Taskflow: A General-purpose Task-parallel Programming System

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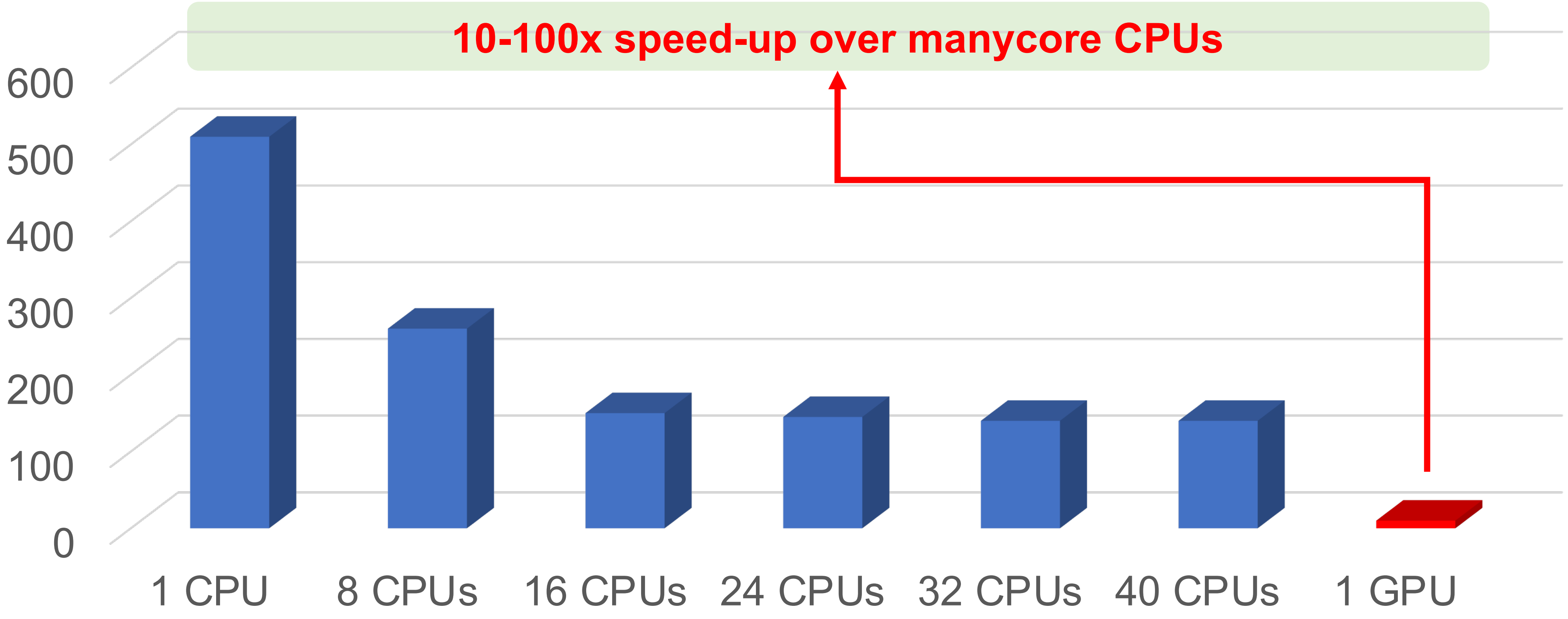
https://taskflow.github.io/

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

Why Parallel Computing?

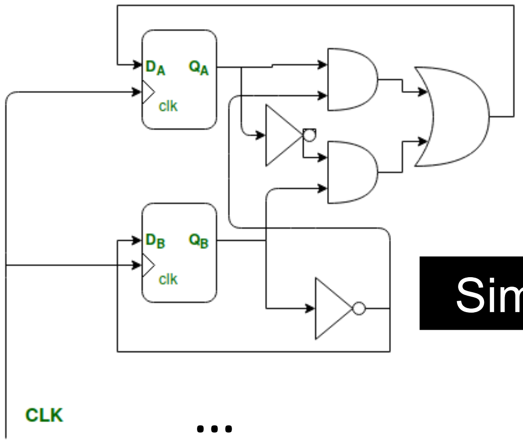
- **Advances performance to a new level previously out of reach**



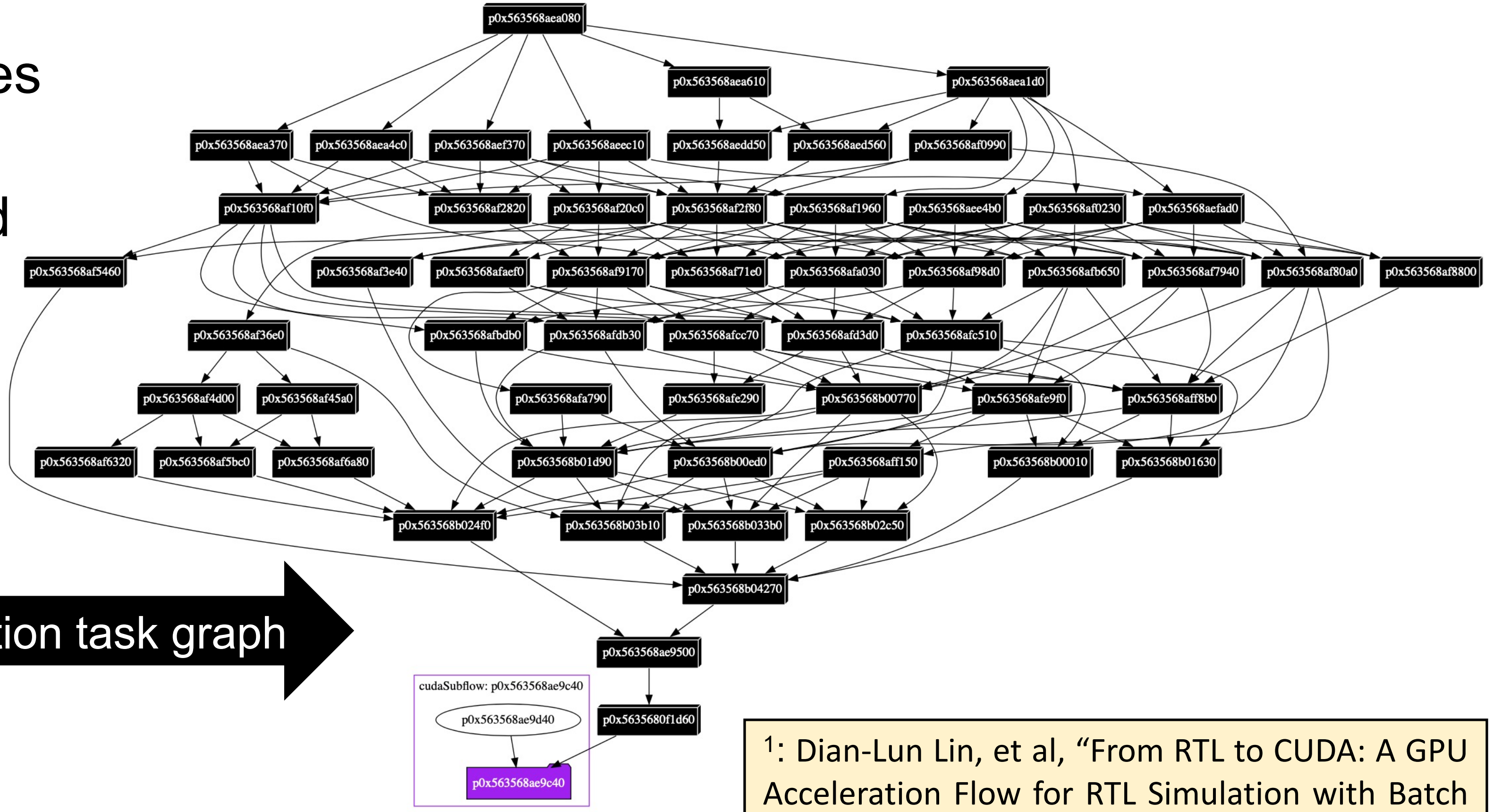
Time (minutes) to speed up a circuit timing analysis algorithm

Today's Parallel Workload is Very Complex

- **GPU-accelerated circuit analysis on a design of <u>500M</u> gates**[1]
  - >100 kernels
  - >100 dependencies
  - >500s to finish
  - >10hrs turnaround



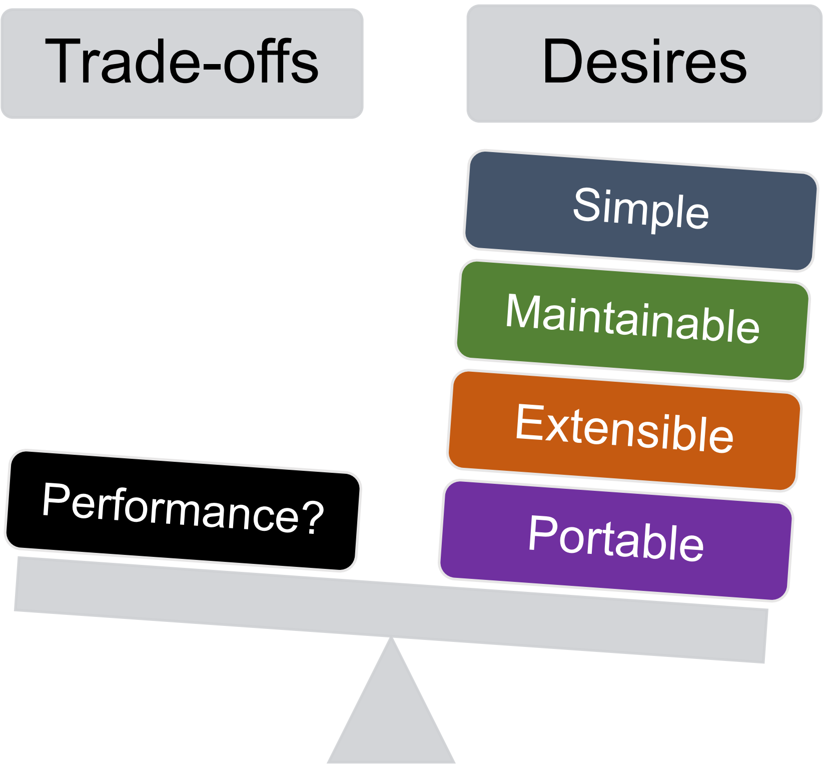
Simulation task graph



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

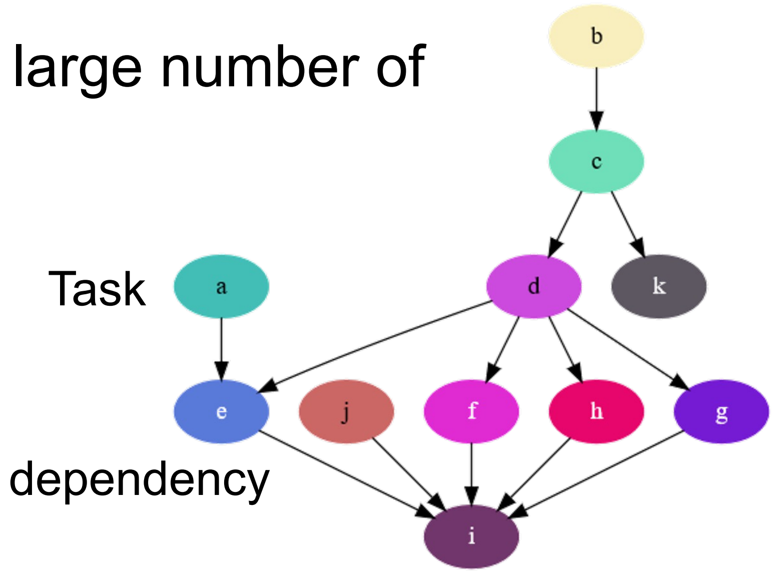
Parallel Programming is Not Easy

- **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:**
  - ***Task graph parallelism*** (TGP) is the best model for future parallel arch
  - Capture programmers' intention in decomposing a heterogeneous algorithm into a top-down task graph
  - Runtime can schedule dependent tasks across a large number of processing units (e.g., CPUs, GPUs)



