Writing and using compile-time heterogeneous hash-table

Denis Panin, NVIDIA
Senior System Software Engineer

```
# create_ip 1.2.3.4 255.255.255.0
```

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map<string, bool(*)(vector<string>)>
```

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bool callback(vector<string> args) {



}
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map<string, bool(*)(vector<string>)>

bool callback(vector<string> args) {
    if (args.size() != 2) return false;
    ipv4 ip = convert_ip(args[0]);
    if (some_error_check) return false;
    ipv4 mask = convert_ip(args[1]);
    if (some_error_check) return false;
    // do actual work
    return true;
}
```

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IT WORKS AND NO ONE IS GOING TO REWRITE IT

But what do we want?

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1. Normal signature -> void create(ipv4 ip)
2. Automatic args count verification.
3. Automatic string arguments conversion.

Adding new command should take 1 string without any boilerplate

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };
```

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };

if (get_arg_count(func) != args.size()) {
    return error;
}
```

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };

if (get_arg_count(func) != args.size()) {
    return error;
}

tuple<get_arg_types(func)> tpl;
```

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };

if (get_arg_count(func) != args.size()) {
    return error;
}

tuple<get_arg_types(func)> tpl;
for (size_t i = 0; i < args.size(); ++i) {
    using target_type = tuple_element_type<i>(tpl);


}
```

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };

if (get_arg_count(func) != args.size()) {
    return error;
}

tuple<get_arg_types(func)> tpl;
for (size_t i = 0; i < args.size(); ++i) {
    using target_type = tuple_element_type(tpl, i);
    tuple[i] = convert_to<target_type>(args[i]);
    if (invalid(tuple[i])) return error;
}
```

```
void func(const T1& t1, T2 t2);
vector<string> args{ "t1_str", "t2_str" };

if (get_arg_count(func) != args.size()) {
    return error;
}

tuple<get_arg_types(func)> tpl;
for (size_t i = 0; i < args.size(); ++i) {
    using target_type = tuple_element_type(tpl, i);
    tuple[i] = convert_to<target_type>(args[i]);
    if (invalid(tuple[i])) return error;
}

func(expand(tpl)...);
```

```
if (fname == "func1")
    execute(func1, vec_args);

if (fname == "func2")
    execute(func2, vec_args);

if (fname == "func3")
    execute(func3, vec_args);
```

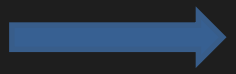
Please no

```
if (fname == "func1")
    execute(func1, vec_args);

if (fname == "func2")
    execute(func2, vec_args);

if (fname == "func3")
    execute(func3, vec_args);
```

We can do better



```
const auto ftbl = make_tuple(
    pair("func1", &func1),
    pair("func2", &func2),
    pair("func3", &func3)
);
lookup_exe(ftbl, "func1", vec_args);
```

Lets make compile-time heterogeneous hash-table with O(1) lookup!

```
size_t cthash(string_view s) {
    size_t hash{ 0 };
    for (char c : s) {
        hash += c * PRIME_1 ^ PRIME_2;
    }
    return hash;
}
```

```
constexpr // yes, really that's enough
size_t cthash(string_view s) {
    size_t hash{ 0 };
    for (char c : s) {
        hash += c * PRIME_1 ^ PRIME_2;
    }
    return hash;
}
```

```
constexpr // yes, really that's enough
size_t cthash(string_view s) {
    size_t hash{ 0 };
    for (char c : s) {
        hash += c * PRIME_1 ^ PRIME_2;
    }
    return hash;
}

struct_with_int<cthash("CSTRING")> si;
```

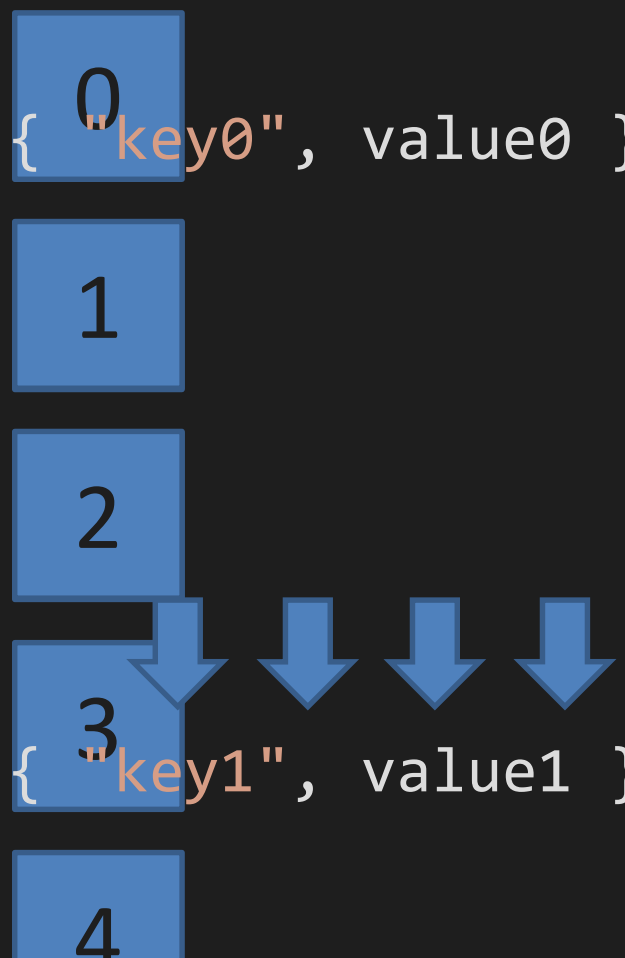
buckets = 5


{ "key4", value4 }
0
{ "key0", value0 }, { "key2", value2 }
1
2
3
{ "key1", value1 }, { "key3", value3 }
4

buckets = 5


