Taskflow: A General-purpose Task-parallel Programming System

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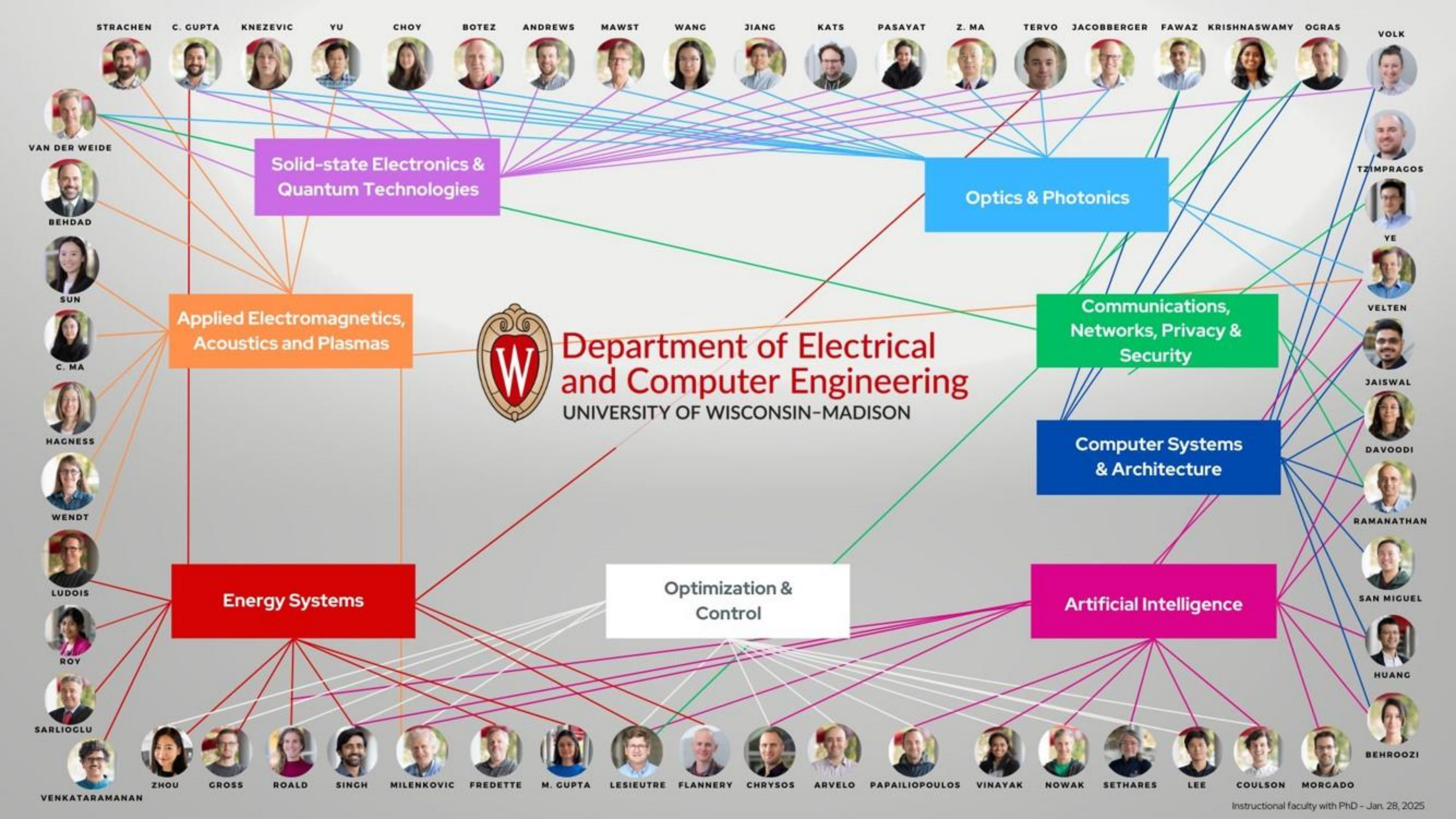
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Takeaways

- Express your parallelism in the right way
- Program static task graph parallelism using Taskflow
- Program dynamic task graph parallelism using Taskflow
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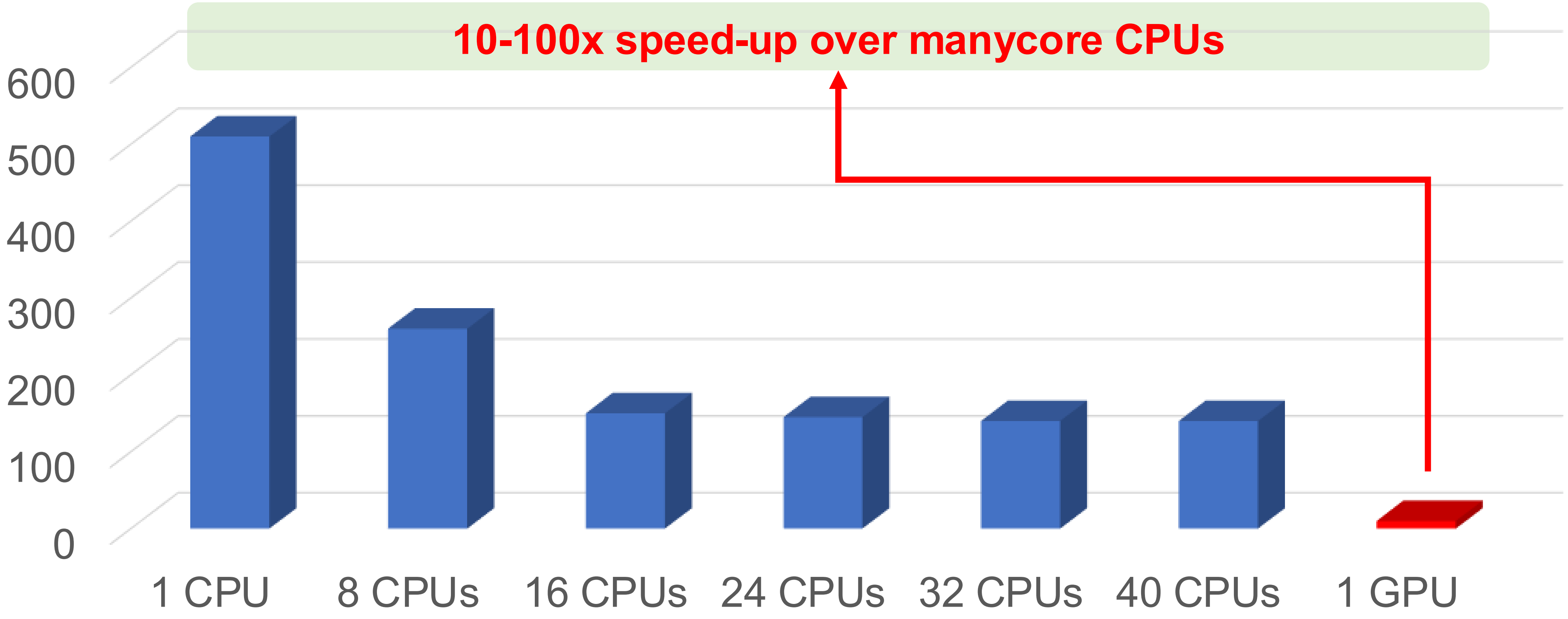
- Demonstrate the efficiency of Taskflow
- Conclude the talk

Why Parallel Computing?

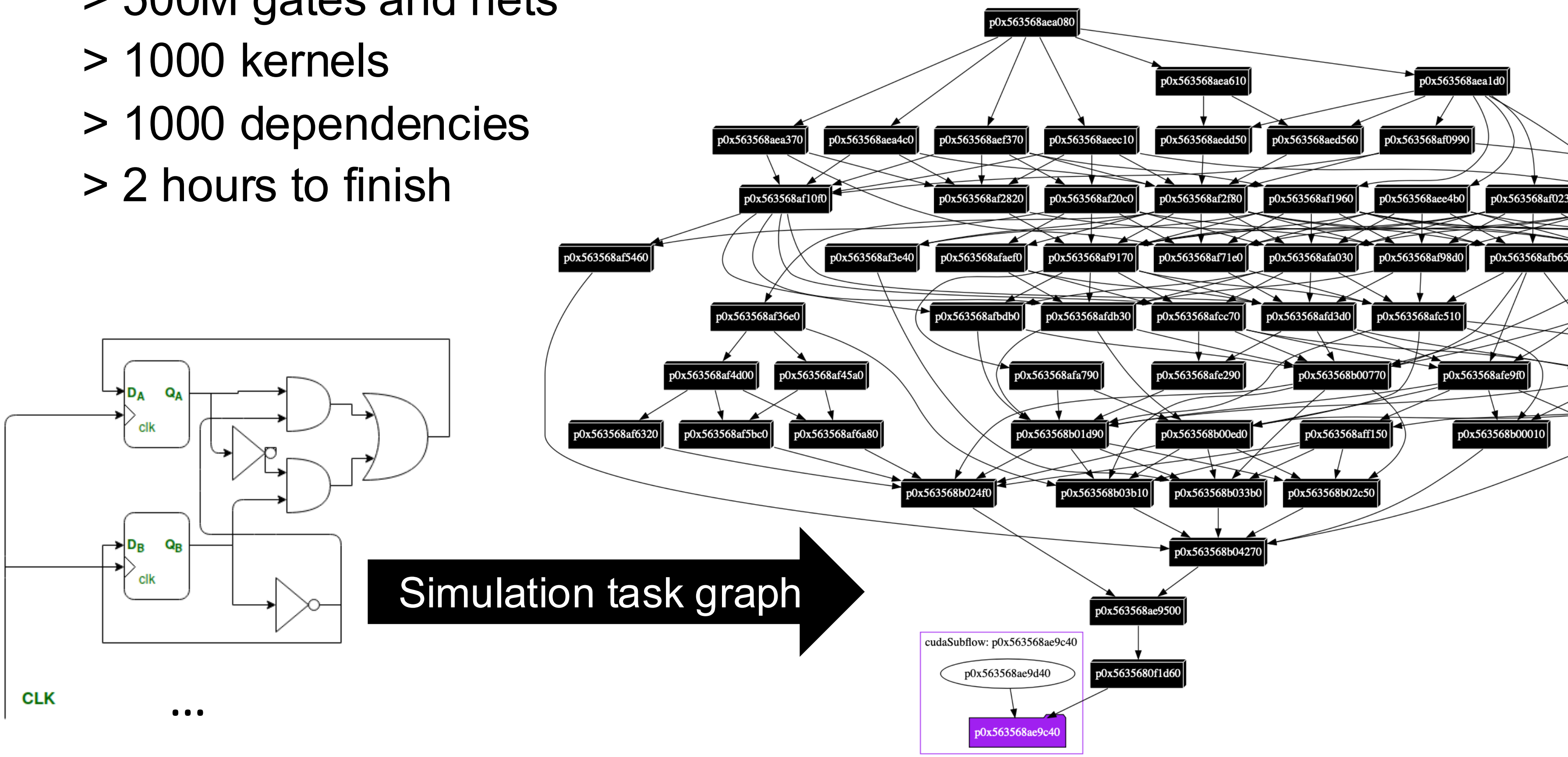
- **Advances performance to a new level previously out of reach**



Time (minutes) to speed up a circuit timing analysis algorithm

Today's Parallel Workload is Very Complex

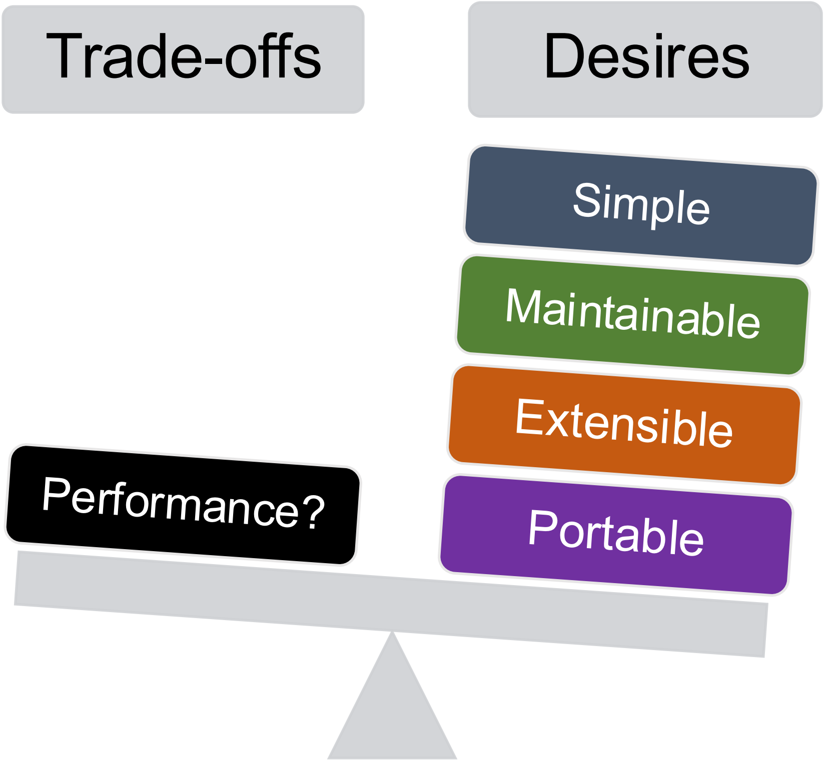
- **GPU-parallel circuit simulation task graph of Nvidia's NVDLA design[1]**
  - > 500M gates and nets
  - > 1000 kernels
  - > 1000 dependencies
  - > 2 hours to finish



