GPU-Accelerated Static Timing Analysis and Beyond

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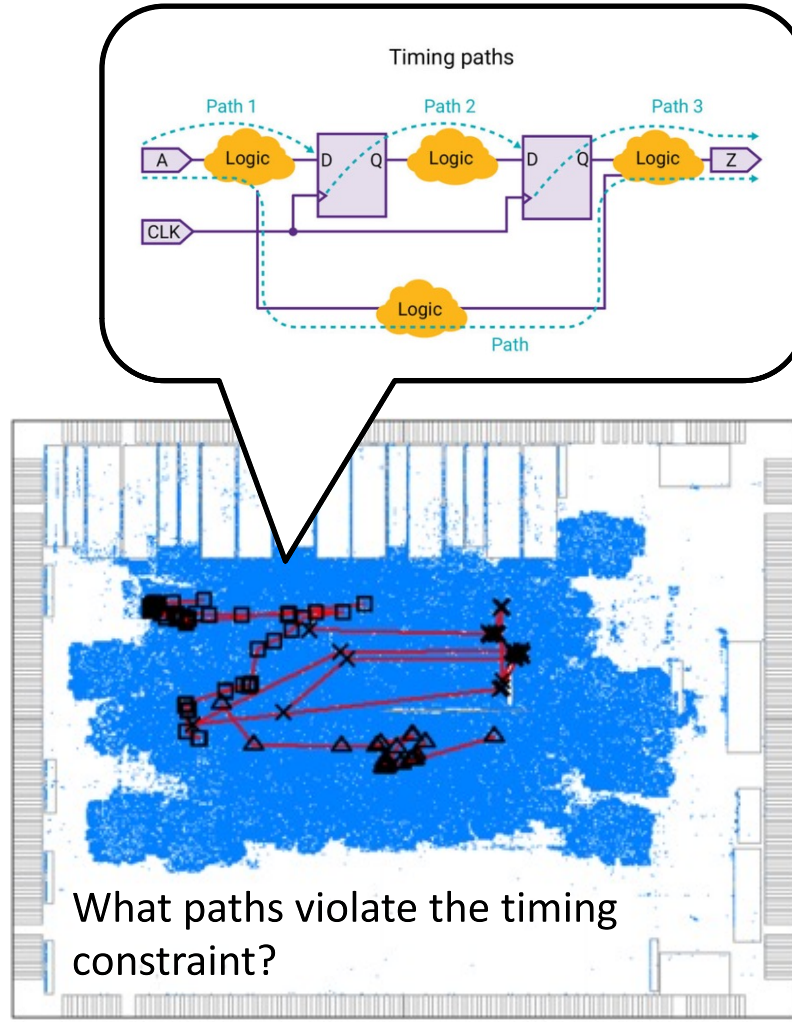
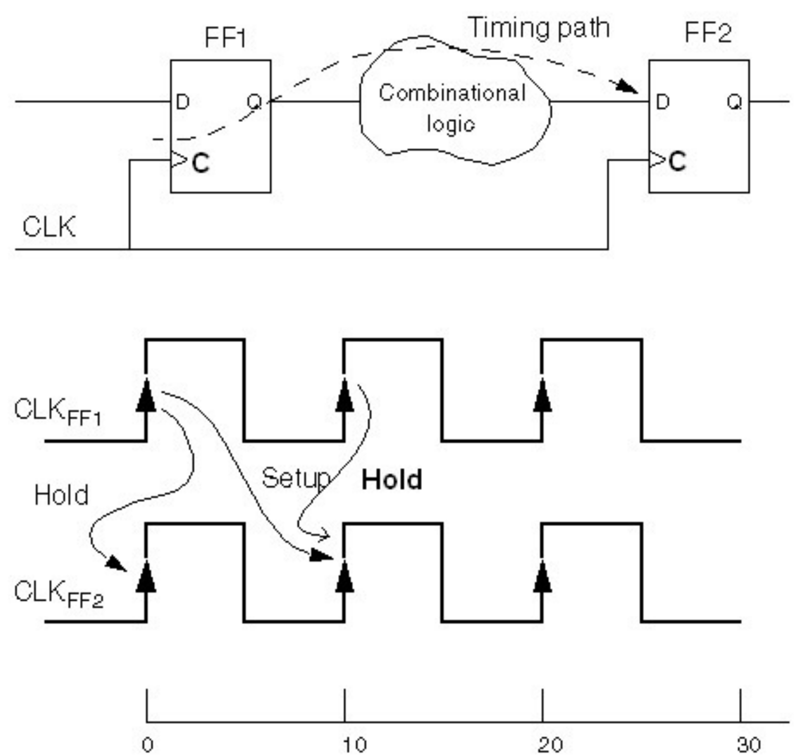
Static Timing Analysis

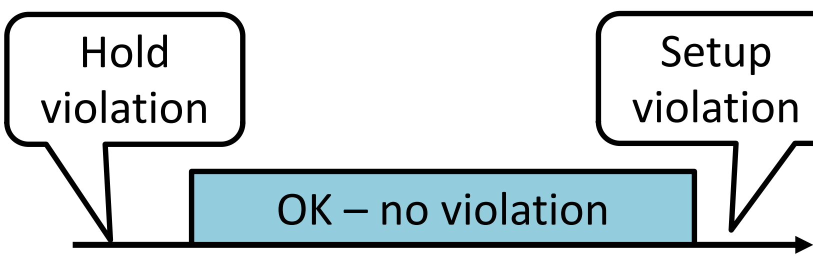
- **Static timing analysis (STA)**
  - Key step in the VLSI design
  - Verify the circuit timing
- **Analyze worst-case timing**
  - Minimum timing values
  - Maximum timing values
- **Challenges**
  - Compute giant graphs
  - Analyze millions of paths
  - Balance the loads
  - …



Timing Checks (Required Arrival Time)

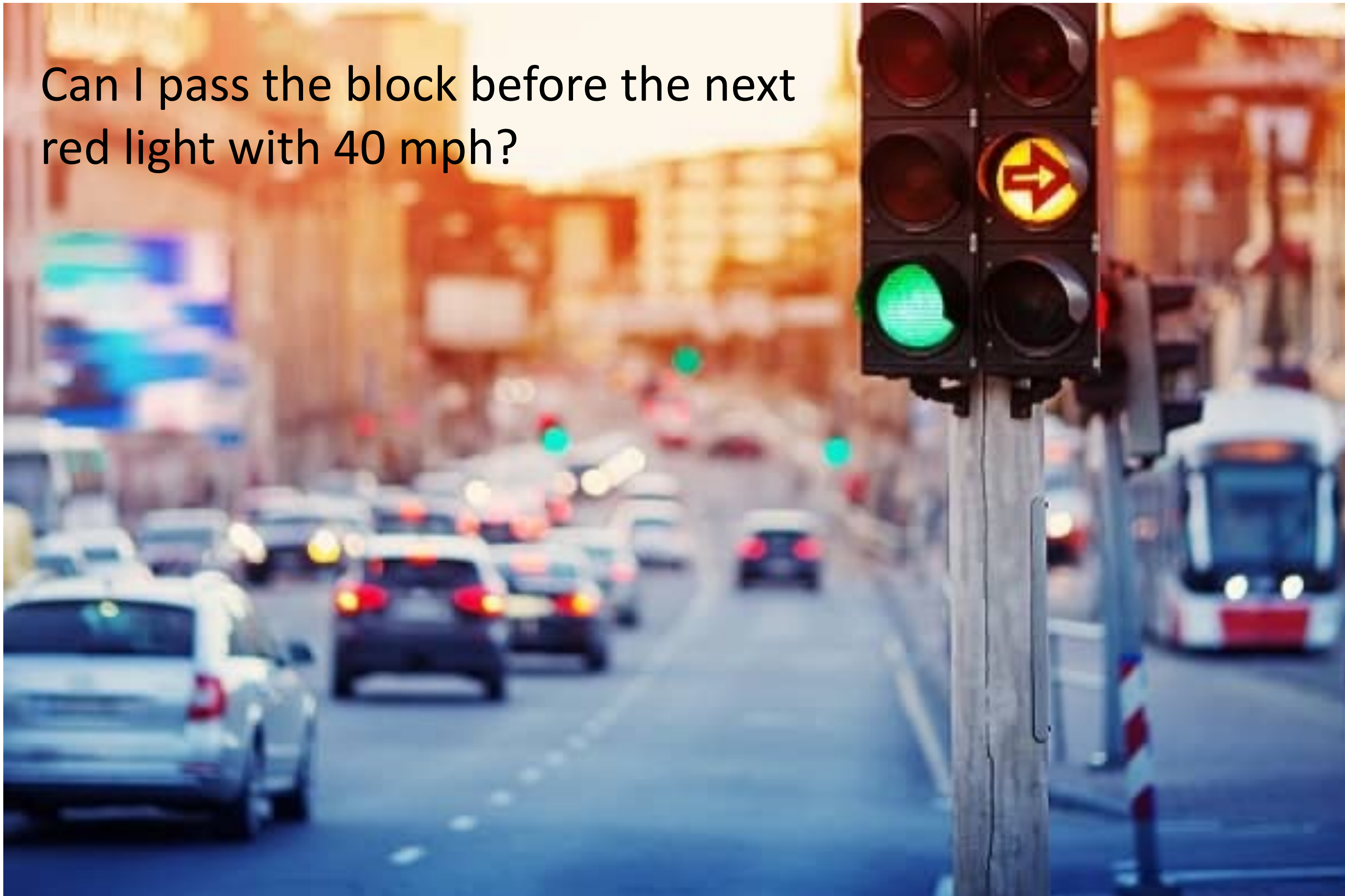
- **Modern circuits are sequential**
  - Drive data signal via clocks
  - Capture data via flip-flops (FF)s
- **Timing constraints**
  - Min required arrival time
    - After clock: hold
  - Max required arrival time
    - Before clock: setup





Required arrival time interval

The “Traffic Light” Analogy



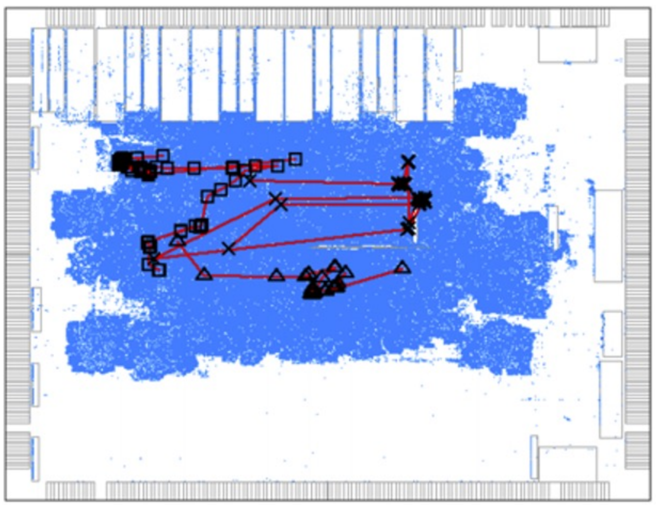
Can I pass the block before the next red light with 40 mph?