```
size_t bucket =
hash("key3") % buckets;
```

buckets = 5

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hash("key3") % buckets;
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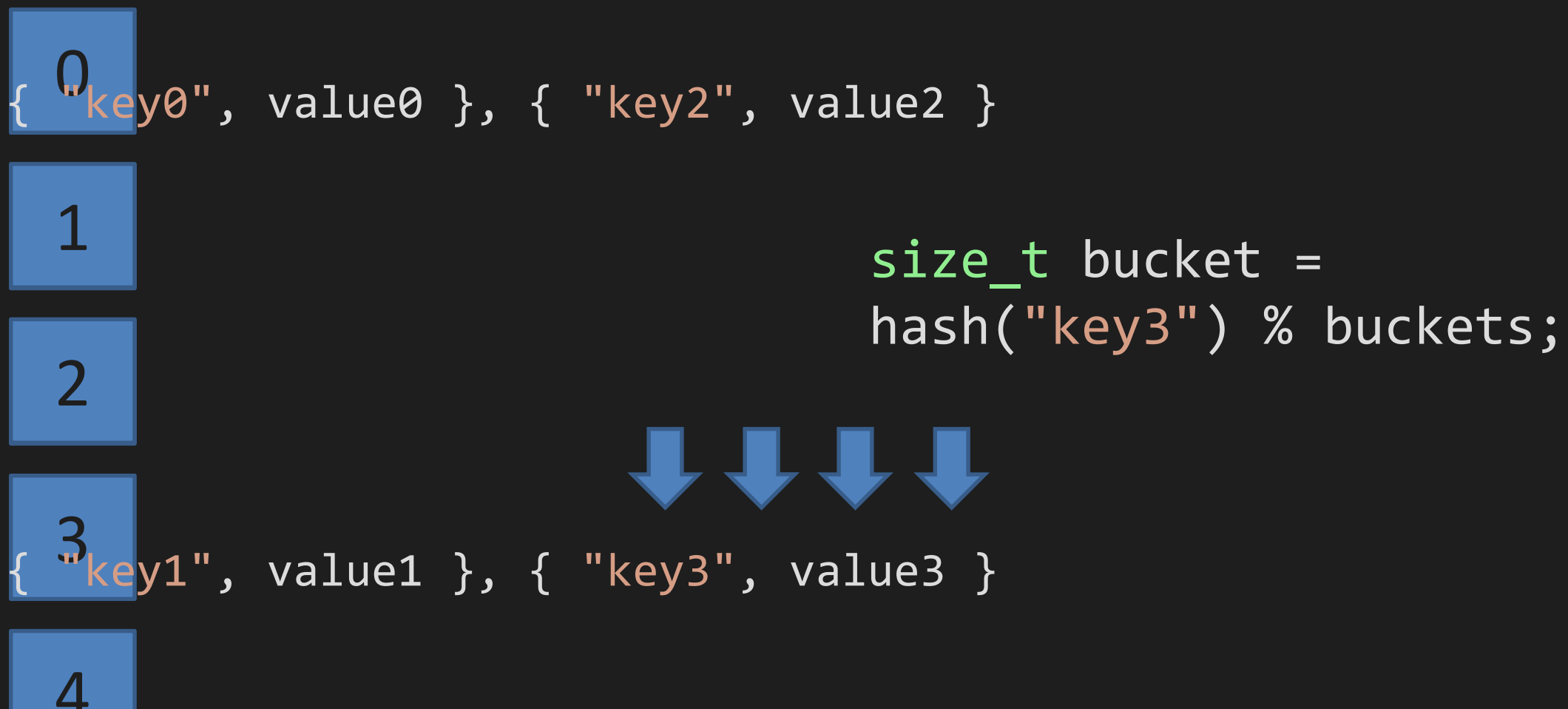
buckets = 5




```
size_t bucket =
hash("key3") % buckets;
```

```
int main() {
    const auto htbl tbl(
        HASH_TABLE_ENTRY("key1", 1),
        HASH_TABLE_ENTRY("key2", nullptr)
    );









}
```

```
int main() {
    const auto htbl tbl(
        HASH_TABLE_ENTRY("key1", 1),
        HASH_TABLE_ENTRY("key2", nullptr)
    );

    tbl.execute("key1", func);
    tbl.execute("key2", func);
    if (!tbl.execute("key3", func))
        cout << "Not found :(" << endl;
}
```

```cpp
int main() {
    const auto htbl tbl(
        HASH_TABLE_ENTRY("key1", 1),
        HASH_TABLE_ENTRY("key2", nullptr)
    );

    const auto func = [](auto val) {
        cout << typeid(val).name() << endl;
    };

    tbl.execute("key1", func);
    tbl.execute("key2", func);
    if (!tbl.execute("key3", func))
        cout << "Not found :(" << endl;
}
```

