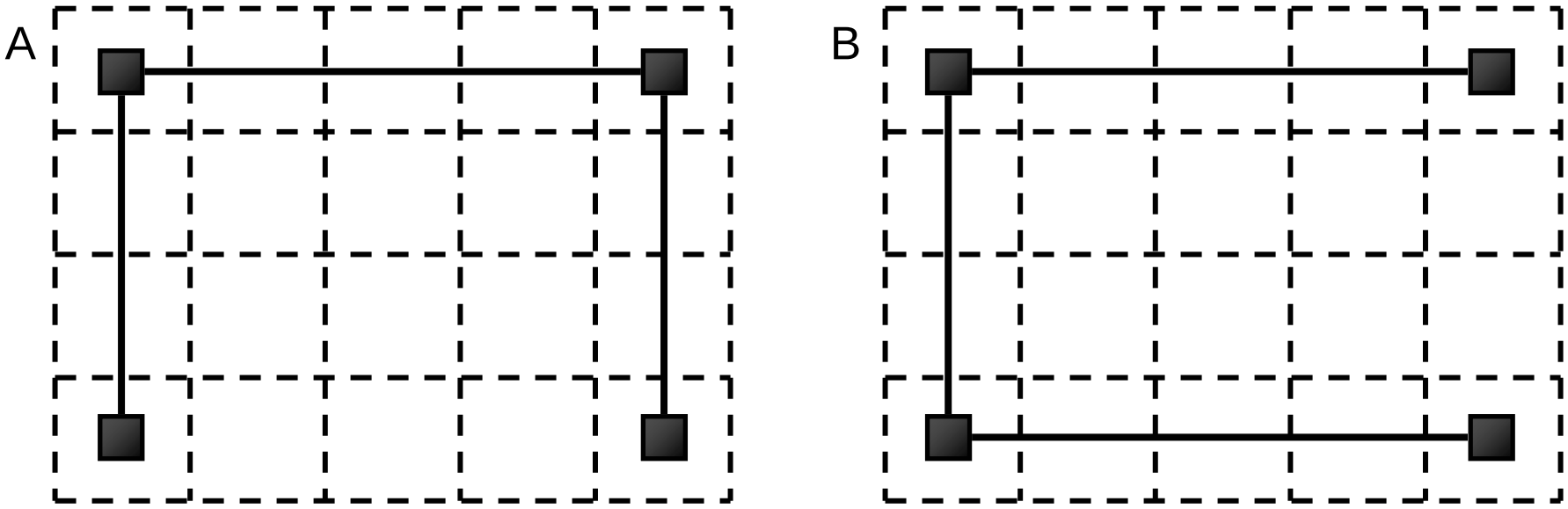
Post-ISPD'07 global routers

Outline of Talk



Single-net Tree-topology Generation

- **FLUTE [Chu and Wong, 2008] extremely popular**
  - Used in virtually every academic router since 2004 (except FGR)
  - Produces optimal Steiner trees for up to 9-pin nets… very fast
- **Problem #1: Assumes 2D routing grid (even if # of bends could be minimized, not good enough)**



- **Preferred direction Steiner trees can help [Yildiz and Madden, TCAD 2002] if made efficient**

Single-net Tree-topology Generation

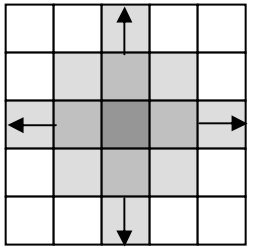
- **Problem #2: Congestion-driven routers operate on routing grids with non-uniform costs**
  - Possibly from congestion manipulation or amplification
  - Possibly from historical factors (e.g., Lagrange multipliers)
  - Hence, Hanan theorem inapplicable
- **Minimum Spanning Trees (MSTs) offer some relief**
  - Optimize arbitrary cost functions
  - Can adapt to congestion encountered dynamically during R&R
  - Relatively easy to implement
- **Obstacle-avoiding Trees are clearly relevant as well**
- **Bottom line:** *standalone constructors must be validated by direct improvements to a complete routing flow*

History-Based Cost Functions

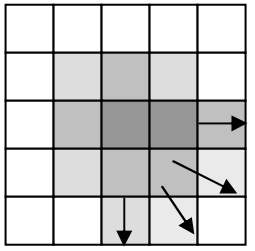
- **Negotiated-congestion routing (NCR) the latest trend in global routing**
  - PathFinder first to use in context FPGAs [McMurchie and Ebeling, 1995]
  - Basic idea: increase cost of resources in high-demand
  - Used in Archer, BoxRouter 2.0, FGR, and NTHU-Route
- **MAIZEROUTER an exception… does not use NCR**
  - Though it *does* manipulate a global cost function over time
  - Less precise than full NCR, but can reduce memory by 2x
- **Why has it taken over a decade to be adopted by academic global routers?**

One possible theory…

- **Purely wirelength-based cost functions are easy**
  - Simple linear-time BFS search suffices
  - Requires basic queue



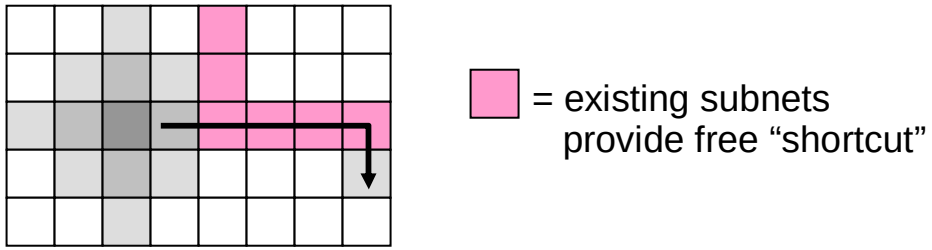
- **NCR imposes non-uniform cost functions**
  - Dijkstra's algorithm (or A*) a must-have
  - Requires heap or priority queue