Building a Good Traffic System is Hard

- Trillions of sections and traffic lights to analyze …

Same, STA is Computationally Challenging

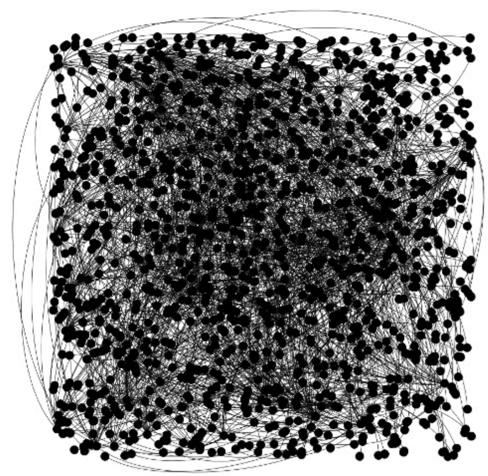
- **STA graphs is extremely large and irregular**
  - Millions to billions of nodes and edges
  - Propagate timing information along giant graphs



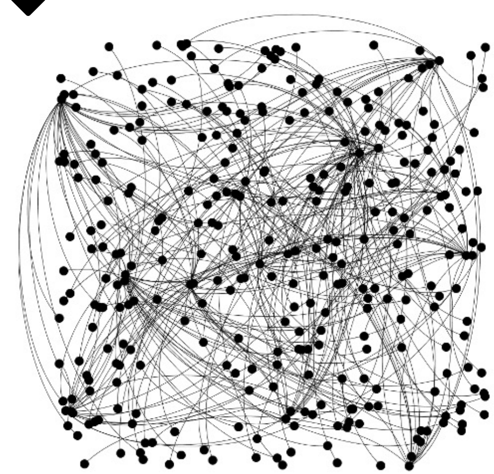
ISPD circuit design (10M gates)

Complete analysis can take **8 hours** and **800 GB RAM**

STA graphs



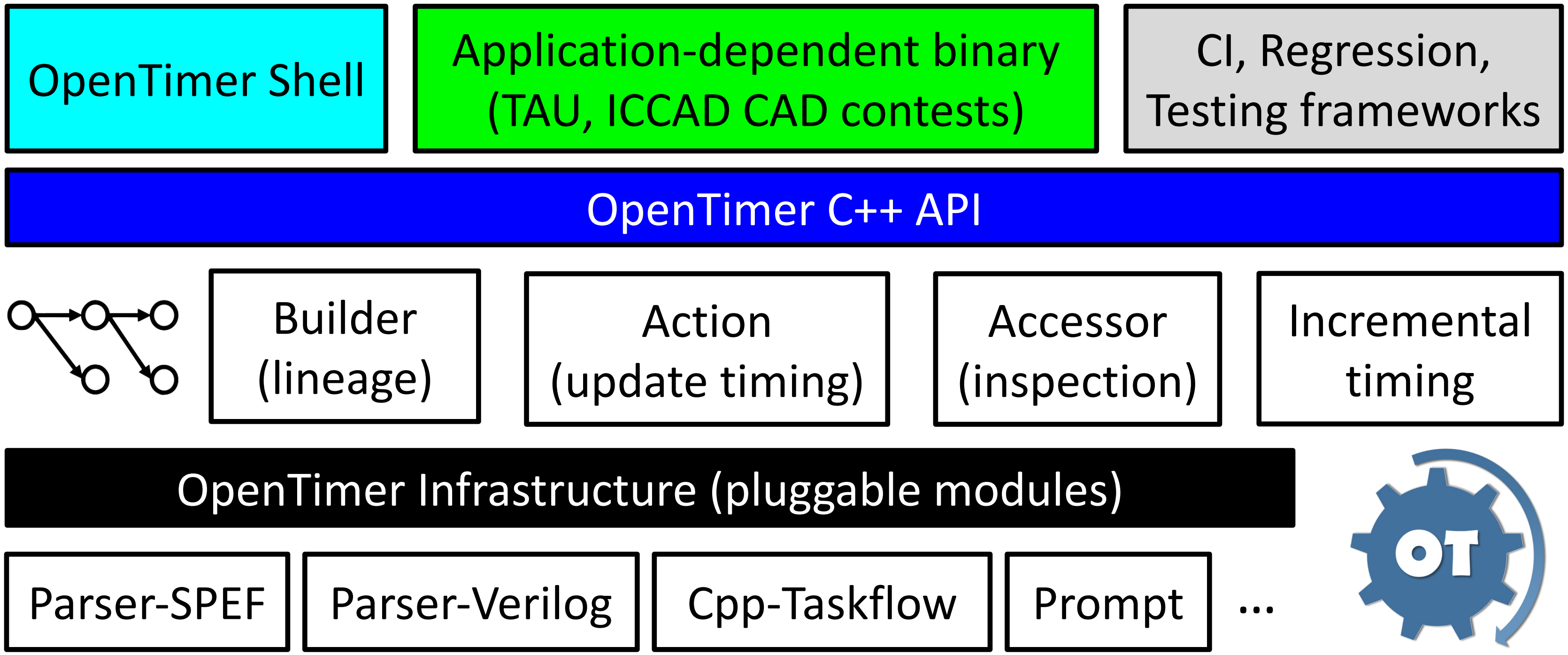
A datapath



STA graphs are extremely large and irregular

Our STA Solution: OpenTimer

- **CPU-parallel timing analysis engine**
  - Two major versions: v1 (2015) and v2 (2020)
  - https://github.com/OpenTimer/OpenTimer

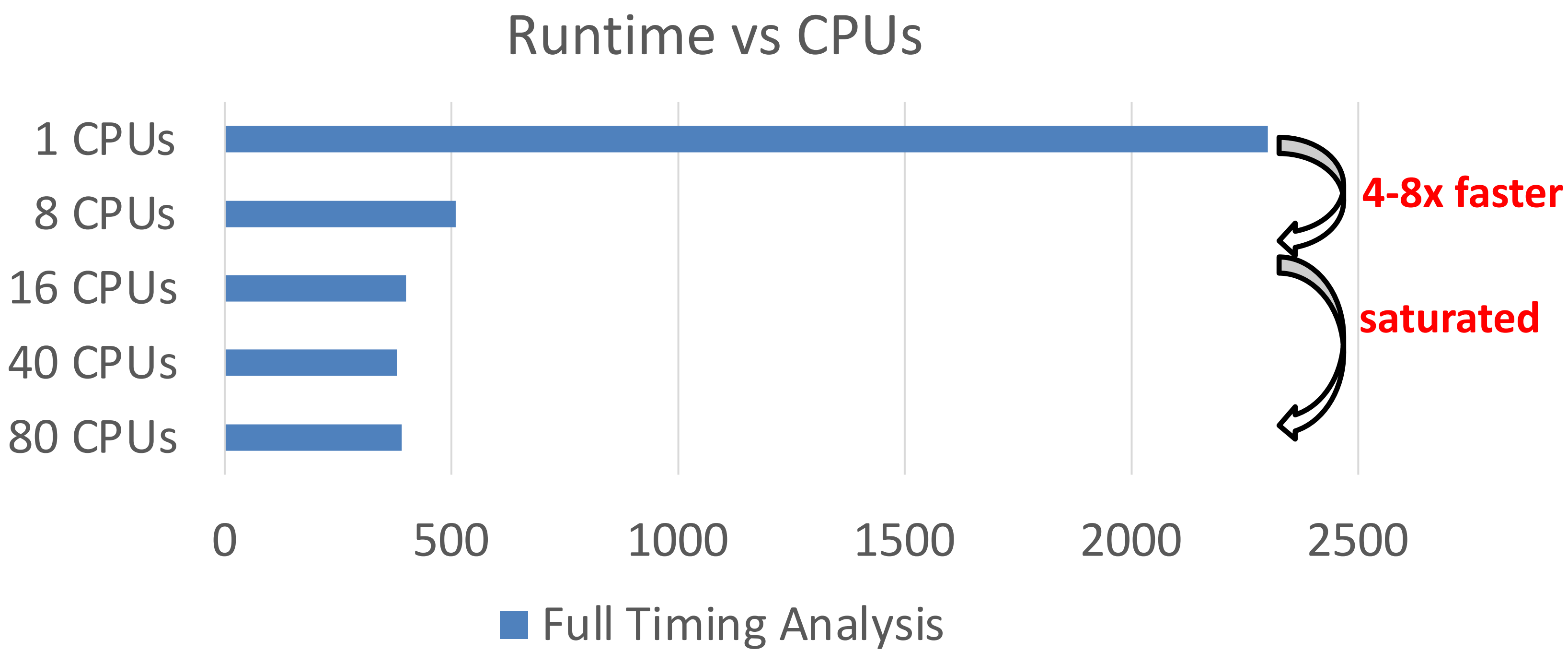


T.-W. Huang et al., "OpenTimer: A High-performance Timing Analysis Tool," IEEE/ACM ICCAD15

T.-W. Huang et al., "OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," IEEE TCAD21

Key Idea: Parallel Timing Analysis

- ❑ **Leverage many-core CPUs to speed up the runtime**
  - ❑ Dramatic speed-up using 8 cores
  - ❑ Yet, scalability saturates at about 10—16 cores

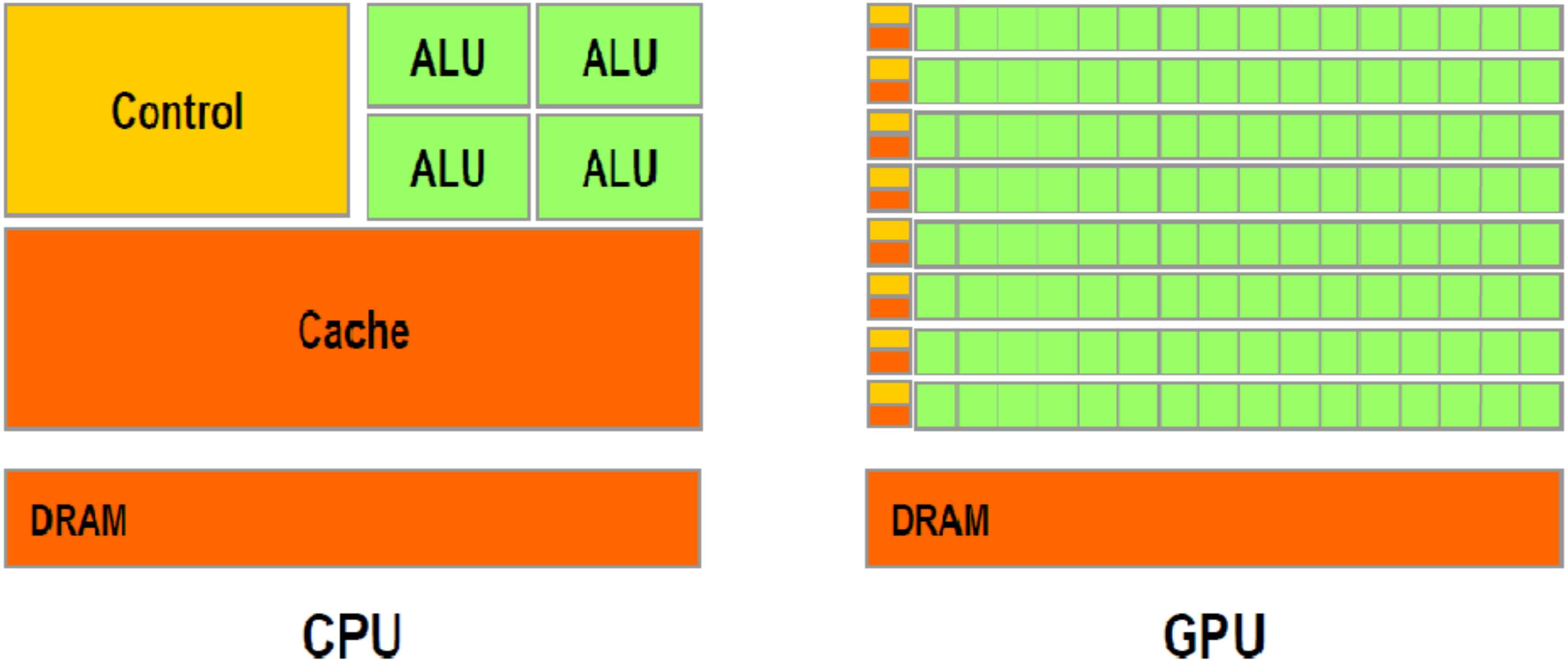


Observed Scalability Bottleneck

- **CPU-only parallelism stagnates at about 10 cores**
  - "Amdahl's Law" limits the strong scalability
  - Circuit graph structures limits the maximum parallelism
    - If the graph has only 10 parallel nodes at a level, we won't achieve 40x speed-up
  - Irregular computations limits the memory bandwidth
    - STA is graph-oriented, not cache-friendly
- **Need to incorporate new parallel paradigms**
  - GPU opens opportunities for new scalability milestones
    - e.g., 100x speed-up reported in logic simulation
    - e.g., 20—80x speed-up reported in placement

