Template Meta-State Machines, Shannon, Madness...

J.M.M^{c}Guiness[1]

[1]accuconf2023@hussar.me.uk

ACCU Conference, Bristol, 2023

Version: 8ccc1

Outline

A very simple piece of code...

Why is this instruction sequence so interesting?

GOTO considered harmful[1]:

```
CALL QWORD PTR [BASE+STRIDE*STATE]
# STATE input, branch-target is Transition.
```

- Because it is at the heart of a state machine.
  - This may be generated as an `if-else` chain.
  - But this could impact the branch-predictor.
- The instruction timing for a computed-GOTO is excellent in modern super-scalar architectures vs mis-prediction of a branch:
  - 1-2 clock cycles vs $O(20)$ estimated from the depth of the pipeline ≈ 20 stages[2], the cost of a pipeline restart.

How to compute the STATE?

- We shall leave aside the computation of the BASE and the STRIDE as they are more easy to compute.
- The STATE may be more complex: because this may be random, not sequential.
    - Thus a perfect, preferably minimal hash should be generated.
    - *Information Entropy, elucidated by Shannon, means there is no general solution...*
    - Persevere: generation of the hash shall be attempted despite those issues...

Problem statement.

1. We shall generate computed-`GOTO`s.
2. No amount of effort shall be sacrificed to attain point 1, above.

Methodology for the investigation.

1. We need to identify a suitable code-base for this:
    1. In this case I chose the FIX-to-MIT translator[3] as the contained meta state-machines are suitable.
       (Upon which I have previously much presented.)
2. Modifications to the code-base shall be made to permit comparative testing.
    1. Computed-`GOTO` vs. a "naïve" meta state-machine that has been implemented with `if-else` chains.
    2. The results shall be statistically significant.
    3. *Using computed-`GOTO`s shall have ramifications.*
        - Which shall be discussed, later.

Results of the investigation.

1. Histograms of the `if-else` vs computed-`GOTO` performance shall be presented.
    1. And discussion of these in detail...
2. A detailed, subjective review of the code that had to be added:
    1. including reviewing the comprehensibility, maintainability and impact on compile-time.
3. Finally, conclusions shall be presented drawn from these analyses.

A low-latency, HFT FIX-to-MIT/BIT translator?

- In trading systems one has this simplified process:
  - Messages sent from a client to an exchange.
    - This involves a state machine.
  - Messages sent from an exchange back to a client.
    - Likewise this includes a state machine.
- Both state machines are on the hot path.
- My numerous previous presentations regarding low-latency optimisations and HFT [3] in C++ motivated this investigation regarding writing the *fastest* meta state-machine possible...
  - To such an extreme that there would *no longer* be statistically significant performance differences!
- Why, oh why?
  - The adventure of writing the code to implement this was beyond anything one may ever wish to sensibly do...

BEWARE!

- This is not a talk about how to optimise code that has not yet been optimised!

  Premature optimisation is the root of all evil[4]!

    - *This talk certainly verges on that...*
- Ensure that one has run one's preferred profiler, etc, beforehand.
    - Heed Amdahl's Law[5].
- Code should be: comprehensible, maintainable & compile reasonably quickly.
    - The code presented here, in my opinion, verges on failing all of those requirements!

The impact of the runtime STATE.

`constrained_override_type`

- The target address is all that is known about the destination object, the `Transition`.
- Specifically, run-time `STATE` shall cause a jump to the related `Transition::process(...)`:
  - in a *generic* manner if a *generic* state machine is to be used,
  - effectively that `STATE` should be an index operation into a collection of `Transitions`,
  - generality shall be provided by generating wrappers for `Transition::process(...)`,
    - the types of the parameters to `process(...)` must be recovered to permit overloading resolution,
  - the state machine that was implemented was based upon the Boost "Meta State Machine"[6].

The transitions - BASE & STRIDE.

(Inspired by discussions with Vladimir Arnost.)
`unordered_tuple`

We shall need a collection of `Transitions` into which the `STATEs` index.

- It was chosen to implement this as a buffer of `alignas(STRIDE) std::array<std::byte,...>` into which the `Transitions` shall be placement-`new`'d.
- Thus the `BASE` & `STRIDE` may be computed at compile-time.
- This collection will require a suitable `operator[]` indexed by the input `STATE`.
    - The `STATEs` shall need hashing... More later...

Beware the angle-bracket, my son...

Much has been written on the pitfalls relating to unconstrained abuse of template meta-programming in C++, amongst such luminaries as:

- "Henney's Hypothesis"[7]:

  For each additional template parameter, the potential number of users is halved.

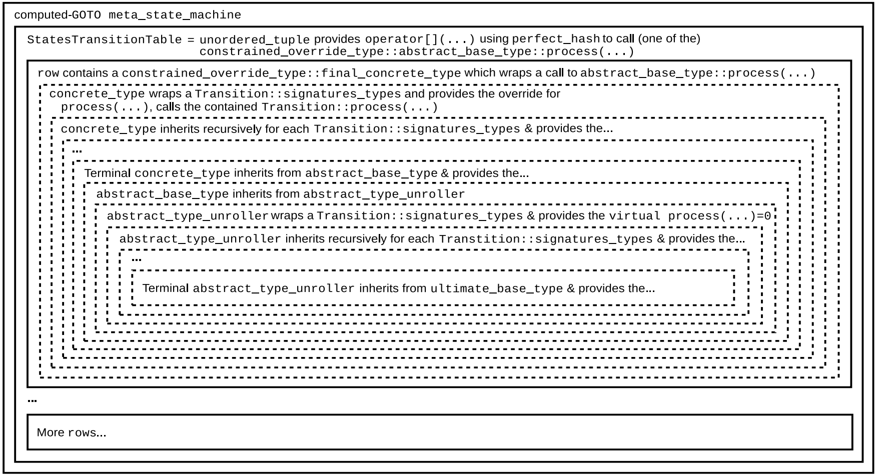
  - I have many of these, in some cases unbounded sets...
- "Template Metaprogramming Made Easy (Huh?)" by Bartosz Milewski[8]:

  ... *Big part of it is that C++ templates are rather ill suited for metaprogramming, to put it mildly.* ...

