Template Task Graphs: An Introduction

ECP Tutorial, September 15, 2022

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If you want to follow the hands-on on your machine

- See https://bit.ly/ttg-tutorial

- Link also available from the ‘Materials for the event’ tab in the ECP tutorial registration page

TTG: Product of EPEXA Collaboration

Objective: better composition of irregular algorithms on top of distributed-memory task runtimes (PaRSEC, MADNESS)



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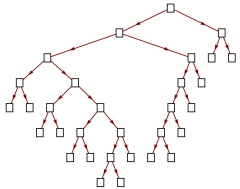
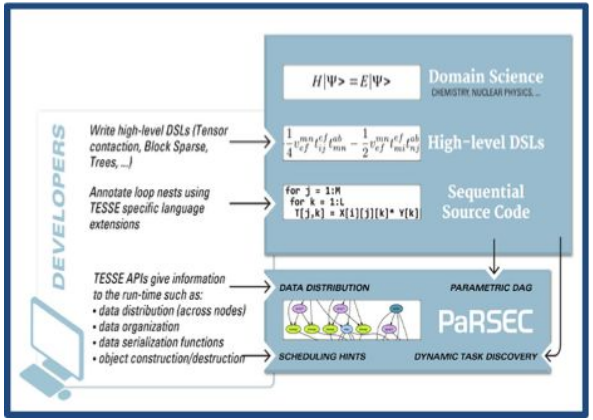
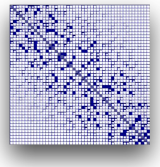


adaptive spectral-element calculus



Ed Valeev
VT



block-rank sparse algebra for quantum chemistry/physics

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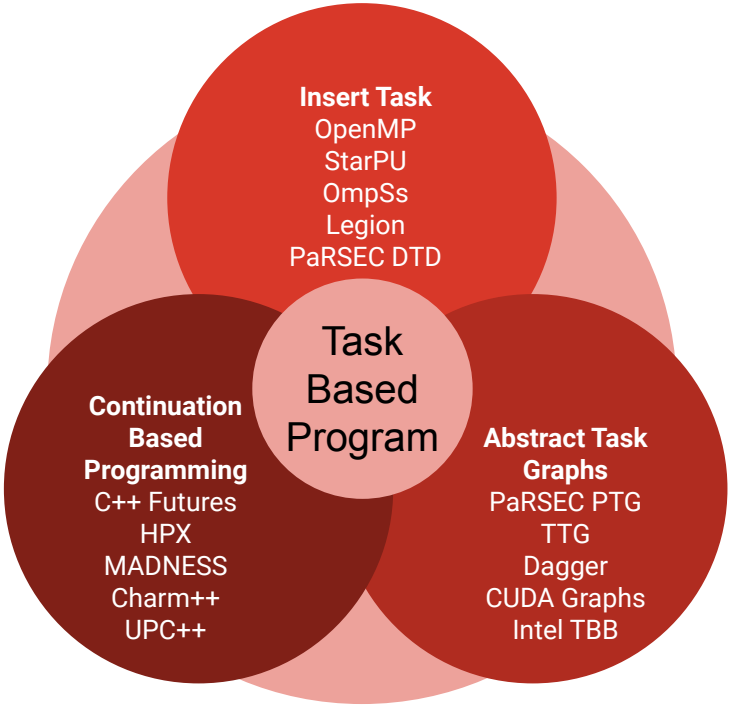
Task-Based Programming Interface

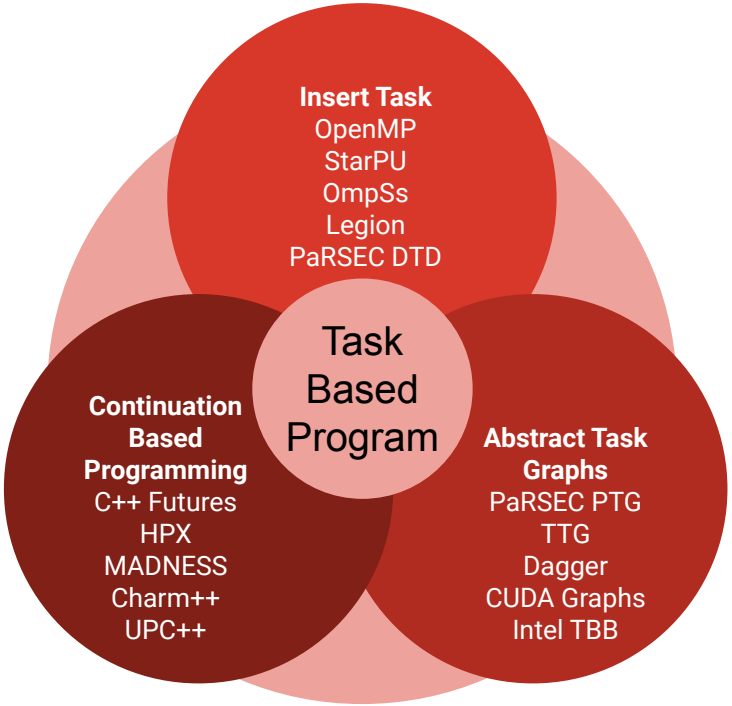
3 categories of task programming approaches:

- Insert Task
  - Sequential task discovery
  - Apparent data access order defines the DAG of tasks
- Continuation-Based Programming
  - Tasks become available when data is available in a future
- Abstract Task Graphs
  - Programmer defines an internal representation of the DAG of tasks



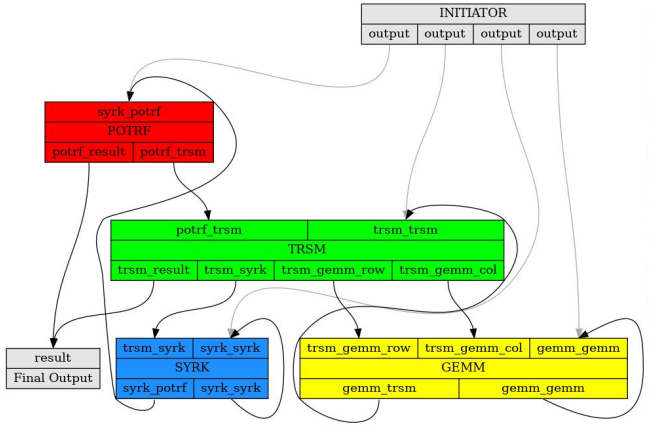
Why TTG?

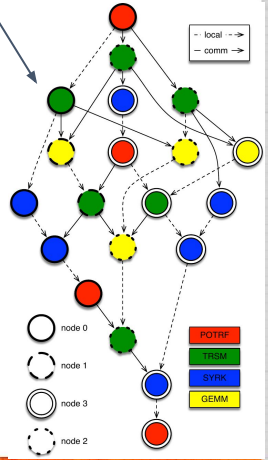
- Split graph setup from execution
  - Abstract Task Graph interface
  - Enables fully distributed DAG of task generation (and execution)
    - Any thread discovers new tasks
    - (Any thread can execute tasks, as in all task-based systems)
- Data-dependent graph traversal
  - Hard/Impossible in most ATG
- Hidden complexities of data movement / task result management



TTG: Overview

- Abstract task graph unfolds into DAG during execution
  - **Template Tasks**: instantiated into tasks at execution
    - One to many: single Template Task can generate a large number of unique Tasks.
    - A task is a template task + a task identifier + input data for that task
  - **Terminals**: input/output points of template tasks
  - **Edges**: connecting input/output terminals
- Tasks **send** data to successors
- Multiple **backends**: PaRSEC, MADNESS





