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How Meta Made Debugging Async Code Easier with Coroutines and Senders

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& JESSICA WONG

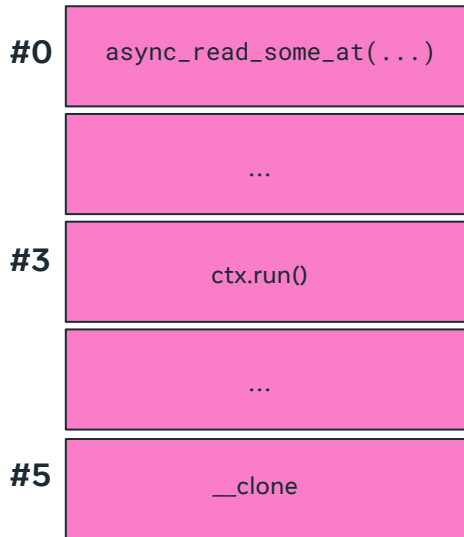


20
24

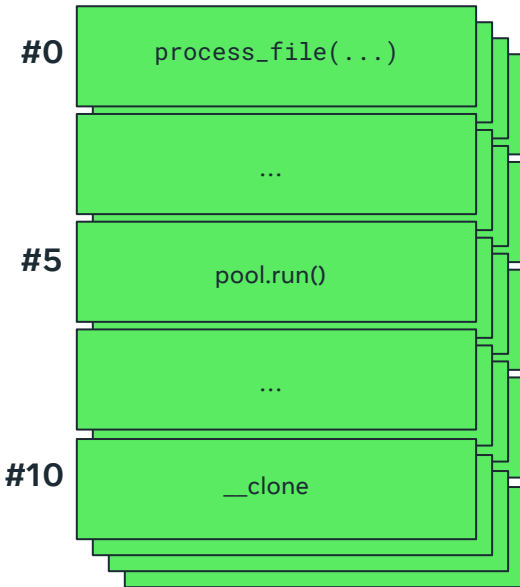


Stack Traces for Async Code are Unhelpful

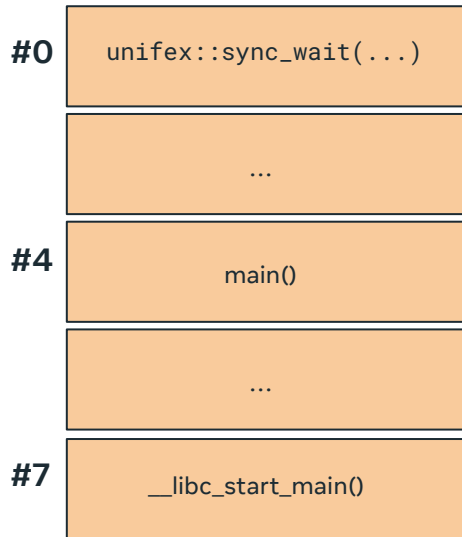
IO Thread:



Threadpool threads:

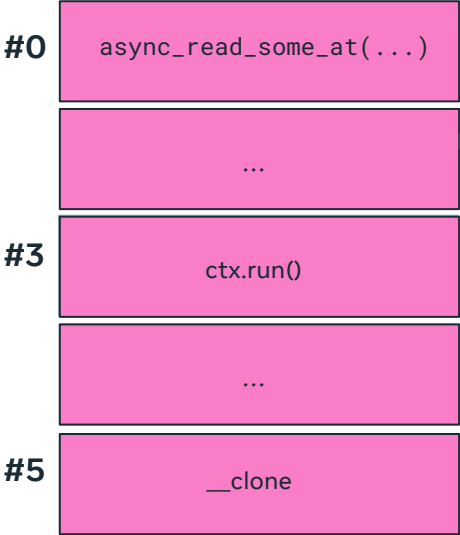


Main thread:

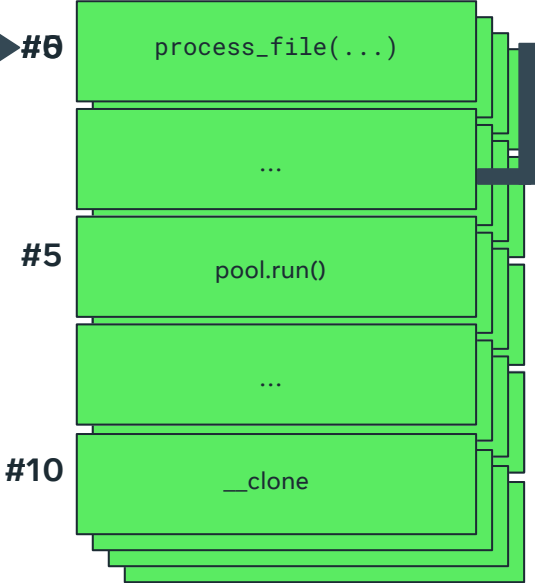


What would be better?

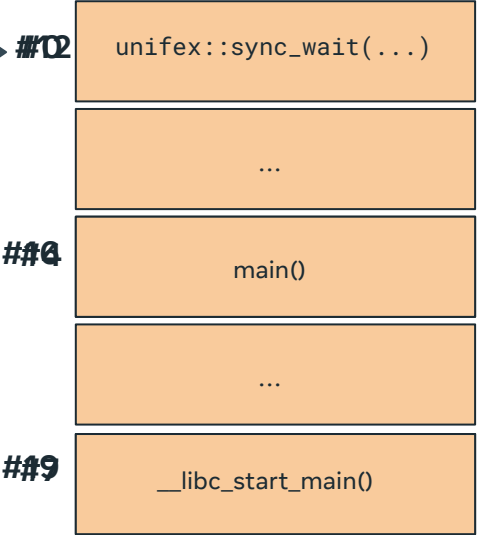
IO Thread:



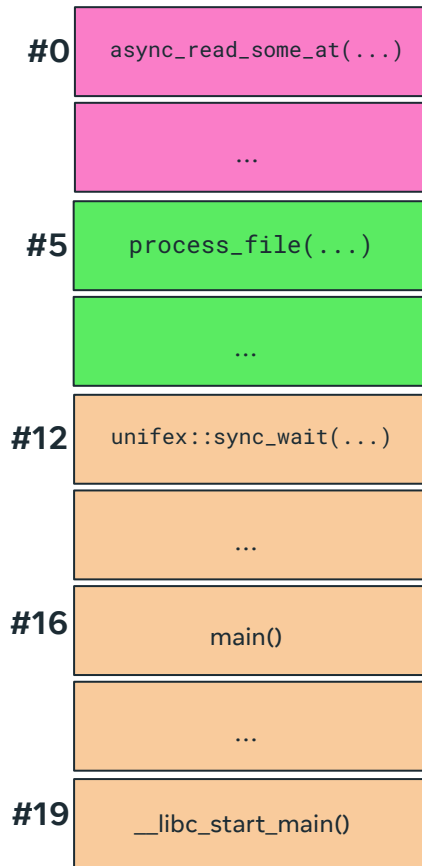
Threadpool threads:



Main thread:



Async Stacks are Better



Structured Concurrency Makes Async Stacks Possible

- Lewis Baker brought them to Folly in 2020
- We spent the last year bringing them to Unifex

Demo

```
int main(int argc, char** argv) {
    unifex::static_thread_pool pool;
    io_uring_context ctx;
    unifex::task<void> task = async_main({argv + 1, argc - 1},
                                         pool, ctx);

    unifex::sync_wait(std::move(task));

    return 0;
}
```

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    return 0;
}
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```
unifex::task<void> async_main(unifex::span<char *> args, auto &pool, auto &io) {  
    auto jobs = args | views::transform(  
        [io](fs::path fileName) -> unifex::task<word_stats> {  
            auto file = unifex::open_file_read_only(io, fileName);  
            return process_file(std::move(file));  
        });  
    auto stats = co_await unifex::on(  
        pool.get_scheduler(), unifex::when_all_range(jobs.begin(), jobs.end()));  
  
    for (std::size_t i = 0; i < stats.size(); ++i) {  
        double mean = (double)stats[i].chars / (double)stats[i].lines;  
        std::printf("Average word length in %s is %g\n", args[i], mean);  
    }  
}
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    }  
}
```



```
struct word_stats { unsigned long chars{}; unsigned long lines{} };
unifex::task<word_stats> process_file(auto file) {
    word_stats result;
    std::array<char, 4096> buffer;
    int64_t offset = 0;
    while (std::size_t bytesRead = co_await async_read_some_at(file, offset, buffer)) {
        auto validBytes = unifex::span(buffer.data(), bytesRead);
        auto newlines = ranges::count(validBytes, '\n');

        result.lines += newlines;
        result.chars += (bytesRead - newlines);

        offset += bytesRead;
    }
    co_return result;
}
```

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```

Demo

```
(lldb) co_bt
frame #0 : 0x0000555555578278 in unifex::_task::_task<(anonymous
namespace)::word_stats, false>::type (anonymous
namespace)::process_file<unifex::linuxos::io_uring_context::async_read_only_file>(uni
fex::linuxos::io_uring_context::async_read_only_file) () at
/home/cppcon/cppcon24-async-demo/src/main.cpp:70
frame #1 : 0x0000555555583b08 in
std::__1::coroutine_handle<void>::resume[abi:ne180100]() const () at
/usr/lib/llvm-18/include/c++/v1/__coroutine/coroutine_handle.h:69
frame #2 : 0x0000555555584045 in unifex::_ch::continuation_handle<void>::resume()
() at /home/cppcon/cppcon24-async-demo/libunifex/include/unifex/continuations.hpp:220
frame #3 : 0x0000555555571da5 in
unifex::_ch::continuation_handle<unifex::_task::_promise<(anonymous
namespace)::word_stats, false>::type>::resume() () at
/home/cppcon/cppcon24-async-demo/libunifex/include/unifex/continuations.hpp:311
frame #4 : 0x0000555555579f86 in unifex::_task::_sr_thunk_task<(anonymous
namespace)::word_stats>::type unifex::_task::inject_stop_request_thunk<(anonymous
namespace)::word_stats, false>(unifex::_task::_sa_task<(anonymous
namespace)::word_stats, false>::type) () at
/home/cppcon/cppcon24-async-demo/libunifex/include/unifex/task.hpp:824
frame #5 : 0x000055555557add3 in
unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper<unifex::_when_all_range::_
element_receiver<unifex::_inject::_rcvr_wrapper<unifex::_with_query_value::_receiver
```

(lldb) co_bt

```
frame #0 : 0x000055555578278 in unifex::_task::_task<(anonymous namespace)::word_stats, fal
frame #1 : 0x0000555555583b08 in std::_1::coroutine_handle<void>::resume[abi:ne180100]() co
frame #2 : 0x0000555555584045 in unifex::_ch::continuation_handle<void>::resume() () at /hom
frame #3 : 0x0000555555571da5 in unifex::_ch::continuation_handle<unifex::_task::_promise<a
frame #4 : 0x0000555555579f86 in unifex::_task::_sr_thunk_task<(anonymous namespace)::word_s
frame #5 : 0x000055555557add3 in unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper
frame #6 : 0x000055555556cd1e in unifex::_task::_task<void, false>::type (anonymous namespac
frame #7 : 0x000055555556cd1e in unifex::_task::_task<void, false>::type (anonymous namespac
frame #8 : 0x000055555557bf83 in unifex::_task::_task<void, false>::type (anonymous namespac
frame #9 : 0x0000555555558986 in auto unifex::_on::_fn::operator()<unifex::_static_thread_po
frame #10: 0x000055555556b244 in decltype(tag_invoke((unifex::_seq::_cpo::_fn)(fp), (unifex:
frame #11: 0x000055555556af27 in auto unifex::_wsa::_make_sender<unifex::_seq::_sndr<unifex:
frame #12: 0x00005555555588b5 in decltype(auto) unifex::_task::_promise<void, false>::type::
frame #13: 0x000055555557dc9c in unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper
frame #14: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:10
frame #15: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:10
frame #16: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:10
frame #17: 0x000055555555761c in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:10
frame #18: 0x00007ffff7b1e083 in __libc_start_main () at ???:0
```

(lldb)

```
0 : 0x0000555555578278 in unifex::_task::_task<(anonymous namespace)::word_stats, false>::type (
1 : 0x0000555555583b08 in std::__1::coroutine_handle<void>::resume[abi:ne180100]() const () at /
2 : 0x0000555555584045 in unifex::_ch::continuation_handle<void>::resume() () at /home/cppcon/cp
3 : 0x0000555555571da5 in unifex::_ch::continuation_handle<unifex::_task::_promise<(anonymous na
4 : 0x0000555555579f86 in unifex::_task::_sr_thunk_task<(anonymous namespace)::word_stats>::type
5 : 0x000055555557add3 in unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper<unifex::_w
6 : 0x000055555556cd1e in unifex::_task::_task<void, false>::type (anonymous namespace)::async_m
7 : 0x000055555556cd1e in unifex::_task::_task<void, false>::type (anonymous namespace)::async_m
8 : 0x000055555557bf83 in unifex::_task::_task<void, false>::type (anonymous namespace)::async_m
9 : 0x0000555555558986 in auto unifex::_on::_fn::operator()<unifex::_static_thread_pool::context
10: 0x000055555556b244 in decltype(tag_invoke((unifex::_seq::_cpo::_fn)(fp), (unifex::_sf::sende
11: 0x000055555556af27 in auto unifex::_wsa::_make_sender<unifex::_seq::_sndr<unifex::_static_th
12: 0x00005555555588b5 in decltype(auto) unifex::_task::_promise<void, false>::type::await_trans
13: 0x000055555557dc9c in unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper<unifex::_i
14: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
15: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
16: 0x0000555555557604 in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
17: 0x000055555555761c in main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:105
18: 0x00007ffff7b1e083 in __libc_start_main () at ???:0
```



```
0 : unifex::_task::_task<(anonymous namespace)::word_stats, false>::type (anonymous namespace)::
1 : std::__1::coroutine_handle<void>::resume[abi:ne180100]() const () at /usr/lib/llvm-18/include
2 : unifex::_ch::continuation_handle<void>::resume() () at /home/cppcon/cppcon24-async-demo/libu
3 : unifex::_ch::continuation_handle<unifex::_task::_promise<(anonymous namespace)::word_stats,
4 : unifex::_task::_sr_thunk_task<(anonymous namespace)::word_stats>::type unifex::_task::inject
5 : unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper<unifex::_when_all_range::_elemen
6 : unifex::_task::_task<void, false>::type (anonymous namespace)::async_main<unifex::_static_th
7 : unifex::_task::_task<void, false>::type (anonymous namespace)::async_main<unifex::_static_th
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9 : auto unifex::_on::_fn::operator()<unifex::_static_thread_pool::context::scheduler, unifex::_
10: decltype(tag_invoke((unifex::_seq::_cpo::_fn)(fp), (unifex::_sf::sender_for<unifex::schedule
11: auto unifex::_wsa::_make_sender<unifex::_seq::_sndr<unifex::_static_thread_pool::context::sc
12: decltype(auto) unifex::_task::_promise<void, false>::type::await_transform<unifex::_seq::_sn
13: unifex::_await::_sender_task<unifex::_inject::_rcvr_wrapper<unifex::_inject::_rcvr_wrapper<u
14: main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
15: main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
16: main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
17: main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:105
18: __libc_start_main () at ???:0
```