[1]: Dian-Lun Lin, et al, "From RTL to CUDA: A GPU Acceleration Flow for RTL Simulation with Batch Stimulus," *ACM ICPP*, 2022

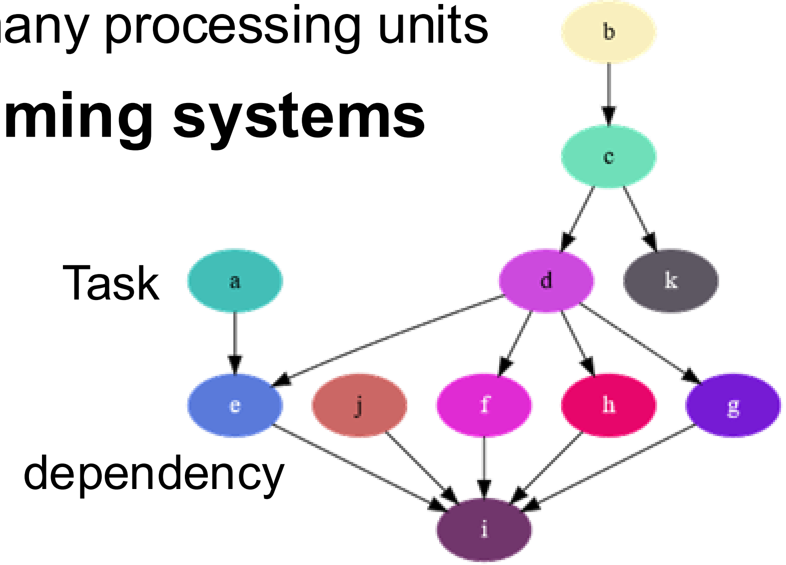
Parallel Programming is Not Easy

- **You need to deal with A LOT OF technical details**
  - Parallelism abstraction (software + hardware)
  - Concurrency control
  - Task and data race avoidance
  - Dependency constraints
  - Scheduling efficiencies (load balancing)
  - Performance portability
  - …
- **And, don't forget about trade-offs**
  - Performance vs Desires



Need a Good Programming Abstraction

- **From user's perspective, the biggest challenge is *transparency***
  - Programming abstraction, runtime optimization, load balancing, etc.
- **Observing from the evolution of parallel programming standards:**
  - ***Task graph parallelism*** (TGP) is the best model for future parallel architectures
    - Capture programmers' intention in decomposing a heterogeneous algorithm into a top-down task graph
    - Runtime can schedule dependent tasks across many processing units
- **Increasing numbers of task-parallel programming systems**



Two Problems of Existing Tools for EDA …

- **EDA has very complex task dependencies**
  - **Example**: analysis algorithms compute the circuit network of multi-millions of nodes and dependencies
  - **Problem**: existing tools are often good at loop parallelism (e.g., embarrassingly-parallel loops) but weak in expressing task graphs at this large scale
- **EDA has very complex control flow**
  - **Example**: synthesis algorithms make essential use of *dynamic control flow* to implement various patterns
    - Combinatorial optimization (e.g., graph algorithms, discrete math)
    - Analytical methods (e.g., physical synthesis)
  - **Problem**: existing tools are often limited to *direct acyclic graph* (DAC) models, requiring users to manually partition their workloads around control-flow or decision-making points

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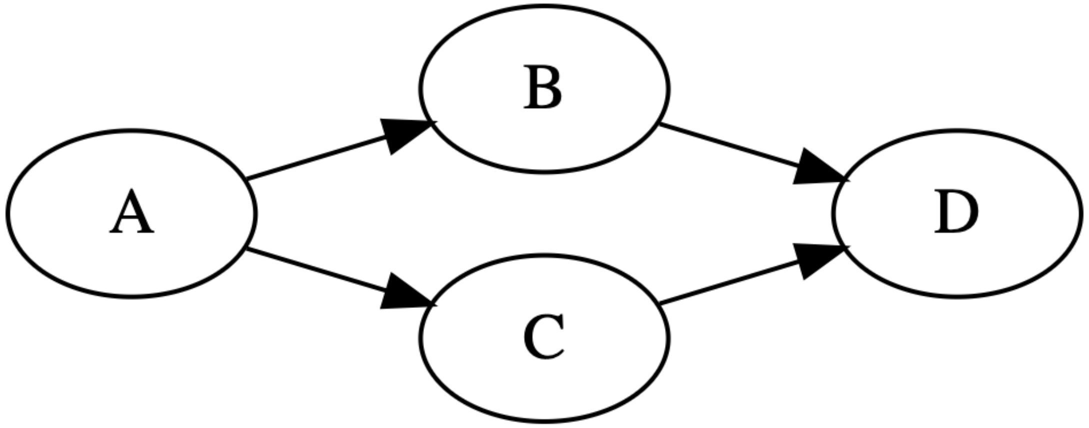
"Hello World" in Taskflow[1]

```
#include <taskflow/taskflow.hpp>
int main(){
    tf::Taskflow taskflow;
    tf::Executor executor;
    auto [A, B, C, D] = taskflow.emplace(
        [] () { std::cout << "TaskA\n"; }
        [] () { std::cout << "TaskB\n"; },
        [] () { std::cout << "TaskC\n"; },
        [] () { std::cout << "TaskD\n"; }
    );
    A.precede(B, C);
    D.succeed(B, C);
    executor.run(taskflow).wait();
    return 0;
}
```

// live: https://godbolt.org/z/j8hx3xnnx



[1]: T.-W. Huang, et. al, "Taskflow: A Lightweight Parallel and Heterogeneous Task Graph Computing System," *IEEE TPDS*, 2022

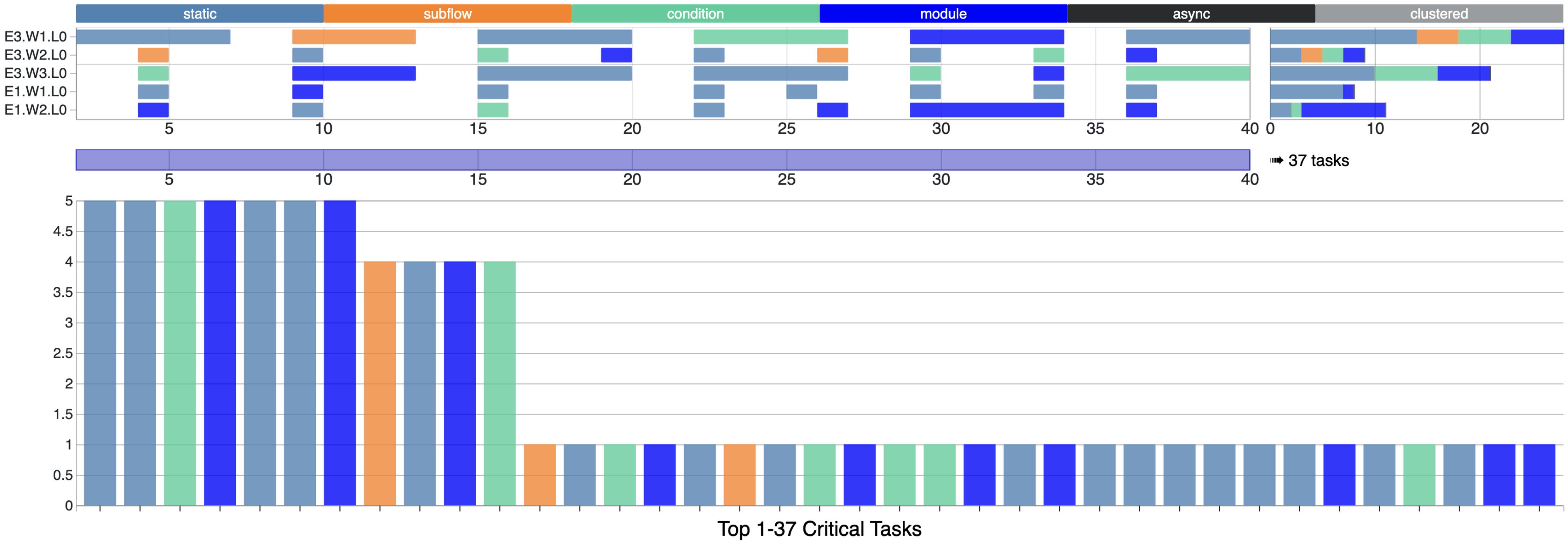
Taskflow Supports Drop-in Integration

- **Taskflow is header-only – *no wrangle with installation***

```
# clone the Taskflow project
~$ git clone https://github.com/taskflow/taskflow.git
~$ cd taskflow
# compile your program and tell it where to find Taskflow header files
~$ g++ -std=c++20 examples/simple.cpp –I ./ -O2 -pthread -o simple
~$ ./simple
TaskA
TaskC
TaskB
TaskD
```

Built-in Task Execution Visualizer

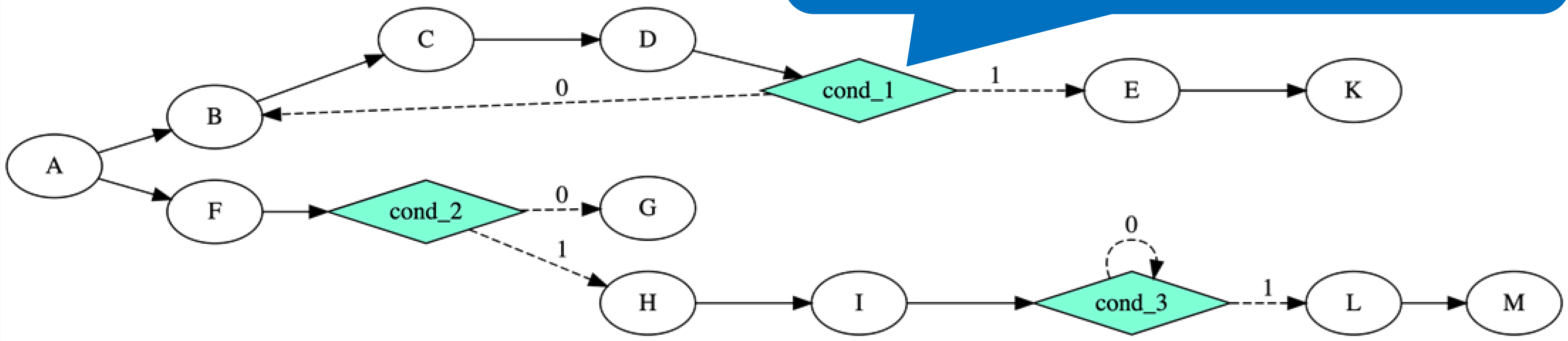
```
# run you program with the env variable TF_ENABLE_PROFILER enabled
# and paste the JSON content to https://taskflow.github.io/tfprof/
~$ TF_ENABLE_PROFILER=simple.json ./simple
```



Control Taskflow Graph Programming (CTFG)

```
// CTFG goes beyond the limitation of traditional DAG-based models
auto cond_1 = taskflow.emplace([](){ return run_B() ? 0 : 1; }); // 0: is the index of B
auto cond_2 = taskflow.emplace([](){ return run_G() ? 0 : 1; }); // 0: is the index of G
auto cond_3 = taskflow.emplace([](){ return loop() ? 0 : 1; }); // 0: is the index of cond_3
cond_1.precede(B, E);         // cycle
cond_2.precede(G, H);         // if-else
cond_3.precede(cond_3, L);    // loop
```

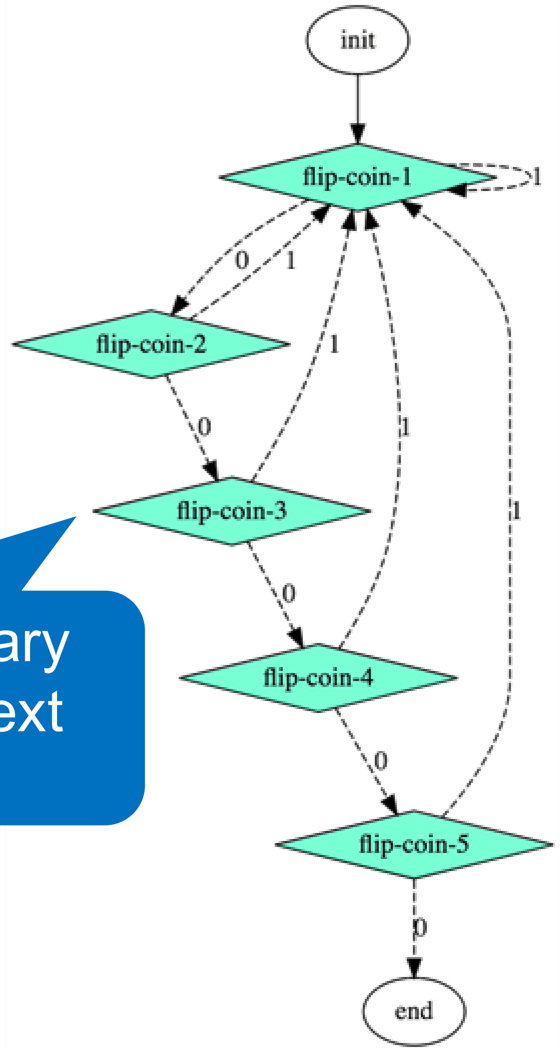
Very difficult for existing DAG-based systems to express an efficient overlap between tasks and control flow …



Non-deterministic Control Flow with CTFG

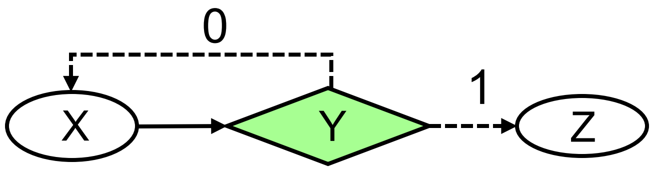
```
auto A = taskflow.emplace([&](){ } );
auto B = taskflow.emplace([&](){ return rand()%2; } );
auto C = taskflow.emplace([&](){ return rand()%2; } );
auto D = taskflow.emplace([&](){ return rand()%2; } );
auto E = taskflow.emplace([&](){ return rand()%2; } );
auto F = taskflow.emplace([&](){ return rand()%2; } );
auto G = taskflow.emplace([&](){});
A.precede(B).name("init");
B.precede(C, B).name("flip-coin-1");
C.precede(D, B).name("flip-coin-2");
D.precede(E, B).name("flip-coin-3");
E.precede(F, B).name("flip-coin-4");
F.precede(G, B).name("flip-coin-5");
G.name("end");
```

Each task flips a binary coin to decide the next task to run



Existing Frameworks on Control Flow?