- **Standard Template Library (STL)**
  - Provides out-of-the-box **`priority_queue`** template
  - Traditionally not covered in Computer Science curriculum
  - Academic researchers may be unwilling (or unable) to create own homebrew implementations

Methodologies for Resource Sharing

- **Shortest-path algorithms optimal for 2-pin nets**
- **What do to for higher-degrees?**
  - Decomposition: split into 2-pin sibling nets
  - Routing these subnets independently is a bad idea
- **Gradual adoption of more intelligent strategies**
  - *FastRoute* uses edge-shifting to leverage neighboring wires
  - FGR's ε-based A* embeds such checks into maze routing, as does MaizeRouter

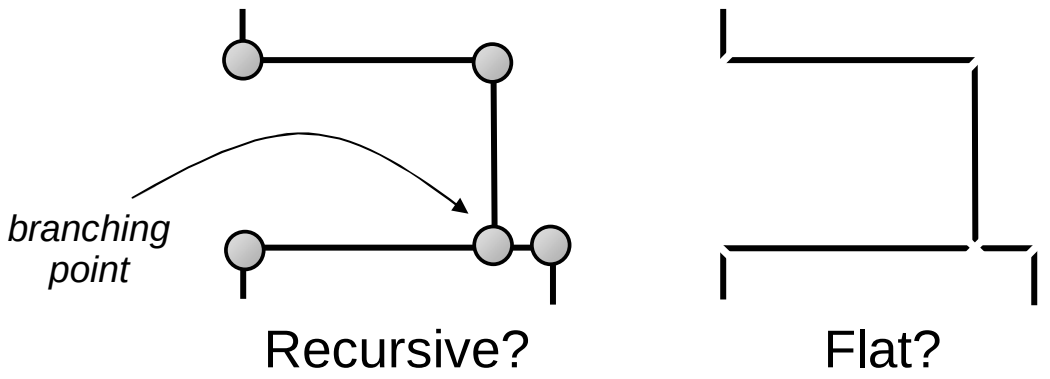


  - Obviates need for more complicated and specialized approaches (e.g., multi-source multi-sink techniques)

Internal Models & Incremental Maintenance

- **Reconstructing entire nets from scratch expensive**
  - *Impractical* for routers that perform net-by-net ripup-and-reroute
  - *Impossible* for routers that focus exclusively on individual segments

- **Specific architectural frameworks not well-described in literature**
  - Not sexy enough?
  - Few gimmicks
  - Reviewers may not be impressed



- **Open-source push helps answer some of these questions**

Resource Recovery

- **Global a routing multi-criteria optimization problem**
- ***But*…**
  - For routable instances, chief objective (overflow) is 0
  - In such cases, reduces to mono-criterion optimization

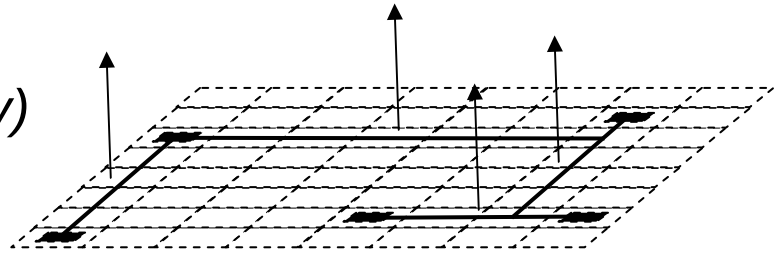
- **Many routers exploit this during post-processing**
  - BoxRouter has *PostRouting* step… maze routing for WL only
  - MaizeRouter has *edge retraction* (not limited to end-game)
  - FGR's full-3D repair (performed once @ end by default)

- **When & how often such recovery should be performed is poorly understood**

Layer Assignment

- **All routers published in past six months are 3-dimensional**
  - Academics arrived late to the party… purely 2D flows referred to as "*degenerate*" in 2005 [Westra and Groeneveld]
- **2007 contest closed the door on flat routing engines**
- **Projection-based approaches currently dominant**

(∞ via capacity)