```
int main() {
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    const auto func = [](auto val) {
        cout << typeid(val).name() << endl;
    };

    tbl.execute("key1", func);
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    if (!tbl.execute("key3", func))
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int main() {
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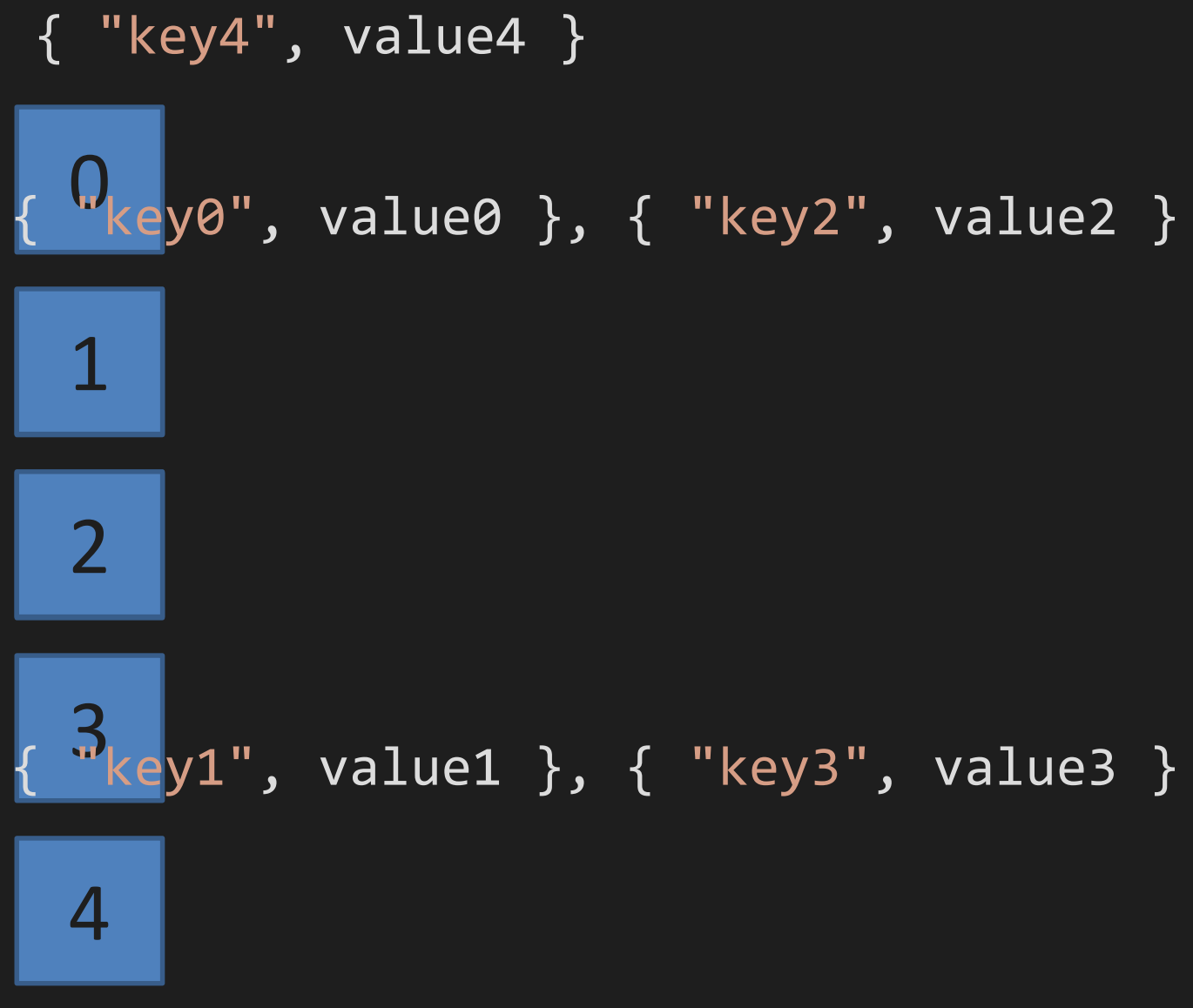
```cpp
int main() {
    const auto htbl tbl(
        HASH_TABLE_ENTRY("key1", 1),
        HASH_TABLE_ENTRY("key2", nullptr)
    );

    const auto func = [](auto val) {
        cout << typeid(val).name() << endl;
    };

    tbl.execute("key1", func);
    tbl.execute("key2", func);
    if (!tbl.execute("key3", func))
        cout << "Not found :(" << endl;
}
```

```
template <size_t HASH, typename VAL>
struct hash_table_entry {
  const string_view key;
  const VAL val;
  static constexpr auto hash = HASH;
};
```

```
#define HASH_TABLE_ENTRY(key, val) \
hash_table_entry<cthash(key), decltype(val)> (key, val)
```


{ "key4", value4 }
0
{ "key0", value0 }, { "key2", value2 }
1
2
3
{ "key1", value1 }, { "key3", value3 }
4

```
tuple(
        tuple( { "key4", value4 } ),

       tuple( { "key0", value0 }, { "key2", value2 } ),

        tuple(),

        tuple(),

      tuple( { "key1", value1 }, { "key3", value3 } )
);
```

```
tuple(
        tuple( { "key4", value4 } ),

       tuple( { "key0", value0 }, { "key2", value2 } ),

        tuple(),
        tuple(),

      tuple( { "key1", value1 }, { "key3", value3 } )
);
```

