Pulling Visitors

Inverting Visitor-Based Control Flow

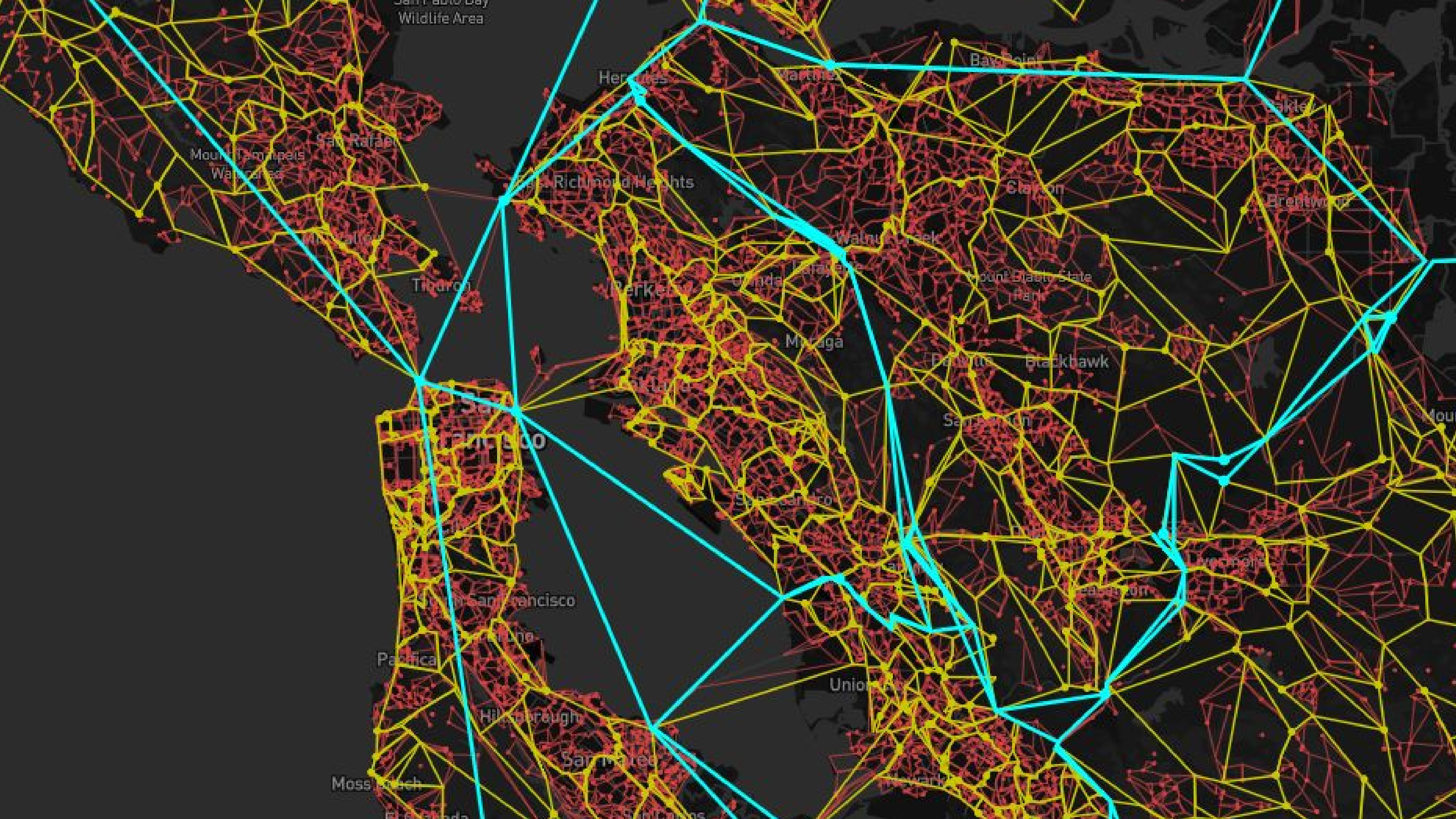
Agenda

Daniel J H, works for Mapbox on Graphs

Boost.Graph introduction, from visitors to iterators

https://github.com/daniel-j-h/cppnow2016 (git.io/cppnow2016-bgl)

Nat Goodspeed, works for Linden Lab on Second Life
Boost.Coroutine problem solution and gory details


San Pablo Bay
Wildlife Area
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Walnut Creek
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Orinda
Berkeley
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Boost.Graph’s Generic Building-Blocks

Data structures (graph types)

Iterators (edges, vertices)

Properties (internal, external)

Algorithms (breadth-first search, dijkstra)

Visitors (examine_vertex)

Graph Concepts

Graph types are models for Graph Concepts, determines functionality

IncidenceGraph (source, target, out_edges)

BidirectionalGraph (in_edges)

VertexListGraph (vertices)

Graph Representations

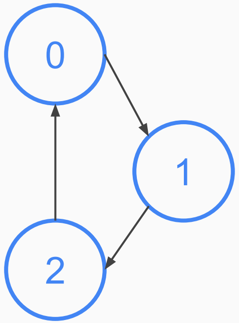
Customizable through template tags: Directed, Undirected, Properties