This presentation contains many such sins...

- *You have been warned...*

Schematic design of computed-GOTO meta state-machine.



computed-GOTO meta_state_machine

StatesTransitionTable = unordered_tuple provides operator[](...) using perfect_hash to call (one of the) constrained_override_type::abstract_base_type::process(...)

row contains a constrained_override_type::final_concrete_type which wraps a call to abstract_base_type::process(...)

concrete_type wraps a Transition::signatures_types and provides the override for process(...), calls the contained Transition::process(...)

concrete_type inherits recursively for each Transition::signatures_types & provides the...

...

Terminal concrete_type inherits from abstract_base_type & provides the...

abstract_base_type inherits from abstract_type_unroller

abstract_type_unroller wraps a Transition::signatures_types & provides the virtual process(...)=0

abstract_type_unroller inherits recursively for each Transtition::signatures_types & provides the...

...

Terminal abstract_type_unroller inherits from ultimate_base_type & provides the...

...

More rows...

The unordered_tuple.

The purpose of this class is to contain all of the transitions:

Schematic of unordered_tuple.

```
template<class TransitionBase, class Hasher, class... Transitions>
class unordered_tuple {
public:
    constexpr size_t max_size = ...;
    constexpr size_t stride = ...;
    TransitionBase &operator[](state_type state) {
        auto base = wrapped_transitions.data();
        auto offset = Hasher(state)*stride;
        return reinterpret_cast<TransitionBase &>(base+offset);
    }
private:
    alignas(stride)
    std::array<std::byte, max_size> wrapped_transitions{};
};
```

Notes: unordered_tuple.

TransitionBase: base class common to all Transitions. Shall be supplied by constrained_override_type as abstract_base_type.

Hasher: hashing algorithm applied to the set of STATEs contained in the Transitions. More details later...

Transitions: The set of Transitions to be contained. Each of which has a copy of the STATE as a value. Each Transition wrapped by a constrained_override_type from the meta_state_machine.

wrapped_transitions: The set of Transitions is placement-new'd into a buffer of suitable alignment & size. Placed with a stride of STRIDE.

Why constrained_override_type?

Warning it is just syntactic sugar!

Consider a naïve if-else implementation of a state machine:

example if-else implementation.

```
state_type msm::process(state_type state, Params... &&p) {
    if (state == NEW_ORDER) {
        return new_order_transition.process(p...);
    } else if (state == ORDER_CANCEL) {
...
}
```

vs:

example computed-GOTO implementation.

```
state_type msm::process(state_type state, Params... &&p) {
    return transitions[state].process(p...);
}
```

Discussion of why `constrained_override_type`?

- In the `if-else` implementation we know the exact transition to call, thus the type and number of parameters at compile-time.
- Whereas in the computed-`GOTO` implementation some form of interface class must be called, as the `STATE` is only known at run-time.
    - Therefore the `process()` method must be provided by some form of base class.
    - But the parameters to it may vary or be of disparate types...!
    - C++ does not support virtual, template member-functions! One cannot write:

virtual, templated member-functions - no!

```
struct foo {
    template<class... Params> virtual void bar(Params... p);
};
```

Purposes: constrained_override_type.

1. Supply a suitable abstract base class for each of the Transitions with suitable declarations of pure-virtual process() methods obtained from each particular Transition.
2. From those base classes, aggregate them in an inheritance chain to compute a TransitionBase abstract base class for the unordered_tuple TransitionBase class.
3. Create wrappers for each Transition so that the wrapper may inherit from the abstract base class so generated and the Transition it will wrap. These wrappers may then be passed to the unordered_tuple.
4. In reality this is overly general for these needs, but I wanted to generalise... Oops...

Notes: constrained_override_type.

As C++ does not yet support reflection, the previous points 1 & 3 imply that each `Transition` must supply some kind of type that lists the return type and parameter types for each declaration of `process()` within each `Transition`, termed `ProcessFns` in the following examples.

Components: constrained_override_type.

We need to generate the pure-virtual methods with the correct declarations for the ProcessFns of the Transition:

Schematic of abstract_type_unroller - base case.

```
template<class RetT, class... Params>
struct abstract_type_unroller<member_function_type<RetT, Params...>>
: ultimate_base_type {
    virtual RetT process(Params ...&&p) const noexcept(false) = 0;
    virtual RetT process(Params ...&&p) noexcept(false) = 0;
};
```

Components: constrained_override_type.

Now generate the remaining pure-virtual methods for the ProcessFns of the Transition:

Schematic of abstract_type_unroller - generate the rest.

```
template<class RetT, class... Params, class... ProcessFns>
... abstract_type_unroller<member_function_type<RetT, Params...>,
    ProcessFns...> : abstract_type_unroller<ProcessFns...> {
    using base_type::base_type;
    using base_type::process;
    virtual RetT process(Params ...&&p) const noexcept(false) = 0;
    virtual RetT process(Params ...&&p) noexcept(false) = 0;
};
```

Declare a type that shall be the abstract base class containing all the pure-virtual methods:

```
using abstract_base_type = abstract_type_unroller<Transitions...>;
using TransitionBase = abstract_base_type;
```

Components: constrained_override_type.

