Dynamic Asynchronous Tasking with Dependencies

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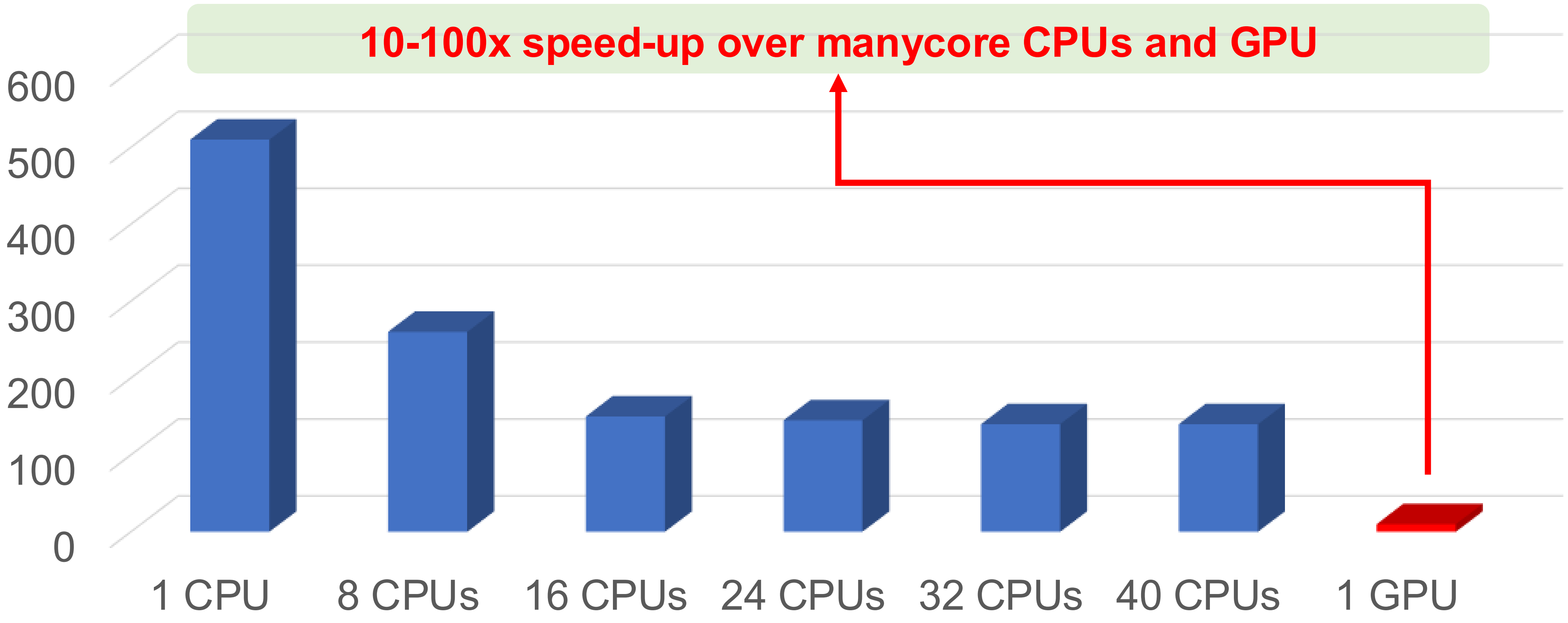
Takeaways

- Understand the importance of asynchronous tasking with dependencies
- Recognize the limitations of existing asynchronous tasking models
- Introduce a new dynamic task graph programming model called AsyncTask
- Overcome the scheduling challenges to support the model
- Demonstrate the efficiency of AsyncTask
- Conclude the talk

Why Parallel Computing?

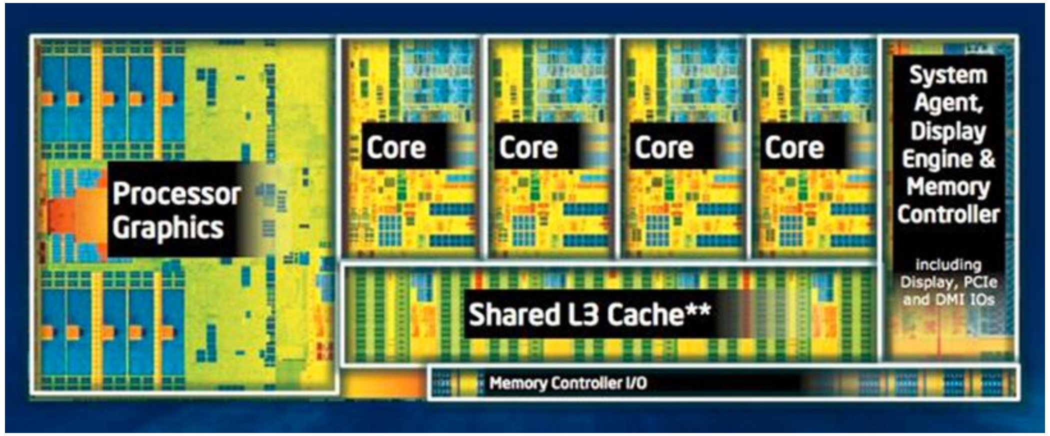
- **Advances performance to a new level previously out of reach**

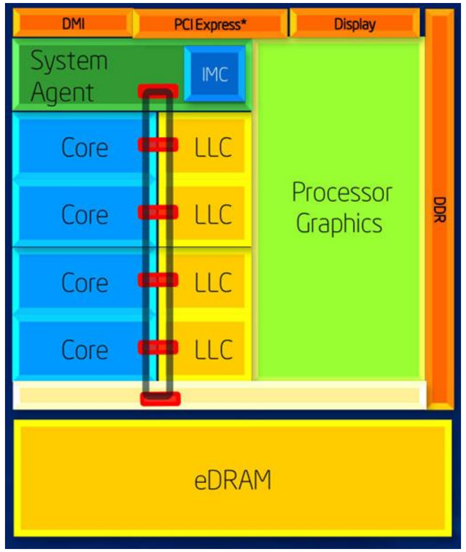


Time (minutes) to train a machine learning model

Modern Hardware is Designed to Run in Parallel

- **Intel Haswell microarchitecture**
  - Released in June 2013
  - Typically comes with four cores
  - Has an integrated GPU
  - 1.4 B transistors with 22 nm technology
  - Sophisticated design for ILP acceleration
  - Deep pipeline – 16 stages
- **Superscalar architecture**
  - Can issue and complete multiple independent instructions per cycle
- **Supports hyper-threading tech (HTT)**
  - Allows a single physical CPU core to appear as two logical processors to the OS

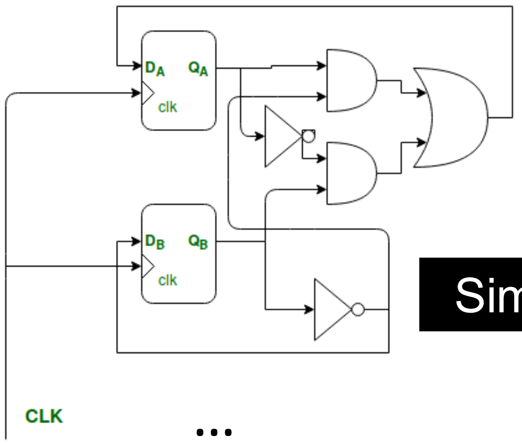




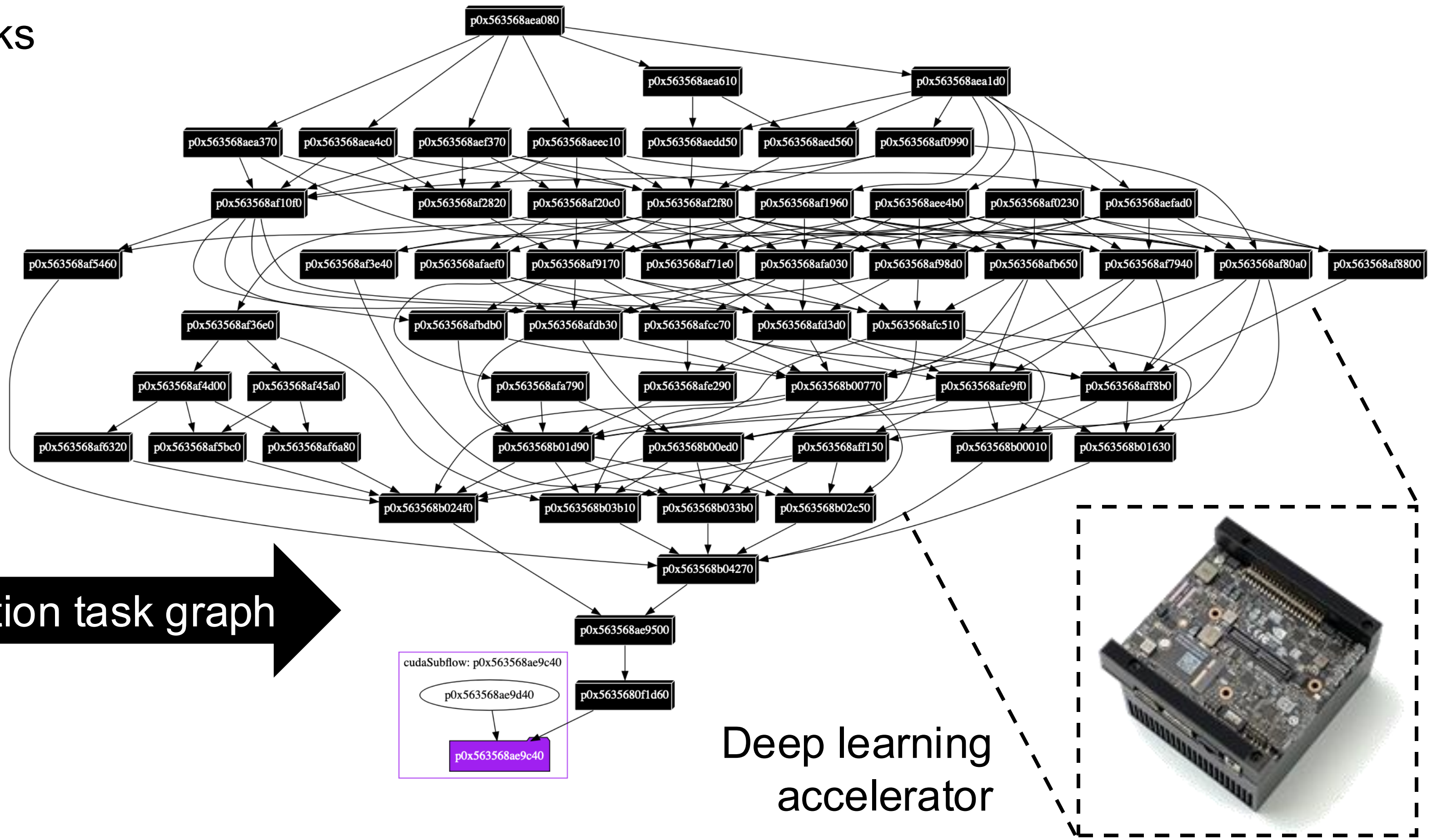
If you don't do parallel programming, you are not utilizing your hardware efficiently …