```
0 : unifex::task<word_stats> process_file<...>(async_read_only_file) () at /home/cppcon/cppcon24-a
1 : std::coroutine_handle<void>::resume[abi:ne180100]() const () at /usr/lib/llvm-18/include/c++
2 : unifex::continuation_handle<void>::resume() () at /home/cppcon/cppcon24-async-demo/libunifex
3 : unifex::continuation_handle<..._promise<word_stats>>::resume() () at /home/cppcon/cppcon24-asy
4 : ..._sr_thunk_task<...> ...inject_stop_request_thunk<...>(..._sa_task<word_stats>) () at /home/cppcon/c
5 : auto unifex::connect_awaitable(task<void>, receiver auto&) () at /home/cppcon/cppcon24-async
6 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&)::'lambda' at /home/cppcon/cppcon
7 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&)::'lambda' at /home/cppcon/cppcon
8 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&) () at /home/cppcon/cppcon24-asy
9 : auto unifex::on(scheduler auto&&, sender auto&&) const () at /home/cppcon/cppcon24-async-dem
10: decltype(auto) tag_invoke(...) () at /home/cppcon/cppcon24-async-demo/libunifex/include/unifex
11: auto unifex::_wsa::_make_sender<...>(auto&&, auto&&) () at /home/cppcon/cppcon24-async-demo/li
12: decltype(auto) ..._promise<void>::await_transform(...) () at /home/cppcon/cppcon24-async-demo/li
13: auto unifex::connect_awaitable(task<void>, receiver auto&) () at /home/cppcon/cppcon24-async
14: main () at /home/cppcon/cppcon24-async-demo/src/main.cpp:103
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0 : unifex::task<word_stats> process_file<...>(async_read_only_file) () at main.cpp:70
1 : std::coroutine_handle<void>::resume[abi:ne180100]() const () at coroutine_handle.h:69
2 : unifex::continuation_handle<void>::resume() () at continuations.hpp:220
3 : unifex::continuation_handle<..._promise<word_stats>>::resume() () at continuations.hpp:311
4 : ..._sr_thunk_task<...> ...inject_stop_request_thunk<...>(..._sa_task<word_stats>) () at task.hpp:824
5 : auto unifex::connect_awaitable(task<void>, receiver auto&) () at connect_awaitable.hpp:234
6 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&)::'lambda' at main.cpp:85
7 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&)::'lambda' at main.cpp:85
8 : unifex::task<void> async_main<...>(span<char*>, auto&, auto&) () at main.cpp:89
9 : auto unifex::on(scheduler auto&&, sender auto&&) const () at on.hpp:51
10: decltype(auto) tag_invoke(...) () at sender_for.hpp:61
11: auto unifex::_wsa::_make_sender<...>(auto&&, auto&&) () at with_scheduler_affinity.hpp:44
12: decltype(auto) ..._promise<void>::await_transform(...) () at task.hpp:384
13: auto unifex::connect_awaitable(task<void>, receiver auto&) () at connect_awaitable.hpp:234
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```

```
int main(int argc, char** argv) {  
    unifex::static_thread_pool pool;  
    io_uring_context ctx;  
    unifex::task<void> task = async_main({argv + 1, argc - 1},  
                                          pool, ctx);  
    unifex::sync_wait(std::move(task));  
  
    return 0;  
}
```

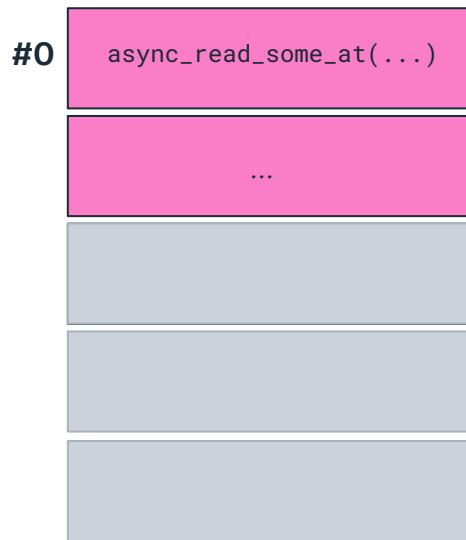
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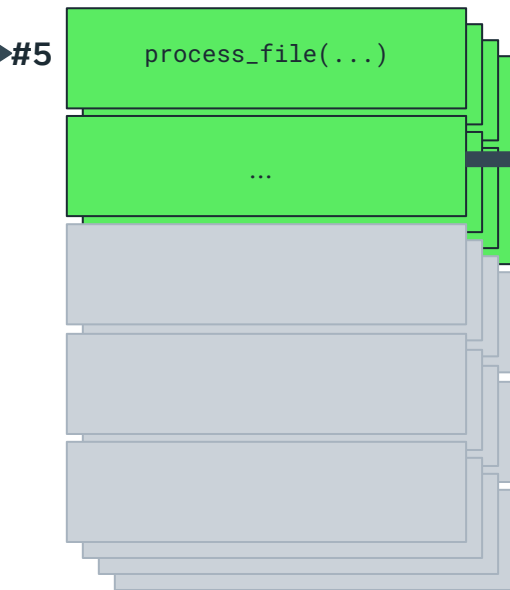
How it works

Async Stacks for Async Code

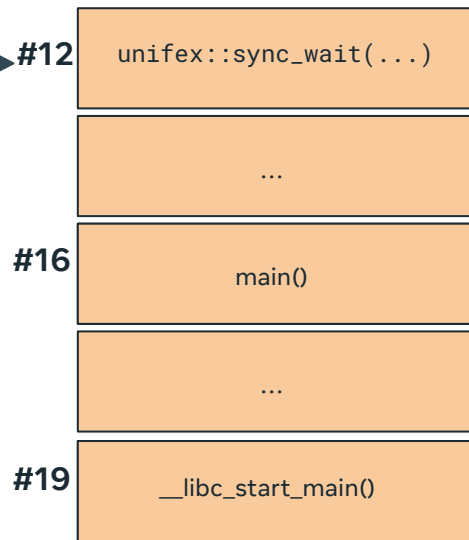
IO Thread:



Threadpool threads:

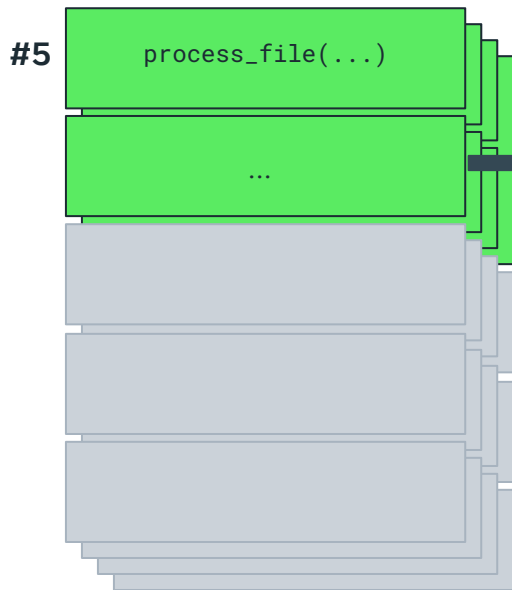


Main thread:

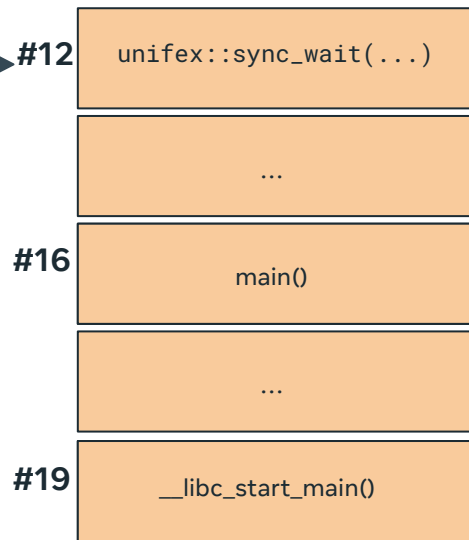


Async Stacks for Async Code

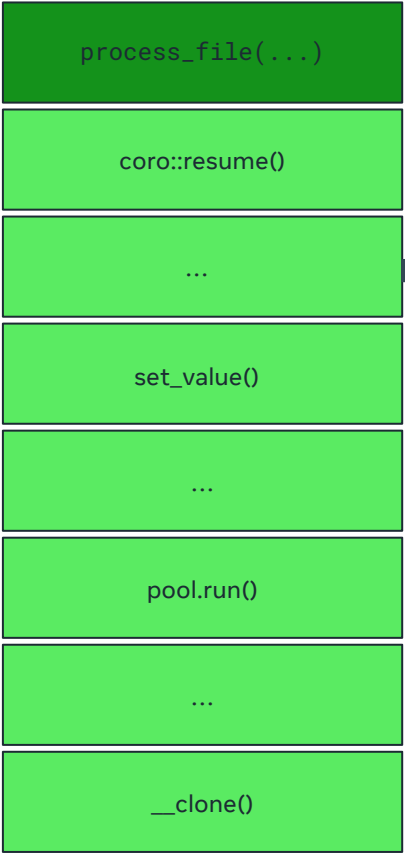
Threadpool threads:



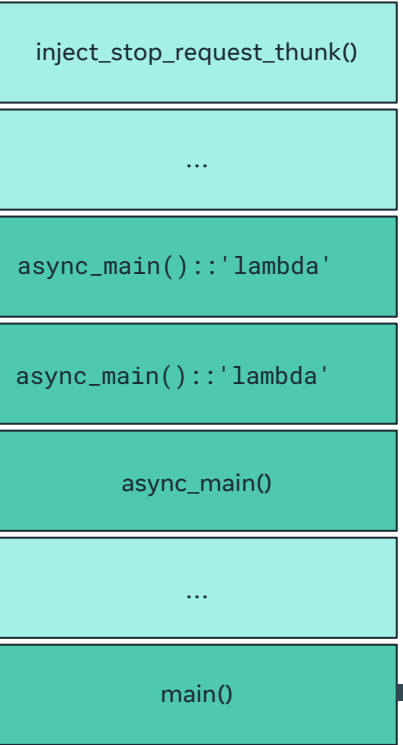
Main thread:



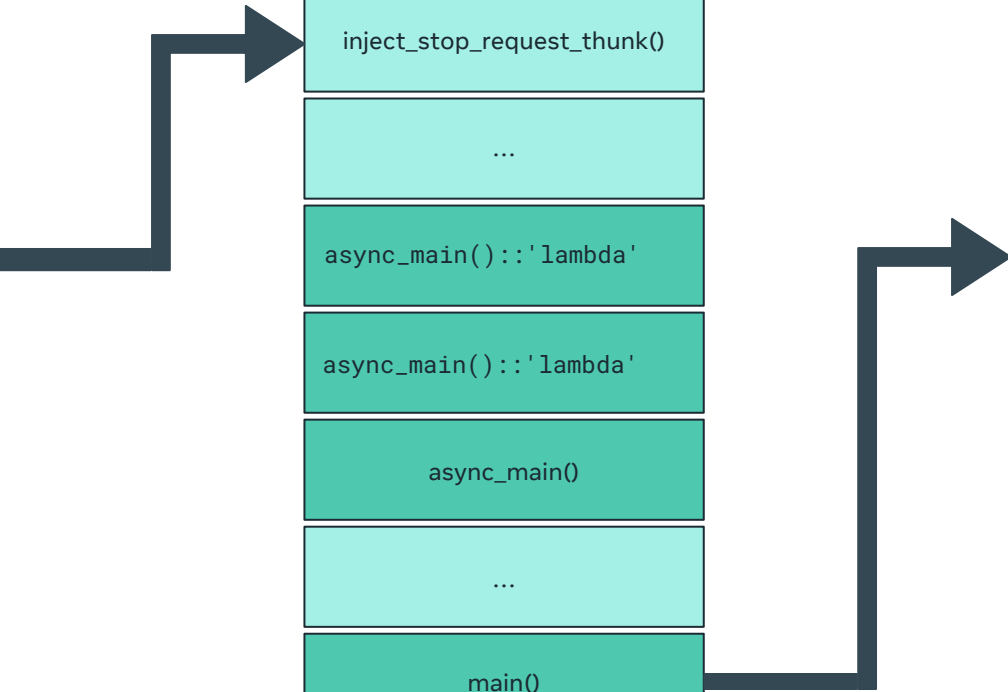
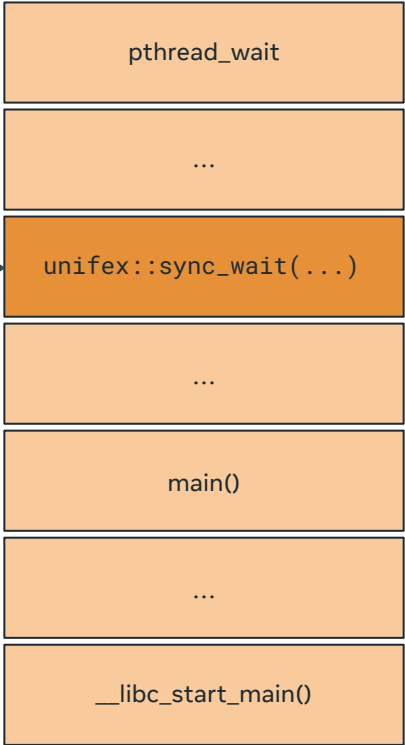
Pool thread:



Async frames:



Main thread:

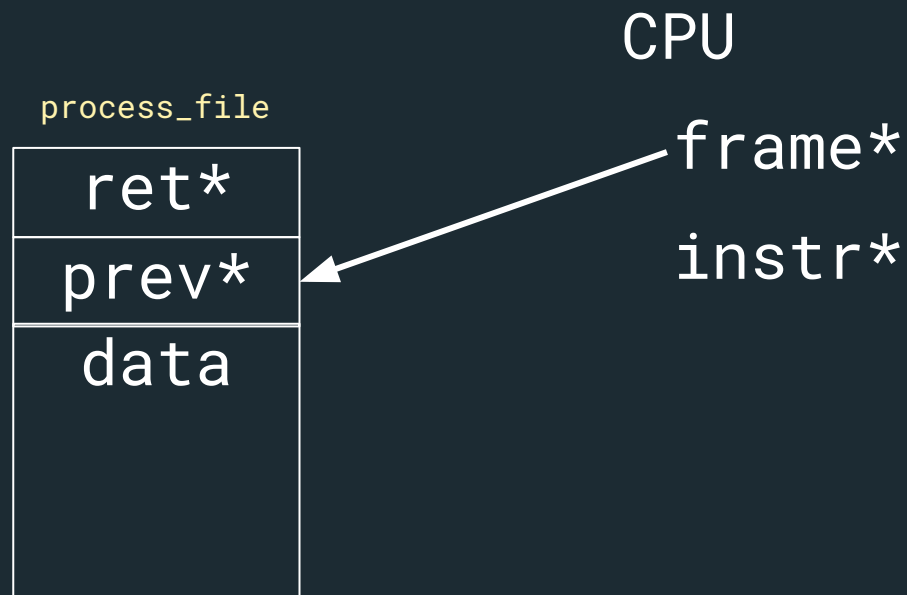


So what do we need?

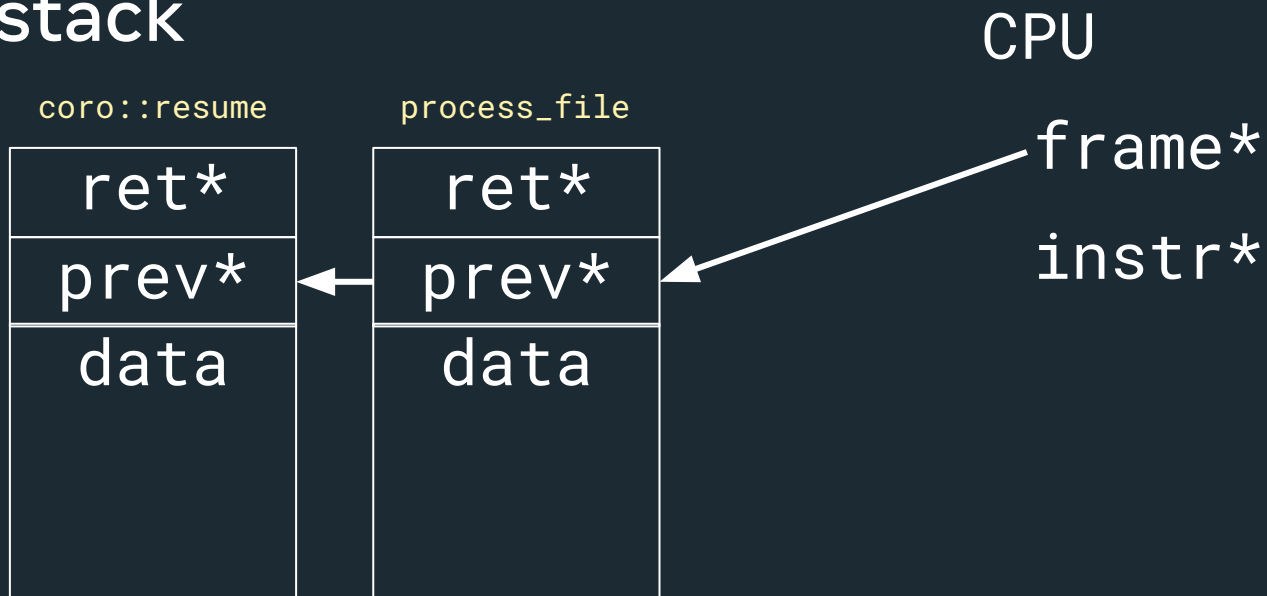
- Walk the regular stack...
 - ...until we find the first async frame How?
- Walk the async stack...
 - ...until we find the end How?
- Walk the regular stack back to main