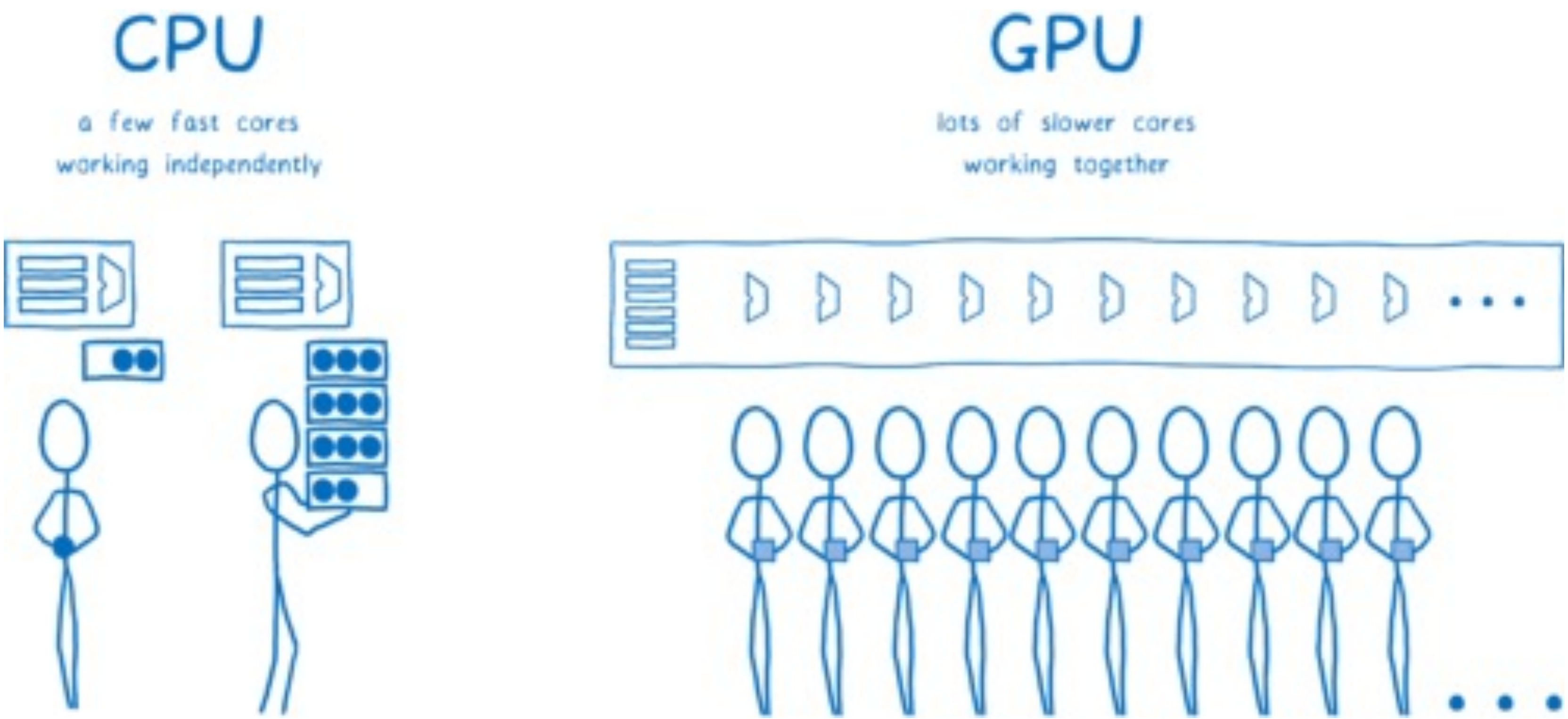
CPU vs GPU

- ❑ **CPU is built for *compute-driven* applications**
  - ❑ A few powerful threads to compute critical blocks fast
- ❑ **GPU is built for *throughput-driven* applications**
  - ❑ Many lightweight threads to compute data at one time



CPU vs GPU (cont'd)

- ❑ **CPU: graph algorithms, irregular data structures, etc.**
- ❑ **GPU: matrix operations, gaming, video, etc.**

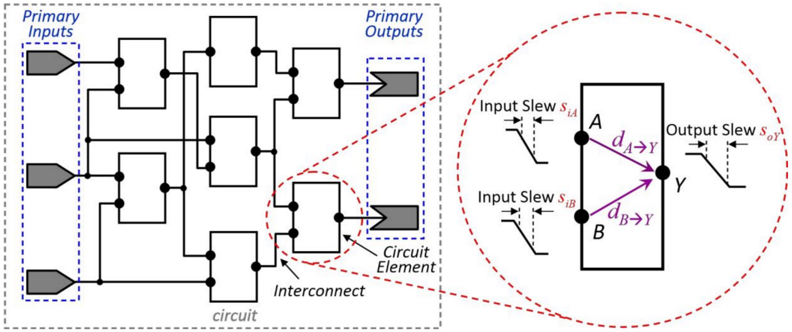


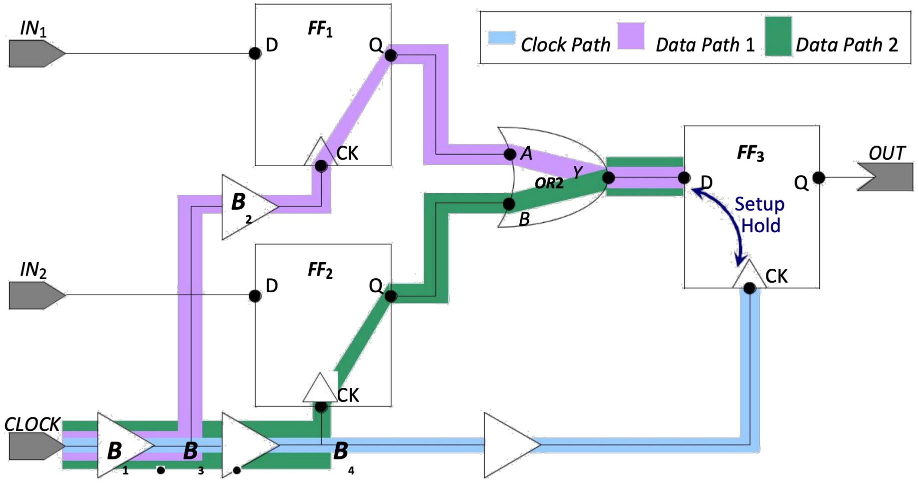
Leverage GPU to Accelerat STA

- **We target two important STA steps:**
  - Graph-based analysis (GBA)
  - Path-based analysis (PBA)
- **We design CPU-GPU collaborative STA algorithms**
  - CPU-GPU task decomposition
  - GPU kernels for timing update

PBA analyzes critical paths one by one on a updated graph

GBA computes the delay, slew, arrival time at each node and edge

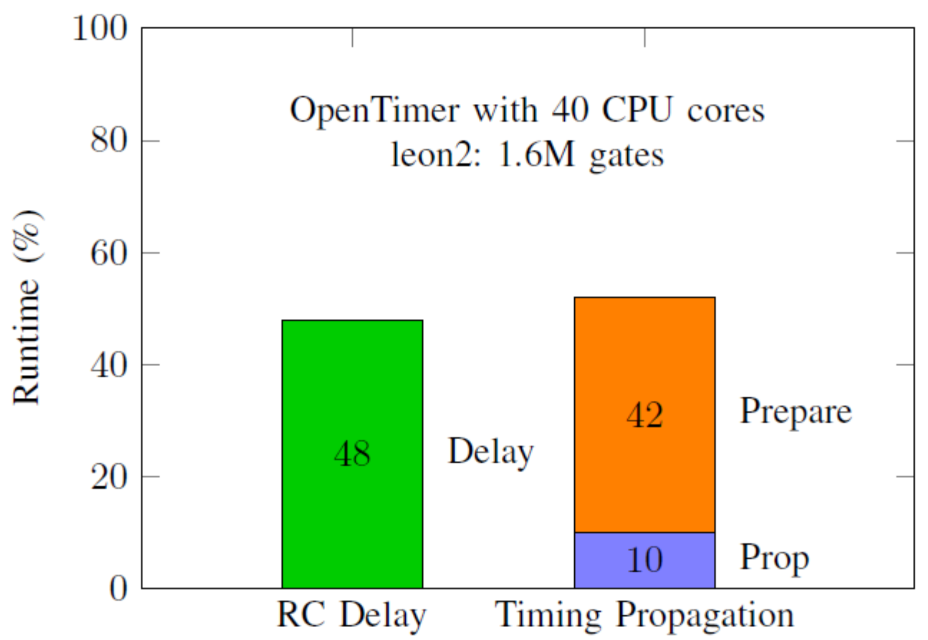




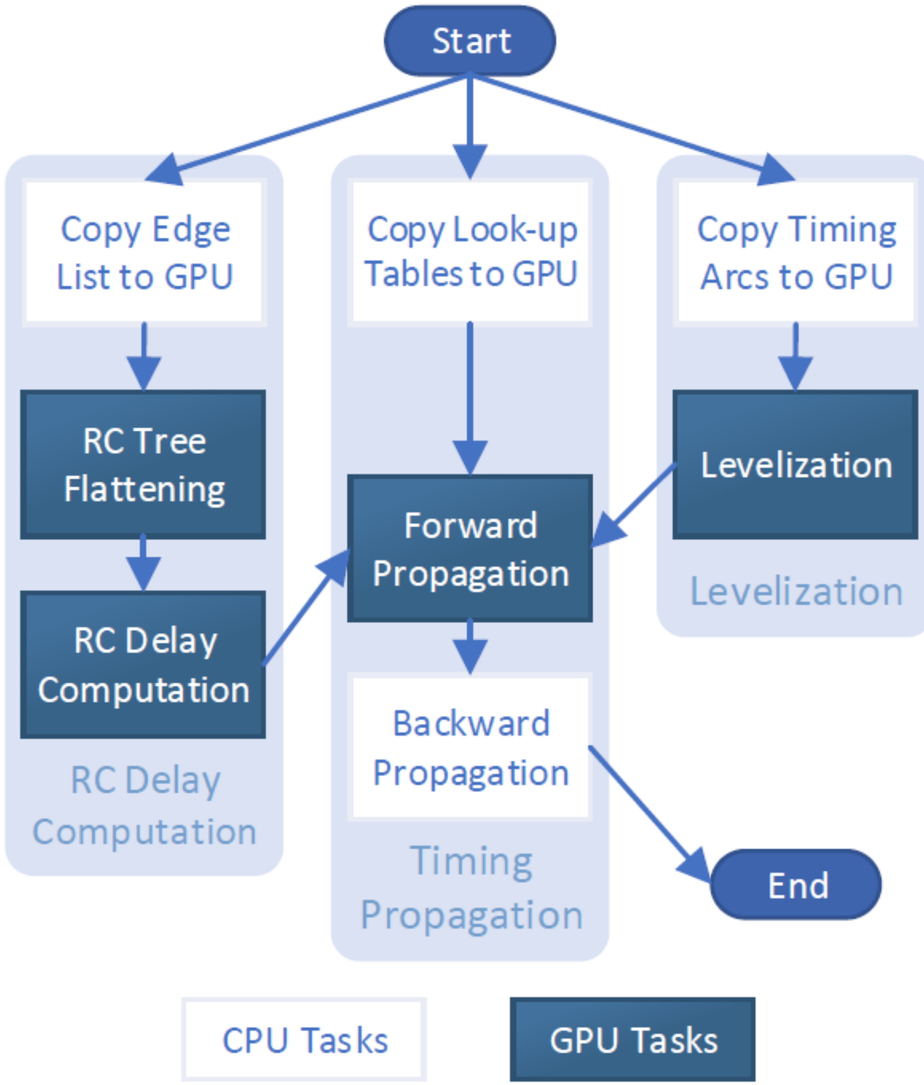
Z Guo, T-W Huang, and Y Lin, "GPU-Accelerated Static Timing Analysis," ***IEEE/ACM ICCAD*****, 2020**

Runtime Breakdown of GBA

- **GBA has three time-consuming steps**
  1. Prepare tasks through levelization → 42% runtime
  2. Compute RC delay → 48% runtime
  3. Propagate timing → 10% runtime