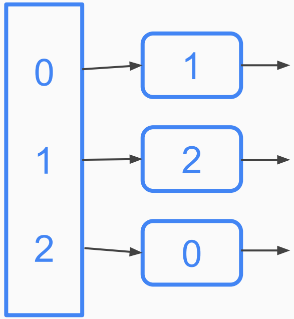
adjacency_list

adjacency_matrix

compressed_sparse_row_graph

adjacency_list<vecS, listS, directedS>





```
using graph_t = adjacency_list<vecS, vecS, directedS>;


graph_t graph(3);

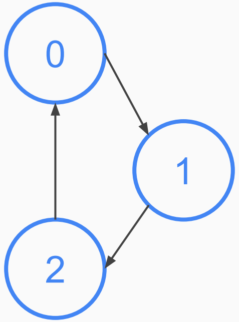

add_edge(0, 1, graph);
add_edge(1, 2, graph);
add_edge(2, 0, graph);
```

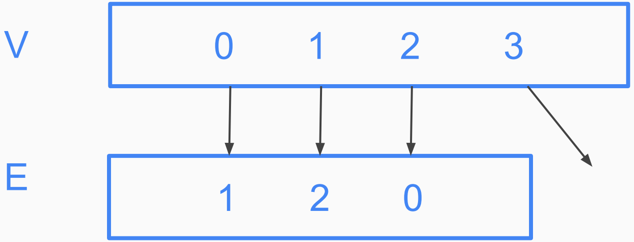
```
struct edge_data_t { int duration = 0; };
using graph_t = adjacency_list<vecS, vecS, directedS, no_property, edge_data_t>;
graph_t graph(3);
add_edge(0, 1, edge_data_t{100}, graph);

auto duration = [&graph](auto edge) { return graph[edge].duration; };
auto positive = [](auto duration) { return duration > 0; };

auto d = accumulate(edges(graph) | transformed(duration) | filtered(positive), 0);
```

compressed_sparse_row_graph<directedS>





V 0 1 2 3

E 1 2 0

```
edges(v):
   first = E[V[v]];
   last  = E[V[v + 1]];
```

```
using graph_t = compressed_sparse_row_graph<directedS>;
using vertex_t = graph_traits<graph_t>::vertex_descriptor;

vector<vertex_t> sources{0, 1, 2};
vector<vertex_t> targets{1, 2, 0};

auto tag = construct_inplace_from_sources_and_targets;
graph_t graph{tag, sources, targets, 3};
```

Graph Algorithms

Visitors provide algorithm customization points

Graph Walk (bfs, dfs)

Shortest Paths (dijkstra, a-star)

Max-Flow / Min-Cut (edmonds_karp_max_flow)

```
struct discover_visitor : default_bfs_visitor {
    void discover_vertex(const vertex_t vertex, const graph_t&) {
        cout << vertex << endl;
    }
};


vertex_t source{0};
breadth_first_search(graph, source, visitor(discover_visitor{}));
```

Use-Case Bidirectional Dijkstra

Baseline router to compare against

Start first search on graph from source

Start second search on reversed graph from target

Step both searches (ping-pong) until they meet in the middle

Problem: how to stop and resume visitors

```
vertex_t middle;


async(dijkstra_shortest_path(graph, source, visitor(ping_pong{middle});

async(dijkstra_shortest_path(rev_graph, target, visitor(ping_pong{middle});
```

Coroutines for Cooperative Multitasking

Bind coroutine to visitor, get lazy Dijkstra generator for free

No explicit synchronization, no threads (concurrency != parallelism)

Aha Moment: can be stopped, can be resumed, proper iterators (stdlib)

Technique works for all visitors, and especially well for Boost.Graph

```
using coro_t = coroutines::asymmetric_coroutine<vertex_t>;

struct dijkstra_stepwise : default_dijkstra_visitor {
    dijkstra_stepwise(coro_t::push_type& sink_) : sink(sink_) {}

    void examine_vertex(const vertex_t vertex, const graph_t&) const {
        sink(vertex);
    }
    coro_t::push_type& sink;
};
```

```
coro_t::pull_type lazy_forward_vertices{[&](auto& sink) {
    dijkstra_shortest_paths_no_color_map(graph, source,
        weight_map(get(&edge_data_t::distance, graph))
        .predecessor_map(forward_prev_map)
        .visitor(dijkstra_stepwise{sink}));
}};

while (lazy_forward_vertices && lazy_backward_vertices)
    // lazy_forward_vertices.get();  lazy_forward_vertices();
```

```
auto poi = [&graph](auto vertex) { return has_poi(vertex, graph); };
auto it = find_if(lazy_forward_vertices, poi);


if (it != end(lazy_forward_vertices))
    std::cout << *it << std::endl;
```