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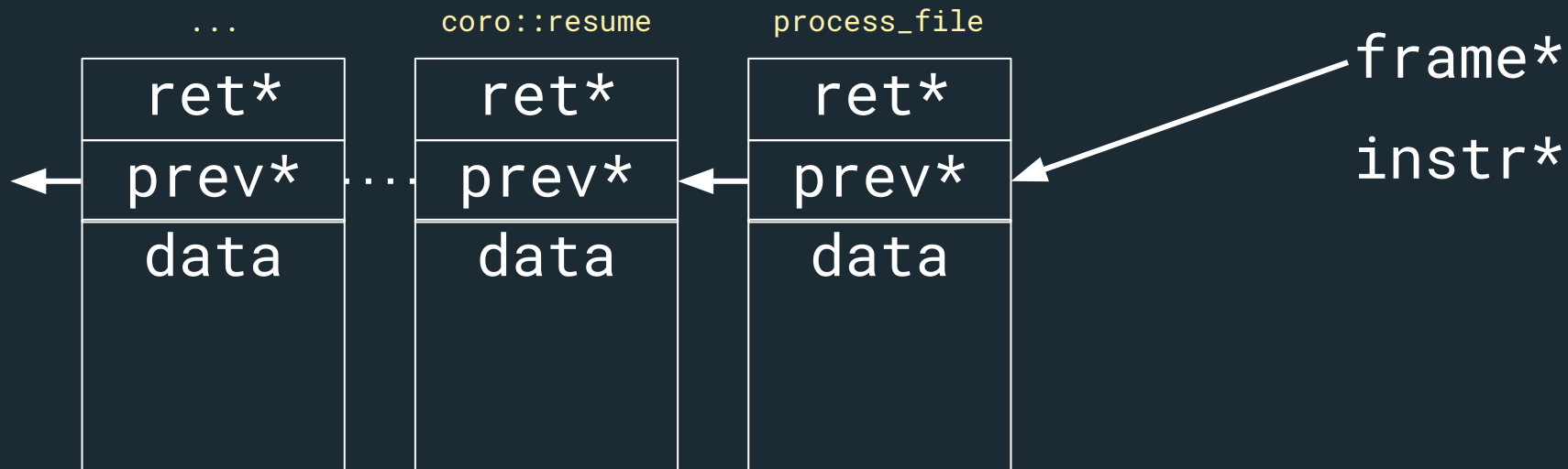
Walking the stack



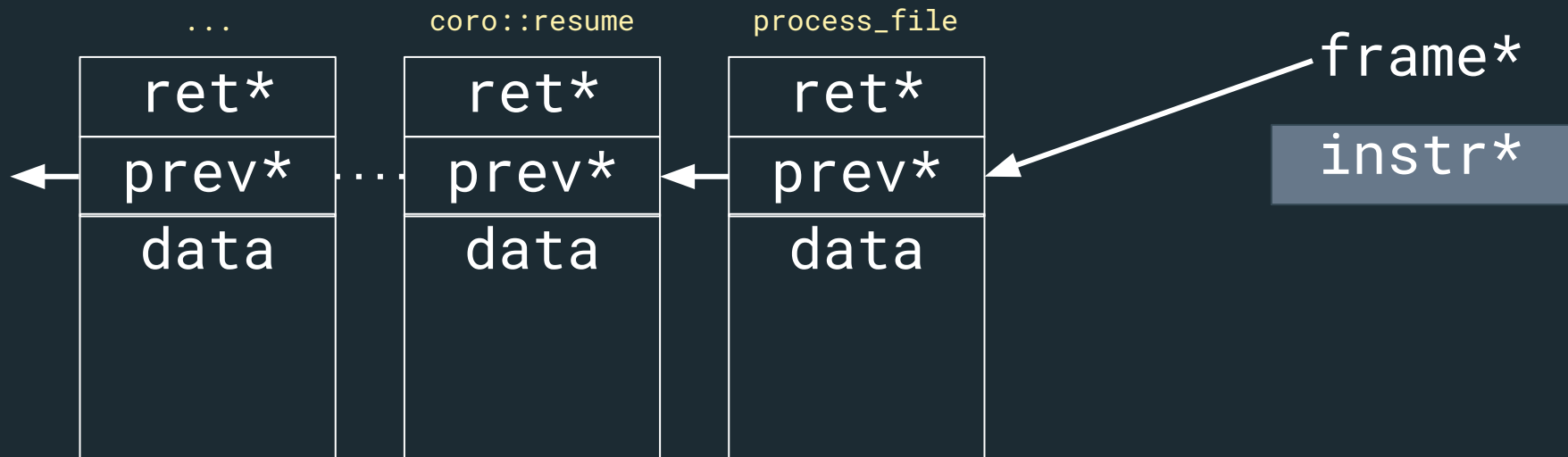
Walking the stack



Walking the stack

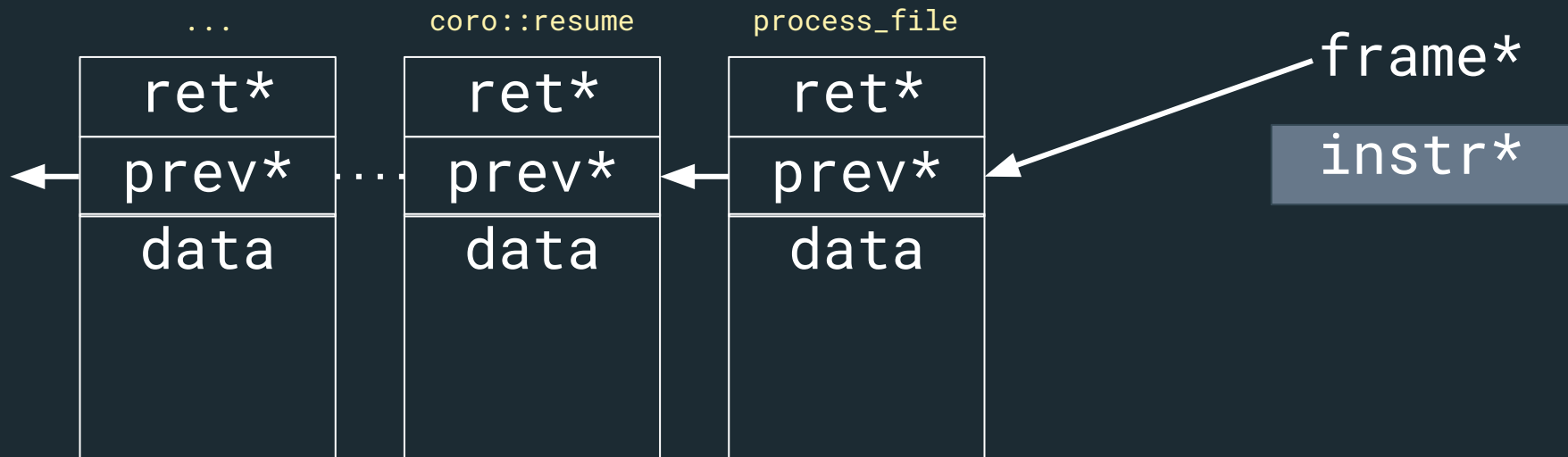


Walking the stack

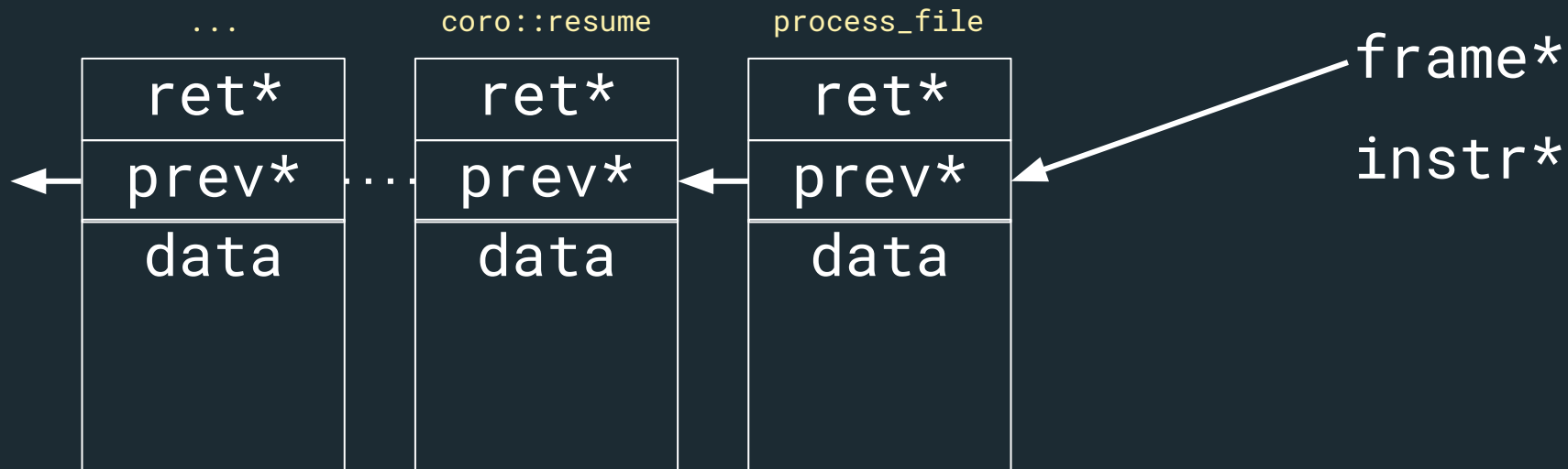


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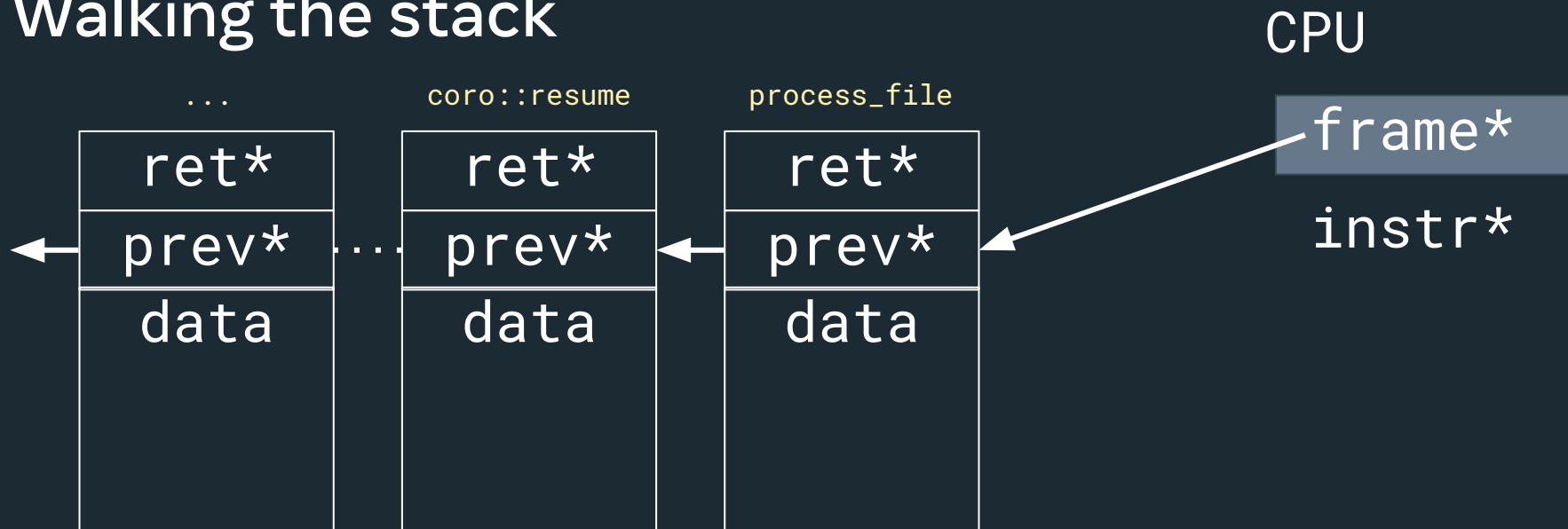

