# Taskflow: A General-purpose Task-parallel Programming System

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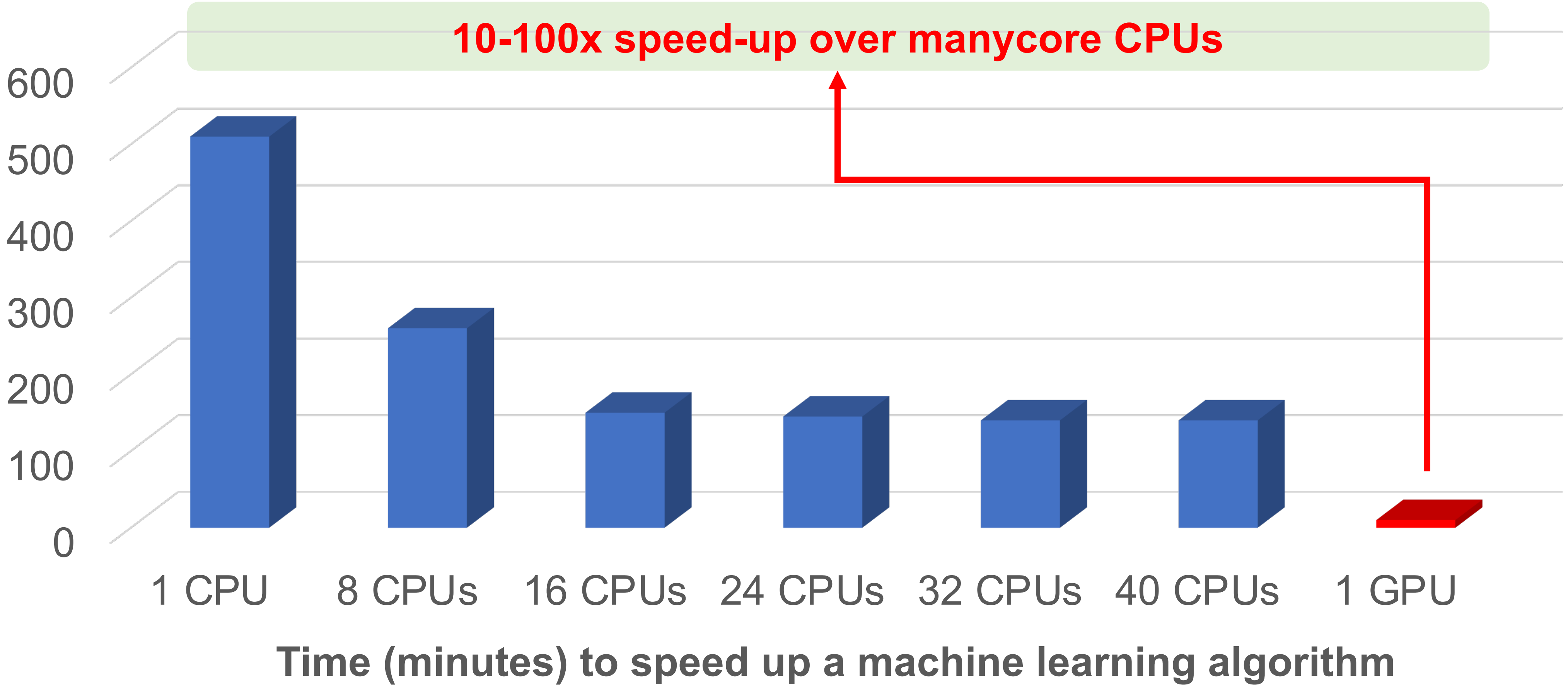
https://taskflow.github.io/

# Takeaways

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

# Why Parallel Computing?

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



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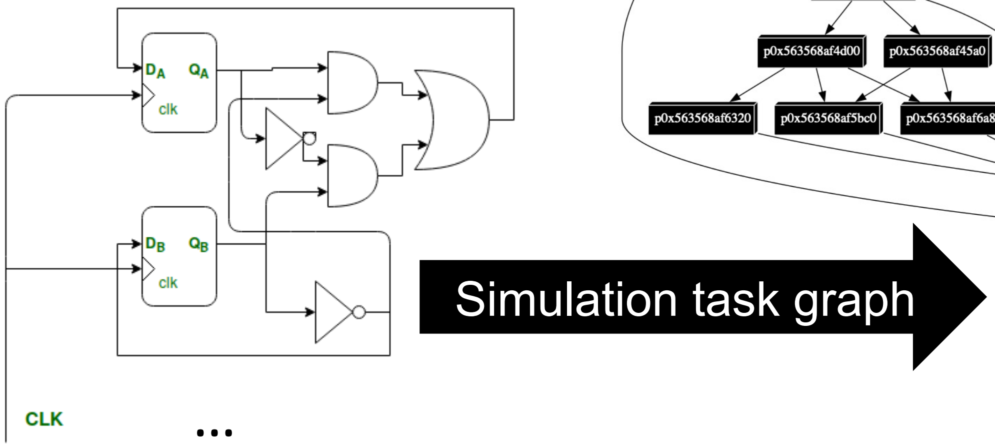
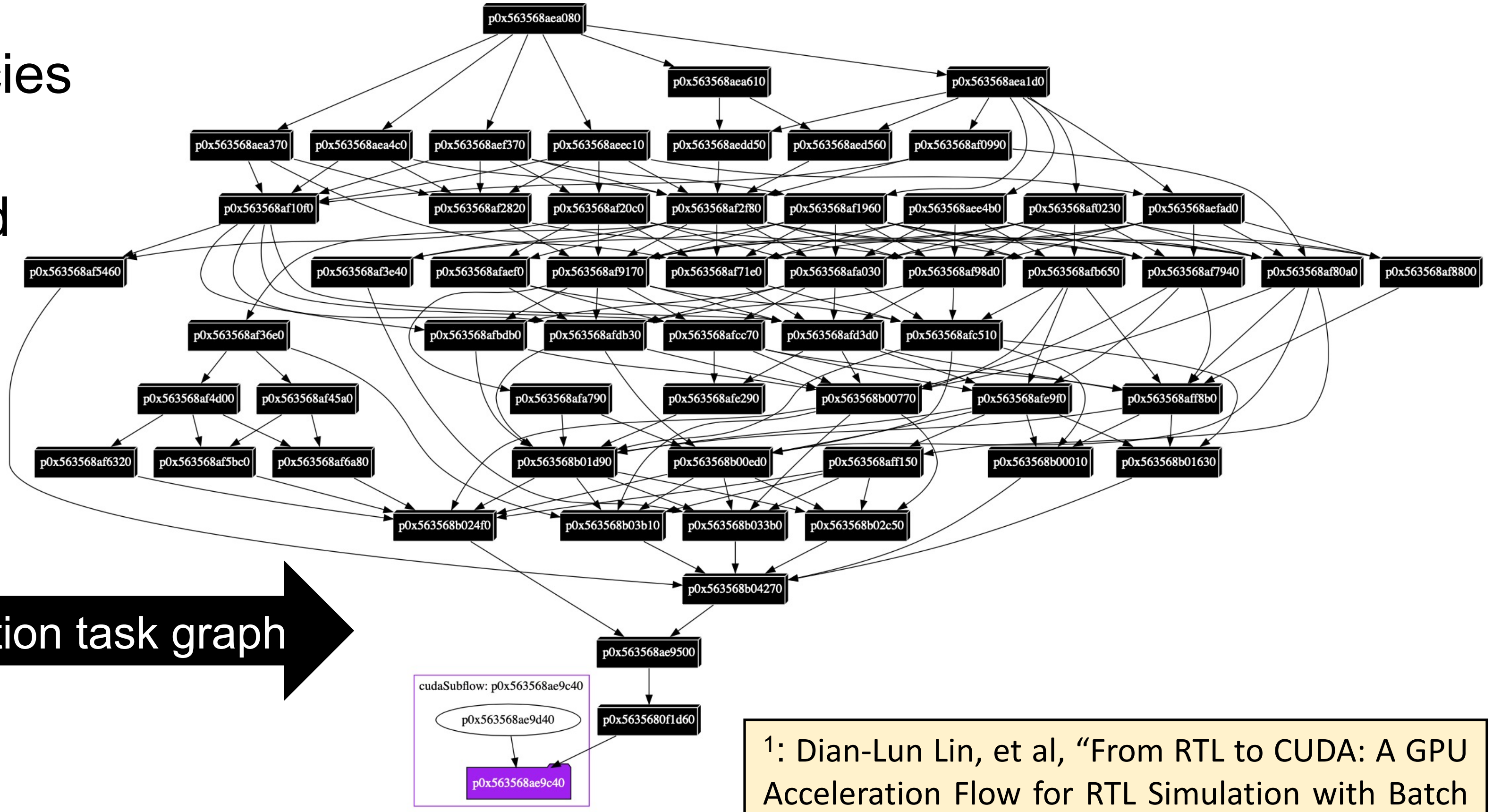
# Today's Parallel Workload is Very Complex

- **GPU-accelerated circuit simulation on a design of <u>500M</u> gates**[1]
  - >1000 kernels
  - >1000 dependencies
  - >500s to finish
  - >10hrs turnaround

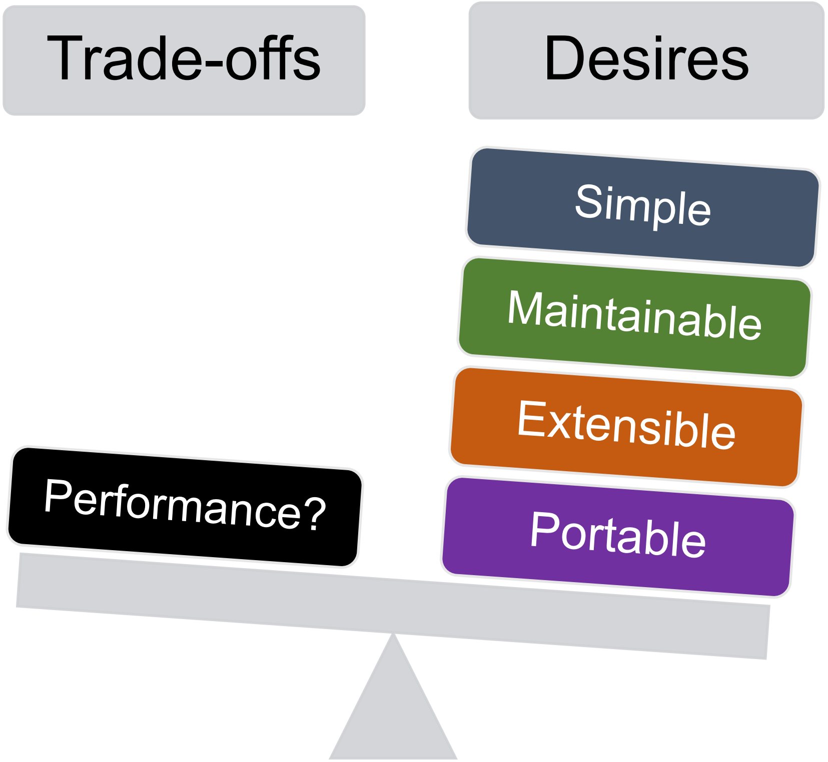



[1]: Dian-Lun Lin, et al, "From RTL to CUDA: A GPU Acceleration Flow for RTL Simulation with Batch Stimulus," *ACM ICPP*, Bordeaux, France, 2022

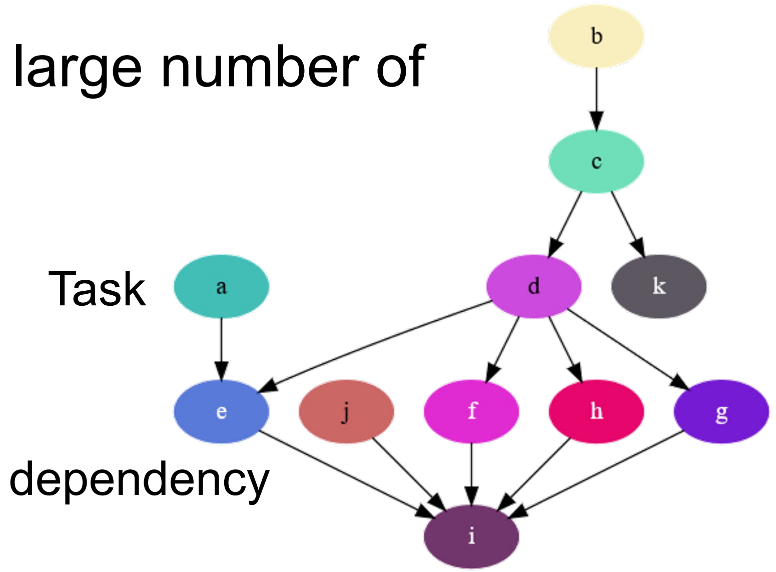
# Parallel Programming is Not Easy

- **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 High-level Programming Model