Problems of Existing Tools for TGP …

- **Cannot handle *complex task dependencies***
  - **Example**: circuit analysis algorithms compute the circuit network of multi-millions of nodes and dependencies
  - **Problem**: existing tools are often good at loop parallelism but weak in expressing heterogeneous task graphs at this large scale
- **Cannot handle *complex control flow***
  - **Example**: optimization 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 *directed acyclic graph* (DAG) that does not anticipate control flow
    - Lack end-to-end parallelism since you need to synchronize at control-flow points

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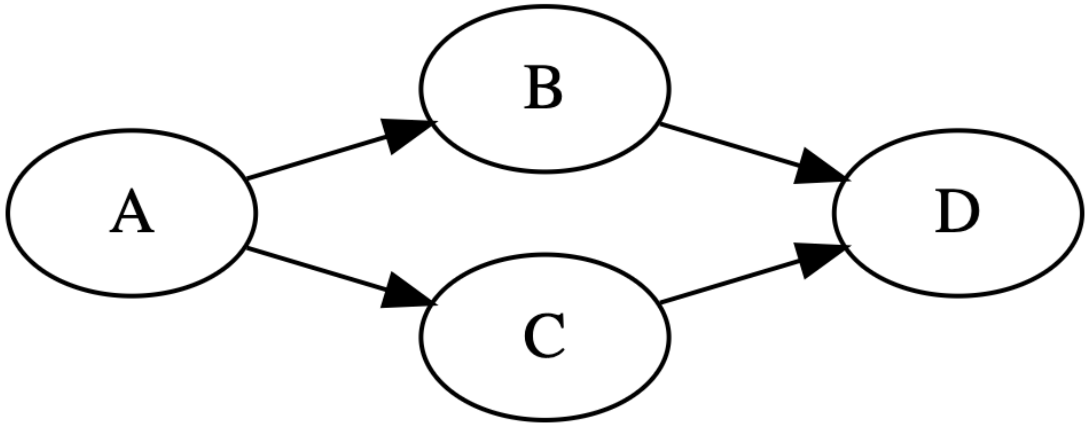
“Hello World” in Taskflow[1]

```
#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*, vol. 33, no. 6, pp. 1303-1320, June 2022

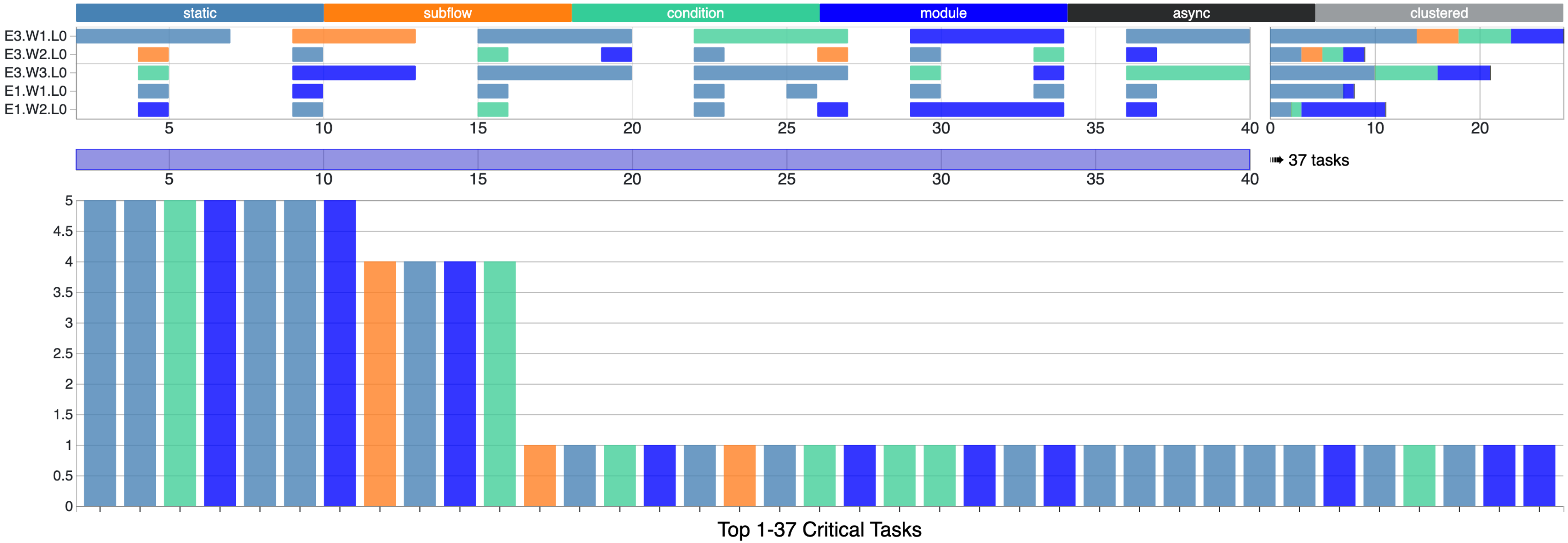
Drop-in Integration

- **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

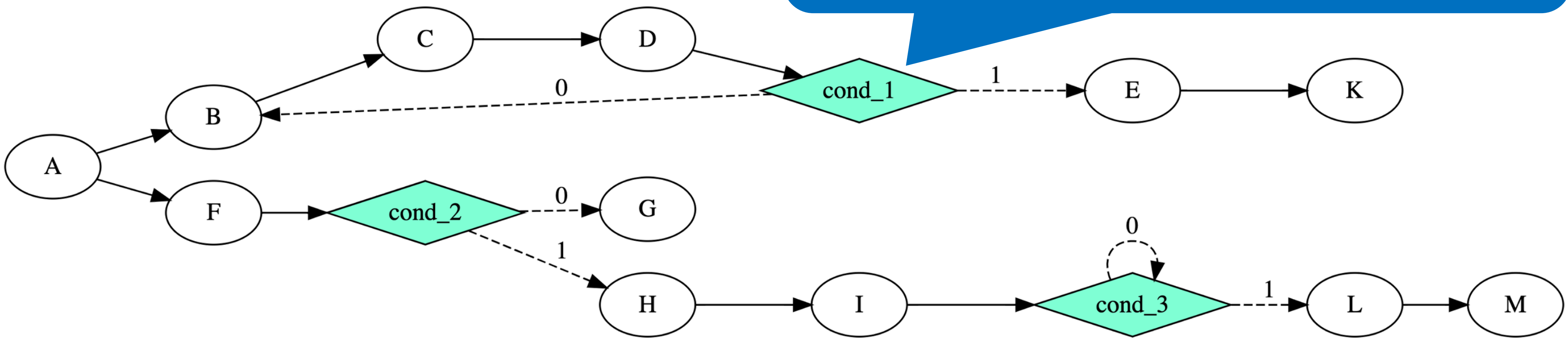
```
# run you program with the env variable TF_ENABLE_PROFILER enabled
# and paste the JSON content to https://taskflow.github.io/tfprof/
~$ TF_ENABLE_PROFILER=simple.json ./simple
```



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
```

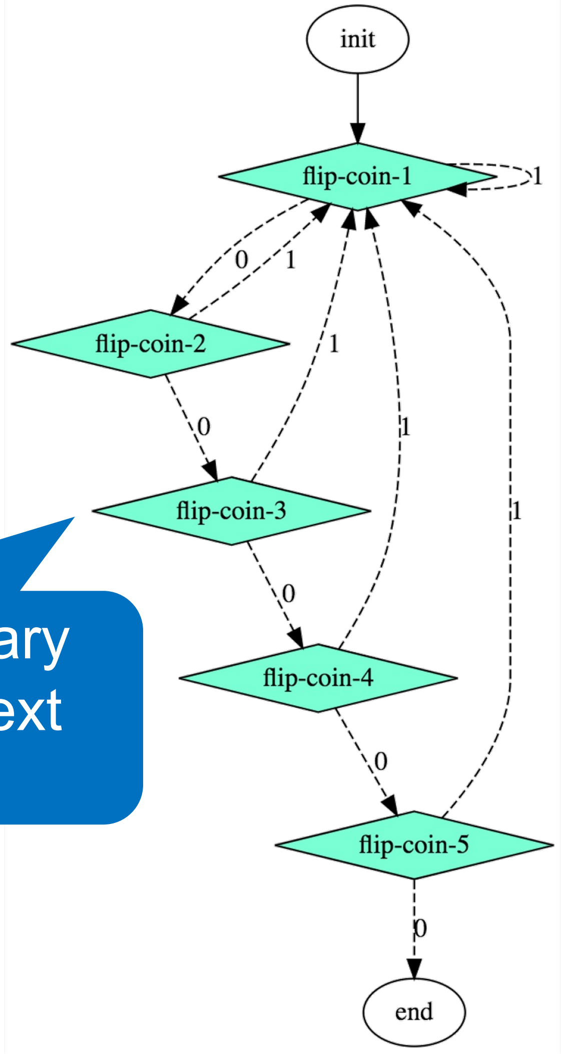
Very difficult for existing DAG-based systems to express an efficient overlap between tasks and control flow …