Today’s Parallel Computing Problem is Very Irregular

- **Computational task graph of a GPU-parallel circuit simulation workload[1]**
  - > 500M gates and nets
  - > 1000 async kernel tasks
  - > 1000 dependencies
  - > hours to finish



Simulation task graph

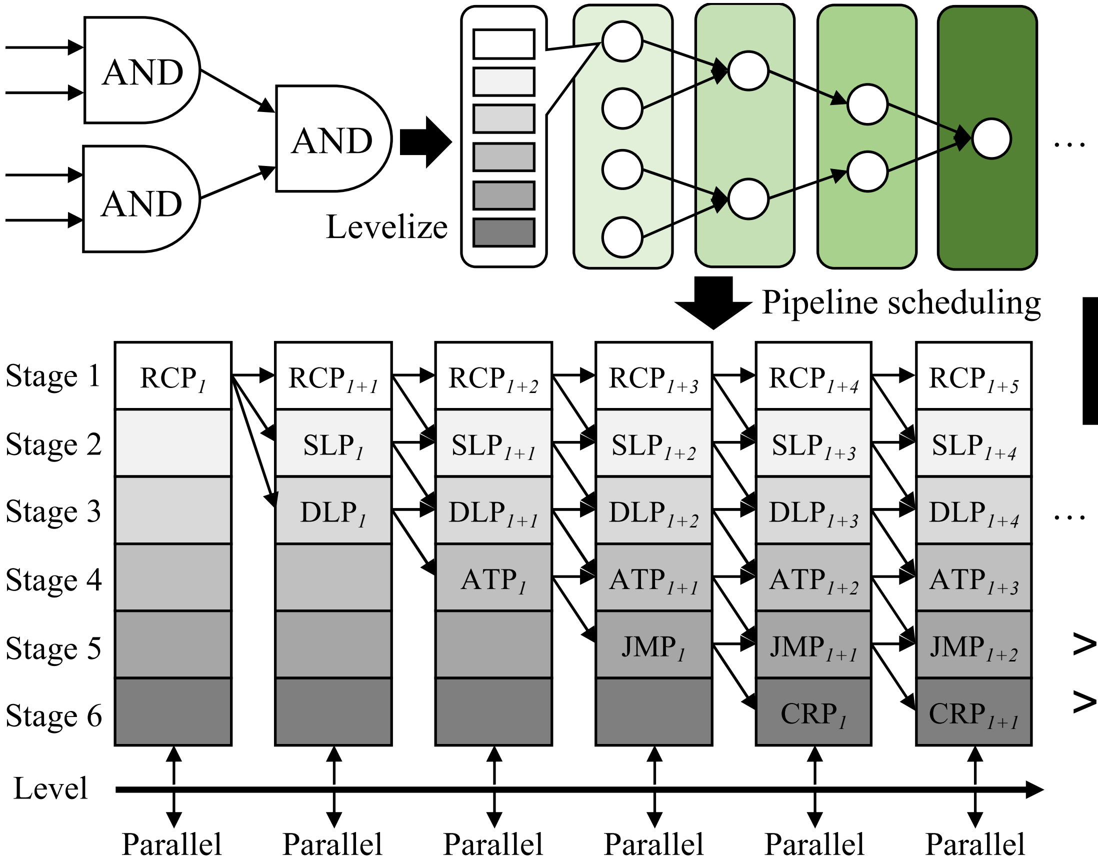


Deep learning accelerator

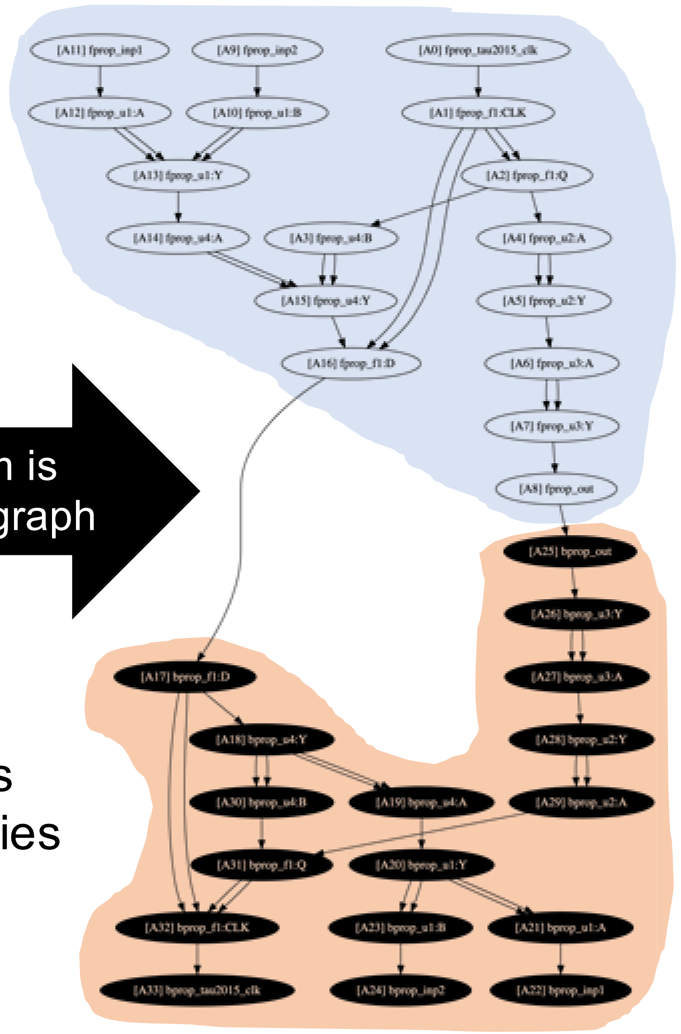
[1]: Dian-Lun Lin, et al, “From RTL to CUDA: A GPU Acceleration Flow for RTL Simulation with Batch Stimulus,” *ACM ICPP*, 2022

Another Example of Irregular Parallel Workload

- **CPU-parallel VLSI static timing analysis algorithm**



Analysis algorithm is modeled as a task graph

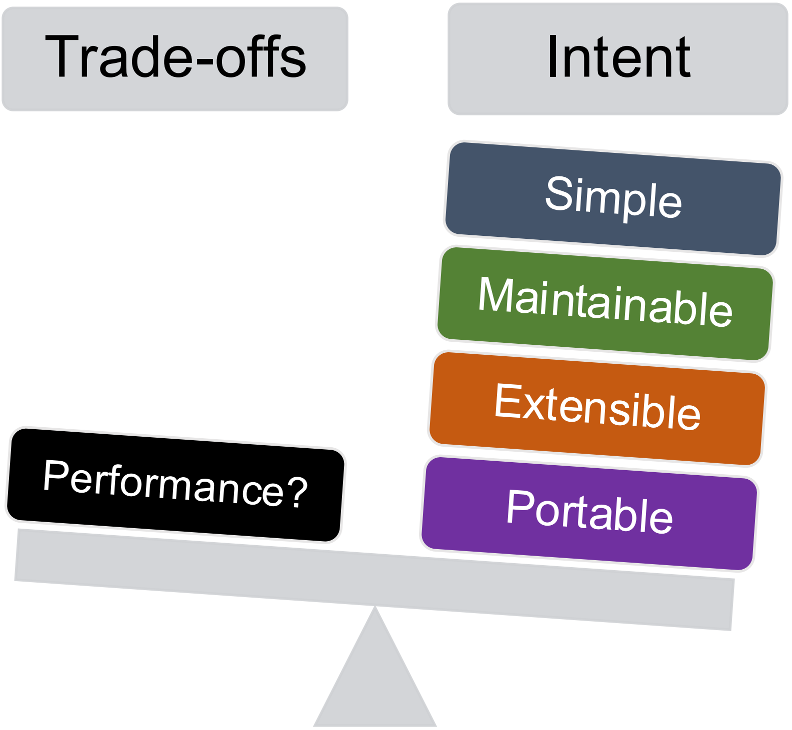


> 100M async tasks
> 150M dependencies

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

Parallelizing such Irregular Problems is Not Easy …

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

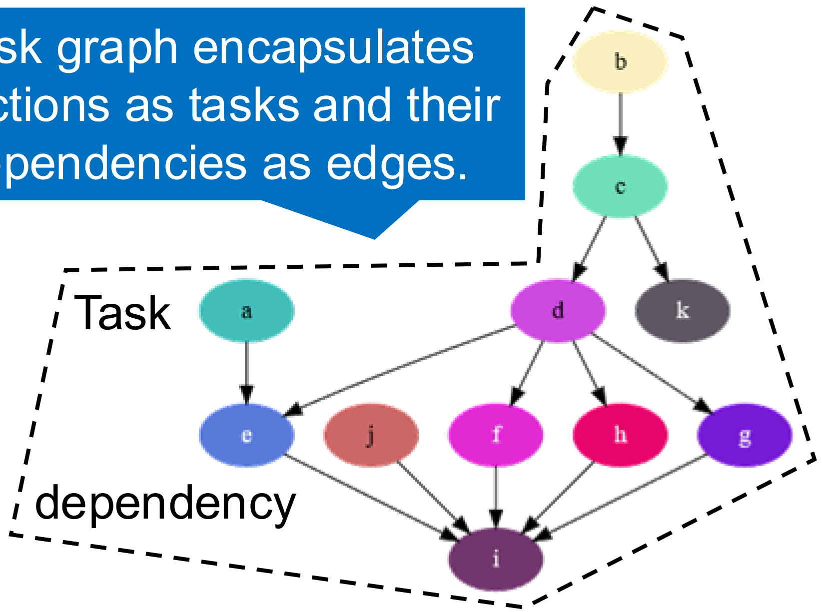


We want a solution that can sit on top to help programmers manage these details as much as possible because programmers care how fast (performance + productivity) they can get things done!

Why Task-parallel Programming (TPP)?