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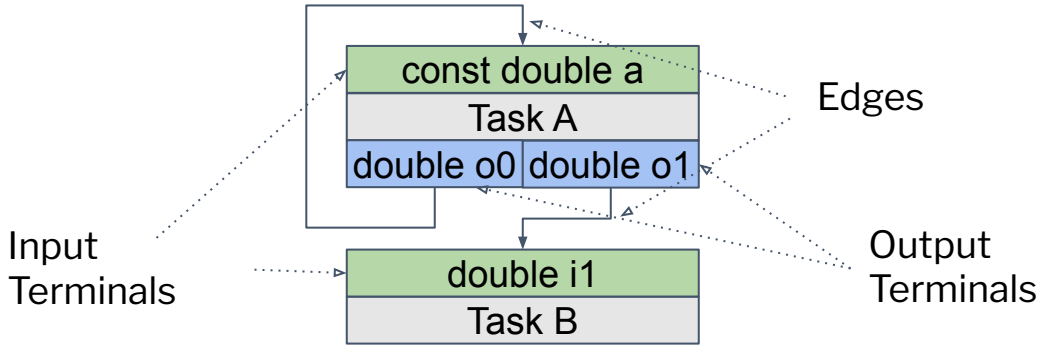
Template Task Graphs: Visual Representation



Template Task Graphs: Visual Representation

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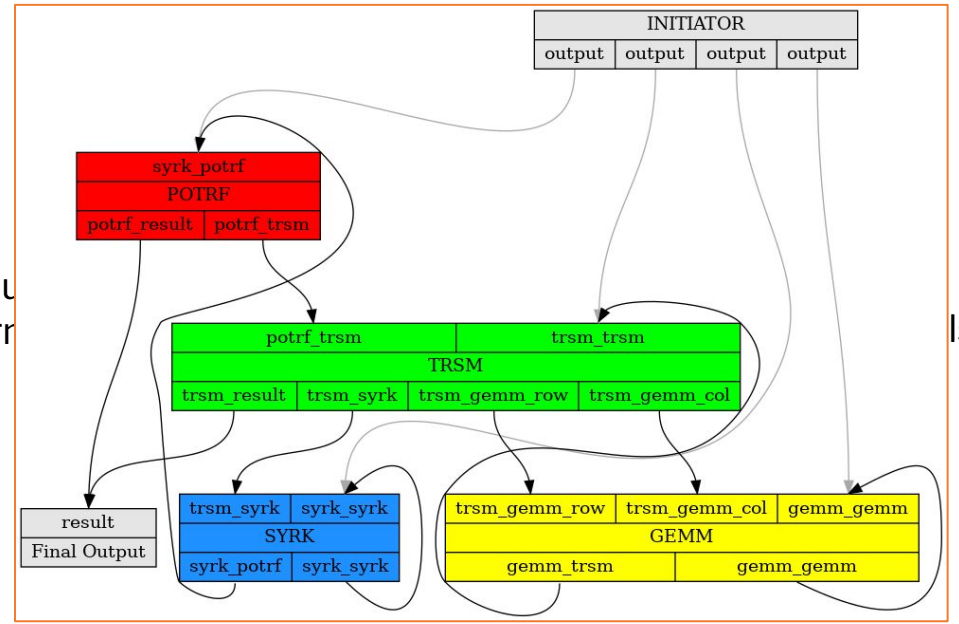

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TTG Execution Model

- SPMD model: all processes execute the same program
- `ttg::World` to query number of processes and ranks
  - Split processes between multiple ‘worlds’
- Single or multiple entry points into the DAG
  - One or more processes kick off computation by feeding information into the task graph
- Worker threads execute (non-preemptive) tasks
  - And while doing so may discover new tasks (and/or fulfill input for existing tasks)
- Fence at the end of the application (ideally), or to synchronize with non-task-based computations
- Composition of Template Task Graphs using Edges (see later)

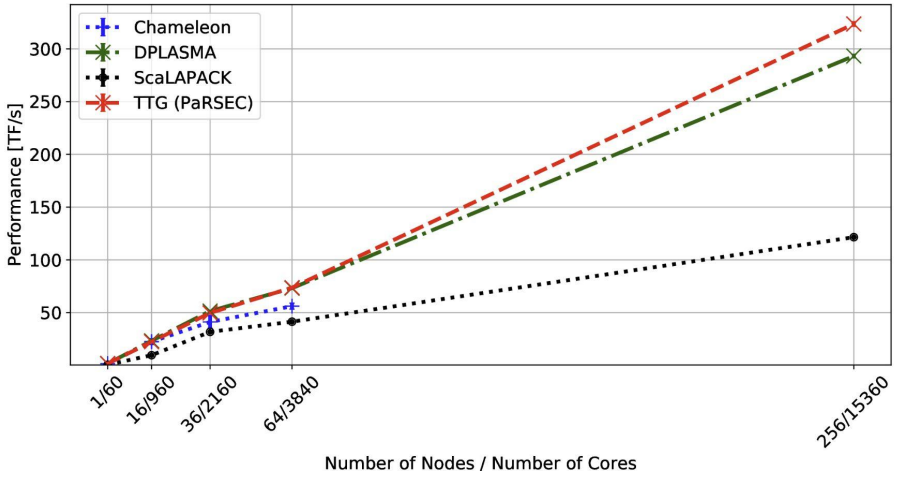
TTG Memory Model

- TTG runtime manages all data fed into the DAG
- Data moves transparently based on the placement of the task consuming the data (see later)
  - No explicit receives
  - Sent/Broadcast data is implicitly received by new tasks, as task input arguments
- Immutable data (const lvalue reference arguments – `const T &`) may be shared between tasks
- Mutable data (rvalue reference arguments – `T&&`) receive private copies, unless the source task moves the data in the send (depending on the runtime backend for TTG).

Cholesky Factorization: Weak Scaling

- Hawk, 1 – 256 nodes
- Matrix: 30k per node, tiles size 512

Performance of TTG matches DPLASMA



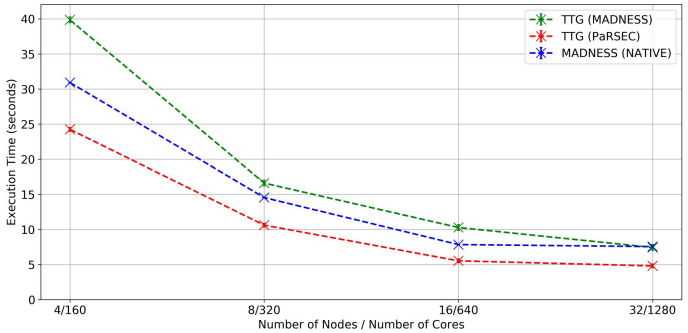
J. Schuchart, P. Nookala, M. M. Javanmard, T. Herault, E. F. Valeev, G. Bosilca, R. J. Harrison. Generalized Flow-Graph Programming Using Template Task-Graphs: Initial Implementation and Assessment. IPDPS, 2022.

Multi-Resolution Analysis (MRA)

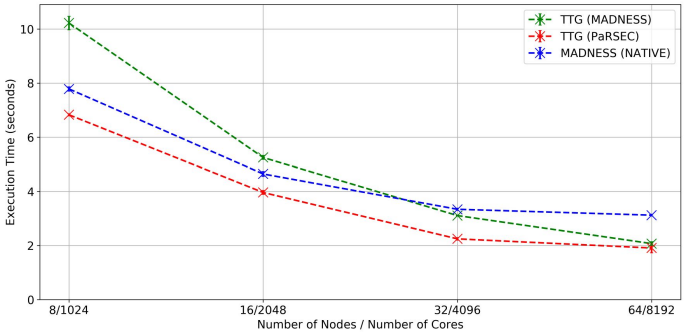
Order-10 multiwavelet representation of 3-D Gaussian functions, originally implemented in MADNESS

- **Seawulf**: 120 Functions, 2x20 threads per node
- **Hawk**: 400 Functions, 8x16 threads per node