- **From user's perspective, the biggest challenge is *transparency***
  - Parallelism 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 parallel algorithm into a top-down task graph
  - Runtime can schedule dependent tasks across a large number of processing units (e.g., CPUs, GPUs)





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# Takeaways

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- Program dynamic task graph parallelism using Taskflow
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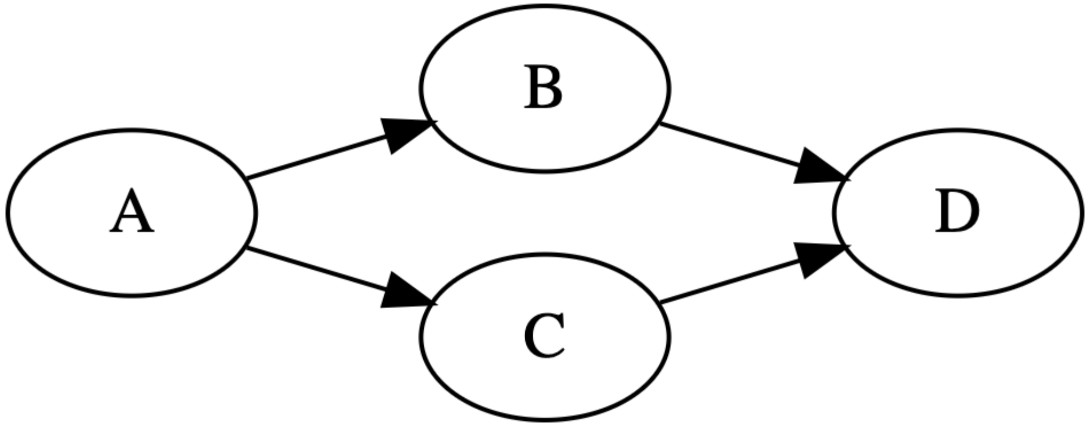
- Conclude the talk

# “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

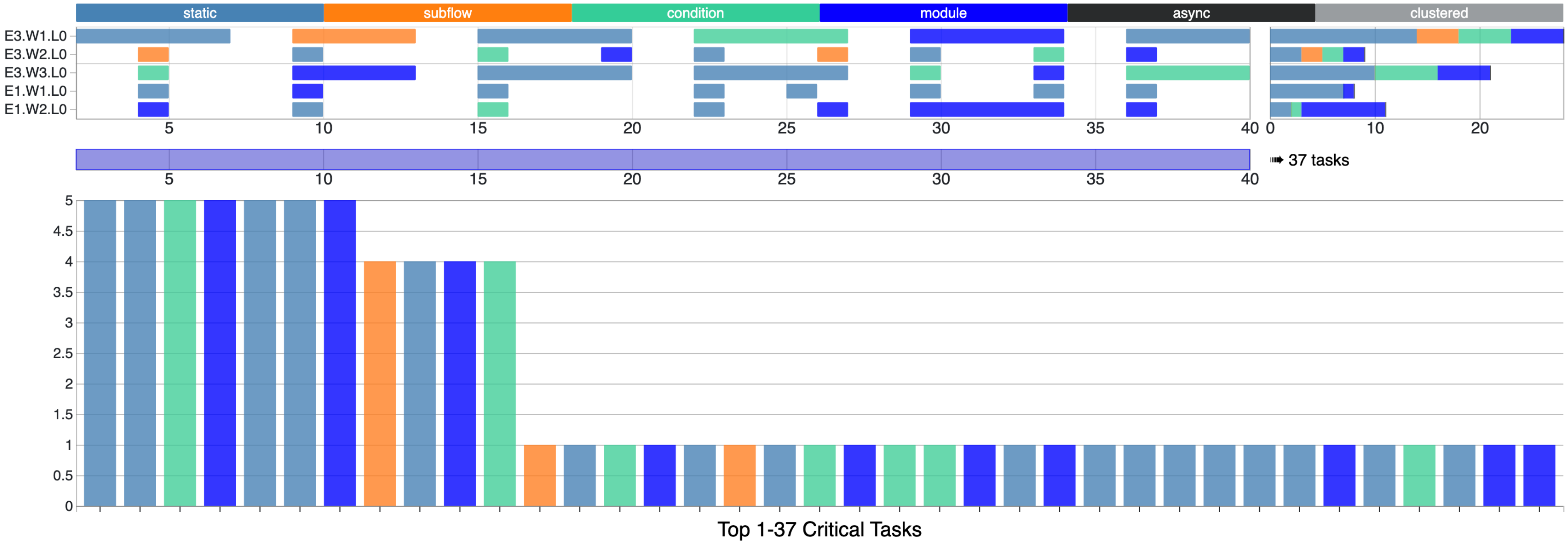
# Drop-in Integration

- **Taskflow is header-only and written in completely standard C++**
  - ☺ 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

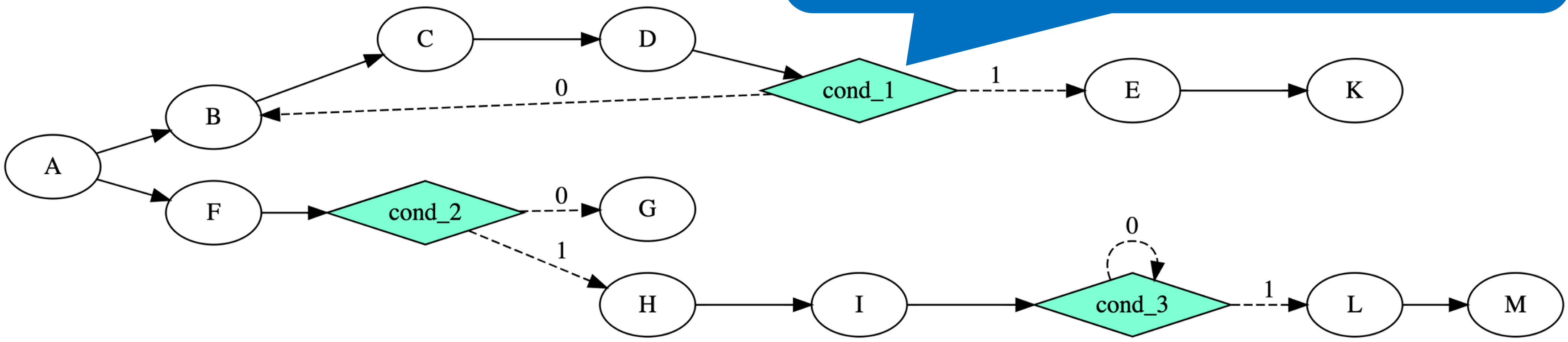
```
# run you program with the env variable TF_ENABLE_PROFILER enabled
# to generate profile data and past it on https://taskflow.github.io/tfprof/
~$ TF_ENABLE_PROFILER=simple.json ./simple
```



# 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 …





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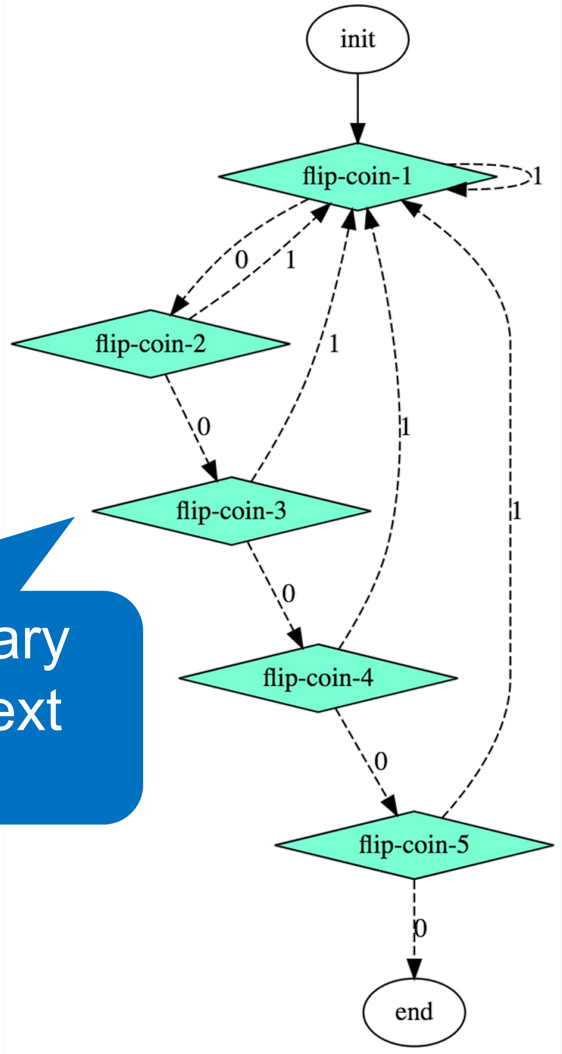
# Non-deterministic Control Flow with CTFG

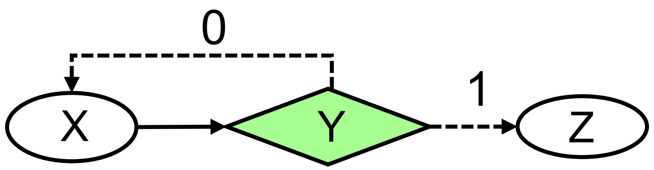
```
auto A = taskflow.emplace([&](){ } );
auto B = taskflow.emplace([&](){ return rand()%2; } );
auto C = taskflow.emplace([&](){ return rand()%2; } );
auto D = taskflow.emplace([&](){ return rand()%2; } );
auto E = taskflow.emplace([&](){ return rand()%2; } );
auto F = taskflow.emplace([&](){ return 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

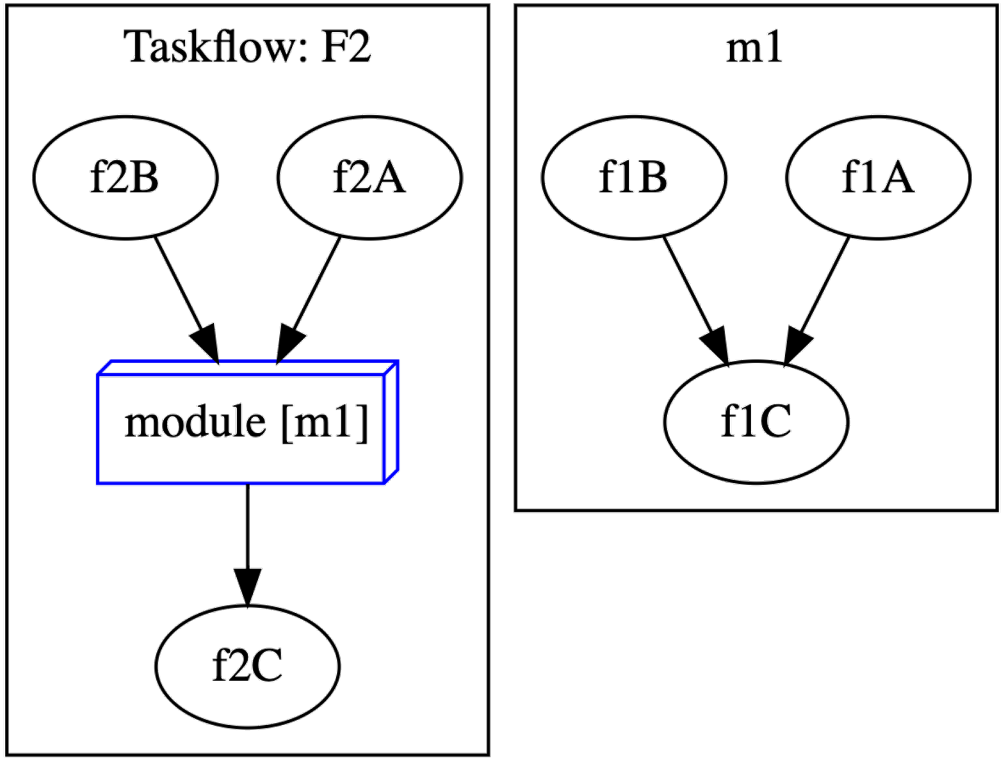



```
tf::Taskflow G;
auto X = G.emplace([](){});
auto Y = G.emplace([](){
  return converged() ? 1 : 0;
});
cond.precede(Z, X);
executor.run(G).wait();
```

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

# Composable Tasking