Don't try this at home,
unless you have >1TB RAM and
few spare weeks

```
create_table(
    pair0, // B1
    pair1, // B4
    pair2, // B1
    pair3, // B4
    pair4, // B0
)
```

```
array(
    { pair4 },
    { pair0, pair2 },
    {},
    { pair1, pair3 },
    {}
)
```

```
create_table(
    pair0, // B1
    pair1, // B4
    pair2, // B1
    pair3, // B4
    pair4, // B0
)
```

```
array(
    { pair4 },
    { pair0, pair2 },
    {},
    { pair1, pair3 },
    {}
)
```

Element count per bucket.
array(1, 2, 0, 2, 0);

```
template <typename TPL>
using hashmeta_t = array<size_t, tuple_size_v<TPL>>;
```

```cpp
template <typename TPL>
using hashmeta_t = array<size_t, tuple_size_v<TPL>>;

hashmeta_t<TPL> occurences = {}; // all zeroes
calc_occurences(tpl, occurences);
```

```cpp
template <typename TPL>
using hashmeta_t = array<size_t, tuple_size_v<TPL>>;

hashmeta_t<TPL> occurences = {}; // all zeroes
calc_occurences(tpl, occurences);

template <size_t IDX = 0, typename TPL>
constexpr void calc_occurences(const TPL& tpl, hashmeta_t<TPL>& arr) {
    static constexpr auto sz = tuple_size_v<TPL>;
    if constexpr (sz > IDX) {
        const auto bucket = tuple_element_t<IDX, TPL>::HASH % sz;
        ++arr[bucket];
        calc_occurences<IDX + 1>(tpl, arr);
    }
}
```

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

```
array(
    { pair4 },
    { pair0, pair2 },
    {},
    { pair1, pair3 },
    {}
)
```

Element count per bucket.
array(1, 2, 0, 2, 0);

Offsets to bucket start.
array(0, 1, 3, 3, 5);

[1, 2, 0, 2, 0] -> [0, 1, 3, 3, 5]

```
template <typename TPL>
constexpr auto calc_offsets(const TPL& tpl) {
    hashmeta_t<TPL> occ = {};
    calc_occurences(tpl, occ);
    hashmeta_t<TPL> off = {};
    for (size_t i = 1; i < tuple_size_v<TPL>; ++i) {
        off[i] = off[i - 1] + occ[i - 1];
    }
    return offsets;
}
```

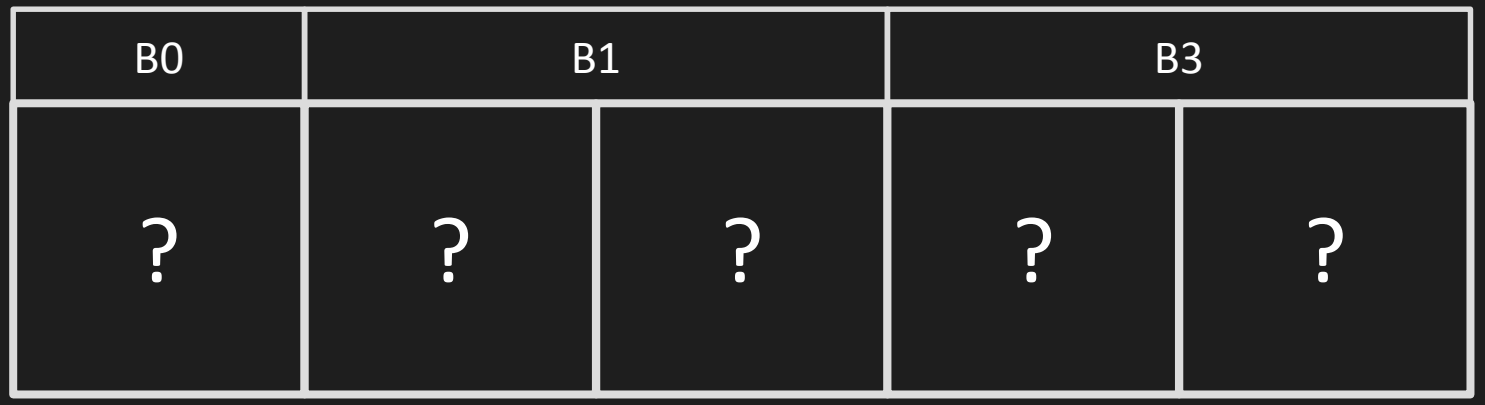
```
create_table(
   pair0, // B1
   pair1, // B3
   pair2, // B1
   pair3, // B3
   pair4, // B0
)
```

Copy of offsets
[0, 1, 3, 3, 5]

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 1, 3, 3, 5]