- **TPP is an effective solution for parallelizing irregular workloads**
  - Captures developers' intention in decomposing an algorithm into a *top-down* task graph
  - Delegates difficult scheduling details (e.g., load balancing) to an optimized runtime
- **Modern parallel programming libraries are moving towards task parallelism**
  - OpenMP 4.0 task dependency clauses (`omp depend`)
  - C++26 execution control library (`std::exec`)
  - TBB flow graph (`tbb::flow::graph`)
  - Taskflow control Taskflow graph (CTFG) model
  - … (many others)

Task graph encapsulates functions as tasks and their dependencies as edges.



OpenMP StarPU kokkos TBB PaRSEC

Takeaways

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Create an Asynchronous Task using std::async[1]

- **A high-level standard library facility to launch a task asynchronously**

```
#include <future>
#include <iostream>

int compute(int v) {
  return v;
}

int main() {
  std::future<int> fu = std::async(std::launch::async, compute, 42);
  std::cout << fu.get() << std::endl;  // prints 42
}
```

Use `std::async` to asynchronously run the function `compute(42)` on a new thread.

Return a `std::future` to wait for this asynchronous task to finish and access its result (i.e., 42)

[1]: C++ std::async interface: https://en.cppreference.com/w/cpp/thread/async.html

An Example Implementation of `std::async`

```
template <typename F, typename... Args>
auto async(F&& func, Args&&... args) {
  using ReturnType = std::invoke_result_t<F, Args...>;
  // promise-future pair for intern-thread sync
  std::promise<ReturnType> prom;
  std::future<ReturnType> fu = prom.get_future();
  std::thread t([prom=std::move(prom),
    f=std::forward<F>(func), ...args=std::forward<Args>(args)] () mutable {
    if constexpr(std::is_void_v<ReturnType>) {
      f(std::move(args)...);
      prom.set_value();
    } else {
      prom.set_value(f(std::move(args)...));
    }
  });
  t.detach();  // mimic fire-and-forget behavior of std::async
  return fu;
}
```

I promise you that I will run your function, and you can access the result from the future object …

We create a thread from a lambda function object that captures the function and its argument (with perfect forwarding[1]) and invoke the function in the body.

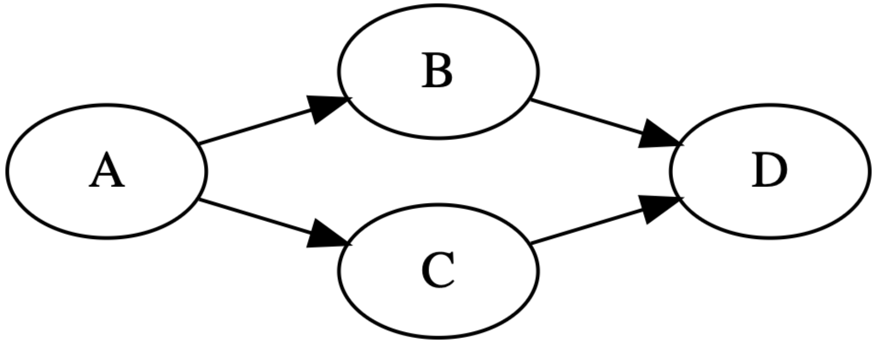
[1]: C++ `std::forward`: https://en.cppreference.com/w/cpp/utility/forward.html

Build a Task Graph w/ `std::async` and `std::future`

- **`std::future` allows us to perform task-specific synchronization**

```
auto A = std::async(std::launch::async,
  [](){ std::cout << "A\n"; }
);
A.wait();
auto B = std::async(std::launch::async,
  [](){ std::cout << "B\n"; }
);
auto C = std::async(std::launch::async,
  [](){ std::cout << "C\n"; }
);
B.wait();
C.wait();
auto D = std::async(std::launch::async,
  [](){ std::cout << "D\n"; }
);
D.wait();
```

We need to wait for A to finish before launching B and C asynchronously.



We need to wait for B and C to finish before launching D asynchronously

By properly synchronizing tasks using `future.wait`, we can dynamically create a task graph (i.e., dynamic task graph)

Sender-Receiver Version (with `std::exec`[1])

- **A standardized abstraction for composing tasks and dependencies**

```
exec::static_thread_pool pool;
auto scheduler = pool.get_scheduler();

// create a sender task for A
auto sa = exec::then(exec::schedule(scheduler), []{ std::cout<<"A\n"; });
exec::sync_wait(sa);  // wait for A

// create two parallel sender tasks for B and C
auto sb = exec::then(exec::schedule(scheduler), []{ std::cout<<"B\n"; });
auto sc = exec::then(exec::schedule(scheduler), []{ std::cout<<"C\n"; });
exec::sync_wait(exec::when_all(sb, sc));  // wait for B and C

// create a sender task for D
auto sd = exec::then(exec::schedule(scheduler), []{ std::cout<<"D\n"; });
exec::sync_wait(sd);  // wait for D
```

Schedule tasks on a pool of worker threads

[1]: C++ execution control library (experimental): https://en.cppreference.com/w/cpp/experimental/execution.html

Intel's TBB Library with `tbb::task_group`[1]

- **A class to create asynchronous tasks and wait for their completion**

```
tbb::task_group tg;

// A
tg.run([] { std::cout << "A\n"; });
tg.wait();

// B and C in parallel
tg.run([] { std::cout << "B\n"; });
tg.run([] { std::cout << "C\n"; });
tg.wait();

// D
tg.run([] { std::cout << "D\n"; });
tg.wait();
```

A class in TBB to create asynchronous tasks and wait for their completion

Need to `task_group::wait` on A before running B and C

Need to `task_group::wait` on B and C before running D

[1]: TBB task group: https://oneapi-spec.uxlfoundation.org/specifications/oneapi/v1.3-rev-1/elements/onetbb/source/task_scheduler/task_group/task_group_cls

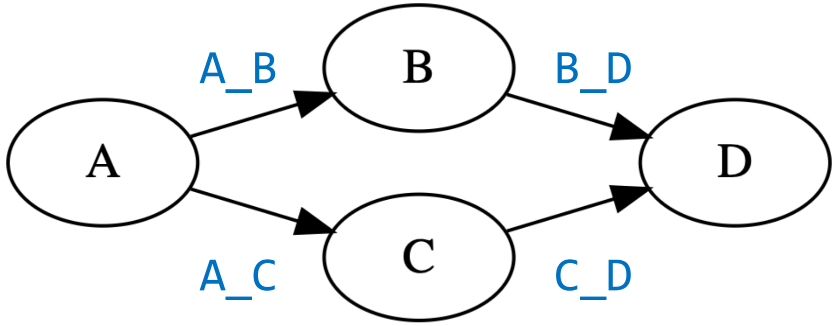
OpenMP Tasking Model with depend Clauses[1]

- **Leverages compiler directives to define tasks and dependencies**

```
#omp parallel
{
  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 << “TaskB\n”;

  #pragma omp task depend(in: B_D, C_D)
  std::cout << “TaskB\n”;
}
```

Define dependency handles

Specify task dependencies using in and out clauses when creating an OpenMP task



With these OpenMP directives, the compiler will insert parallel code that launches asynchronous tasks and enforces their dependencies.

[1]: OpenMP task dependency clauses (version 5, 2008): https://www.openmp.org/spec-html/5.0/openmpsu99.html

OpenCilk Version

- **A fork-join programming model relying on compiler-generated parallel code**
  - With language extensions like `cilk_spawn` and `cilk_sync`

```
void A() { std::cout << "A\n"; }
void B() { std::cout << "B\n"; }
void C() { std::cout << "C\n"; }
void D() { std::cout << "D\n"; }
int main() {
  A();

  cilk_spawn B();
  C();
  cilk_sync;

  D();
}
```

You need a compiler that supports OpenCilk syntax to run this code.

Spawn a child task on B using `cilk_spawn` and continue with C in the main thread

Synchronize both B and C using `cilk_sync` before running task D

[1]: OpenCilk: https://www.opencilk.org/

Limitations of Existing Async Tasking Models

- **Tasks and their dependencies are decoupled during task graph creation**
  - If dependencies are not expressed alongside the task creation logic, it's difficult to reason about the overall task graph structure
  - Without a clear dependency structure, the runtime loses opportunities to optimize task placement and load balancing when constructing an asynchronous task
- **Correct placement of `wait` calls is left to programmers**
  - Programmers must determine a correct synchronization order at a fine-grained level
    - In the worst case, the number of `waits` equals the number of dependencies
  - In practice, many applications only care about the completion of the entire task graph instead of intermediate tasks, making such fine-grained waiting unnecessary, costly, and buggy
- **Limited support for building highly dynamic task graphs**
  - Highly dynamic task graphs → those whose structures, dependencies, and task content are highly dependent on runtime variables or dynamic control-flow results
    - Ex: OpenMP is not a good fit for this scenario as it relies on static compiler directives
- **May require a non-standard C++ compiler to generate parallel code**

Takeaways

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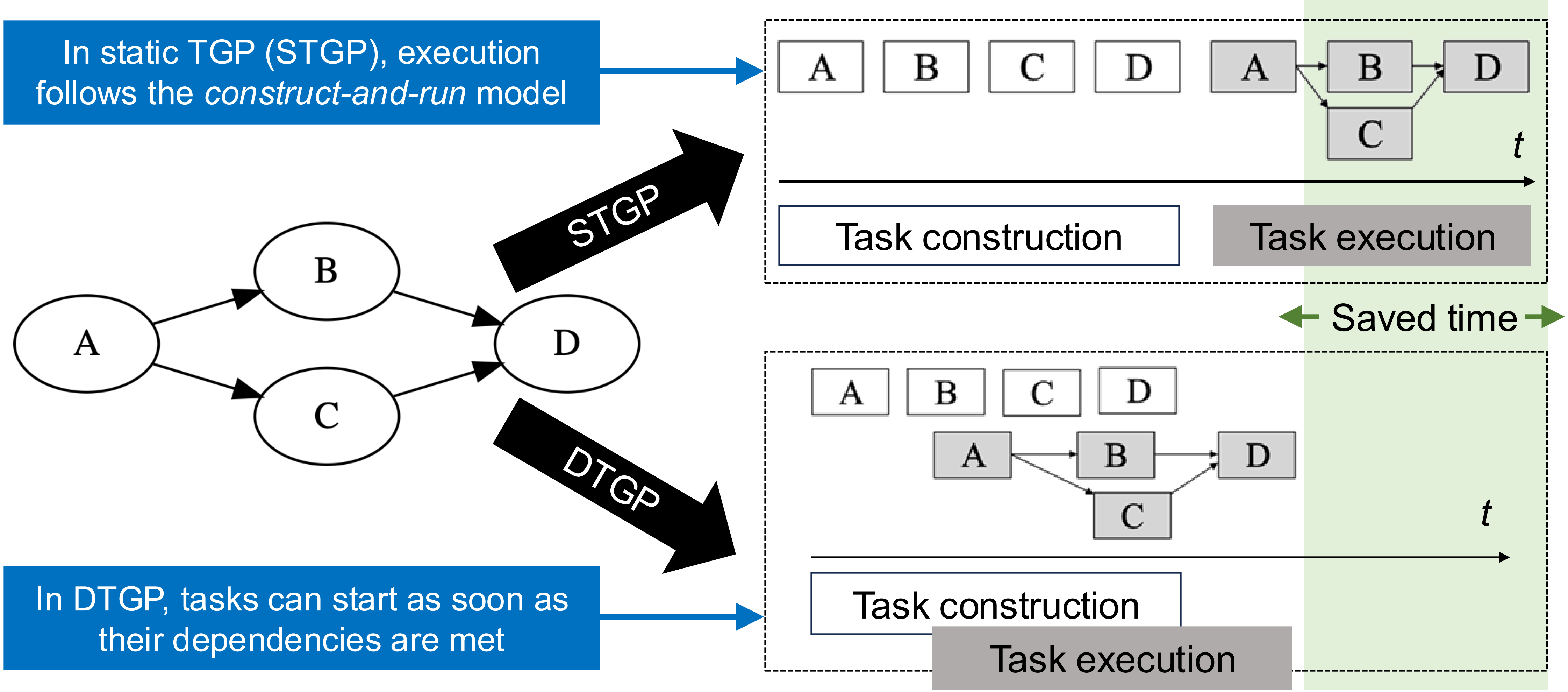
Static vs Dynamic Task Graph Programming (TGP)