```
tf::Taskflow m1, f2;
auto [f1A, f1B] = m1.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(m1);
f1_module_task.succeed(f2A, f2B)
                .precede(f2C);
```



# Everything is Composable in Taskflow

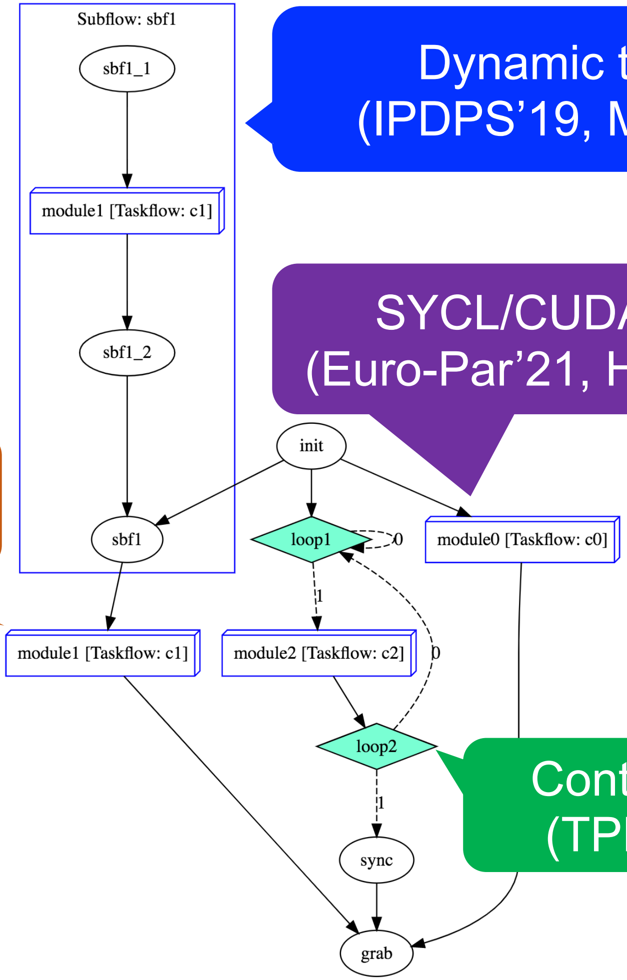
- **End-to-end parallelism in one graph**
  - Task, dependency, control flow all together
  - Scheduling with whole-graph optimization
  - Efficiently overlap tasks with control flow
- **Largely improved productivity!**

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.

8 Reply Share Report Save Follow

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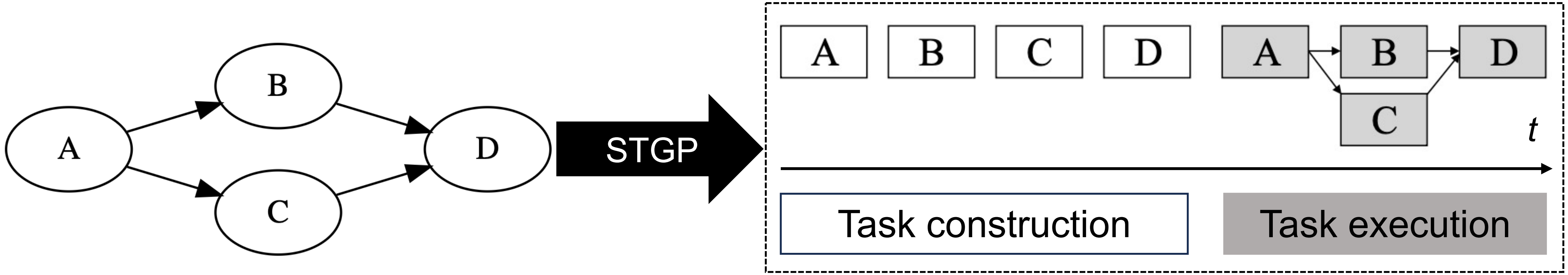
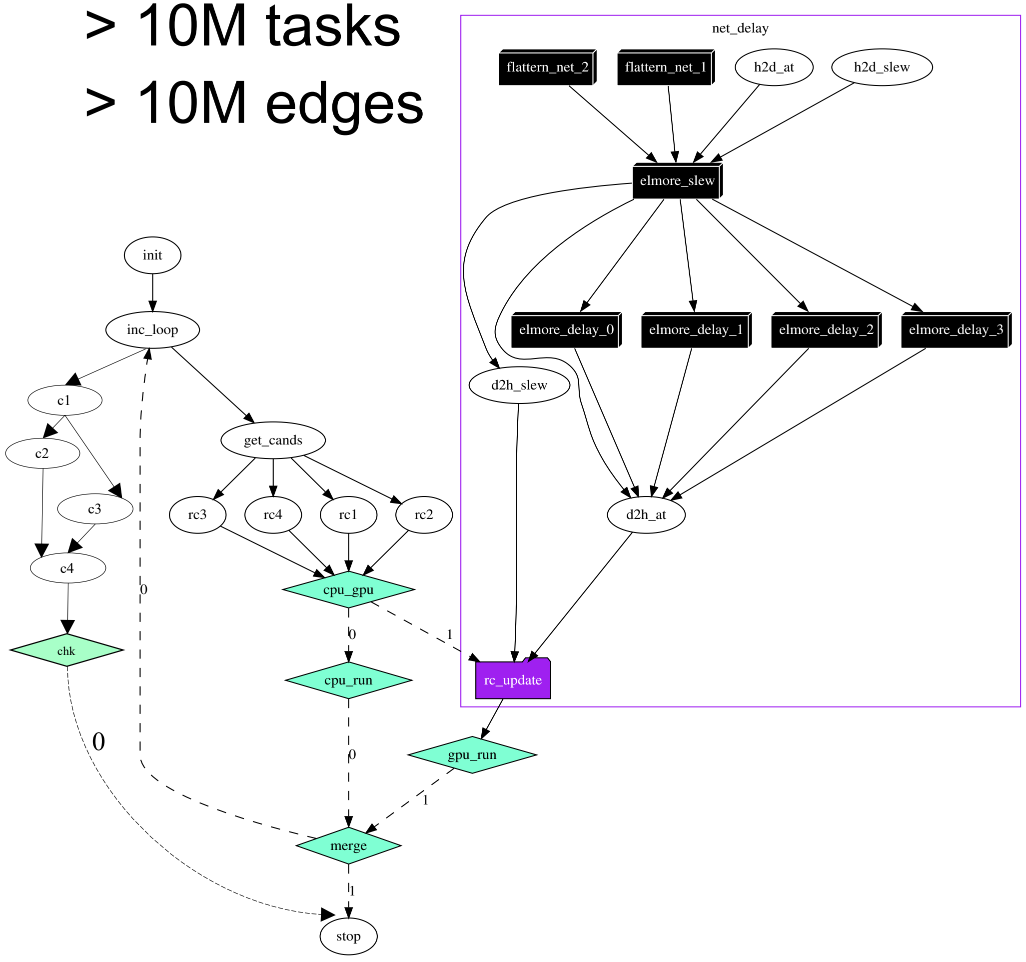
# Static Task Graph Parallelism (STGP)

- **In STGP, the graph structure must be known at compile time**
  - Construct-and-run model – *Construct the task graph first and then run it*
- **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 expressions of TGP**
  - *Task graph structure cannot depend on runtime values or control-flow results*

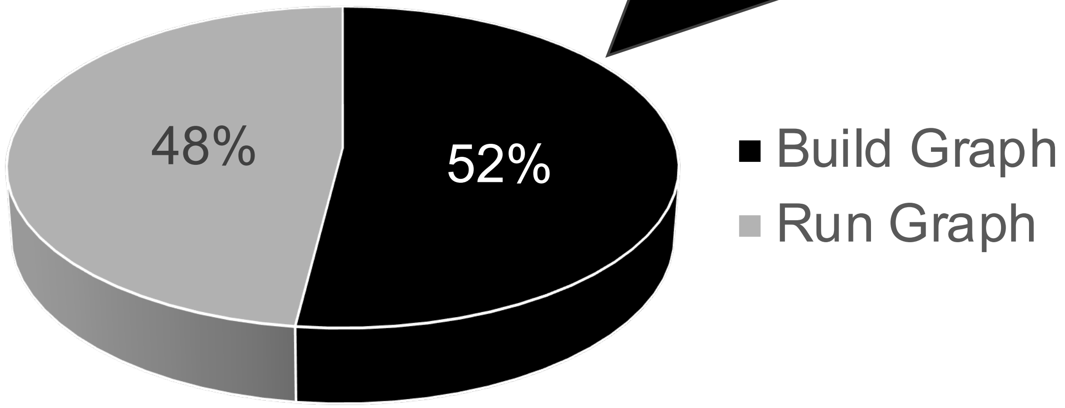


# Problem of STGP: Example #1

- **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




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

# Problem of STGP: Example #2

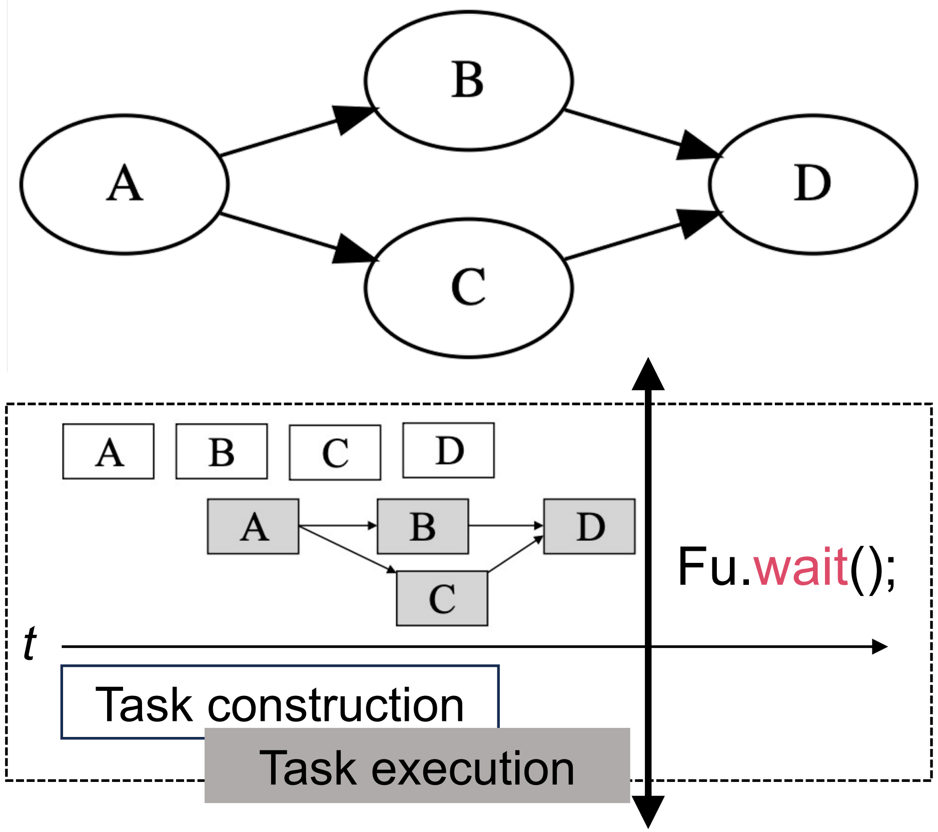
- **TGP that depends on dynamic control-flow results**

```
if (a == true) {
  G1 = build_task_graph1();
  if (b == true) {
    G2 = build_task_graph2();
    G1.precede(G2);
    if (c == true) {
      … // another level of dynamic 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) {
    {
      … // another level of dynamic TGP
    }
}
```

# Dynamic TGP (DTGP) in Taskflow

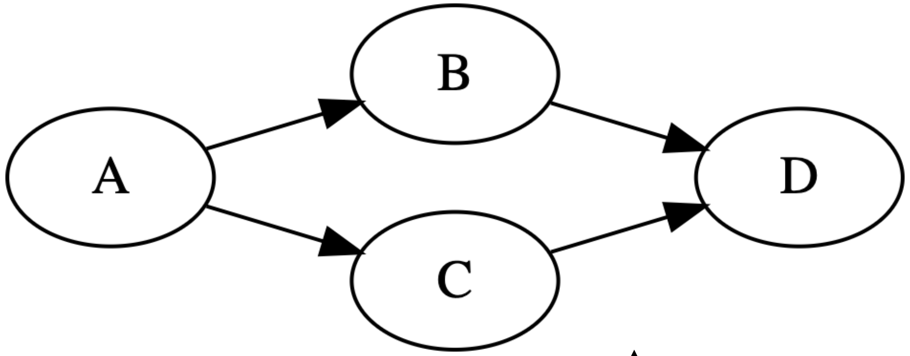
```
// Live: https://godbolt.org/z/j76ThGbWK
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";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