Walking the stack



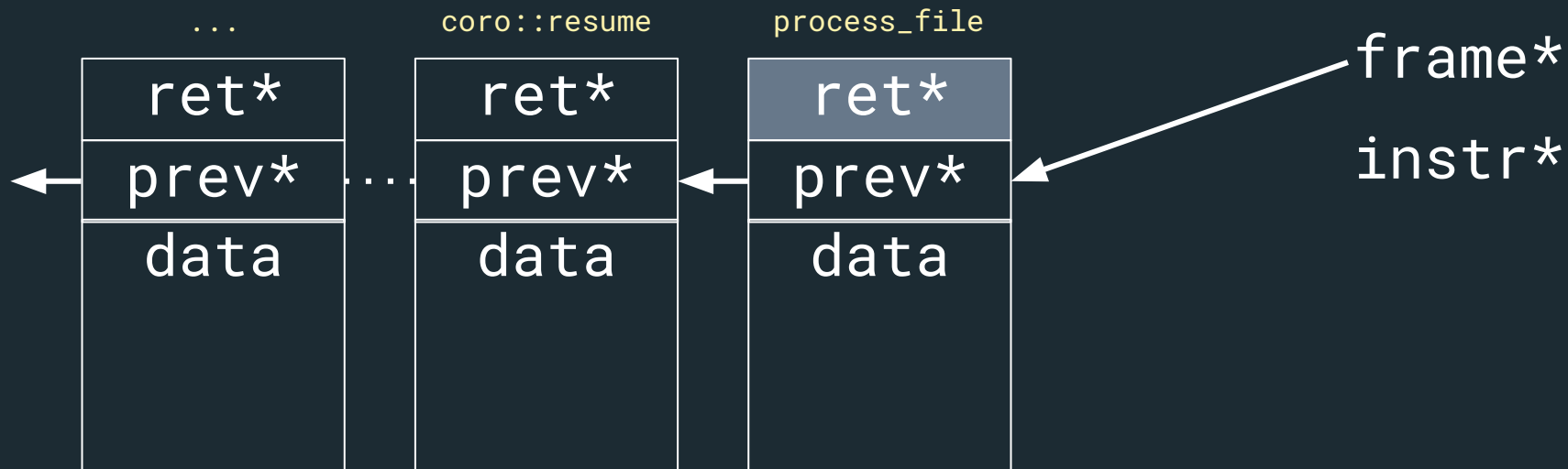
Walking the stack



Walking the stack



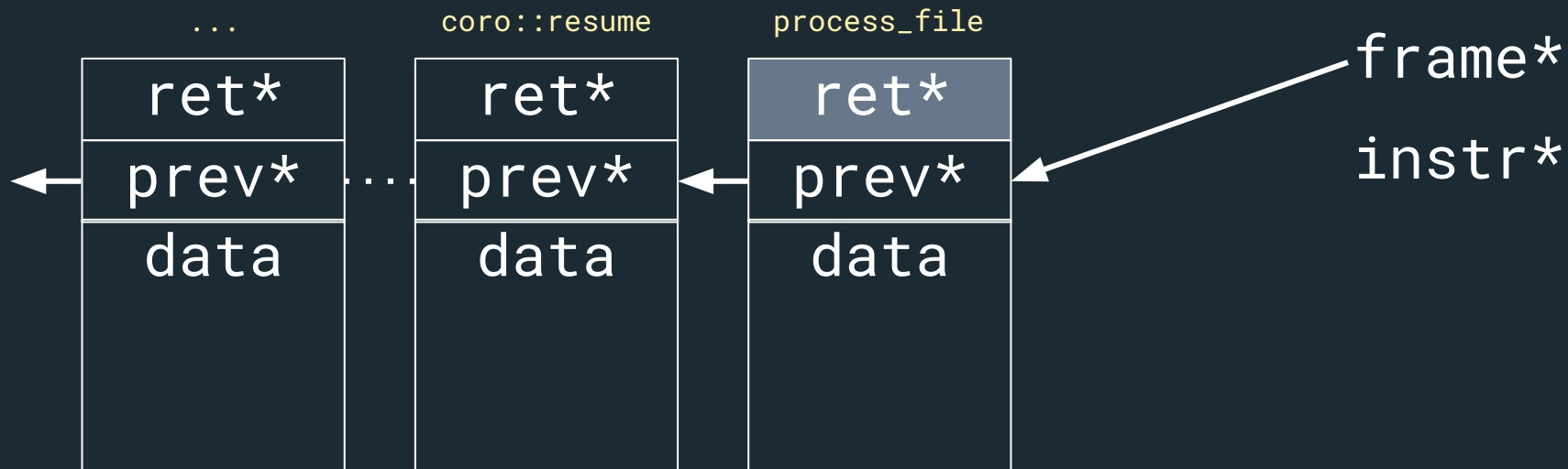
Walking the stack



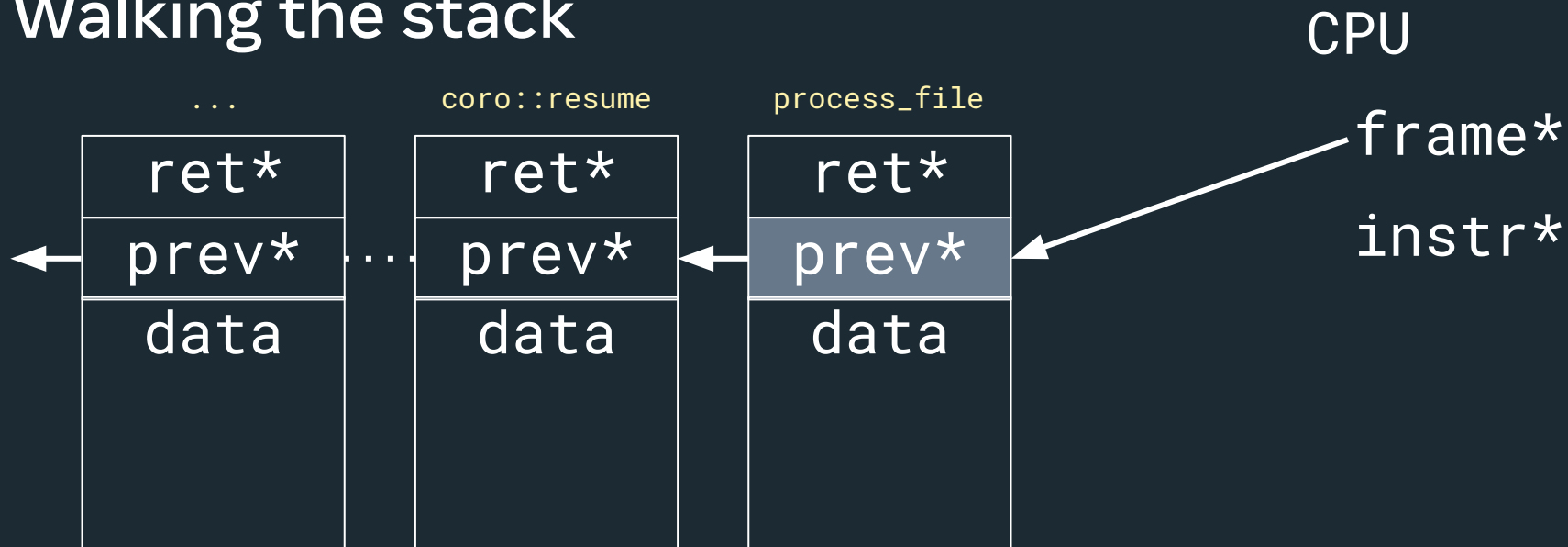
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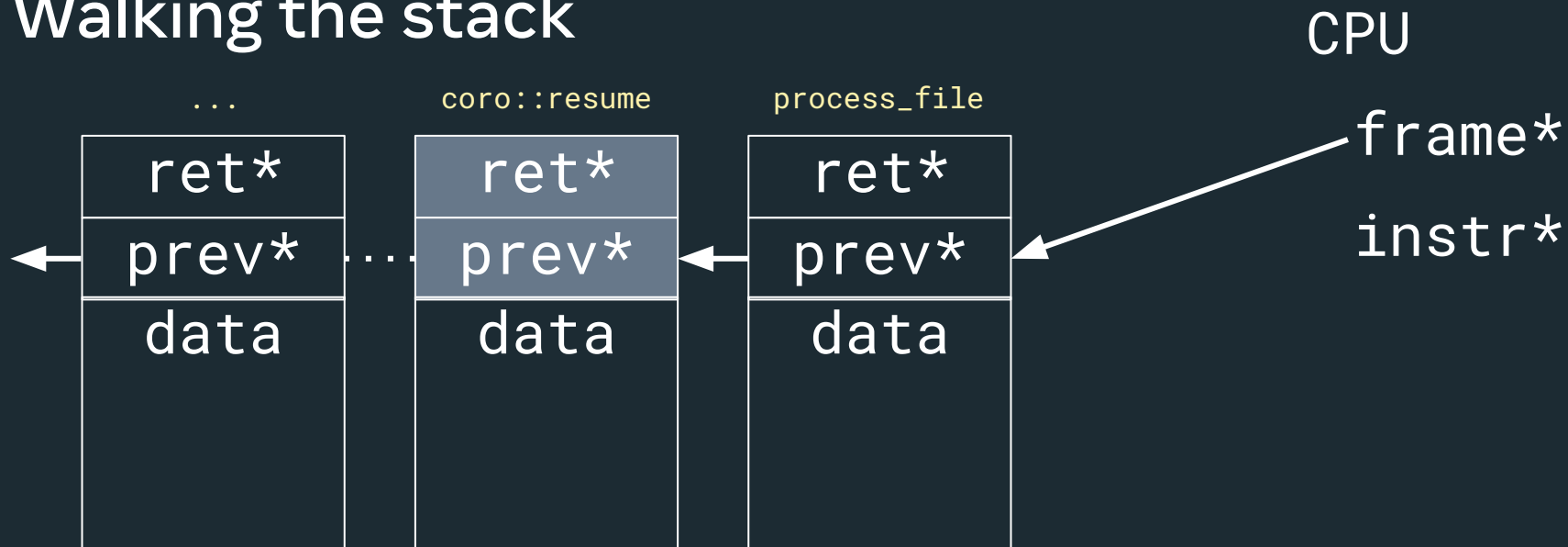
Walking the stack



Walking the stack

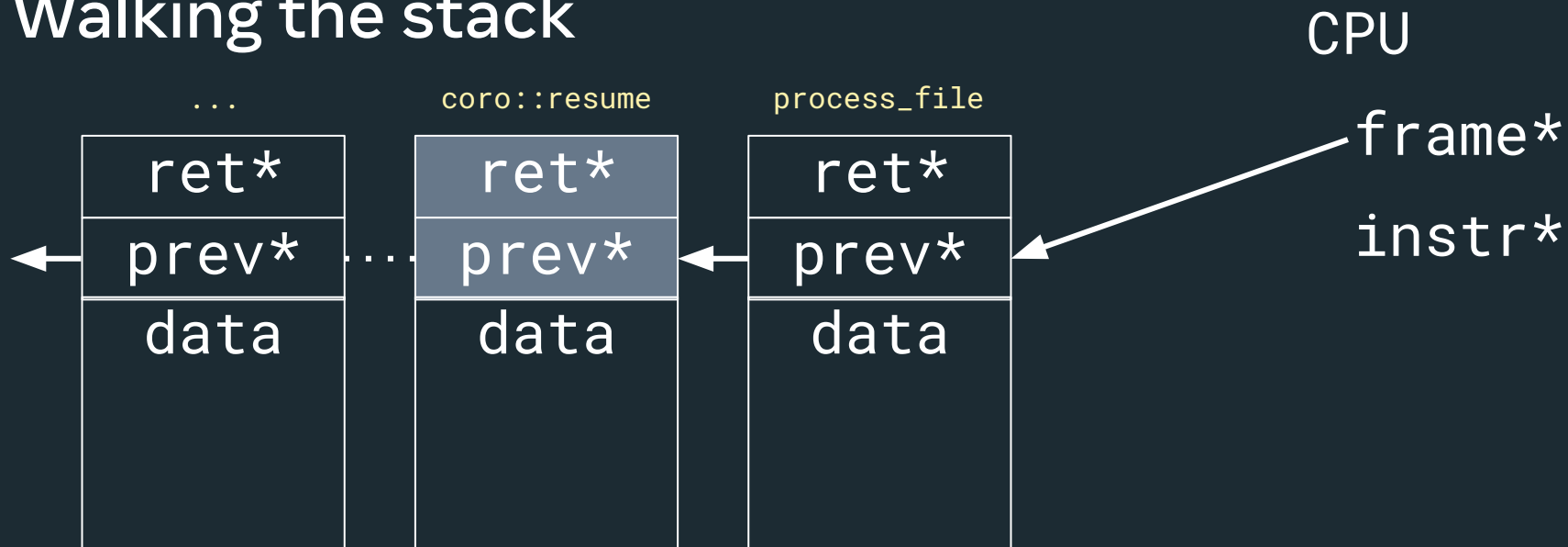


Walking the stack

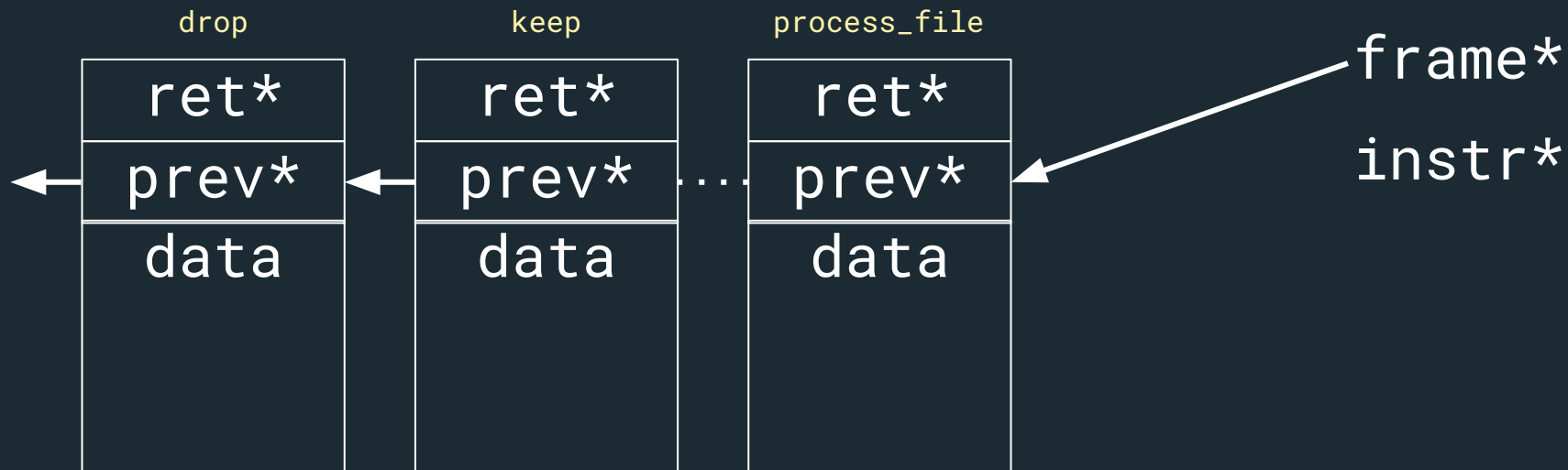


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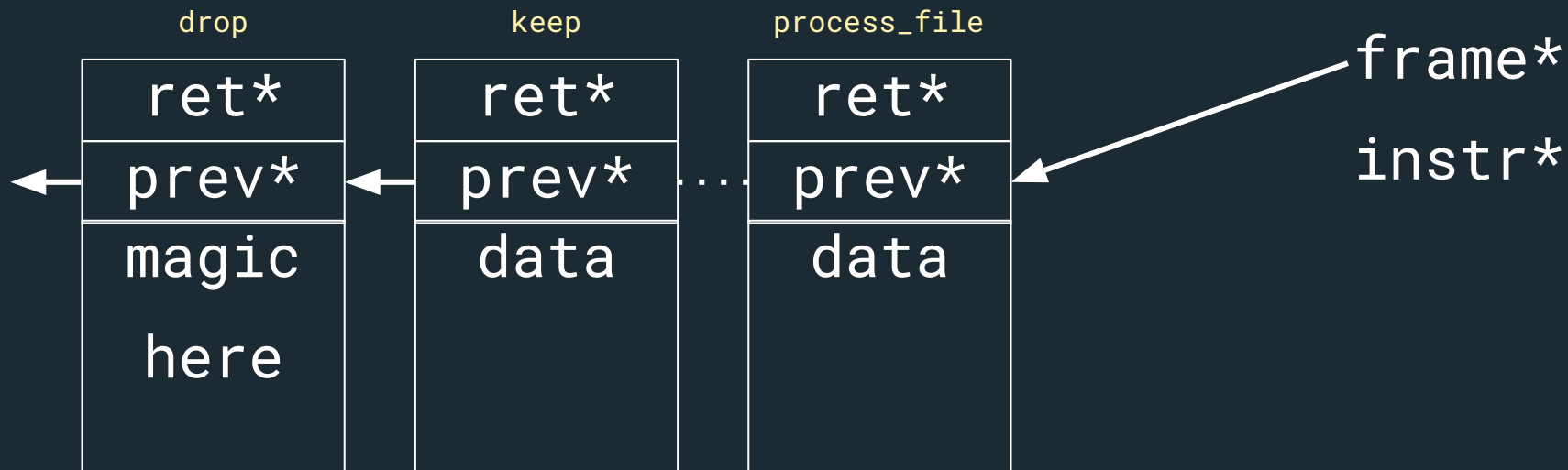
Walking the stack