- **All examples we've discussed so far are dynamic TGP (DTGP)**

In static TGP (STGP), execution follows the *construct-and-run* model

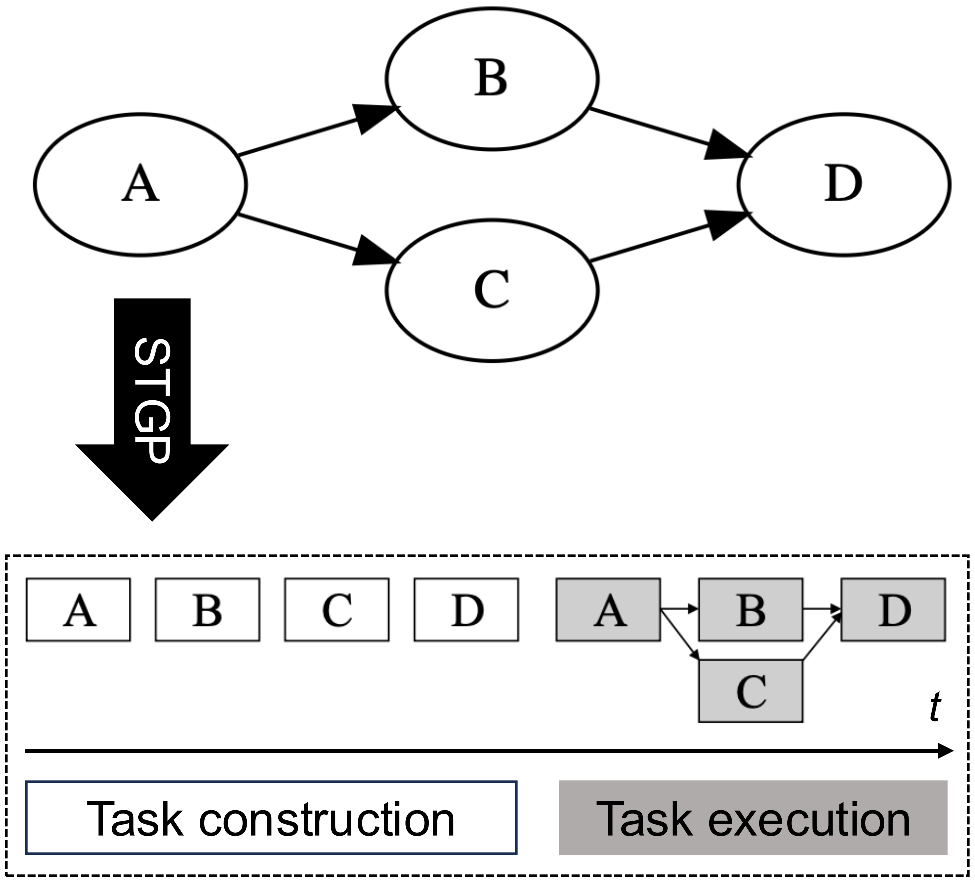


In DTGP, tasks can start as soon as their dependencies are met

Static Task Graph Programming in Taskflow[1]

```cpp
#include <taskflow/taskflow.hpp>  // Live: https://godbolt.org/z/j8hx3xnnx

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;
}
```



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

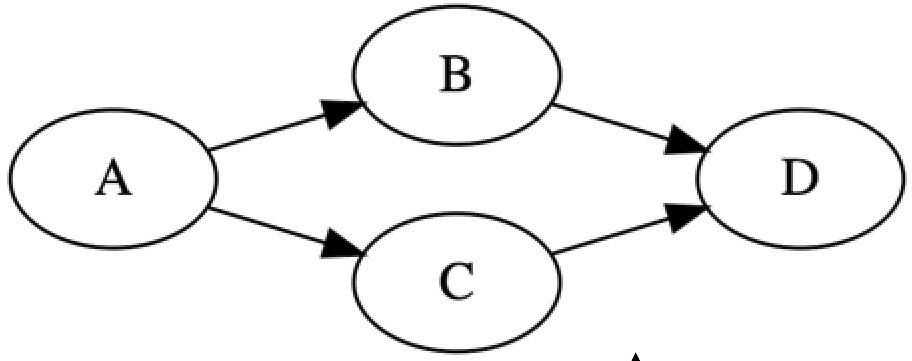
AsyncTask: Dynamic Task Graph Programming in Taskflow

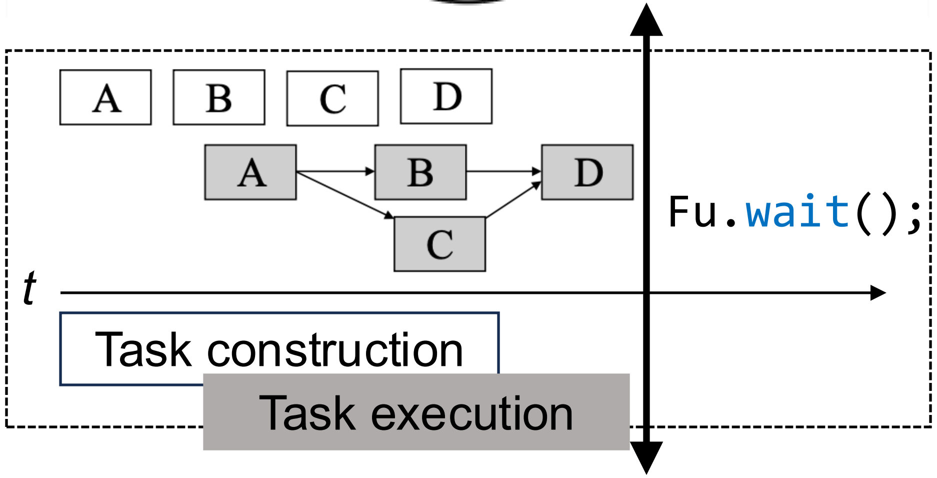
```cpp
// Live: https://godbolt.org/z/j76ThGbWK

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();
```





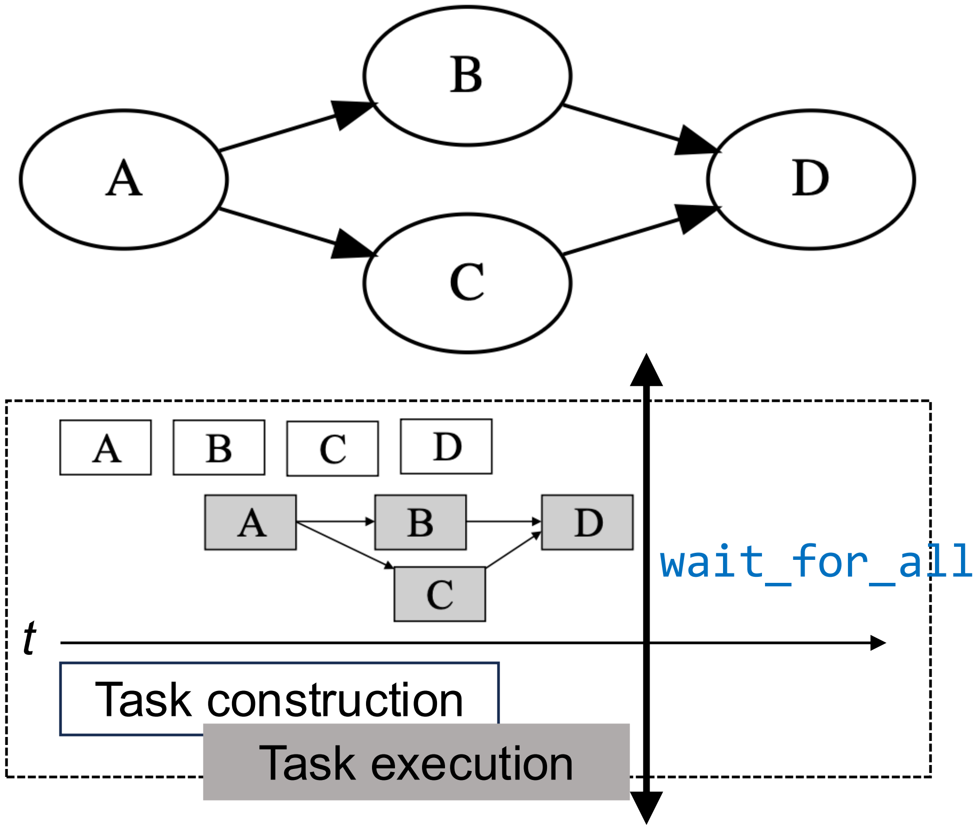
Specify variable task dependencies using C++ variadic parameter pack