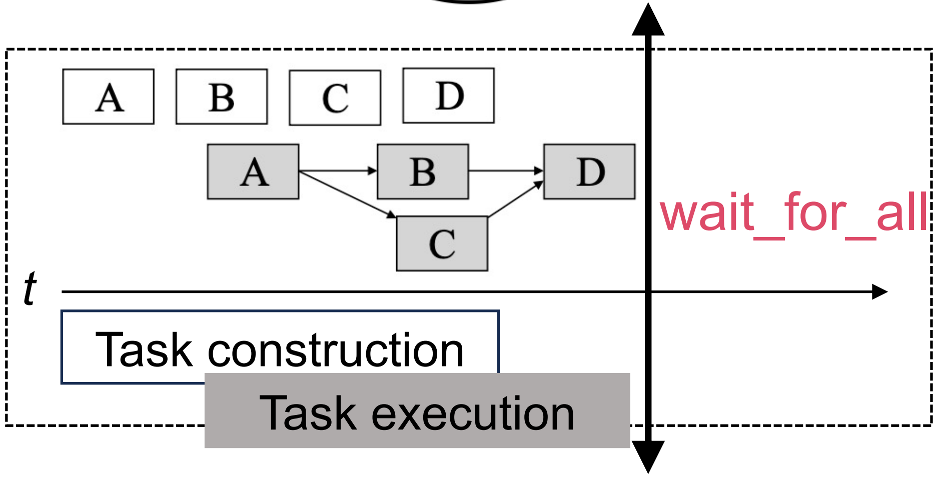



Specify arbitrary task dependencies using C++ variadic parameter pack

# silent_dependent_async is cheaper

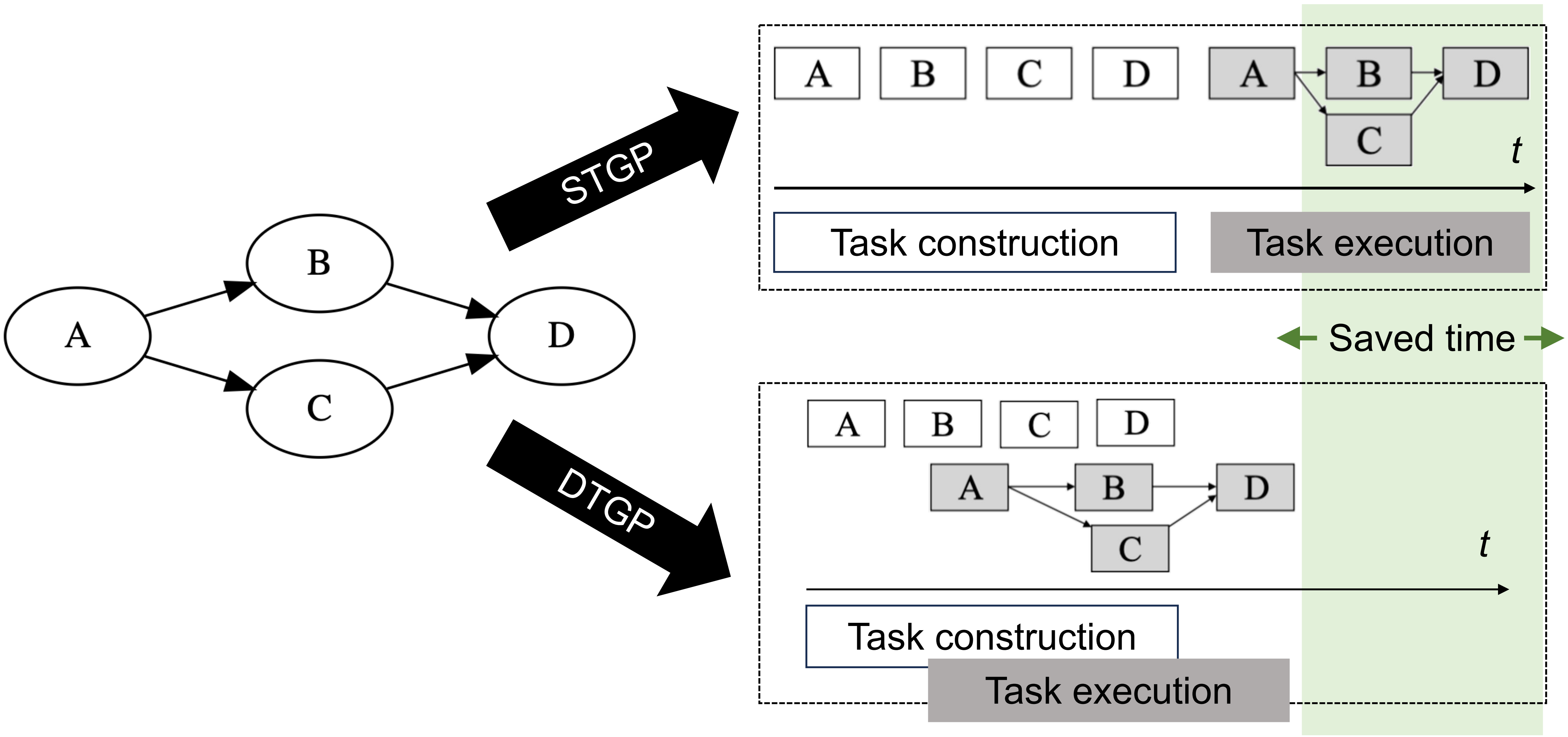
```
// Live: https://godbolt.org/z/T87PrTarx
tf::Executor executor;
auto A = executor.silent_dependent_async([](){
    std::cout << "TaskA\n";
});
auto B = executor.silent_dependent_async([](){
    std::cout << "TaskB\n";
}, A);
auto C = executor.silent_dependent_async([](){
    std::cout << "TaskC\n";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

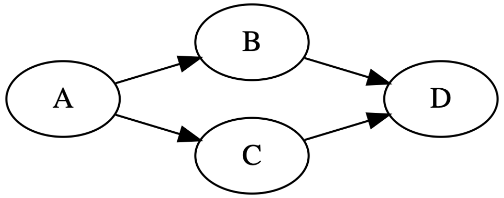
# Comparison between STGP and DTGP

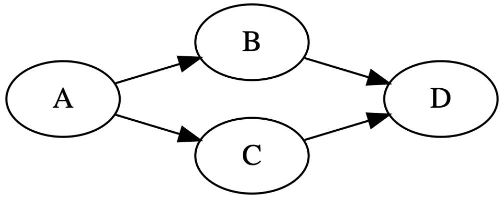


# DTGP Needs a Correct Topological Order

```
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



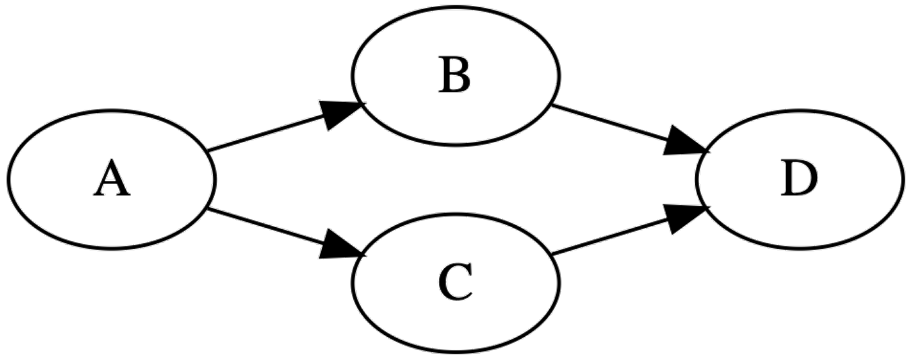

Topological order #2: A→C→B→D

```
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 doesn't Work

```
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 variable 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());
```

# Existing DTGP Libraries: C++ Async

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

Block until A completes

Block until A completes

Block until B and C complete

# Existing DTGP Libraries: OpenMP/Kokkos

## OpenMP “dependency clauses”

```
#omp parallel num_threads(hardware_concurrency())
{
   int A_B, A_C, B_D, C_D;
   #pragma omp task depend(out: A_B, A_C)
   {
      std::cout << “TaskA\n” ;
   }
   #pragma omp task depend(in: A_B; out: B_D)
   {
      std::cout << “TaskB\n” ;
   }
   #pragma omp task depend(in: A_C; out: C_D)
   {
      std::cout << “TaskC\n” ;
   }
   #pragma omp task depend(in: B_D, C_D)
   {
      std::cout << “TaskD\n” ;
   }
}
```

## Kokkos “task template”

```
struct A {
   template <class TeamMember> KOKKOS_INLINE_FUNCTION
   void operator()(TeamMember& member) { std::cout << "TaskA\n"; }
};
struct B {
   template <class TeamMember> KOKKOS_INLINE_FUNCTION
   void operator()(TeamMember& member) { std::cout << "TaskB\n"; }
};
struct C {
   template <class TeamMember> KOKKOS_INLINE_FUNCTION
   void operator()(TeamMember& member) { std::cout << "TaskC\n"; }
};
struct D {
   template <class TeamMember> KOKKOS_INLINE_FUNCTION
   void operator()(TeamMember& member) { std::cout << "TaskD\n"; }
};
auto scheduler = scheduler_type(/* ... */);
auto futA = Kokkos::host_spawn(Kokkos::TaskSingle(scheduler), A());
auto futB = Kokkos::host_spawn(Kokkos::TaskSingle(scheduler, futA), B());
auto futC = Kokkos::host_spawn(Kokkos::TaskSingle(scheduler, futA), C());
auto futD = Kokkos::host_spawn(
  Kokkos::TaskSingle(scheduler, when_all(futB, futC)), D()
);
… (more code to follow)
```

# Existing DTGP Libraries: PARSEC

```
int A(parsec_task_t* this_task) {
  int *out;
  unpack_args(this_task, &out);
  printf("TaskA\n");
  return APARSEC_HOOK_RETURN_DONE;
}
int B(parsec_task_t* this_task) {
  int *out, *in;
  unpack_args(this_task, &in, &out);
  printf("TaskB\n");
  return APARSEC_HOOK_RETURN_DONE;
}
int C(parsec_task_t* this_task) {
  int *in, *out;
  unpack_args(this_task, &in, &out);
  printf("TaskC\n");
  return APARSEC_HOOK_RETURN_DONE;
}
int D(parsec_task_t* this_task) {
  int *in1, *in2, *out;
  unpack_args(this_task, &in1, &in2, &out);
  printf("TaskD\n");
  return APARSEC_HOOK_RETURN_DONE;
}
```