We now need a class that has an is-a Transition for which the ProcessFns may be called:

Schematic of concrete_type - base case.

```
template<class abstract_base_type, class Transition, class RetT,
class... Params>
struct concrete_type<abstract_base_type, Transition,
member_function_type<RetT, Params...>>
: Transition, abstract_base_type {
    template<class... Args>
    explicit concrete_type(Args &&...args) noexcept(...)
    : Transition(std::forward<Args>(args)...), abstract_base_type() {
    }
    RetT process(Params &&...p) const noexcept(...) override {
        return this->Transition::process(std::forward<Params>(p)...);
    }
    RetT process(Params &&...p) noexcept(...) override {
        return this->Transition::process(std::forward<Params>(p)...);
    }
};
```

Components 1/2: constrained_override_type.

Now generate the rest for all of the Transitions:

Schematic of concrete_type - generate the rest.

```
template<class abstract_base_type, class Transition, class RetT,
class... Params, class... ProcessFns>
struct concrete_type<abstract_base_type,
member_function_type<RetT, Params...>, ProcessFns...>
: concrete_type<abstract_base_type, Transition, ProcessFns...> {
    using
base_t = concrete_type<abstract_base_type, Transition, ProcessFns...>;
    using base_t::base_t;
    using base_t::process;
    RetT process(Params &&...p) const noexcept(...) override {
        return this->Transition::process(std::forward<Params>(p)...);
    }
    RetT process(Params &&...p) noexcept(...) override {
        return this->Transition::process(std::forward<Params>(p)...);
    }
};
```

Components 2/2: `constrained_override_type`.

Declare an equivalent type that shall be the concrete class containing all the overridden wrappers for the `Transition::process()` methods:

```
template<class T>
struct finalizer final : T {
    using T::T;
};
using final_concrete_type =
finalizer<concrete_type<abstract_base_type, Transitions...>>;
```

Compare to `abstract_base_type`, above.

Reflections 1/2: `constrained_override_type`.

The `final_concrete_type` may be used inside `unordered_tuple` to supply the `process()` methods that should be called according to the `STATE`s in a type-safe manner.

- Ultimately, the generated `concrete_type` has been inherited-from with the `final` keyword to remove all virtual-function calls by `finalizer<T>`. The fact that all of the types are fully defined before use is also vital for this.
- We have now recovered the type information for the return and parameter types for each of the `Transition::process()`'s, so they may be called safely.

Reflections 2/2: constrained_override_type.

- This requires that each Transition defines signatures_types (ProcessFns) that contains the return and parameter types for each Transition::process() declared:

```
using signatures_types = std::pair<
    return_type,    // N.B. all process() methods return the same type.
    std::tuple<
        std::tuple<first_parameter_for_first_overload, ...>,
        std::tuple<first_parameter_for_second_overload, ...>
    >
>;
```

Introducing schematic of: meta_state_machine.

```
template<class StateTransitionTable>
struct machine {
    using states_type = typename StateTransitionTable::states_type;
    template<class... Args> machine(Args &&...args) noexcept(...);
    template<class... Params> states_type
    process(states_type state, Params &&...p) const noexcept(...) {
        return table[state].process(std::forward<Params>(p)...);
    }
    template<class... Params> states_type
    process(states_type state, Params &&...p) noexcept(...) {
        return table[state].process(std::forward<Params>(p)...);
    }
    StateTransitionTable table;
};
```

- The chief item of interest is the `StateTransitionTable`: it combines the `unordered_tuple` & `constrained_override_type`.
- U.B. would happen if the wrong `Transition` were called via a valid, but mis-computed hash of a `STATE`...

Schematic details of: `StateTransitionTable`.

```
template<class...  Transitions>
using StateTransitionTable = unordered_tuple<
    states_type,
    wrapped_first_row_t::abstract_base_type,
    perfect_hash<get_state_as_hash<Transitions>::value...>,
    wrapped_first_row_t::template final_type<Transition>,
    detuple_make_rows<
        Transitions,
        make_row_wrappers_t<Transitions::signatures_types...>::type
    >::type...
>;
```

Notes for: StateTransitionTable.

abstract_base_type: introduced earlier in the discussion regarding constrained_override_type.

perfect_hash: the generated hasher that shall be discussed in the next section...

make_row_wrappers_t: a meta-function that extracts the details from signatures_types for use by...

detuple_make_rows: wraps the ProcessFns in each Transition in the StateTransitionTable with a constrained_override_type:

```
template<Transition>
using detuple_make_row =
constrained_override_type::result_type<Transition>;
```

Schematic exchange to client: meta_state_machine.

```
using StateTransitionTable = rows<
    row<
        ServerHeartbeat_t::static_type,
        just_send_to_client<ClientHeartbeat_t>,    // Example
Transition.
        ClientHeartbeat_t::static_type
    >,
    row<
        ExecutionReport_t::static_type,
        ExecutionReportResponse,    // Example Transition.
        ExecutionReportResponse::exit_values
    >,
    ...,
    row<
        MsgTypes_t::MatchAll,
        send_specified_msg<Reject_t>,    // Example Transition.
        Reject_t::static_type
    >
>;
```

Note that the definitions of `rows` and `row` have been omitted for brevity, see [3] for more details.

The hashing algorithm: requirements.