Seawulf



Hawk



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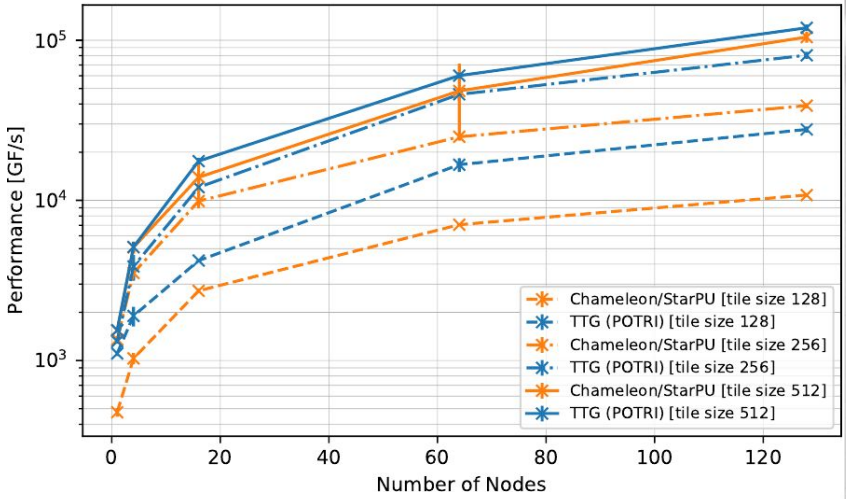
Performance of POTRI (TRTRI+LAUUM)

- Composing graphs of two consecutive operations allows data to flow between the graphs without synchronization
- Results show performance benefits of graph composition and of the distributed task discovery (small tile sizes)



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TTG API: Basics Overview

`ttg::make_tt()`	Create a new Template Task with input/output edges

`ttg::send()`
`ttg::sendk()`
`ttg::sendv()`
	Send data along an edge (key+value, key only, value only)

`ttg::Edge<K, T>`	Edge connecting two Template Tasks with key type K and value type T (K and T may be void)
`ttg::edges()`	Collection of edges to pass to ttg::make_tt as input and output edes of TT
`ttg::make_executable()`	Check that all Template Tasks are connected and reachable; prepare for execution
`ttg::execute()`	Start execution of a Template Task Graph
`ttg::fence()`	Wait for completion of running graphs
`TT::invoke()`	Create a new task instance with given arguments
`ttg::print()`	Pretty print (avoids multithreaded garbled output, and adds some information like the rank)

TTG API: Task Functions

Function object invoked once all inputs are satisfied.

Key is optional (for task templates with single task instance)

```
[=](const keyT &k) {
  ttg::print("This is task B(" , k, ")");
}
```

control flow (= flow of "void" data)

```
[=](const keyT &k, const T& val) {
  ttg::print("This is task B(" , k, ", " val, ")");
}
```

immutable data

```
[=](const keyT &k, T&& val) {
  ttg::print("This is task B(" , k, ", " val, ")");
}
```

mutable data

```
[=](const keyT &k, auto& val) {
  ttg::print("This is task B(" , k, ", " val, ")");
}
```

immutable generic data

```
[=](const keyT &k, auto&& val) {
  ttg::print("This is task B(" , k, ", " val, ")");
}
```

mutable generic data

Alternative 1: build your own programming environment

- Get TTG
  - `git clone https://github.com/TESSEorg/ttg.git`
  - `cd ttg`
  - `git checkout 73b59714461ae5b18307fec01cfac1ada30a108a`
- Pre-requisites:
  - C++-17 compiler (gcc>10, clang>10,icc…)
  - MPI, HWLOC, flex, bison, (Ninja), CMake (>3.20), git
  - For profiling capabilities: python3, pandas
  - To get all the tests: Eigen3, Boost, MKL
- Compile in a build directory (no compilation in source)
  - `mkdir build`
  - `cd build`
  - `cmake -DCMAKE_BUILD_TYPE=Release -DCMAKE_INSTALL_PREFIX=/usr [-DPARSEC_PROF_TRACE=ON -DPARSEC_PROF_GRAPHER=ON] [-DBUILD_TESTING=FALSE] [-G Ninja] ../`
  - `make (or ninja)`
  - `make install`

Alternative 2: Use Docker

Get the docker from docker hub

```
> docker pull therault/ttg-tutorial-22-09-15:latest
```

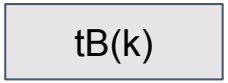
Run it in interactive mode, with volume sharing

```
> docker run --name ttg-tutorial \
             -it --rm \
             -v $PWD/:/home/tesse/tutorial \
             therault/ttg-tutorial-22-09-15
tesse@dcede646b2c1:~$ ls
Dockerfile  ttg  tutorial  ubuntu-preseed.txt
tesse@dcede646b2c1:~$ ls tutorial
ECP-Sept-22
```

First TTG program: single template task

```
auto tb = ttg::make_tt([](const int &k) {
    ttg::print("This is task B(" , k, ")");
  },
  ttg::edges(),
  ttg::edges(),
  "B", {}, {});
ttg::make_executable(tb);
```

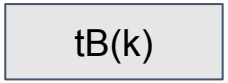
Template Task Graph



First TTG program: single template task

```
auto tb = ttg::make_tt( [](const int &k) {
    ttg::print("This is task B(" , k, ")");
  },
  ttg::edges(), ttg::edges(),
  "B", {}, {});
ttg::make_executable(tb);
if(tb->get_world().rank() == 0) {
  tb->invoke(0);
  tb->invoke(1);
}
ttg::execute();
ttg::fence(tb->get_world());
```

Template Task Graph

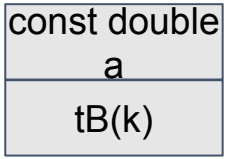


DAG of Tasks

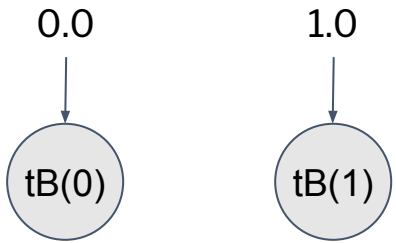
First TTG program: single template task

```
ttg::Edge<int, double> to_B("to_B");
auto tb = ttg::make_tt(
  [](const int &k, const double &a) {
    ttg::print("This is task B(" , k, ")",
               " it received value ", a,
               " for input a");
  },
  ttg::edges(to_B), ttg::edges(),
  "B", {"a"}, {});
ttg::make_executable(tb);
if(tb->get_world().rank() == 0) {
  tb->invoke(0, 0.0);
  tb->invoke(1, 1.0);
}
ttg::execute();
ttg::fence(tb->get_world());
```

Template Task Graph



DAG of Tasks

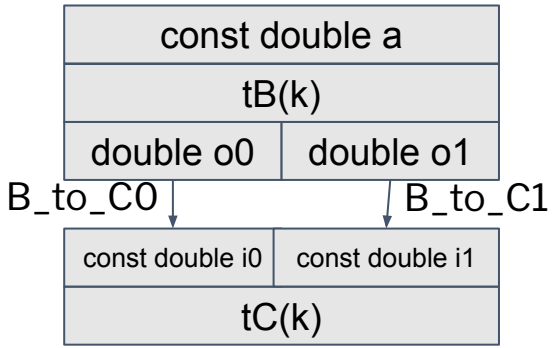


First TTG program: task to task

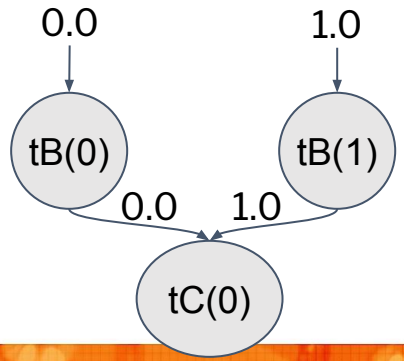
```
ttg::Edge<int, double> to_B("to_B");
ttg::Edge<int, double> B_to_C0("B_to_C0");
ttg::Edge<int, double> B_to_C1("B_to_C1");

auto tb = ttg::make_tt([](const int &k, const double &a) {
    ttg::print("This is task B(" , k, ") it received value ", a,
               " for input a");
    if(0 == k) ttg::send<0>(0, a);
    if(1 == k) ttg::send<1>(0, a);
  },
  ttg::edges(to_B), ttg::edges(B_to_C0, B_to_C1),
  "B", {"a"}, {"o0", "o1"});
auto tc = ttg::make_tt([](const int &k, const double &i0, const double &i1)
  {
    ttg::print("This is task C(", k, ") it received values ", i0,
               " and ", i1);
  },
  ttg::edges(B_to_C0, B_to_C1), ttg::edges(),
  "C", {"i0", "i1"}, {});
ttg::make_executable(tb);
if(tb->get_world().rank() == 0) {
  tb->invoke(0, 0.0);
  tb->invoke(1, 1.0);
}
ttg::execute();
ttg::fence(tb->get_world());
```