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();
```

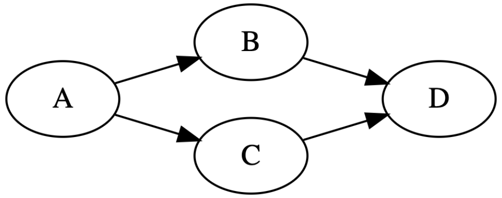


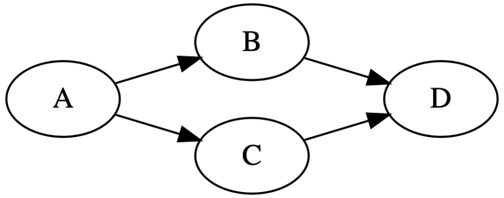
Wait for the entire graph to finish.

Need 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

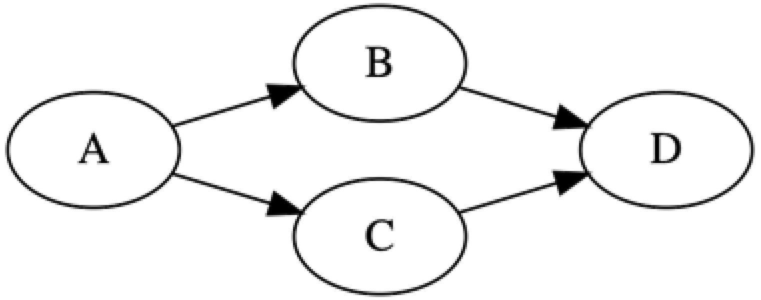
```
auto A = executor.silent_dependent_async(
  [](){ std::cout << "TaskA\n"; }
);
auto C = executor.silent_dependent_async(
  [](){ std::cout << "TaskC\n"; }, A
);
auto B = executor.silent_dependent_async(
  [](){ std::cout << "TaskB\n"; }, A
);
auto D = executor.silent_dependent_async(
  [](){ std::cout << "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) prevents you from expressing a correct dynamic task graph.

Variable Range of Task Dependencies

- **Both methods can take a variable range of dependent-async tasks**
  - Useful when the task dependencies come as a runtime variable (e.g., loaded from a file)

```
// 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 task that depends on tasks, A, B, C, and D
executor.silent_dependent_async([](){}, tasks.begin(), tasks.end());
```

While this feature may look trivial, I found it very difficult to achieve with existing asynchronous tasking libraries because their task creation and dependency expression are decoupled from each other …

DTGP is Flexible for Runtime-driven Execution

- **Assemble task graphs driven by runtime variables and control-flow results**

```
if (a == true) {
  G1 = build_task_graph1();
  if (b == true) {
    G2 = build_task_graph2();
    G1.precede(G2);
    if (c == true) {
      … // defined other TGPs
    }
  }
  else {
    G3 = build_task_graph3();
    G1.precede(G3);
  }
}
```

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

This type of dynamic task graph is very difficult to achieve using static task graph programming …

AsyncTask doesn't Touch Data Abstraction

- **Focus on coarse-grained task parallelism not fine-grained data parallelism**
  - Our goal is to have users describe tasks and their dependencies in an expressive language

```
template <typename F, typename... Tasks>
auto dependent_async(F&& func, Tasks&&... tasks) {
    ...
}
```

This is how `std::async` is implemented
(e.g., `args` are captured with perfect forwarding)

  - Users describe `func` as a lambda and capture necessary data or `func` arguments themselves
- **The advantage of this decision is twofold:**
  - Users retain full control over data layout and ownership, allowing them to optimize data structures and memory layout for their specific application domains
  - Letting users decide how and where to store data keeps AsyncTask lightweight and non-intrusive – no need to modify existing data structures to fit our framework
    - Ex: Models that count on data abstraction (e.g., Fastflow, TBB pipeline) require users to rewrite their code to library-specific data abstraction in order to gain parallelism

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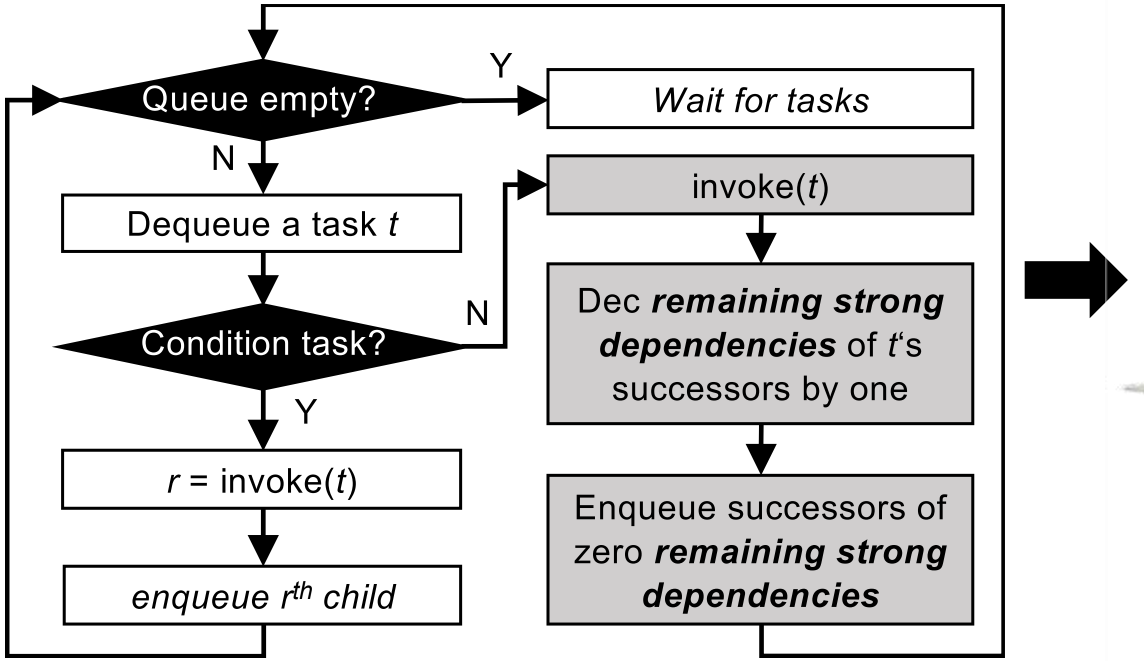
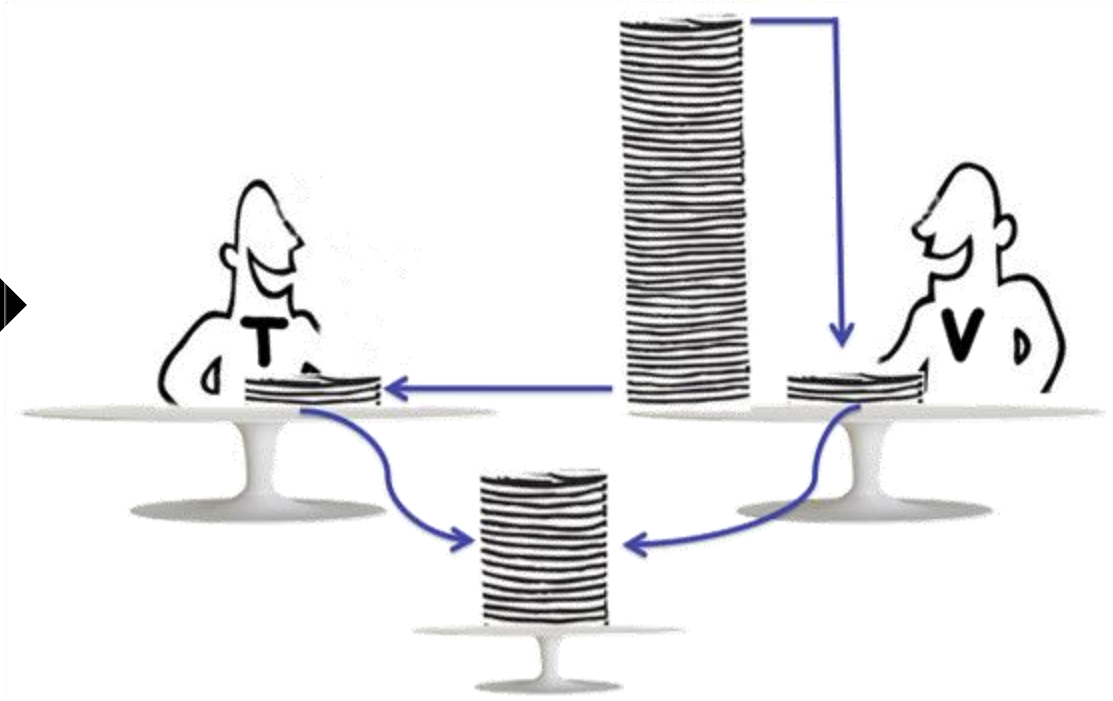
Overview: Taskflow's Work-stealing Scheduler[1]