- *We know the discreet set of* `STATE`*s a posteriori: it is part of the MIT specifications[9].*
- A perfect hash is required, preferably minimal.
- The generated hash-function must have as few instructions as possible.
    - Existing hash-generators such as `gperf`[10] do not fit all of the above criteria.
        - The generated hash functions are many lines of assembly, we require $\ll 20$ instructions.
- We need to create a generator for this highly-optimised hash algorithm.
    - Minor relaxation: the hashing need not be stable in the sense of order of the `STATE`s in the domain.
- Generated hash-function shall be checked to ensure no collisions.

The hashing algorithm: requirements.

- *We know the discreet set of* `STATE`*s a posteriori: it is part of the MIT specifications[9].*
- A perfect hash is required, preferably minimal.
- The generated hash-function must have as few instructions as possible.
  - Existing hash-generators such as `gperf`[10] do not fit all of the above criteria.
    - The generated hash functions are many lines of assembly, we require $\ll 20$ instructions.
- We need to create a generator for this highly-optimised hash algorithm.
  - Minor relaxation: the hashing need not be stable in the sense of order of the `STATE`s in the domain.
- Generated hash-function shall be checked to ensure no collisions.

The xor_modulo_hash algorithm: design.

(Inspired by discussions with Dr. Richard A. Harris[11], deceased.)

```
size_t xor_modulo_hash(state_type state, uint64_t seed,
size_t denominator) {
    return (state ^ seed) % denominator;
}
```

- ^ operation: the seed shuffles the bits in the STATE so in a sense adds extra entropy to the algorithm.
  - Brute-force search attempts to find an acceptable seed (enumerates domain of all seeds).
- % operation: constrains the output of the algorithm, also:
  - Range is $[0, \ldots, \texttt{denominator})$, i.e. how minimal hash shall be.
  - Experimentation: denominator must be odd.
  - Strength reduction: optimise potentially very slow %.
- Fixed {seed, denominator} instantiates a hash function, written to a C++ header-file.

Generating the seed and denominator, 1/3.

- Surprisingly *slow*: on my AMD Ryzen 9 3900 at over 4GHz it can take over 15 minutes.
  - No surprise as brute-force!
  - Searching for the `seed` is embarrassingly parallel:
    - Developed `find_first_of(...)` a data-parallel algorithm as part of PPD[12]: it searches the input domain $[start, ..., end)$ to find a suitable `seed` for a suitable `predicate`.

Generating the seed and denominator, 2/3.

- May *never* find a suitable `seed` with a sufficiently small `denominator` for the set of input `STATE`s.
  1. A perfect, minimal hash $\forall$ sets of `STATE`s input does not exist.
     - The entropy added by the `seed` and `denominator` will be inadequate for the majority of inputs.
     - Shannon: there is only so much information in the inputs and a very constrained amount of entropy that may be added in the `xor_modulo_hash` algorithm.
     - One may need a different algorithm.
     - For the same `denominator` the smallest `seed` was used.
     - If a `seed` of 0 found we should use that optimisation!
  2. Experimentation revealed that usually a `denominator` $> (n+1)$ was required, where n is the number of `STATE`s input, i.e. a classic space-time trade-off.
     - Collision-free hash has been guaranteed by design as the `unordered_tuple` has no collision-avoidance mechanism.

Generating the seed and denominator, 3/3.

1. Experience indicates that $\forall$ inputs required, solutions were always found.
2. ***The build may fail because generating the hash for the set of*** `STATE`***s may fail!***
3. Note that the compiler is very unlikely to generate this for us:
    1. The set of `STATE`s are effectively random numbers: the MIT specifications have been bizarre in this regard.
        - Oh! Would it be moot if exchanges just used $\mathbb{N}$atural numbers...
    2. Usually the transformation goes something like: `if-else` to `switch`, then analyse the `switch` to see if a computed-`GOTO` may be generated (only simple cases) or use bisection then cluster then table or recurse otherwise `if-else`.
    3. Avoids "there ain't no such thing as a general, minimal, and perfect hash" by "bisection with divide-and-conquer".

Test 1: Micro-benchmark: methodology.

- Implements a cut-down version of the FIX-to-MIT/BIT Translator (more later) client-to-exchange, meta state-machine:
  - Has all of the correct values for the `STATE`s,
  - Same number of `Transitions`, but highly simplified.
- A comparison of the performance of `if-else` vs `computed-GOTO` was made.
  - The selection of the input `STATE` was randomized to try and defeat the branch-predictor.
- Unless otherwise noted, g++ v12.2.1 and clang++ v15.0.1 were used.

Test 1: Micro-benchmark: methodology.

- Implements a cut-down version of the FIX-to-MIT/BIT Translator (more later) client-to-exchange, meta state-machine:
    - Has all of the correct values for the `STATE`s,
    - Same number of `Transitions`, but highly simplified.
- A comparison of the performance of `if-else` vs `computed-GOTO` was made.
    - The selection of the input `STATE` was randomized to try and defeat the branch-predictor.
- Unless otherwise noted, g++ v12.2.1 and clang++ v15.0.1 were used.

Test 2: A Simple FIX-to-MIT/BIT Translator.

- This translator is a heavily-templated library:
  - listens to socket (the client-side) for FIX-format[13] messages,
  - sends & receives binary-protocol MIT/BIT-format[9] messages via a server-side socket.
  - Two tests:
    1. In-order: one sends then receives the response repeatedly.
    2. Out-of-order: sends all orders, then waits to receive all the responses.
- Uses Boost.ASIO, but numerous other optimisations, including the above, used SSE2 & higher instructions.
- Neither a Solarflare card nor OpenOnload drivers were used.
  - Would have reduced context-switches.
- Previous presentations have more detail [14].

Test 2: A Simple FIX-to-MIT/BIT Translator.

