A General-purpose Parallel and Heterogeneous Task Programming System at Scale

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How can we make it easier for scientific software developers to program large parallel and heterogeneous resources with high performance scalability and simultaneous high productivity?
Real Experience: Parallelizing VLSI CAD Software

- CAD has many of the most difficult CS problems
- multidisciplinary, irregular, dynamic, billions of tasks, etc

Computational problems of 10B+ transistors

Irregular + dynamic + iterative + conditional control flows

Partial task graph
(50M tasks, >24 hrs to finish)
CAD is Demanding New Parallelism!

Yet, most existing solutions are incremental ...

- Augment codebase with OpenMP, Pthreads, MPI, Intel TBB, and CUDA to introduce incremental parallelism
- Solutions are heavily hard-coded by resorting everything to “heroic programmers”

Why are we sluggishly changing this?

- Existing programming tools (HPX, SYCL, Kokkos, RAJA, PaRSEC, StarPU, etc.) are perfect in data-parallel programs but short in:
  - Steep learning curve of new models (syntax + semantic)
  - Dynamic/conditional/cyclic control flows
  - Composition to handle complex heterogeneous workflows
- Lack of automatic transition and verification tools
A General-purpose Parallel Task Programming System

- Task-based approach scales best with parallel architecture
- We need to handle various computational needs
  - Dynamic controls, cyclic flows, composition, irregularity
- Transition tools to ease the adoption of new models
  - Never acceptable if everything is done manually

This is an on-going large system project with many components under construction!
"Hello World" in Cpp-Taskflow [IPDPS19]

#include <taskflow/taskflow.hpp>  // Cpp-Taskflow is header-only
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);  // A runs before B
    A.precede(C);  // A runs before C
    B.precede(D);  // B runs before D
    C.precede(D);  // C runs before D
    executor.run(taskflow);  // create an executor to run the taskflow
    return 0;
}
“Hello World” in OpenMP

```c
#include <omp.h>  // OpenMP is a lang ext to describe parallelism in compiler directives
int main(){
    #omp parallel num_threads(std::thread::hardware_concurrency())
    {
        int A_B, A_C, B_D, C_D;
        #pragma omp task depend(out: A_B, A_C)
        {
            std::cout << "TaskA
";
        }
        #pragma omp task depend(in: A_B; out: B_D)
        {
            std::cout << " TaskB
";
        }
        #pragma omp task depend(in: A_C; out: C_D)
        {
            std::cout << " TaskC
";
        }
        #pragma omp task depend(in: B_D, C_D)
        {
            std::cout << "TaskD
";
        }
    }
    return 0;
}
```

OpenMP task clauses are **static and explicit**; Programmers are responsible for a proper order of writing tasks consistent with sequential execution.
“Hello World” in Intel’s TBB Library

#include <tbb.h>  // Intel’s TBB is a general-purpose parallel programming library in C++
int main(){
    using namespace tbb;
    using namespace tbb::flow;
    int n = task_scheduler_init::default_num_threads () ;
task scheduler_init init(n);
    graph g;
    continue_node<continue_msg> A(g, [] (const continue msg &)
    {
        std::cout << “TaskA” ;
    });
    continue_node<continue_msg> B(g, [] (const continue msg &)
    {
        std::cout << “TaskB” ;
    });
    continue_node<continue_msg> C(g, [] (const continue msg &)
    {
        std::cout << “TaskC” ;
    });
    continue_node<continue_msg> D(g, [] (const continue msg &)
    {
        std::cout << “TaskD” ;
    });
    make_edge(A, B);
    make_edge(A, C);
    make_edge(B, D);
    make_edge(C, D);
    A.try_put(continue_msg());
g.wait_for_all();
}

Use TBB’s FlowGraph for task parallelism

Declare a task as a continue_node

TBB has excellent performance in generic parallel computing. Its drawback is mostly in the ease-of-use standpoint (simplicity, expressivity, and programmability).
“Hello Universe” in Cpp-Taskflow

Dynamic tasking

Composable tasking for *complex workflows*

Conditional tasking for *cyclic* and *dynamic* control flows

More on: [https://github.com/cpp-taskflow/cpp-taskflow](https://github.com/cpp-taskflow/cpp-taskflow)
Concurrent CPU-GPU Task Programming

auto ha = hf.host([](){});
auto hb = hf.host([](){});
auto hc = hf.host([](){});
auto sa = hf.span(1024);
auto sb = hf.span(1024);
auto sc = hf.span(1024);

auto op = hf.kernel(
    {(1024+32-1)/32}, 32, 0, fn_kernel, sa, sb, sc);

auto cc = hf.copy(host_data, sc, 1024);

ha.precede(sa);
hb.precede(sb);
op.succeed(sa, sb, sc).precede(cc);
cc.succeed(hc);

kernel is non-trivial, but what makes heterogeneous programming difficult is the “surrounding tasks”
Real Use Case: VLSI Timing Analysis

- OpenTimer v1: A VLSI Static Timing Analysis Tool
  - v1 first released in 2015 (open-source under GPL)
  - Loop-based parallelisms using OpenMP 4.0

- OpenTimer v2: A New Parallel Incremental Timer
  - v2 first released in 2018 (open-source under MIT)
  - Task-based parallel decomposition using Cpp-Taskflow

Saved 4K lines of parallel code!
Cost to develop is $275K with OpenMP vs $130K with Cpp-Taskflow! (measured by sloccount)

v2 (Cpp-Taskflow) is 1.4-2x faster than v1 (OpenMP)
Current and Future Work

- **A general-purpose parallel task programming system**
  - Simple, efficient, and transparent using modern C++
  - Multithreading and CPU-GPU tasking
  - Real case use in VLSI timing analysis with billion-tasking

- **On-going items**
  - Developing new task models using cudaGraph
  - Developing accelerator bridge to handle other devices
  - Developing transition tools to ease the adoption

- **Open to collaboration for more use cases!!!**
  - [https://github.com/cpp-taskflow/cpp-taskflow](https://github.com/cpp-taskflow/cpp-taskflow)