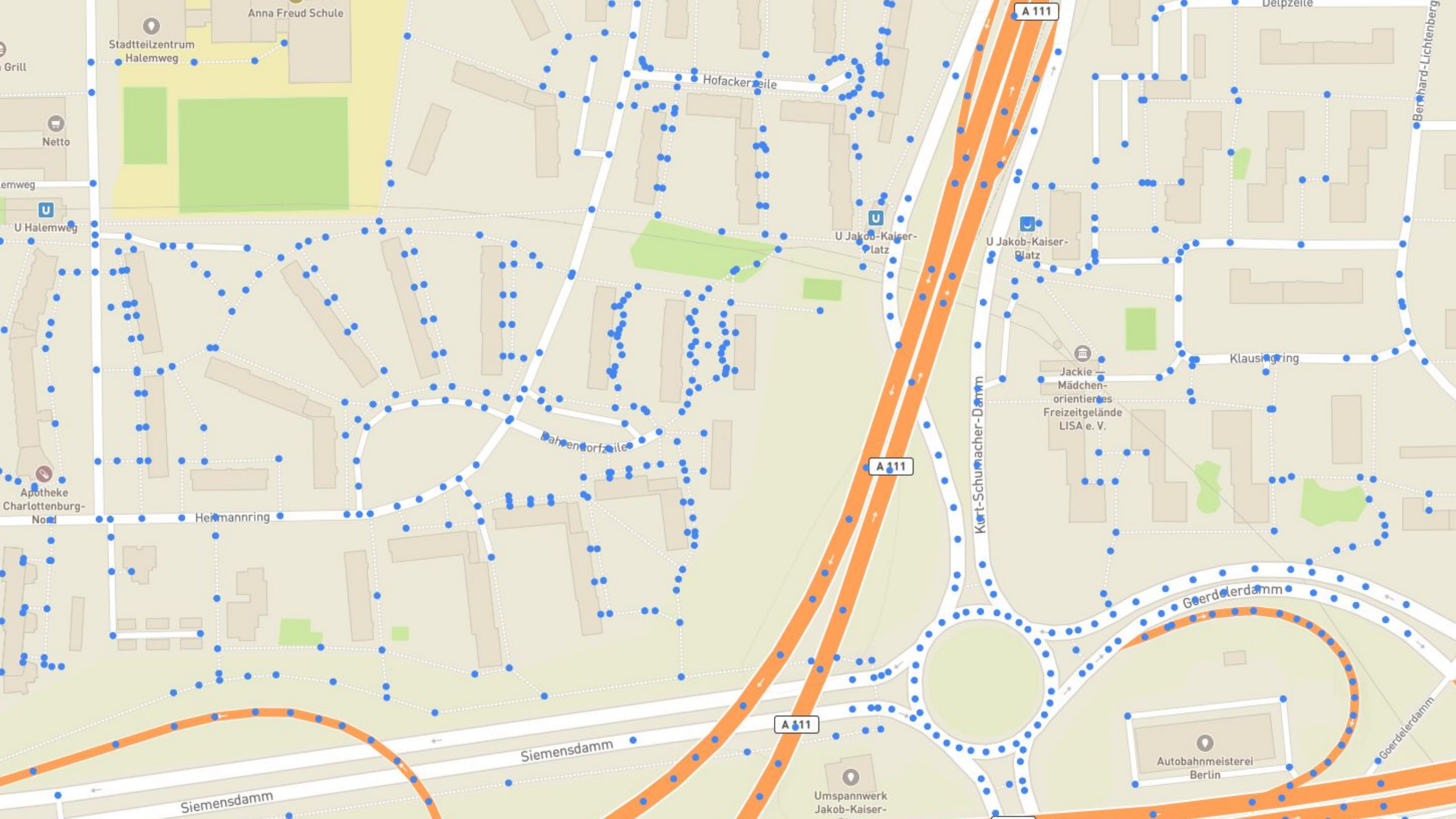
Give Boost.Graph a try!

OpenStreetMap (extract nodes and ways: libosmium)

Construct graph, add properties (location, Boost.Geometry Haversine distance)

Route on the graph (Boost.Geometry’s RTree for initial coordinate lookup)

Visualize the graph (simplification: tippecanoe)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Stadtteilzentrum Halemweg
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Delpzeile
Bernhard-Lichtenberg
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Goerdelerdamm
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Siemensdamm
Autobahnmeisterei Berlin
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Our Take Aways

Powerful trio: Boost.Graph + Boost.Range + Boost.Geometry

Switching to 32 bit vertex and edge index types in CSR (size_t default)

Parallel Boost.Graph vs. r3.4xlarge (120 GB RAM), r3.8xlarge (250 GB RAM)

Boost.Graph + Boost.Coroutine: from visitors to generators, stdlib integration

Generic EventVisitors

Specific visitor

```
using coro_t = coroutines::asymmetric_coroutine<vertex_t>;
struct dijkstra_stepwise : default_dijkstra_visitor {
    dijkstra_stepwise(coro_t::push_type& sink_) : sink(sink_) {}

    void examine_vertex(const vertex_t vertex, const graph_t&) const {
        sink(vertex);
    }
    coro_t::push_type& sink;
};
```

Specific visitor

```
using coro_t = coroutines::asymmetric_coroutine<vertex_t>;
struct dijkstra_stepwise : default_dijkstra_visitor {
    dijkstra_stepwise(coro_t::push_type& sink_) : sink(sink_) {}

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    }
    coro_t::push_type& sink;
};
```

Specific visitor

```
using coro_t = coroutines::asymmetric_coroutine<vertex_t>;
struct dijkstra_stepwise : default_dijkstra_visitor {
    dijkstra_stepwise(coro_t::push_type& sink_) : sink(sink_) {}

    // ...
};

dijkstra_shortest_paths(graph, source,
                        visitor(dikjstra_stepwise{sink}));
```

Specific visitor

```
using coro_t = coroutines::asymmetric_coroutine<vertex_t>;
struct dijkstra_stepwise : default_dijkstra_visitor {
    dijkstra_stepwise(coro_t::push_type& sink_) : sink(sink_) {}

    // ...
};

dijkstra_shortest_paths(graph, source,
                        visitor(dikjstra_stepwise{sink}));
```