- **Task-level scheduling**



- **Worker-level scheduling**

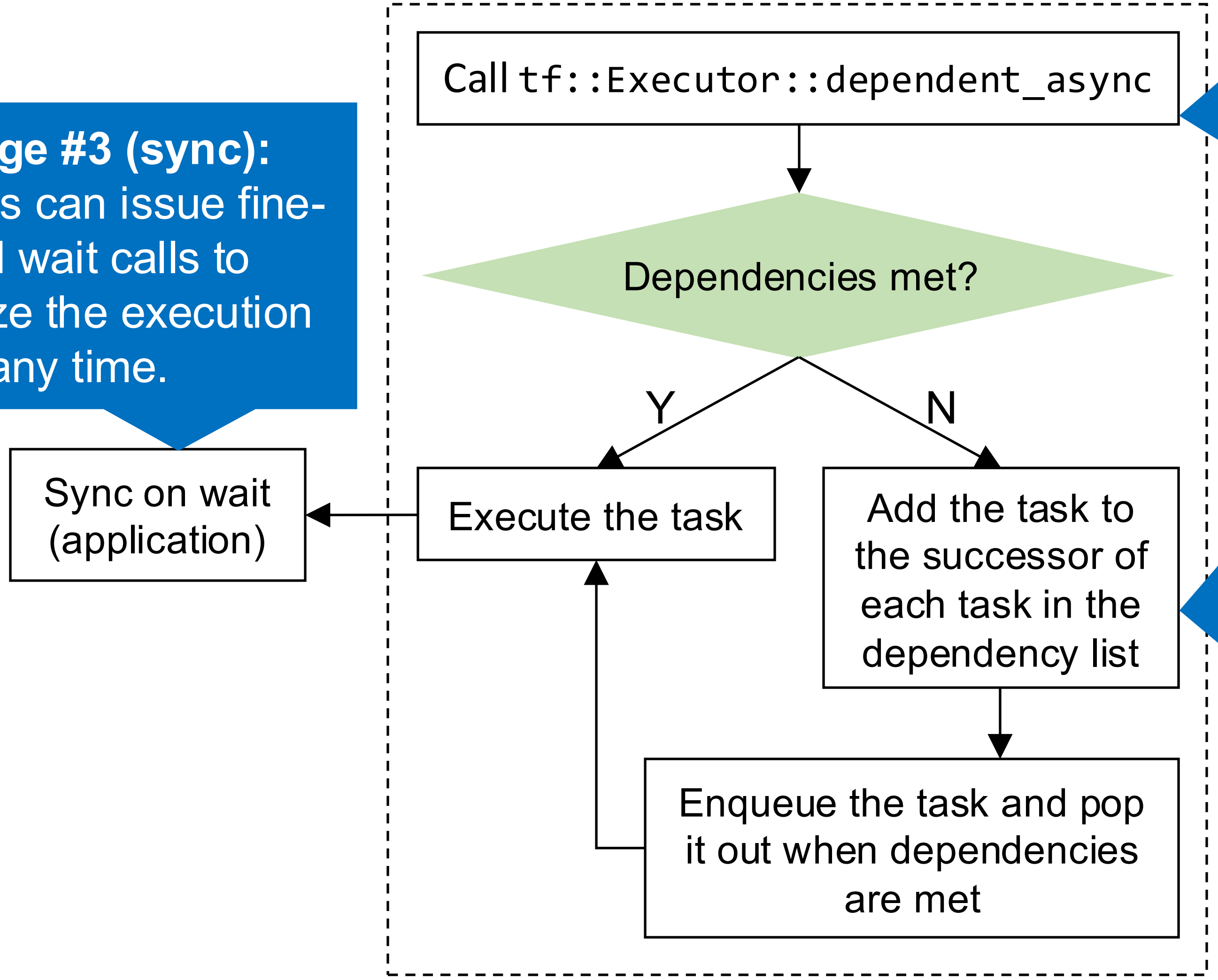


Key results: schedule tasks with in-graph control flow with a strong balance between the number of active workers and dynamically generated tasks – *low latency, energy efficient, and high throughput*

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

Scheduling a Dynamic Task Graph

Challenge #3 (sync): Applications can issue fine-grained wait calls to synchronize the execution at any time.

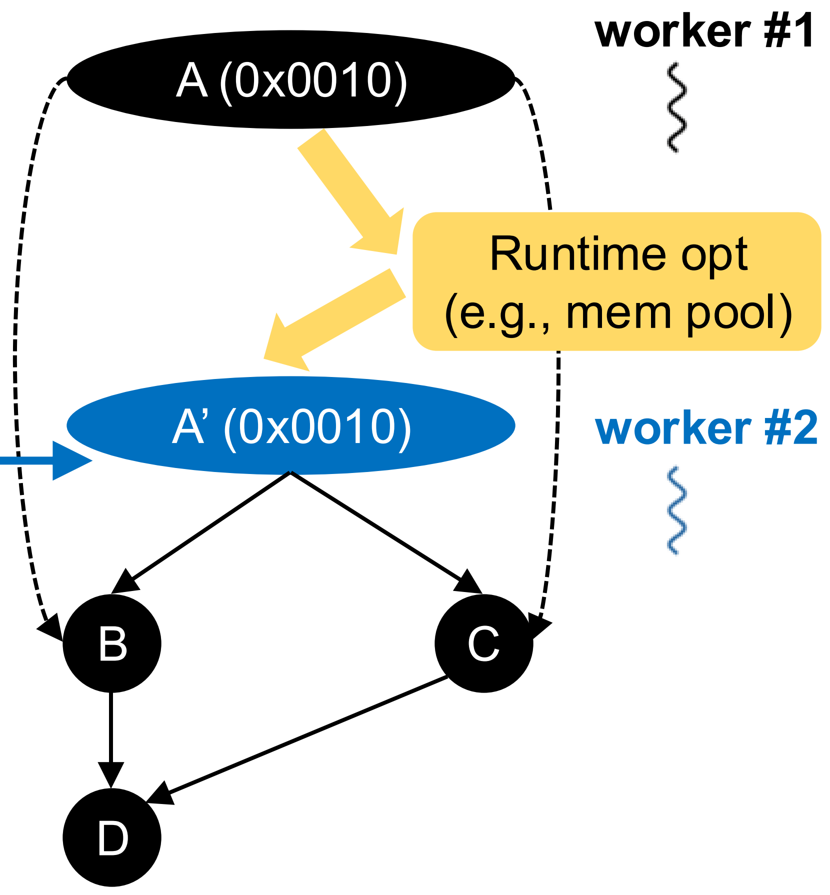


Challenge #1 (ABA): Dependent async tasks must exist correctly – we cannot specify a task dependency that points to an invalid memory location.

Challenge #2 (race): Since task graph construction and execution in DTGP can happen simultaneously, multiple workers may concurrently access the successor of a dependent-async task.

Solving Challenge #1: ABA Problem

```
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

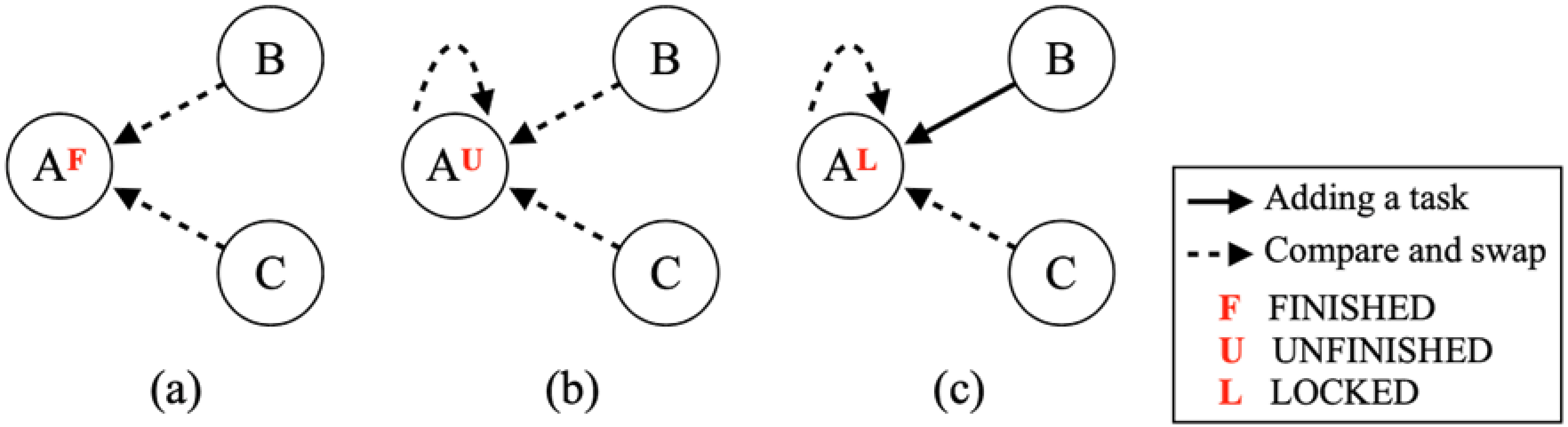
Retain a Shared Ownership of Each Task Needed

```
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` acts 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**
  - Meanwhile, A may want to remove some of its successor when the task finishes



- **Use compare-and-swap (CAS) with spinning to enable exclusive access**
  - Spinning does not incur much overhead because most task graphs are sparse
  - If you task graph is very dense, probably DTGP is not the right solution to your application