```
int main() {
  /* additional boilerplate code to initialize PARSEC runtime
environment (e.g., taskpool, dtd_tp, dependency data, etc.) */
  int *out;
  parsec_dtd_insert_task(A,
    tile_of_key(dependency, 0), INPUT, ARSEC_DTD_ARG_END
  );
  parsec_dtd_insert_task(B,
    tile_of_key(dependency, 0), INPUT,
    tile_of_key(dependency, 1), OUTPUT, PARSEC_DTD_ARG_END
  );
  parsec_dtd_insert_task(C,
    tile_of_key(dependency, 0), INPUT,
    tile_of_key(dependency, 2), OUTPUT, PARSEC_DTD_ARG_END
  );
  parsec_dtd_insert_task(D,
    tile_of_key(dependency, 1), INPUT,
    tile_of_key(dependency, 2), INPUT,
    tile_of_key(dependency, 3), OUTPUT, PARSEC_DTD_ARG_END
  );
  parsec_taskpool_wait();
}
```

# Limitations of Existing DTGP Libraries

1. **Suffer from large verbosity from the ease-of-use standpoint**
   - The code does not explain itself – *I know this is subjective, but most applications just care how fast they can get things done …*
2. **Count on dataflow to express task dependencies**
   - Users need to explicitly define per-edge data to specify a task dependency
     - OpenMP's **in-out** dependency clauses
     - PARSEC's **INPUT-OUTPUT** keywords and **tile_of_key** constructs
3. **Rely on complex data structure to schedule tasks**
   - Libomp implements a lock-based hash table to schedule tasks
     - Key: address of the input and output data of a task
     - Value: a list of tasks accessing that input and output data
   - Frequent access to this data structure results in large runtime overhead

# Takeaways

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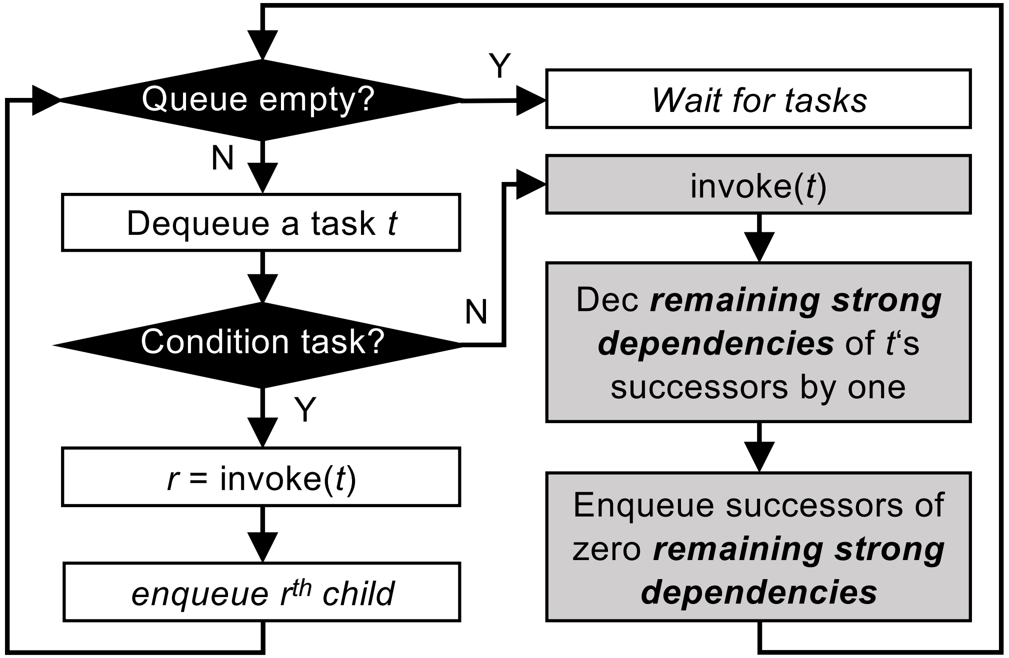
- Program task graph parallelism using Taskflow
- Program dynamic task graph parallelism using Taskflow
- Overcome the scheduling challenges
- Demonstrate the efficiency of Taskflow in industrial application
- Conclude the talk

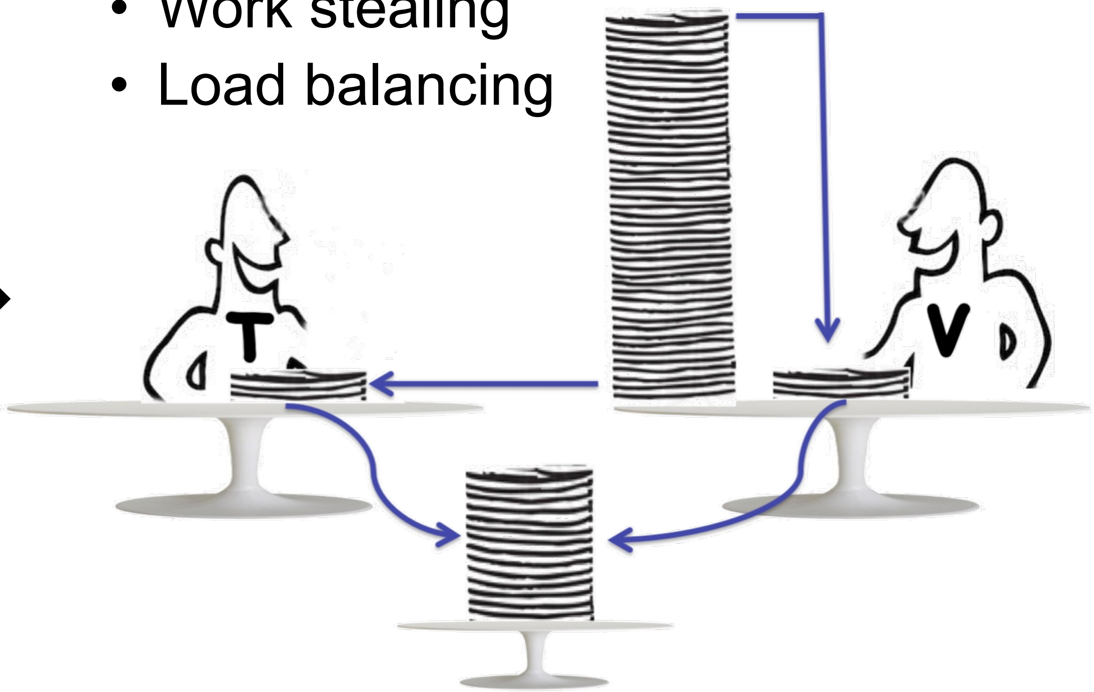
# STGP Scheduling Algorithm

## • 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*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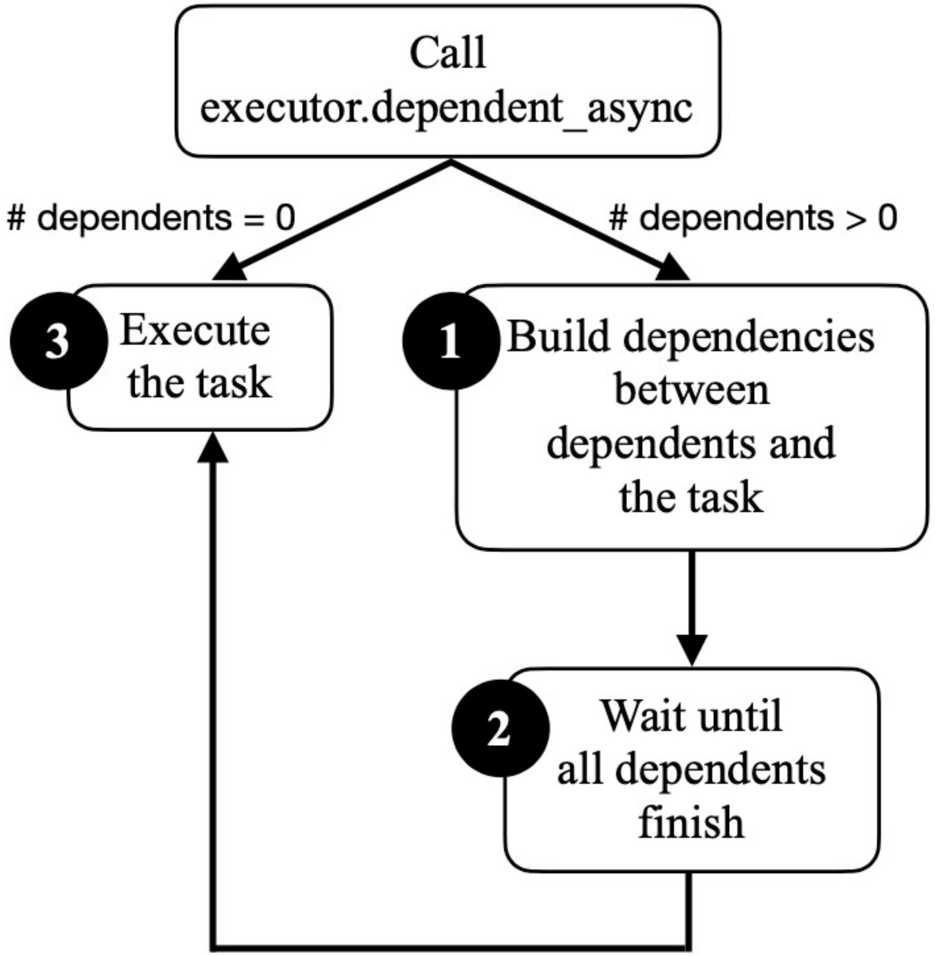
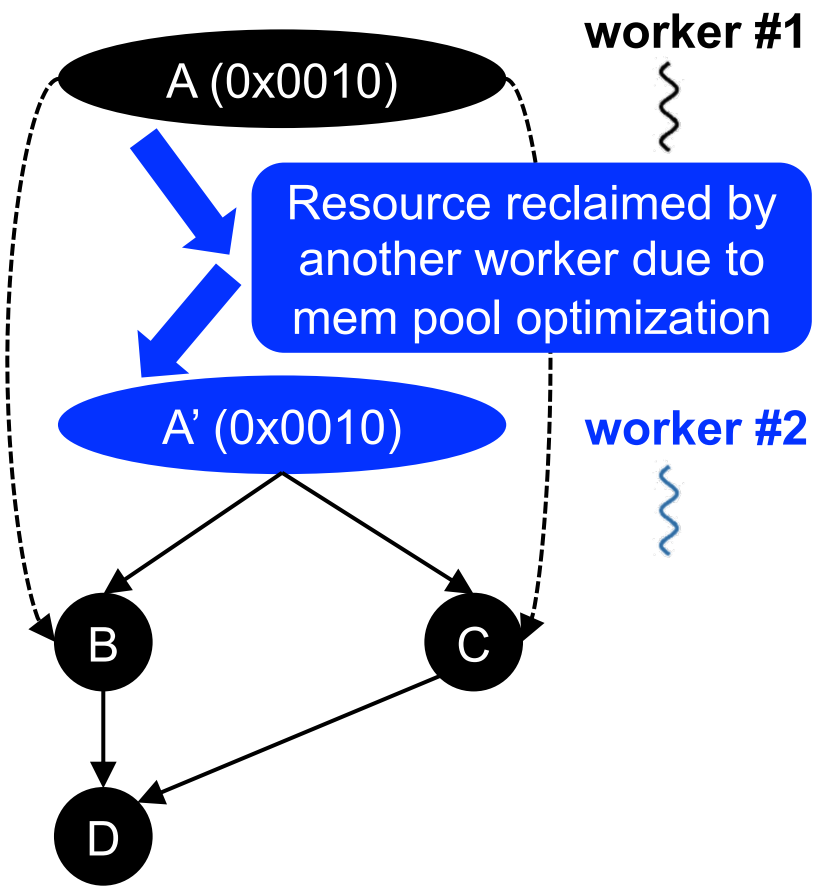
# DTGP Scheduling Algorithm

- **The algorithm has three parts:**
  - Build dependencies
  - Wait for dependents to finish
  - Execute the task
- **Three key scheduling challenges:**
  1. **ABA** – *a specified task dependency must exist correctly*
  2. **Data race** – *multiple threads may simultaneously modify the dependency structure of a task*
  3. **Synchronization** – *application can issue a global synchronization at any time 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

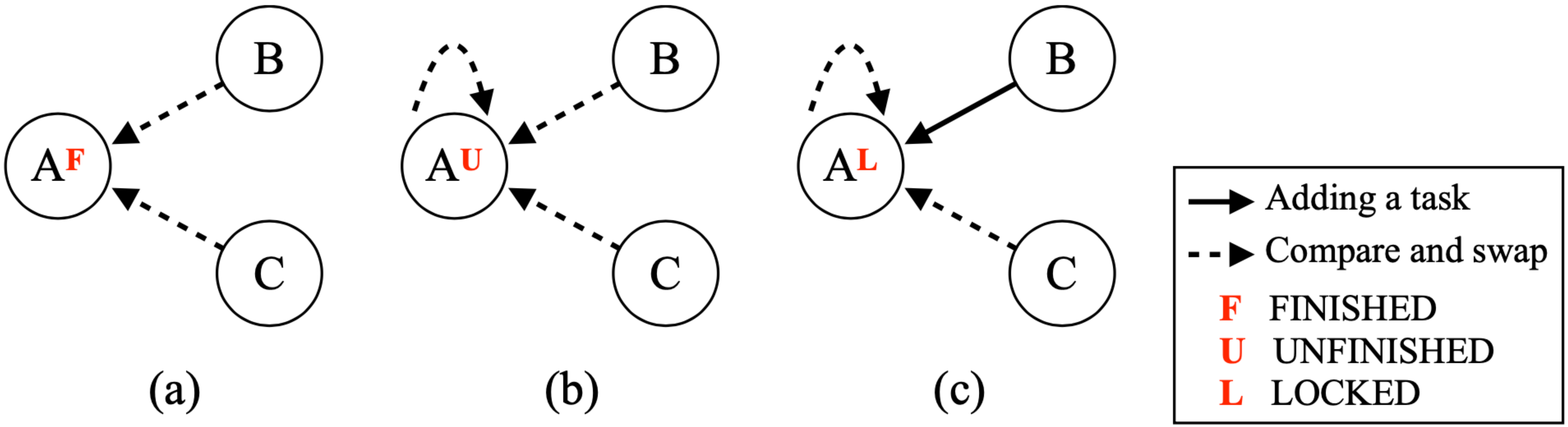
# Retain Shared Ownership of Every Task