- **Most existing libraries are DAG-based**
  - Do not anticipate conditional execution …
- **Unroll a task graph over fixed iterations**
  - Task graph size becomes very large …
- **What about dynamic control flow?**
  - Resort to client-side partitions of the task graph around each decision-making points
  - Synchronize the execution of partitioned task graphs around decision-making points
  - Lack end-to-end parallelism



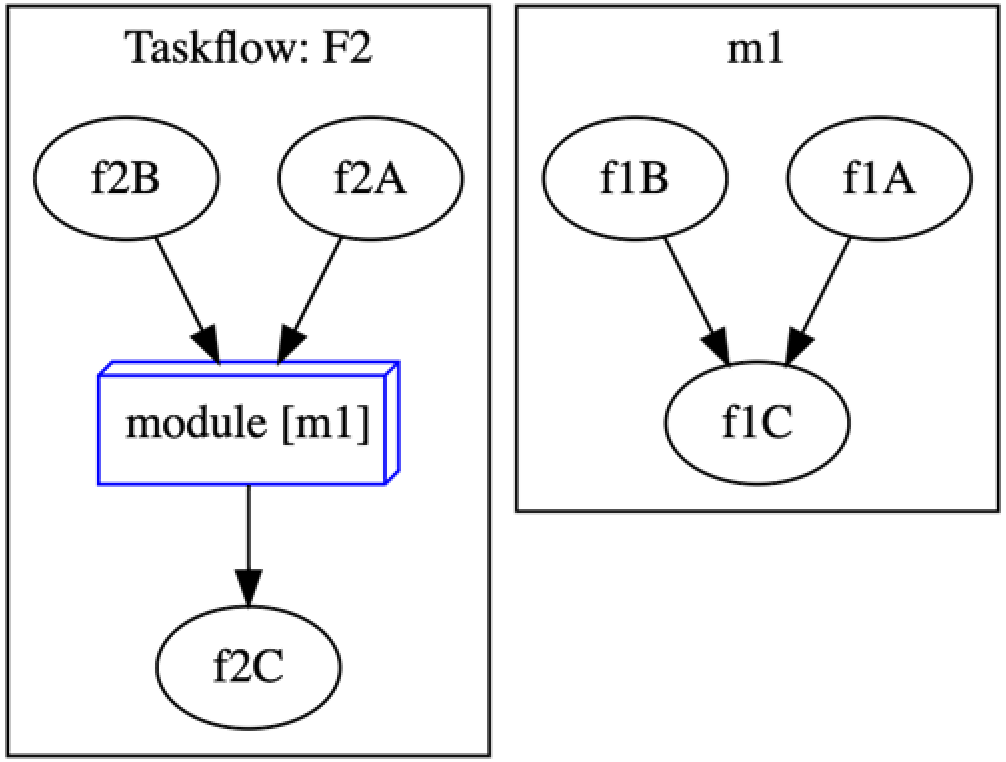

```
tf::Taskflow G;
auto X = G.emplace([](){});
auto Y = G.emplace([](){
  return converged() ? 1 : 0;
});
cond.precede(Z, X);
executor.run(G).wait();
```

```
tbb::flow::graph[1] X, Y, Z;
do {
  X.run();
  Y.run();
} while (!converged());
Z.run();
```

[1]: oneAPI Threading Building Blocks (oneTBB): https://github.com/uxlfoundation/oneTBB

Composable Tasking

```
tf::Taskflow f1, f2;
auto [f1A, f1B] = f1.emplace(
  []() { std::cout << "Task f1A\n"; },
  []() { std::cout << "Task f1B\n"; }
);
auto [f2A, f2B, f2C] = f2.emplace(
  []() { std::cout << "Task f2A\n"; },
  []() { std::cout << "Task f2B\n"; },
  []() { std::cout << "Task f2C\n"; }
);
auto f1_module_task = f2.composed_of(f1);
f1_module_task.succeed(f2A, f2B)
              .precede(f2C);
```

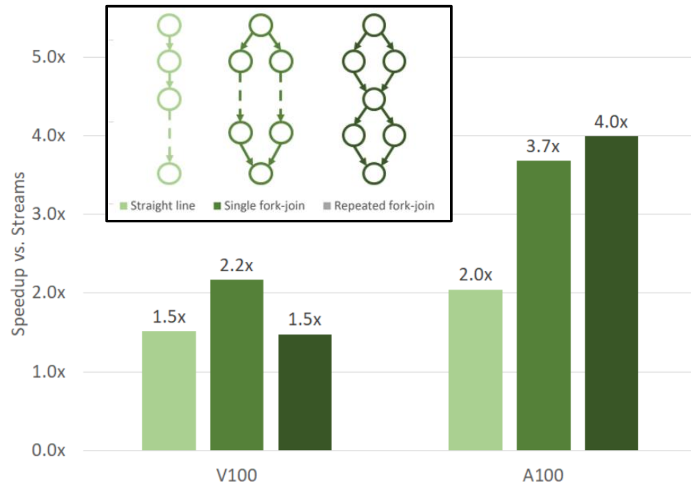


GPU Tasking with CUDA Graph[1]

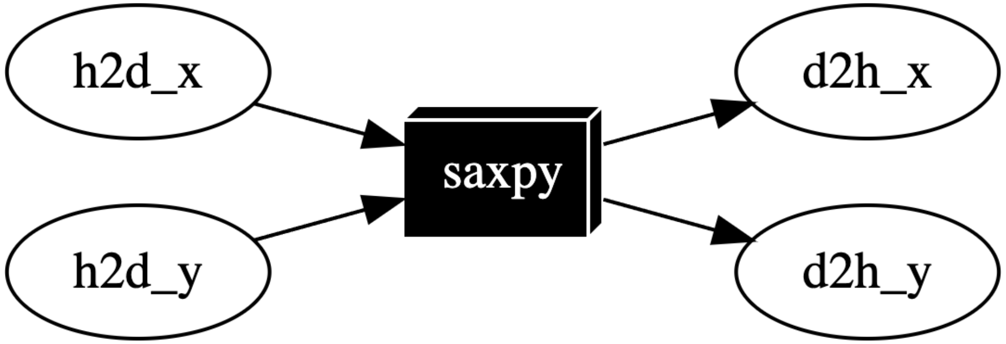
```
tf::cudaGraph cg;
auto h2d_x = cg.copy(dx, hx.data(), N);
auto h2d_y = cg.copy(dy, hy.data(), N);
auto d2h_x = cg.copy(hx.data(), dx, N);
auto d2h_y = cg.copy(hy.data(), dy, N);

// saxpy kernel with 4 blocks each of 512 threads
auto kernel = cg.kernel(4, 512, 0, saxpy, N, 2f, dx, dy);
kernel.succeed(h2d_x, h2d_y).precede(d2h_x, d2h_y);

// create an executable and run it 10 times
tf::cudaGraphExec exec(cg);
tf::cudaStream stream;
stream.run_n(exec, 10).synchronize();
```



Advantage of CUDA Graph



[1]: Dian-Lun Lin and Tsung-Wei Huang, "Efficient GPU Computation using Task Graph Parallelism," *Euro-Par*, 2021

Everything is Composable in Taskflow

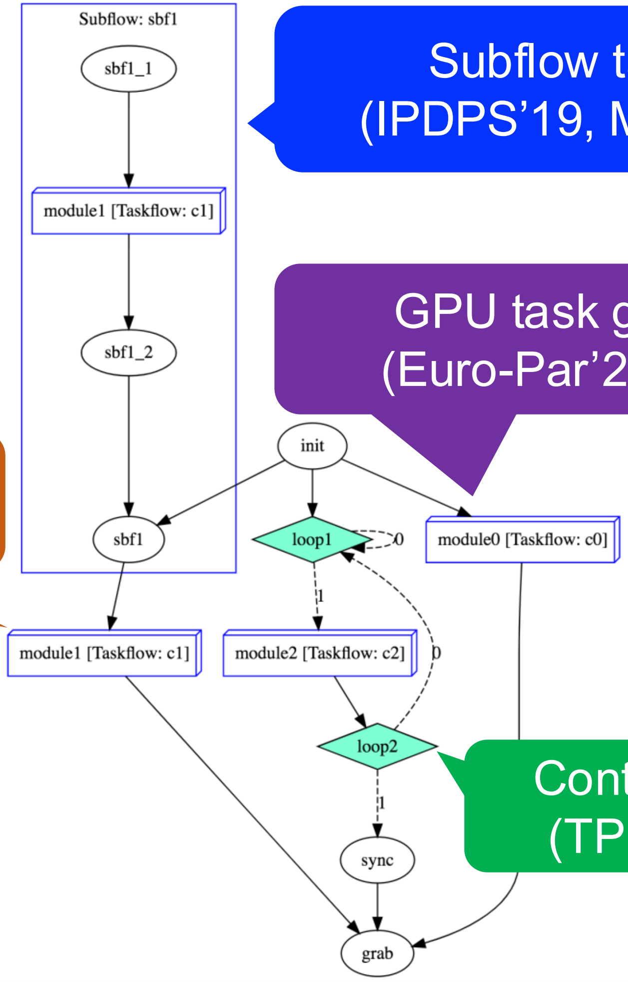
- **End-to-end parallelism in one graph**
  - Task, dependency, control flow all together
  - Scheduling with whole-graph optimization
  - Efficient overlap among heterogeneous tasks
- **Largely improved productivity!**

Subflow task (IPDPS’19, MM’19)

GPU task graph (Euro-Par’21,’24)

Composition (HPDC’22, ICPP’22, HPEC’19)

Control flow (TPDS’22)



Industrial use-case of productivity improvement using Taskflow[1]

jcelerier
ossia score

Reddit: https://www.reddit.com/r/cpp/ [under taskflow]

I've migrated https://ossia.io from TBB flow graph to taskflow a couple weeks ago. Net +8% of throughput on the graph processing itself, and took only a couple hours to do the change. Also don't have to fight with building the TBB libraries for 30 different platforms and configurations since it's header only.