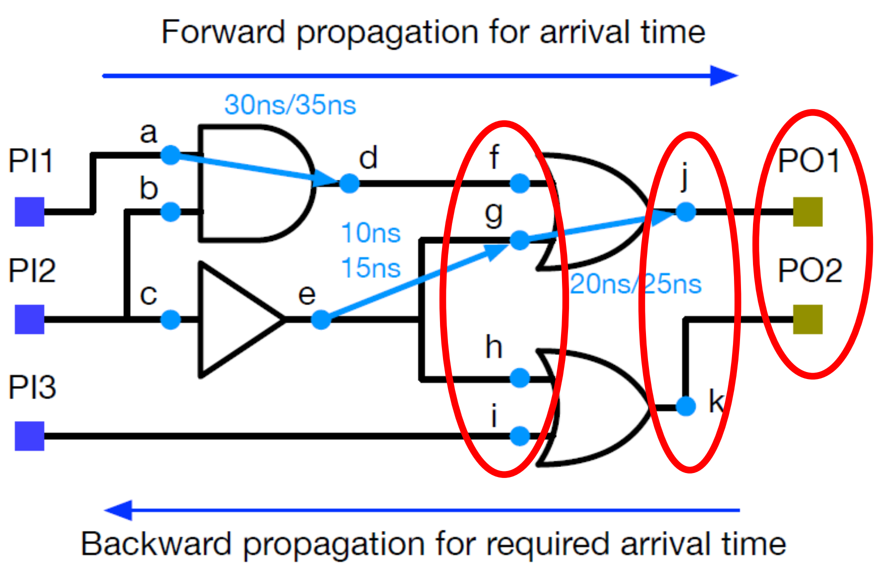


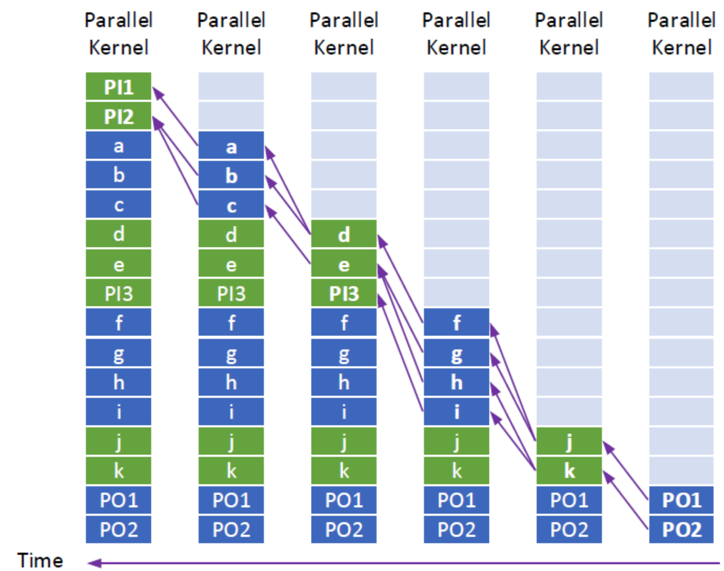
GPU-Accelerated GBA Algorithm Flow



Step #1: Levelization

- Levelize the circuit graph to a 2D levellist
  - Nodes at the same level can run in parallel (red circle)
  - Nodes at the same level can be modeled as a batch

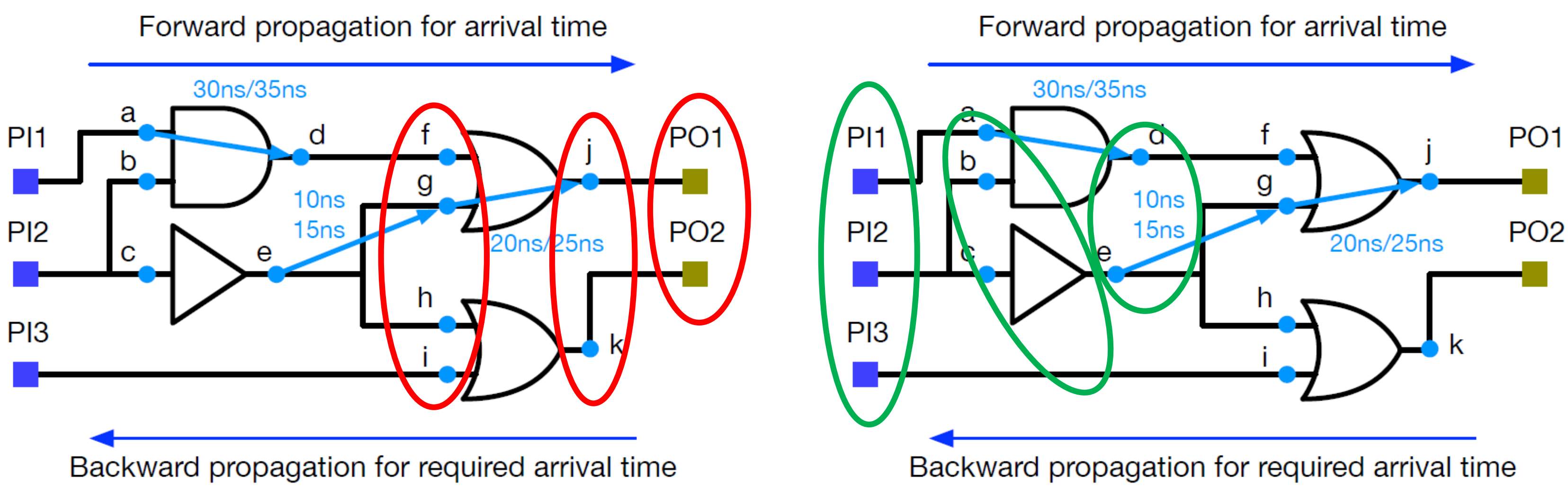




- GPU-accelerated levelization using parallel frontiers

Step #1: Levelization (cont'd)

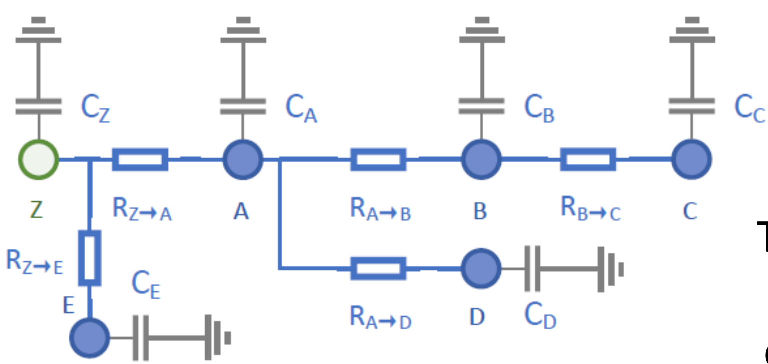
- Levelize the graph backward rather than forward



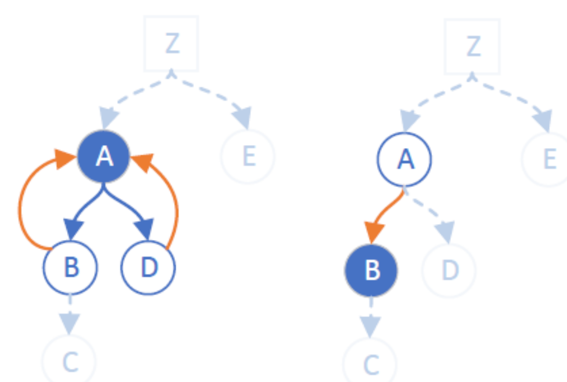
Benchmark	#nodes	Max In-degree	Max Out-degree
netcard	3999174	8	260
vga_lcd	397809	12	329
wb_dma	13125	12	95

Step #2: RC Update

- **The Elmore delay model**
- **Phase 1:** $load_u = \sum_{v \text{ is child of } u} cap_v$
  - For example, $load_A = cap_A + cap_B + cap_C + cap_D = cap_A + load_B + load_D$
- **Phase 2:** $delay_u = \sum_{v \text{ is any node}} cap_v \times R_{Z \to LCA(u,v)}$
  - For example, $delay_B = cap_A R_{Z\to A} + cap_D R_{Z\to A} + cap_B R_{Z\to B} + cap_C R_{Z\to B} = delay_A + R_{A\to B} load_B$



Two-phase tree traversal to compute delay



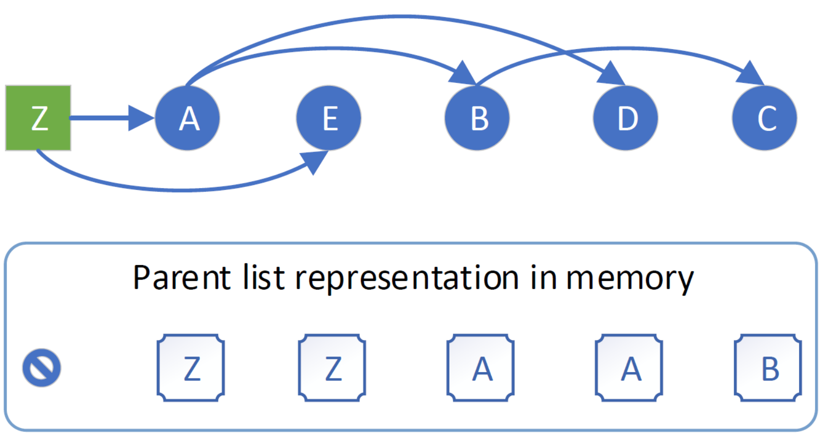
(a) Upward (b) Downward

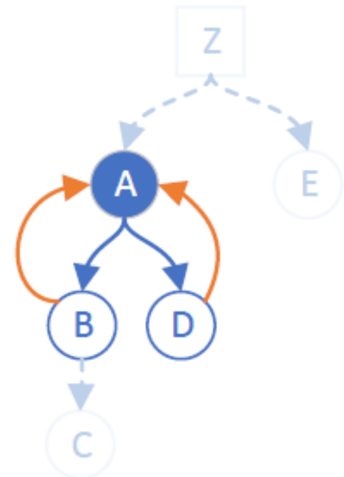
Step #2: RC Update Upward Phase

- ❑ **Store the parent index of each node on GPU**
- ❑ **Perform dynamic programming on trees**

```
DFS_load(u):
    load[u] = cap[u]
    For child v of u:
        DFS_load(v)
        load[u] += load[v]
```

```
GPU_load:
    For u in [C, D, B, E, A]:
        load[u] += cap[u]
        load[u.parent] += load[u]
```





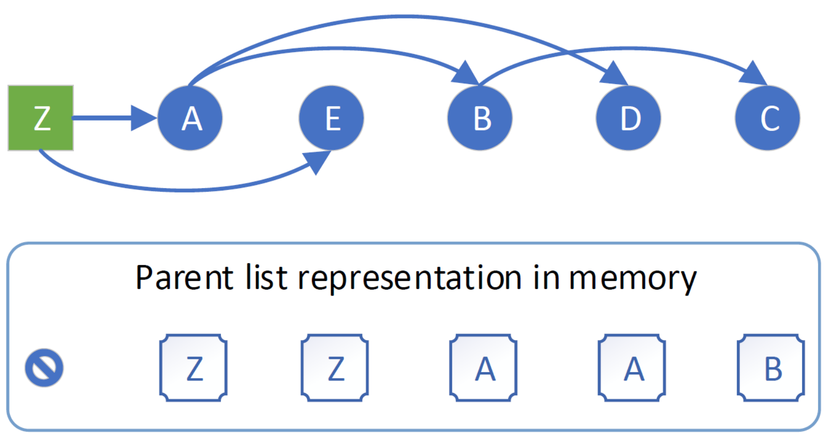
(a) Upward

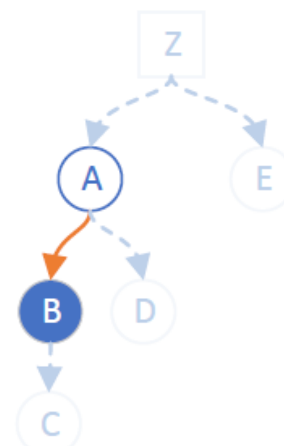
Step #2: RC Update Downward Phase

- Store the parent index of each node on GPU
- Perform dynamic programming on trees

```
DFS_delay(u):
    For child v of u:
        temp := R[u,v]*load[v]
        delay[v] = delay[u] + temp
        DFS_delay(v)
```

```
GPU_delay:
    For u in [A, E, B, D, C]:
        temp := R[u.parent,u]*load[u]
        delay[u]=delay[u.parent] + temp
```