EventVisitor mechanism

```
struct dijkstra_stepwise {
    // part of the EventVisitor API
    typedef boost::on_examine_vertex event_filter;

    explicit dijkstra_stepwise(coro_t::push_type& sink_) : sink{sink_} {}

    void operator()(const vertex_t vertex, const graph_t&) { sink(vertex); }

    coro_t::push_type& sink;
};
```

EventVisitor mechanism

```
struct dijkstra_stepwise {
  // part of the EventVisitor API
  typedef boost::on_examine_vertex event_filter;

  // ...

};

dijkstra_shortest_paths(graph, source,
                        visitor(boost::make_dijkstra_visitor(
                                dijkstra_stepwise{sink}));
```

EventVisitor mechanism

```
template <typename Tag>
struct dijkstra_stepwise {
    // part of the EventVisitor API
    typedef Tag event_filter;

    explicit dijkstra_stepwise(coro_t::push_type& sink_) : sink{sink_} {}

    void operator()(const vertex_t vertex, const Graph&) { sink(vertex); }

    coro_t::push_type& sink;
};
```

EventVisitor mechanism

```
template <typename Tag>
struct dijkstra_stepwise {
    typedef Tag event_filter;

    // ...

};

dijkstra_shortest_paths(graph, source,
                                        visitor(boost::make_dijkstra_visitor(
                                                    dijkstra_stepwise<boost::on_examine_vertex>{sink})));
```

EventVisitor mechanism

```
template <typename Tag>
struct dijkstra_stepwise {
    typedef Tag event_filter;

    // ...

};

template <typename Tag>
make_dijkstra_stepwise(coro_t::push_type& sink_, Tag) {
    return dijkstra_stepwise<Tag>(sink_);
}
```

EventVisitor mechanism

```
template <typename Tag>
make_dijkstra_stepwise(coro_t::push_type& sink_, Tag) {
  return dijkstra_stepwise<Tag>(sink_);
}

dijkstra_shortest_paths(graph, source,
                               visitor(boost::make_dijkstra_visitor(
                                      make_dijkstra_stepwise(sink, boost::on_examine_vertex()))));
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
class CoroEventVisitorBase
{
public:
        // required by EventVisitor API
        typedef Tag event_filter;
        typedef typename boost::coroutines::asymmetric_coroutine<EdgeOrVertex>::push_type coro_t;
        CoroEventVisitorBase(coro_t& sink):
           mSink(sink)
        {}
protected:
        coro_t& mSink;
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
class CoroEventVisitorBase
{
public:
        // required by EventVisitor API
        typedef Tag event_filter;
        typedef typename boost::coroutines::asymmetric_coroutine<EdgeOrVertex>::push_type coro_t;
        CoroEventVisitorBase(coro_t& sink):
          mSink(sink)
        {}
protected:
        coro_t& mSink;
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
class CoroEventVisitorBase
{
public:
        // required by EventVisitor API
        typedef Tag event_filter;
        typedef typename boost::coroutines::asymmetric_coroutine<EdgeOrVertex>::push_type coro_t;
        CoroEventVisitorBase(coro_t& sink):
          mSink(sink)
        {}
protected:
        coro_t& mSink;
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
struct CoroEventVisitor:
        public  CoroEventVisitorBase<EdgeOrVertex, Tag>
{
        typedef CoroEventVisitorBase<EdgeOrVertex, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
        template <typename Graph>
        void operator()(EdgeOrVertex eu, const Graph&) {
           super::mSink(eu);
        }
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
struct CoroEventVisitor:
          public  CoroEventVisitorBase<EdgeOrVertex, Tag>
{
          typedef CoroEventVisitorBase<EdgeOrVertex, Tag> super;
          template <typename Coro>
          CoroEventVisitor(Coro& sink): super(sink) {}
          template <typename Graph>
          void operator()(EdgeOrVertex eu, const Graph&) {
              super::mSink(eu);
          }
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
auto make_coro_visitor(boost::coroutines::push_coroutine<EdgeOrVertex>& sink, Tag) {
        return CoroEventVisitor<EdgeOrVertex, Tag>(sink);
}
```

```
dijkstra_shortest_paths(graph, source,
                        visitor(boost::make_dijkstra_visitor(
                                make_coro_visitor(sink, boost::on_examine_vertex()))));
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
auto make_coro_visitor(boost::coroutines::push_coroutine<EdgeOrVertex>& sink, Tag) {
        return CoroEventVisitor<EdgeOrVertex, Tag>(sink);
}
```

```
dijkstra_shortest_paths(graph, source,
                        visitor(boost::make_dijkstra_visitor(
                            make_coro_visitor(sink, boost::on_examine_vertex()))));
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
auto make_coro_visitor(typename boost::coroutines::asymmetric_coroutine<EdgeOrVertex>::push_type& sink, Tag) {
        return CoroEventVisitor<EdgeOrVertex, Tag>(sink);
}

dijkstra_shortest_paths(graph, source,
                visitor(boost::make_dijkstra_visitor(
                        make_coro_visitor<vertex_t>(sink, boost::on_examine_vertex()))));
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename Tag>
auto make_coro_visitor(typename boost::coroutines::asymmetric_coroutine<EdgeOrVertex>::push_type& sink, Tag) {
	return CoroEventVisitor<EdgeOrVertex, Tag>(sink);
}
```

```
dijkstra_shortest_paths(graph, source,
				visitor(boost::make_dijkstra_visitor(
					make_coro_visitor<vertex_t>(sink, boost::on_examine_vertex()))));
```