Solving Challenge #3: Synchronization

- **Users can issue both coarse- and fine-grained synchronizations at any time**
  - Coarse-grained sync: `executor.wait_for_all()`
  - Fine-grained sync: `future.wait()`

```
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

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

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

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

We leverage C++20 atomic variables to perform waiting/notifying operations[1], which allows much of the synchronization to occur in user space rather than in the kernel space (~11% performance improvement).

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

Our Scheduling Algorithm is Lock-free[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

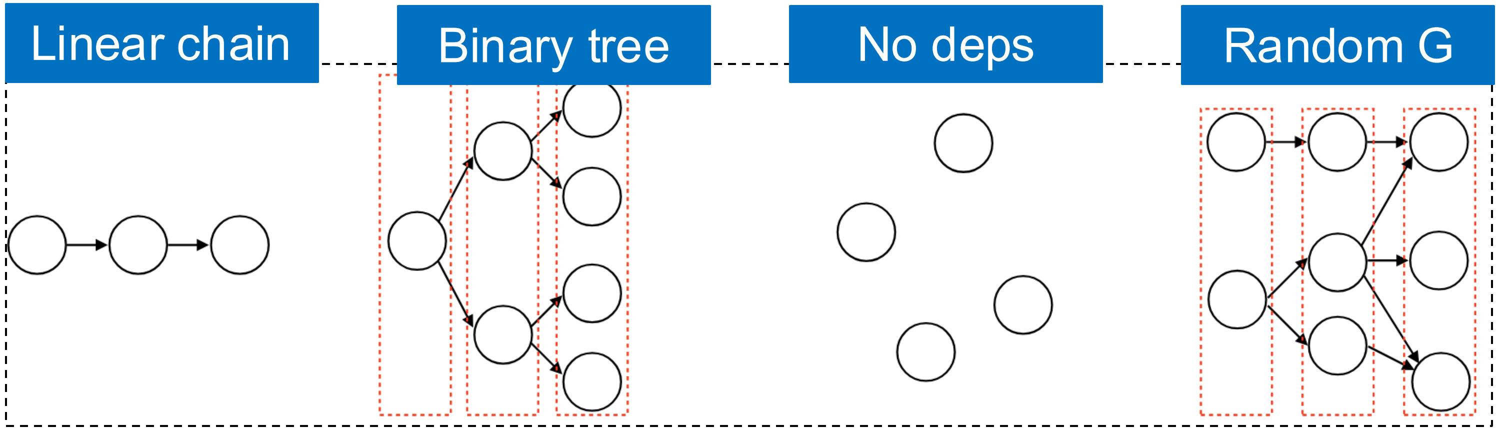
[1]: Cheng-Hsiang Chiu, et. al, "Programming Dynamic Task Parallelism for Heterogeneous EDA Algorithms," *IEEE/ACM ICCAD*, 2023

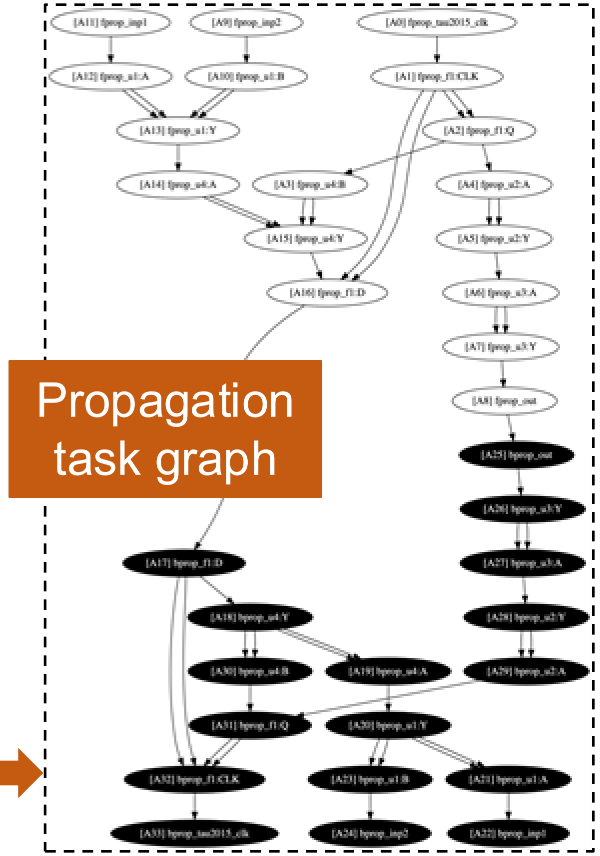
Takeaways

- Understand the importance of asynchronous tasking with dependencies
- Recognize the limitations of existing asynchronous tasking models
- Introduce a new dynamic task graph programming model called AsyncTask
- Overcome the scheduling challenges to support the model
- Demonstrate the efficiency of AsyncTask
- Conclude the talk

Evaluation of AsyncTask (1/2)

- **Evaluated on both microbenchmarks and a real-world application**
  - Study the performance of AsyncTask w/o and w/ the impact of application tasks
- **Microbenchmarks**
  - Measure the performance on four commonly used graph patterns





- **Real-world application: VLSI Static Timing Analysis[1]**
  - Parallelize the timing propagation algorithm using AsyncTask

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

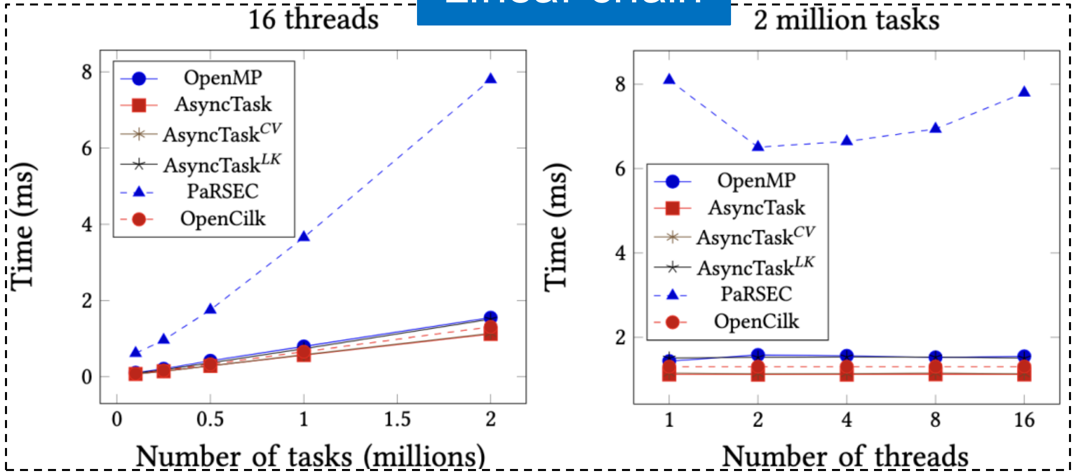
Evaluation of AsyncTask (2/2)

- **We consider the following baselines:**
  - OpenMP tasking: https://www.openmp.org/spec-html/5.0/openmpsu99.html
  - PaRSEC: https://github.com/ICLDisco/parsec
  - OpenCilk: https://github.com/opencilk
  - AsyncTask^{LK}: replaced AsyncTask's scheduler with OpenMP's task scheduler[1]
    - 💡We want to see how good our lock-free scheduling algorithm is
  - AsyncTask^{CV}: replaced AsyncTask's atomic wait with `std::condition_variable`
    - 💡We want to see how good our C++20-based notification algorithm is
- **We compiled all programs using g++12 with `-std=c++20` and `-O3`**