Non-deterministic Control Flow with CTFG

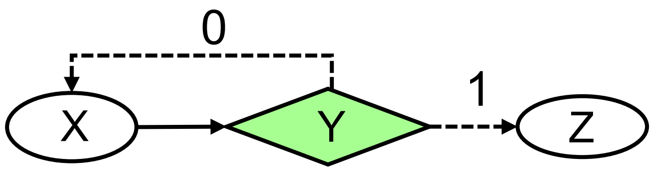
```
auto A = taskflow.emplace([&](){ } );
auto B = taskflow.emplace([&](){ return rand()%2; } );
auto C = taskflow.emplace([&](){ return rand()%2; } );
auto D = taskflow.emplace([&](){ return rand()%2; } );
auto E = taskflow.emplace([&](){ return rand()%2; } );
auto F = taskflow.emplace([&](){ return 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?**
  - Have no choice but resort to a client-side partition of the task graph
  - Synchronize the execution of partitioned task graphs around decision-making points
  - Lack end-to-end parallelism

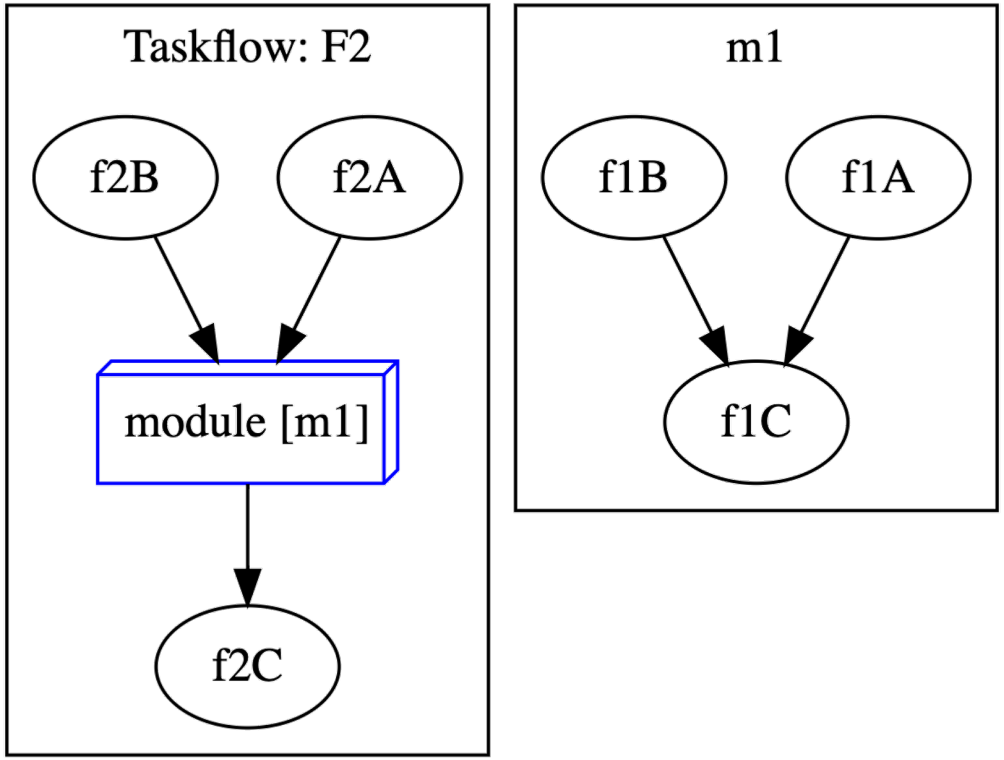



```
tf::Taskflow G;
auto X = G.emplace([](){});
auto Y = G.emplace([](){
  return converged() ? 1 : 0;
});
cond.precede(Z, X);
executor.run(G).wait();
```

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

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);
```



Everything is Composable in Taskflow

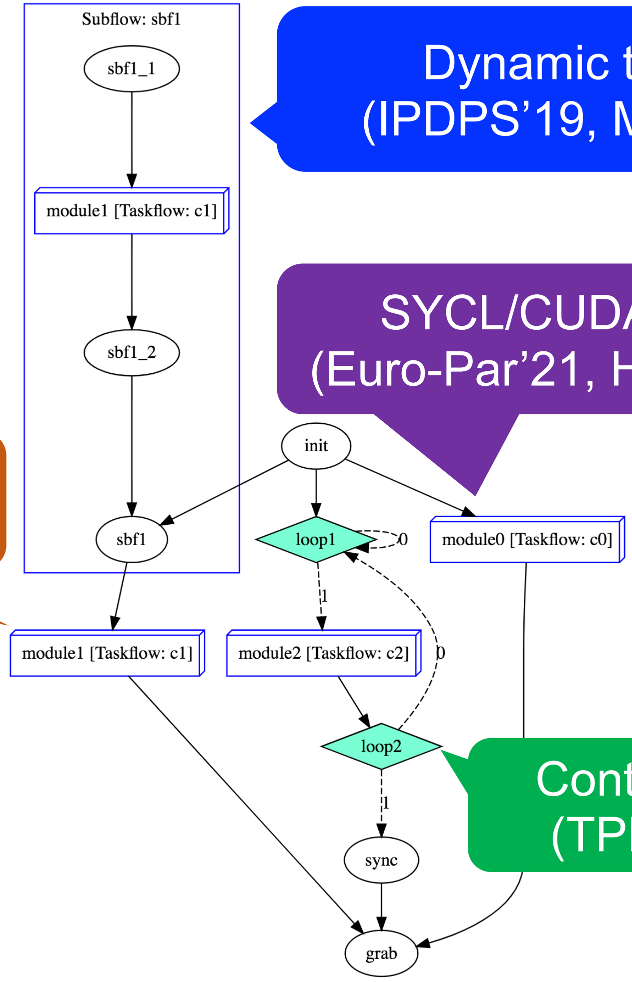
- **End-to-end parallelism in one graph**
  - Task, dependency, control flow all together
  - Scheduling with whole-graph optimization
  - Efficient overlap among heterogeneous tasks
- **Largely improved productivity!**

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

Dynamic task (IPDPS'19, MM'19)

SYCL/CUDA task (Euro-Par'21, HPEC'20)

Control flow (TPDS'22)



Industrial use-case of productivity improvement using Taskflow

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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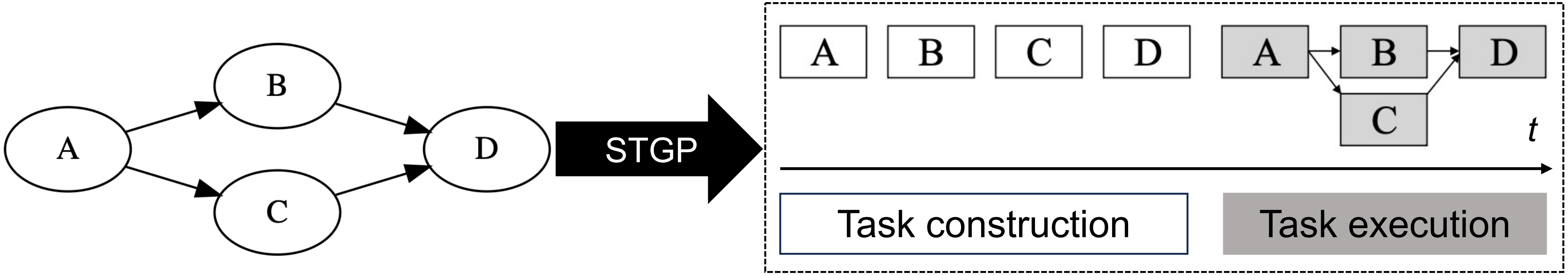
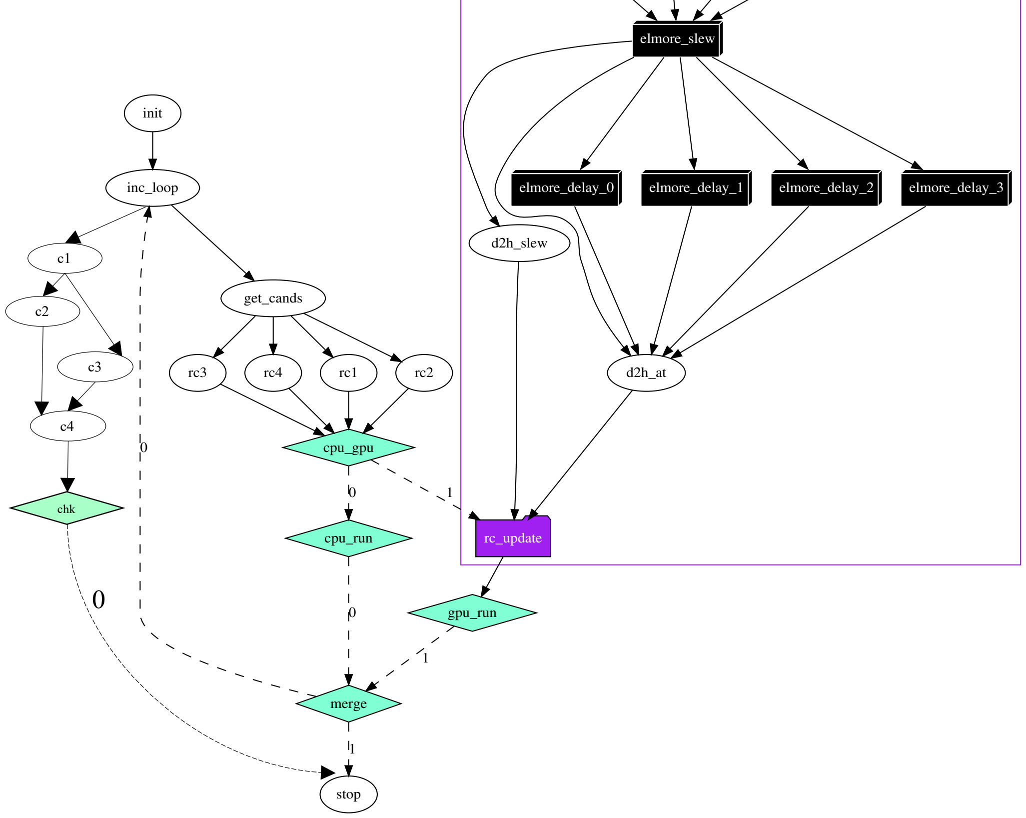
Static Task Graph Parallelism (STGP)

- **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

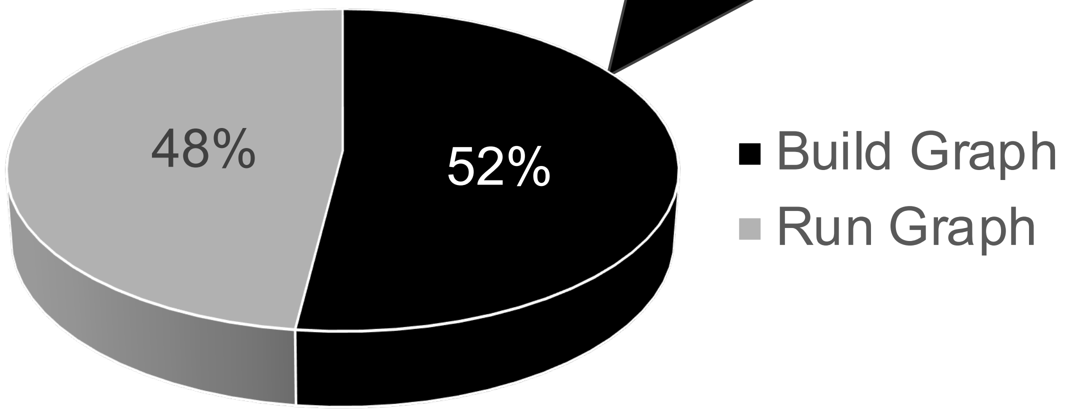


Problem of STGP: Example #1

- **Runtime breakdown of a task-parallel circuit analysis algorithm**[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