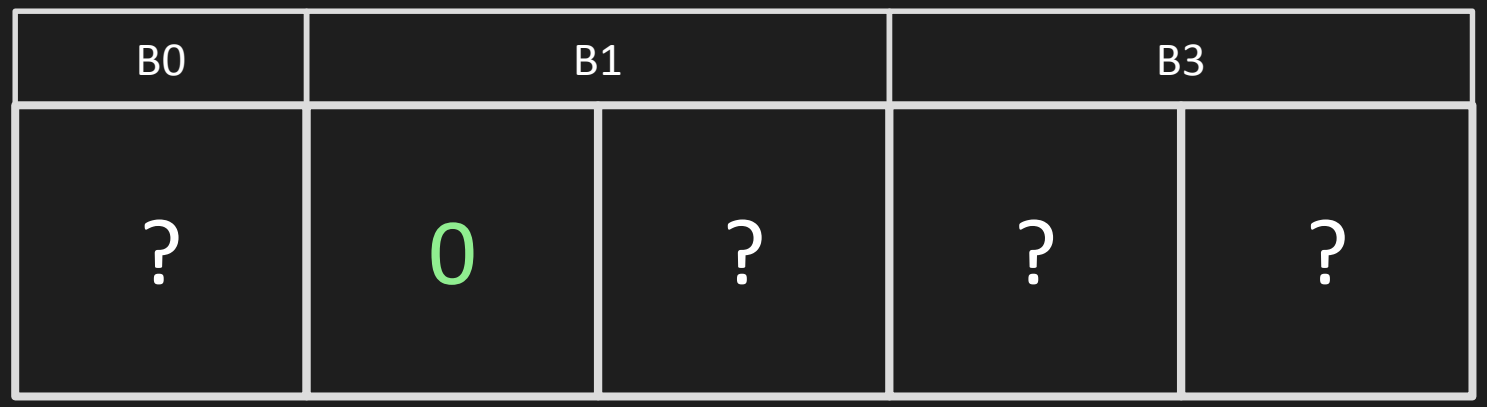
Array of indexes



```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 1, 3, 3, 5]

2



Array of indexes

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 2, 3, 3, 5]

4

Array of indexes

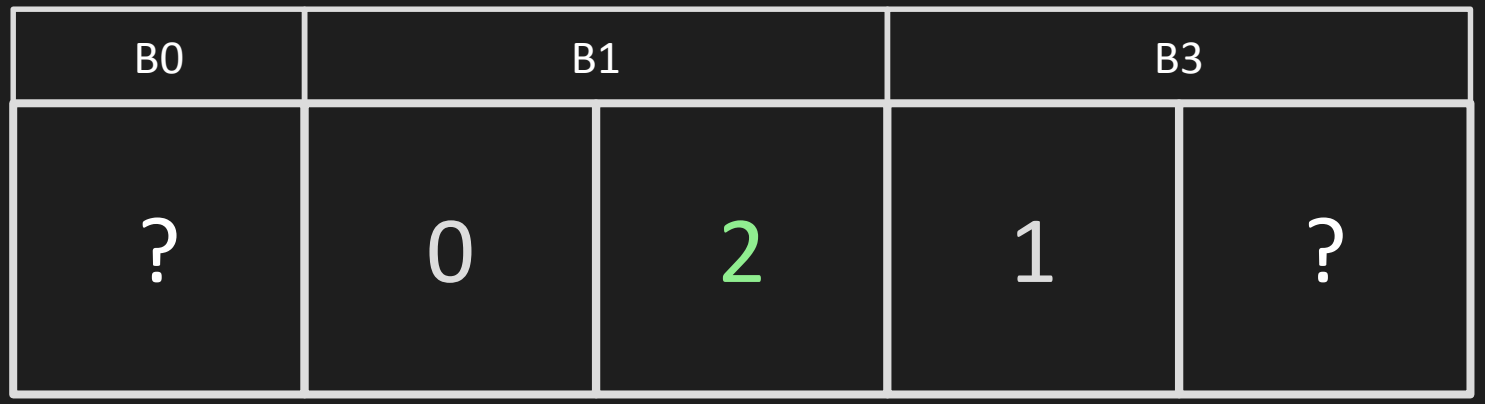
B0	B1		B3	
?	0	?	1	?

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 2, 3, 4, 5]

3

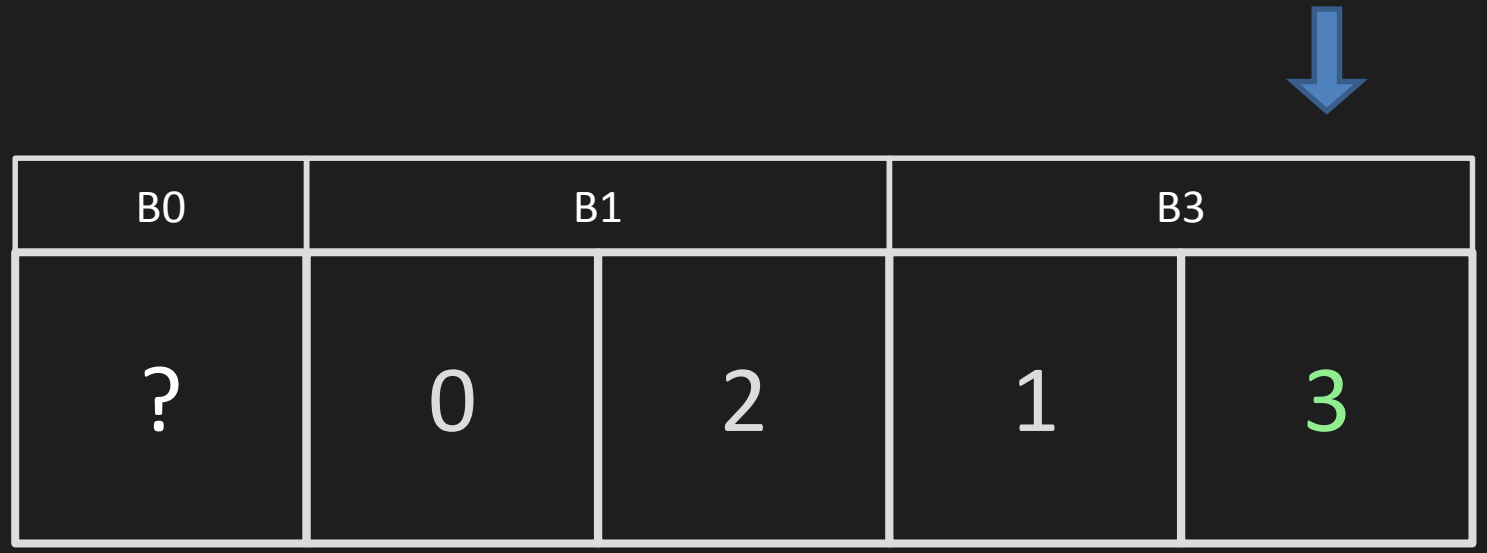
Array of indexes