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[1]: OSSIA’s experience with Taskflow: https://www.reddit.com/r/cpp/comments/g8ebnj/cpptaskflow_a_generalpurpose_parallel_and/

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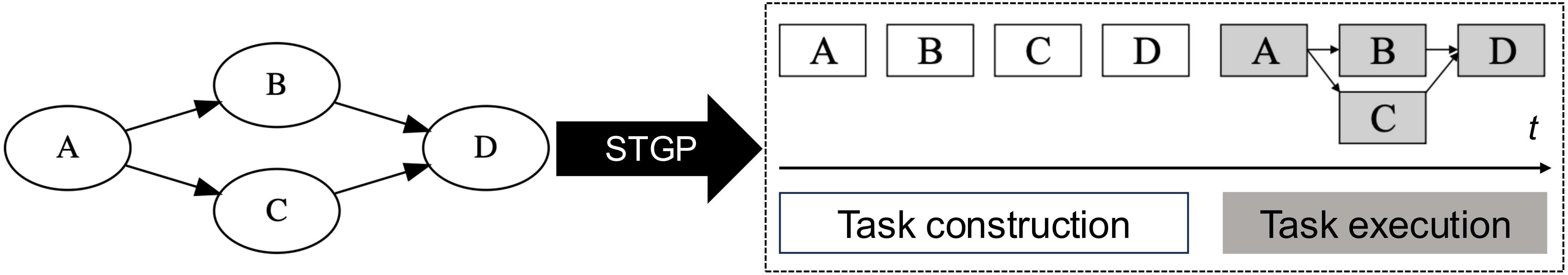
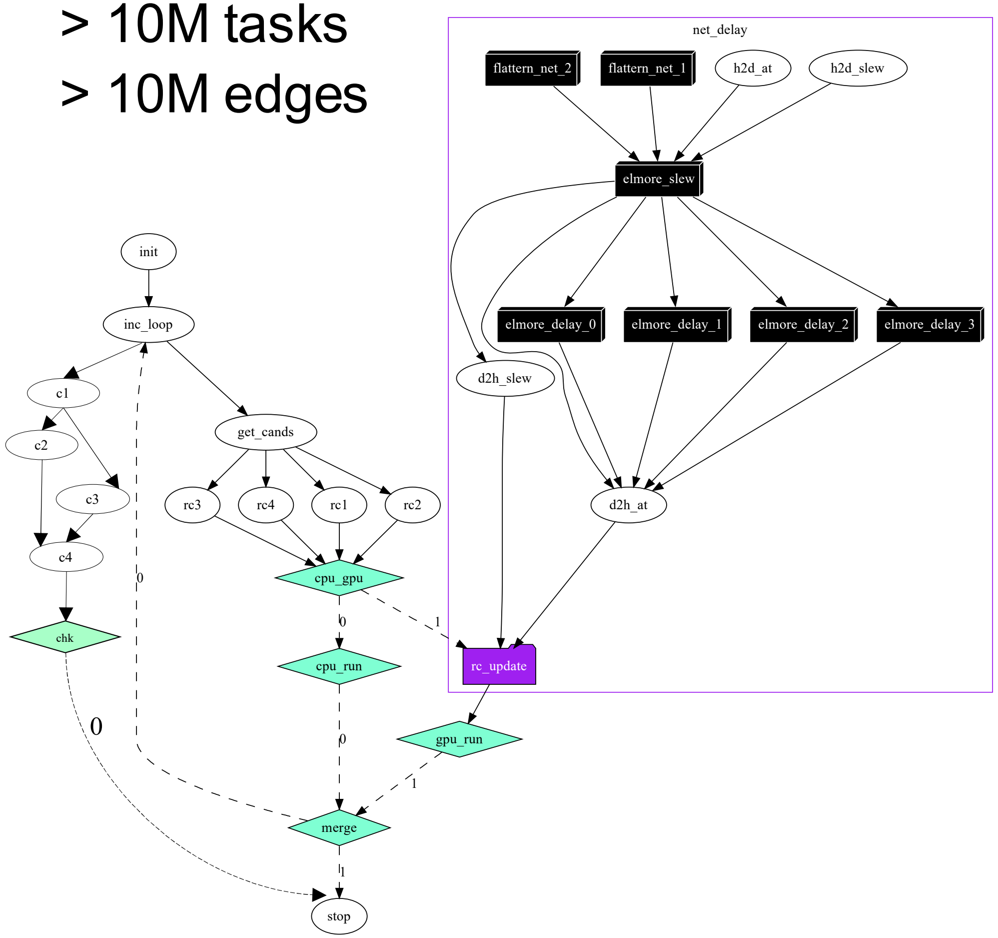
Static Task Graph Parallelism (STGP)

- **In STGP, the graph structure must be known up front**
  - Execution of STGP is based on the *construct-and-run* model
- **Lack of overlap between task construction and task execution**
  - For large task graphs (e.g., multi-million tasks and dependencies), such an overlap can bring a significant performance advantage
- **Lack of flexible and dynamic expression of TGP**
  - Task graph structure cannot depend on runtime values or control-flow results

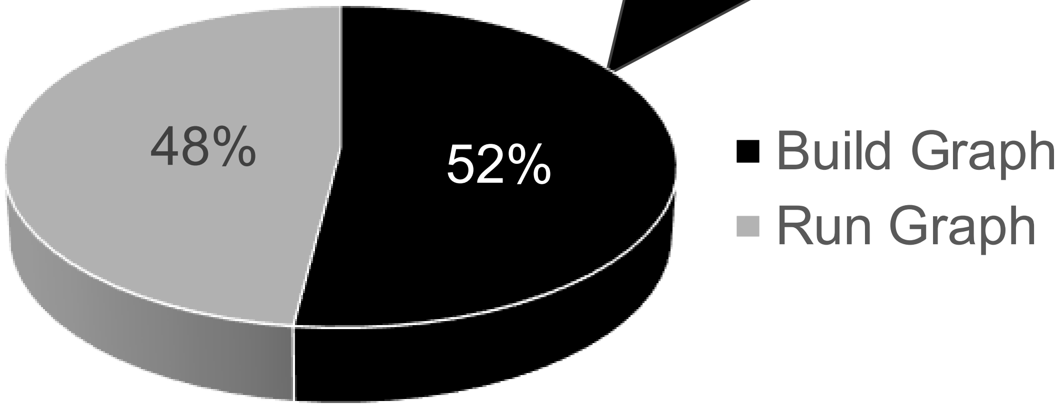


Problem of STGP: Example #1

- **Runtime breakdown of a task-parallel circuit timing analyzer**[1]
  - > 10M tasks
  - > 10M edges



Task graph construction time takes over 50% of the entire runtime (typically done in one thread)



[1]: Tsung-Wei Huang, et al, "OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," IEEE TCAD, 2022

Problem of STGP: Example #2

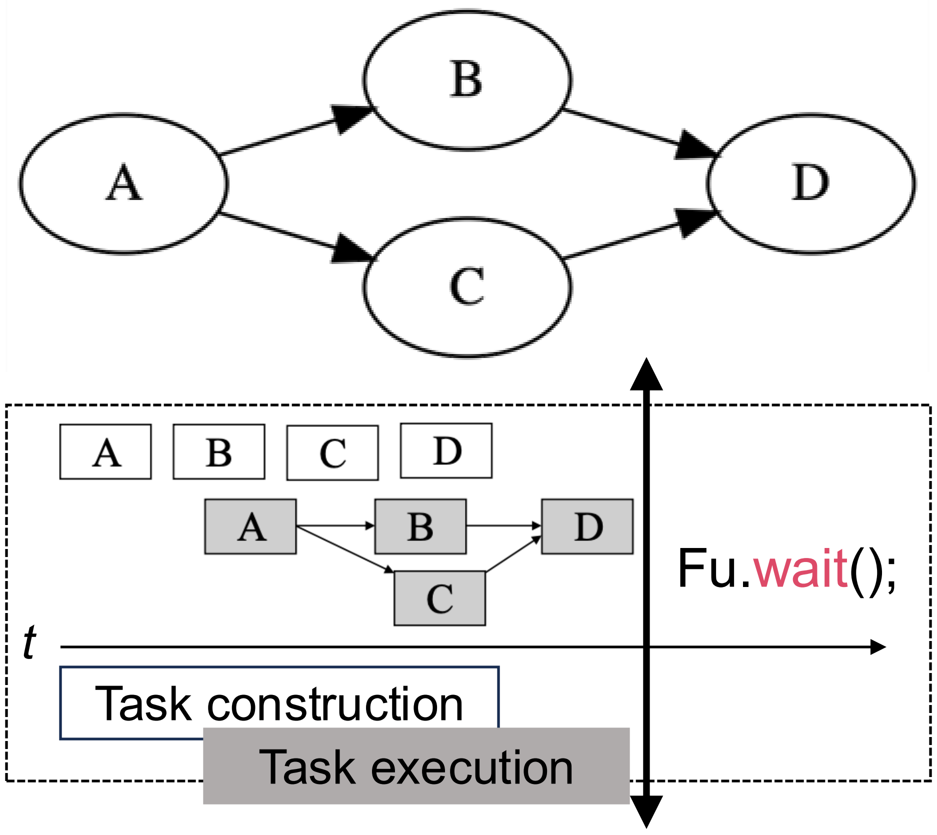
- **Express TGP that depends on runtime variables…?**

```
if (a == true) {
  G1 = build_task_graph1();
  if (b == true) {
    G2 = build_task_graph2();
    G1.precede(G2);
    if (c == true) {
      … // need another different TGP
    }
  }
  else {
    G3 = build_task_graph3();
    G3.precede(G1);
}
```

```
G1 = build_task_graph1();
G2 = build_task_graph2();
if (G1.num_tasks() == 100) {
    G1.precede(G2);
}
else {
    G3 = build_task_graph3();
    G2.precede(G1, G3);
    if (G2.num_dependencies() >= 10) {
    {
      … // define dependencies on the fly
    }
}
```

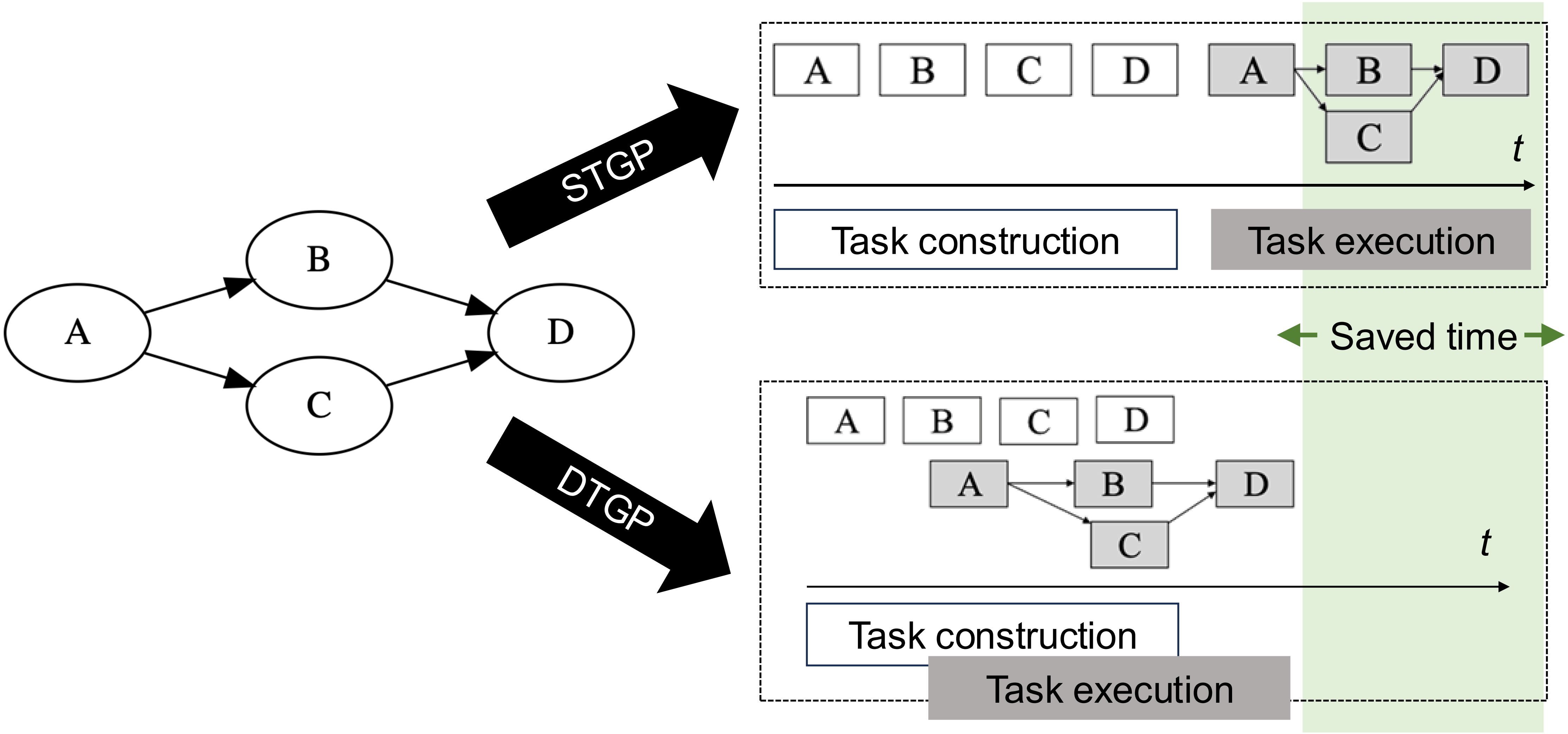
Dynamic TGP (DTGP) in Taskflow

```
// Live: https://godbolt.org/z/j76ThGbWK
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
auto [D, Fu] = executor.dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
Fu.wait();
```



Specify arbitrary task dependencies using C++ variadic parameter pack

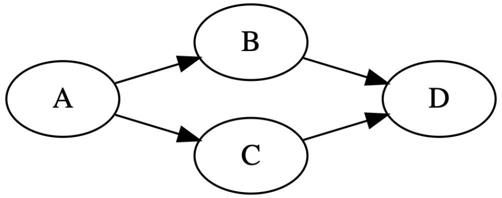
Comparison between STGP and DTGP

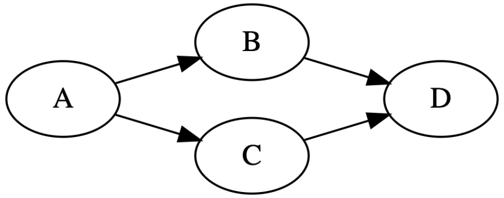


DTGP Needs a Correct Topological Order

```
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
auto D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
```