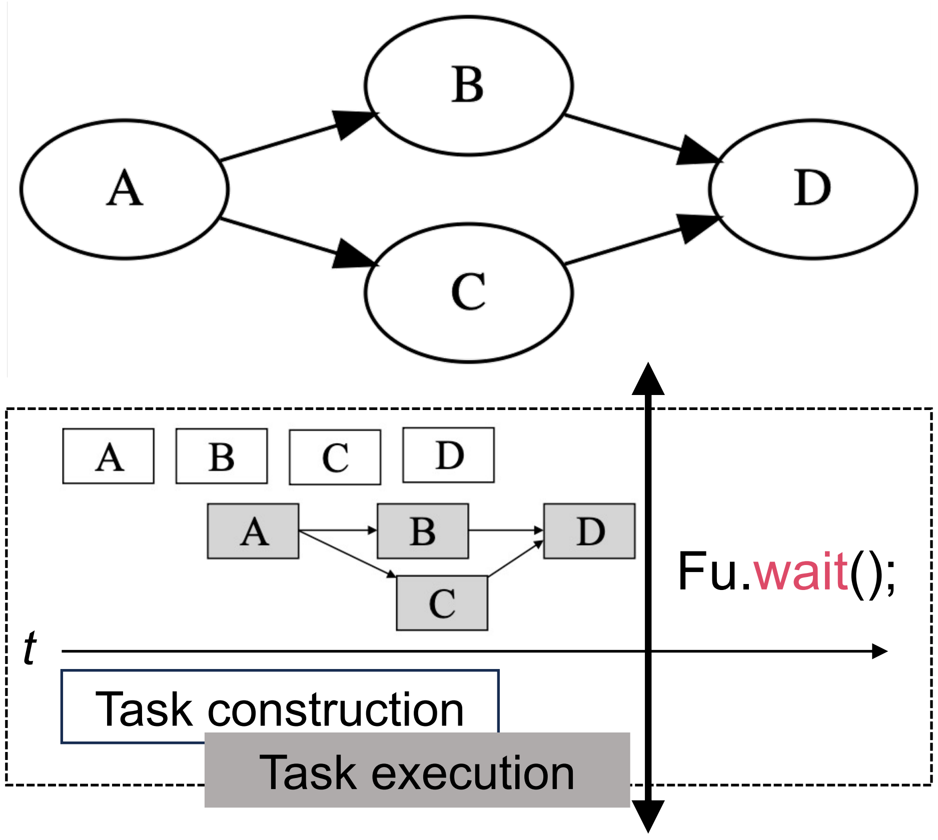
- **Express TGP that depends on runtime variables…?**

```
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

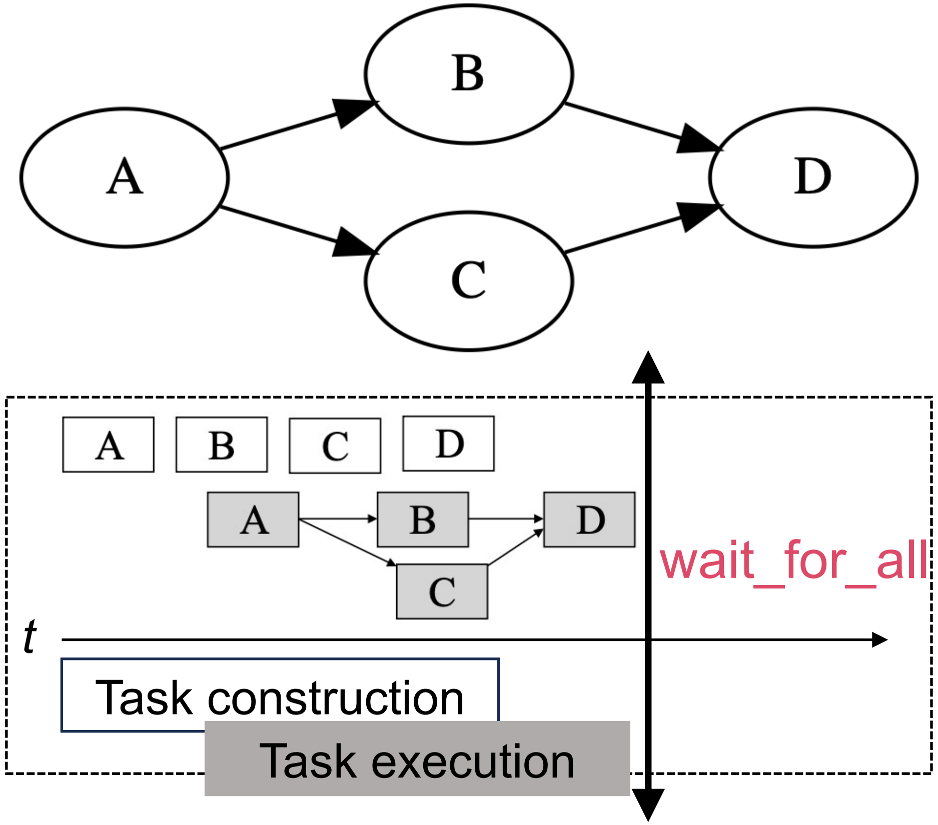
```
// Live: https://godbolt.org/z/j76ThGbWK
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";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



Specify arbitrary task dependencies using C++ variadic parameter pack

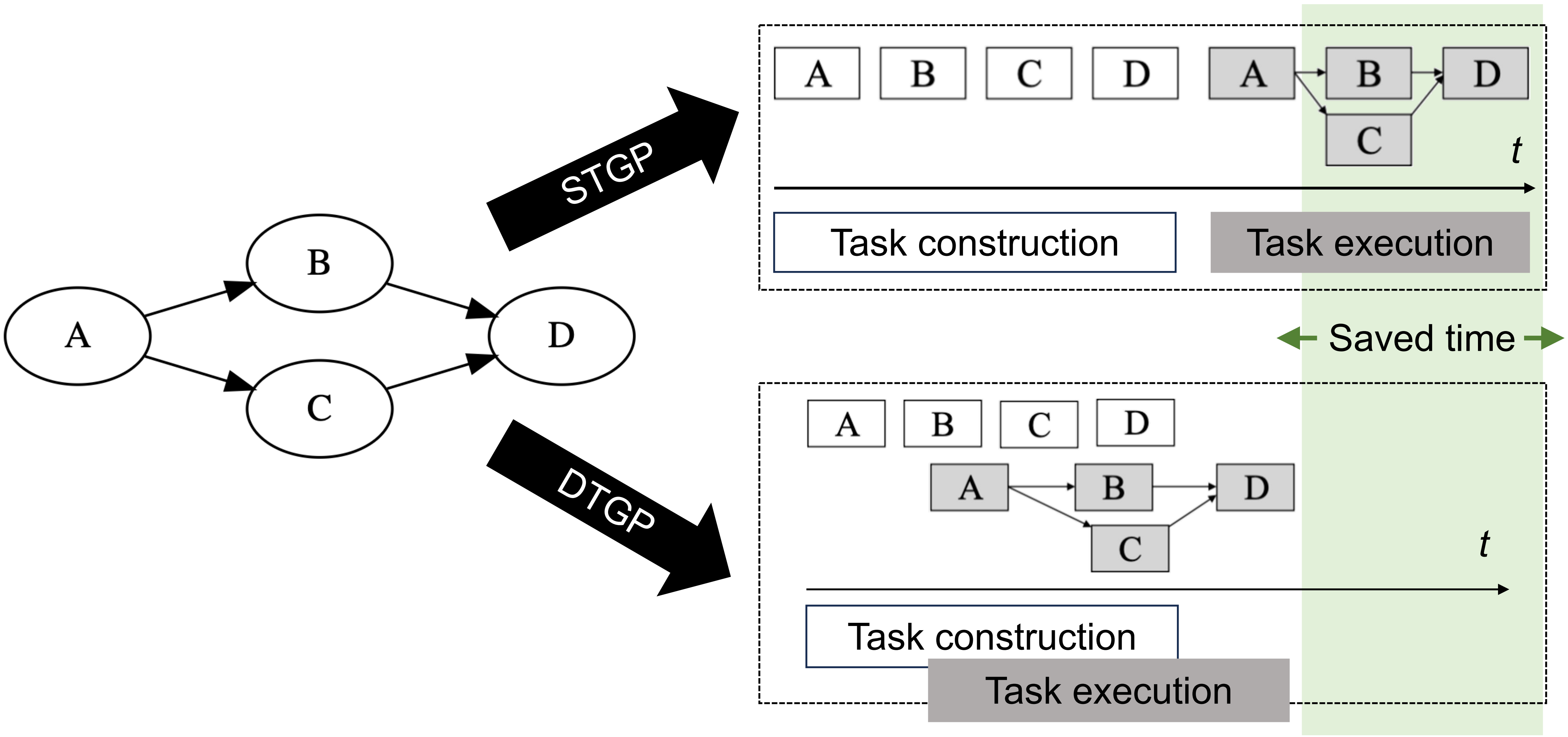
Wait for All Tasks to Finish

```
// 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();
```



Block the caller until all tasks (A, B, C, and D) finish

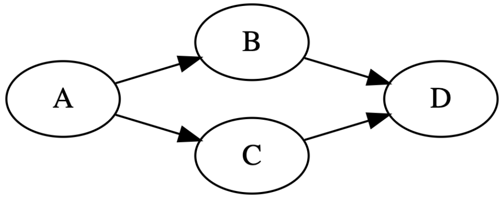
Comparison between STGP and DTGP

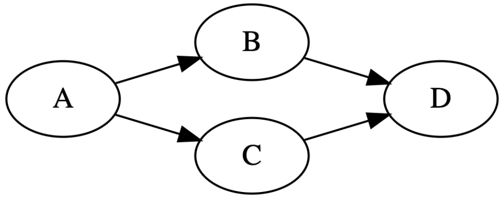


DTGP Needs a Correct Topological Order

```
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





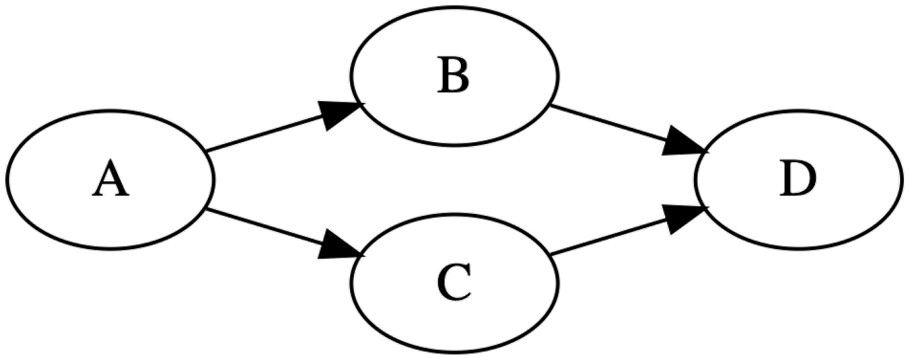
Topological order #2: A→C→B→D