```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 3, 3, 4, 5]

5

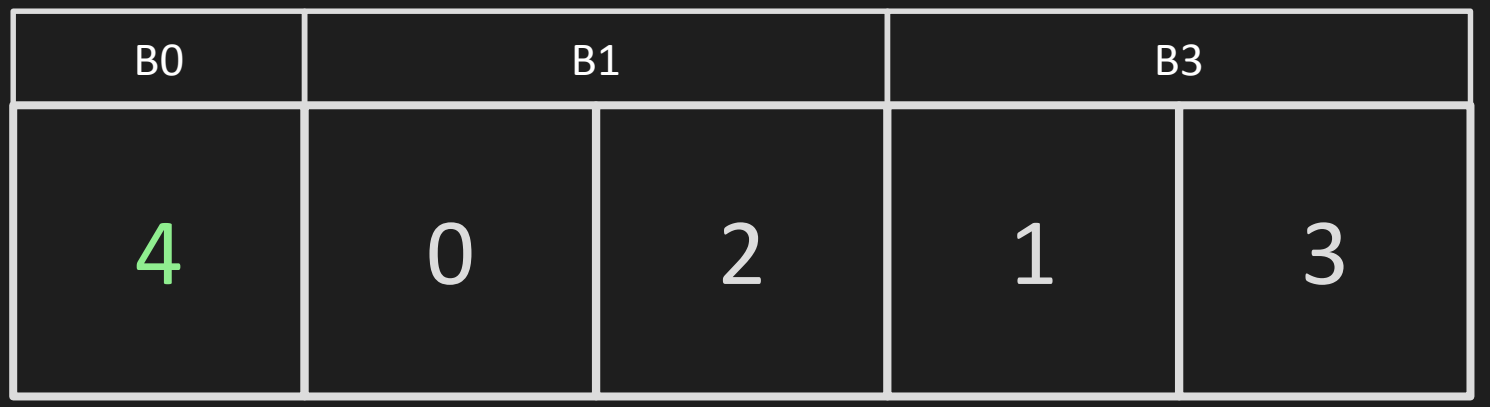


Array of indexes

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Copy of offsets
[0, 3, 3, 5, 5]

1



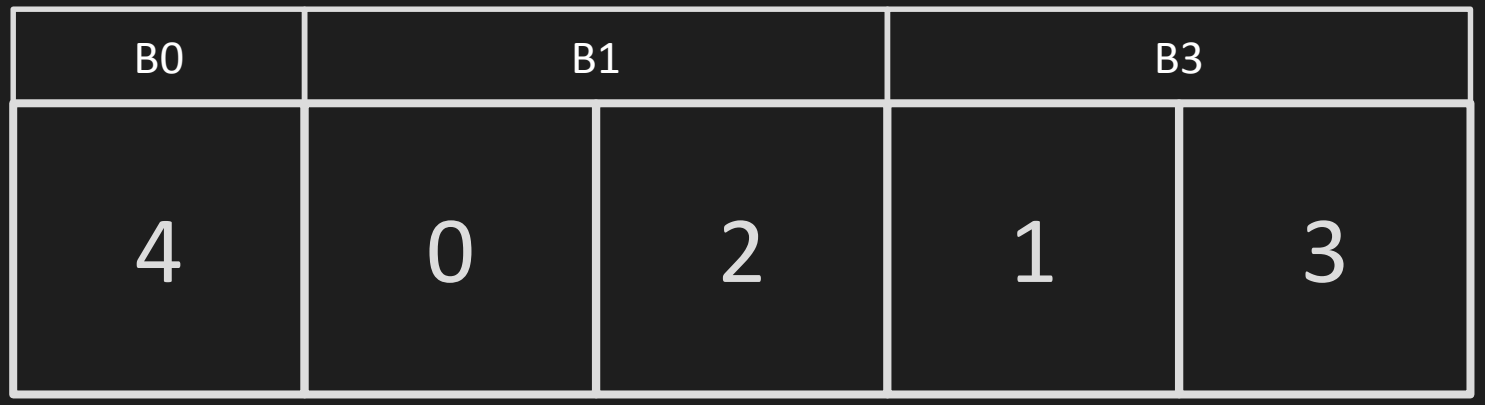
Array of indexes

```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Original offsets
[0, 1, 3, 3, 5]

Copy of offsets
[1, 3, 3, 5, 5]

Array of indexes



```
create_table(
    pair0, // B1
    pair1, // B3
    pair2, // B1
    pair3, // B3
    pair4, // B0
)
```

Original offsets
[0, 1, 3, 3, 5]

Indexes
[4, 0, 2, 1, 3]

```
template <size_t IDX = 0, typename TPL>
constexpr void calc_indexes_impl(const TPL& tpl,
                hashmeta_t<TPL>& offs, hashmeta_t<TPL>& idxes) {
    if constexpr (tuple_size_v<TPL> > IDX) {
        const auto bucket = tuple_element_t<IDX, TPL>::HASH
                            % tuple_size_v<TPL>;
        const auto place = offs[bucket]++;
        idxes[place] = IDX;
        calc_indexes_impl<IDX + 1>(tpl, offs, idxes);
    }
}
```