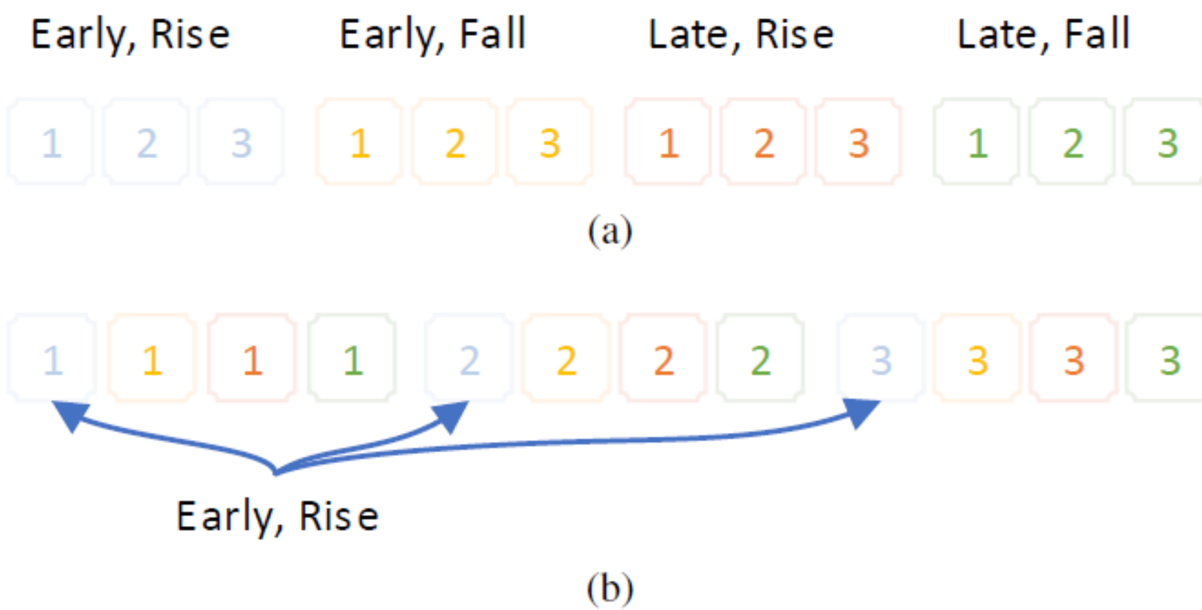




(b) Downward

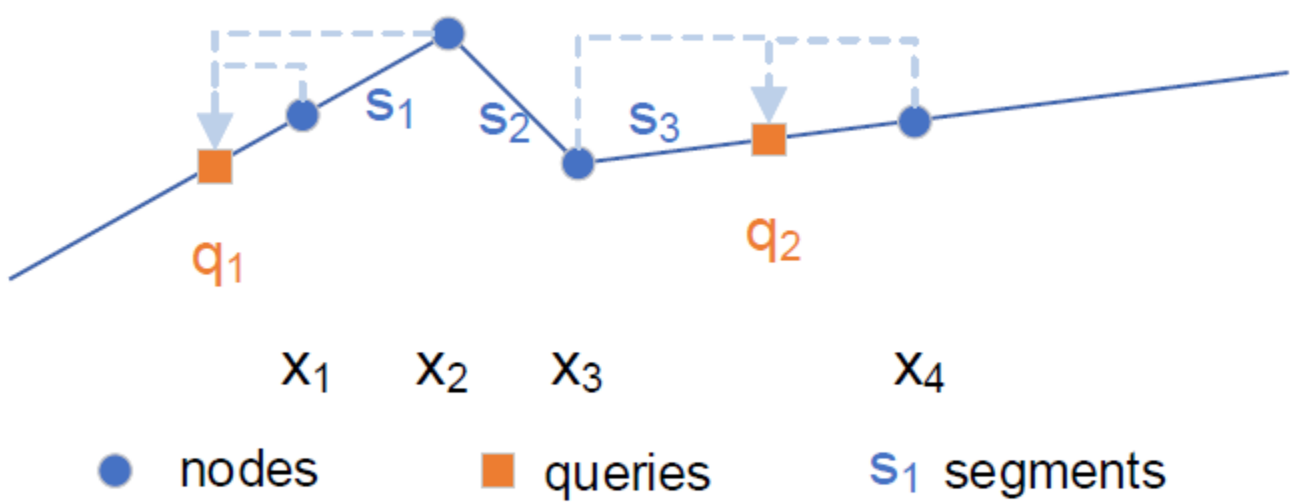
Step #2: RC Update Memory Coalesce

- ❑ **Consecutive threads access consecutive memory**
- ❑ **RC update has four cases: {Rise, Fall} x {Early, Late}**



Step #3: Cell Delay Update

- **Perform linear inter- and extra-polation in batches**
  - x-axis and then y-axis



Experiment Setting

- **Machine configuration**
  - Nvidia CUDA, RTX 2080
  - 40 Intel Xeon Gold 6138 CPU cores
- **Execution parameters for GPU kernels**
  - RC Tree Flattening
    - 64 threads per block with one block for each net
  - Levelization
    - 128 threads per block
  - RC delay computation
    - 4 threads for each net (one for each Early/Late and Rise/Fall condition) with a block of 64 nets
  - Cell delay computation
    - 4 threads for each arc, with a block of 32 arcs

Overall Performance

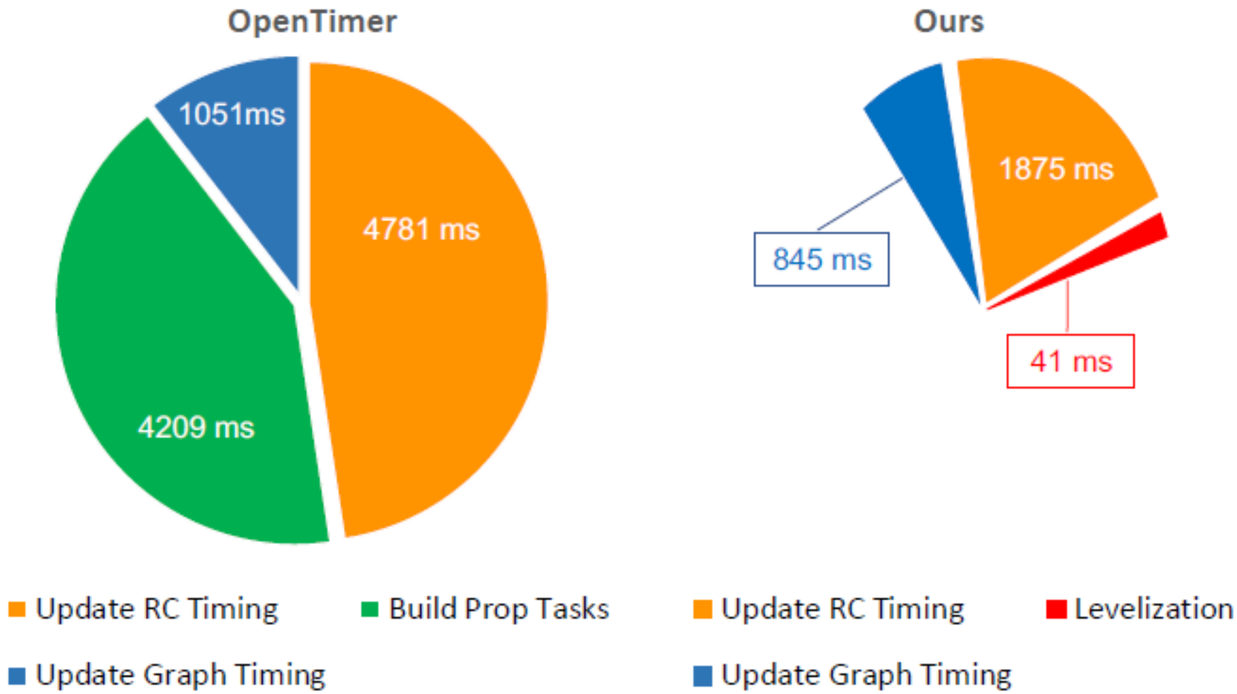
- **Comparison with OpenTimer of 40 CPUs**
  - Run on large TAU15 Benchmarks (>20K gates)

Benchmark	# PIs	# POs	# Gates	# Nets	# Pins	# Nodes	# Edges	OpenTimer Runtime (40 CPUs)	Our Runtime (40 CPUs 1 GPU)	
									Runtime	Speed-up
aes_core	260	129	22938	23199	66751	413588	453508	156 ms	138 ms	1.13×
vga_lcd	85	99	139529	139635	397809	1966411	2185601	829 ms	311 ms	2.67×
vga_lcd_iccad	85	99	259067	259152	679258	3556285	3860916	1480 ms	496 ms	2.98×
b19	22	25	255278	255300	782914	4423074	4961058	1831 ms	585 ms	3.13×
cordic	34	64	45359	45393	127993	7464477	820763	274 ms	167 ms	1.64×
des_perf	234	140	138878	139112	371587	2128130	2314576	832 ms	325 ms	2.56×
edit_dist	2562	12	147650	150212	416609	2638639	2870985	1059 ms	376 ms	2.86×
fft	1026	1984	38158	39184	116139	646992	718566	241 ms	148 ms	1.63×
leon2	615	85	1616369	1616984	4328255	22600317	24639340	10200 ms	2762 ms	3.69×
leon3mp	254	79	1247725	1247979	3376832	17755954	19408705	7810 ms	2585 ms	3.02×
netcard	1836	10	1496719	1498555	3999174	21121256	23027533	9225 ms	2571 ms	3.60×
mgc_edit_dist	2562	12	161692	164254	450354	2436927	2674934	1021 ms	368 ms	2.77×
mgc_matrix_mult	3202	1600	171282	174484	492568	2713241	2994343	1138 ms	377 ms	3.02×
tip_master	778	857	37715	38493	95524	533690	570154	163 ms	143 ms	1.14×

 # PIs: number of primary inputs **# POs**: number of primary outputs **# Gates**: number of gates **# Nets**: number of nets
 # Pins: number of pins **# Nodes**: number of nodes in the STA graph **# Edges**: number of edges in the STA graph

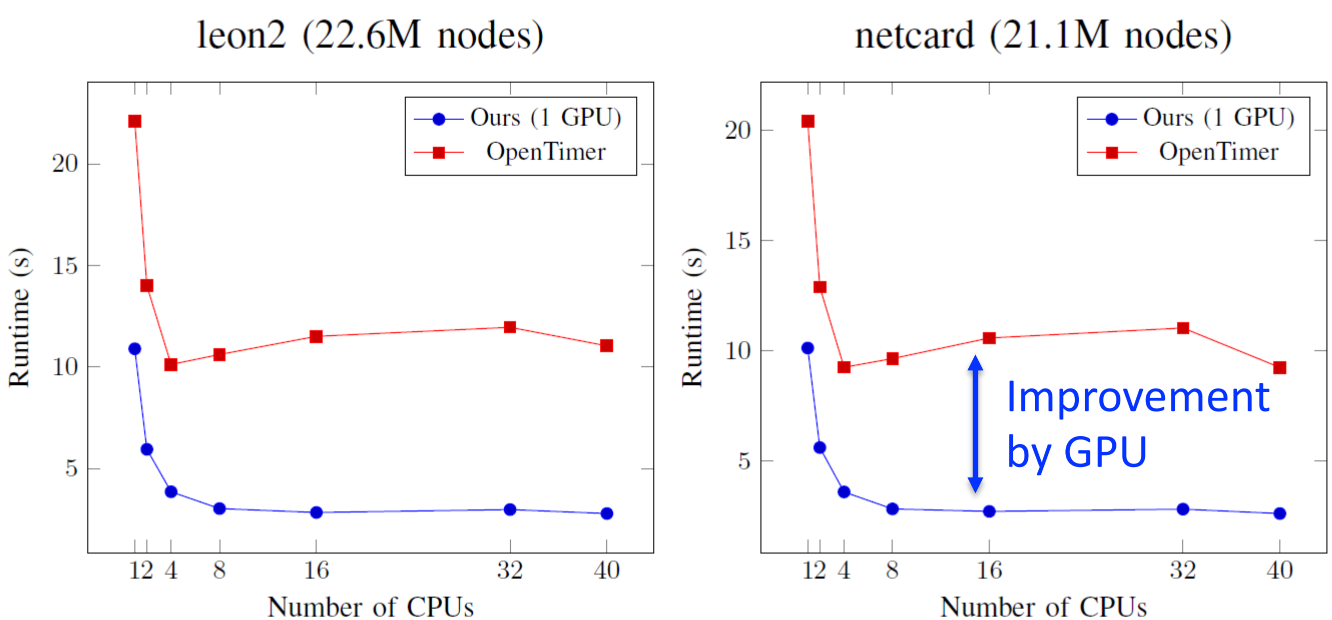
Runtime Breakdown

- Circuit leon2 (21 M nodes)



Runtime vs CPUs

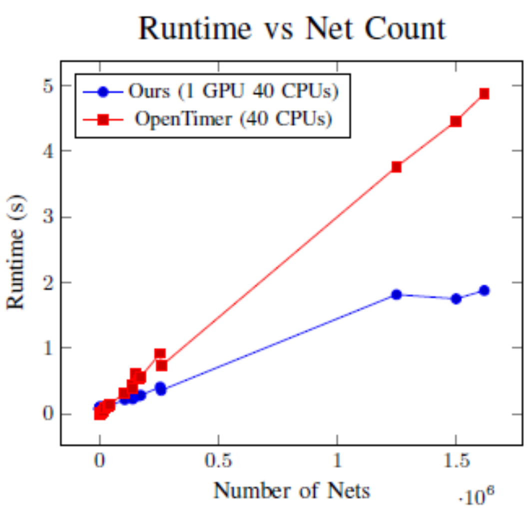
- ❑ **Significant performance gap between CPU and GPU**