- This translator is a heavily-templated library:
  - listens to socket (the client-side) for FIX-format[13] messages,
  - sends & receives binary-protocol MIT/BIT-format[9] messages via a server-side socket.
  - Two tests:
    1. In-order: one sends then receives the response repeatedly.
    2. Out-of-order: sends all orders, then waits to receive all the responses.
- Uses Boost.ASIO, but numerous other optimisations, including the above, used SSE2 & higher instructions.
- Neither a Solarflare card nor OpenOnload drivers were used.
  - Would have reduced context-switches.
- Previous presentations have more detail [14].

Test 2: A Simple FIX-to-MIT/BIT Translator.

- This translator is a heavily-templated library:
  - listens to socket (the client-side) for FIX-format[13] messages,
  - sends & receives binary-protocol MIT/BIT-format[9] messages via a server-side socket.
  - Two tests:
    1. In-order: one sends then receives the response repeatedly.
    2. Out-of-order: sends all orders, then waits to receive all the responses.
- Uses Boost.ASIO, but numerous other optimisations, including the above, used SSE2 & higher instructions.
- Neither a Solarflare card nor OpenOnload drivers were used.
  - Would have reduced context-switches.
- Previous presentations have more detail [14].

Test 2: More details.

- A FIX New Order message is sent to a socket,
    - translated to MIT/BIT native binary format,
        - sent over sockets to a basic simulator,
        - which responds with a fill,
    - translated back to a FIX fill message.
- Sent back to the client.
- Computer was quiescent; `numactl` was not used, threads were pinned.
    - Highly optimised kernel, Gentoo/Linux.
        - Lap-brick: Single AMD Ryzen 9 3900, 12 physical cores, $\geq$ 4.0GHz, DDR4 RAM & NVMe storage.

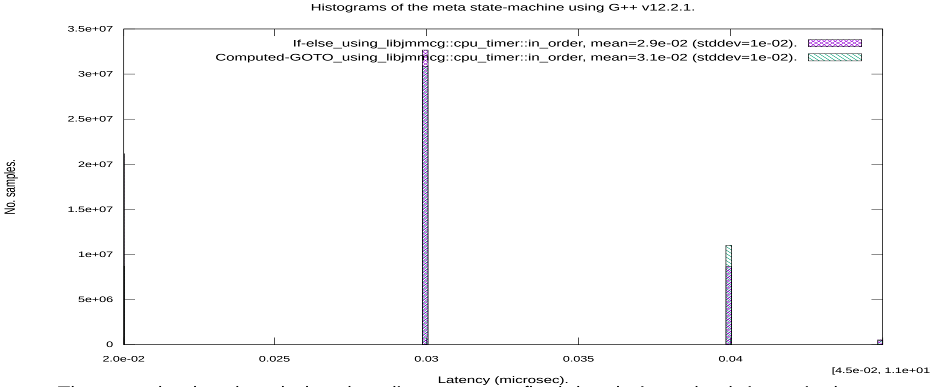
Test 2: More details.

- A FIX New Order message is sent to a socket,
  - translated to MIT/BIT native binary format,
    - sent over sockets to a basic simulator,
    - which responds with a fill,
  - translated back to a FIX fill message.
- Sent back to the client.
- Computer was quiescent; `numactl` was not used, threads were pinned.
  - Highly optimised kernel, Gentoo/Linux.
    - Lap-brick: Single AMD Ryzen 9 3900, 12 physical cores, $\geq$ 4.0GHz, DDR4 RAM & NVMe storage.

Test 2: More details.

- A FIX New Order message is sent to a socket,
  - translated to MIT/BIT native binary format,
    - sent over sockets to a basic simulator,
    - which responds with a fill,
  - translated back to a FIX fill message.
- Sent back to the client.
- Computer was quiescent; `numactl` was not used, threads were pinned.
  - Highly optimised kernel, Gentoo/Linux.
    - Lap-brick: Single AMD Ryzen 9 3900, 12 physical cores, $\geq$ 4.0GHz, DDR4 RAM & NVMe storage.

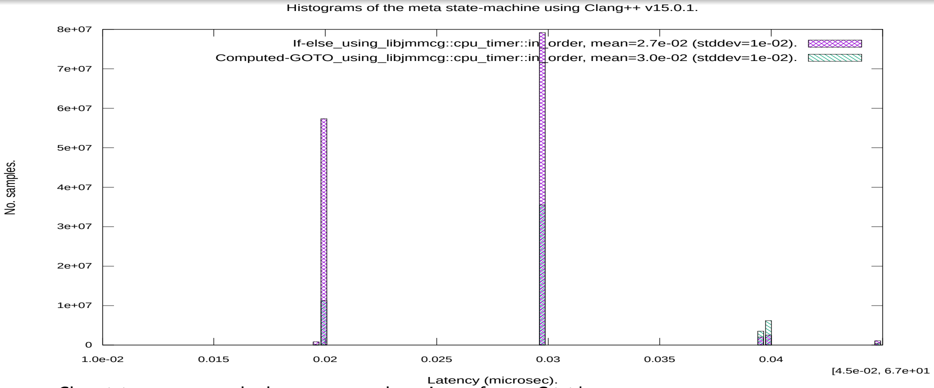
Test 1: Micro-benchmark: results G++ ($\leq 2\%$ MAD[15]).



There are only 4 branches: the branch-predictor never gets flooded as the internal code is too simple.

- The BTB has ≈ 32 slots - so never flooded, works beautifully.
- When used, the predictor was very accurate $\geq 98\%$: modern predictors also use Markov chains.

Test 1: Micro-benchmark: results Clang++ ($\leq 2\%$ MAD).



Clang++ generates code that appears to be twice as fast as G++!