```
template <typename ... ARGS>
class htbl {
public:
    constexpr htbl(ARGS&&... args) :
        m_tup(forward_as_tuple(args...)),
        m_off(calc_offsets(m_tup)),
        m_idx(calc_indexes(m_tup, m_off))
    {}

    template <typename FN>
    bool execute(const char* key, const FN& fn) const;

private:
    const tuple<ARGS...> m_tup;
    const array<size_t, sizeof...(ARGS)> m_off;
    const array<size_t, sizeof...(ARGS)> m_idx;
};
```

m_off [0, 1, 3, 3, 5] m_idx[4, 0, 2, 1, 3]

```
template <typename FN>
bool execute(const char* key, const FN& fn) const {
    const auto bucket = calc_hash(key) % tuple_size_v<TPL>;

    const auto from = m_off[bucket];
    const auto to = (bucket + 1 == tuple_size_v<TPL>) ?
                    tuple_size_v<TPL> :
                    m_off[bucket + 1];
    ...
```

m_off [0, 1, 3, 3, 5] m_idx[4, 0, 2, 1, 3]

```
template <typename FN>
bool execute(const char* key, const FN& fn) const {
    ...
    for (size_t i = from; i < to; ++i) {
        if (big_switch(m_tup, m_idx[i], key, fn) {
            return true;
        }
    }
    return false;
}
```

```
template <typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {



    switch (idx) {
        case 0: if (get<0>.key == key) { func(get<0>.val); return true; }


        case 1: if (get<1>.key == key) { func(get<1>.val); return true; }


        case 2: if (get<2>.key == key) { func(get<2>.val); return true; }


        ...
    }
    return false;
}
```

```cpp
template <typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {



    switch (idx) {
        case 0: if constexpr (0 < tuple_size_v<TPL>)
                if (get<0>.key == key) { func(get<0>.val); return true; }

        case 1: if constexpr (1 < tuple_size_v<TPL>)
                if (get<1>.key == key) { func(get<1>.val); return true; }

        case 2: if constexpr (2 < tuple_size_v<TPL>)
                if (get<2>.key == key) { func(get<2>.val); return true; }

        ...
    }
    return false;
}
```

```cpp
template <typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {

    static_assert(tuple_size_v<TPL> > 3, "meh");

    switch (idx) {
        case 0: if constexpr (0 < tuple_size_v<TPL>)
                if (get<0>.key == key) { func(get<0>.val); return true; }

        case 1: if constexpr (1 < tuple_size_v<TPL>)
                if (get<1>.key == key) { func(get<1>.val); return true; }

        case 2: if constexpr (2 < tuple_size_v<TPL>)
                if (get<2>.key == key) { func(get<2>.val); return true; }

        ...
    }
    return false;
}
```

Token stream injection (Maybe C++23)

```
switch (idx) {
    case N: if constexpr (N < tuple_size_v<TPL>)
        if (get<N>.key == key) { ... };
    ...
}
```

Token stream injection (Maybe C++23)

```
switch (idx) {
    case N: if constexpr (N < tuple_size_v<TPL>)
        if (get<N>.key == key) { ... };
    ...
}

switch (idx) {
    constexpr {
        for (size_t N : tuple_size_v<TPL>) {
          -> { case N: ... }
        }
    }
    default: return false;
}
```

John Carmack

@ID_AA_Carmack

Following

Saw comment // NEW BOOST CODE, and had a moment of panic before realizing it was vehicle boost, not C++ boost

2:05 PM - 15 Jun 2011

136 Retweets **51** Likes

14 136 51

```cpp
template <typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {

    static_assert(tuple_size_v<TPL> > 3, "meh");

    switch (idx) {
        case 0: if constexpr (0 < tuple_size_v<TPL>)
                if (get<0>.key == key) { func(get<0>.val); return true; }

        case 1: if constexpr (1 < tuple_size_v<TPL>)
                if (get<1>.key == key) { func(get<1>.val); return true; }

        case 2: if constexpr (2 < tuple_size_v<TPL>)
                if (get<2>.key == key) { func(get<2>.val); return true; }

        ...
    }
    return false;
}
```

```
template <typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {

    #define MAX_SWITCHES 50
    static_assert(MAX_SWITCHES > tuple_size_v<TPL>, "booooost");

    switch (idx) {
        BOOST_PP_REPEAT(MAX_SWITCHES, NV_SWITCH, 1);
    }

    return false;
}

#define NV_SWITCH(unused, IDX, unused2)                                  \
case IDX: if constexpr (0 < tuple_size_v<TPL>)                           \
if (get<IDX>.key == key) { func(get<IDX>.val); return true; }
```

```cpp
template <size_t BEG = 0, typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {
    switch (idx) {
        case BEG * 10 + 0: if constexpr (BEG * 10 + 0 < tuple_size_v<TPL>)
            { /* code for element BEG * 10 + 0; */ return true; }
        ...









