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

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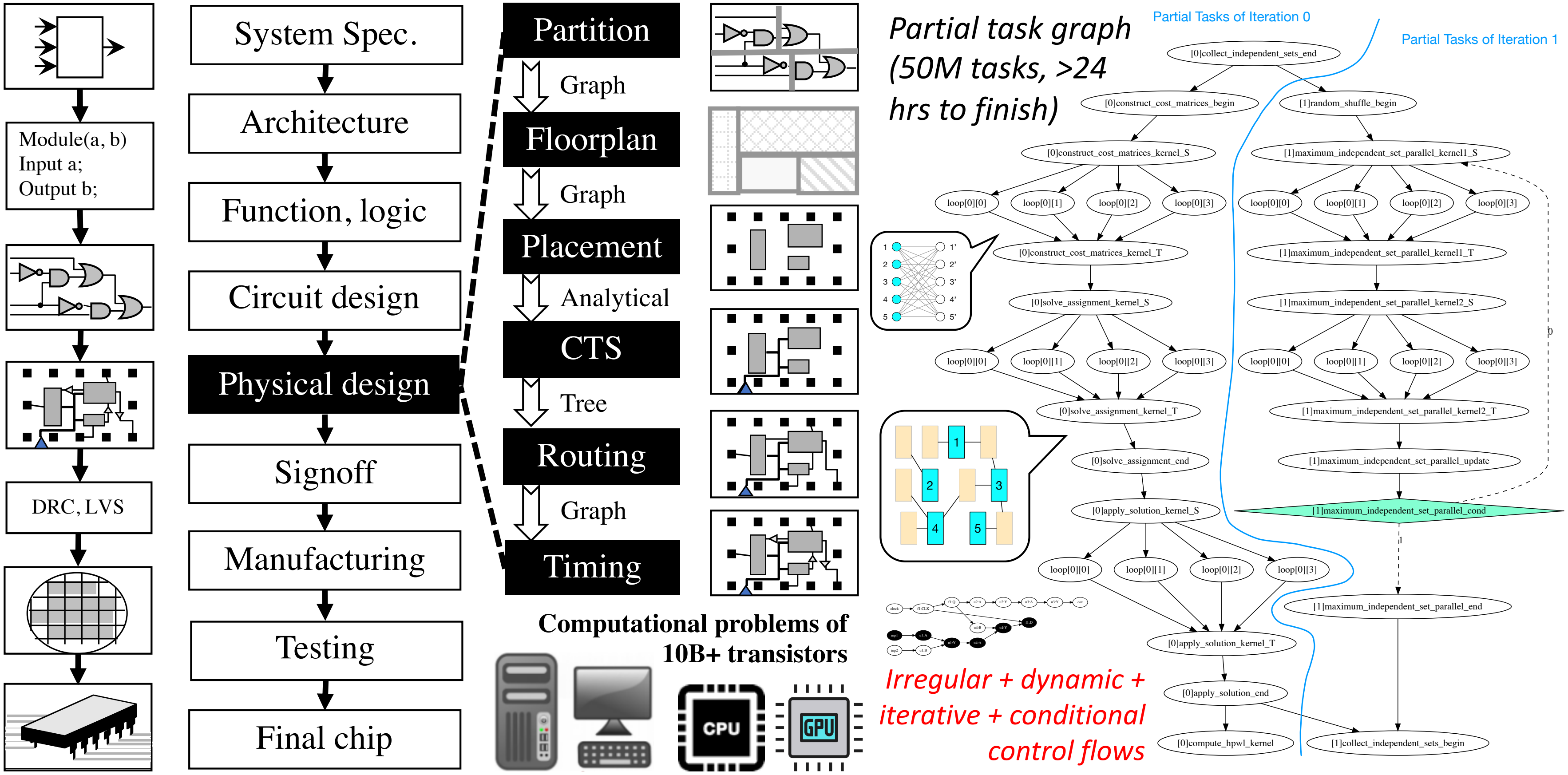
How can we make it easier for scientific software developers to program large parallel and heterogeneous resources with high performance scalability and simultaneous high productivity?