```
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 a task is alive when being 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
…
executor.wait_for_all();  // wait for other tasks 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 ← 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
```

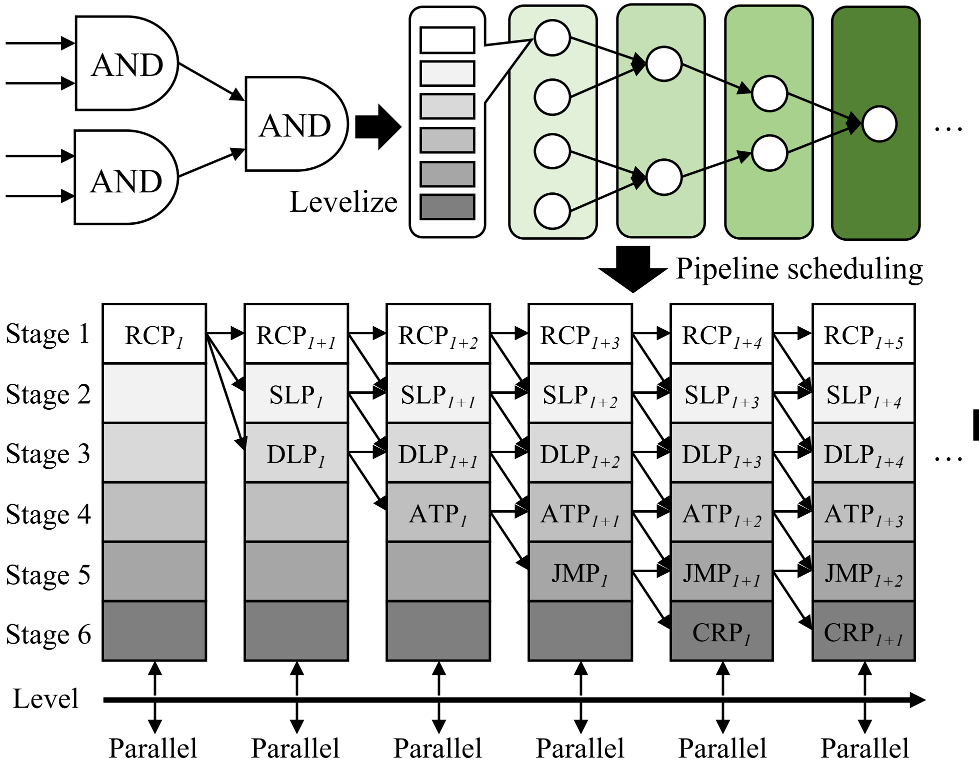
[1]: Cheng-Hsiang Chiu, et. al, "Programming Dynamic Task Parallelism for Heterogeneous EDA Algorithms," *IEEE/ACM ICCAD*, CA, 2023

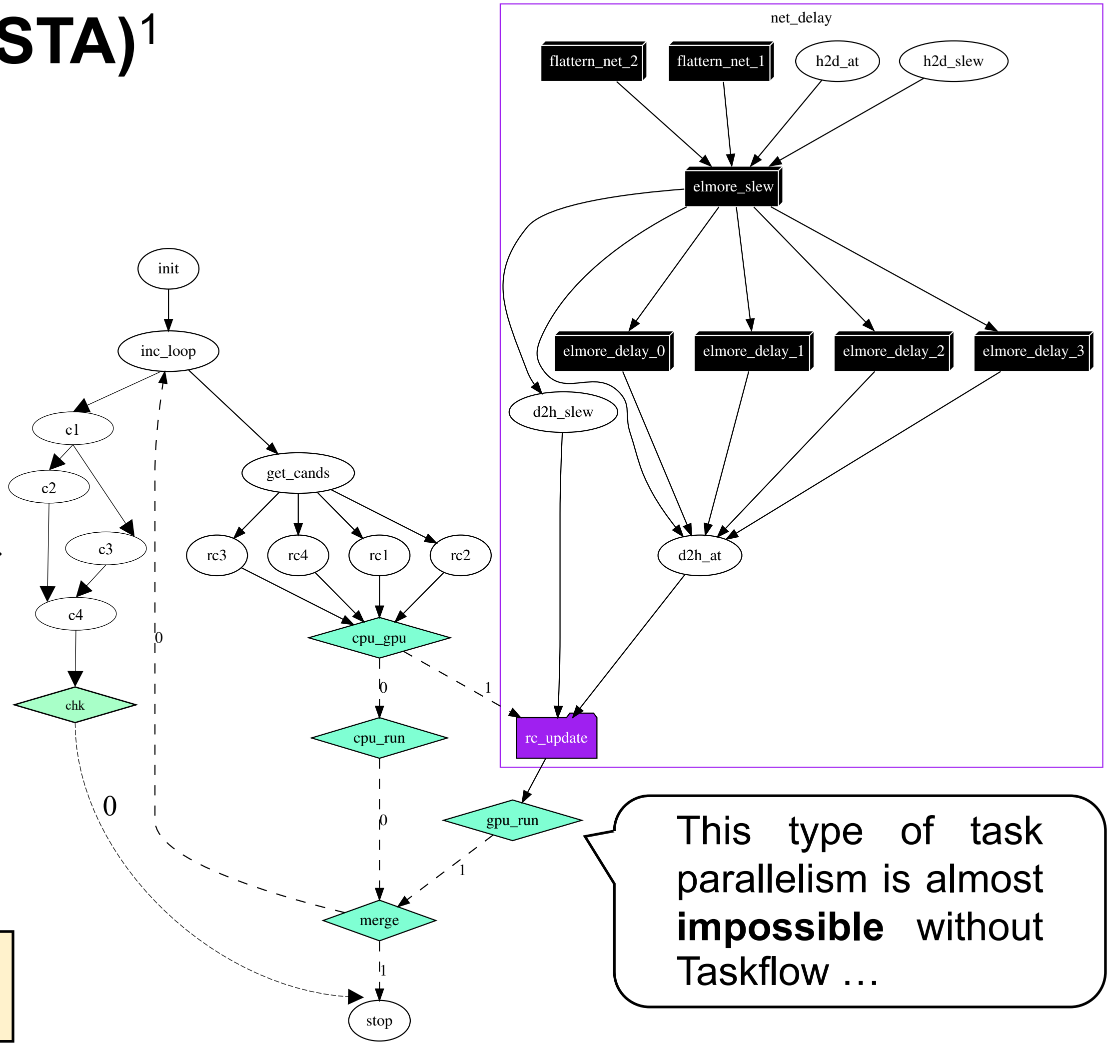
# Takeaways

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

# Experimental Results – STGP

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

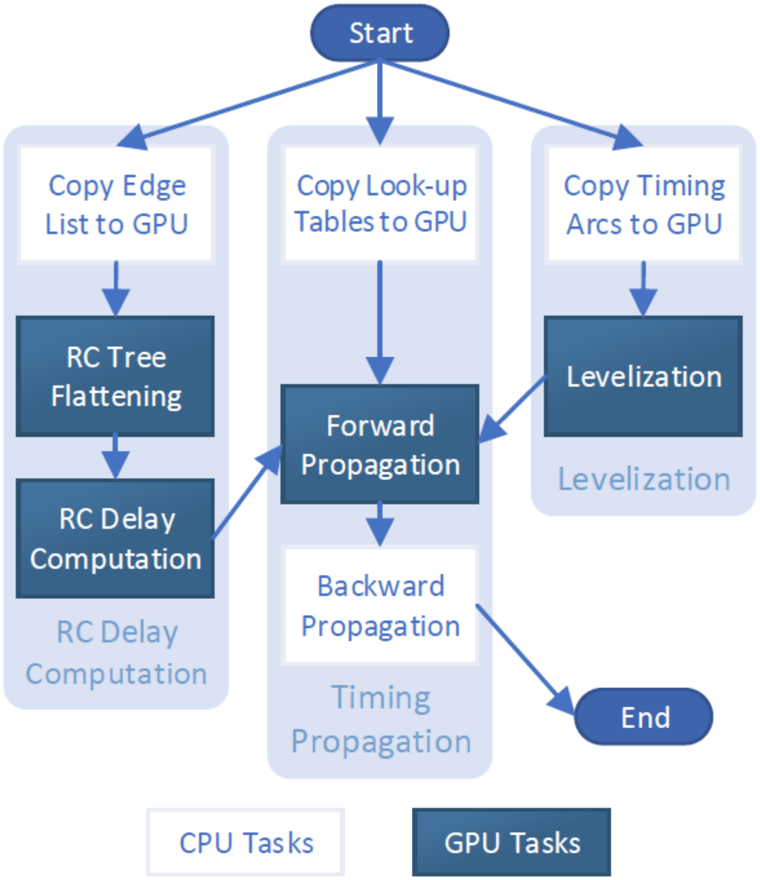


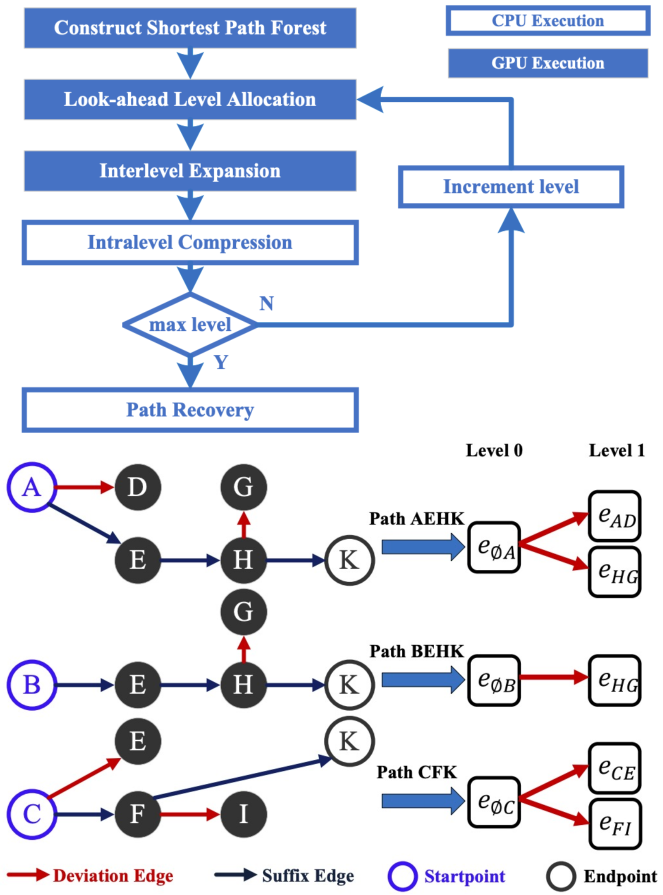

This type of task parallelism is almost **impossible** without Taskflow …

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

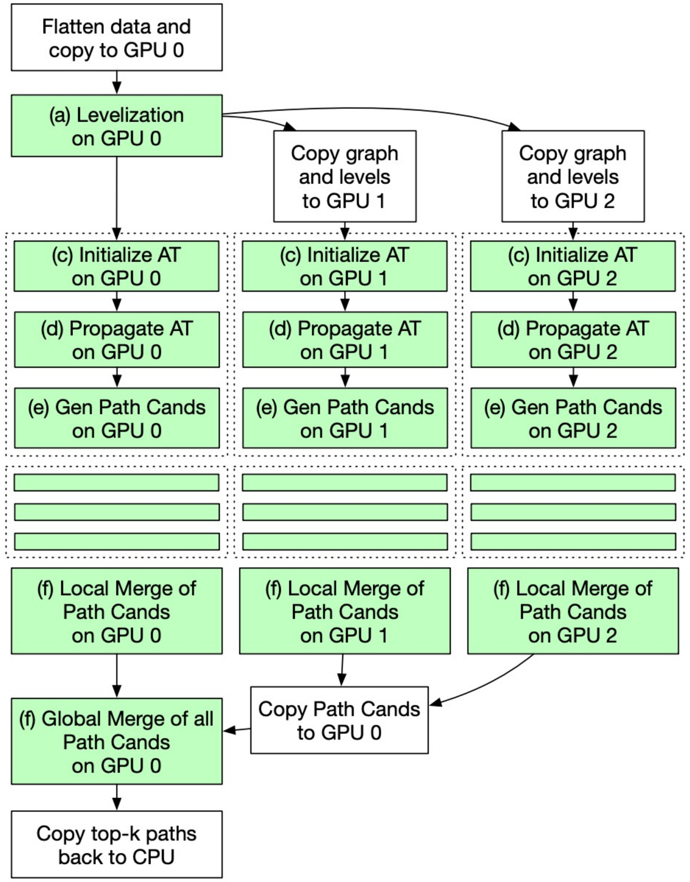
# Task-parallel STA Alg with CPU and CPU




GPU-based graph analysis (ICCAD'20)