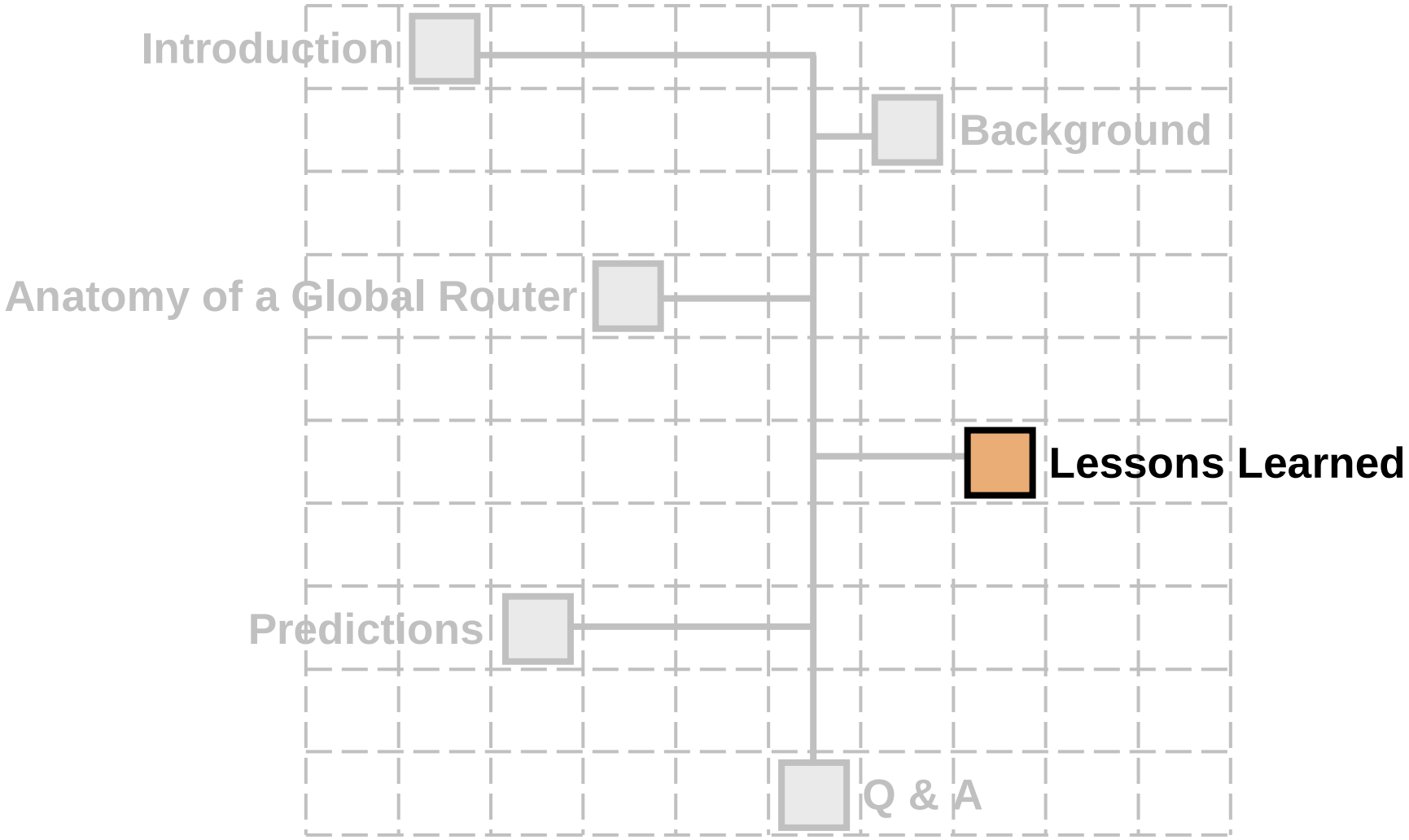


- **No strategies for varying routing pitches and wire sizes**
  - Represents a significant disconnect from true physical models
  - Presents attractive challenge for future research

Layer Assignment

- **Cost of vias changes the game**
  - 3x the cost of a normal routing segment
  - Commonly **50% of cost** in solutions to 2007 benchmarks
- **Possible to consider "mix" between 2D / 3D flows**
  - *Via aware* maze routing operates on single pair of horizontal and vertical layers
  - True via cost (or inflated cost) can be tracked explicitly
  - Drawbacks: memory increase, # node expansions increases

Outline of Talk



Research in Routing vs. Placement

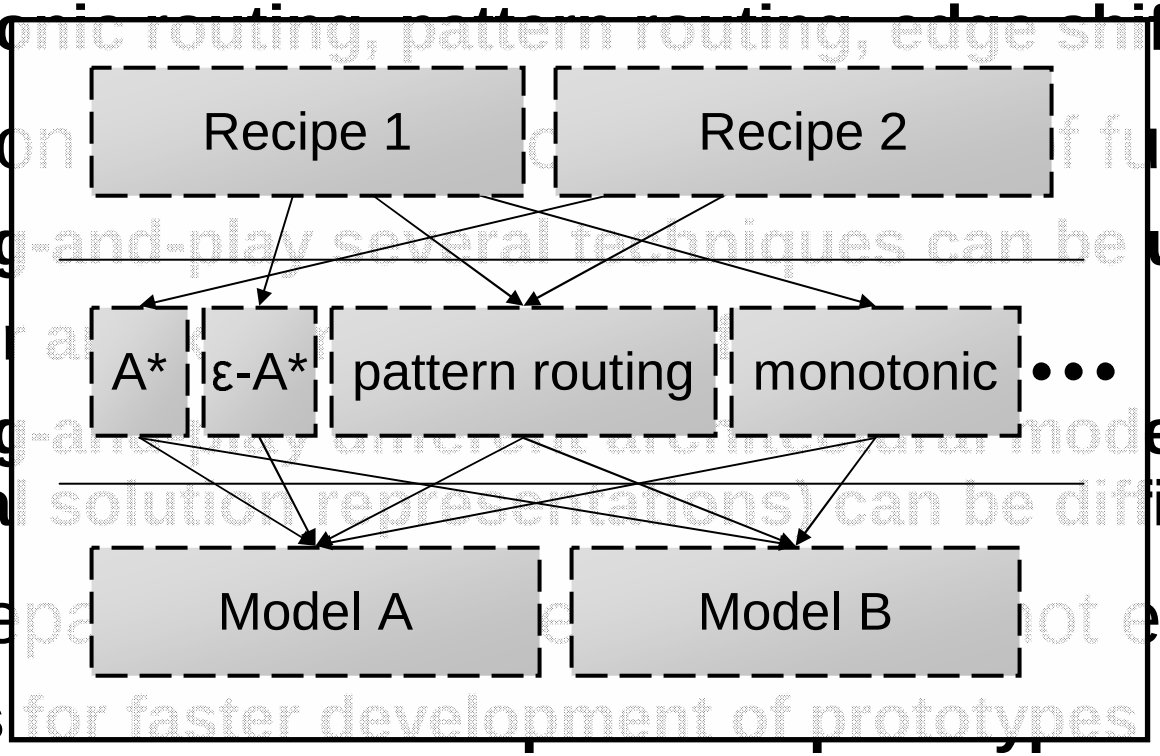
- Effort to build successful router different than successful placer
  - **Relatively fewer successful algorithmic frameworks**
  - **Amount of code needed is relatively small**