Topological order #1: A→B→C→D





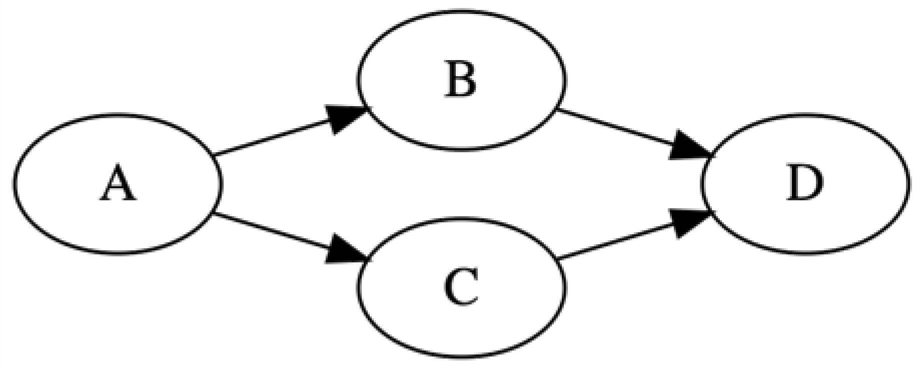
Topological order #2: A→C→B→D

```
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
```

Incorrect Topological Order …

```
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B-is-unavailable-yet, C-is-unavailable-yet);

auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
executor.wait_for_all();
```



An incorrect topological order (A→D→B→C) disallows us from expressing correct DTGP

Variable Range of Task Dependencies

- **Both methods can take a range of dependent-async tasks**
  - useful when the task dependencies come as a runtime variable

```
// Live: https://godbolt.org/z/6Pvco4KeE
std::vector<tf::AsyncTask> tasks = {
  executor.silent_dependent_async([](){ std::cout << "TaskA\n"; }),
  executor.silent_dependent_async([](){ std::cout << "TaskB\n"; }),
  executor.silent_dependent_async([](){ std::cout << "TaskC\n"; }),
  executor.silent_dependent_async([](){ std::cout << "TaskD\n"; })
};

// create a dependent-async tasks that depends on tasks, A, B, C, and D
executor.dependent_async([](){}, tasks.begin(), tasks.end());

// create a silent-dependent-async tasks that depends on tasks, A, B, C, and D
executor.silent_dependent_async([](){}, tasks.begin(), tasks.end());
```

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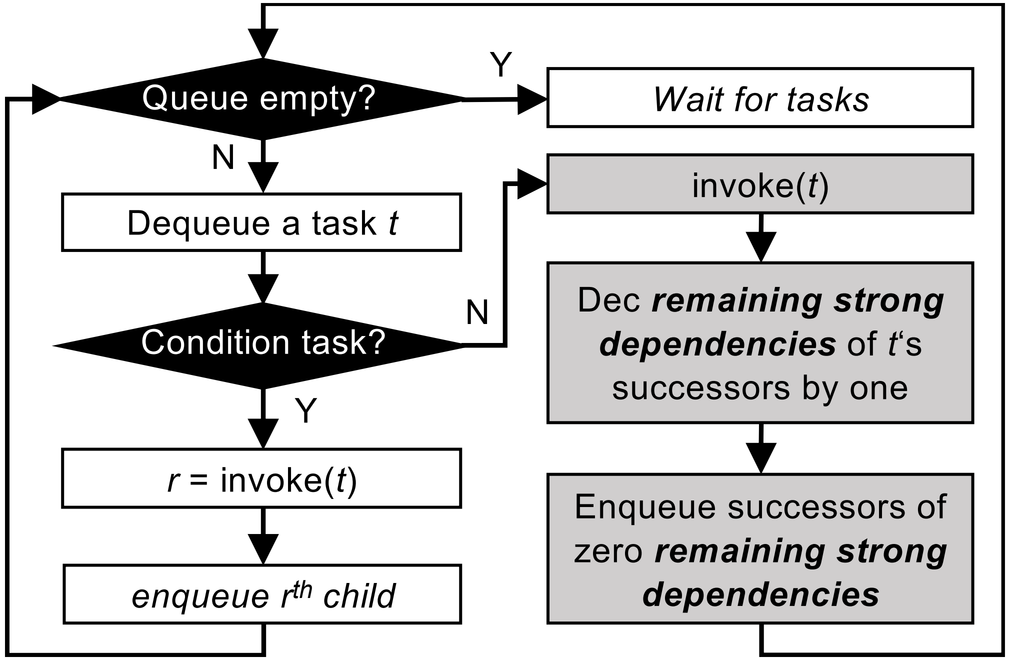
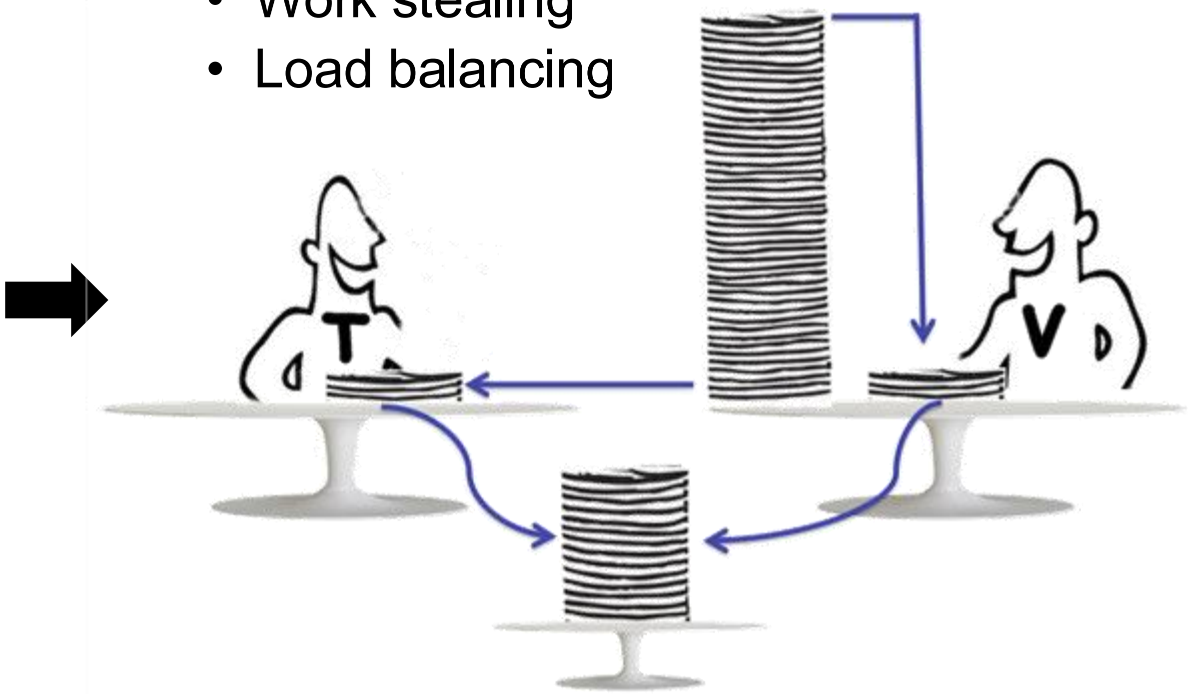
STGP Scheduling Algorithm

- **Task-level scheduling**



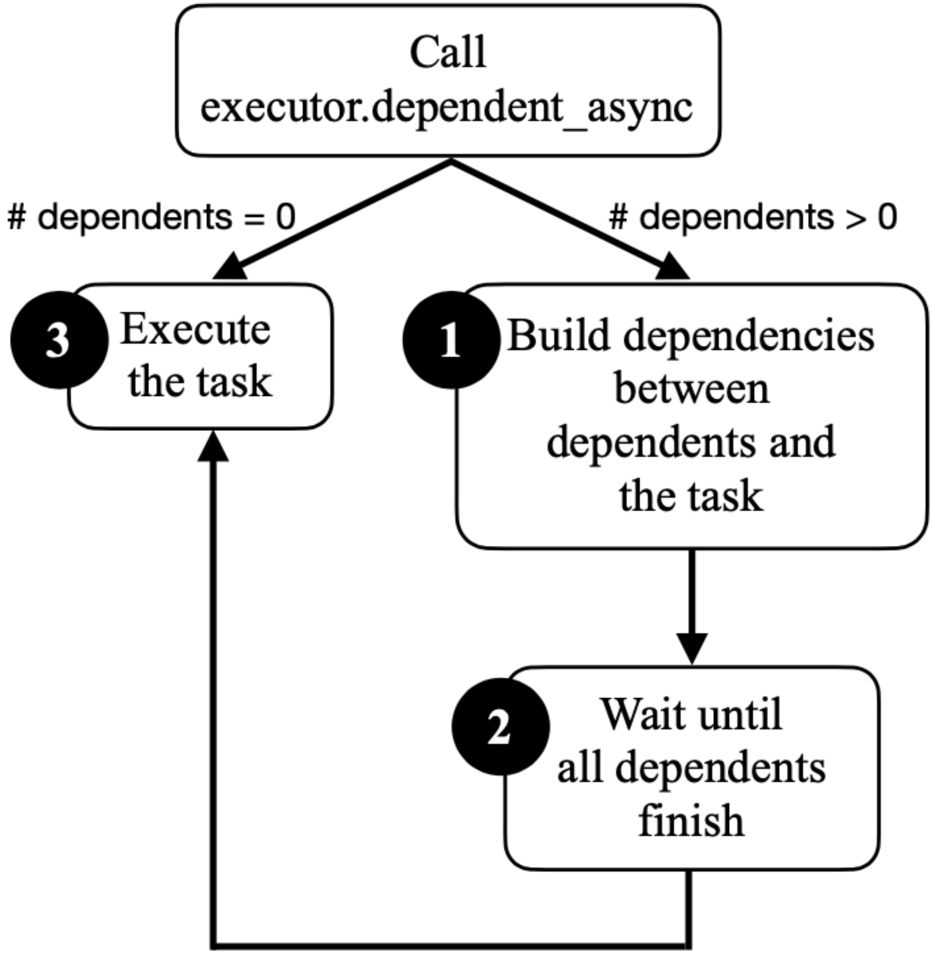
- **Worker-level scheduling**
  - Work stealing
  - Load balancing



Key results: schedule tasks with in-graph control flow with a strong balance between the number of active workers and dynamically generated tasks – *low latency, energy efficient, and high throughput*

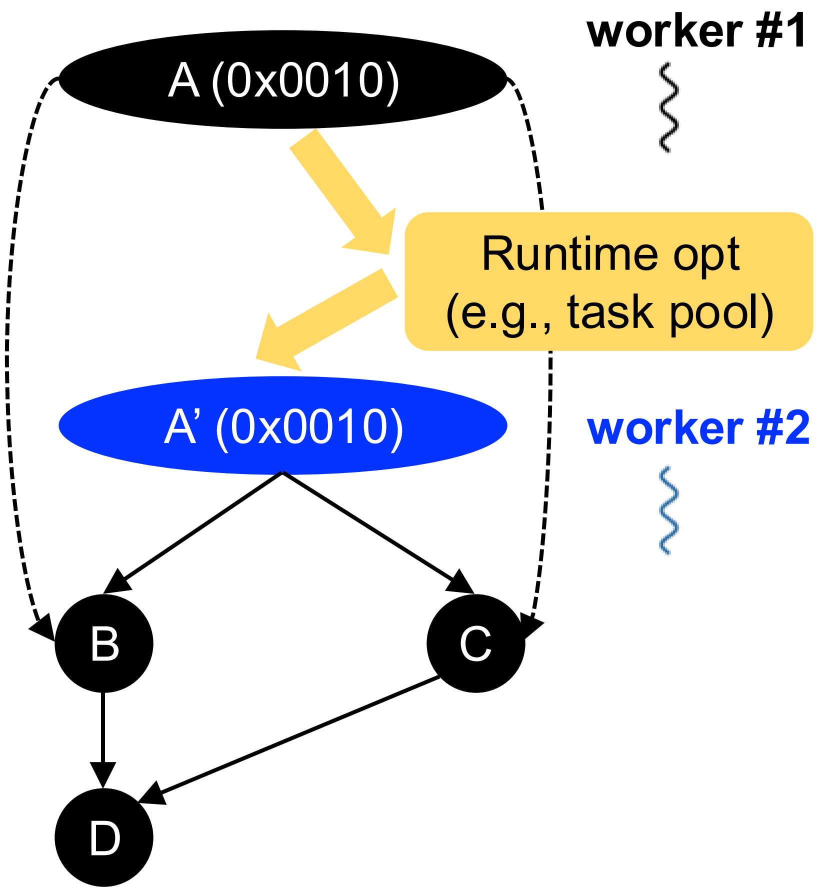
DTGP Scheduling Algorithm

- **The algorithm has three parts:**
  - Build dependencies
  - Wait for dependents to finish
  - Execute the task
- **Three key scheduling challenges:**
  1. **ABA** – *a specified dependent task must exist correctly*
  2. **Data race** – *multiple threads may simultaneously add and remove successors to and from a task*
  3. **Synchronization** – *application can issue a global synchronization at anytime to wait for all tasks to finish*



Solving Challenge #1: ABA Problem[1]

```
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
auto D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
executor.wait_for_all();
```