GPU-based path analysis (DAC'21)




GPU-based CPPR (ICCAD'21)

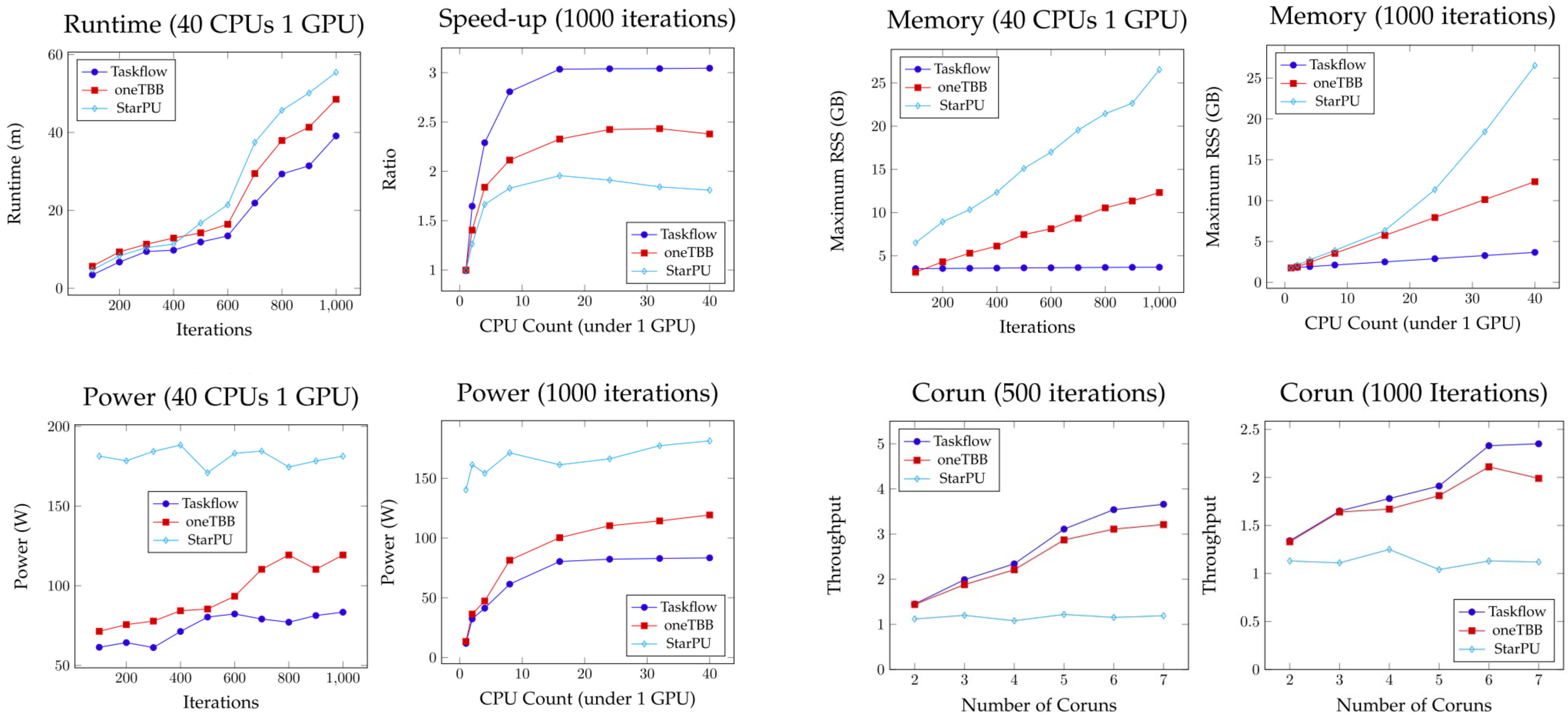
# Task-parallel Path Generation Algorithm[1]

- **Applied Taskflow to accelerate path-based analysis on GPU**
  - Ex: leon3mp (1.6M gates): **611x speed-up** over 1 CPU (**44x** over 40 CPUs)
  - **Best paper award** in ACM TAU 2021

| 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× |

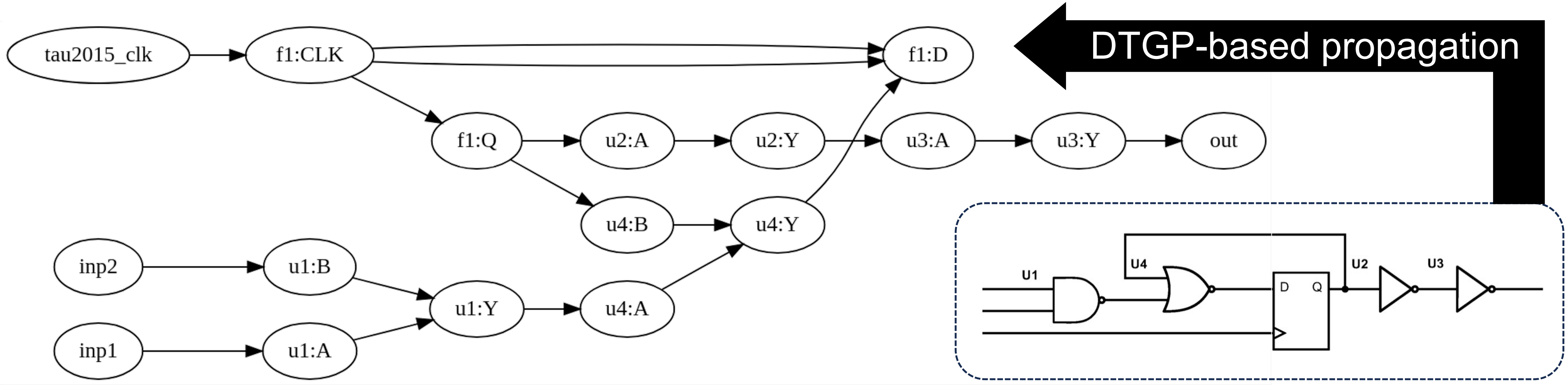
[1]: Guannan Guo, Tsung-Wei Huang, Yibo Lin, and Martin Wong, "GPU-accelerated Path-based Timing Analysis," *IEEE/ACM Design Automation Conference (DAC)*, CA, 2021

# Comparison with Existing TGP Systems



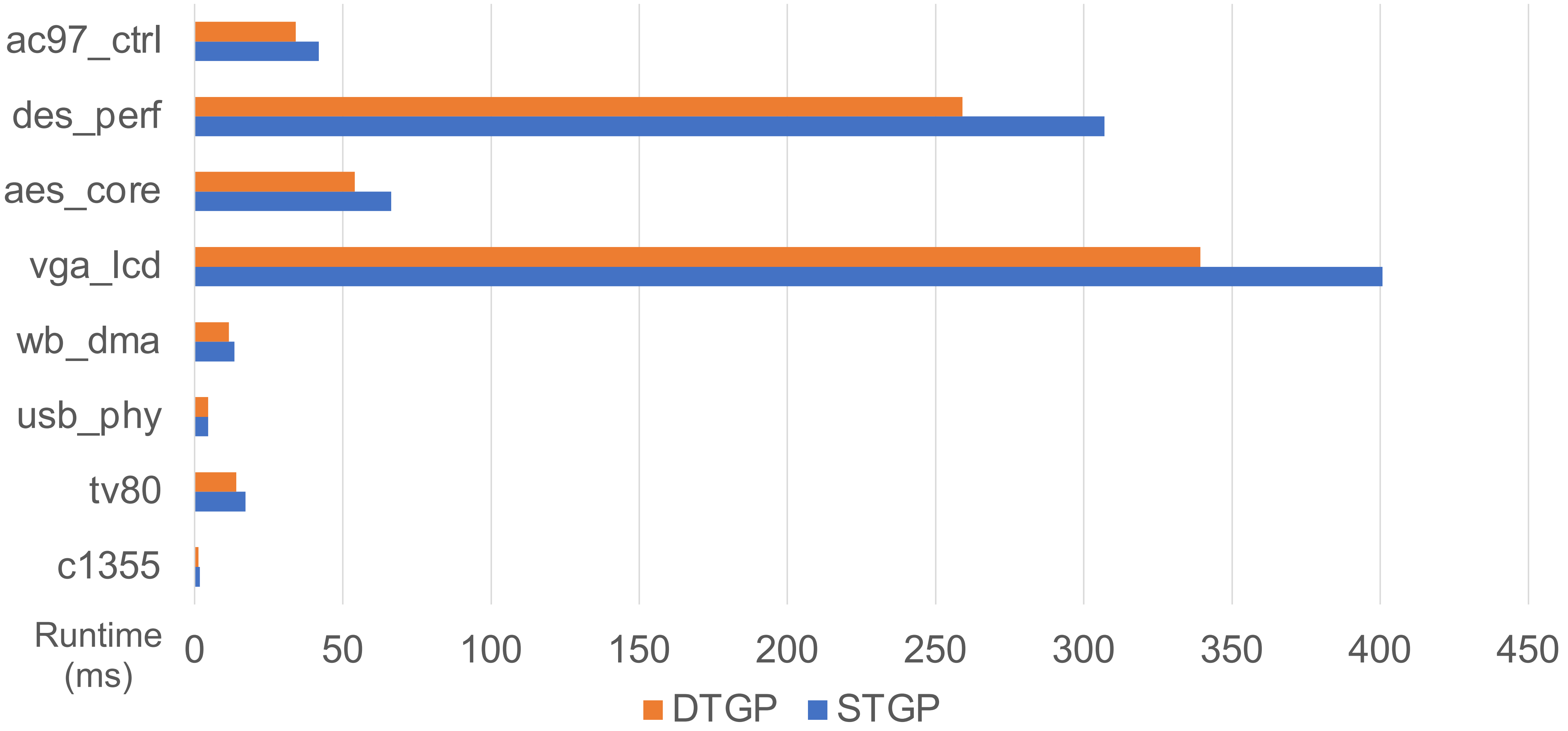
# Experimental Results – DTGP

- **Evaluated on a real-world static timing analysis application**[1]
  - Formulated the timing propagation algorithm into a dynamic task graph
  - Ex (below): a task graph for a full-timing propagation on a five-gate circuit