Global Router	Lines of Code	*FLUTE*	ILP
BoxRouter 2.0 [48]	12,986	✓	✓
Labyrinth [44]	6,556		
FGR 1.0 [49]	3,621		
MAIZEROUTER [50]	2,048	✓	

- Similarities between trends in progress for both problems
  - **Literature published before a concerted benchmarking effort inconclusive**
  - **Focus on modern benchmark suite with a clear objective ensures trustworthy evaluation**

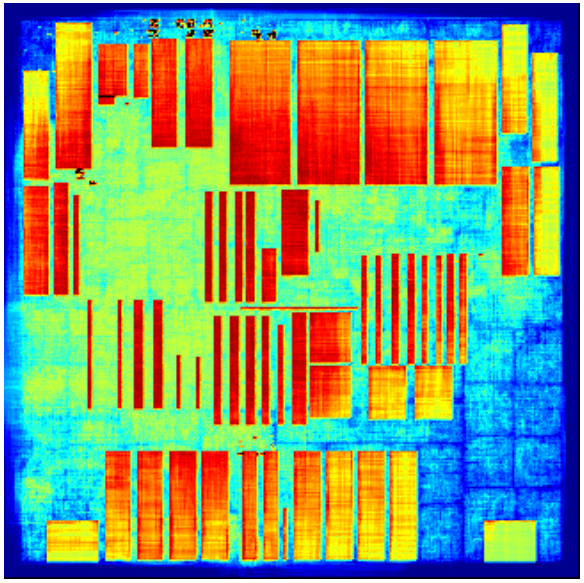
Ingredients vs. Recipes

- Veritable “tool box” of individual techniques exists
  - **monotonic routing, pattern routing, edge shifting, etc.**
- Interaction of full recipe
  - **To plug-and-play several techniques can be useful (Archer a**
  - **To plug-and-play different architectural models (e.g., internal solution representations) can be difficult**
- Clean separation not easy, but:
  - **Allows for faster development of prototypes**
  - **Enables an open standard for routing technology**

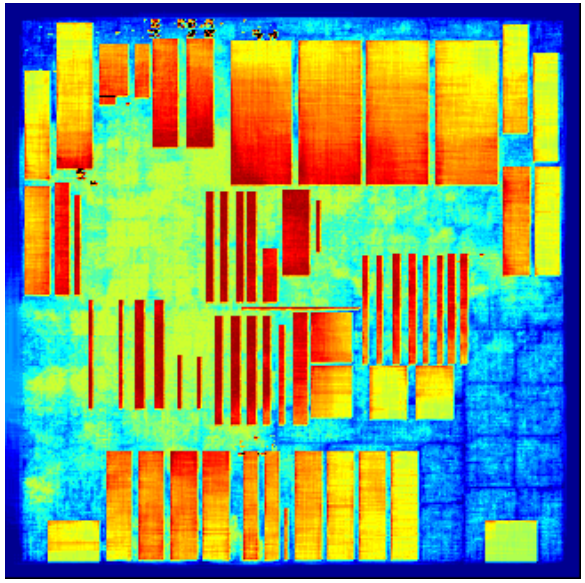


Evaluation of Routing Solutions

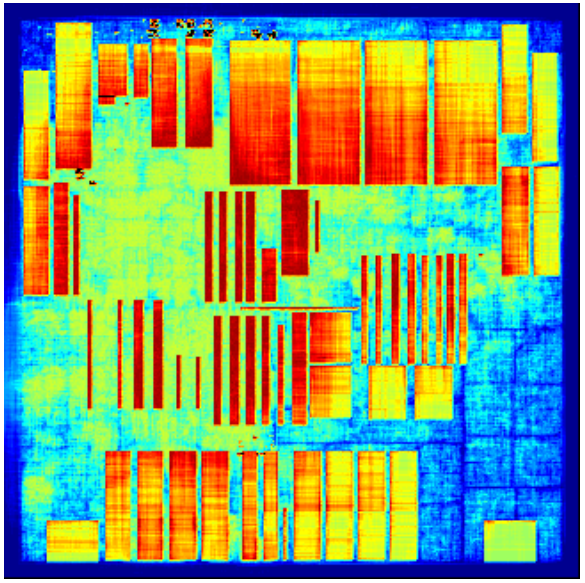
- Scalar metrics reflect small amount of information
  - **Of course, routability / overflow is critical**
- Congestion maps useful for identifying problem areas