Real Experience: Parallelizing VLSI CAD Software

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



Module(a, b)
Input a;
Output b;

DRC, LVS

System Spec. → Architecture → Function, logic → Circuit design → Physical design → Signoff → Manufacturing → Testing → Final chip

Partition → Graph → Floorplan → Graph → Placement → Analytical → CTS → Tree → Routing → Graph → Timing

Computational problems of 10B+ transistors

Partial task graph (50M tasks, >24 hrs to finish)

Irregular + dynamic + iterative + conditional control flows

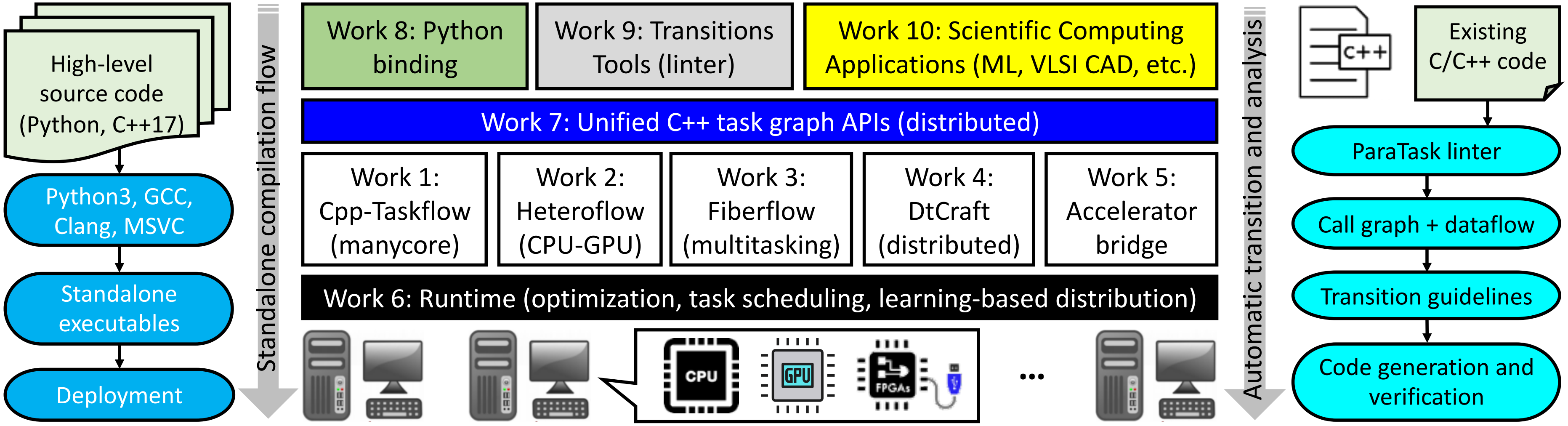
CPU
GPU
Partial Tasks of Iteration 0
Partial Tasks of Iteration 1
[0]collect_independent_sets_end
[0]construct_cost_matrices_begin
[1]random_shuffle_begin
[0]construct_cost_matrices_kernel_S
[1]maximum_independent_set_parallel_kernel1_S
loop[0][0]
loop[0][1]
loop[0][2]
loop[0][3]
[0]construct_cost_matrices_kernel_T
[1]maximum_independent_set_parallel_kernel1_T
[0]solve_assignment_kernel_S
[1]maximum_independent_set_parallel_kernel2_S
[0]solve_assignment_kernel_T
[1]maximum_independent_set_parallel_kernel2_T
[0]solve_assignment_end
[1]maximum_independent_set_parallel_update
[0]apply_solution_kernel_S
[1]maximum_independent_set_parallel_cond
[0]apply_solution_kernel_T
[1]maximum_independent_set_parallel_end
[0]apply_solution_end
[0]compute_hpwl_kernel
[1]collect_independent_sets_begin
1
2
3
4
5
1'
2'
3'
4'
5'

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 arch**
- ❑ **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



High-level source code (Python, C++17)

Python3, GCC, Clang, MSVC

Standalone executables

Deployment

Standalone compilation flow

Work 8: Python binding

Work 9: Transitions Tools (linter)

Work 10: Scientific Computing Applications (ML, VLSI CAD, etc.)

Work 7: Unified C++ task graph APIs (distributed)

Work 1: Cpp-Taskflow (manycore)

Work 2: Heteroflow (CPU-GPU)

Work 3: Fiberflow (multitasking)

Work 4: DtCraft (distributed)

Work 5: Accelerator bridge

Work 6: Runtime (optimization, task scheduling, learning-based distribution)

Automatic transition and analysis

Existing C/C++ code

ParaTask linter

Call graph + dataflow

Transition guidelines

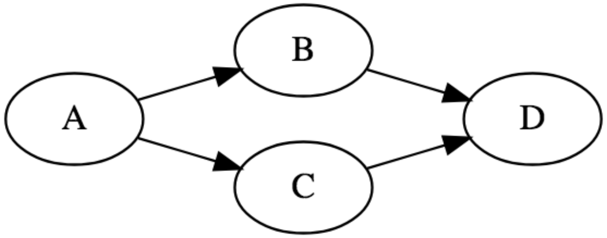
Code generation and verification

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;
}
```

*Only **17 lines** of code to get a parallel task execution!*



“Hello World” in OpenMP