CoroEventVisitor mechanism

```
namespace boost {
namespace coroutines {

template< typename T >
struct asymmetric_coroutine
{
        typedef push_coroutine< T > push_type;
        typedef pull_coroutine< T > pull_type;
};

}}
```

CoroEventVisitor mechanism

```
using graph_t = boost::compressed_sparse_row_graph<boost::directedS>;
using vertex_t = typename boost::graph_traits<graph_t>::vertex_descriptor;
using edge_t = typename boost::graph_traits<graph_t>::edge_descriptor;
using coro_t = boost::coroutines::asymmetric_coroutine<vertex_t>;

coro_t::pull_type generator{[&](coro_t::push_type& sink) { //
  dijkstra_shortest_paths(graph, source, visitor(boost::make_dijkstra_visitor(
                                          make_coro_visitor(sink,
                                                            boost::on_examine_vertex()))));
}};
```

CoroEventVisitor mechanism

```
// coroutine type producing vertex_t, graph_t tuples

typedef std::tuple<vertex_t, const graph_t&> VertexGraph;

typedef boost::coroutines::asymmetric_coroutine<VertexGraph> vgcoro_t;
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename TupleGraph, typename Tag>
struct CoroEventVisitor<std::tuple<EdgeOrVertex, TupleGraph>, Tag>:
        public  CoroEventVisitorBase<std::tuple<EdgeOrVertex, TupleGraph>, Tag>
{
        typedef std::tuple<EdgeOrVertex, TupleGraph> Tuple;
        typedef CoroEventVisitorBase<Tuple, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
        template <typename Graph>
        void operator()(EdgeOrVertex eu, const Graph& g) {
            super::mSink(Tuple(eu, g));
        }
};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename TupleGraph, typename Tag>
struct CoroEventVisitor<std::tuple<EdgeOrVertex, TupleGraph>, Tag>:
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        CoroEventVisitor(Coro& sink): super(sink) {}
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        void operator()(EdgeOrVertex eu, const Graph& g) {
           super::mSink(Tuple(eu, g));
        }
};
```

CoroEventVisitor mechanism

```
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struct CoroEventVisitor<std::tuple<EdgeOrVertex, TupleGraph>, Tag>:
        public  CoroEventVisitorBase<std::tuple<EdgeOrVertex, TupleGraph>, Tag>
{
        typedef std::tuple<EdgeOrVertex, TupleGraph> Tuple;
        typedef CoroEventVisitorBase<Tuple, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
        template <typename Graph>
        void operator()(EdgeOrVertex eu, const Graph& g) {
            super::mSink(Tuple(eu, g));
        }
};
```

CoroEventVisitor mechanism

```
// coroutine type producing vertex_t, graph_t tuples
typedef std::tuple<vertex_t, const graph_t&> VertexGraph;
typedef boost::coroutines::asymmetric_coroutine<VertexGraph> vgcoro_t;

vgcoro_t::pull_type generator{[&](vgcoro_t::push_type& sink) { //
    dijkstra_shortest_paths(graph, source, visitor(boost::make_dijkstra_visitor(
                                               make_coro_visitor(sink,
                                                                   boost::on_examine_vertex())))));
}};
```

CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename TupleGraph, typename Tag>
struct CoroEventVisitor<std::tuple<EdgeOrVertex, TupleGraph>, Tag>:
        public  CoroEventVisitorBase<std::tuple<EdgeOrVertex, TupleGraph>, Tag>
{
        typedef std::tuple<EdgeOrVertex, TupleGraph> Tuple;
        typedef CoroEventVisitorBase<Tuple, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
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        void operator()(EdgeOrVertex eu, const Graph& g) {
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CoroEventVisitor mechanism

```
template <typename EdgeOrVertex, typename TupleGraph, typename Tag>
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{
        typedef std::tuple<EdgeOrVertex, TupleGraph> Tuple;
        typedef CoroEventVisitorBase<Tuple, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
        template <typename Graph>
        void operator()(EdgeOrVertex eu, const Graph& g) {
           super::mSink(Tuple(eu, g));
        }
};
```

EventVisitor redux

```
boost::dijkstra_shortest_paths(G, s,
   boost::make_dijkstra_visitor(
    std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
    std::make_pair(boost::record_predecessors(p.begin(),
                                               boost::on_tree_edge()),
                   copy_graph(G_copy, boost::on_examine_edge())))) );
```

EventVisitor redux

```
boost::dijkstra_shortest_paths(G, s,
  boost::make_dijkstra_visitor(
   std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
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```

EventVisitor redux

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   std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
   std::make_pair(boost::record_predecessors(p.begin(),
                                                         boost::on_tree_edge()),
                  copy_graph(G_copy, boost::on_examine_edge())))) );
```

EventVisitor redux

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  boost::make_dijkstra_visitor(
   std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
   std::make_pair(boost::record_predecessors(p.begin(),
                          boost::on_tree_edge()),
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EventVisitor redux

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boost::dijkstra_shortest_paths(G, s,
  boost::make_dijkstra_visitor(
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EventVisitor redux

```
boost::dijkstra_shortest_paths(G, s,
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   std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
   std::make_pair(boost::record_predecessors(p.begin(),
                          boost::on_tree_edge()),
           copy_graph(G_copy, boost::on_examine_edge()))) );
```