```
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 accept a range of dependent 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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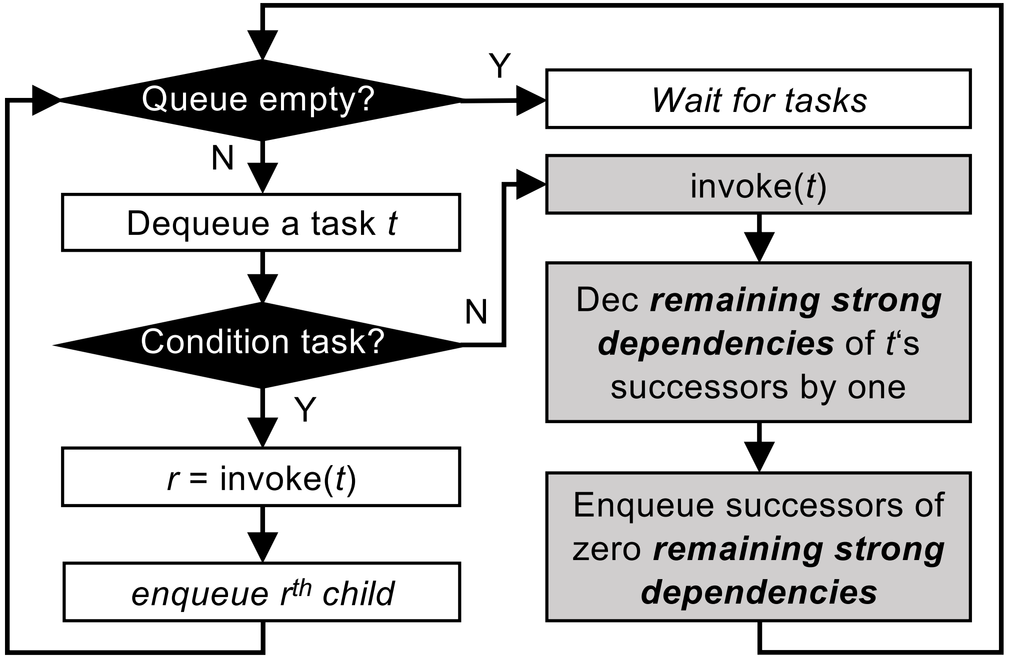
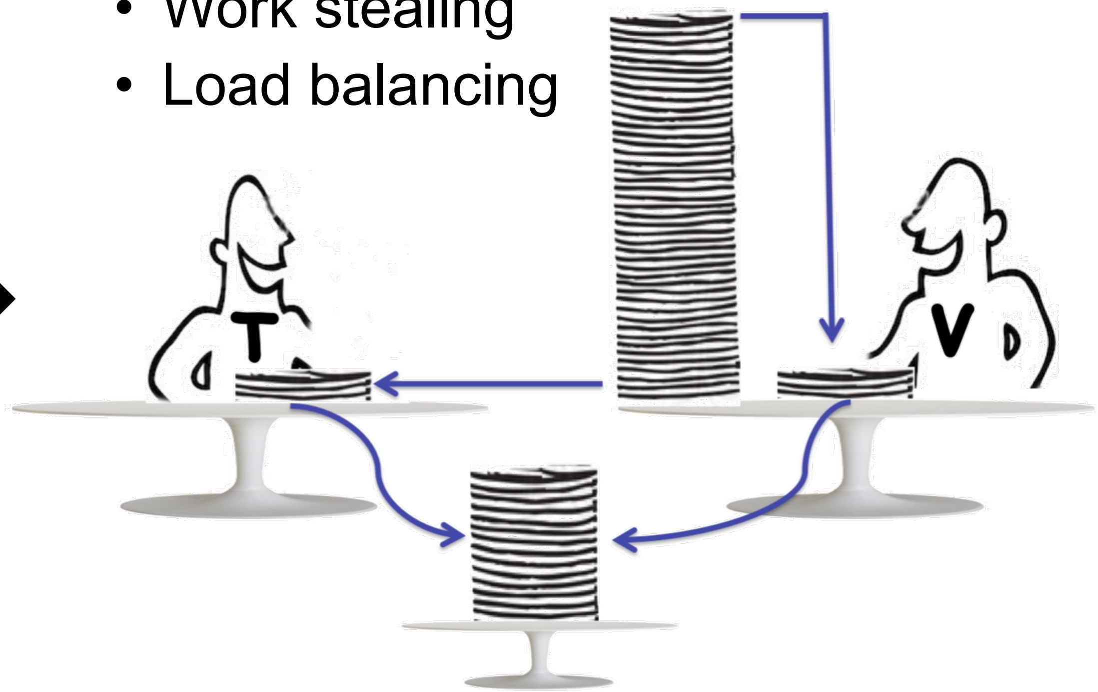
STGP Scheduling Algorithm

- **Task-level scheduling**



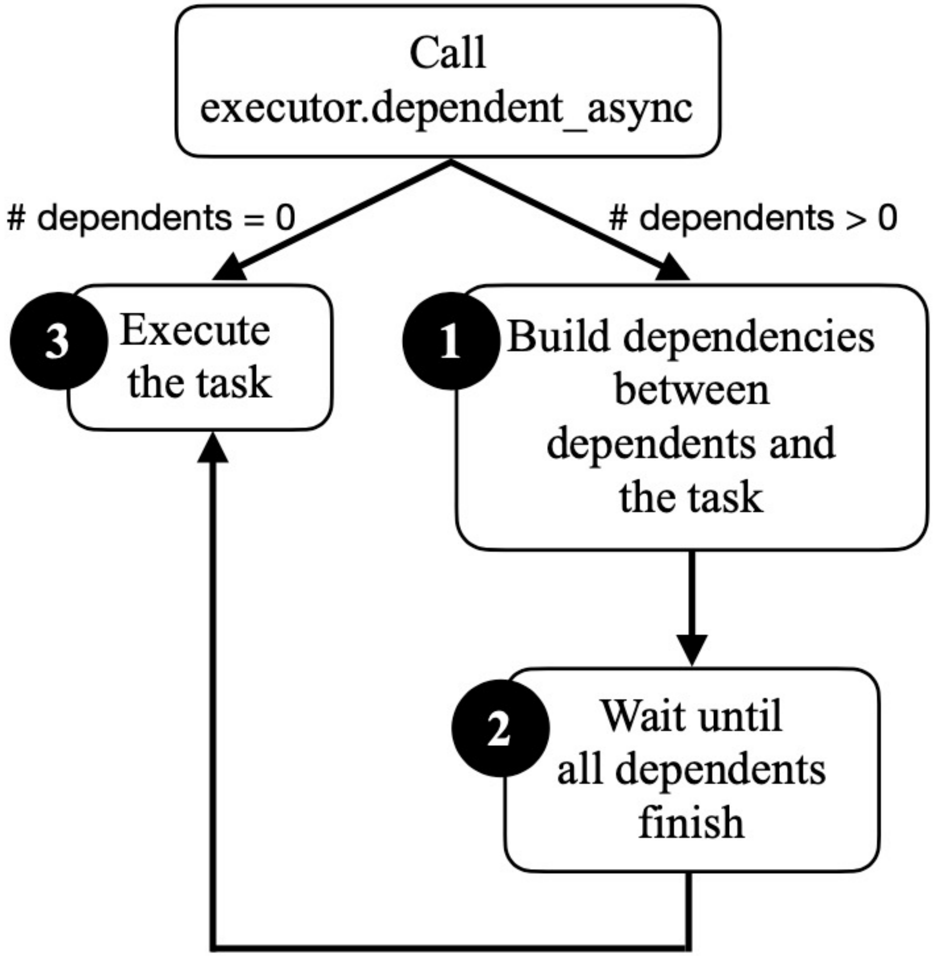
- **Worker-level scheduling**
  - Work stealing
  - Load balancing



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*

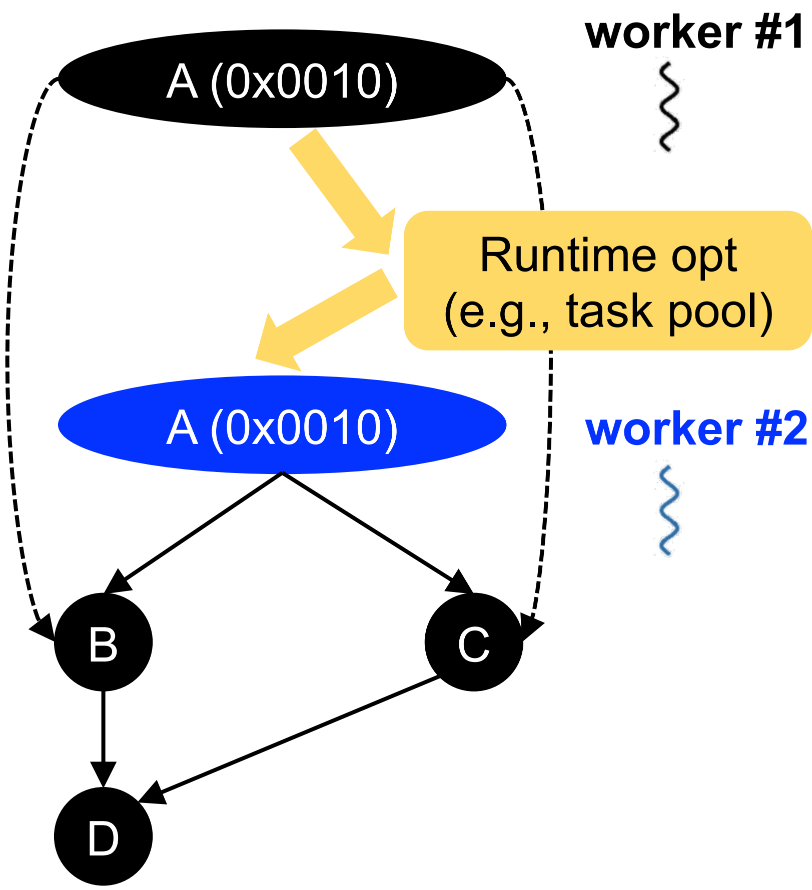
DTGP Scheduling Algorithm

- **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

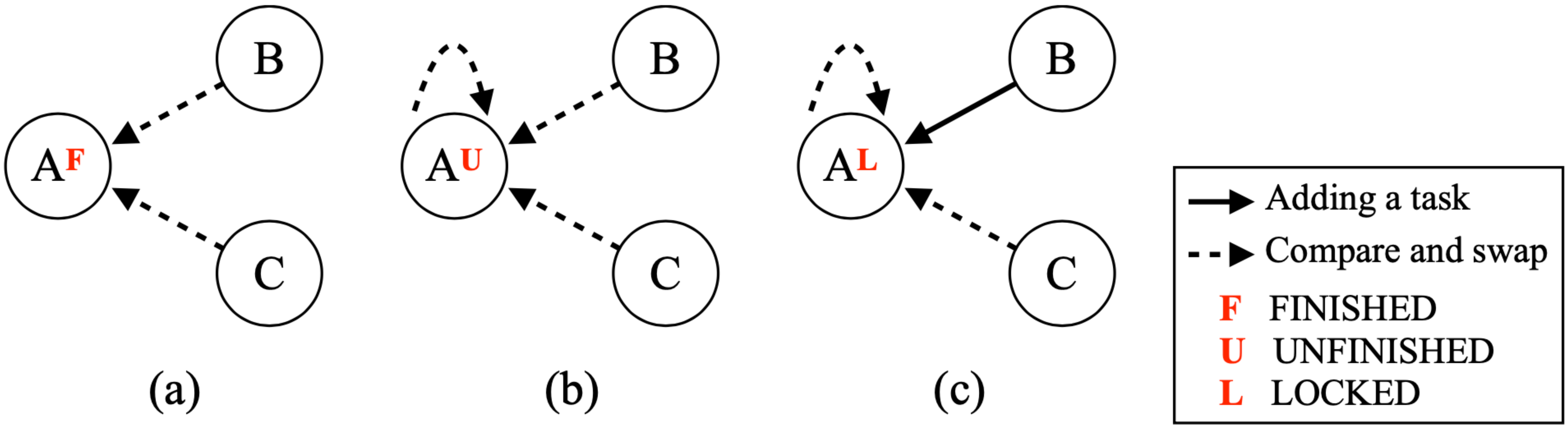
Retain Shared Ownership of Every Task

```
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**
  - executor.wait_for_all();