```
#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\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” ;
      }
   }
   return 0;
}
```

Task dependency clauses

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Task dependency clauses

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> C(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();
}
```

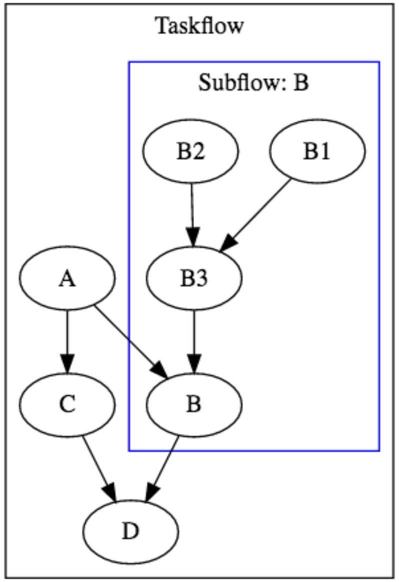
Use TBB’s FlowGraph for task parallelism

Declare a task as a continue_node

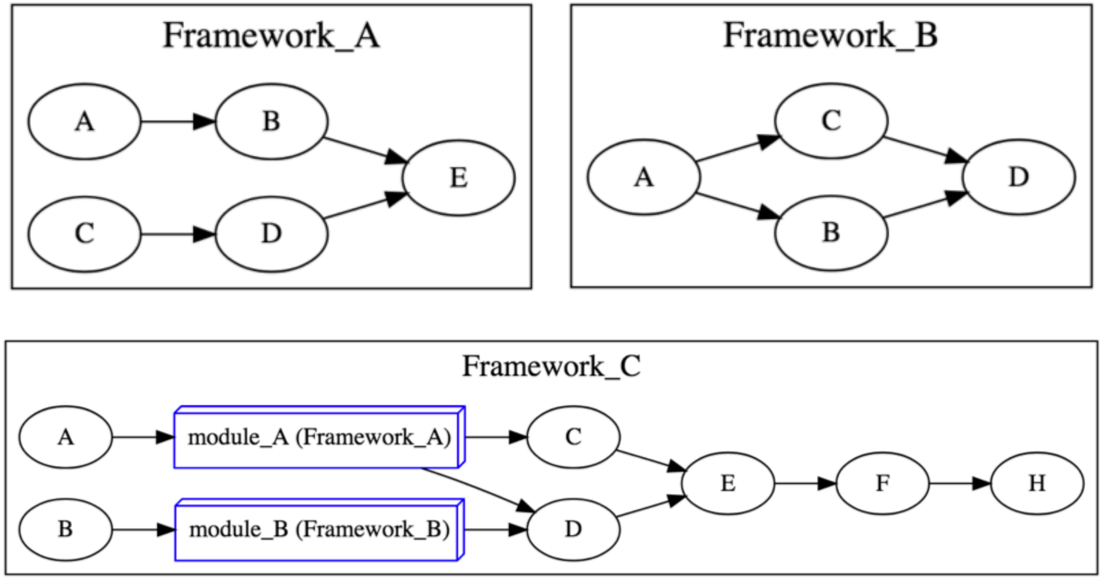
TBB has excellent performance in generic parallel computing. Its drawback is mostly in the ease-of-use standpoint (simplicity, expressivity, and programmability).