EventVisitor detour

```
boost::dijkstra_shortest_paths(G, s,
   boost::make_dijkstra_visitor(
    std::make_pair(boost::record_distances(d, boost::on_tree_edge()),
    std::make_pair(boost::record_predecessors(p.begin(),
                                              boost::on_tree_edge()),
                   copy_graph(G_copy, boost::on_examine_edge())))) );
```

EventVisitor detour

```
template <typename EventVisitor>
auto evisitors(EventVisitor visitor) {
        return visitor;
}

template <typename EventVisitor, typename... EventVisitors>
auto evisitors(EventVisitor visitor, EventVisitors... rest) {
        return std::make_pair(visitor, evisitors(rest...));
}

template <typename... EventVisitors>
auto make_dijkstra_visitor(EventVisitors... visitors) {
        return boost::make_dijkstra_visitor(evisitors(visitors...));
}
```

EventVisitor detour

```
boost::dijkstra_shortest_paths(G, s,
  make_dijkstra_visitor(
    boost::record_distances(d, boost::on_tree_edge()),
    boost::record_predecessors(p.begin(), boost::on_tree_edge()),
    copy_graph(G_copy, boost::on_examine_edge())) );
```

CoroEventVisitor mechanism

```
boost::dijkstra_shortest_paths(G, s,
  make_dijkstra_visitor(
    make_coro_visitor(sink, boost::on_discover_vertex()),
    make_coro_visitor(sink, boost::on_examine_vertex()),
    make_coro_visitor(sink, boost::on_finish_vertex())) );
```

CoroEventVisitor mechanism

std::type_index(typeid(boost::on_examine_vertex))