MAIZEROUTER

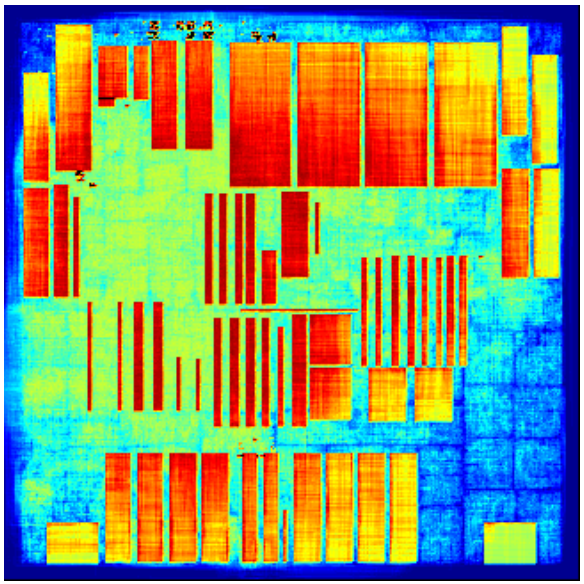


FGR



BoxRouter 2.0

Routing Utilization Difference Maps



MAIZEROUTER

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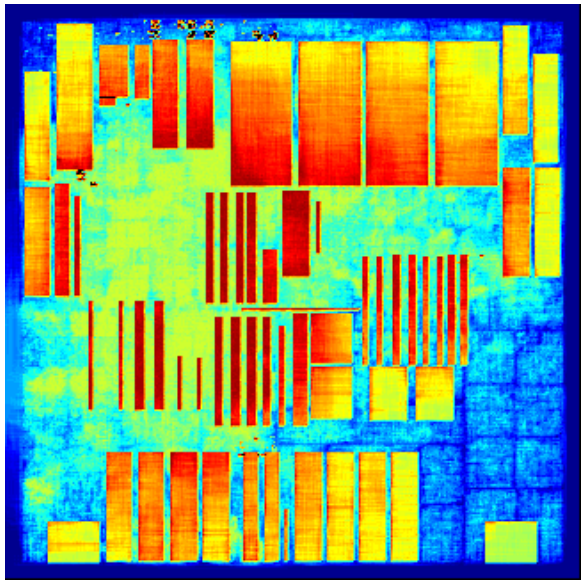

FGR

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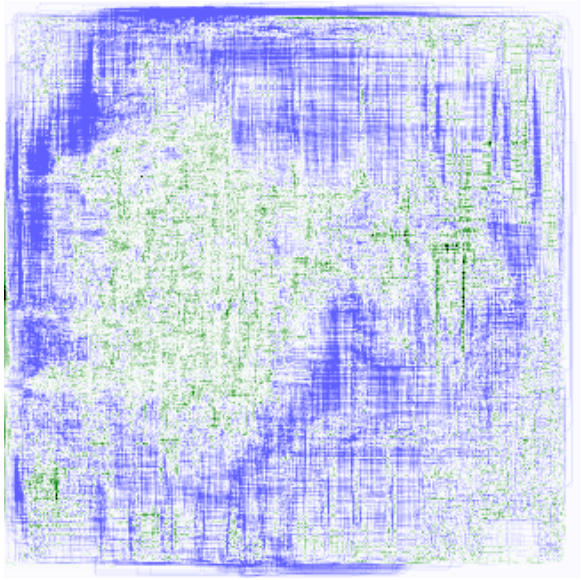

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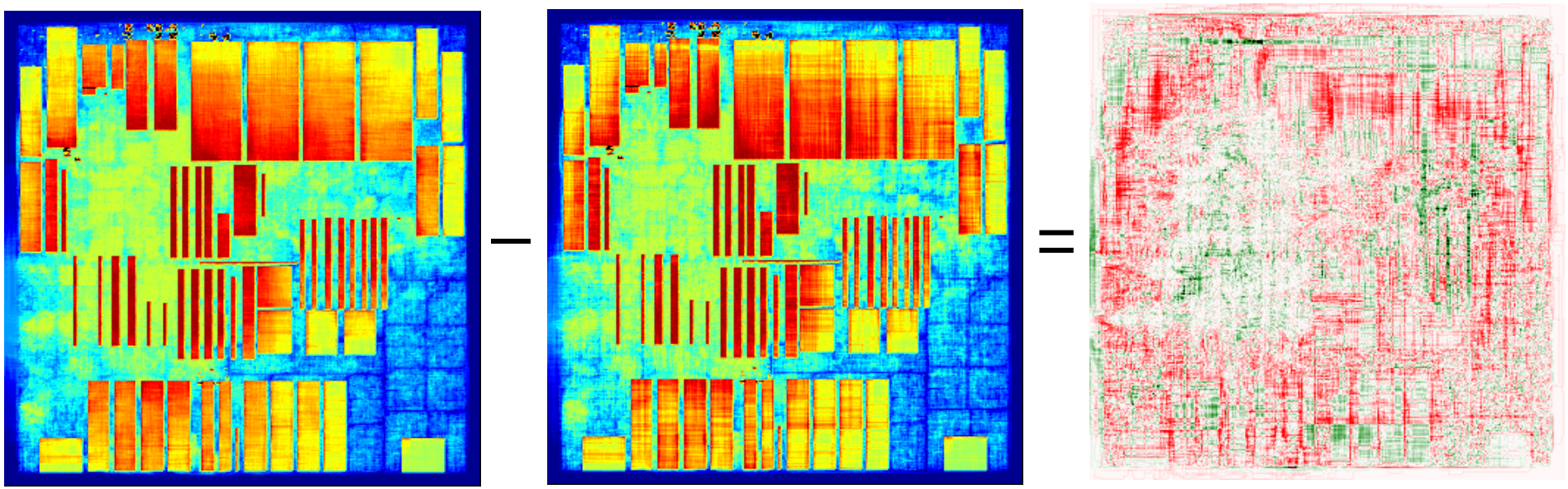