Template Task Graph



DAG of Tasks

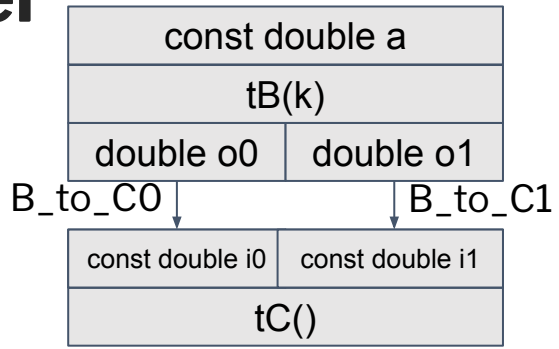


First TTG program:
C doesn't need a parameter

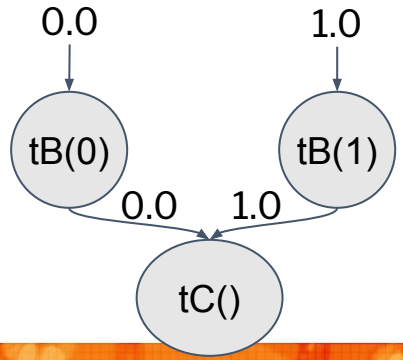
```
ttg::Edge<int, double> to_B("to_B");
ttg::Edge<void, double> B_to_C0("B_to_C0");
ttg::Edge<void, double> B_to_C1("B_to_C1");

auto tb = ttg::make_tt( [](const int &k, const double &a) {
    ttg::print("This is task B(" , k, ")",
               " it received value ", a,
               " for input a");
    if(0 == k) ttg::sendk<0>(a);
    if(1 == k) ttg::sendk<1>(a);
  }, ttg::edges(to_B), ttg::edges(B_to_C0, B_to_C1),
  "B", {"a"}, {"o0", "o1"});
auto tc = ttg::make_tt<void>([](const double &i0, const double &i1) {
    ttg::print("This is task C()",
               " it received values ", i0,
               " and ", i1);
  }, ttg::edges(B_to_C0, B_to_C1), ttg::edges(),
  "C", {"i0", "i1"}, {});
ttg::make_executable(tb);
if(tb->get_world().rank() == 0) {
  tb->invoke(0, 0.0);
  tb->invoke(1, 1.0);
}
ttg::execute();
ttg::fence(tb->get_world());
```

Template Task Graph



DAG of Tasks



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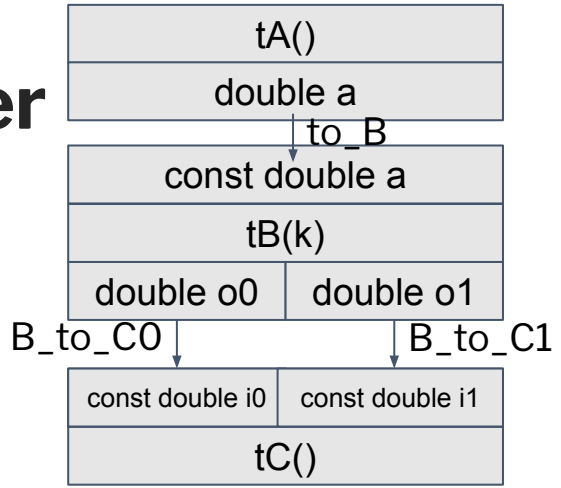
First TTG program:
C doesn't need a parameter

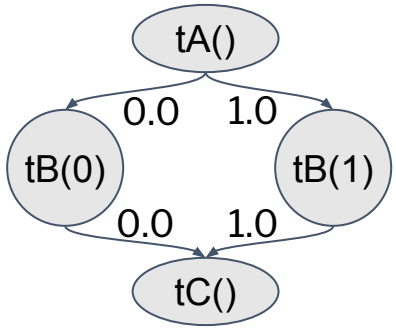
```
ttg::Edge<int, double> to_B("to_B");
ttg::Edge<void, double> B_to_C0("B_to_C0");
ttg::Edge<void, double> B_to_C1("B_to_C1");

auto ta = ttg::make_tt<void>([]() {
    ttg::send<0>(0, 0.0);
    ttg::send<0>(1, 1.0);
  }, ttg::edges(), ttg::edges(to_B),   "A", {}, {"a"});
auto tb = ttg::make_tt([=]( const int &k, const double &a) { <...>
},
  ttg::edges(to_B), ttg::edges(B_to_C0, B_to_C1),
  "B", {"a"}, {"o0", "o1"});
auto tc = ttg::make_tt<void>(
  [](const double &i0, const double &i1) { <...>  },
  ttg::edges(B_to_C0, B_to_C1), ttg::edges(),
  "C", {"i0", "i1"}, {});
ttg::make_executable(ta);
if(ta->get_world().rank() ==  0) {
  ta->invoke();
}
ttg::execute();
ttg::fence(tb->get_world());
```

Template Task Graph



DAG of Tasks



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First TTG program: full code

ttg-tutorial/intro/first.cc

```
#include <ttg.h>

int main(int argc, char **argv) {
  ttg::initialize(argc, argv, -1);

  ttg::Edge<int, double> A_B("A->B");
  ttg::Edge<void, double> B_C0("B->C0");
  ttg::Edge<void, double> B_C1("B->C1");

  auto wa = ttg::make_tt<void>([]() {
    ttg::send<0>(0, 0.0);
    ttg::send<0>(1, 0.0);
  }, ttg::edges(), ttg::edges(A_B), "A", {}, {"to B"});

  auto wb = ttg::make_tt([](const int &k,
                            const double &a) {
    if(0 == k) ttg::sendv<0>(a);
    if(1 == k) ttg::sendv<1>(a);
  }, ttg::edges(A_B), ttg::edges(B_C0, B_C1),
  "B", {"from A"},
  {"to 1st input of C", "to 2nd input of C"});

  auto wc = ttg::make_tt<void>([](const double &a,
                                  const double &b) {
    ttg::print("Received ", a, "+", b );
  }, ttg::edges(B_C0, B_C1), ttg::edges(),
  "C", {"From B", "From B"}, {});
```

ttg-tutorial/intro/first.cc (cont.)

```
 ttg::make_graph_executable(wa);

  if (wa->get_world().rank() == 0) wa->invoke();

  ttg::execute();
  ttg::fence(wa->get_world());

  ttg::finalize();
  return EXIT_SUCCESS;
}
```