- Some issue in the code-generation by G++?
- Pipeline hazards affecting the outcome?
  - 4 conditionals in the `Transitions`, so can be accommodated by the hardware.

Test 2: if-else: G++ generated code.

```
405:  movzx eax,WORD PTR [rbp-0x2b2]    #    if-else::msm.process(state, p...);
40c:  cmp ax,0x44    #    return state==Transition1::start
? transition1.process(p...) : Transition2::process(p...);
410:  jne 997
416:  call Transition2::process(p...)
997:  cmp ax,0x46    #    return state==Transition3::start
? transition3.process(p...) : Transition4::process(p...);
99b:  jne 9ab
99d:  call Transition4::process(p...)
9ab:  cmp ax,0x47
9af:  jne 9ba
9b5:  call Transition1::process(p...)
9ba:  call Transition3::process(p...)
```

The compiler generated the expected jumps.

Test 2: computed-GOTO: G++ generated code.

```
3c5:  movzx eax,WORD PTR [rbp-0x2c6]    #    hash::msm.process(state, p...);
3cc:  mov ecx,0xcccccccd
3d1:  mov BYTE PTR [rbp-0x2a8],0x0
3d8:  mov DWORD PTR [rbp-0x2a4],0x44    #    state
3e2:  mov rsi,r15
3e5:  vmovdqa xmm3,XMMWORD PTR [rbp-0x330]
3ed:  vmovdqa xmm2,XMMWORD PTR [rbp-0x310]
3f5:  mov edx,eax
3f7:  vmovdqa xmm1,XMMWORD PTR [rbp-0x320]
3ff:  vmovdqa xmm0,XMMWORD PTR [rbp-0x340]
407:  imul rdx,rcx
40b:  shr rdx,0x22
40f:  lea edx,[rdx+rdx*4]    #    Address computations from wrappers?
412:  sub eax,edx
414:  lea rdx,[rbp-0x2c7]    #    Address computations from wrappers?
41b:  shl rax,0x5    #    denominator - strength reduction!
41f:  vmovdqa XMMWORD PTR [rbp-0x150],xmm3
427:  vmovdqa XMMWORD PTR [rbp-0x1b0],xmm2
42f:  lea rdi,[rbx+rax*1+0x40]    #    Address computations from wrappers?
434:  vmovdqa XMMWORD PTR [rbp-0x190],xmm1
43c:  vmovdqa XMMWORD PTR [rbp-0x130],xmm0
444:  mov rax,QWORD PTR [rdi]
447:  call QWORD PTR [rax+0x18]    #    The computed-GOTO! As a virtual-method call...
```

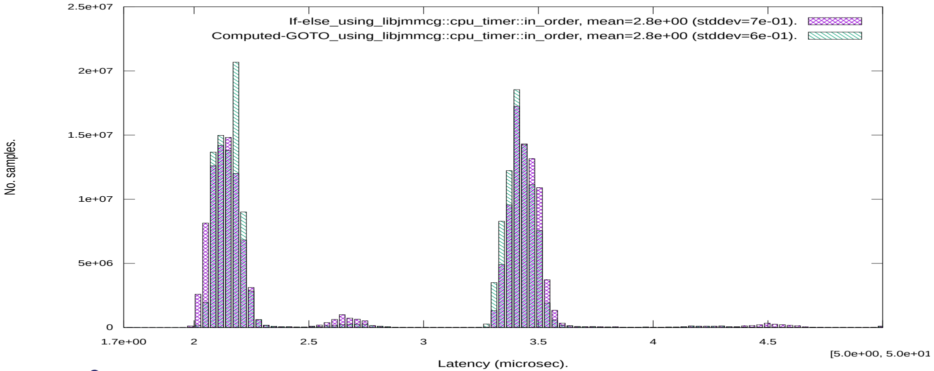
Test 2: computed-GOTO: reflections re. generated code.

The compiler generated the expected computed-`GOTO`:

- Disappointing that the code-generation takes so many assembly instructions.
- Lots of code-motion and inlining makes the calls to hashing and indexing make the assembly complex to decipher...
- The multiple `lea` instructions may be causing AGIs...
  - Causing pipeline stalls: inadequate de-virtualisation?
- Recall we need this to be $\ll 20$ clock-cycles, which this is unlikely to be.
- Godbolt[16] could not be used.
  - Instead `objdump -drwCS -Mintel` with a lot of editing.

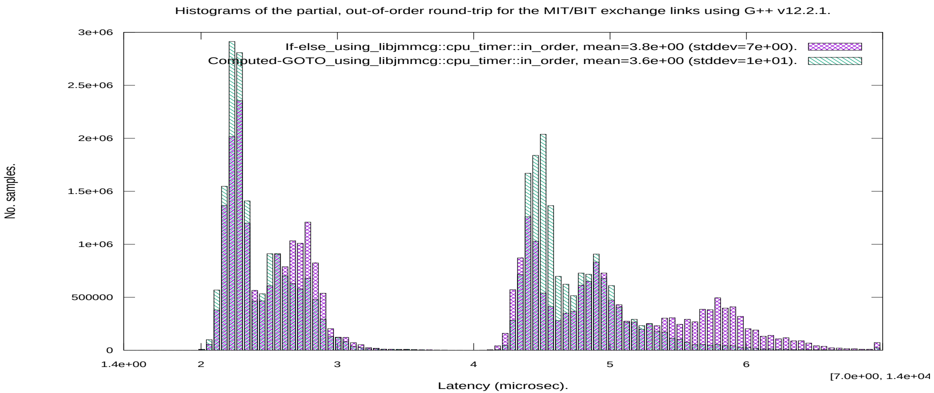
Test 2: `if-else` vs computed-`GOTO`: histogram, in-order G++ ($\leq 5\%$ MAD).