    - Large circuits can compose millions of tasks and 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

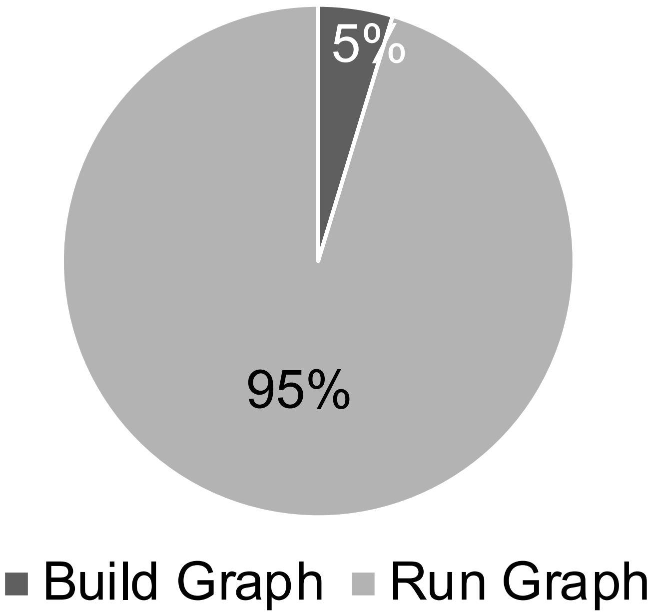
# Runtime Comparison: STGP vs DTGP



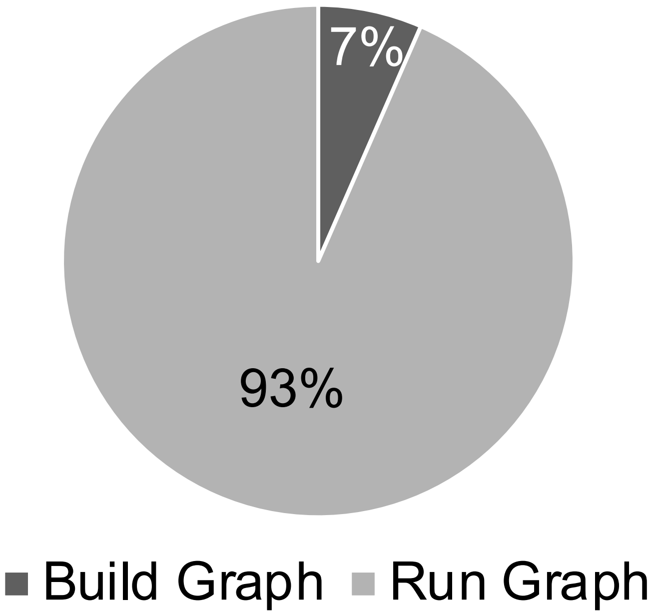
# Runtime Breakdown of STGP

- **Graph construction time increases as the circuit size increases**

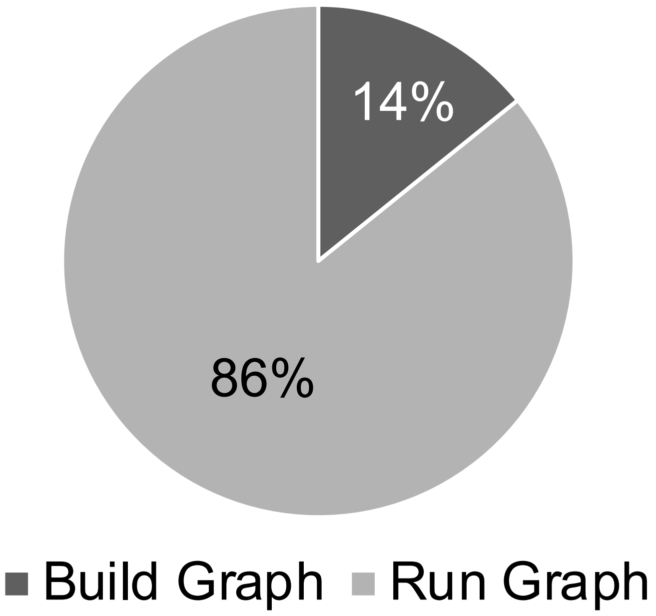
c1355
(617 tasks)




des_perf
(304K tasks)

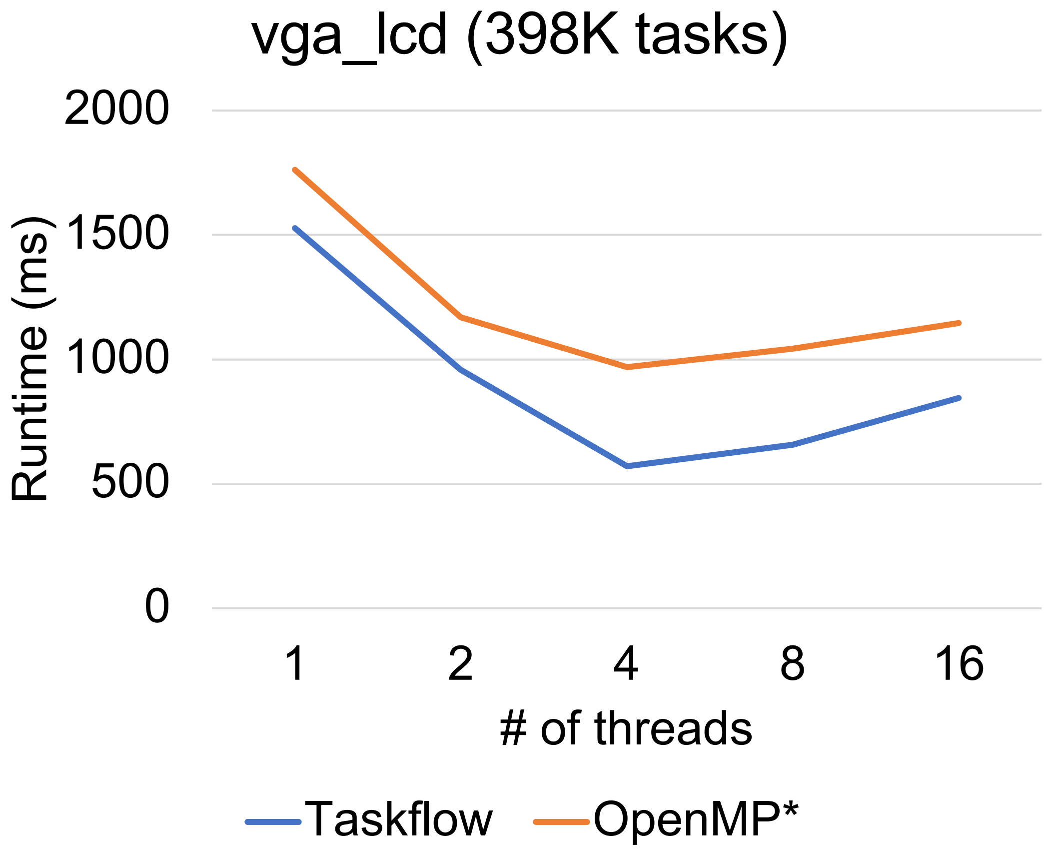


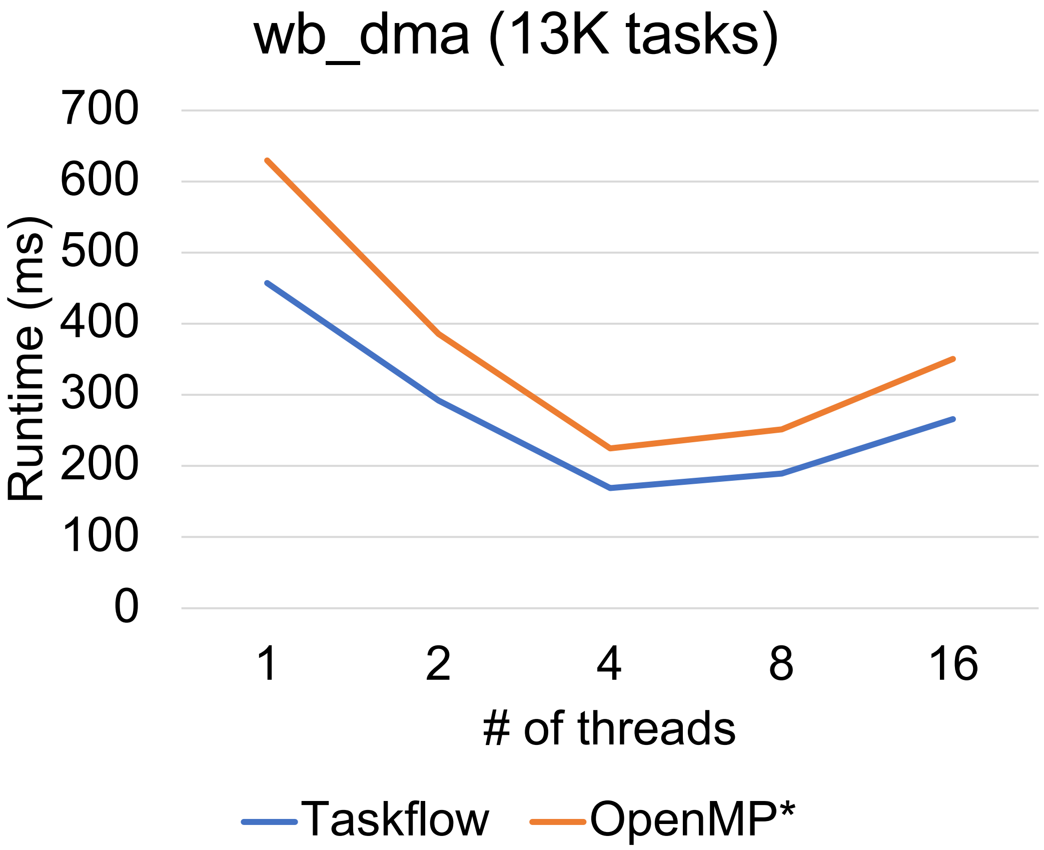

vga_lcd
(398K tasks)



# Runtime Comparison with OpenMP

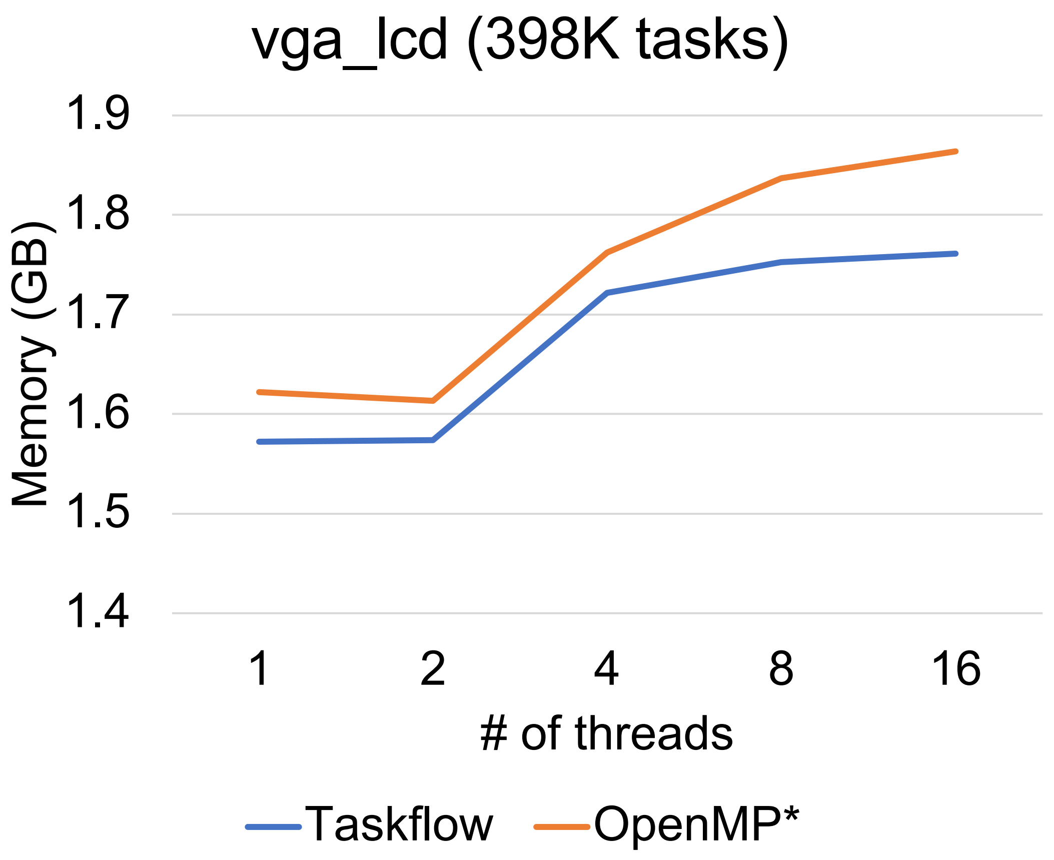
- **Taskflow scales better than OpenMP with increasing # threads**

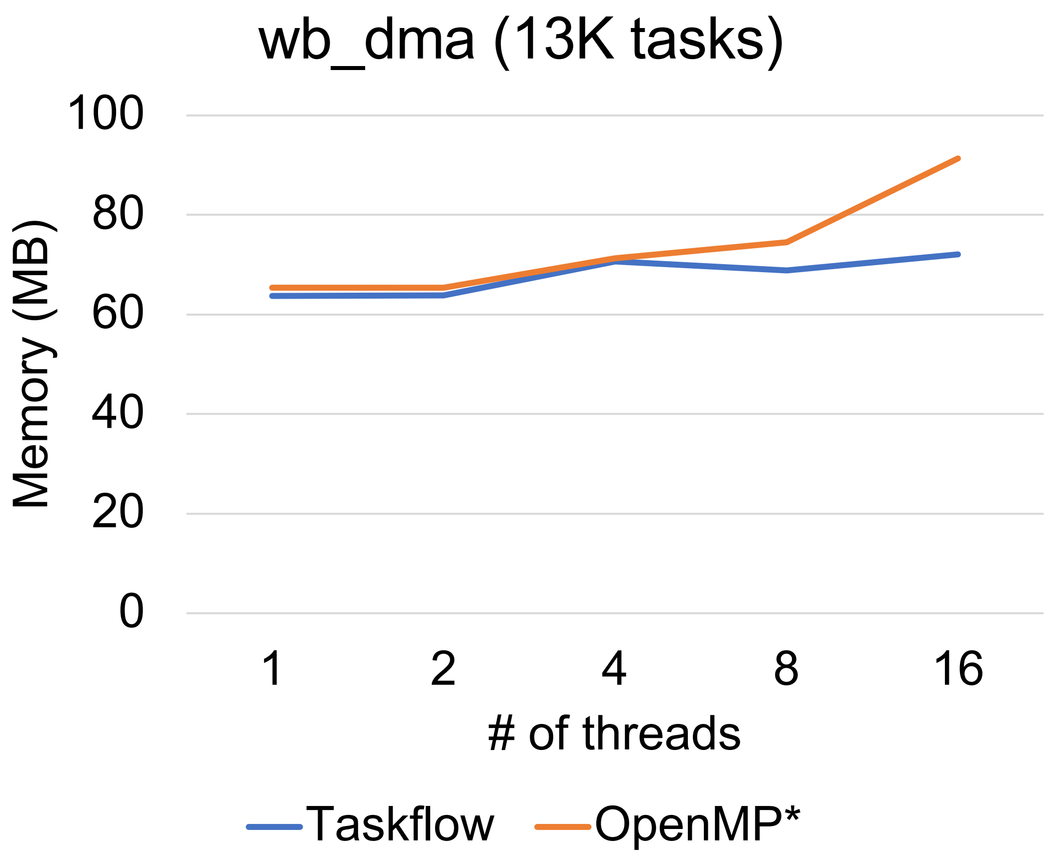


# Memory Comparison with OpenMP*

- Taskflow scales better than OpenMP with increasing # threads



# Conclusion

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

# Thank You for using Taskflow!

# Thank you for Sponsoring Taskflow!

# 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();
```