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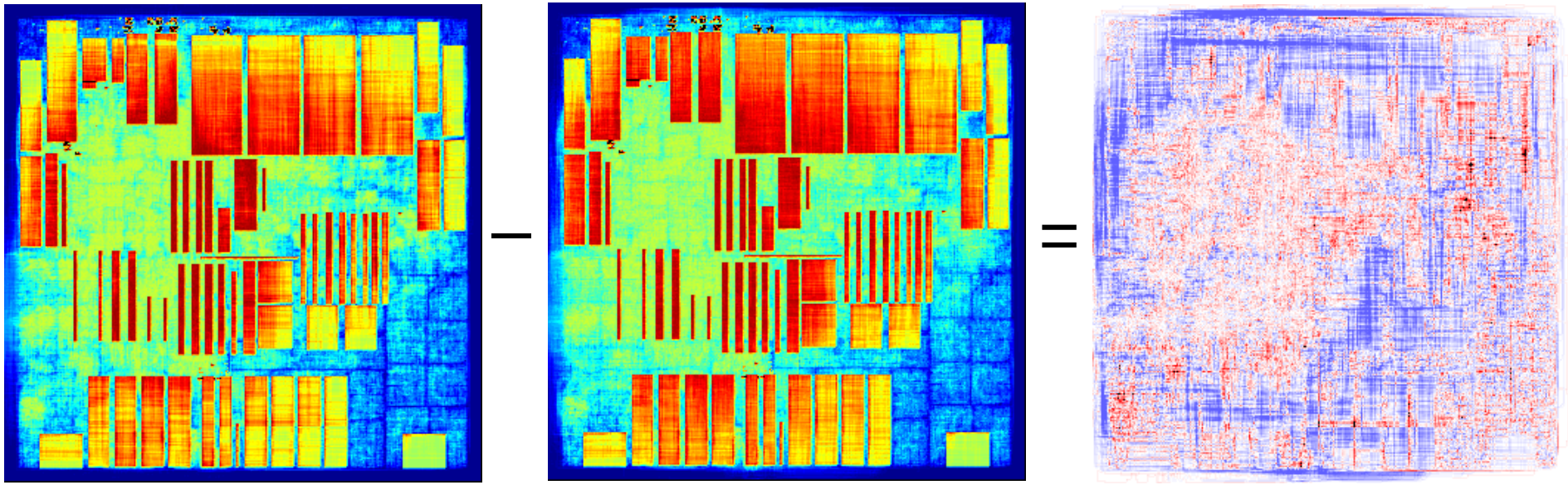
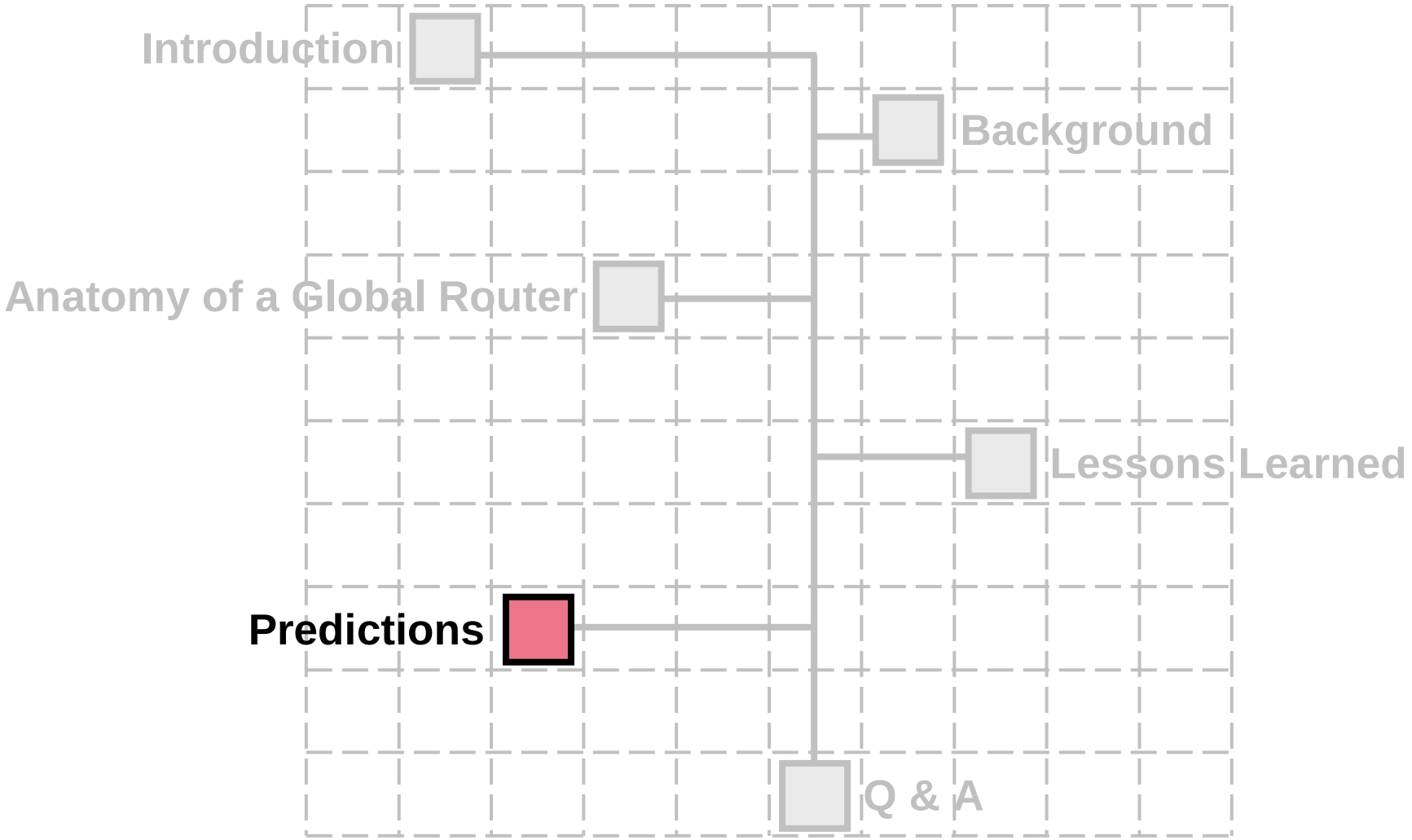