```
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;
});
```

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

Lock-free Scheduling Algorithm[1]

Algorithm 1 dependent_async(callable, deps)

Create a *future*
$num\_deps \leftarrow$ sizeof($deps$)
$task \leftarrow$initialize_task($callable, num\_deps, future$)
for all $dep \in deps$ **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: $dep\_state \leftarrow dep.state$
2: $target\_state \leftarrow UNFINISHED$
3: **if** dep_state.CAS($target\_state, LOCKED$) **then**
4:     $dep.successors$.push($task$)
5:     $dep\_state \leftarrow UNFINISHED$
6: **else if** $target\_state == FINISHED$ **then**
7:     $num_deps \leftarrow$AtomDec($task.join\_counter$)
8: **else**
9:     goto line 2
10: **end if**

Algorithm 3 schedule_async_task(task)

$target\_state \leftarrow UNFINISHED$
while not $task.state$.CAS($target\_state, FINISHED$) **do**
    $target\_state \leftarrow UNFINISHED$
end while
Invoke($task.callable$)
for all $successor \in task.successors$ **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

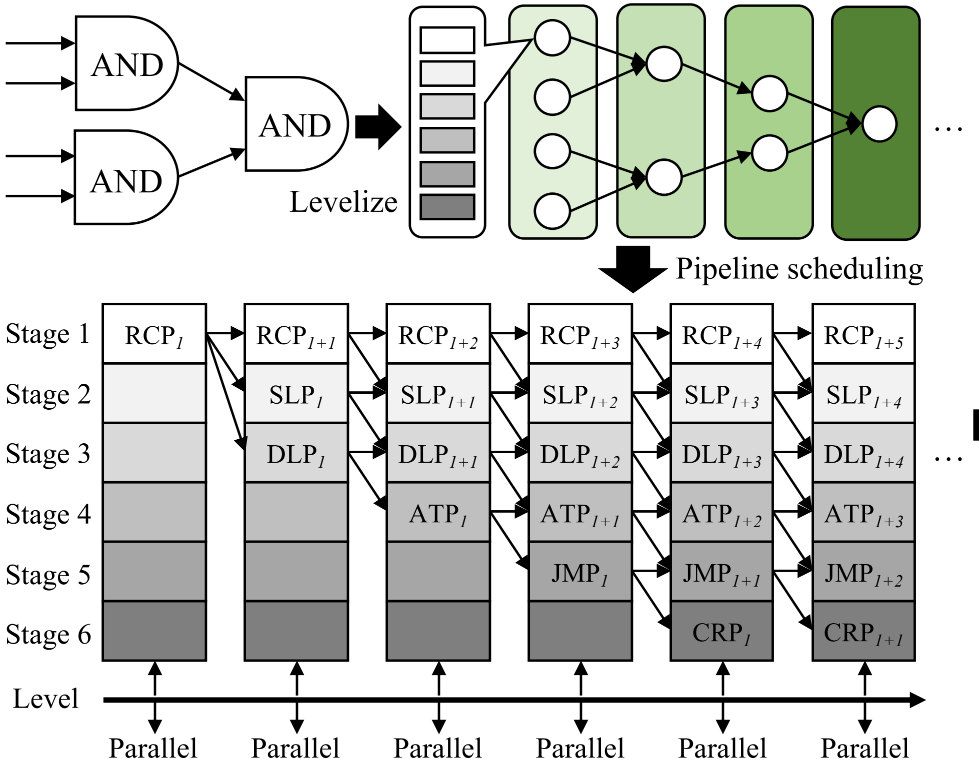
[1]: Cheng-Hsiang Chiu, et. al, "Programming Dynamic Task Parallelism for Heterogeneous EDA Algorithms," *IEEE/ACM ICCAD*, CA, 2023

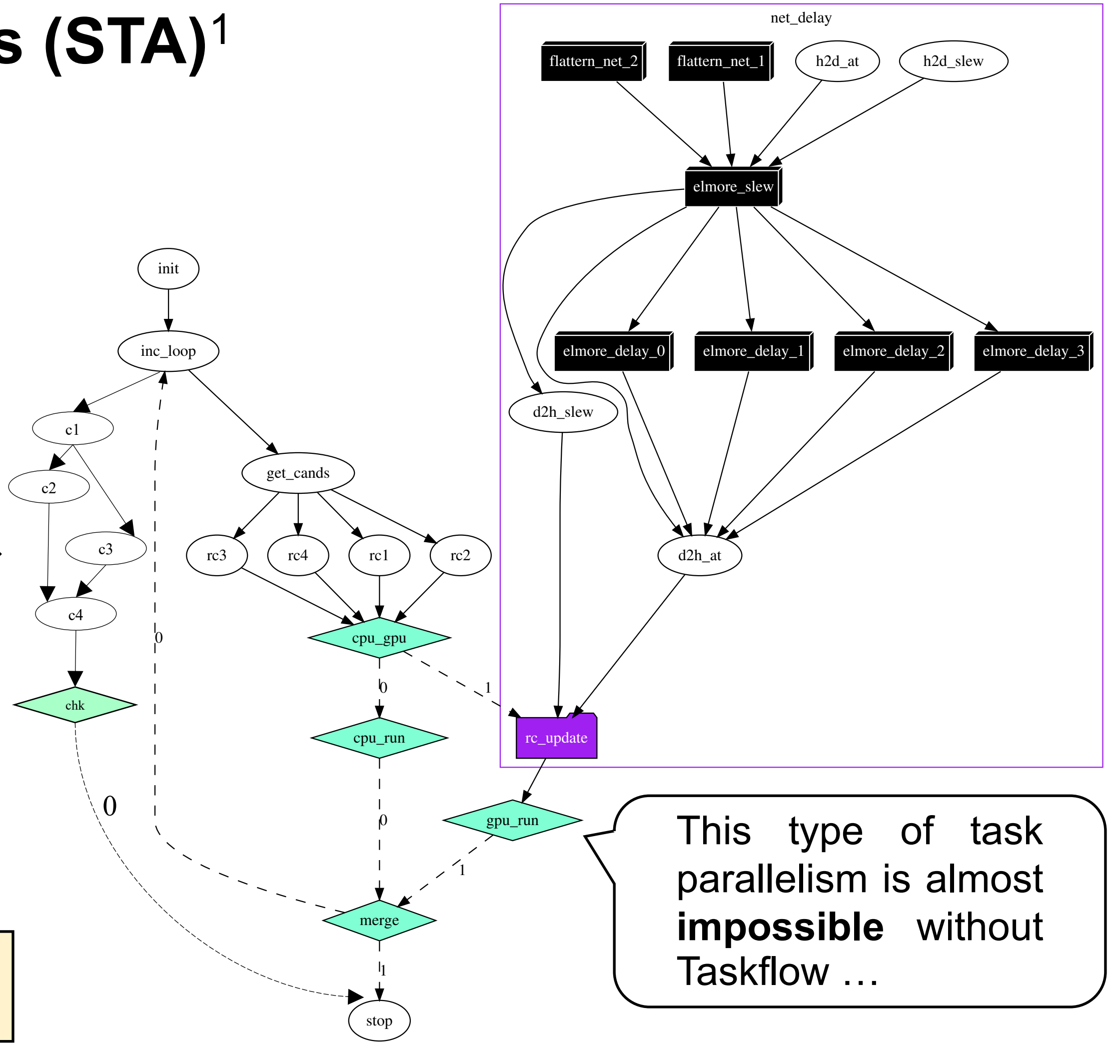
Takeaways

- 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 w/ STGP