    }

    return false;
}
```

```cpp
template <size_t BEG = 0, typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {
    switch (idx) {
        case BEG * 10 + 0: if constexpr (BEG * 10 + 0 < tuple_size_v<TPL>)
            { /* code for element BEG * 10 + 0; */ return true; }
        ...
        // same for +1 to +8
        ...
        case BEG * 10 + 9: if constexpr (BEG * 10 + 9 < tuple_size_v<TPL>)
            { /* code for element BEG * 10 + 9; */ return true; }



    }

    return false;
}
```

```cpp
template <size_t BEG = 0, typename TPL, typename FN>
auto big_switch(const TPL& tpl, size_t idx, string_view key, const FN& func) {
    switch (idx) {
        case BEG * 10 + 0: if constexpr (BEG * 10 + 0 < tuple_size_v<TPL>)
            { /* code for element BEG * 10 + 0; */ return true; }
        ...
        // same for +1 to +8
        ...
        case BEG * 10 + 9: if constexpr (BEG * 10 + 9 < tuple_size_v<TPL>)
            { /* code for element BEG * 10 + 9; */ return true; }

        default:           if constexpr (BEG * 10 + 10 < tuple_size_v<TPL>)
            { return big_switch<BEG + 1>(tpl, idx, key, func);
    }

    return false;
}
```

Let's use heterogeneous hash-table for initial idea of string-to-func mapping!

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {



};

tbl.execute("key1", functor);
```

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {
    using TUP = get_fn_info<decltype(val)>::args;


};

tbl.execute("key1", functor);
```

```
template <typename RET, typename ... ARGS>
auto get_args(function<RET(ARGS...)>) {
    return tuple<decay_t<ARGS>...>{};
}
```

```cpp
template <typename RET, typename ... ARGS>
auto get_args(function<RET(ARGS...)>) {
    return tuple<decay_t<ARGS>...>{};
}

template <typename FN>
struct get_fn_info {
    using args = decltype(
        get_args(
            function{ std::declval<FN>() }
        )
    );
};
```

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {
    using TUP = get_fn_info<decltype(val)>::args;


};

tbl.execute("key1", functor);
```

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {
    using TUP = get_fn_info<decltype(val)>::args;
    const TUP conv = convert<TUP>(params);

};

tbl.execute("key1", functor);
```

```cpp
template <typename T>
T converter(const string& str) {
    static_assert(is_same_v<T, void>);
}

template <>
int converter<int>(const string& str) {
    return stoi(str);
}

template <>
float converter<float>(const string& str) {
    return stof(str);
}
```

```
std::make_index_sequence<N> is alias
std::index_sequence<0, 1, 2, ..., N - 1>

fn1(make_index_sequence<5>{});

template <size_t ... N>
void fn1(index_sequence<N...>) {
    accept_any(N...);
    // accept_any(0, 1, 2, ..., N - 1);
}
```

```cpp
template <typename ... ARGS>
void fn(tuple<ARGS...> tpl) {
    fn_helper(tpl,
      make_index_sequence<sizeof...(ARGS)>{});
}

template <typename TPL, size_t ... N>
void fn_helper(TPL tpl, index_sequence<N...>)  {
    accept_any(get<N>(tpl)...);
    // accept_any(get<0>(tpl), ..., get<N-1>(tpl));
}
```

```
template <typename TPL, typename CONT>
TPL converter(const CONT& cont) {
    return converter_impl<TPL>(cont,
        make_index_sequence<tuple_size_v<TPL>>{});
}
```

```
template <typename TPL, typename CONT, size_t ... N>
auto converter_impl(const CONT& cont,
                    index_sequence<N...>) {
    return make_tuple(
        convert<tuple_element_t<N, TPL>>(cont[N])...
    );
}
```

```
template <typename TPL, typename CONT, size_t ... N>
auto converter_impl(const CONT& cont,
                    index_sequence<N...>) {
    return make_tuple(
        convert<tuple_element_t<N, TPL>>(cont[N])...
    );
}

    return make_tuple(
        convert<tuple_element_t<0, TPL>>(cont[0]),
        convert<tuple_element_t<1, TPL>>(cont[1])
    )
```

```
template <typename TPL, typename CONT, size_t ... N>
auto converter_impl(const CONT& cont,
                    index_sequence<N...>) {
    return make_tuple(
        convert<tuple_element_t<N, TPL>>(cont[N])...
    );
}

    return make_tuple(
        convert<int>(cont[0]),
        convert<float>(cont[1])
    )
```

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {
    using TUP = get_fn_info<decltype(val)>::args;
    const TUP conv = convert<TUP>(params);

};

tbl.execute("key1", functor);
```

```
void fn1(int, float);

const auto htbl tbl(
    HASH_TABLE_ENTRY("key1", &fn1),
);

vector<string> params{ "3", "5.7" };
const auto functor = [&params](auto val) {
    using TUP = get_fn_info<decltype(val)>::args;
    const TUP conv = convert<TUP>(params);
    apply(val, conv);
};

tbl.execute("key1", functor);
```

```
static const htbl tbl(
   HASH_TABLE_ENTRY("hello",
      htbl(HASH_TABLE_ENTRY("world", &func))
   )
);
```

Nested hash tables can be used for multi-word commands like "hello world arg1 arg2"

```
static const htbl tbl(
   HASH_TABLE_ENTRY("hello",
      htbl(HASH_TABLE_ENTRY("world", &func))
   )
);
```

Nested hash tables can be used for multi-word commands like "hello world arg1 arg2"

```
struct functor {
    template <typename ... ARGS>
    bool operator()(const htbl<ARGS...>& tbl) const ( ... );

    template <typename FN>
    bool operator()(const FN& fn) const ( ... );
}
```

THE END

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