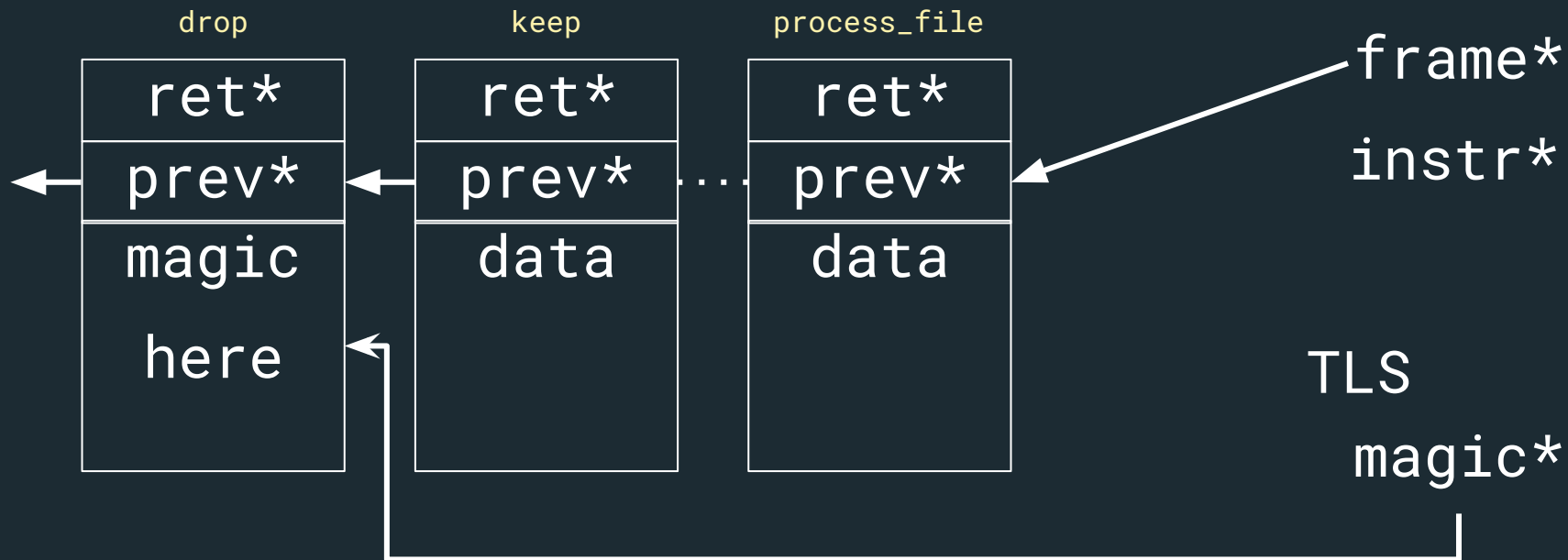
Walking the stack



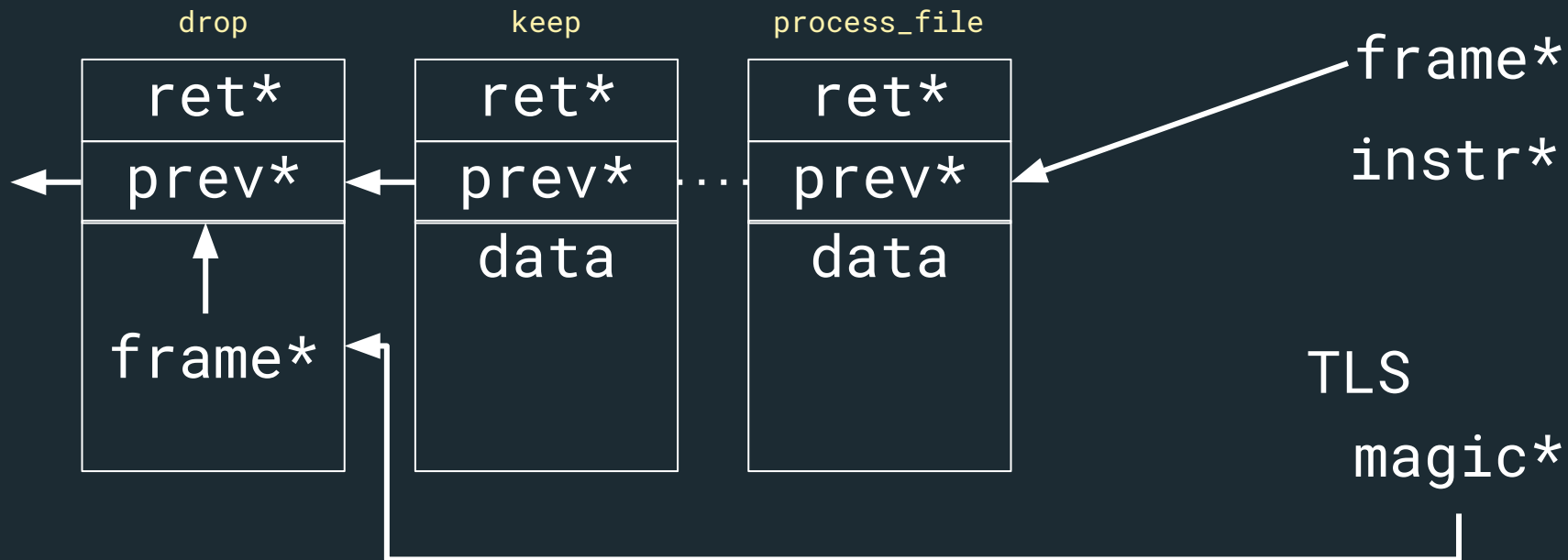
Walking the stack



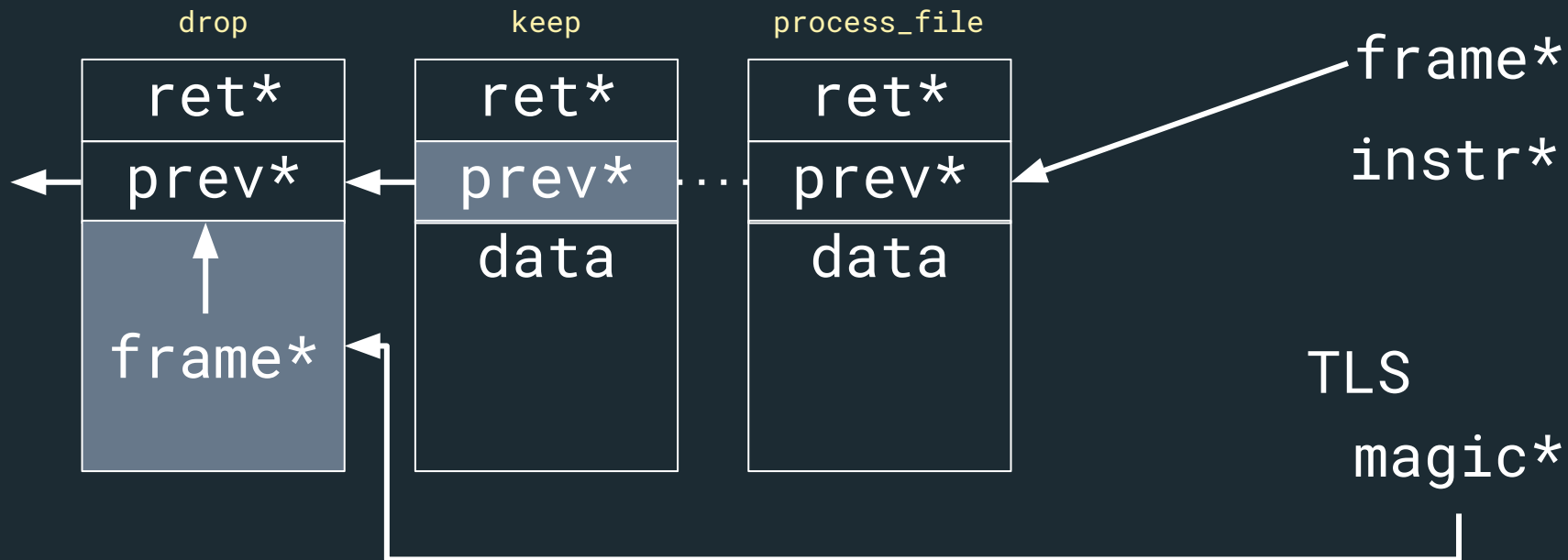
Walking the stack



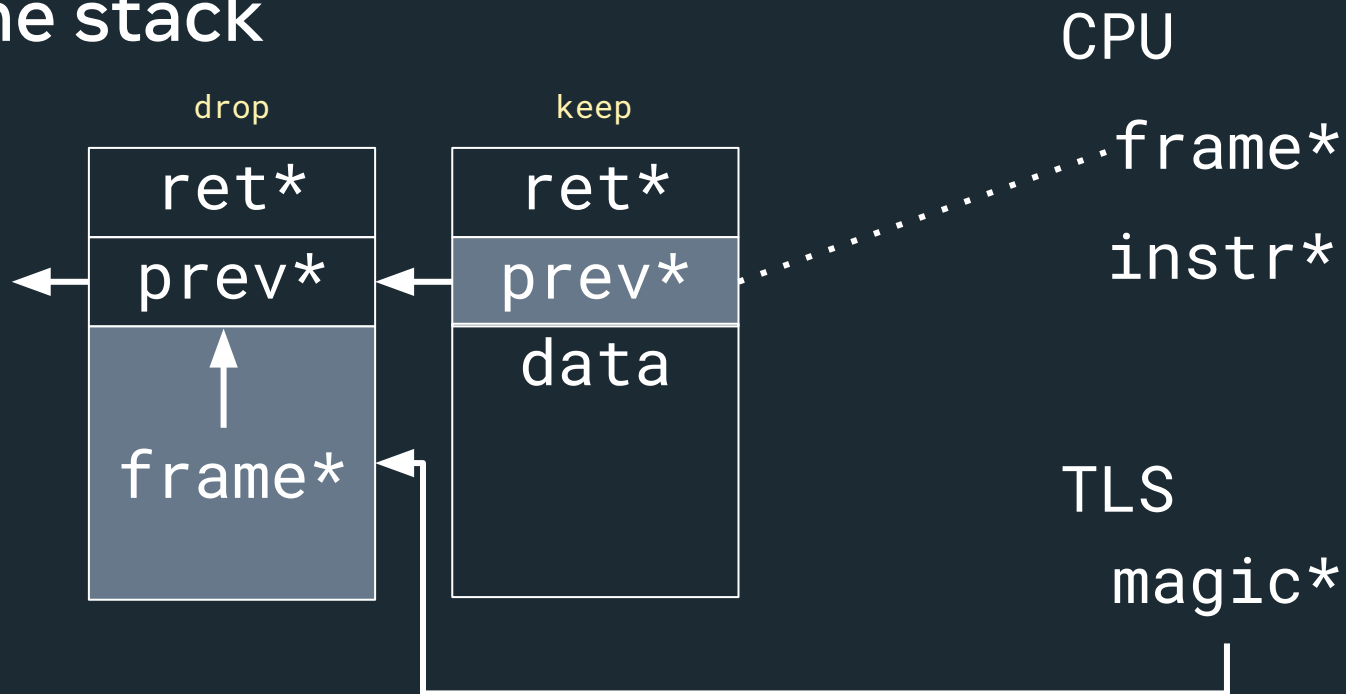
Walking the stack



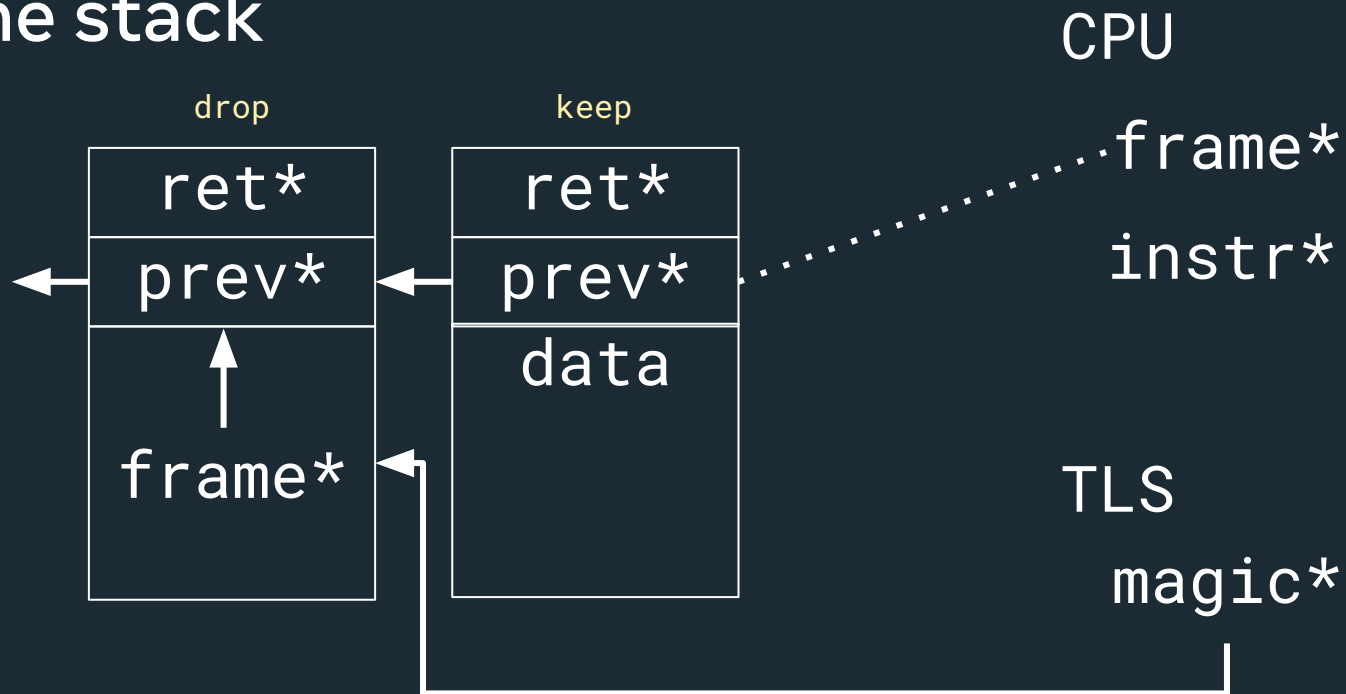
Walking the stack



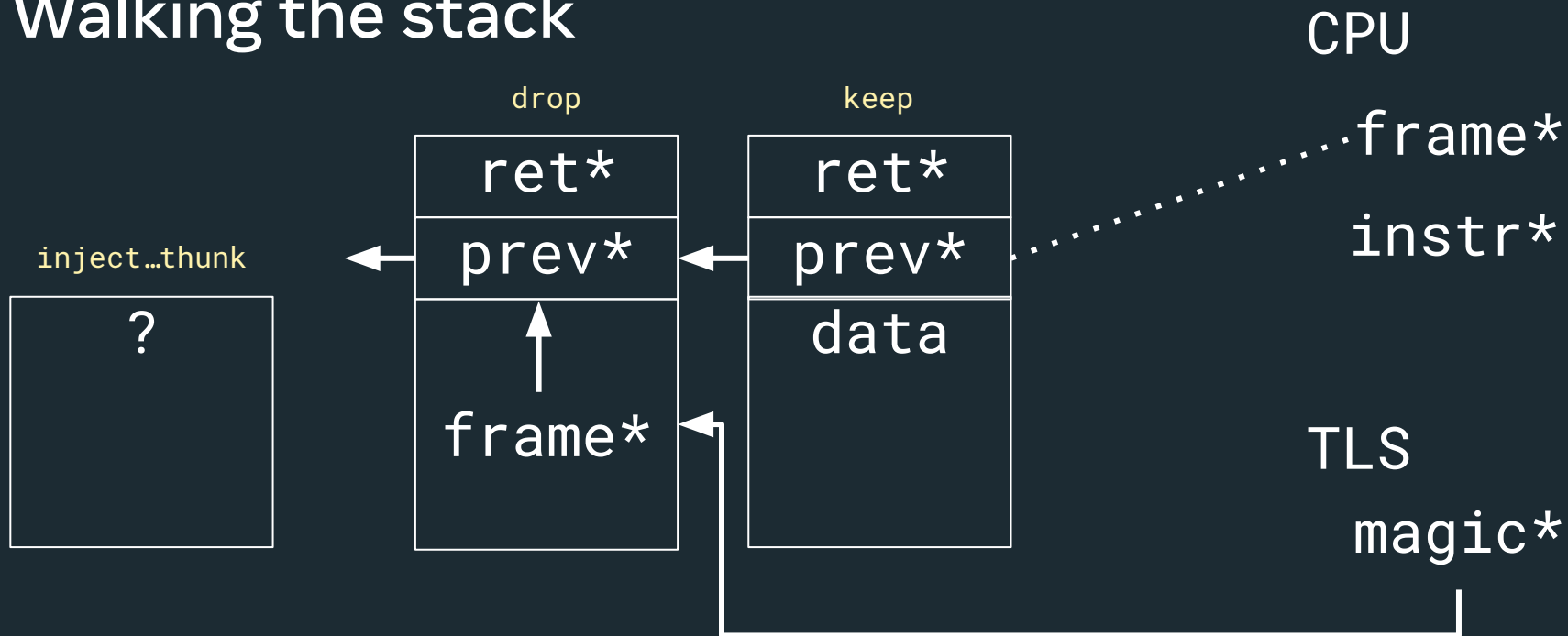
Walking the stack



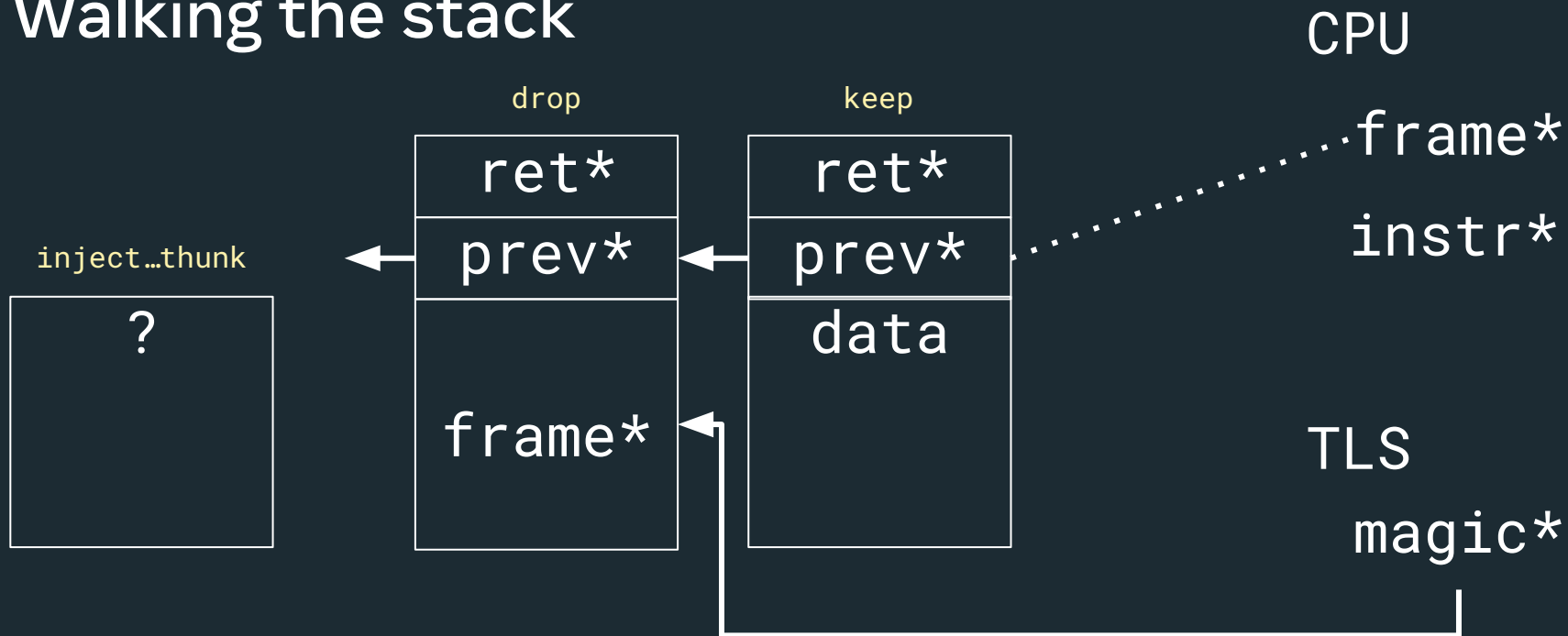