First TTG program: how to compile

ttg-tutorial/intro/CMakeLists.txt

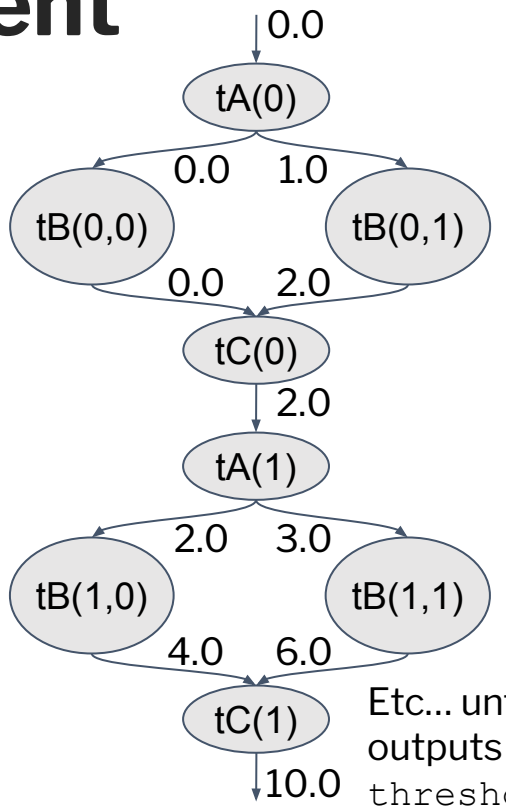
```
cmake_minimum_required(VERSION 3.19)

project(TTG-Example CXX)


find_package(ttg REQUIRED)


add_executable(first-parsec first.cc)

target_compile_definitions(first-parsec PRIVATE
TTG_USE_PARSEC=1)

target_link_libraries(first-parsec PRIVATE ttg-parsec)


add_executable(first-mad first.cc)

target_compile_definitions(first-mad PRIVATE TTG_USE_MADNESS=1)

target_link_libraries(first-mad PRIVATE ttg-mad)
```

```
> cd ttg-tutorial/intro
> mkdir build
> cd build
> cmake -G Ninja ../
> ninja
> ./first-parsec
> ./first-madness
```

Hands-on: Extend first example to become data-dependent

Transform the first example so it becomes iterative and iterates until a threshold is reached.

- Add a new parameter to each tasks, which denotes the iteration number
  - Tasks of type tB now take a std::pair<int, int> as keys
  - Tasks of type tA and tC take a single int
- Tasks of type tA receive an input of type double
  - They send that input to tB(iteration, 0), and input+1.0 to tB(iteration, 1)
- Tasks of type tB double their input and send them to tC
- Tasks of type tC sum their inputs, and if it is lower than threshold (a variable defined in the main program), continue the iteration



Etc... until tC outputs a value > `threshold`

Tips for debugging

- `ttg::make_graph_executable(wa->get())` returns a boolean. That boolean is `true` iff the graph is connected (it should be in all cases studied here)
- You can also call `ttg::verify()(wa->get())` to verify that the graph is connected and issue additional warnings on elements that can be statically checked.
- ttg::Dot()(wa->get()) returns a String that is a GraphViz DOT representation of the TTG. Print it and use the dot tool to visualize it
- `ttg::trace_on();` will enable detailed tracing of the execution

- In the code, you can do:

```
using ttg::Debugger;
auto dbg = std::make_shared<Debugger>();
Debugger::set_default_debugger(dbg);
dbg->set_exec(argv[0]);
dbg->set_prefix(wa->get_context().rank());
// dbg->set_cmd("lldb_xterm");
dbg->set_cmd("gdb_xterm");
```

- At runtime, with PaRSEC, you can generate a DOT file per rank by setting the MCA parameter `parsec_dot` to a base filename. This will generate at runtime the DAG of tasks. Use command `parsec-dotmerger` to merge multiple DOT files into one if you do a distributed run.
  - DOT files might need some hand-fixing if you interrupt the execution because of a deadlock
- At runtime, you can also generate a profile file and analyze it (see end of talk)

Data-Dependent Diamond

ttg-tutorial/intro/first.cc

```
#include <ttg.h>

using Key2 = std::pair<int, int>;
namespace std {
  std::ostream & operator<<(std::ostream &os,
                            const  Key2 &key) {
    os << "{" << std::get<0>(key) << ", "
       << std::get<1>(key) << "}";
    return os;
  }
} // namespace std

int main(int argc, char **argv) {
  ttg::initialize(argc, argv, -1);

  ttg::Edge<Key2, double> A_B("A->B");
  ttg::Edge<int, double> B_C0("B->C0");
  ttg::Edge<int, double> B_C1("B->C1");
  ttg::Edge<int, double> C_A("C->A");

  double threshold = 100.0;

  auto wa = ttg::make_tt([](const int it,
                            const double &a) {
    ttg::send<0>(Key2{it, 0}, a);
    ttg::send<0>(Key2{it, 1}, a+1.0);
  }, ttg::edges(C_A), ttg::edges(A_B), "A",
  {"from C"}, {"to B"});
```

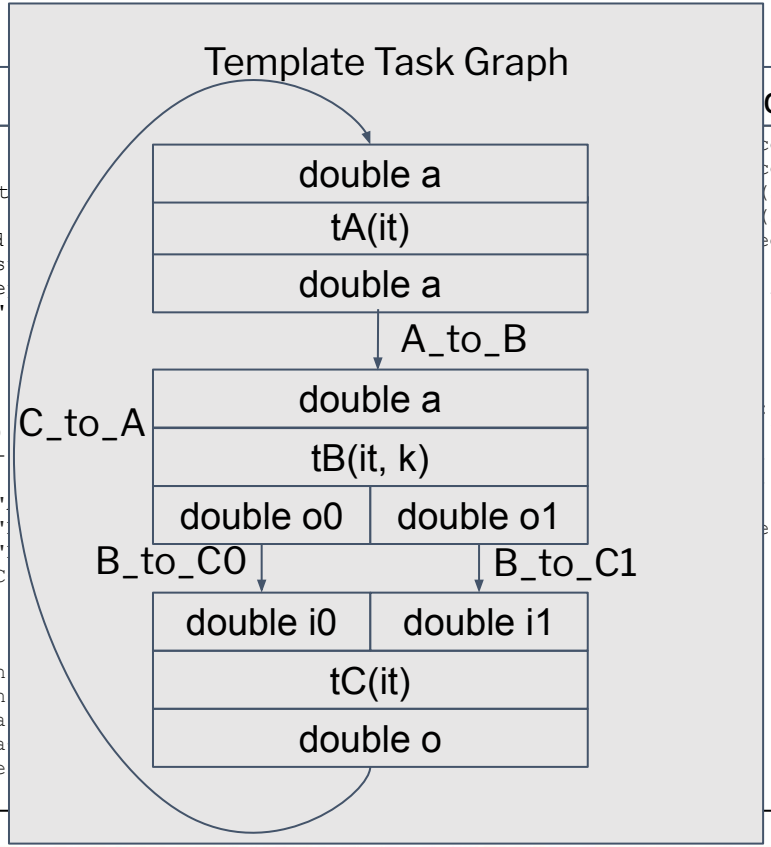
ttg-tutorial/intro/first.cc (cont.)

```
 auto wb = ttg::make_tt([](const Key2 &k,
                           const double &a) {
    if(0 == k) ttg::send<0>(std::get<0>(k), 2.0*a);
    if(1 == k) ttg::send<1>(std::get<0>(k), 2.0*a);
  }, ttg::edges(A_B), ttg::edges(B_C0, B_C1),
  "B", {"from A"},
  {"to 1st input of C", "to 2nd input of C"});

  auto wc = ttg::make_tt([=](const int &it,
                             const double &a,
                             const double &b) {
    if(a+b < threshold) ttg::send<0>(it+1, a+b);
    else ttg::print("Result ", a + b );
  }, ttg::edges(B_C0, B_C1), ttg::edges(A_C),
  "C", {"From B", "From B"}, {"To A"});

  ttg::make_graph_executable(wa);

  if (wa->get_world().rank() == 0) wa->invoke(0, 0.0);

  ttg::execute();
  ttg::fence(wa->get_world());

  ttg::finalize();
  return EXIT_SUCCESS;
}
```

Data-Dependent Diamond

ttg-tutorial/intro/first.cc

```
#include <ttg.h>

using Key2 = std::pair<int, int
namespace std {
  std::ostream & operator<<(std
                            cons
    os << "{" << std::get<0>(ke
       << std::get<1>(key) << "
    return os;
  }
} // namespace std

int main(int argc, char **argv)
  ttg::initialize(argc, argv, -

  ttg::Edge<Key2, double> A_B("
  ttg::Edge<int, double> B_C0("
  ttg::Edge<int, double> B_C1("
  ttg::Edge<int, double> C_A("C

  double threshold = 100.0;

  auto wa = ttg::make_tt([](con
                          con
    ttg::send<0>(Key2{it, 0}, a
    ttg::send<0>(Key2{it, 1}, a
  }, ttg::edges(C_A), ttg::edge
  {"from C"}, {"to B"});
```



c (cont.)

```
const Key2 &k,
const double &a) {
(std::get<0>(k), 2.0*a);
(std::get<0>(k), 2.0*a);
edges(B_C0, B_C1),

2nd input of C"});

(const int &it,
 const double &a,
 const double &b) {
:send<0>(it+1, a+b);
", a + b );
 ttg::edges(A_C),
 {"To A"});

e(wa);

 == 0) wa->invoke(0, 0.0);

);
```

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Template Task Graph Extended Features

Custom Key Types

Arbitrary types can be used to identify tasks. They need to be **equality-comparable** and **hashable**.