Histograms of the partial, in-order round-trip for the MIT/BIT exchange links using G++ v12.2.1.



- Kurtosis crucial: usual statistics fail us - need the histogram to tell all.
- Computed-`GOTO` out-performs `if-else`, despite curious assembly generated.

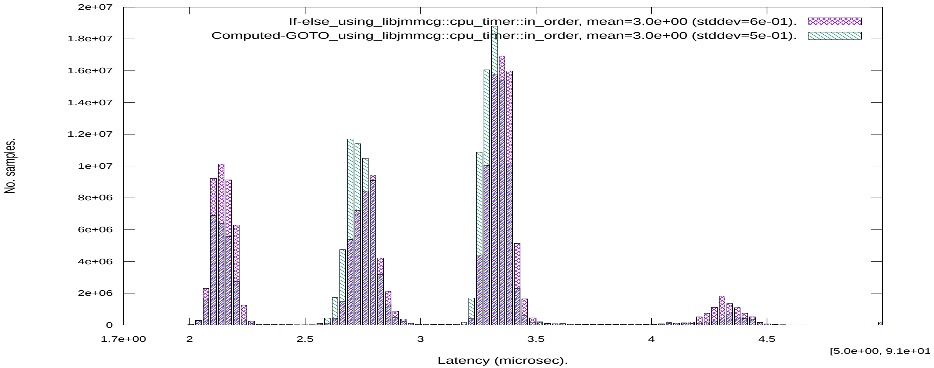
Test 2: `if-else` vs computed-`GOTO`: histogram, out-of-order G++ ($\leq 7\%$ MAD).



- Computed-`GOTO` out-performs `if-else`, outliers for the latter a serious problem for algos.

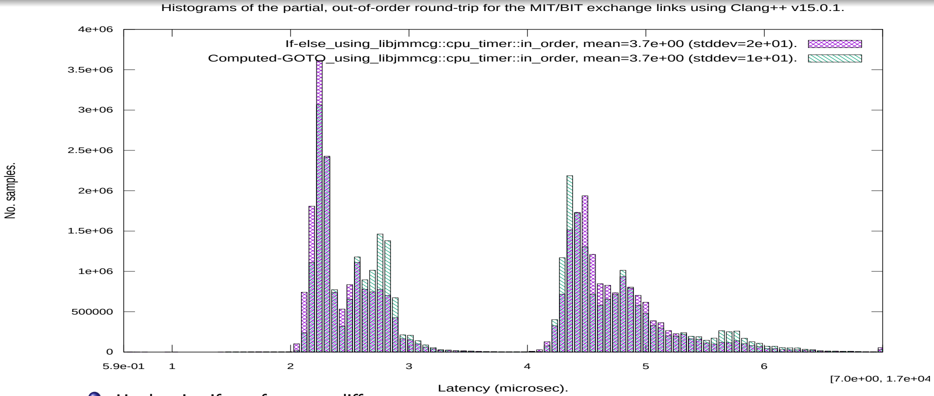
Test 2: `if-else` vs computed-GOTO: histogram, in-order Clang++ ($\leq 4\%$ MAD).

Histograms of the partial, in-order round-trip for the MIT/BIT exchange links using Clang++ v15.0.1.



- The roughly 750nsec resonance, likely due to hardware hazards, is most curious.

Test 2: `if-else` vs computed-`GOTO`: histogram, out-of-order Clang++ ($\leq 5\%$ MAD).



- Hard to justify performance difference.
- The consistent difference between G++ and Clang++ deserves better analysis.

Test 2: Reflections: Performance differences.

- Very small improvements: micro-optimisation “noise floor” hit!
  - Computed-`GOTO`: the generated assembly looks suspicious...
  - Yet it outperforms `if-else` from evidence in histograms.
- The FIX-to-MIT/BIT-Translator test had the same input `STATE`, so executed the same `Transition`:
  - Ideal for a branch-predictor, as a highly predictable conditional-jump!
  - Surprising computed-`GOTO` *beat it*!
  - Researchers at Intel, AMD, etc, etc work very hard to improve the branch-predictor...
- `objdump` has issues generating the disassembly...

Reflections: Code complexity, maintainability and compile-time performance.

- The complexity of the code is outrageous:
  - It looks very much like write-once code: maintainability is lost.
  - Required: a modern compiler that supports C++ very well.
    - g++ v12.2.1 & clang++ v15.0.1 used.
  - The compile-time was not significantly increased...
    - The translation unit takes over 6 minutes to compile on my lap-brick.
    - Less powerful computers could take 10s of minutes...
- Over 10Gb of RAM is required to compile the translation unit.
  - Limits parallelisation of the build...
- The build scripts for `cmake` become much more complex...

Reflections: Issues regarding `xor_modulo_hash` algorithm.

- The hash function must be generated first to permit inlining, which serialises the build.
    - Requires parallelisation or is excessively slow.
- The hash may fail to be generated:
    - Meta state-machine cannot be generated! ***Code simply will not compile!***
    - Critical issue in production code - ***never*** rely on luck to compile one's code...!
    - Use `if-else` or another; $\ll 20$ clock cycles to run: more sophisticated algorithms may have excessive run-times vs `if-else`. Common algorithms e.g. `std::hash`, Hsieh[17] or Murmur2[18]: too slow for our purpose.
- Speculation: more `STATE`s and their values may make generation of the algorithm more likely to fail.
    - Currently `STATE`s ≤ 7 in any of the meta state-machines.

Conclusions. 1/2.