Walking the stack



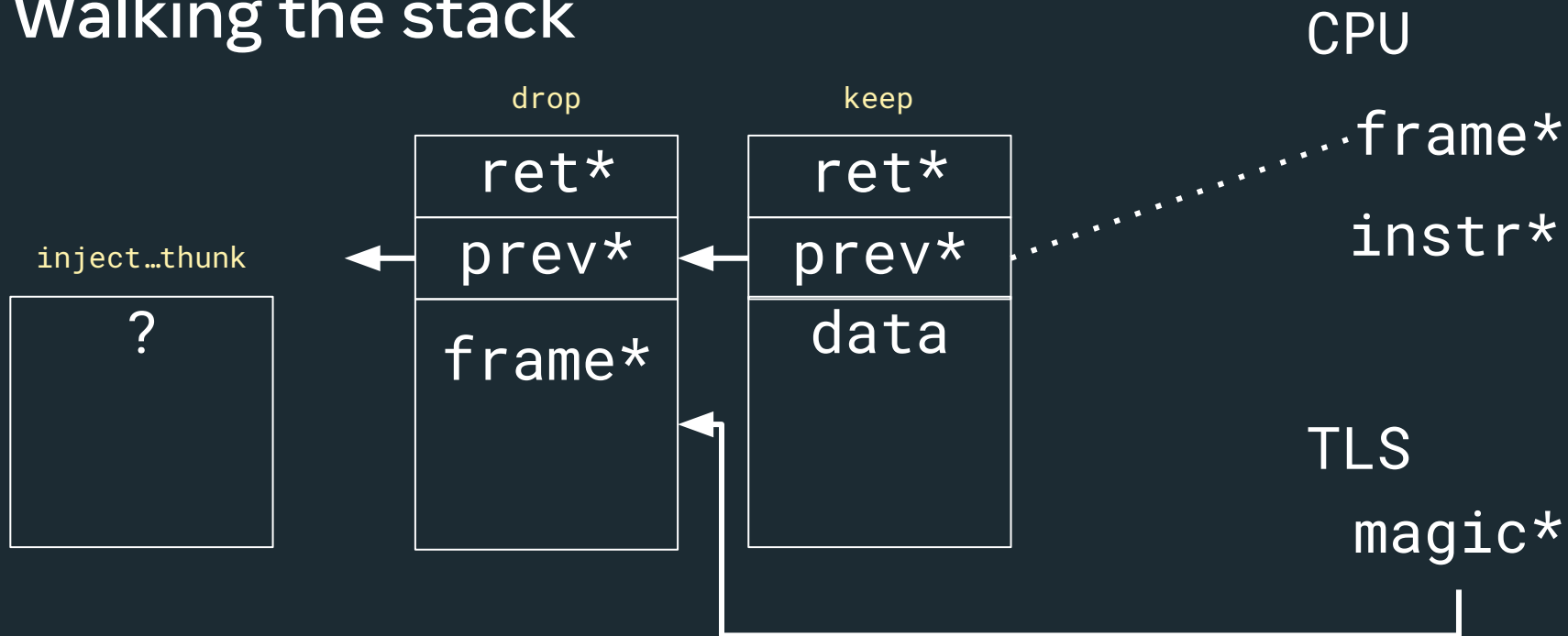
Walking the stack



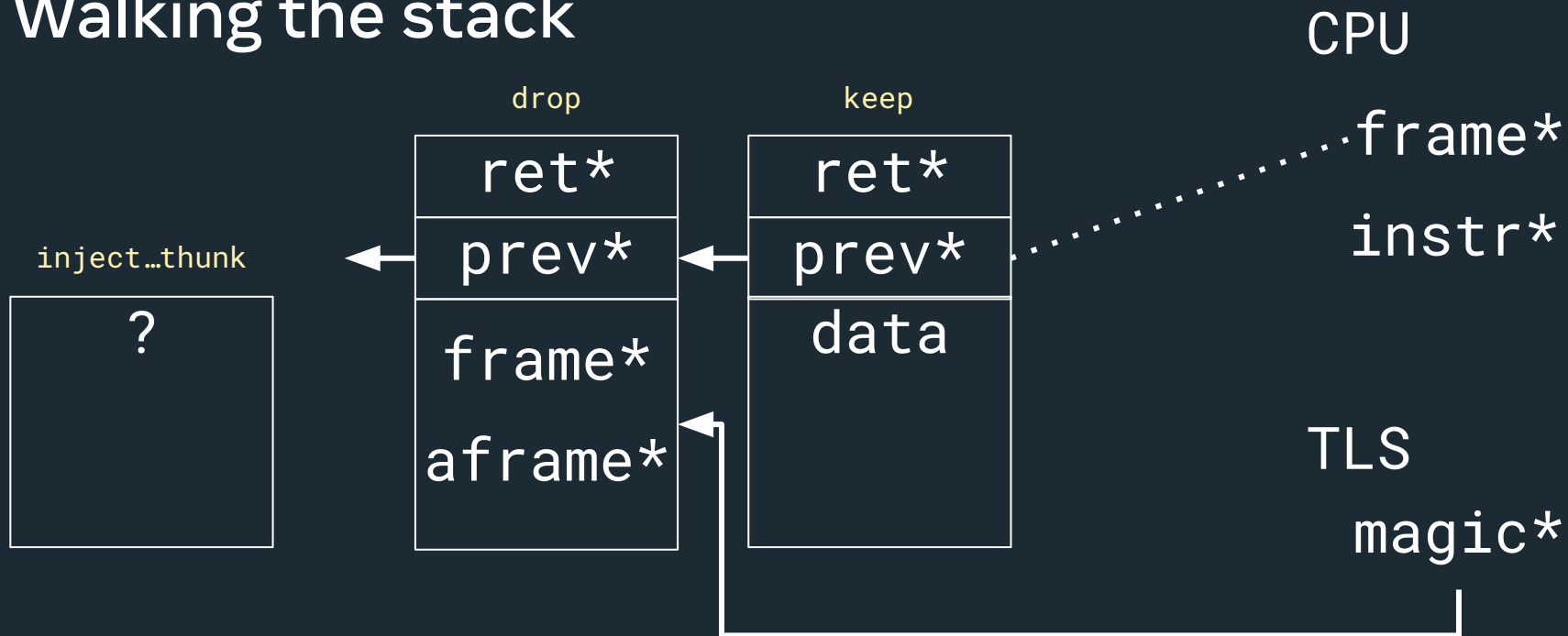
Walking the stack



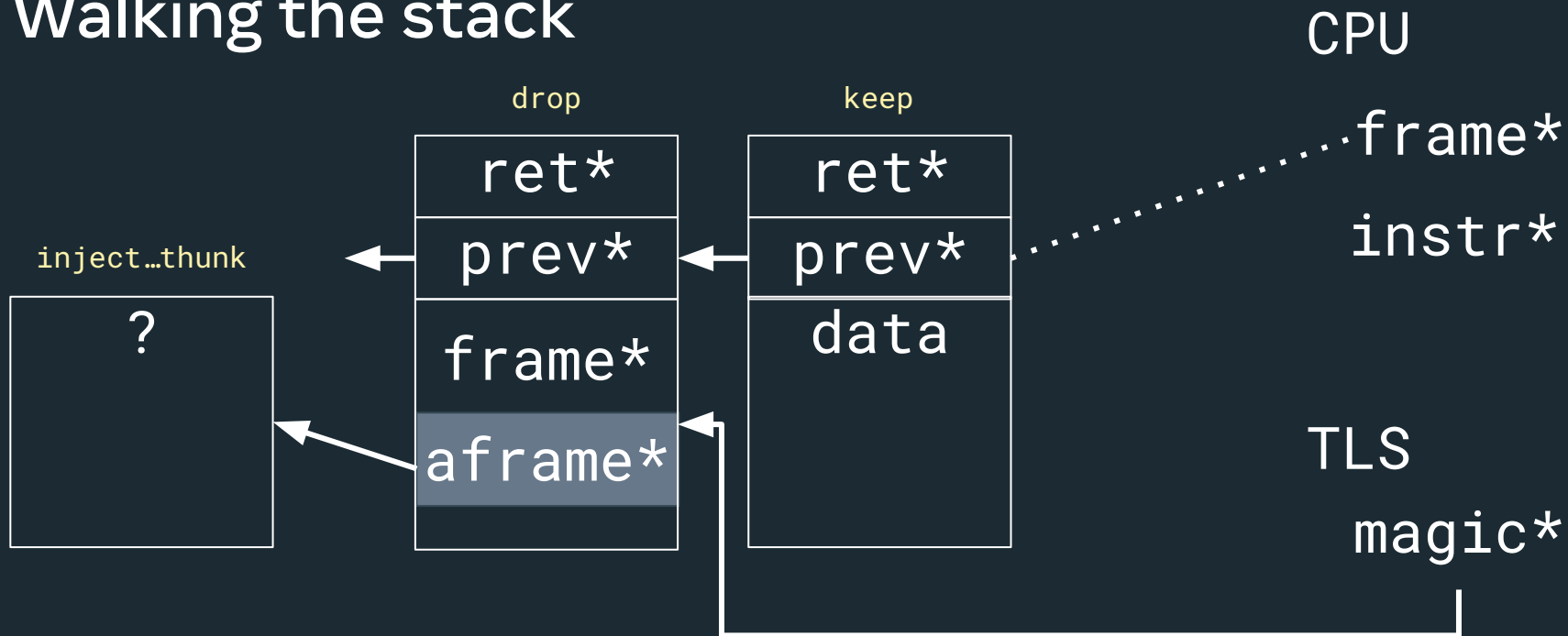
Walking the stack



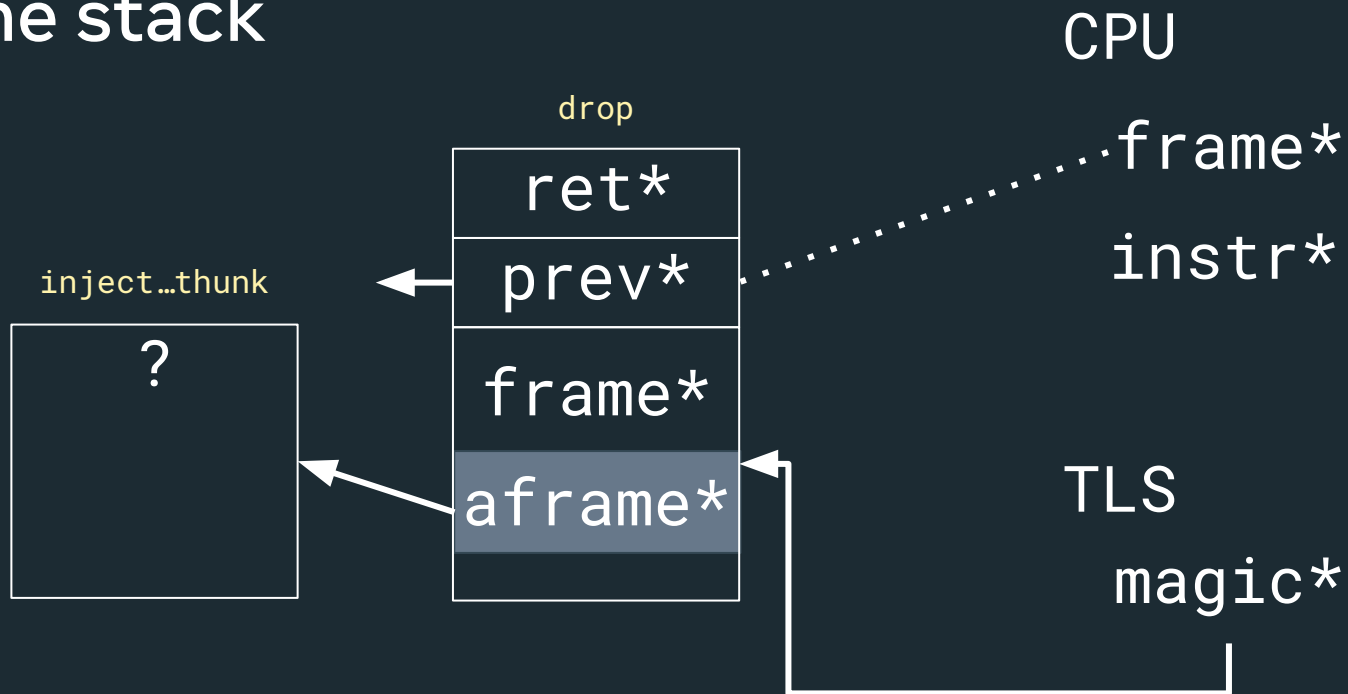
Walking the stack



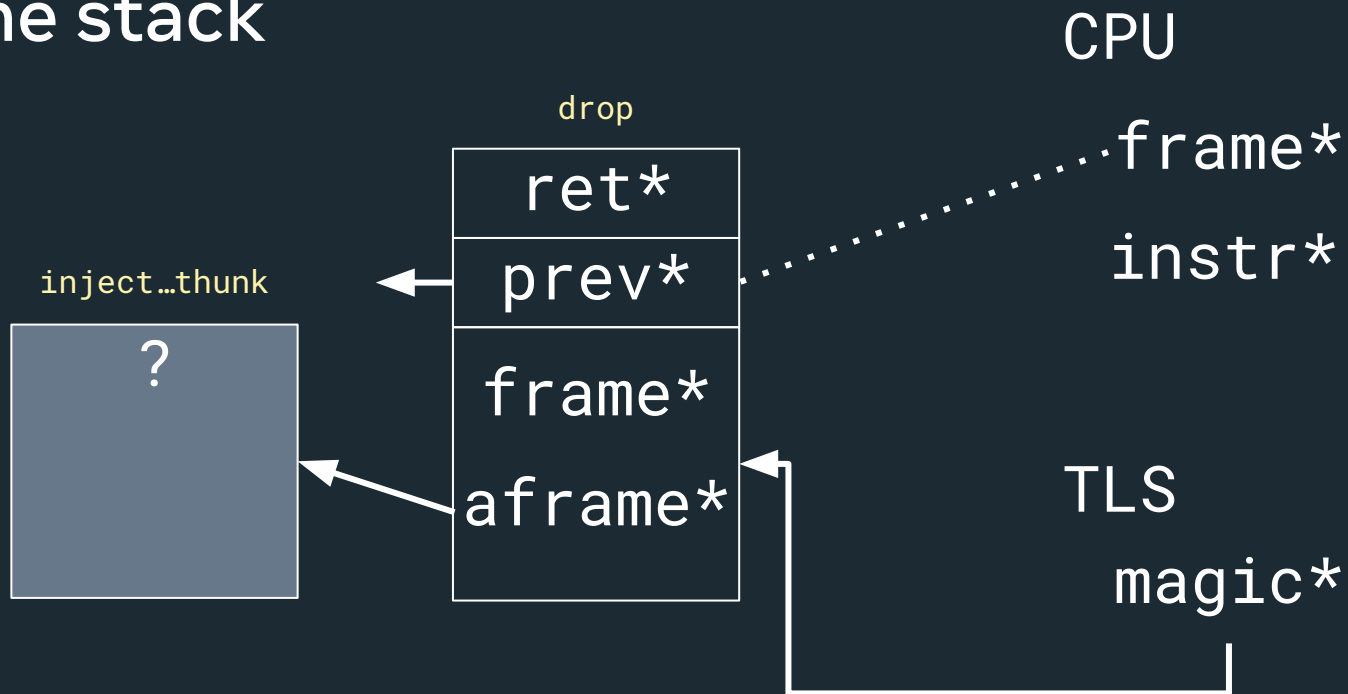
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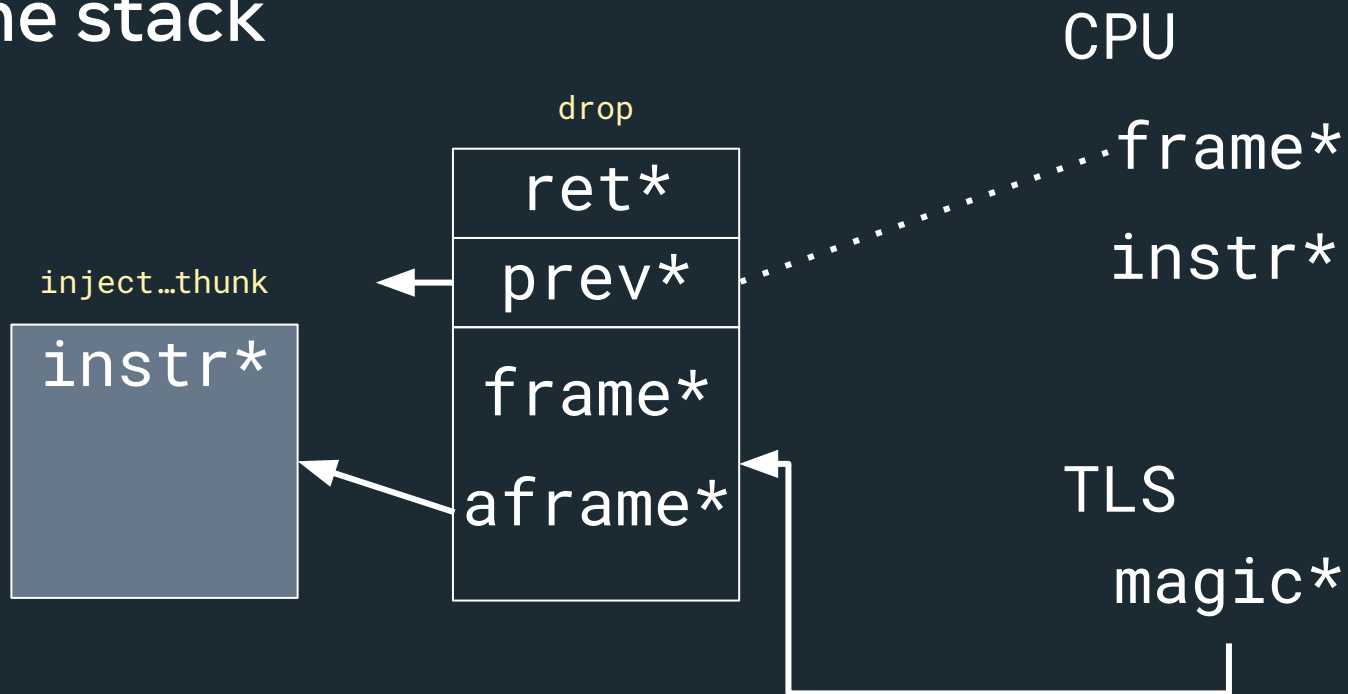
Walking the stack