By default, key hashes are used to determine the process to execute on (more later).

Custom types should provide a custom hash function.

The PaRSEC backend will warn about too many collisions.

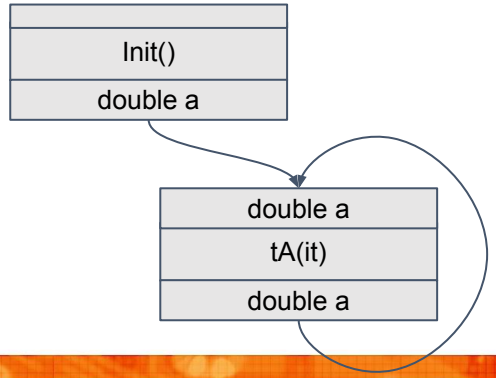
```
struct Key {
  int32_t x;
  int16_t y;
  bool operator==(const Key& other)
const{
    return other.x == x && other.y == y;
  }
  size_t hash() const {
    return ((int64_t)x << 32) ^ y;
  }
};
```

Fusing Edges

Inputs to a terminal can come from multiple edges, but only one at a time.

Edges can be fused into a virtual edge, each satisfying the input. More than one input for a task is erroneous.

```
ttg::Edge<int, double> A_A("A->A");
ttg::Edge<int, double> I_A("Init->A");

ttg::Edge<int, double>  a_in = ttg::fuse(A_A, I_A);

auto init = ttg::make_tt([](const int it,
                            const double &a) {
    ...
  }, ttg::edges(), ttg::edges(I_A), "Init", ...);

auto wa = ttg::make_tt([](const int it,
                          const double &a) {
    ...
  }, ttg::edges(a_in), ttg::edges(A_A), "A", ...);
```



Hands On: 1D Stencil

A simple 1D stencil with 3 template tasks: Init, Update, Result. Cell size and count is configurable (see -h).
One task per cell.

First task: Add the `ttg::send` calls to the Init and Update tasks. The `myLeft` border should be sent on the `I_L` and `V_L` edges, `myRight` on the `I_R` and `V_R` edges.

Reminder:

```
ttg::send<TerminalId>(key, std::move(data));
```

Where the keys are

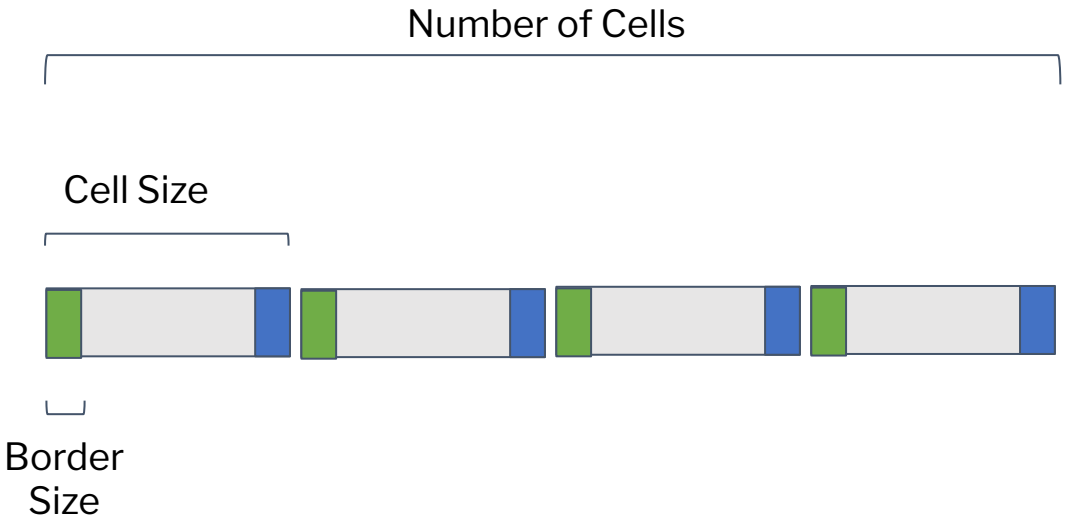
```
Key2{step+1, (key.x + nbCells - 1) % nbCells}
Key2{step+1, (key.x)}
Key2{step+1, (key.x + 1) % nbCells}
```

for the left, center, and right successors.

Build and run:

```
$ cmake ../
$ make -C ../Stencil/Task1
$ mpirun -n 2 Stencil/Task1/stencil1-parsec
```

Stencil Cells



Process Placement & Priorities

By default, tasks are mapped round-robin to processes based on the hash of the key.

Process placement can be controlled through the **keymap** of a TT

Similar mechanism to set priorities of tasks using **priomap**

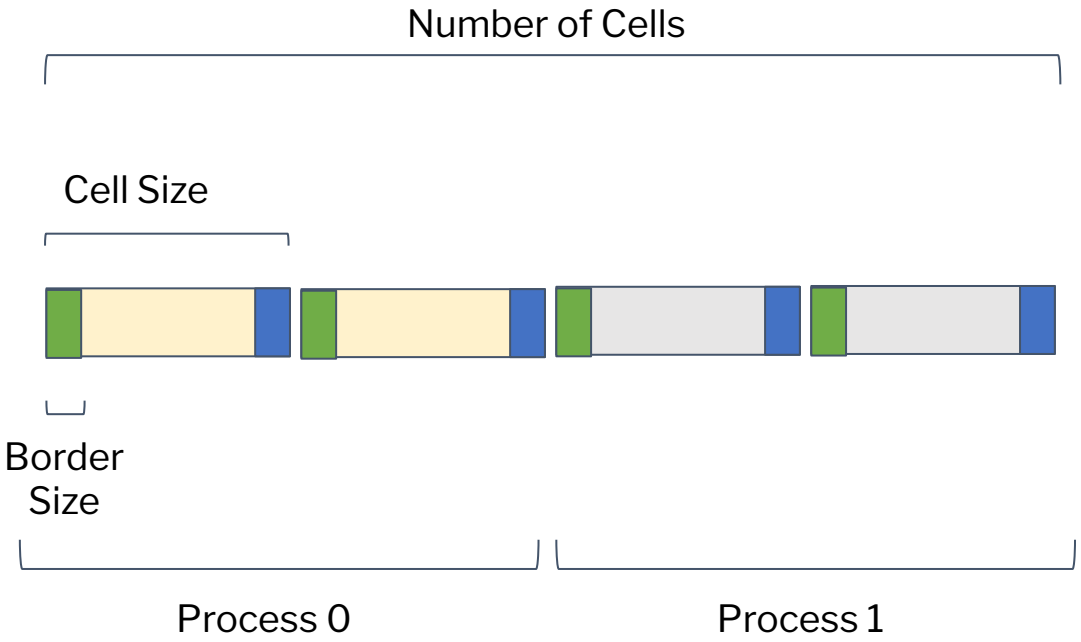
```
struct Key {
  int x;
  int y;
};

auto wa = ttg::make_tt(
    [](const Key& key){
        ...
    }, ...);

// return the process that own x
wa->set_keymap([=](const Key& key){
    return process_of(key.x);
});

// y determines the priority of the task
wa->set_priomap([](const Key2& key){ return key.y; });
```