- Exorbitant effort taken to achieve little result?
  - In terms of speed-up: yes.
    - Suspicious assembly-generation may have reduced the performance.
- Managed to force the compiler to generate the computed-`GOTO` with C++:
  - *Heroic effort:* implemented library to recover type-information for `Transition::process(...)` : minimal intrusiveness for users.
  - *Madness*: implemented a data-parallel algorithm to attempt (yes, *Shannon*) to compute minimal, perfect hashes for a high-performance hash.
  - An extremely high-performance *Template Meta-Progammed* state-machine has been implemented as a library[3].

Conclusions. 1/2.

- Exorbitant effort taken to achieve little result?
  - In terms of speed-up: yes.
    - Suspicious assembly-generation may have reduced the performance.
- Managed to force the compiler to generate the computed-`GOTO` with C++:
  - *Heroic effort:* implemented library to recover type-information for `Transition::process(...)` : minimal intrusiveness for users.
  - *Madness*: implemented a data-parallel algorithm to attempt (yes, *Shannon*) to compute minimal, perfect hashes for a high-performance hash.
  - An extremely high-performance *Template Meta-Progammed* state-machine has been implemented as a library[3].

Conclusions, 2/2.

- Choice of micro-optimisation investigated would have been vital:

  Premature optimisation is the root of all evil[4]!

  - The techniques that had to be used may serve as a warning to others...
- I did this so that you would not have to!
- My sincere thanks to:
  - Jon Chesterfield for his patience and tolerance: he listened to me talk about this since 2017...
  - My reviewers: Paul Evans & Vladimir Arnost.
- For more information on methodology or notes, please contact: *accuconf2023@hussar.me.uk*

Conclusions, 2/2.

- Choice of micro-optimisation investigated would have been vital:

  Premature optimisation is the root of all evil[4]!

  - The techniques that had to be used may serve as a warning to others...
- I did this so that you would not have to!
- My sincere thanks to:
  - Jon Chesterfield for his patience and tolerance: he listened to me talk about this since 2017...
  - My reviewers: Paul Evans & Vladimir Arnost.
- For more information on methodology or notes, please contact: *accuconf2023@hussar.me.uk*

Conclusions, 2/2.

- Choice of micro-optimisation investigated would have been vital:

  Premature optimisation is the root of all evil[4]!

  - The techniques that had to be used may serve as a warning to others...
- I did this so that you would not have to!
- My sincere thanks to:
  - Jon Chesterfield for his patience and tolerance: he listened to me talk about this since 2017...
  - My reviewers: Paul Evans & Vladimir Arnost.
- For more information on methodology or notes, please contact: ***accuconf2023@hussar.me.uk***

An outstanding success: introducing Dr. Cassio Neri & Prof. Lorenz Schneider...

- An outstanding micro-optimisation regarding date-conversions:
    - “Euclidean affine functions and their application to calendar algorithms”[19]
- Basically optimises the conversion between the Gregorian calendar and Unix Epoch-based offsets.
- Used in all *nix kernels, `libc`, `<chrono>`, Microsoft .Net (including C♯, etc), Android...
    - Literally billions of installations...
- The most successful micro-optimisation I have *ever* heard of!

For Further Reading I

- Dijkstra, E. W. "Go To statement considered harmful, Commm." ACzl/I, II (3) (1968): 147-148, https://doi.org/10.1145/988056.988069
- https://agner.org/optimize/instruction_tables.ods
- http://libjmmcg.sf.net/
- https://hans.gerwitz.com/2004/08/12/premature-optimization-is-the-root-of-all-evil.html
- Gustafson, J.L. (2011). "Amdahl's Law." In: Padua, D. (eds) Encyclopedia of Parallel Computing. Springer, Boston, MA, https://doi.org/10.1007/978-0-387-09766-4_77

For Further Reading II

- https://www.boost.org/doc/libs/1_81_0/libs/msm/doc/HTML/index.html
- https://www.oreilly.com/library/view/extended-stl-volume/9780321305503/ch14.html
- Bartosz Milewski "Template Metaprogramming Made Easy (Huh?)", https://bartoszmilewski.com/2009/09/08/template-metaprogramming-made-easy-huh/
- http://www.borsaitaliana.it/borsaitaliana/gestione-mercati/migrazionemillenniumit-mit/mit203nativetradinggatewayspecification.en_pdf.htm
- https://www.gnu.org/software/gperf/

For Further Reading III

- https://web.archive.org/web/20221208124607/https://thusspakeak.com/
- M^{c}Guiness, J., Egan, C., “A Domain-Specific Embedded Language for Programming Parallel Architectures.”, DCABES 2013, https://www.researchgate.net/publication/340902083_A_Domain-Specific_Embedded_Language_for_Programming_Parallel_Architectures/references
- https://fiximate.fixtrading.org

For Further Reading IV

- M^{c}Guiness, J., "A Performance Analysis of a Simple Trading System...", CPPNow, Aspen, 2019, https://www.researchgate.net/publication/340926245_A_Performance_Analysis_of_a_Simple_Trading_System
- "http://mathbits.com/MathBits/TISection/Statistics1/MAD.html
- https://gcc.godbolt.org
- http://www.azillionmonkeys.com/qed/hash.html
- https://simonhf.wordpress.com/2010/09/25/murmurhash160/

For Further Reading V

Neri, C., Schneider, L., “Euclidean affine functions and their application to calendar algorithms”, Software Practice and Experience 53(1), December 2022, http://dx.doi.org/10.1002/spe.3172, https://www.researchgate.net/publication/365981828_Euclidean_affine_functions_and_their_application_to_calendar_algorithms