Walking the stack



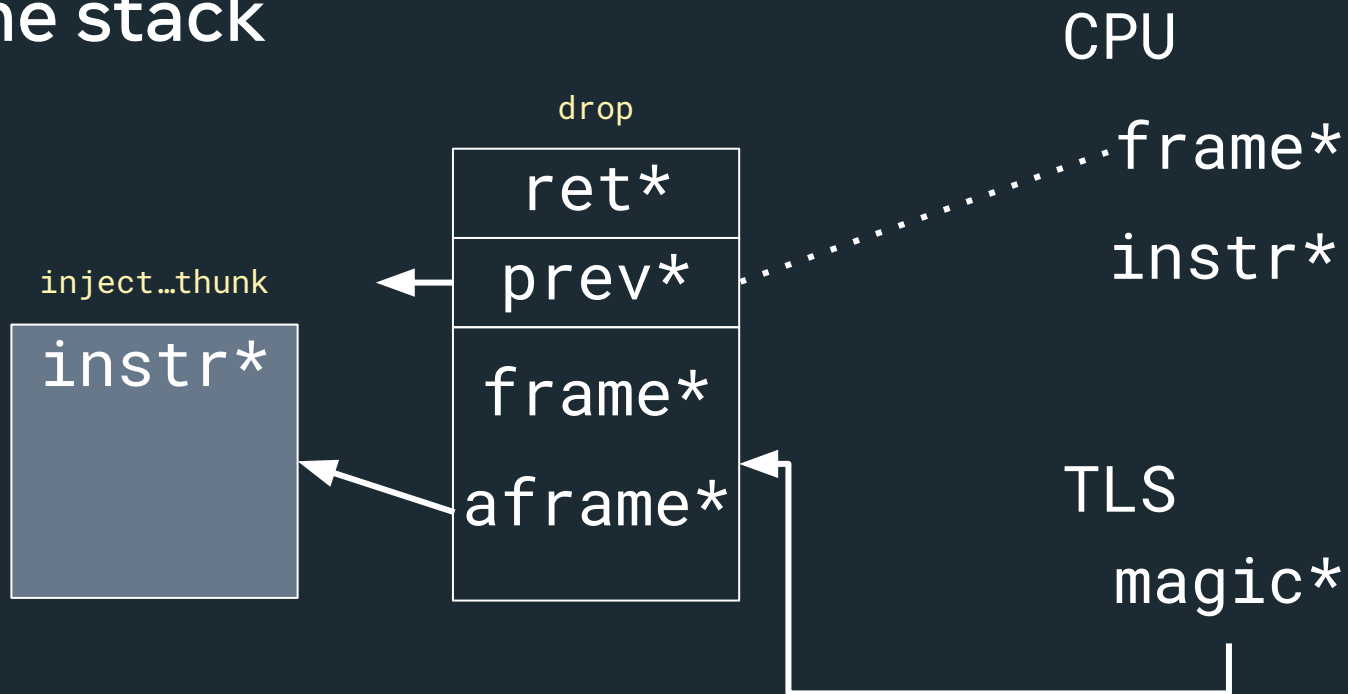
Walking the stack



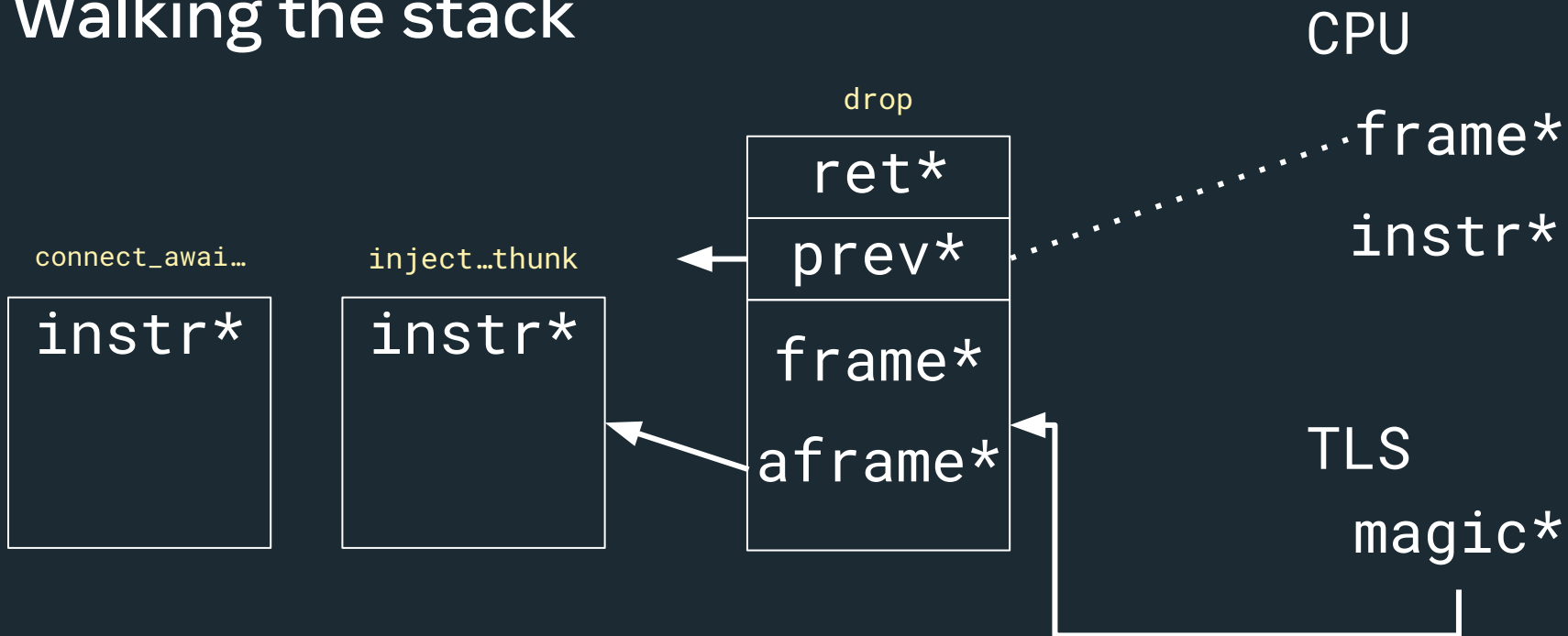
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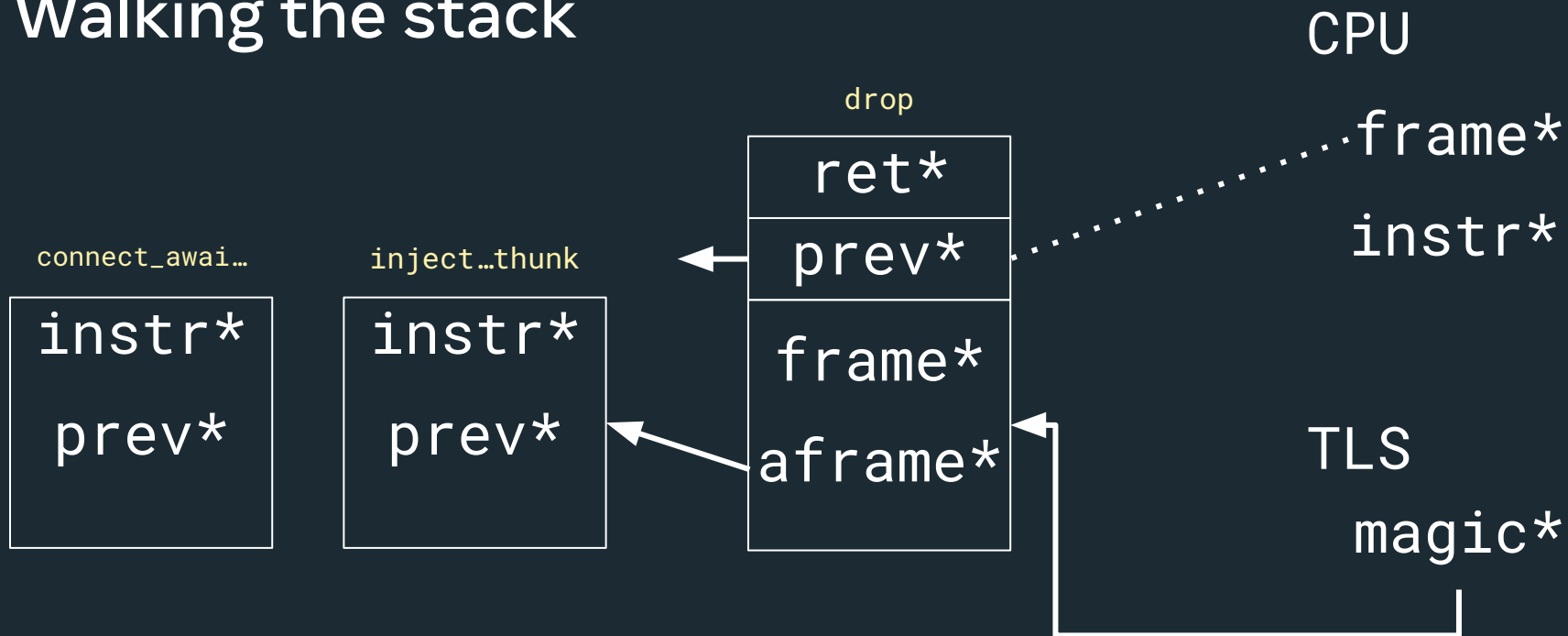
Walking the stack