  - 64-bit Linux machine with 128 GB RAM and 20 Intel i5-13500 CPU cores at 4.8 GHz
  - All data is an average of ten runs to reduce variance

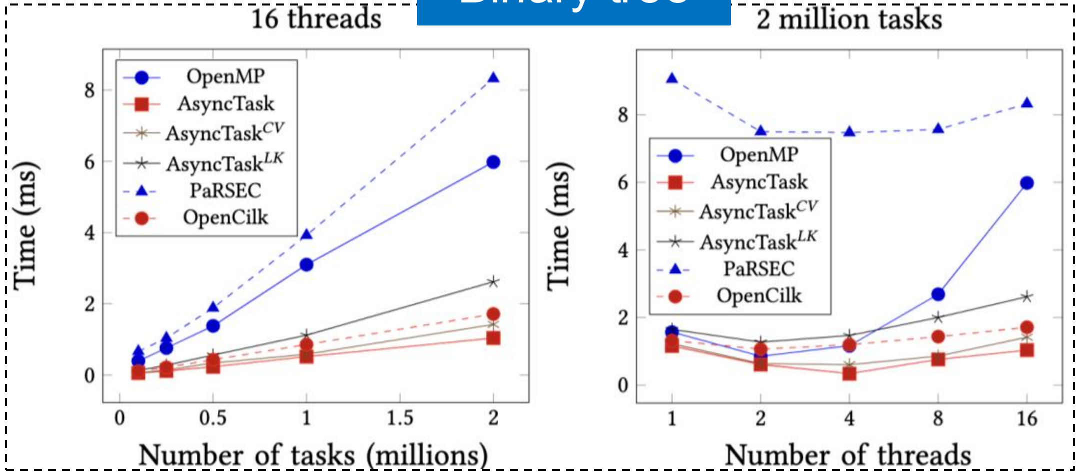
[1]: OpenMP task graph scheduler leverages a lock-based hash table to keep track of tasks and their dependency handles

Microbenchmarks

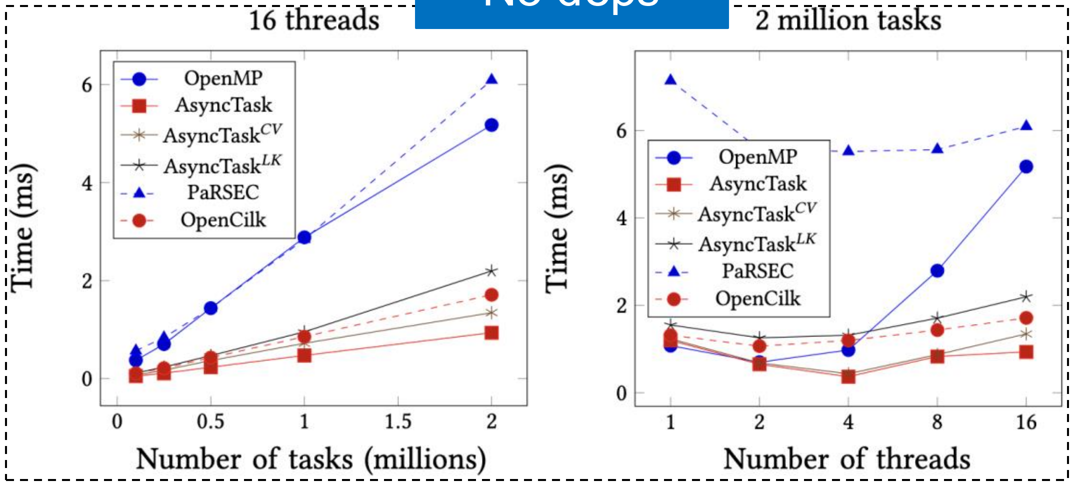
Linear chain



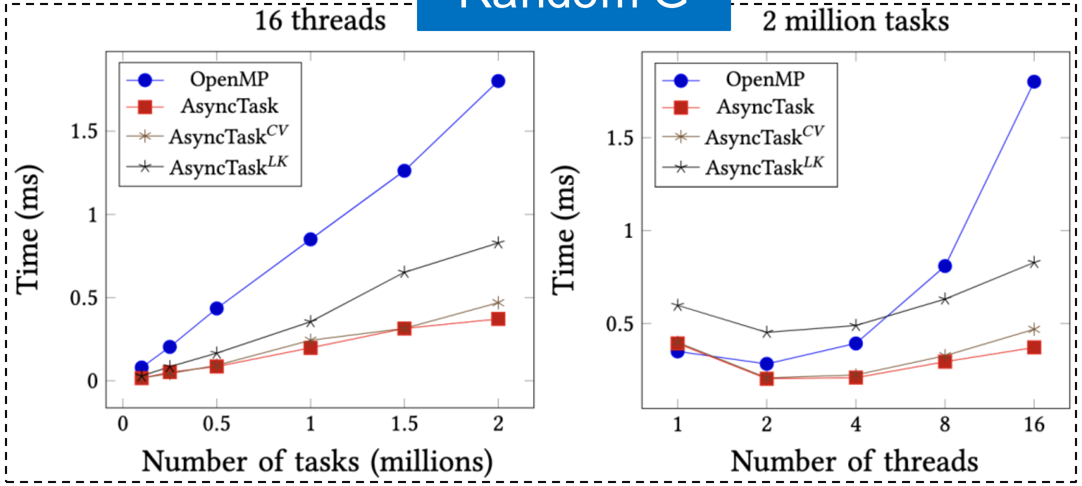
Binary tree



No deps

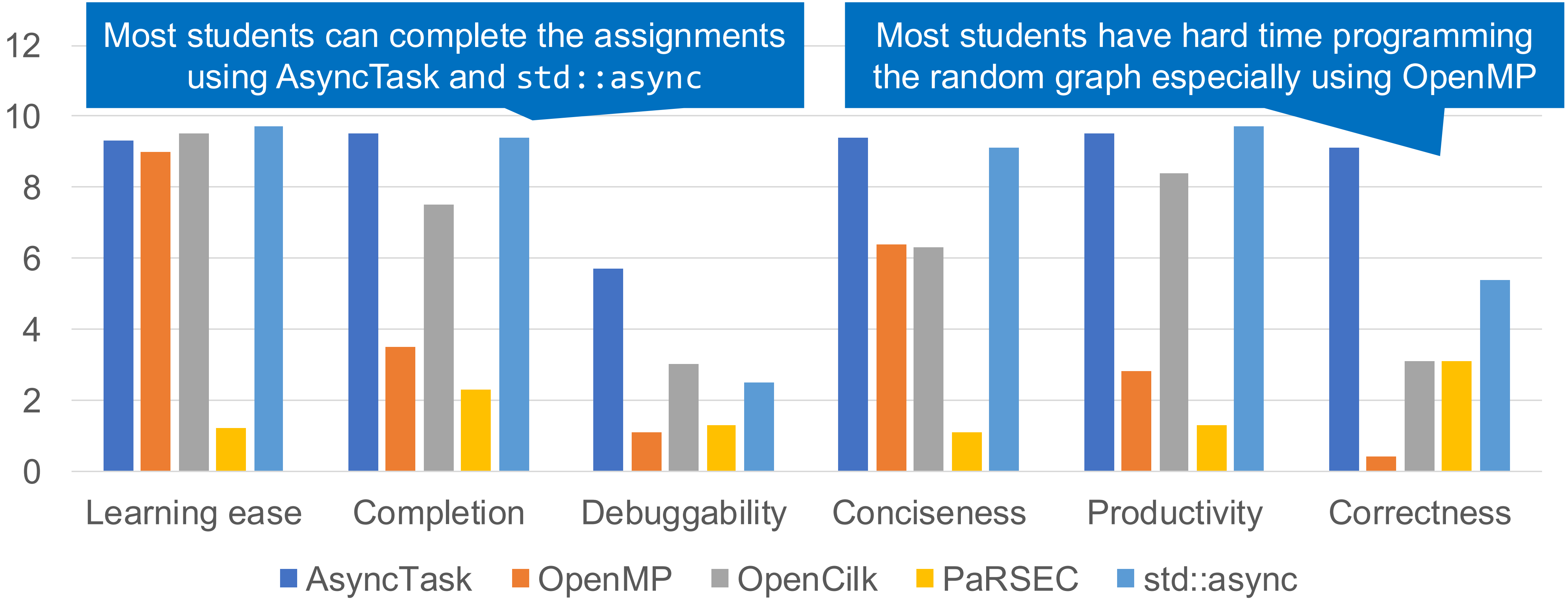


Random G



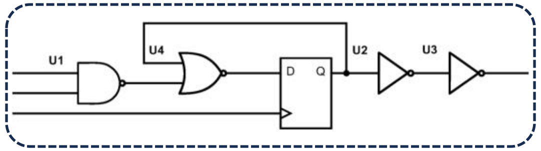
Ease of Use of AsyncTask

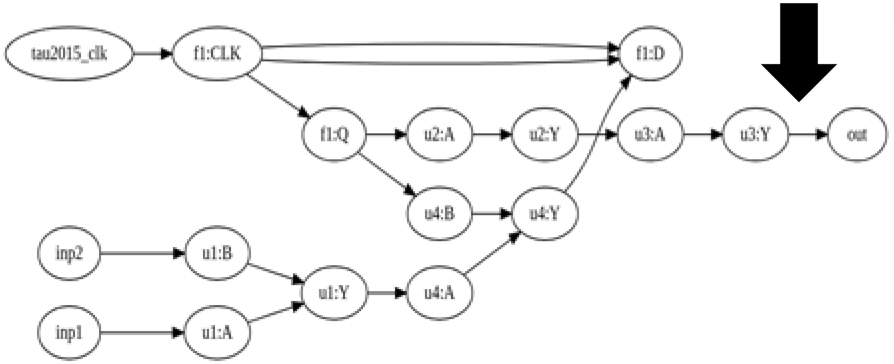
- **Surveyed 300+ graduate students in my HPC course at UW-Madison**
  - Asked students to finish four microbenchmarks using five DTGP models
  - Rated each library in 1–10 (the higher the better) by the end of this programming assignment

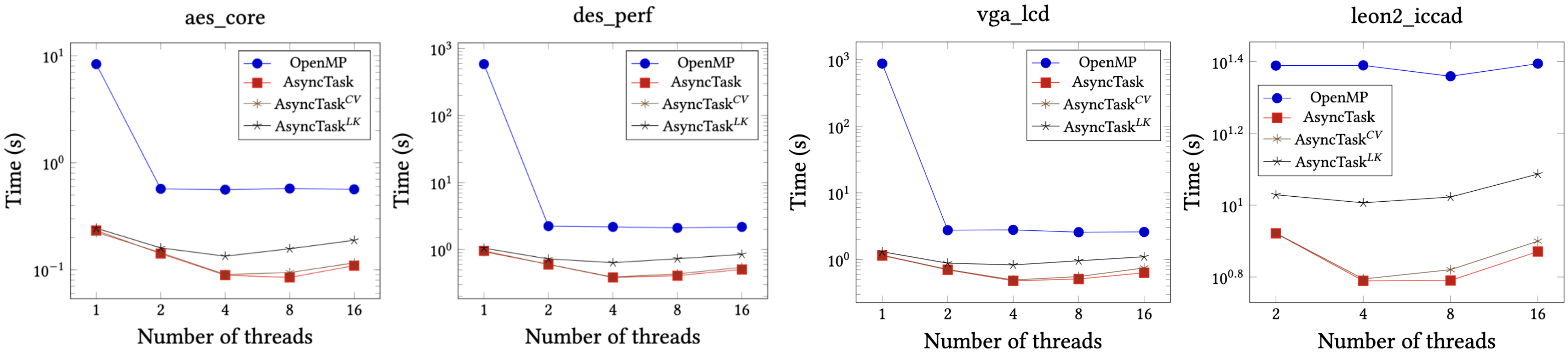


Real-world Application: Static Timing Analysis (STA)

- **Implemented task-parallel STA[1] using AsyncTask**
  - Models the timing propagation as a dynamic task graph
  - Propagates timing data from inputs to outputs
- **Evaluated on four industrial circuit graphs**
  - aes_core: 66,751 tasks and 86,446 dependencies
  - des_perf: 303,690 tasks and 387,291 dependencies
  - vga_lcd: 397,809 tasks and 498,863 dependencies
  - leon2: 4,328,255 tasks and 7,984,262 dependencies

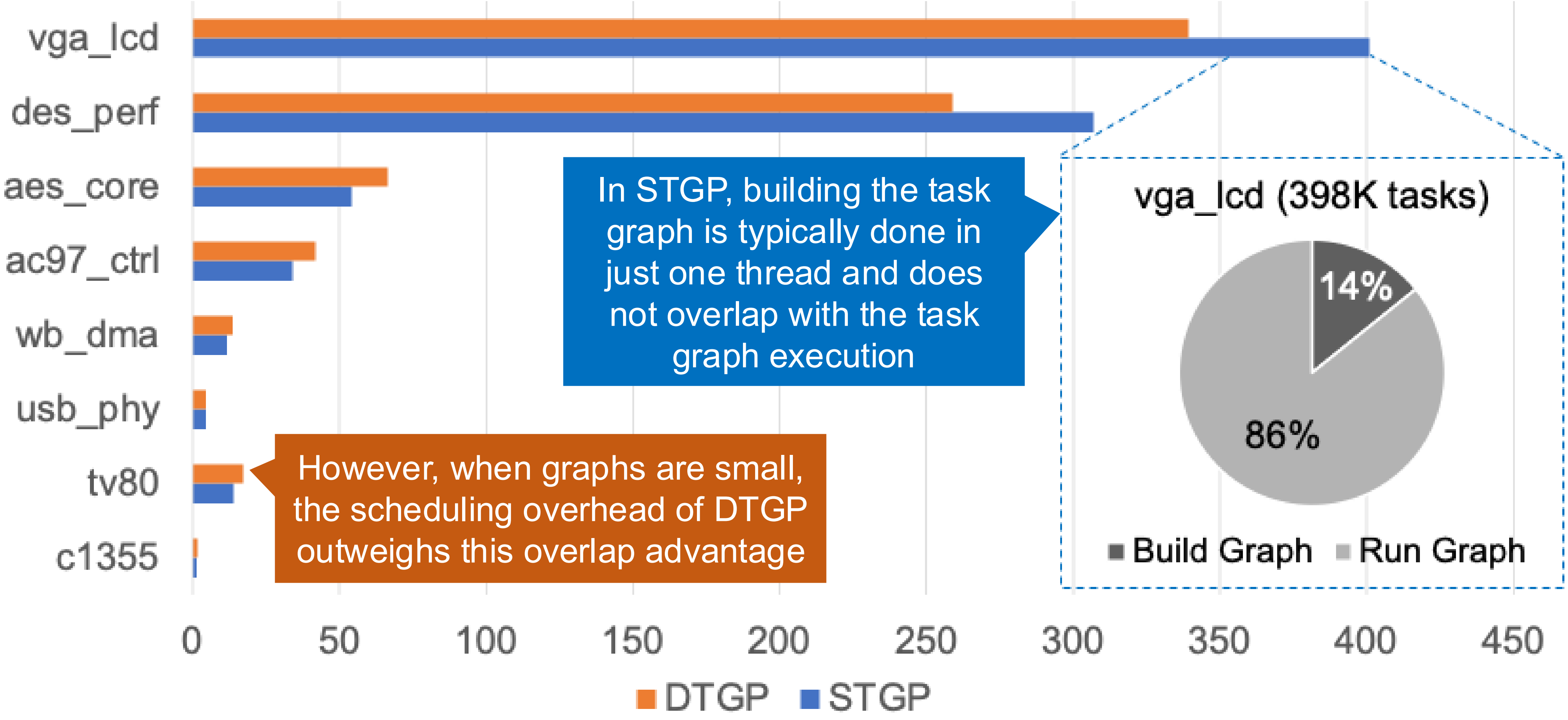






[1]: Tsung-Wei Huang, et al, “OpenTimer v2: A New Parallel Incremental Timing Analysis Engine,” *IEEE TCAD*, 2022

Runtime Comparison: STGP[1] vs DTGP



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

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Everything has been Integrated to Taskflow[1]

- **Taskflow is a header-only C++ library for task-parallel programming**
  - Started in 2018 to help DARPA parallelize critical design automation workloads
- **Using AsyncTask is very easy**

```
# clone the Taskflow project
~$ git clone https://github.com/taskflow/taskflow.git
~$ cd taskflow

# compile your program and tell your compiler where to find Taskflow header files
~$ g++ -std=c++20 examples/simple.cpp –I ./ -O2 -pthread -o simple
~$ ./simple
TaskA
TaskC
TaskB
TaskD
```


[1]: Taskflow: A General-purpose Task-parallel Programming system in Modern C++: https://taskflow.github.io/

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();
```

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();
```


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