Hands On: Process Placement

Second Task:
Add process placement control for the Init, Update, and PrintResult tasks to minimize communication.

```
auto init = ttg::make_tt(
    [](const Key& key){
        ...
    }, ...);

// x determines the process to execute on
init->set_keymap([=](const int& key){
    // each process receives one chunk of cells
    // to reduce communication
    return key / (numCells / numProcs);
});
```

Stencil Cells



Copy Handling, constness, and moving of data

Each object moving through the DAG is tracked by TTG

We rely on C++ constness and move semantics to facilitate copy handling

This helps us reduce copies of large objects

Local data leads to a new copy

```
// Sending mutable data
[](const int &k, T&& a) {
    mutate(a);             // updates a
    ttg::send<0>(k+1, a); // creates a new copy
    reset(a);              // a is mutated again
    ttg::send<1>(k+1, a); // create yet another copy
}

// Moving input data
[](const int &k, T&& a) {
    mutate(a); // update a
    ttg::send<0>(k+1, std::move(a)); // no new copy
}

// Forwarding const input data
[](const int &k, const T& a) {
    ttg::send<0>(k-1, a); // no new copy
    ttg::send<0>(k,   a); // no new copy
    ttg::send<0>(k+1, a); // no new copy
}

// Sending stack-based data
[](const int &k) {
    T a = new_obj(k);
    ttg::send<0>(k-1, std::move(a)); // potential copy
}
```

Hands On: Reusing Data Copies

Observation:

Only one task consumes the left and right boundary so we can reuse the boundary buffers, instead of allocating a new one. This saves 2 allocations for each task.

Third Task:
Reuse the boundary objects and move them back into `ttg::send`.

Reminder:

```
// Moving input data
[](const int &k, T&& a) {
    compute_on_a(a); // read-only
    update(a);       // update a
    ttg::send<0>(k+1, std::move(a)); // no new copy
}
```

Question:
What happens if there are multiple tasks taking L and R buffers as inputs?

Serializing Custom Types

TTG uses memcpy for trivially copyable types

Custom types are serialized using serialization APIs from MADNESS or Boost

```
namespace madness {
  namespace archive {
    template <class Archive, typename T>
    struct ArchiveStoreImpl<Archive, MatrixTile<T>> {
      static inline void store(const Archive& ar,
                               const MatrixTile<T>& t)
{
        ar << tile.rows() << t.cols() << t.lda();
        ar << wrap(t.data(), t.rows() * t.cols());
      }
    };
```

Store metadata and payload in the archive

```
    template <class Archive, typename T>
    struct ArchiveLoadImpl<Archive, MatrixTile<T>> {
      static inline void load(const Archive& ar,
                              MatrixTile<T>& t) {
        int rows, cols, lda;
        ar >> rows >> cols >> lda;
        tile = MatrixTile<T>(rows, cols, lda);
        ar >> wrap(t.data(), t.rows() * t.cols());
      }
    };
  }  // namespace archive
}  // namespace madness
```

Read metadata and payload from the archive

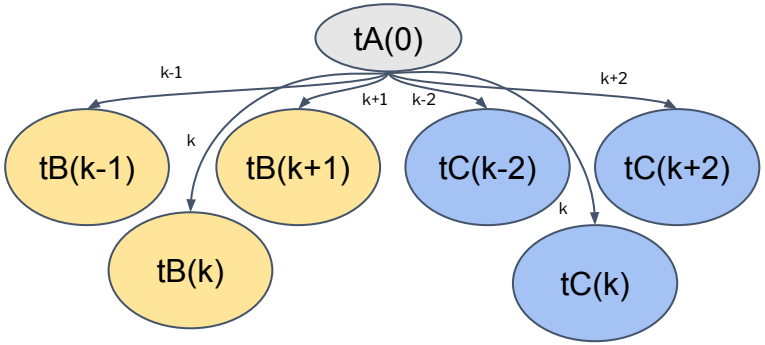
Broadcasting Data

Sending the same data to multiple successor **at once** is more efficient if done using ttg::broadcast

One set of keys for each output terminal

Avoids additional data copies

```
[](const int &k,
   T&& a) {
    mutate(a); // updates a
    std::array<int, 3> successorsA = {k-1, k, k+1};
    std::array<int, 3> successorsB = {k-2, k, k+2};
    ttg::broadcast<0, 1>(successorsA,  // out terminal 0
                         successorsB, // out terminal 1
                         std::move(a));
}
```



Efficient Communication: split-metadata interface

Zero-copy data transfers are available through a type trait: `ttg::SplitMetadataDescriptor<T>`

Overloads provide access to metadata, access to data, and a way to construct an empty object from metadata.

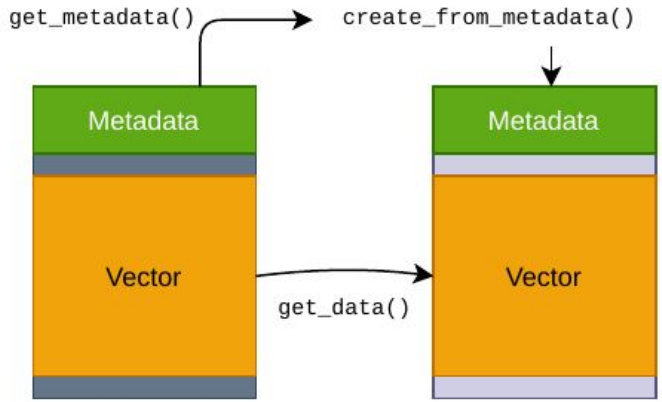
TTG will copy directly between objects.

```
struct MatrixTile {
  using metadata_t = typename std::tuple<int, int,
int>;
  ...
}

namespace ttg {

  template <typename T>
  struct SplitMetadataDescriptor<MatrixTile<T>> {
    auto get_metadata(const MatrixTile<T>& t) {
      return t.get_metadata();
    }

    auto get_data(MatrixTile<T>& t) {
      std::array<ttg::iovec, 1> v =
                  {t.size() * sizeof(T),
                   t.data()});
      return v;
    }

    auto create_from_metadata(
      const typename MatrixTile<T>::metadata_t& meta) {
        return MatrixTile<T>(meta);
    }
  };

}  // namespace ttg
```

iovecs of payload ranges

Efficient Communication: split-metadata interface

Zero-copy data transfers are available through a type trait: `ttg::SplitMetadataDescriptor<T>`




```
struct MatrixTile {
  using metadata_t = typename std::tuple<int, int,
int>;
  ...
}

namespace ttg {

  template <typename T>
  struct SplitMetadataDescriptor<MatrixTile<T>> {
    auto get_metadata(const MatrixTile<T>& t) {
      return t.get_metadata();
    }

    auto get_data(MatrixTile<T>& t) {
      std::array<ttg::iovec, 1> v =
                  {t.size() * sizeof(T),
                   t.data()});
      return v;
    }

    auto create_from_metadata(
      const typename MatrixTile<T>::metadata_t& meta) {
        return MatrixTile<T>(meta);
    }
  };

}  // namespace ttg
```

iovecs of payload ranges

Generic Task Arguments

Since C++14, Lambdas can have generic arguments using `auto`

TTG supports generic arguments, using `auto&&` for mutable arguments and `auto&` for const arguments. Types are inferred from the Edges.