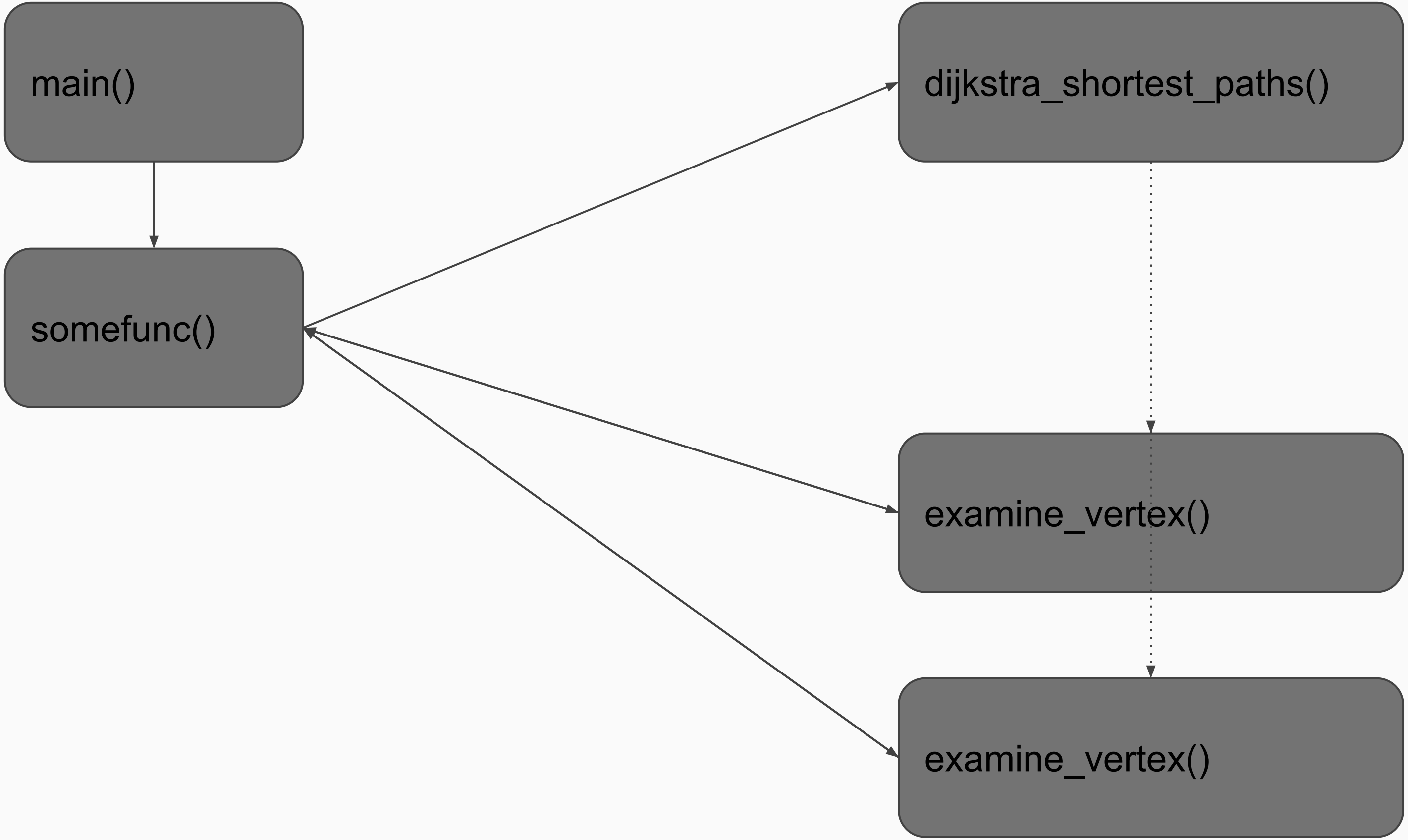
CoroEventVisitor mechanism

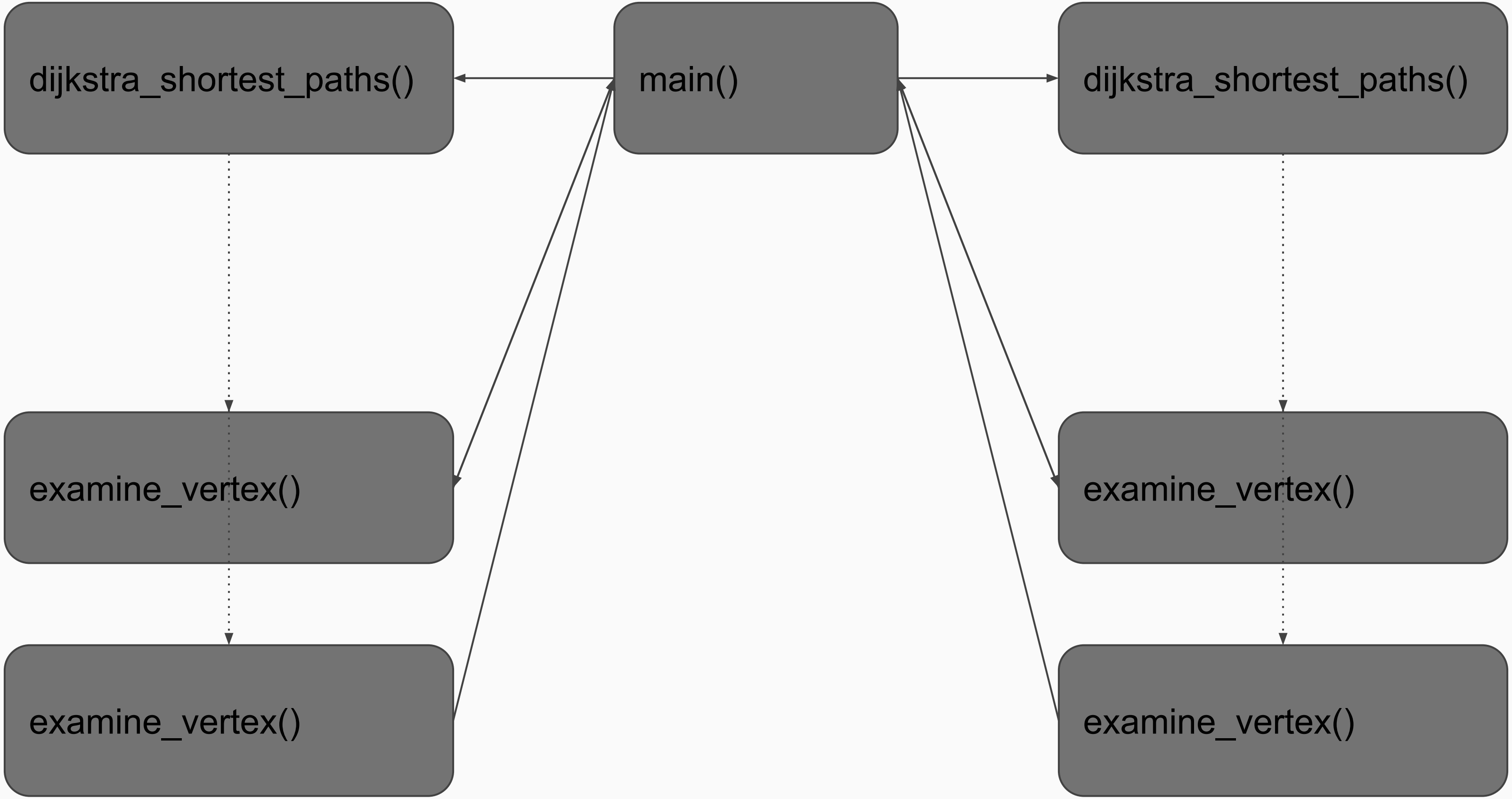
```
template <typename EdgeOrVertex, typename TupleGraph, typename Tag>
struct CoroEventVisitor<std::tuple<EdgeOrVertex, TupleGraph, std::type_index>, Tag>:
  public  CoroEventVisitorBase<std::tuple<EdgeOrVertex, TupleGraph, std::type_index>, Tag>
{
        typedef std::tuple<EdgeOrVertex, TupleGraph, std::type_index> Tuple;
        typedef CoroEventVisitorBase<Tuple, Tag> super;
        template <typename Coro>
        CoroEventVisitor(Coro& sink): super(sink) {}
        template <typename Graph>
        void operator()(EdgeOrVertex eu, const Graph& g) {
           super::mSink(Tuple(eu, g, std::type_index(typeid(Tag))));
        }
};
```

But how do you get away with that?
Coroutines and Stacks

Each coroutine runs on its own stack

- Stack depth in opaque algorithm doesn’t matter


main()
somefunc()
dijkstra_shortest_paths()
examine_vertex()
examine_vertex()



dijkstra_shortest_paths()

main()

dijkstra_shortest_paths()

examine_vertex()

examine_vertex()