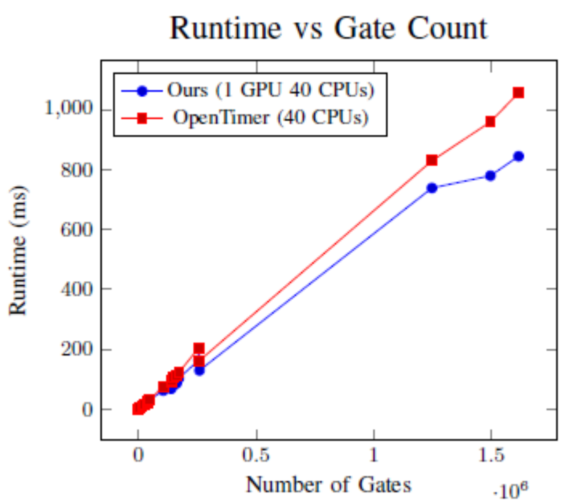


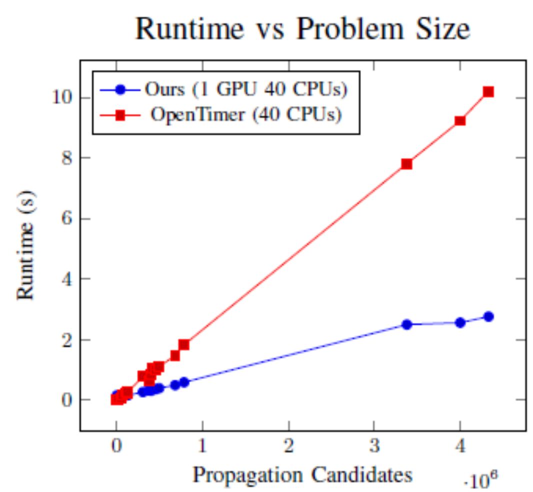
Our runtime of 1 CPU and 1 GPU is very close to OpenTimer of 40 CPUs

Runtime vs Problem Sizes

- ❑ **Problem size matters for GPU acceleration**
- ❑ **When to enable GPU acceleration?**
  - ❑ Net count > 20K
  - ❑ Gate count > 50K
  - ❑ Propagation candidate count > 15K





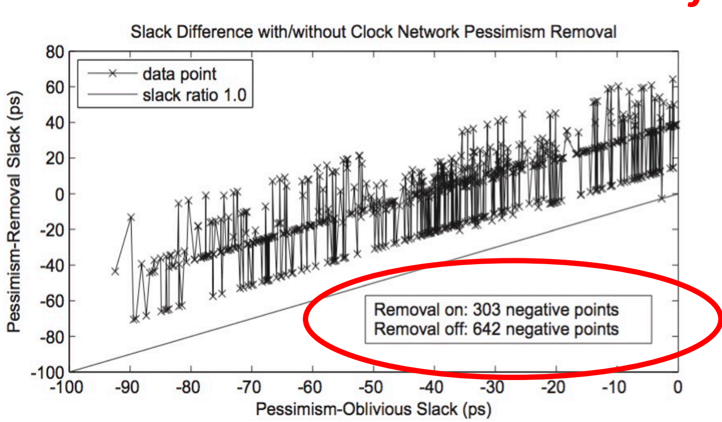


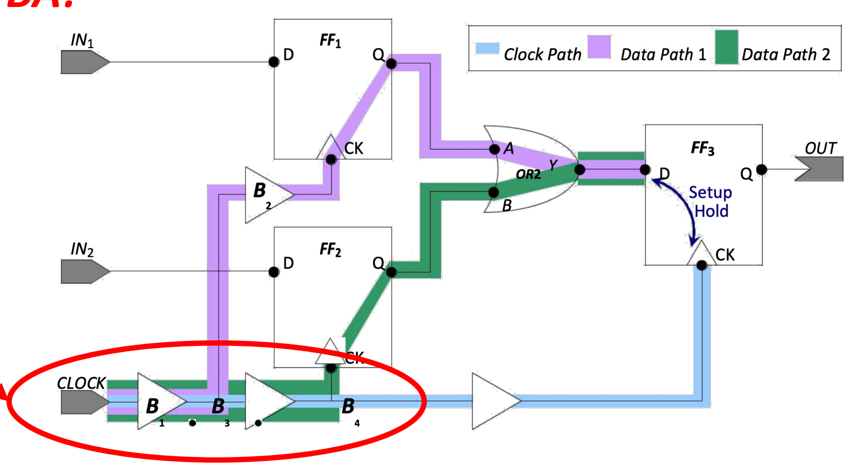
G guo, T-W Huang, Y Lin, and M Wong, "GPU-Accelerated Path-based Timing Analysis," *IEEE/ACM DAC*, 2021

Path-based Analysis (PBA)

- **Identify a set of critical paths from a updated graph**
  - Exponential number of paths in the circuit graph
- **Re-analyze each path with path-specific update**
  - Re-propagate the slew and remove pessimism
  - Advanced on-chip variation (AOCV)
  - Common path pessimism removal (CPPR)
  - …

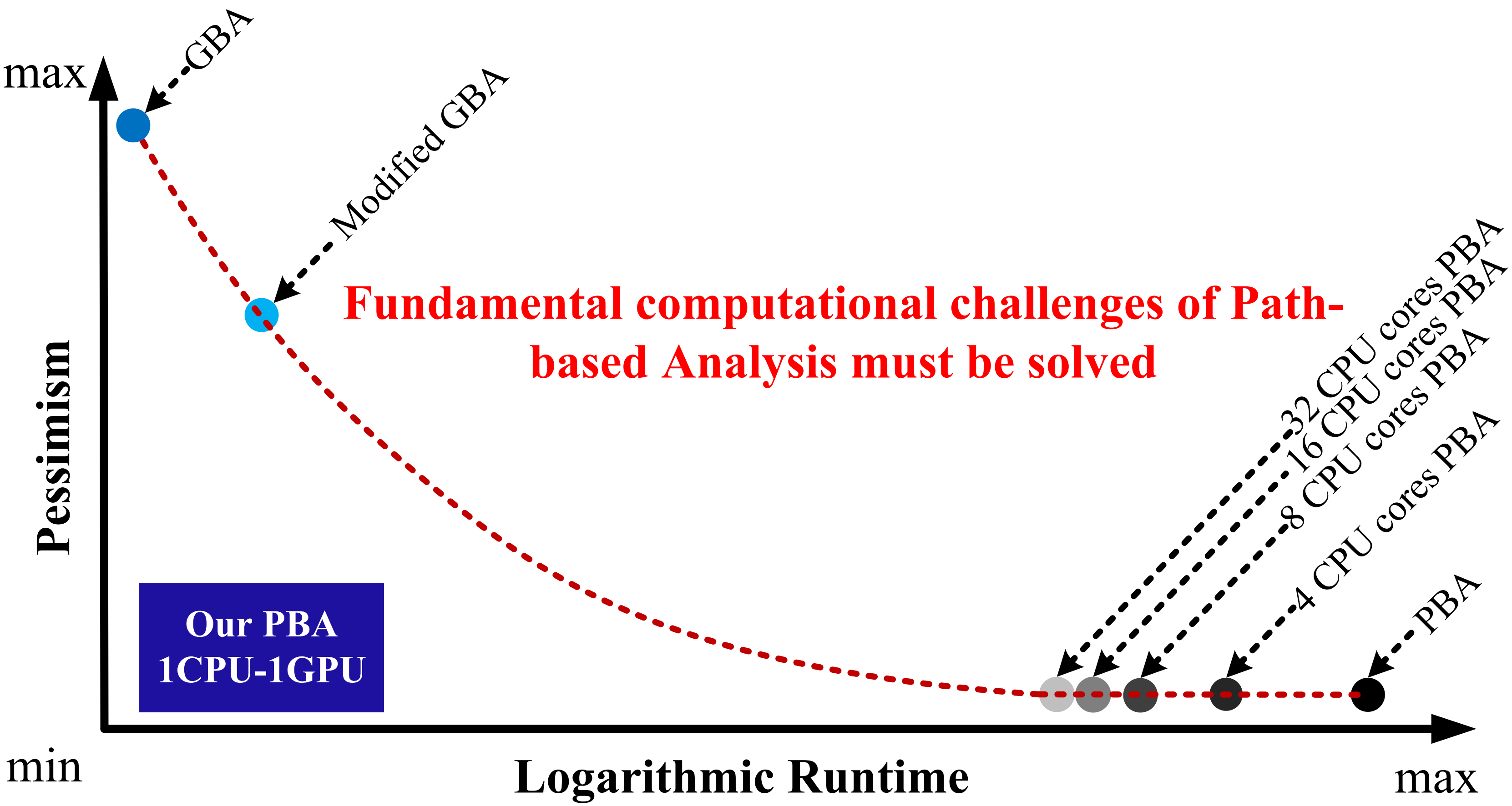
Paths marked failing at GBA may become passing after PBA!