"Hello Universe" in Cpp-Taskflow

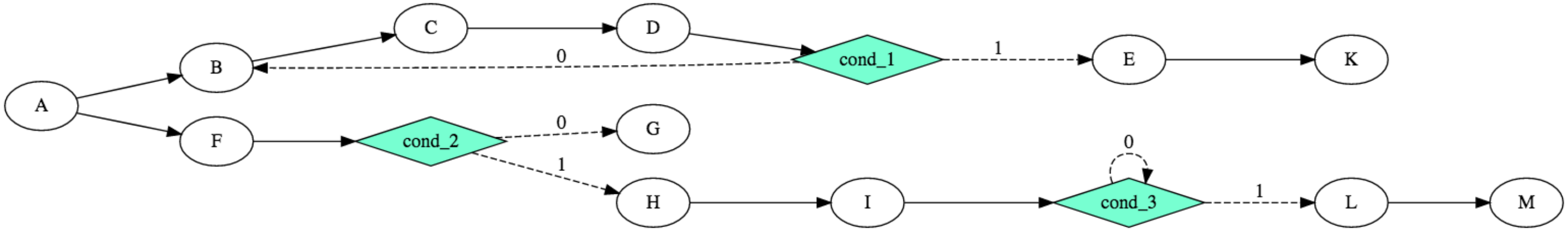
Dynamic tasking



Composable tasking for *complex workflows*



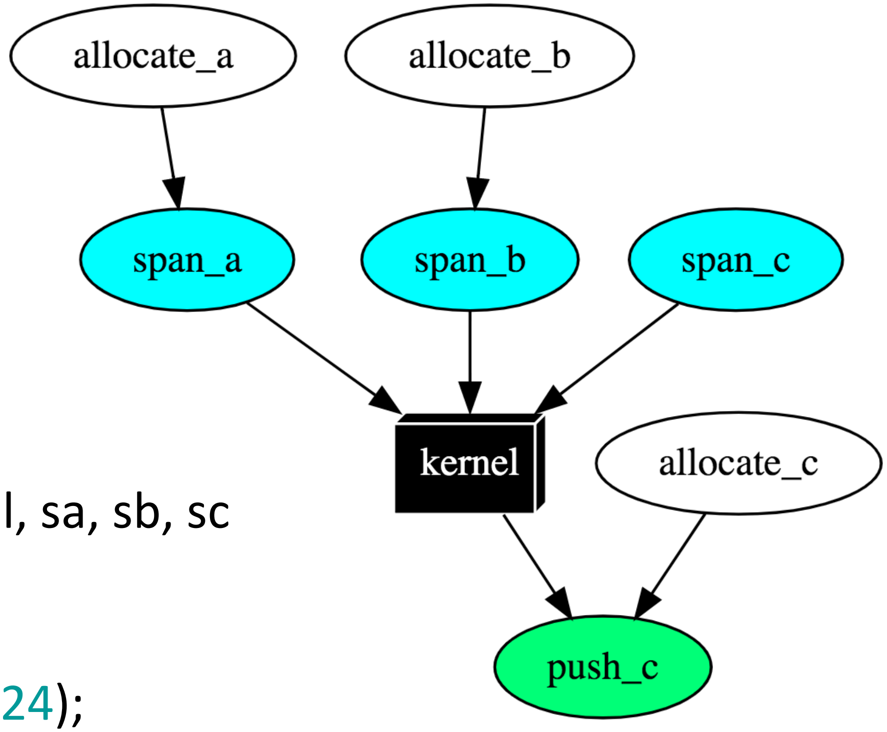
Conditional tasking for *cyclic* and *dynamic* control flows



More on: https://github.com/cpp-taskflow/cpp-taskflow

Concurrent CPU-GPU Task Programming

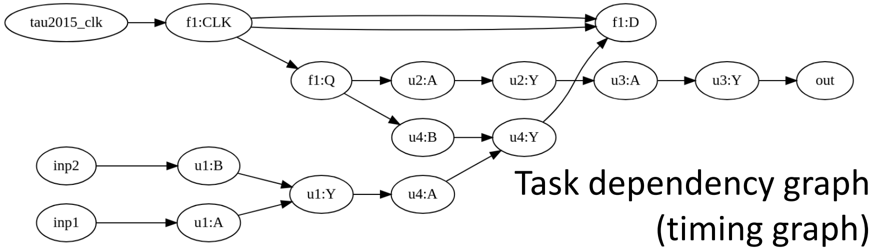
```
auto ha = hf.host([](){});
auto hb = hf.host([](){});
auto hc = hf.host([](){});
auto sa = hf.span(1024);
auto sb = hf.span(1024);
auto sc = hf.span(1024);

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"

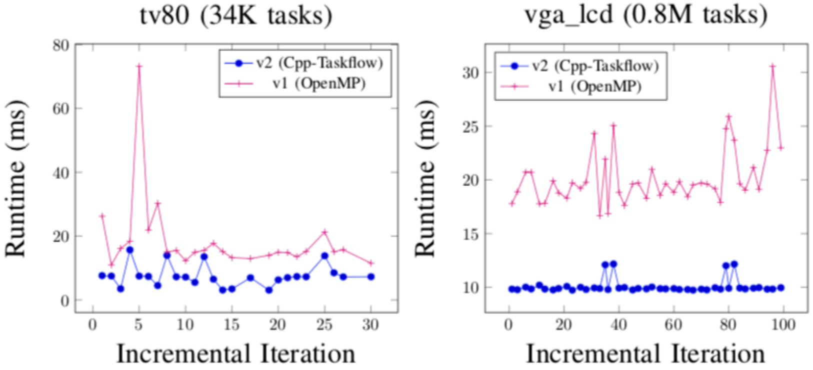
Real Use Case: VLSI Timing Analysis

- □ **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



Task dependency graph
(timing graph)

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/tsung-wei-huang/DtCraft