BoxRouter 2.0 — MAIZEROUTER

Outline of Talk



Algorithms

- **Projection-based layer assignment will eventually lose**
  - Search space of full 3D-flow large, but more realistic for complex designs
- **Opportunities for parallelization?**
  - Preliminary experiments have not shown promise

Open-Source Tools

- **Open-source *detailed* routers may become available**
  - Demand for OpenAccess interfaces will continue to grow
- **Open-source timing-driven routers unlikely**
  - Academic community still strongly tied to wirelength-driven objectives
  - “Approximating model vs. approximating solution”

Benchmarks

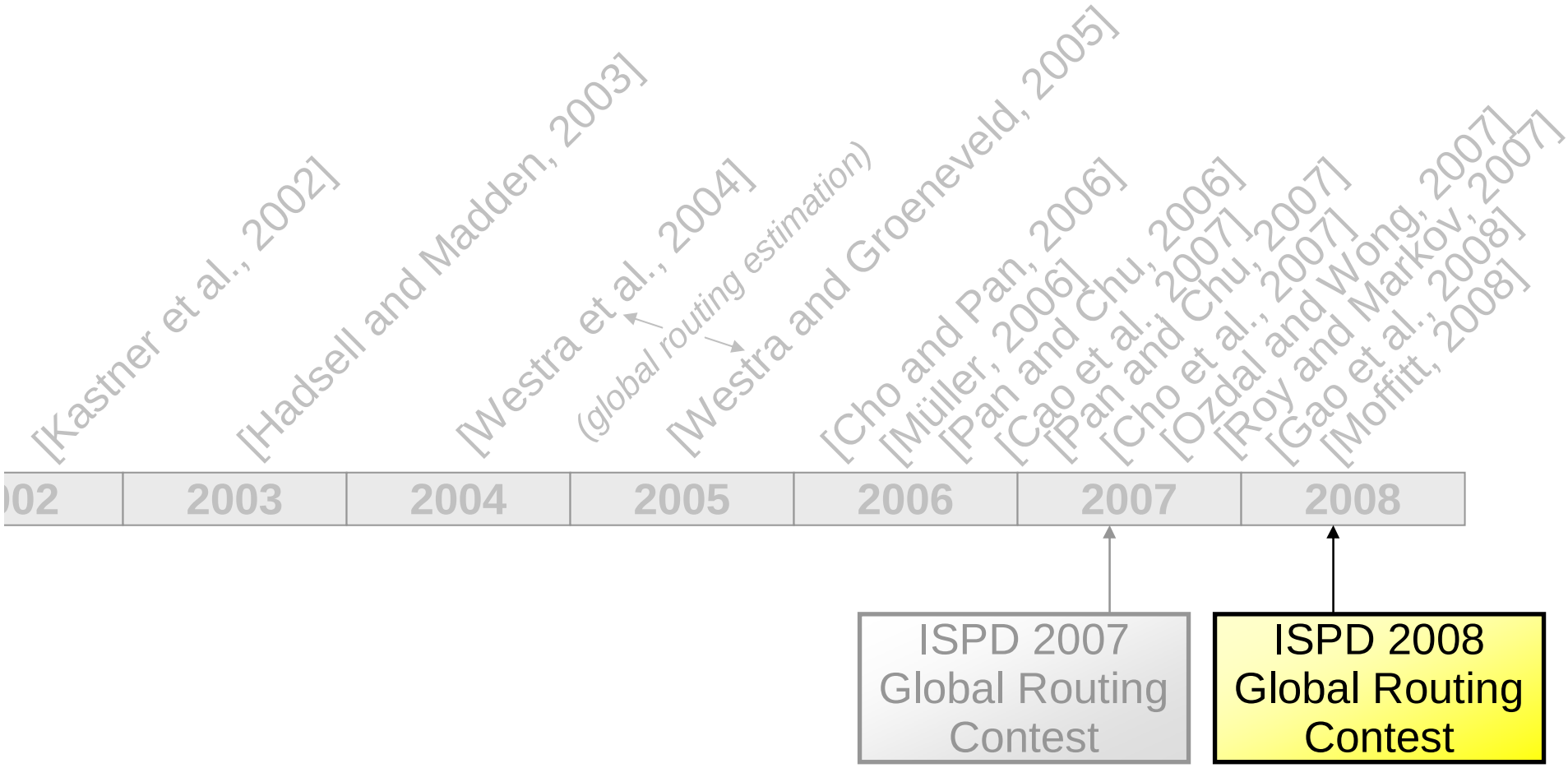
- … will become larger and more complex (45nm design rules, up to 9 metal layers, finer grids, etc.)
- Detailed routing instances will become available (not sure who will provide them)