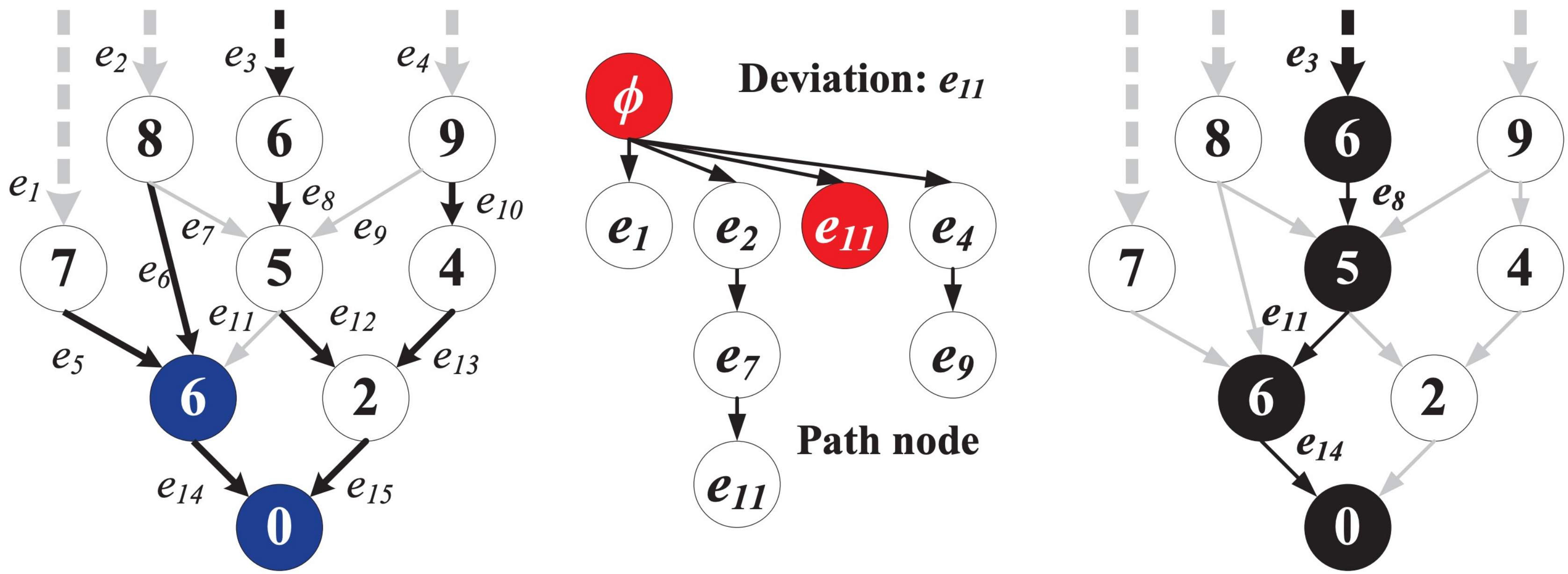
PBA is Extremely Time-Consuming

- Speed vs Accuracy (pessimism removal) tradeoff



A Key Step: Generate Critical Paths

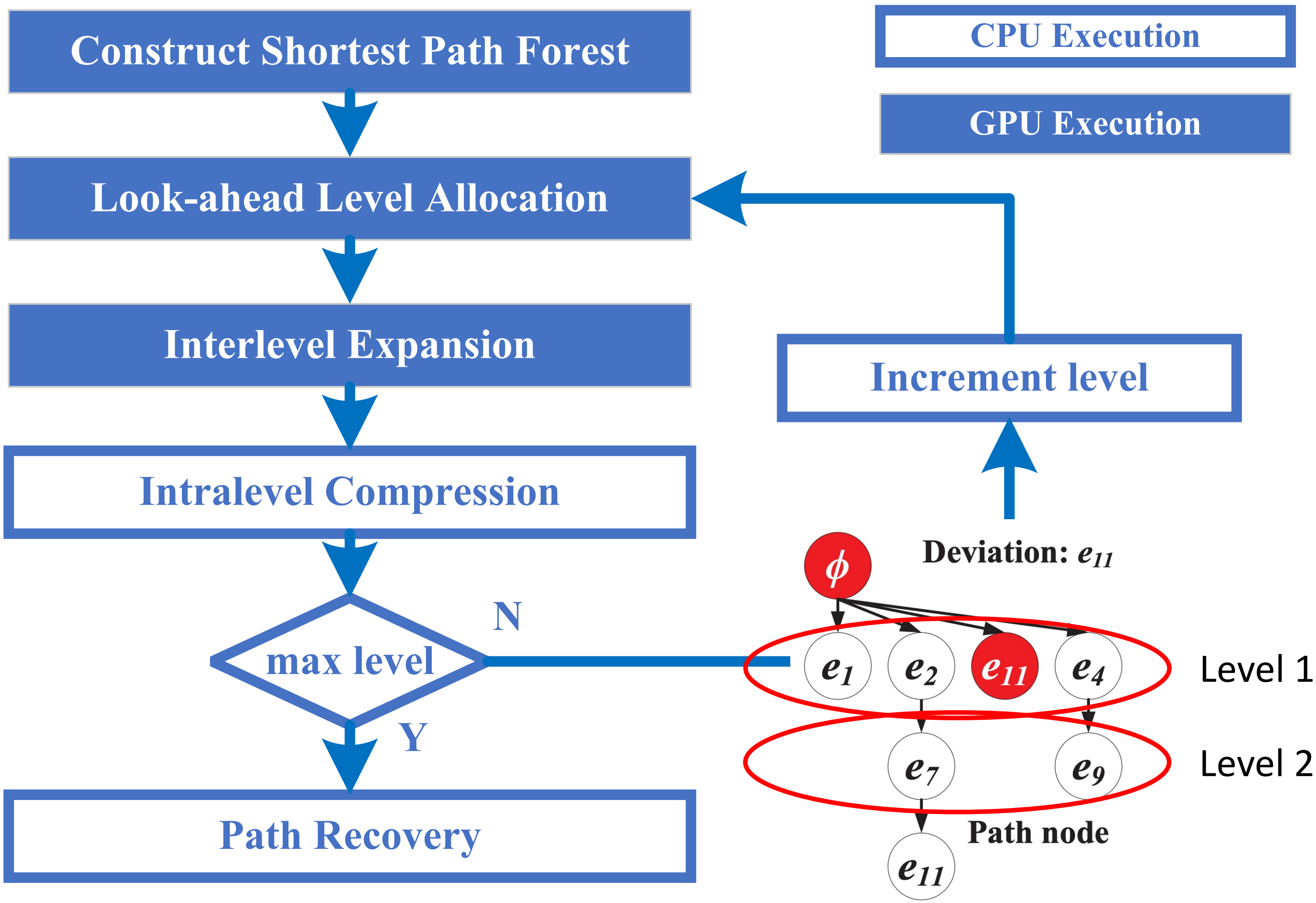
- **OpenTimer adopts implicit path representation**
  - Each path is represented using *O(1)* space and time
  - Each path is ranked through a *prefix* tree & a *suffix* tree



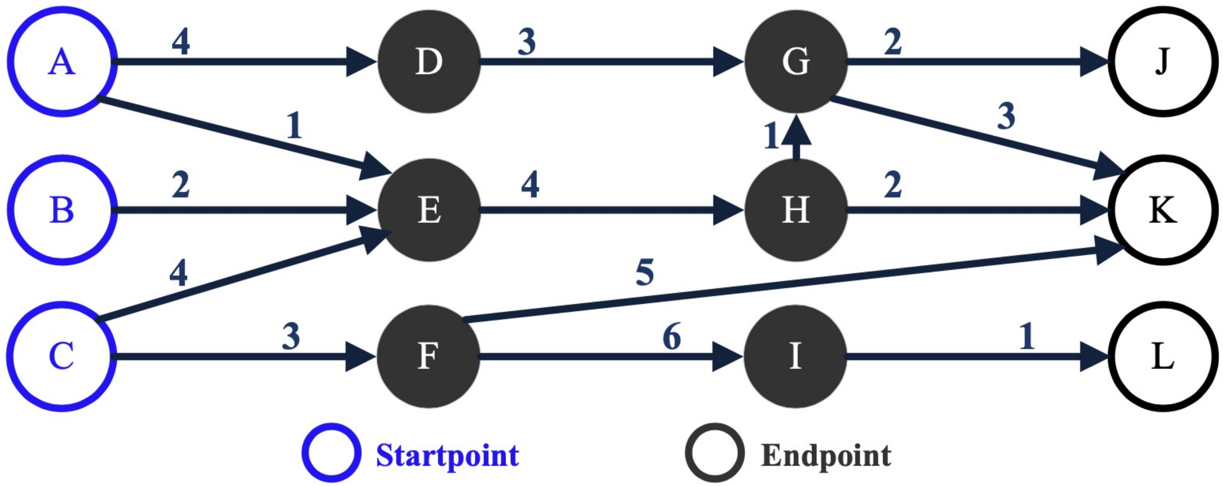
Path suffix: $\langle e_{14} \rangle$ + Path prefix: $\langle e_3, e_8, e_{11} \rangle$ = Path: $\langle e_3, e_8, e_{11}, e_{14} \rangle$

T.-W. Huang et al., "OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," IEEE TCAD21

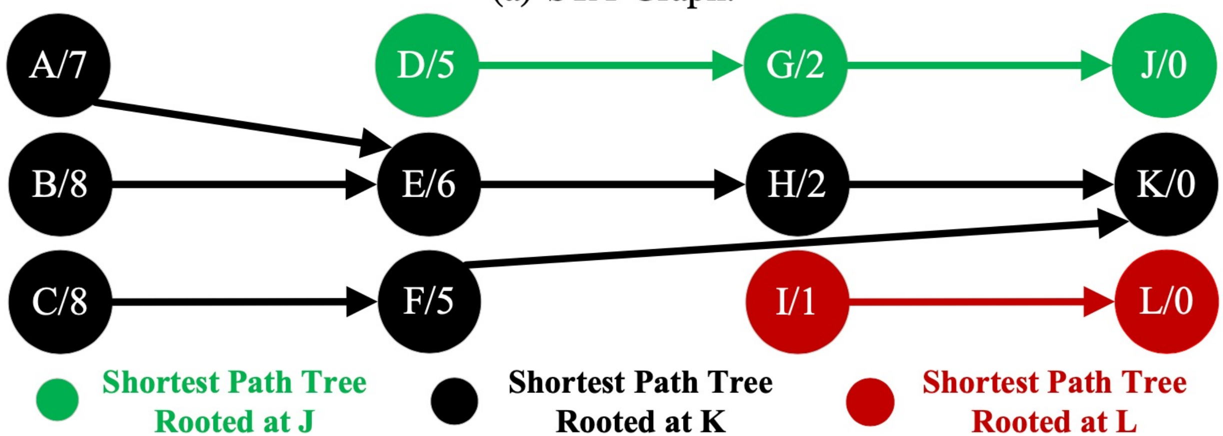
GPU-Accelerated PBA Algorithm Flow



Step #1: Generate Suffix Tree on GPU

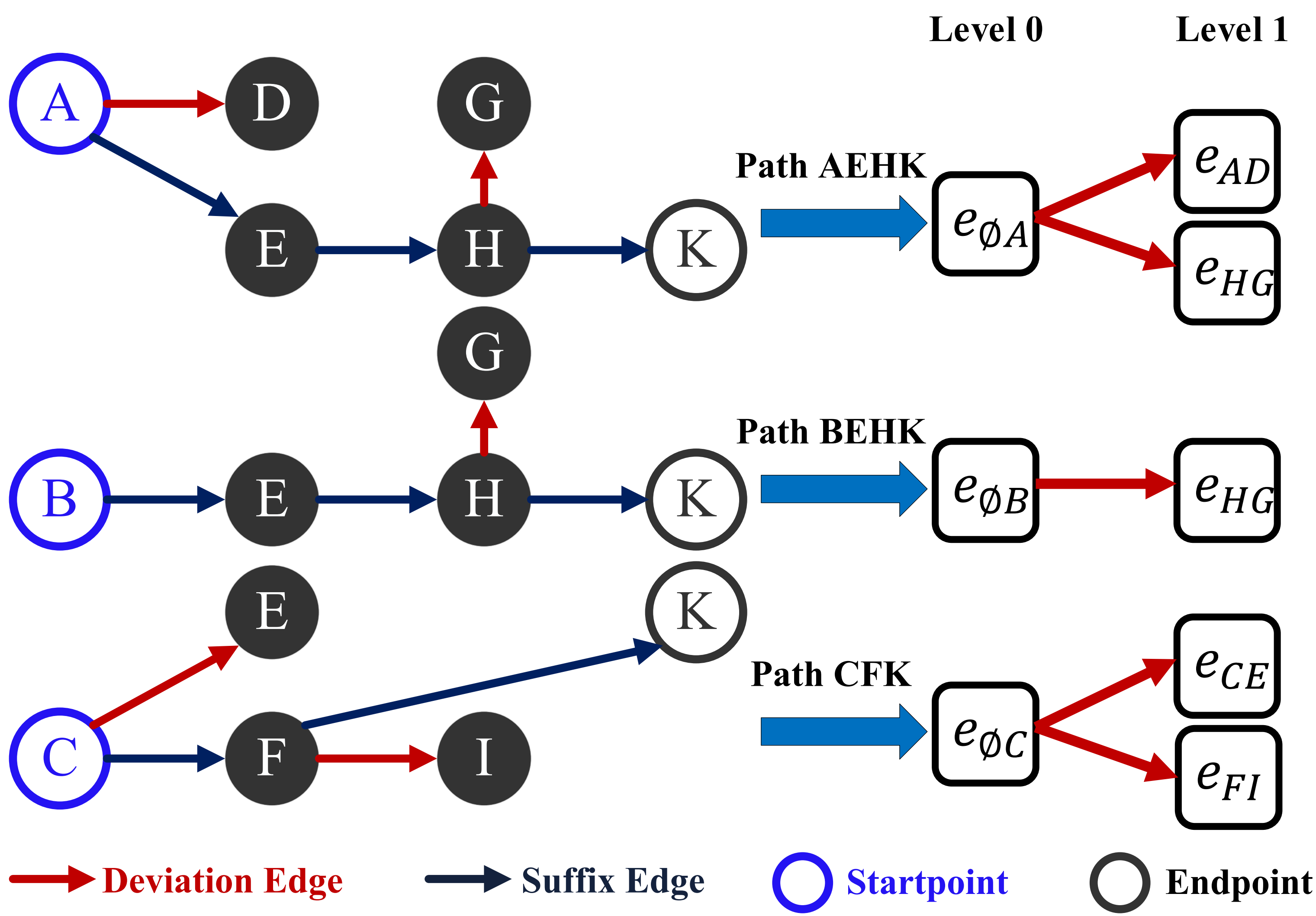


(a) STA Graph.



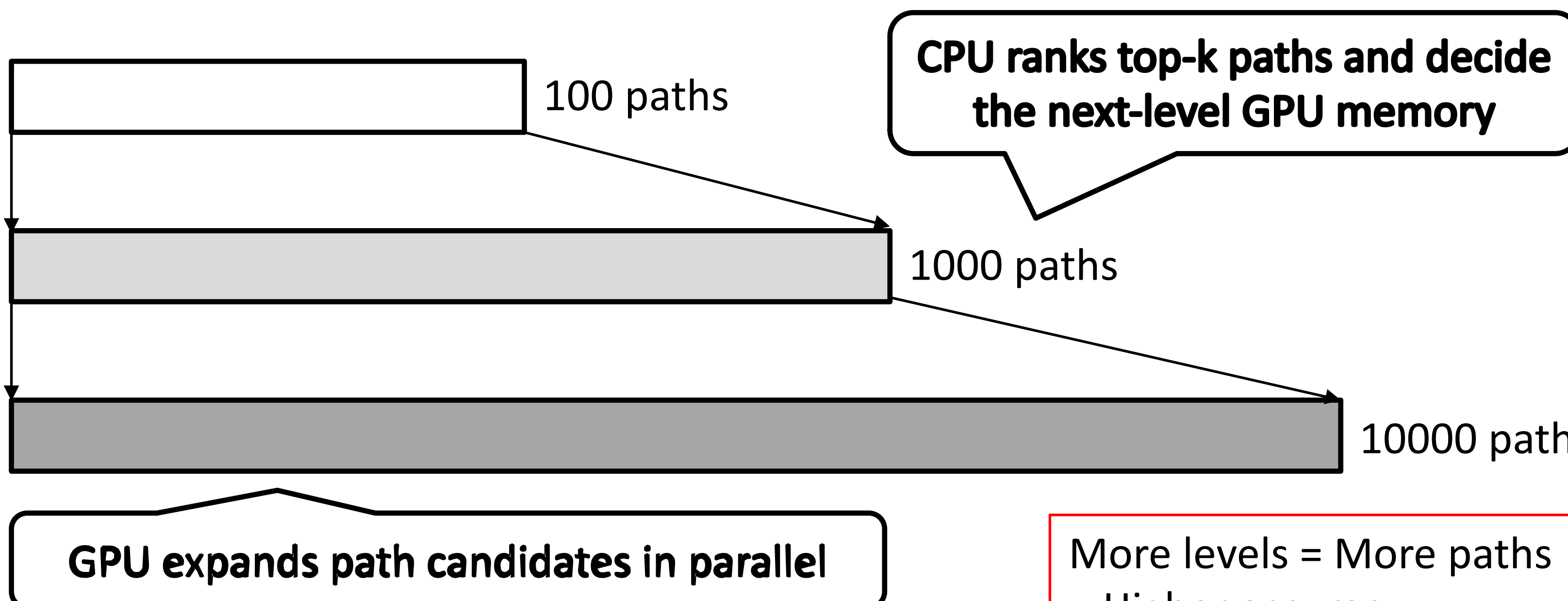
(b) Shortest path forest.