[1]: ABA Problem: https://en.wikipedia.org/wiki/ABA_problem

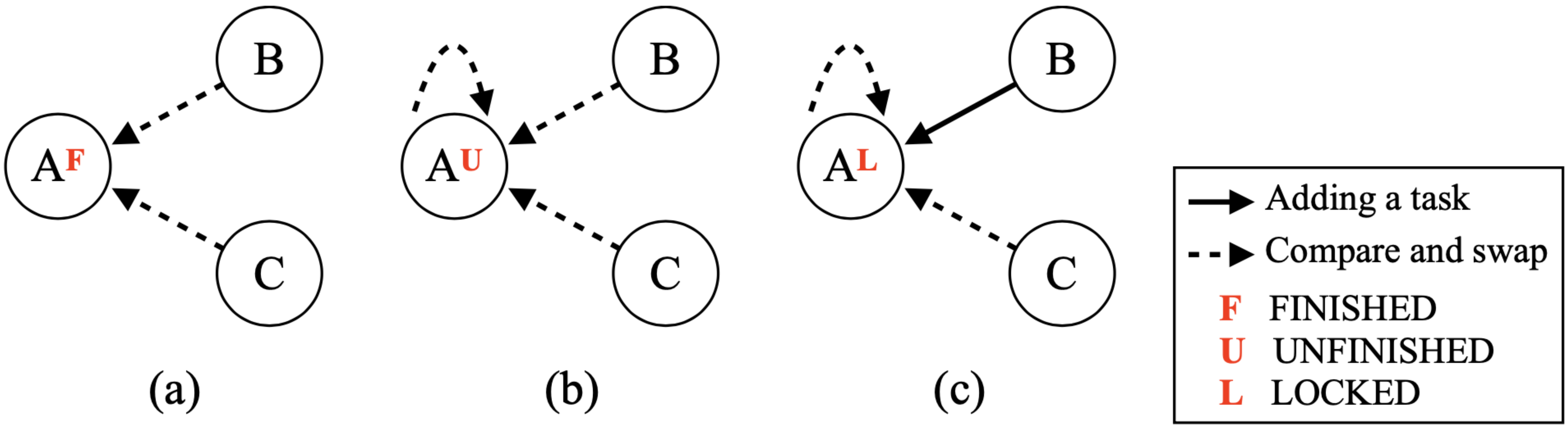
Retain Shared Ownership of Every Task

```
tf::Executor executor;
tf::AsyncTask A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
tf::AsyncTask B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
tf::AsyncTask C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
tf::AsyncTask D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
executor.wait_for_all();
```

tf::AsyncTask acks like a std::shared_ptr to ensure tasks stay alive when they are used

Solving Challenge #2: Data Race

- **Both B and C want to add themselves to the successors of A**
  - In the meantime, A may want to remove its successor
- **Apply compare-and-swap (CAS) to enable exclusive access**
  - As a result, constructing a dynamic task graph can be completely thread-safe



Solving Challenge #3: Synchronization

- **Application can issue a global synchronization at any time**
  - Ex: executor.wait_for_all(), future.get(), etc.

```
tf::Executor executor;
auto A  = executor.silent_dependent_async([](){});
auto B  = executor.silent_dependent_async([](){}, A);
executor.wait_for_all();  // wait for A and B to finish

auto C  = executor.silent_dependent_async([](){}, A);
auto D  = executor.silent_dependent_async([](){}, B, C);
executor.wait_for_all();  // wait for C and D to finish
```

```
// lock-based solution
std::unique_lock lock(mutex);
cv.wait(lock, [&](){
    return num_tasks == 0;
});
```

C++17

```
// atomic wait-based solution
auto n = num_tasks.load();
while(n != 0) {
    num_tasks.wait(n);
    n = num_tasks.load();
});
```

C++20

Taskflow uses C++20 atomic variables to perform waiting/notifying operations; many synchronizations can happen at user space instead of kernel

[1]: C++20 atomic wait/notify: https://en.cppreference.com/w/cpp/atomic/atomic/wait

Lock-free Scheduling Algorithm[1]

Algorithm 1 dependent_async(callable, deps)

```
Create a future
num_deps ← sizeof(deps)
task ← initialize_task(callable, num_deps, future)
for all dep ∈ deps do
    process_dependent(task, dep, num_deps)
end for
if num_deps == 0 then
    schedule_async_task(task)
end if
return (task, future)
```

Algorithm 2 process_dependent(task, dep, num_deps)

```
1: dep_state ← dep.state
2: target_state ← UNFINISHED
3: if dep_state.CAS(target_state, LOCKED) then
4:     dep.successors.push(task)
5:     dep_state ← UNFINISHED
6: else if target_state == FINISHED then
7:     num_deps ← AtomDec(task.join_counter)
8: else
9:     goto line 2
10: end if
```

Algorithm 3 schedule_async_task(task)

```
target_state ← UNFINISHED
while not task.state.CAS(target_state, FINISHED) do
    target_state ← UNFINISHED
end while
Invoke(task.callable)
for all successor ∈ task.successors do
    if AtomDec(successor.join_counter) == 0 then
        schedule_async_task(successor)
    end if
end for
if AtomDec(task.ref_count) == 0 then
    Delete task
end if
```

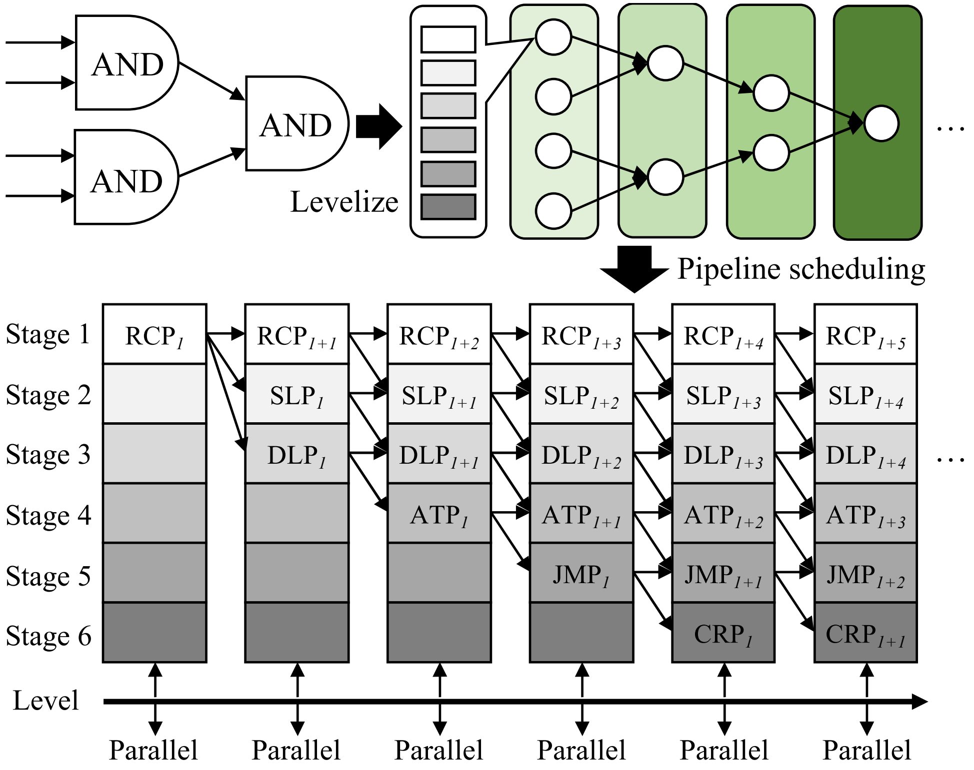

[1]: Cheng-Hsiang Chiu, et. al, "Programming Dynamic Task Parallelism for Heterogeneous EDA Algorithms," *IEEE/ACM ICCAD*, 2023

Takeaways

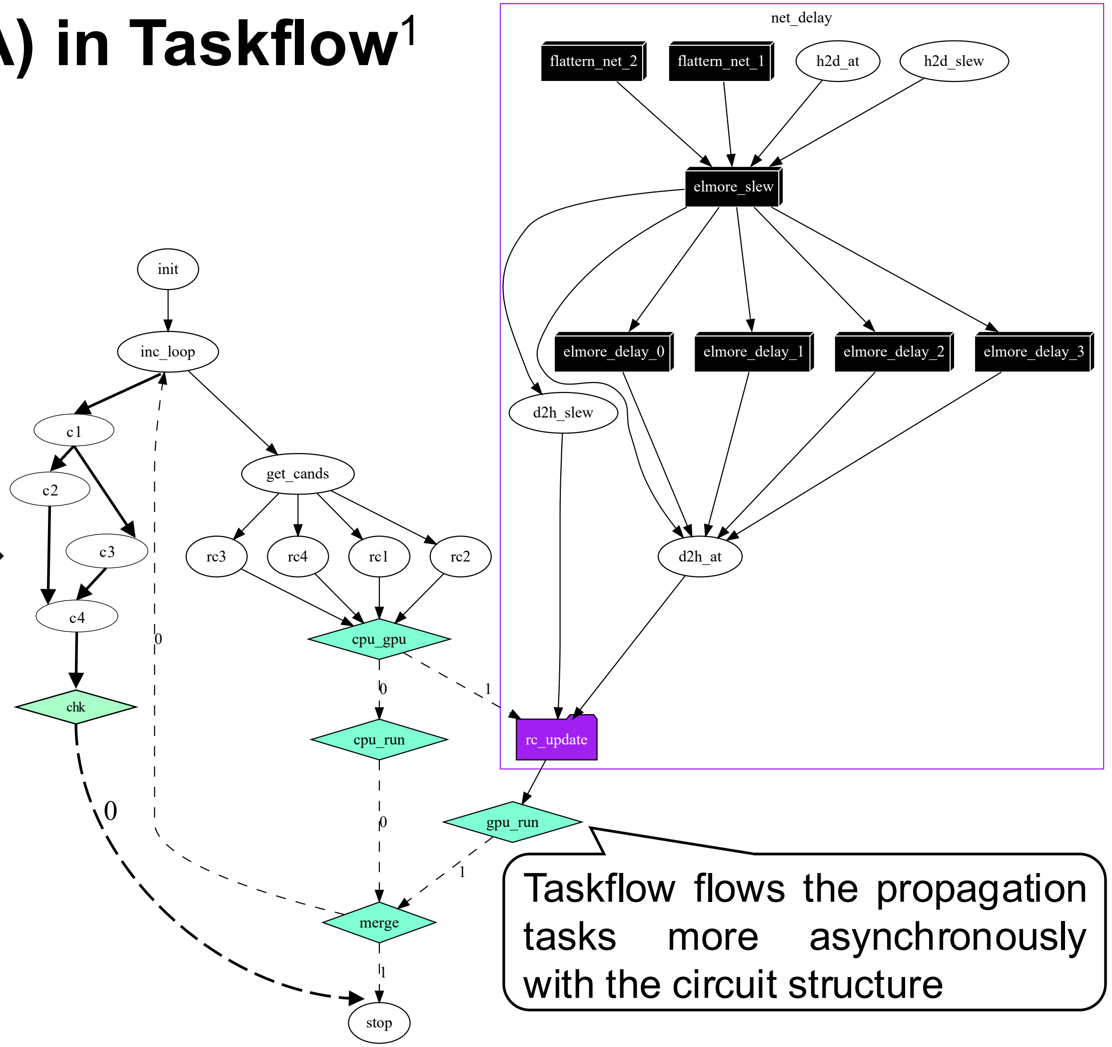
- Express your parallelism in the right way
- Program static task graph parallelism using Taskflow
- Program dynamic task graph parallelism using Taskflow
- Overcome the scheduling challenges
- Demonstrate the efficiency of Taskflow
- Conclude the talk

Case Study 1: Task-parallel STA

- **Model graph-based analysis (GBA) in Taskflow[1]**



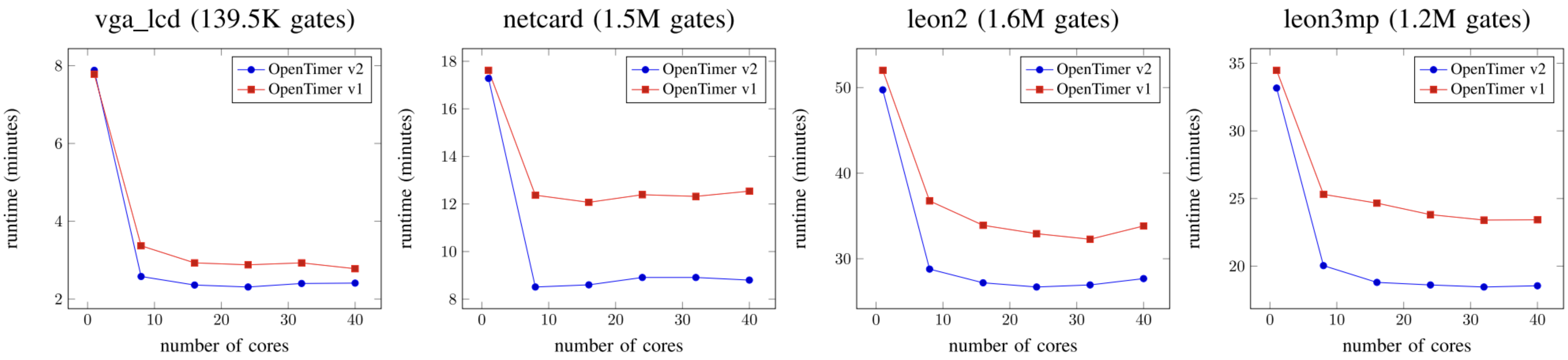
Loop-parallel level-by-level timing propagation in GBA



[1]: Tsung-Wei Huang, et al, "OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," *IEEE TCAD*, 2022