- **Accelerating static timing analysis (STA)**[1]



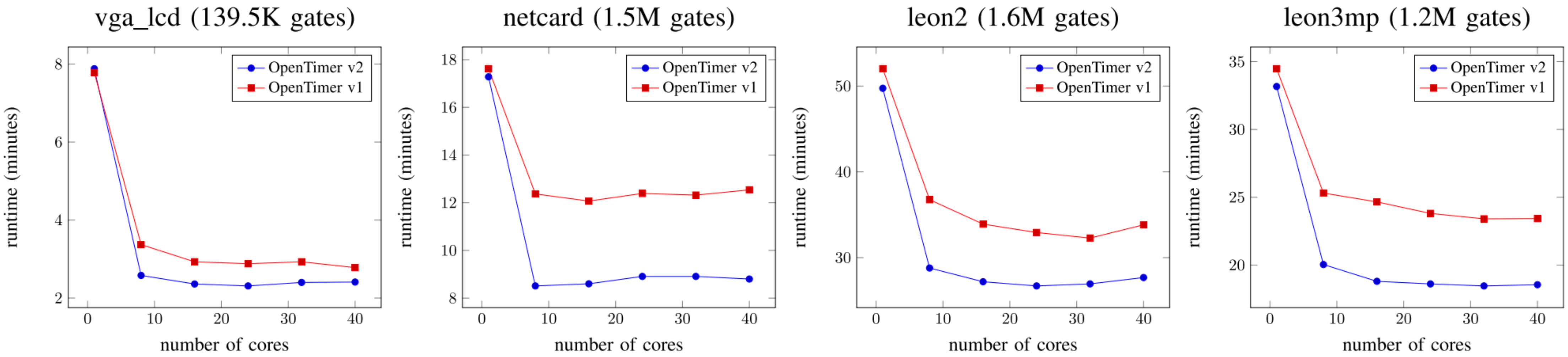


This type of task parallelism is almost **impossible** without Taskflow …

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

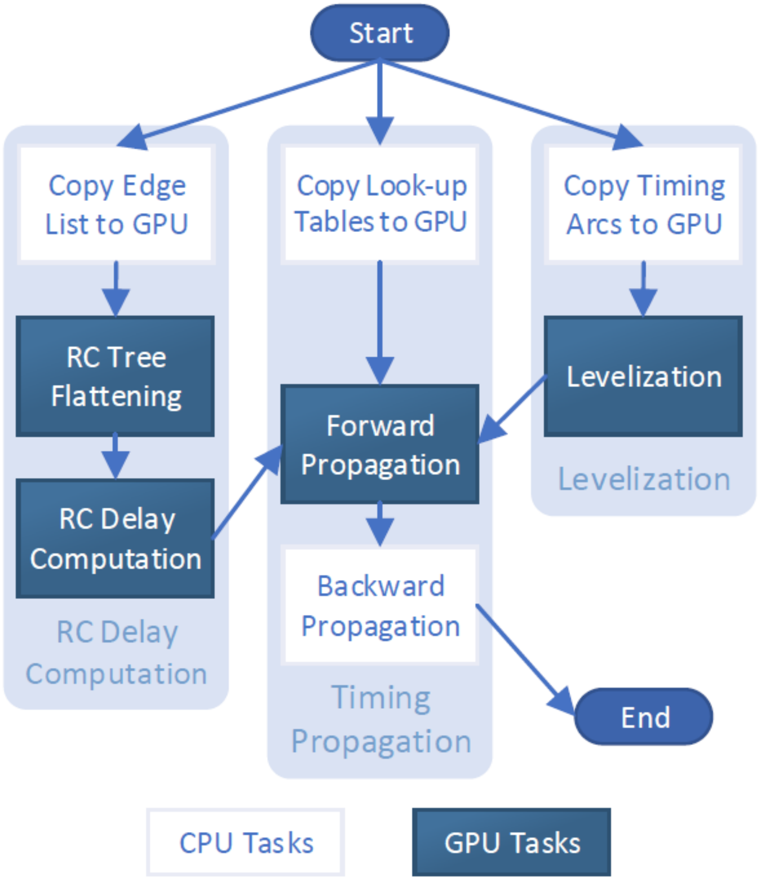
Levelization-based vs Task-parallel STA

- **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/)

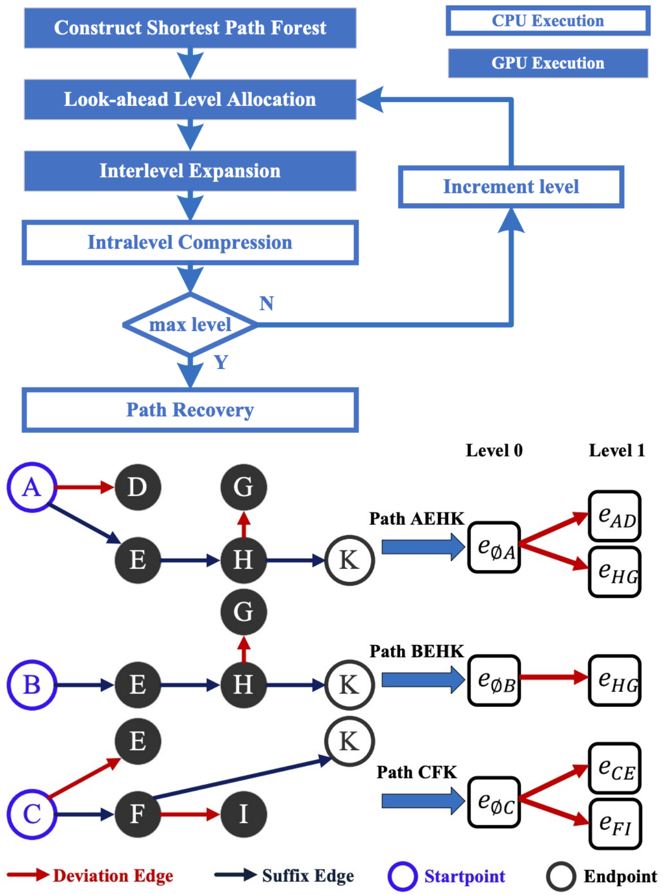


[1]: Tsung-Wei Huang and Martin Wong, "OpenTimer: A High-Performance Timing Analysis Tool," *IEEE/ACM ICCAD*, 2015
[2]: Tsung-Wei Huang, et al, “OpenTimer v2: A New Parallel Incremental Timing Analysis Engine,” *IEEE TCAD,* 2022

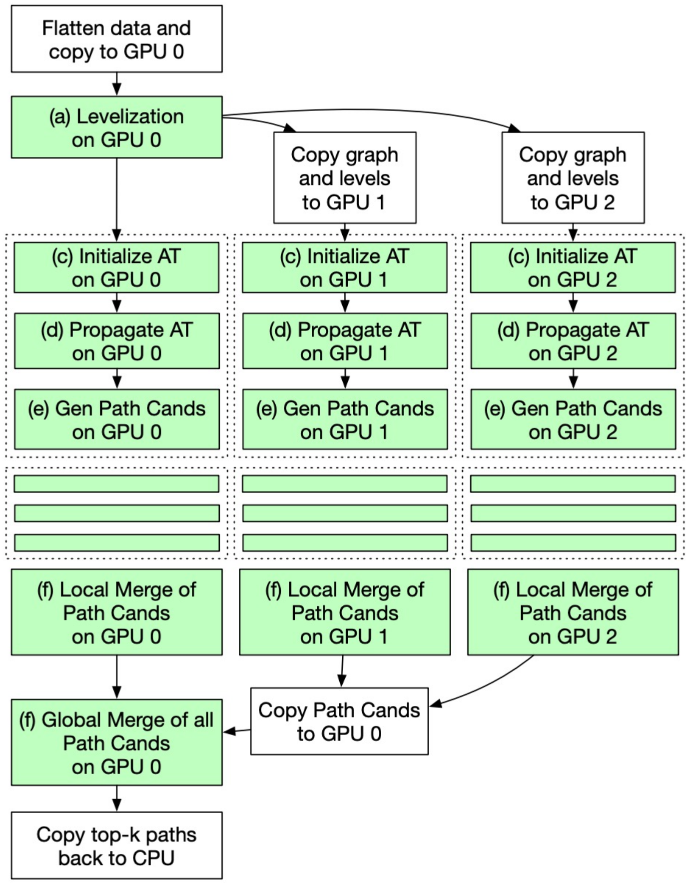
Our Research on Task-parallel STA



GPU-based graph analysis (ICCAD'20)



GPU-based path analysis (DAC'21)



GPU-based CPPR (ICCAD'21)

Example: Path-based Analysis with GPU

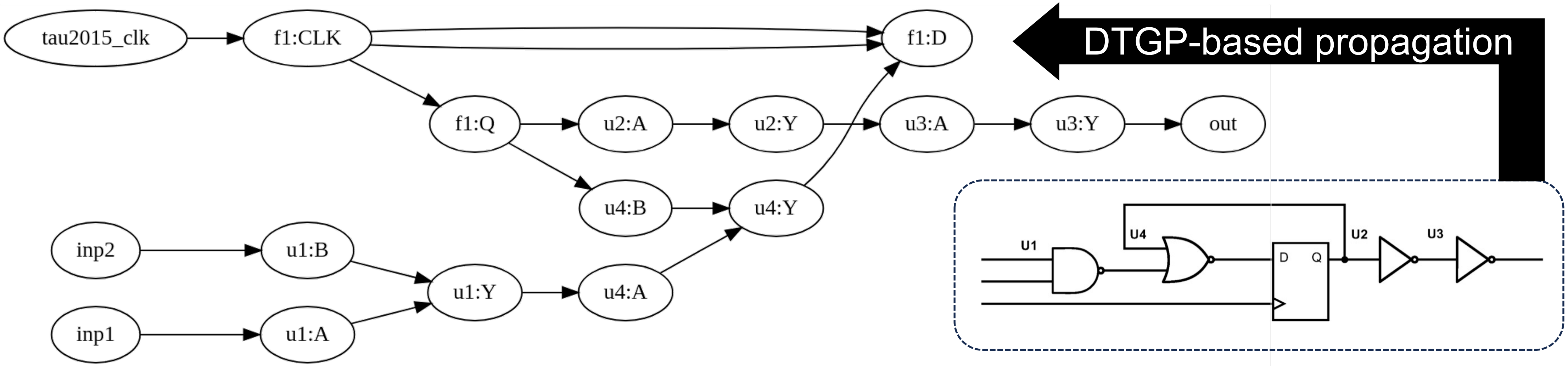
- **Applied Taskflow + GPU to accelerate path-based analysis**
  - **611x speed-up** over 1 CPU and **44x** over 40 CPUs on a large design
  - Evaluated on an Nvidia RTX 3090 GPU

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×

[1]: Guannan Guo, Tsung-Wei Huang, Yibo Lin, and Martin Wong, "GPU-accelerated Path-based Timing Analysis," *IEEE/ACM Design Automation Conference (DAC)*, CA, 2021

Case Study 2: Task-parallel STA w/ DTGP

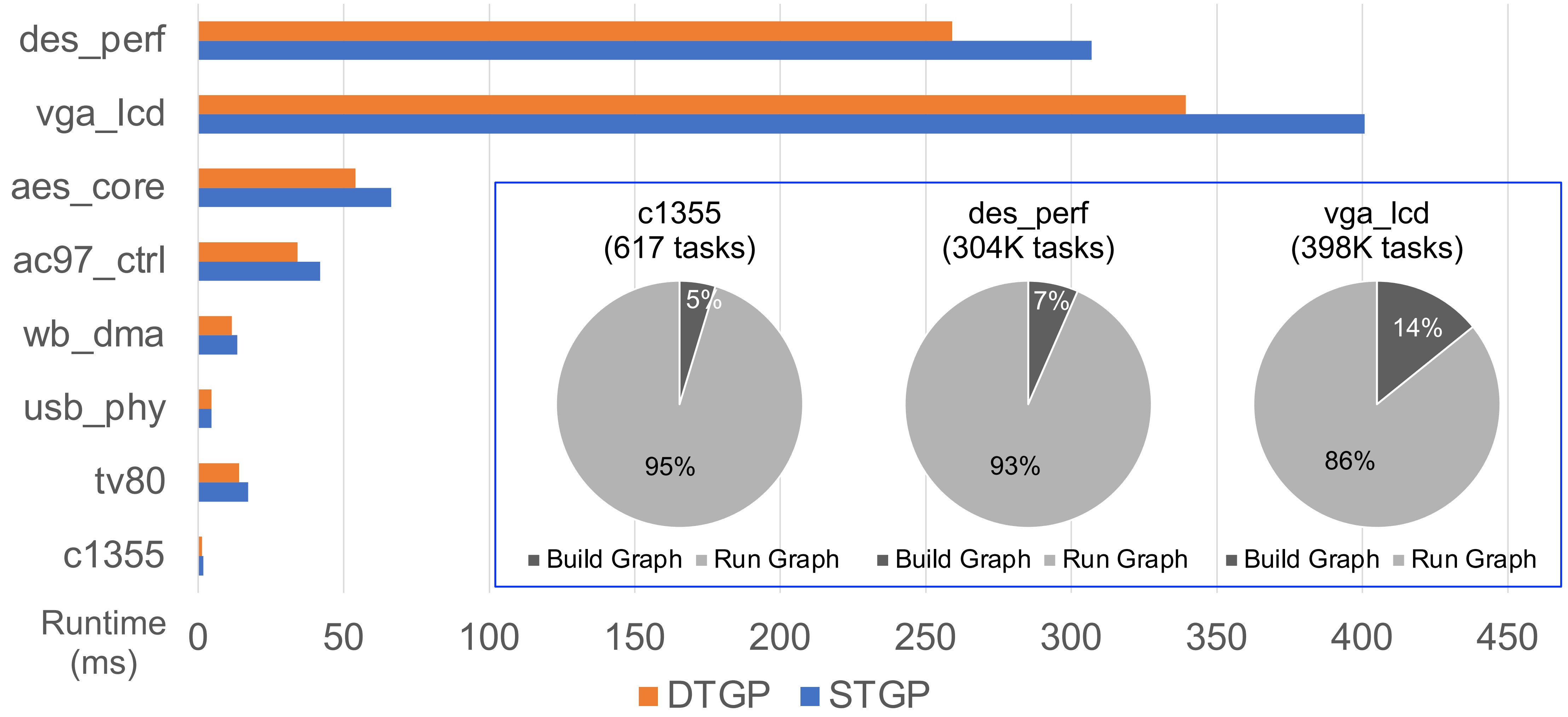