Step #2: Expand Prefix Tree on GPU



Step #2: Expand Prefix Tree on GPU (cont'd)

- **Iteratively grow GPU memory at each expansion**
  - Each iteration uses GPU to decide path candidates
  - Each iteration uses CPU to prune path candidates
  - Each path candidate takes O(1) space "deviation edge"



More levels = More paths = Higher accuracy

Experiment Setting

- **Machine configuration**
  - Nvidia CUDA, RTX 2080
  - 40 Intel Xeon Gold 6138 CPU cores
- **Measure the accuracy-runtime tradeoff**
  - "MDL" stands for maximum deviation level
- **Execution parameters for GPU kernels**
  - Suffix tree kernel
    - 1024 threads per block
  - Prefix tree kernel
    - 1024 threads per block

Overall Performance

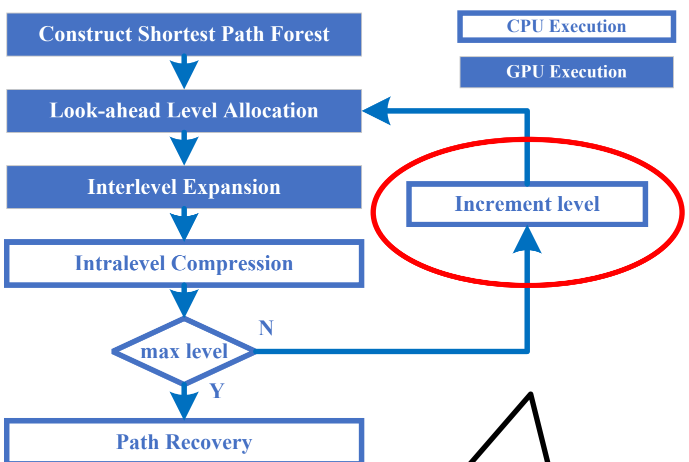
- Compare with OpenTimer's CPU-based PBA
  - Report speed-up at different MDLs

Benchmark	#Pins	#Gates	#Arcs	OpenTimer Runtime	Our Algorithm #MDL=10		Our Algorithm #MDL=15		Our Algorithm #MDL=20	
					Runtime	Speed-up	Runtime	Speed-up	Runtime	Speed-up
leon2	4328255	1616399	7984262	2875783	4708.36	611×	5295.49ms	543×	5413.84	531×
leon3mp	3376821	1247725	6277562	1217886	5520.85	221×	7091.79ms	172×	8182.84	149×
netcard	3999174	1496719	7404006	752188	2050.60	367×	2475.90ms	304×	2484.08	303×
vga_lcd	397809	139529	756631	53204	682.94	77.9×	683.04ms	77.9×	706.16	75.3×
vga_lcd_iccad	679258	259067	1243041	66582	720.40	92.4×	754.35ms	88.3×	766.29	86.9×
b19_iccad	782914	255278	1576198	402645	2144.67	188×	2948.94ms	137×	3483.05	116×
des_perf_ispd	371587	138878	697145	24120	763.79	31.6×	766.31ms	31.5×	780.56	30.9×
edit_dist_ispd	416609	147650	799167	614043	1818.49	338×	2475.12ms	248×	2900.14	212×
mgc_edit_dist	450354	161692	852615	694014	1463.61	474×	1485.65ms	467×	1493.90	465×
mgc_matric_mult	492568	171282	948154	214980	994.67	216×	1075.90ms	200×	1113.26	193×

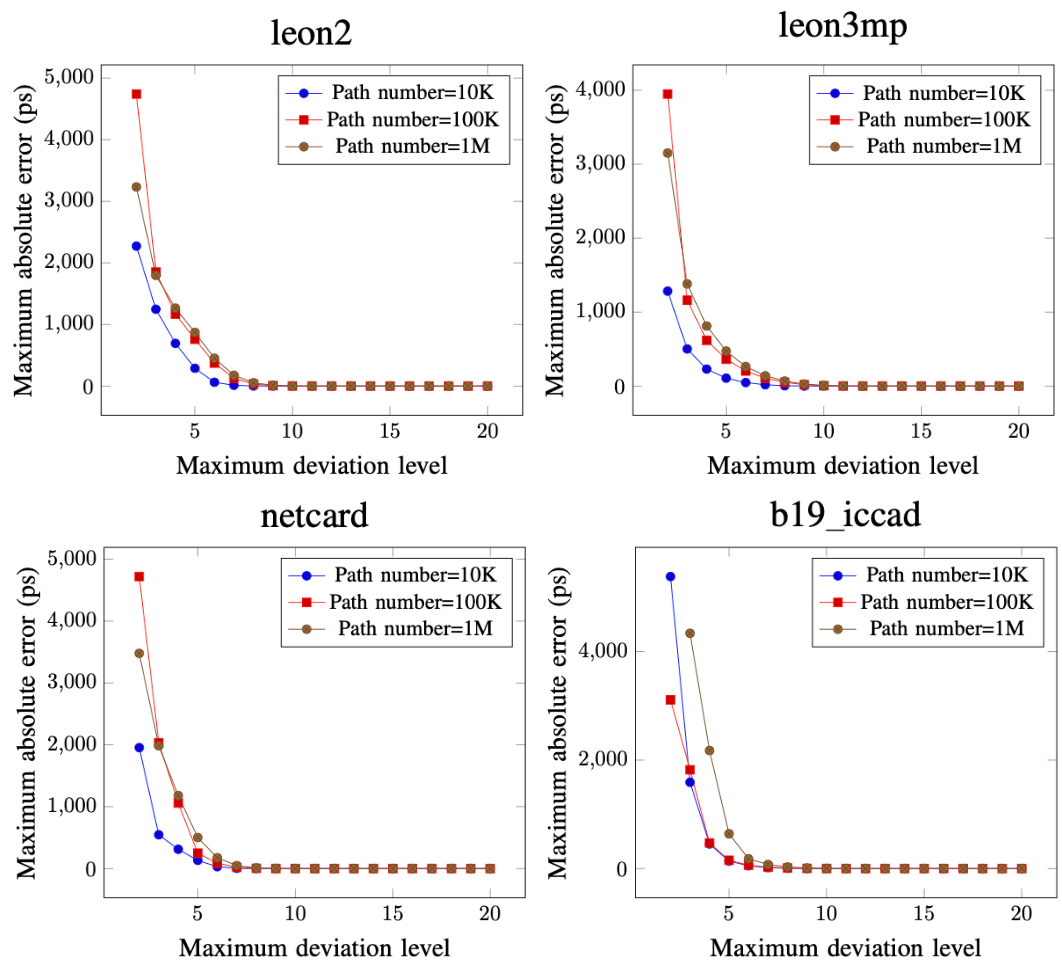
- Achieve significant speed-up at large designs
  - 611x speed-up in leon2 (1.3M gates)
  - 221x speed-up in leon3mp (1.2M gates)

Path Accuracy vs MDL

- ❑ Achieve decent accuracy at 10—12 GPU iterations



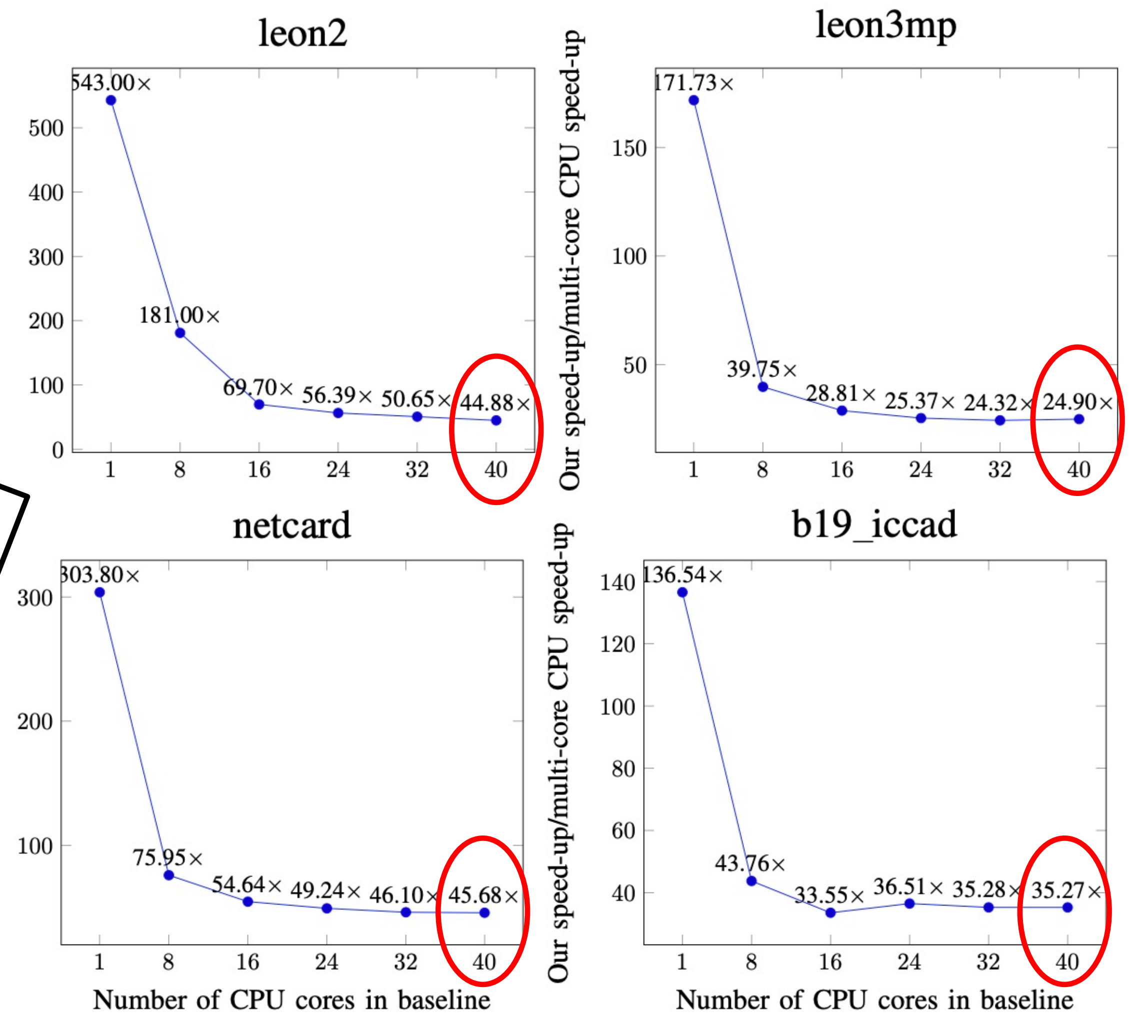
More GPU expansions (iterations) lead to higher numbers of paths and thus better accuracy



Path Accuracy vs MDL

- one GPU is even faster than OpenTimer with 40 CPUs
  - 44x on leon2
  - 25x on leon3mp
  - 46x on netcard
  - 35x on b19

In fact, according to our experiments, our GPU-accelerated PBA is always faster than OpenTimer's CPU baseline regardless of the core count



Conclusion

- **Introduced the runtime challenges of STA**
  - Knew graph-based analysis
  - Knew path-based analysis
- **Accelerated the graph-based analysis using GPU**
  - Achieved 4x speed-up on large designs
- **Accelerated the path-based analysis using GPU**
  - Achieved 600x speed-up on large designs
- **Future work**
  - Design GPU-accelerated incremental timing
  - Design load-balanced PBA algorithms on GPU
  - Leverage modern GPU graph parallelism

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