Levelization-based vs Task-parallel GBA

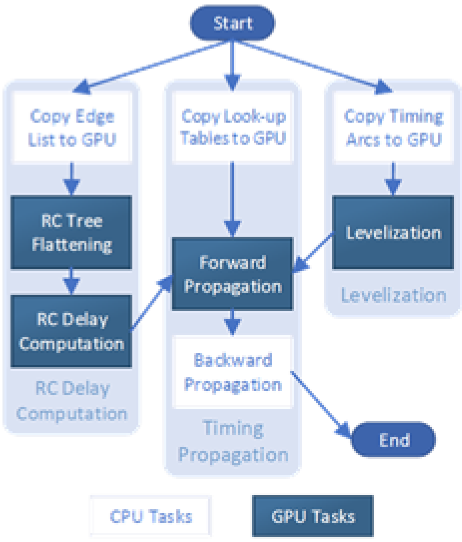
- **OpenTimer v1: levelization-based parallel timing propagation[1]**
  - Implemented using OpenMP “parallel_for” primitive
- **OpenTimer v2: task-parallel timing propagation[2]**
  - Implemented using Taskflow (https://taskflow.github.io/)



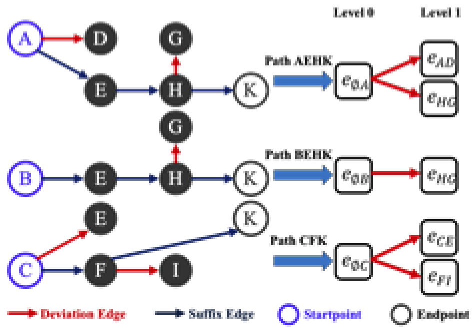
💡Taskflow allows us to more asynchronously parallelize the timing propagation

[1]: Tsung-Wei Huang and Martin Wong, “OpenTimer: A High-Performance Timing Analysis Tool,” *IEEE/ACM ICCAD*, 2015
[2]: Tsung-Wei Huang, et al, “OpenTimer v2: A New Parallel Incremental Timing Analysis Engine,” *IEEE TCAD*, 2022

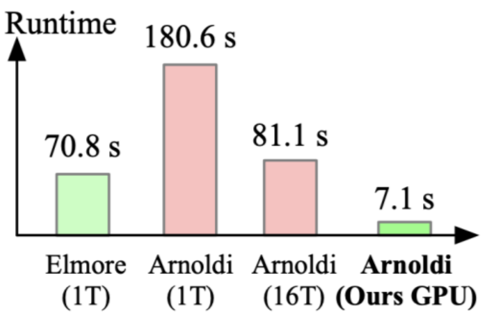
Our Research atop Task-parallel STA



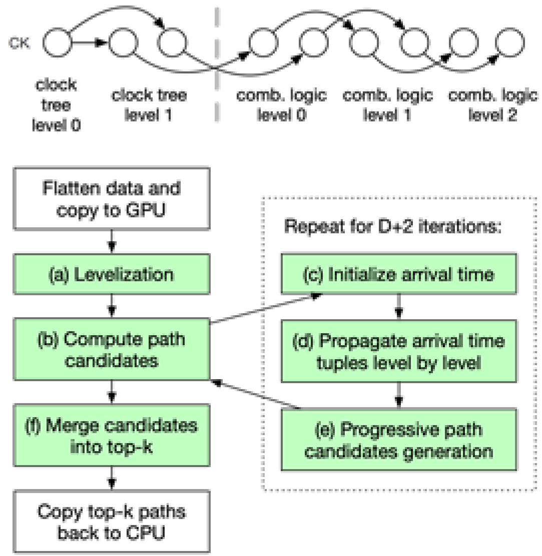
GPU-accelerated GBA (ICCAD'20, DAC'24)



GPU-accelerated PBA (DAC'21, TCAD'23)



GPU-accelerated CCS (DATE'24, DAC'24)



GPU-accelerated CPPR (ICCAD'21, TCAD'22)

Taskflow-powered STA engine[1]

4x faster

25–45x faster

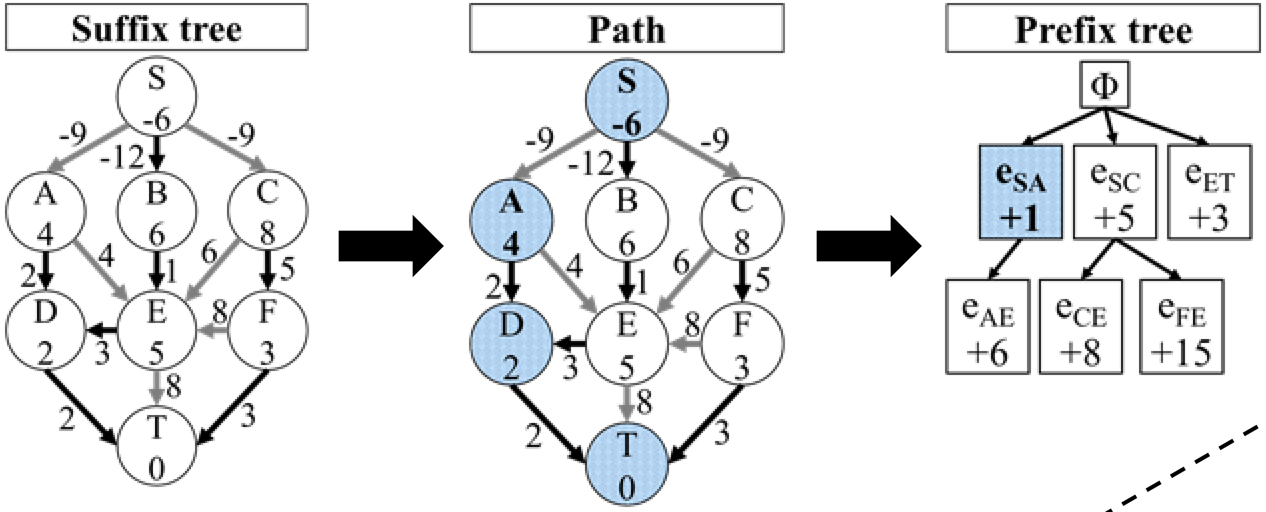
7–14x faster

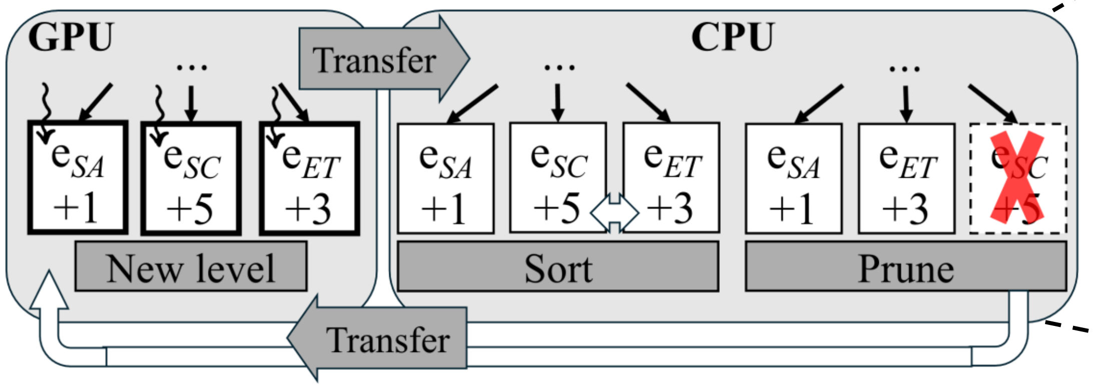
16x faster

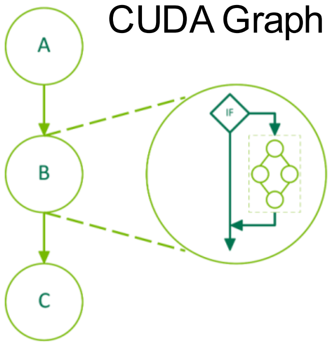
[1]: Tsung-Wei Huang, et al, "OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," *IEEE TCAD*, 2022

GPU-accelerated Path-based Analysis (PBA)

- **A GPU-parallel path generation algorithm[1]**







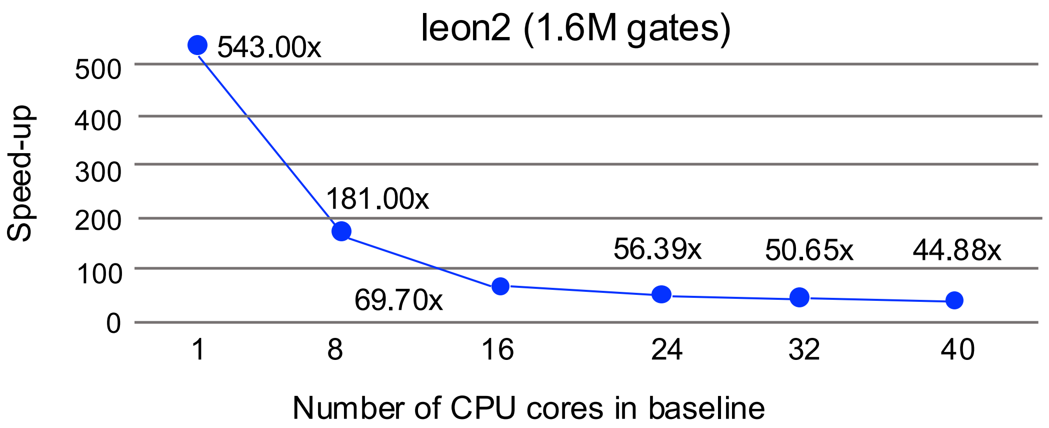
Input : G^+ in CSR format, N as #vertices, M as #edges, vertices$[N]$, edges$[M]$, weights$[M]$
Input : Shortest path forest, forest$[N]$ as edge array, distances$[N]$ as distance array
Input : currLevel as current level
Input : levelSize as the number of entries in current level
Result: Explore critical path candidates in next level

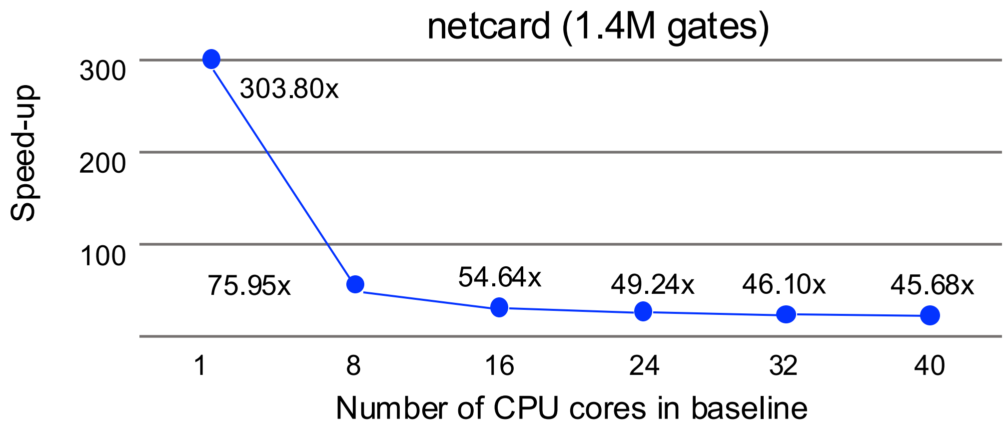
```
tid ← blockIdx.x ∗ blockDim.x + threadIdx.x;
if tid ≥ levelSize then
    return;
end
offset ← (tid == 0) ? 0 : currLevel[tid-1].childOffset;
level ← currLevel[tid].level;
slack ← currLevel[tid].slack;
v ← currLevel[tid].to;
while v is not endpoint do
    edgeStart ← vertices[v];
    edgeEnd ← (v == N-1) ? M : vertices[v+1];
    for eid ← edgeStart to edgeEnd do
        neighbor ← edges[eid];
        weight ← weights[eid];
        if eid is deviation edge then
            /* Fill out child path data */
            newPath ← nextLevel[offset];
            newPath.level ← level+1;
            newPath.from ← v;
            newPath.to ← neighbor;
            newPath.parent ← tid;
            newPath.childOffset ← 0;
            newPath.slack ← slack + distances[neighbor] +
              weight - distances[v];
            offset ← offset + 1;
        end
    end
    /* Traverse along the shortest path forest */
    v = forest[v];
end
return;
```


[1]: G. Guo, et al, "A GPU-Accelerated Framework for Path-Based Timing Analysis," *IEEE TCAD*, 2023