Contests

- **Absolutely critical** to continued progress in PD
- Some dangers…
- Open source requirements will lead to tougher competition
- (Eventually) Less emphasis on solving “carved off” instances, more emphasis on broader synergistic flows

ISPD 2005: Placement	ISPD 2006: Placement	ISPD 2007: Global Routing	ISPD 2008: Global Routing	**ISPD 2009: ???**

Without further ado…



Backup Slides

Full ISPD '07 Routing Contest Results

	Router	adaptec1		adaptec2		adaptec3		adaptec4		adaptec5		newblue1		newblue2		newblue3	
		ovfl	wlen	ovfl	wlen	ovfl	wlen	ovfl	wlen	ovfl	wlen	ovfl	wlen	ovfl	wlen	ovfl	wlen
3-D	1. MaizeRouter′	0	100	0	98	0	214	0	194	2	305	1348	102	0	140	32840	184
	2. BoxRouter′	0	104	0	103	0	236	0	212	0	298	400	102	0	155	38976	196
	3. FGR′	60	91	50	92	0	203	0	186	2480	265	2668	93	0	136	53648	168
	4. FastRoute′	122	249	500	244	0	523	0	469	9894	708	2602	248	0	380	34236	443
	5. NTHU-R(3)′	3476	194	3588	177	64	406	0	303	20632	505	5526	180	0	232	38146	317
	6. FlexRouter′	8698	120	7370	114	950	269	18	227	21802	336	7636	111	0	171	39488	216
	7. Bockenem′	1240	254	10428	211	166498	407	7370	392	98950	576	3936	220	674	272	301052	309
	8. NTU1-R(9)′	62638	115	24738	112	31178	413	1342	252	208804	556	17872	115	0	168	148646	203
	9. NTU2-R(13)′	32488	253	13662	243	43332	668	4064	600	120602	719	6570	200	0	362	64102	605
2-D	1. FGR′	0	56	0	54	0	133	0	126	0	156	1218	48	0	78	36970	108
	2. MaizeRouter′	0	62	0	57	0	138	0	128	2	177	1348	51	0	80	32588	115
	3. BoxRouter′	0	59	0	56	0	141	0	129	0	164	400	51	0	80	38976	112
	4. FastRoute′	122	90	500	82	0	203	0	171	9680	252	1934	74	0	115	34236	155
	5. NTHU-R(3)′	3474	79	3588	66	64	176	0	142	20630	258	5526	56	0	88	38146	161
	6. Bockenem′	608	80	880	95	3266	178	396	157	3496	232	2754	84	0	99	100078	130
	7. NCTU-R(10)′	3800	81	5178	76	98	184	8	160	16400	236	6722	68	0	105	34310	147
	8. FlexRouter′	8698	65	7370	59	950	155	18	135	21802	181	7636	51	0	82	39488	119
	9. NTU2-R(13)′	32520	62	13860	62	43332	402	4064	143	119822	438	6570	53	0	89	64130	119
	10. NTU1-R(9)′	93608	58	24738	57	31178	142	1342	133	208804	166	17872	50	0	81	148646	117

TABLE IV
COMPLETE SOLUTION STATISTICS FOR ALL ENTRIES TO THE ISPD 2007 GLOBAL ROUTING COMPETITION

	a1	a2	a3	a4	a5	n1	n2	n3	avg
MaizeRouter	1	1	2	2	2	2	2	1	**1.6**
BoxRouter	2	2	3	3	1	1	3	4	**2.4**
FGR	3	3	1	1	3	4	1	6	**2.8**
FastRoute	4	4	4	5	4	3	8	2	**4.3**
NTHU-R(3)	6	5	5	4	5	6	6	3	**5.0**
FlexRouter	7	6	6	6	6	8	5	5	**6.1**
Bockenem	5	7	9	9	7	5	9	8	**7.4**
NTU1-R(9)	8	8	7	7	9	9	4	7	**7.4**
NTU2-R(13)*	9	9	8	8	8	7	7	9	**8.1**

TABLE V
FINAL RANKING OF ROUTERS OVER 3D BENCHMARKS

	a1	a2	a3	a4	a5	n1	n2	n3	avg
FGR	1	1	1	1	1	2	1	4	**1.5**
MaizeRouter	3	3	2	2	3	3	2	1	**2.4**
BoxRouter	2	2	3	3	2	1	3	6	**2.8**
FastRoute	4	4	4	5	5	4	10	2	**4.8**
NTHU-R(3)	6	6	5	4	7	6	6	5	**5.6**
Bockenem	5	5	8	8	4	5	8	9	**6.5**
NCTU-R(10)	7	7	6	6	6	8	9	3	**6.5**
FlexRouter	8	8	7	7	8	9	5	7	**7.4**
NTU2-R(13)	9	9	10	10	10	7	7	8	**8.8**
NTU1-R(9)	10	10	9	9	9	10	4	10	**8.9**

TABLE VI
FINAL RANKING OF ROUTERS OVER 2D BENCHMARKS