Generic and concrete argument types should not be mixed.

```
auto tt = ttg::make_tt(
            [](auto& k,  /* the key */
               auto&& a, /* mutable */
               auto& b   /* immutable/const */ ) {
                 ...
            }, ...);
```

Making a TTG

- Template Task Graph = collection of template tasks + collection of (exposed) input terminals + collection of (exposed) output terminals + name
- Until now: implicit TTG
  - empty input terminals, empty output terminals, implicit name
  - All TTs declared since last fence belong to the implicit TTG
- Use of explicit TTG: library-like fine-grain composition of operations

```
auto make_diamond_ttg(ttg::Edge<void, double> &input,
  ttg::Edge<void, double> &output, double threshold) {
  ttg::Edge<int, double> dispatch_A("dispatch->A");
  ttg::Edge<Key2, double> A_B("A->B");
  ttg::Edge<int, double> B_C0("B->C0");
  ttg::Edge<int, double> B_C1("B->C1");
  ttg::Edge<int, double> C_A("C->A");

  auto dispatch = ttg::make_tt([](const double &i) {
    ttg::send<0>(0, std::move(i));
  }, ttg::edges(input), ttg::edges(dispatch_A), <...>);
  auto wa = ttg::make_tt(<...>,
        ttg::edges( ttg::fuse(dispatch_A, C_A)),
        ttg::edges(A_B), <...>);
  auto wb = ttg::make_tt(<...>,
        ttg::edges(A_B), ttg::edges(B_C0, B_C1),
<...>);
  auto wc = ttg::make_tt([=](const int &it,
                             const double &a,
                             const double &b) {
    if(a+b < threshold) ttg::send<0>(it+1, a+b);
    else ttg::sendv<1>(a + b);
  }, ttg::edges(B_C0, B_C1),
     ttg::edges(A_C,  output), <...>);

  auto ins = std::make_tuple(
                      dispatch->template in<0>());
  auto outs = std::make_tuple(wc->template out<1>());
  std::vector<std::unique_ptr<ttg::TTBase>> ops(4);
  ops[0] = std::move(dispatch);
  ops[1] = std::move(wa);
  ops[2] = std::move(wb);
  ops[3] = std::move(wc);

  return make_ttg(std::move(ops), ins, outs, "Diamond");
}
```

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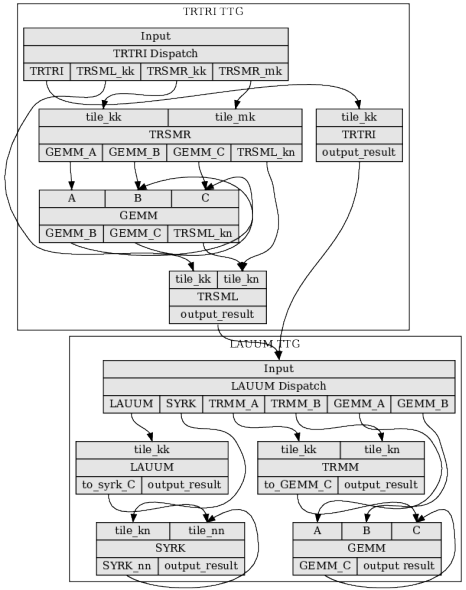
Composing TTGs

- Goal:
  - Fine grain composition of DAGs of tasks
    - Between TTGs
    - Between Task Systems
  - Re-enable Library-like software composition
  - But maintain fine-grain asynchronicity / efficiency
- Approach:
  - Expose inputs and outputs as single input and output terminals
  - Define dispatcher tasks that distribute the input data to the appropriate tasks
  - Output final updates as they are generated
  - Use fused edges to extract intermediate results when necessary




```
namespace potri {
  auto ttg(MatrixT<double> &A,
           ttg::Edge<Key2, Tile<double>>&input,
           ttg::Edge<Key2, Tile<double>>&output) {
    ttg::Edge<Key2, Tile<double>> trtri_lauum("t2l");
    auto ttg_trtri = trtri::ttg(A, input, trtri_lauum);
    auto ttg_lauum = lauum::ttg(A, trtri_lauum, output);
    <... Define ops, ins, outs ...>
    return make_ttg(std::move(ops), ins, outs, "POTRI TTG");
  }
}
```

Pull and Streaming Terminals

Pull Terminals

- Edges act as bi-directional links between tasks.
- Logically preceding task is instantiated to send the data.
  - Eg. reading from memory, generating data on the fly, recursive construction.
- Greedy (at task creation) or lazy (when all other inputs are available) pulling of data to control resource utilization.

Streaming Terminals

- Computation on streaming data.
  - Eg. operations on trees in multidimensional numerical calculus algorithms.
- General reduction or accumulation operations.
- Size of the stream can be set statically or dynamically.

Worlds and ranks

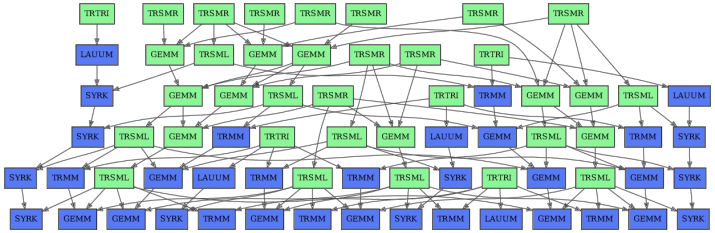
Worlds are a context for tasks and represent the set of processes executing them.

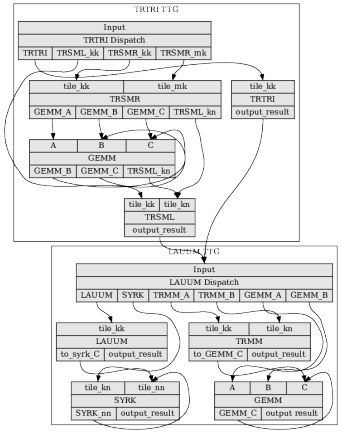
Each process is assigned a rank in a world.

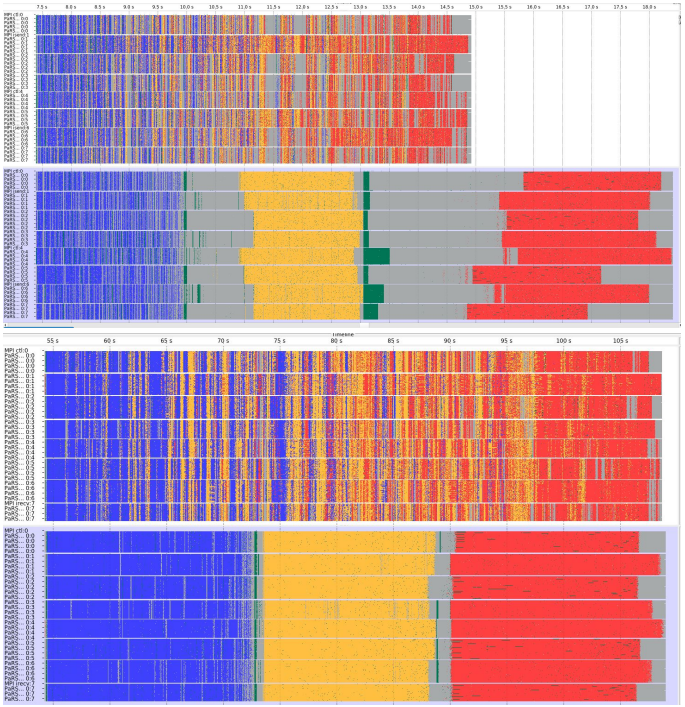
Eventually, TTG will provide ways to manage process sets and derive new worlds from them.

```
ttg::World world = ttg::default_execution_context();

std::cout << "Proc " <<  world.rank()
          << " of "  <<  world.size() << std::endl;


ttg::Edge<Key2, double> A_B("A->B");
ttg::Edge<int, double> C_A("C->A");

double threshold = 100.0;

auto wa = ttg::make_tt([](const int it,
                          const double &a) {
    ttg::send<0>(Key2{it, 0}, a);
    ttg::send<0>(Key2{it, 1}, a+1.0);
  }, ttg::edges(C_A), ttg::edges(A_B), "A",
  {"from C"}, {"to B"});

if (world.rank() == 0) wa->invoke(0, 0);
```

Performance Analysis: Profiling tools







Conclusions & Future Work

TTG provides scalable task graph discovery

Compact representation of abstract task graphs removes complexity at execution time

Task graph composition enables synchronization-free execution

Add support for GPU device offloading (work in progress)

Finalize pull terminal functionality

First official release