- **STGP works pretty well for task-parallel static timing analysis**
  - However, STGP may result in suboptimal performance for large circuits
  - Why? constructing a large task graph can be “very” time-consuming …
- **Reformulated the timing propagation into a dynamic task graph**
  - Ex (below): a task graph for a full-timing propagation on a five-gate circuit



17 tasks & 18 dependencies

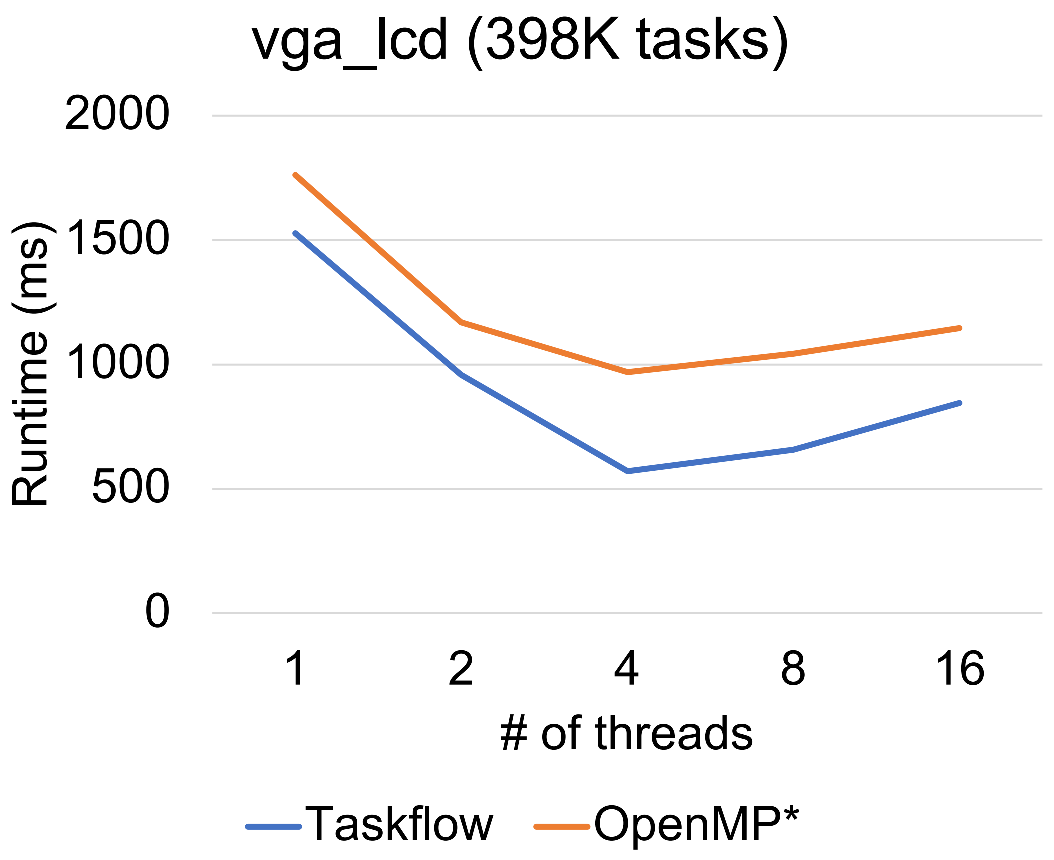
[1]: T.-W. Huang, et. al, ”OpenTimer v2: A New Parallel Incremental Timing Analysis Engine," *IEEE TCAD*, vol. 40, no. 4, pp. 776-789, April 2021

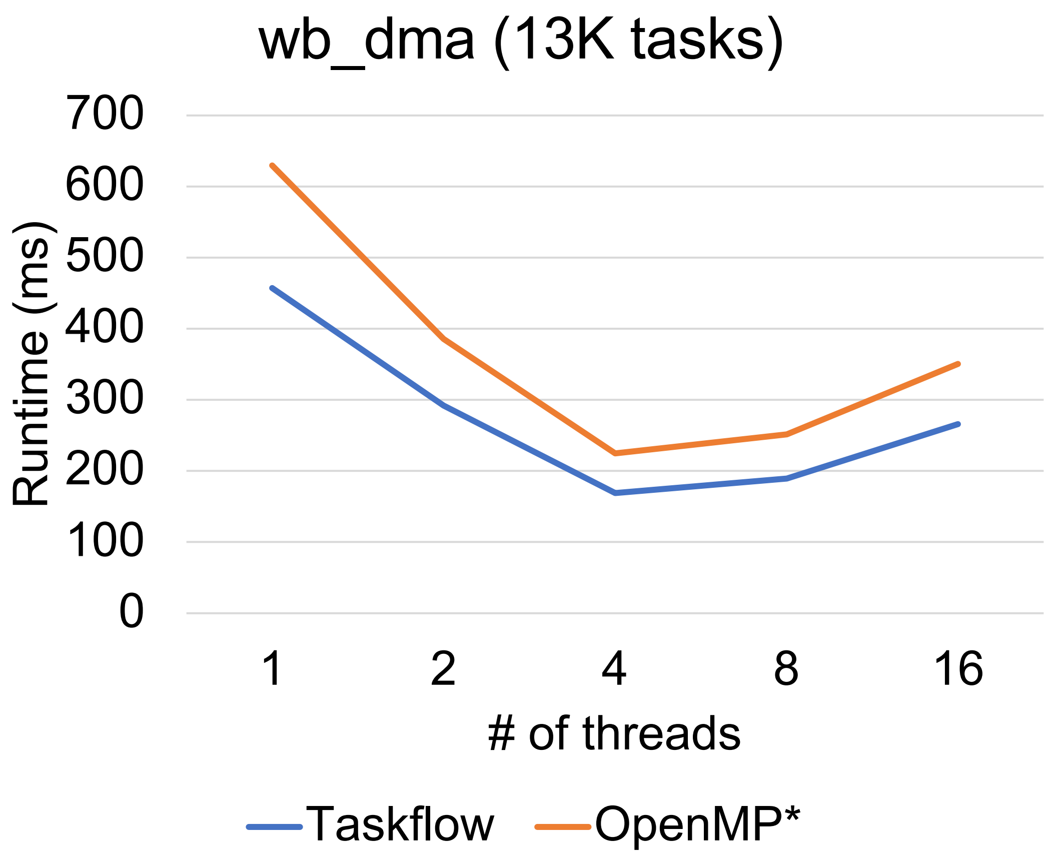
Runtime Comparison: STGP vs DTGP



Runtime Comparison with OpenMP

- **#omp depend([depend-modifier,]dependence-type : locator-list)**

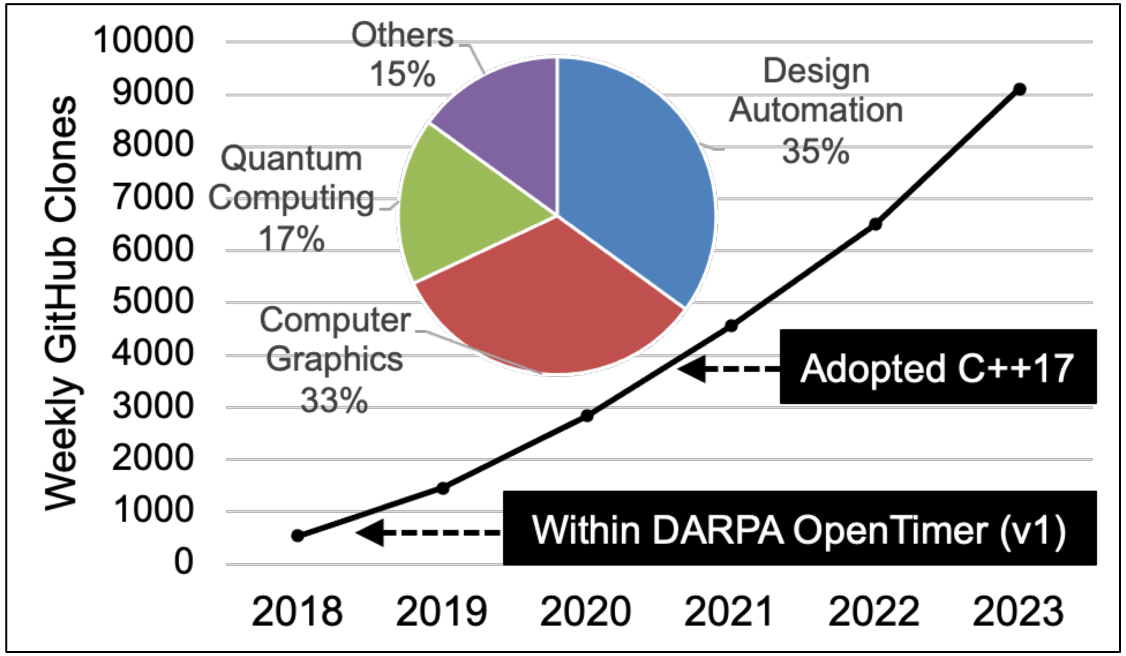




Other Industrial Applications of Taskflow

- **Quantum computing**
  - Xanadu deploys Taskflow in their quantum simulator
- **Computer graphics/rendering**
  - Vulkan officially recommends using Taskflow
- **FPGA synthesis**
  - Vivado uses Taskflow for synthesis
- **Embedded/edge computing**
  - Tesseract (robotics planning)
  - Cruise (autonomous car)
  - Reveal.Tech (drone vision)
  - Tesseract Robotic (planning tool)
  - …

https://vkguide.dev/docs/extra-chapter/multithreading/



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

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();
```