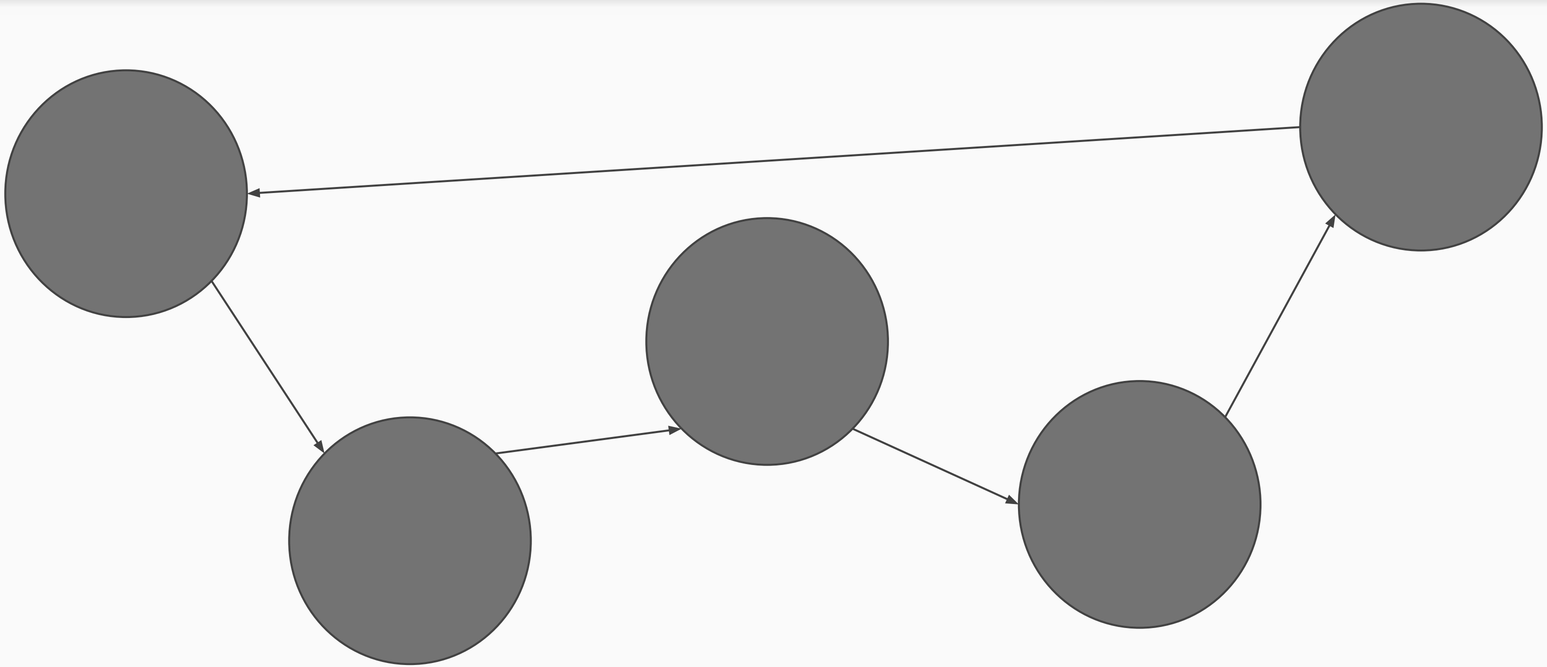
examine_vertex()

examine_vertex()

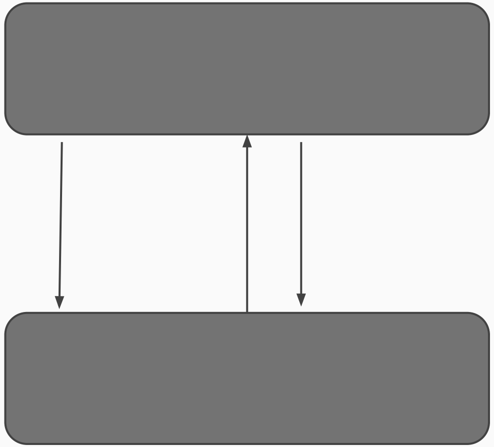
Boost.Coroutine

- Symmetric coroutines
- Asymmetric coroutines

Symmetric Coroutines



Asymmetric Coroutines



push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::push_type mycoro(
        [](boost::coroutines::asymmetric_coroutine<int>::pull_type& source) {
                ...
        });
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::push_type mycoro(
        [](boost::coroutines::asymmetric_coroutine<int>::pull_type& source) {
                ...
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```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::push_type mycoro(
    [](boost::coroutines::asymmetric_coroutine<int>::pull_type& source) {
        ...
    });
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(
    [](boost::coroutines::asymmetric_coroutine<int>::push_type& sink) {
        …
    });
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(
        [](boost::coroutines::asymmetric_coroutine<int>::push_type& sink) {
                sink(17);
        });
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(...);

while (mycoro) {
    int foo = mycoro.get();
    mycoro();
}
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(...);

while (mycoro) {
    int foo = mycoro.get();
    mycoro();
}
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push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(...);

while (mycoro) {
    int foo = mycoro.get();
    mycoro();
}
```

push_type, pull_type

```
boost::coroutines::asymmetric_coroutine<int>::pull_type mycoro(...);

for (int foo : mycoro) {
    // ...
}
```

This tactic is applicable to *any* library whose API involves callbacks or visitors.

Questions?

https://gist.github.com/nat-goodspeed/