Performance of GPU-based Path Generation

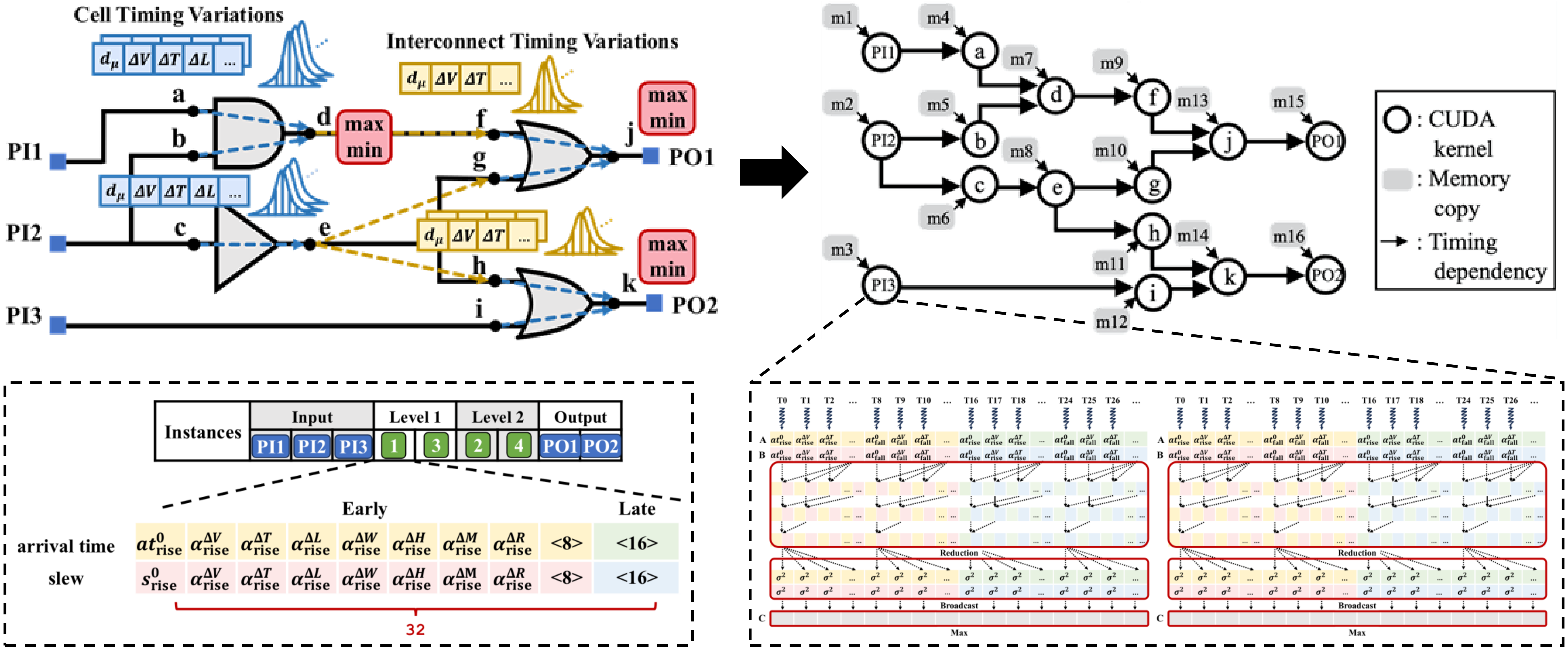
Benchmark	#Pins	#Gates	#Arcs	OpenTimer Runtime	Our Algorithm #MDL=10		Our Algorithm #MDL=15		Our Algorithm #MDL=20	
					Runtime	Speed-up	Runtime	Speed-up	Runtime	Speed-up
leon2	4328255	1616399	7984262	2875783	4708.36	611×	5295.49ms	543×	5413.84	531×
leon3mp	3376821	1247725	6277562	1217886	5520.85	221×	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×





Case Study 2: GPU-accelerated SSTA

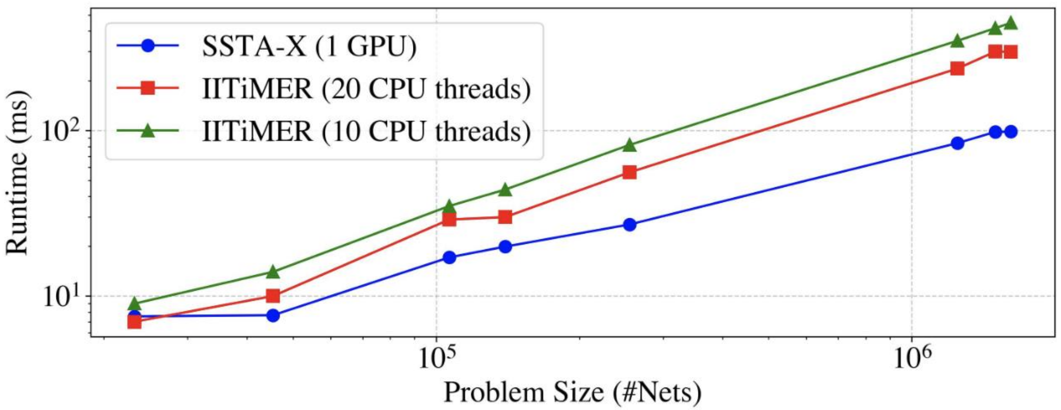
- **Model the SSTA propagation workload into a GPU task graph**

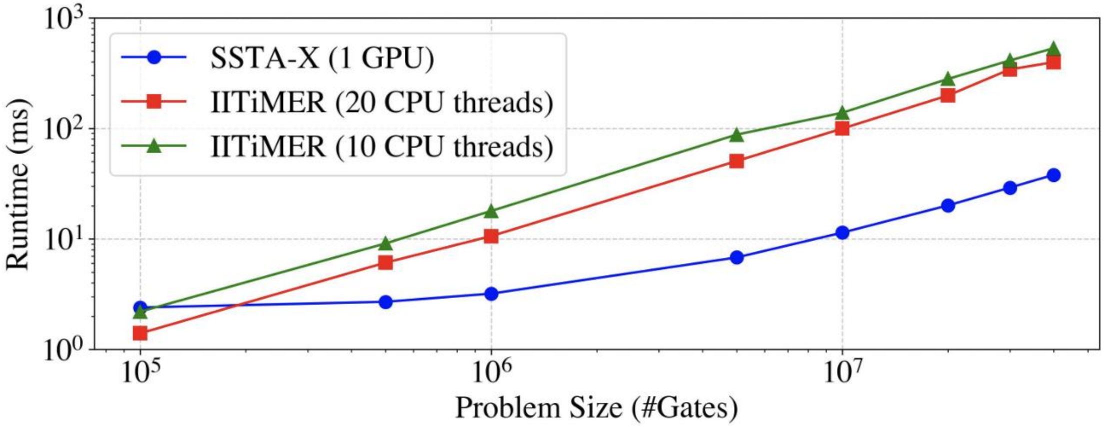


[1]: Chih-Chun Chang, et. al, "SSTA-X: GPU-Accelerated First-Order Block-Based Statistical Static Timing Analysis," *under submission*

GPU-accelerated STA vs CPU-parallel SSTA[1]

Circuit	#Gates	#Nets	#Pins	Runtime (ms)				Speedup of SSTA-X over			Error Rate vs. MC-SSTA
				MC-SSTA 20 CPUs	IITiMER 1 CPUs	IITiMER 20 CPUs	**SSTA-X 1 GPU**	MC-SSTA 20 CPUs	IITiMER 1 CPUs	IITiMER 20 CPUs	μ and σ^2 (%)
aes_core	22938	23199	66751	3483	129	26	**20**	174.15×	6.45×	1.30×	0.29
b19	255278	255300	782914	54989	1411	335	**134**	410.36×	10.50×	2.50×	0.38
cordic	45359	45393	127993	7286	226	70	**30**	242.86×	7.53×	2.33×	0.07
des_perf	138878	139112	371587	11403	580	115	**52**	219.28×	11.15×	2.21×	0.36
leon2	1616369	1616984	4328255	178620	6912	1667	**554**	322.41×	12.47×	3.01×	0.32
leon3mp	1247725	1247979	3376832	167752	5455	1487	**476**	352.42×	11.46×	3.10×	0.40
netcard	1496719	1498555	3999174	209258	6668	1799	**590**	354.67×	11.30×	3.04×	0.34
vga_lcd	139529	139635	397809	20233	674	157	**72**	281.01×	9.36×	2.18×	2.11
vga_lcd_iccad	259067	259152	679258	27455	1068	295	**103**	266.55×	10.36×	2.86×	0.41
Average								327.96×	11.32×	2.81×	0.58

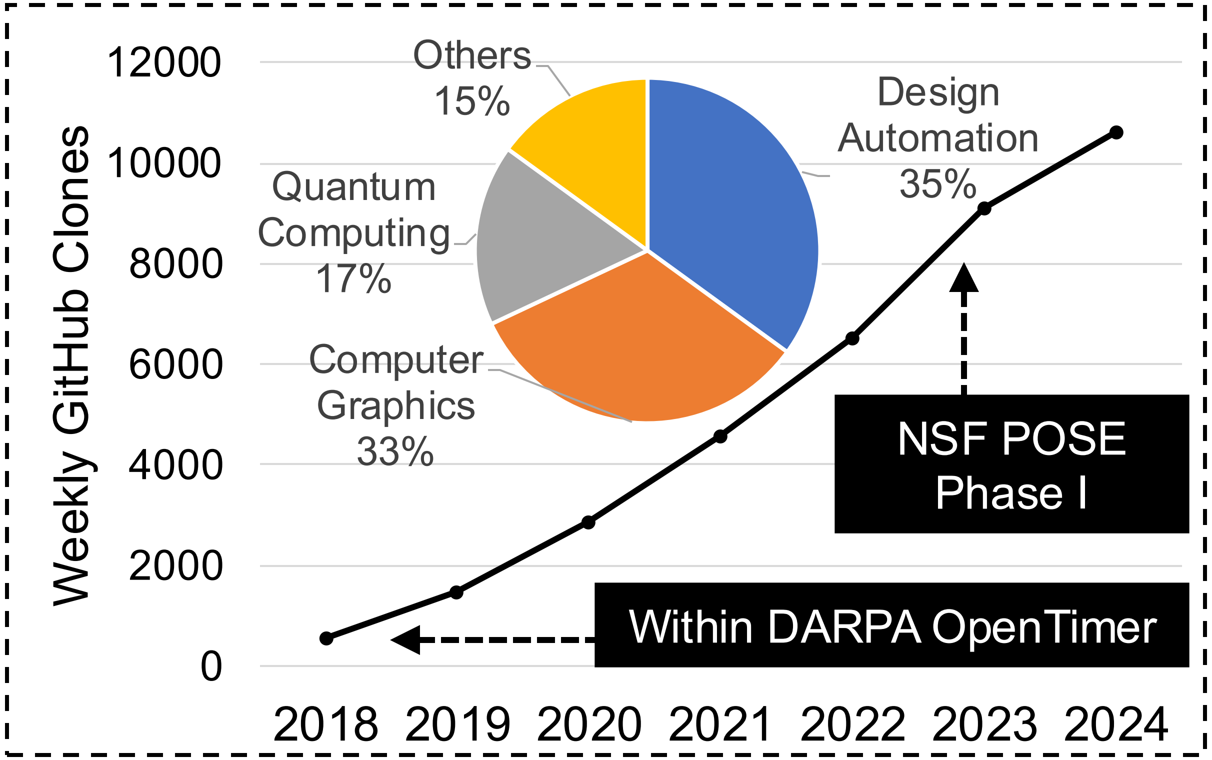




[1]: Chih-Chun Chang, et. al, "SSTA-X: GPU-Accelerated First-Order Block-Based Statistical Static Timing Analysis," *under submission*

Other Industrial Applications of Taskflow

- **Quantum computing**
  - Xanadu used Taskflow in their state vector-based simulator, JET
- **Computer graphics and game rendering**
  - Vulkan recommends Taskflow for parallelizing your rendering engines
- **FPGA physical design**
  - Vivado uses Taskflow for synthesis
- **Embedded/edge computing**
  - Tesseract (robotics planning)
  - Cruise (autonomous car)
  - Reveal.Tech (drone vision)
  - Tesseract Robotic (planning tool)
  - …
- **C++26 std::exec (coming soon)**
  - Benefit millions of C++ developers ☺



[1]: Nvidia's implementation of C++26 std::exec: https://github.com/NVIDIA/stdexec/tree/main/include/execpools/taskflow

Conclusion

- Expressed your parallelism in the right way
- Programmed static task graph parallelism using Taskflow
- Programmed dynamic task graph parallelism using Taskflow
- Overcame the scheduling challenges
- Demonstrated the efficiency of Taskflow
- Concluding the talk

Thank you for using Taskflow!

…

Thank you for Sponsoring Taskflow!

NSF

DARPA

NUMFOCUS
OPEN CODE = BETTER SCIENCE

intel

Google Summer of Code

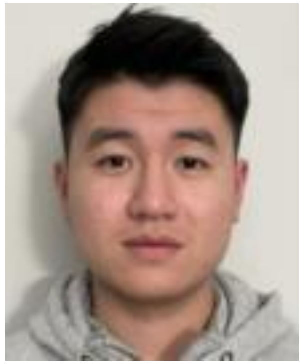
NVIDIA

Acknowledgment: Excellent PhD Students

- **Please contact me if you have any intern/full-time opportunities!**
  - We specialize in CAD, HPC, and GPU heterogeneous programming!
  - https://tsung-wei-huang.github.io/team/ (or tsung-wei.huang@wisc.edu)






Questions?

Taskflow: https://taskflow.github.io

Static task graph parallelism

```
// Live: https://godbolt.org/z/j8hx3xnnx
tf::Taskflow taskflow;
tf::Executor executor;
auto [A, B, C, D] = taskflow.emplace(
    [] () { std::cout << "TaskA\n"; }
    [] () { std::cout << "TaskB\n"; },
    [] () { std::cout << "TaskC\n"; },
    [] () { std::cout << "TaskD\n"; }
);
A.precede(B, C);
D.succeed(B, C);
executor.run(taskflow).wait();
return 0;
```

Dynamic task graph parallelism

```
// Live: https://godbolt.org/z/T87PrTarx
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";
}, A);
auto D = executor.silent_dependent_async([](){
    std::cout << "TaskD\n";
}, B, C);
executor.wait_for_all();
```