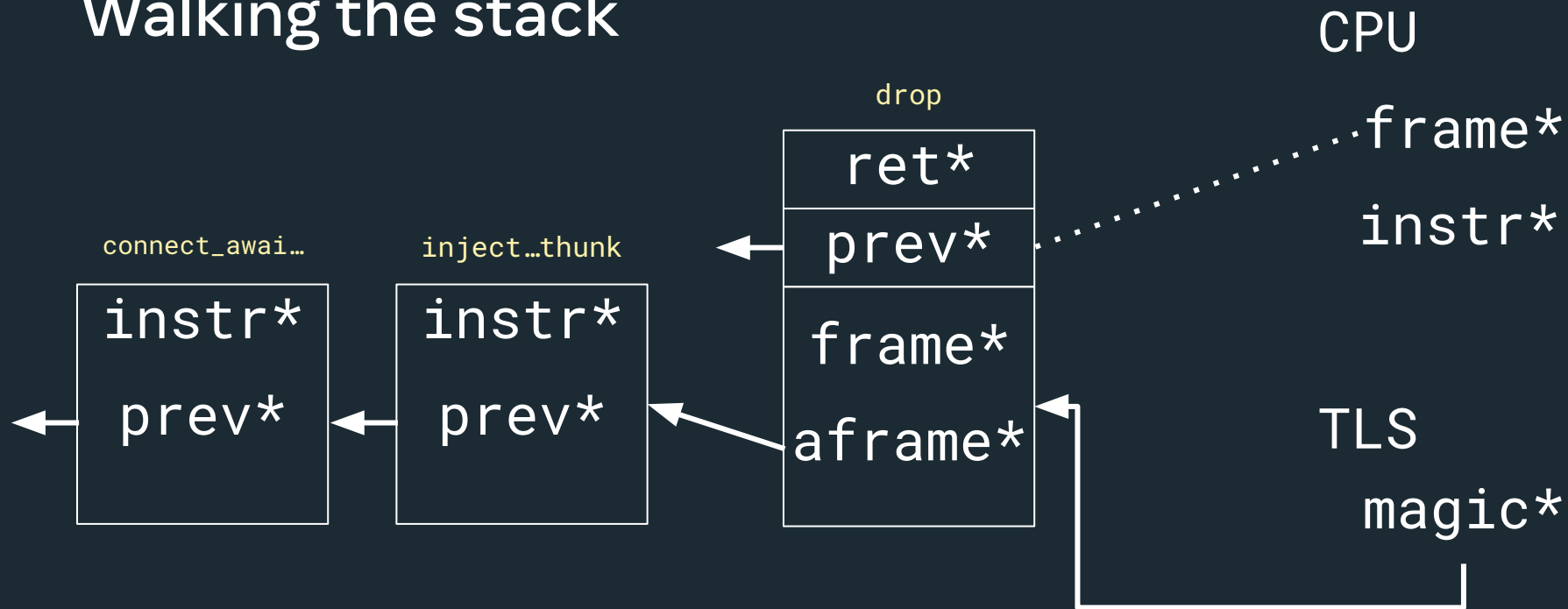
Walking the stack



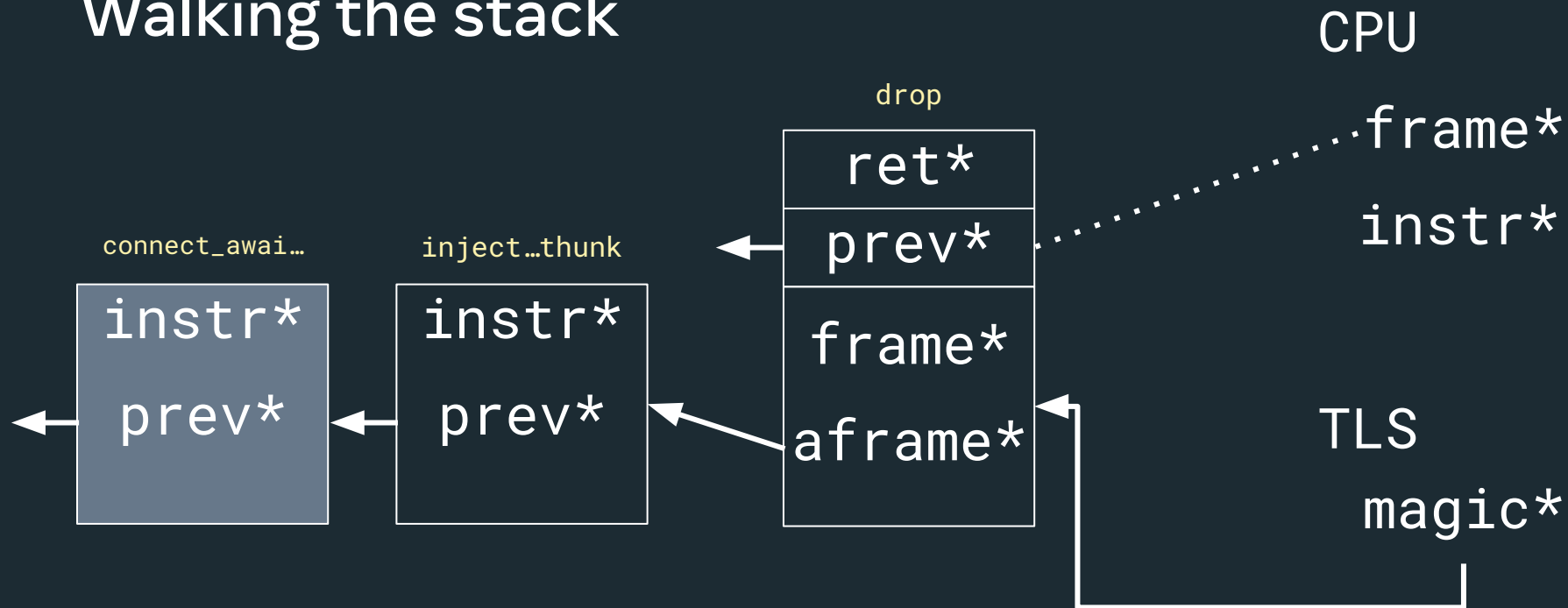
Walking the stack



Walking the stack



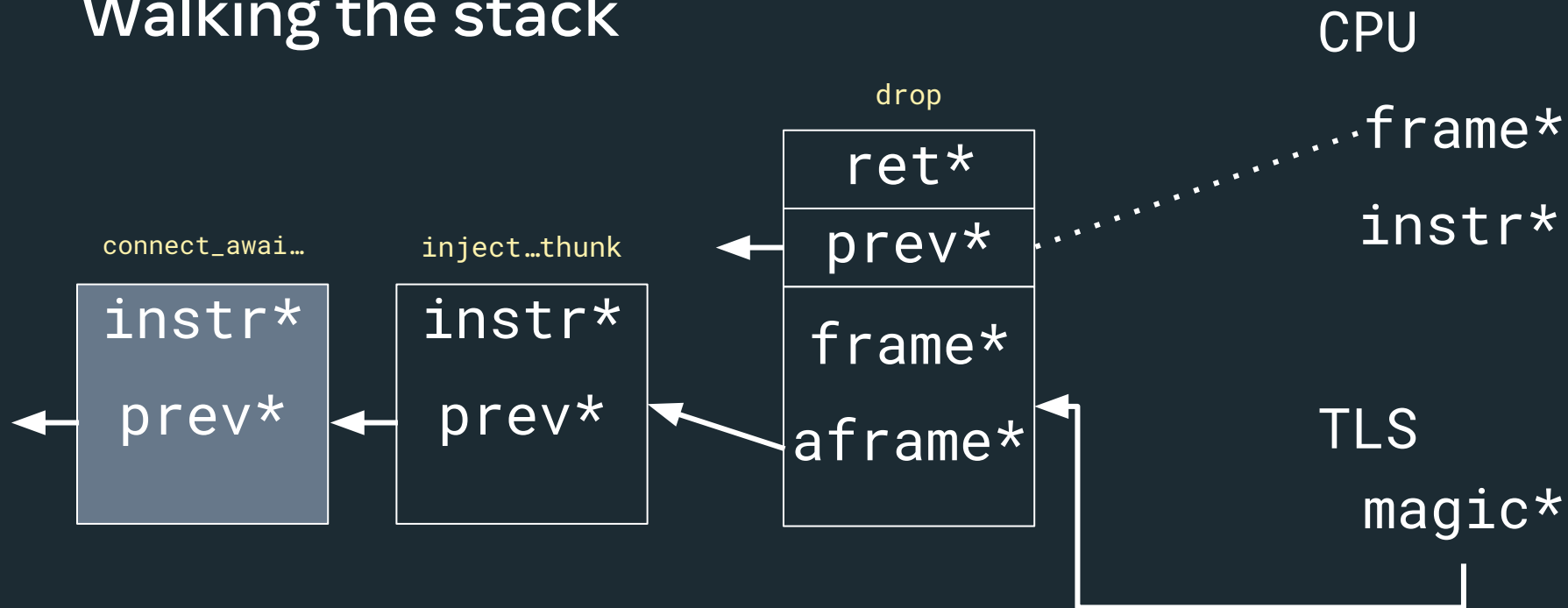
Walking the stack



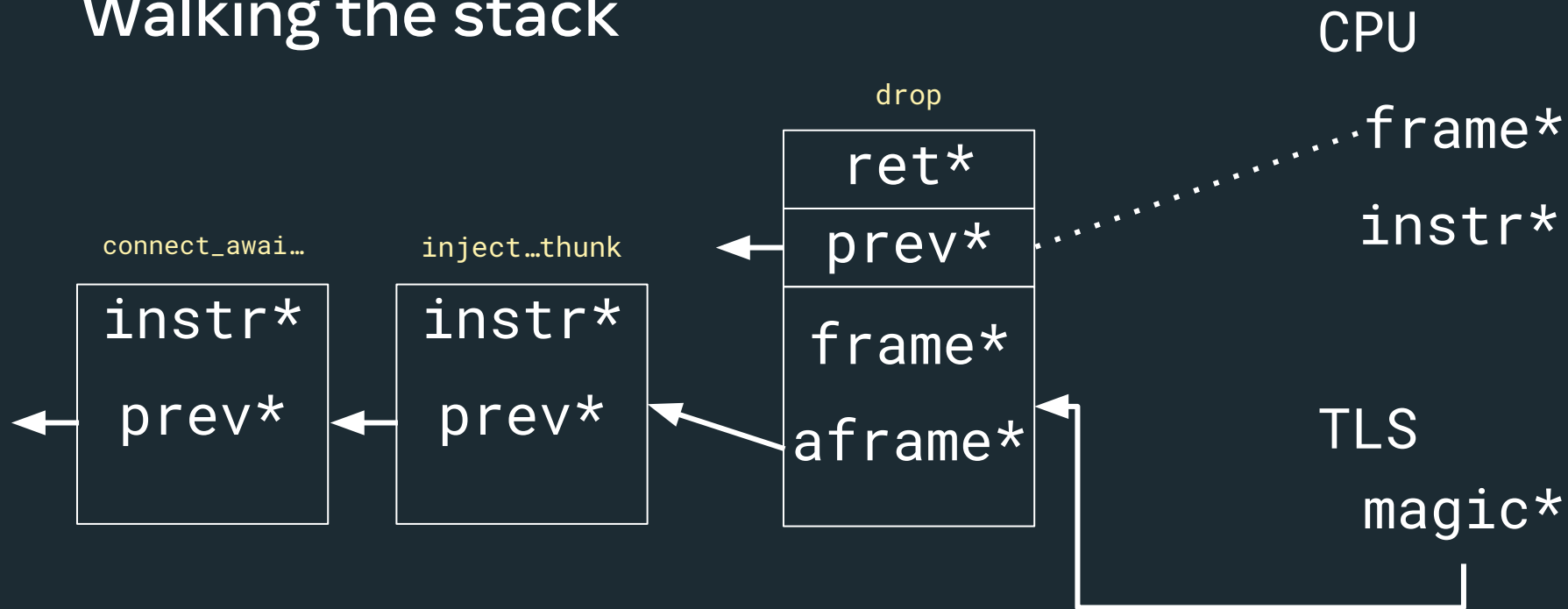
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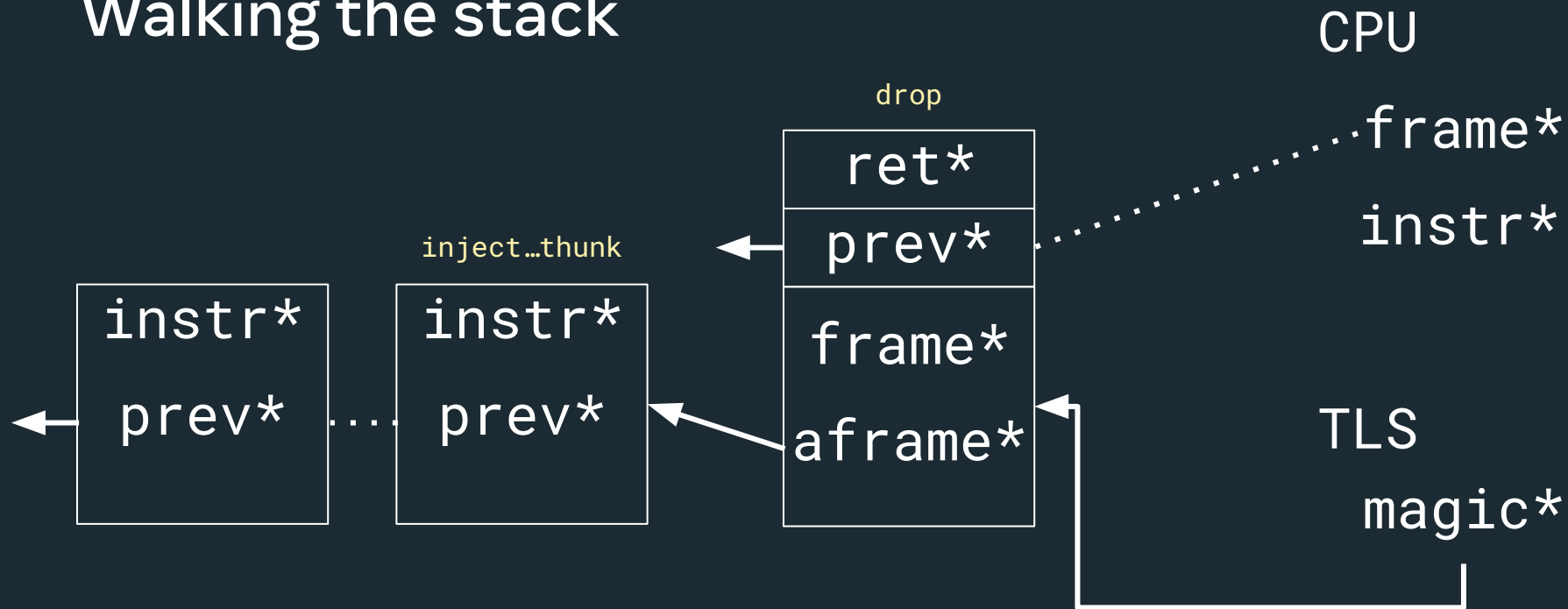
Walking the stack



Walking the stack

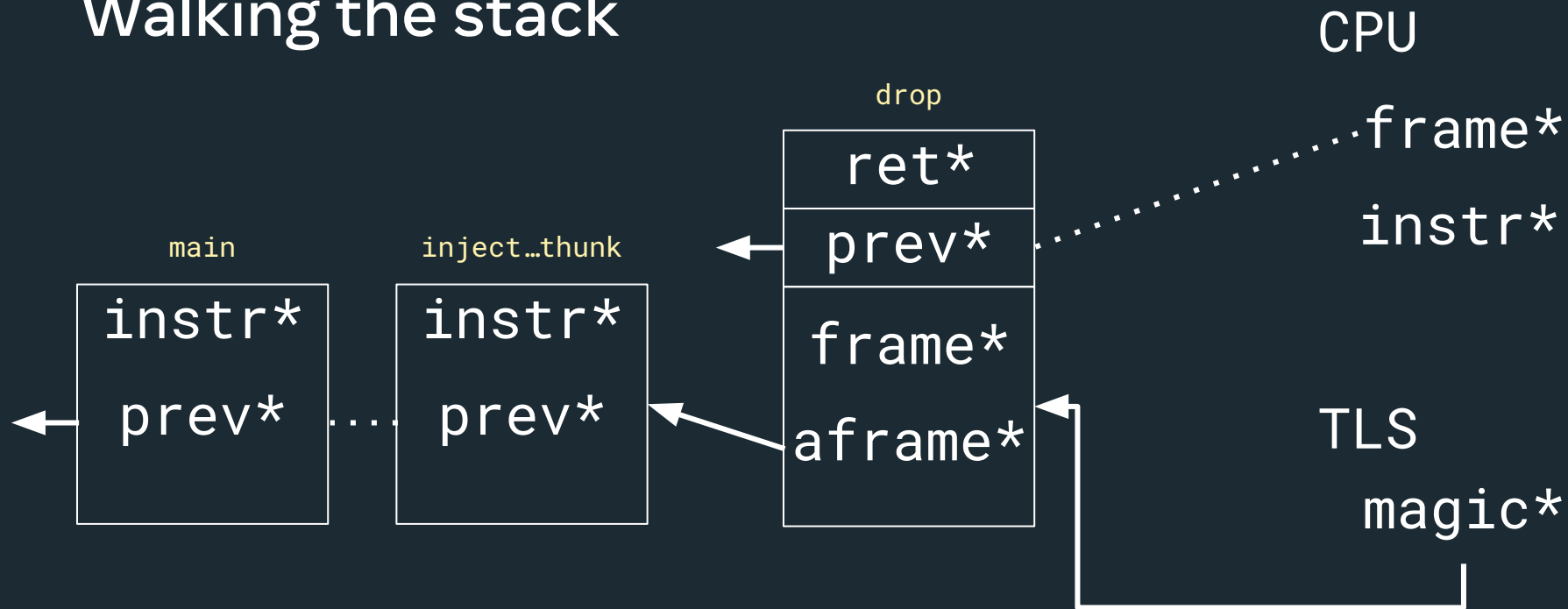


Walking the stack

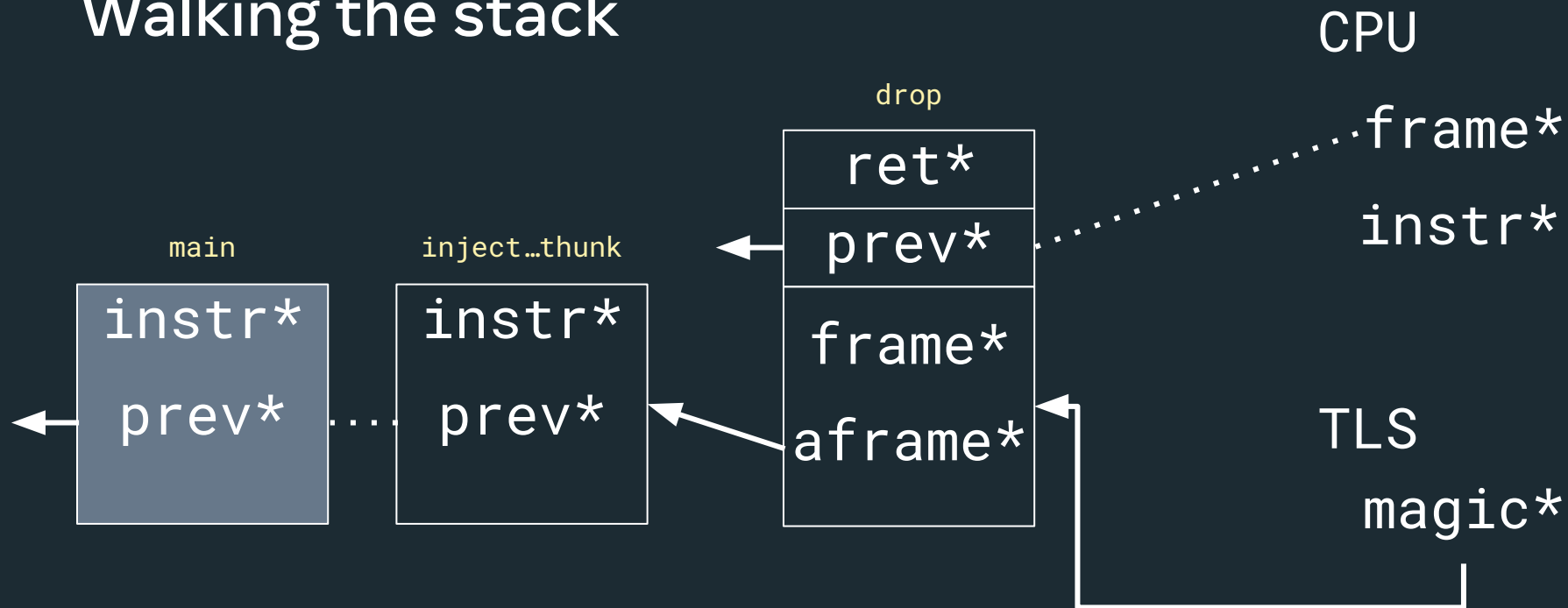


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10: decltype(auto) tag_invoke(...) () at sender_for.hpp:61
11: auto unifex::_wsa::_make_sender<...>(auto&&, auto&&) () at with_scheduler_affinity.hpp:44
12: decltype(auto) ..._promise<void>::await_transform(...) () at task.hpp:384
13: auto unifex::connect_awaitable(task<void>, receiver auto&) () at connect_awaitable.hpp:234
14: main () at main.cpp:103
15: main () at main.cpp:103
16: main () at main.cpp:103
```

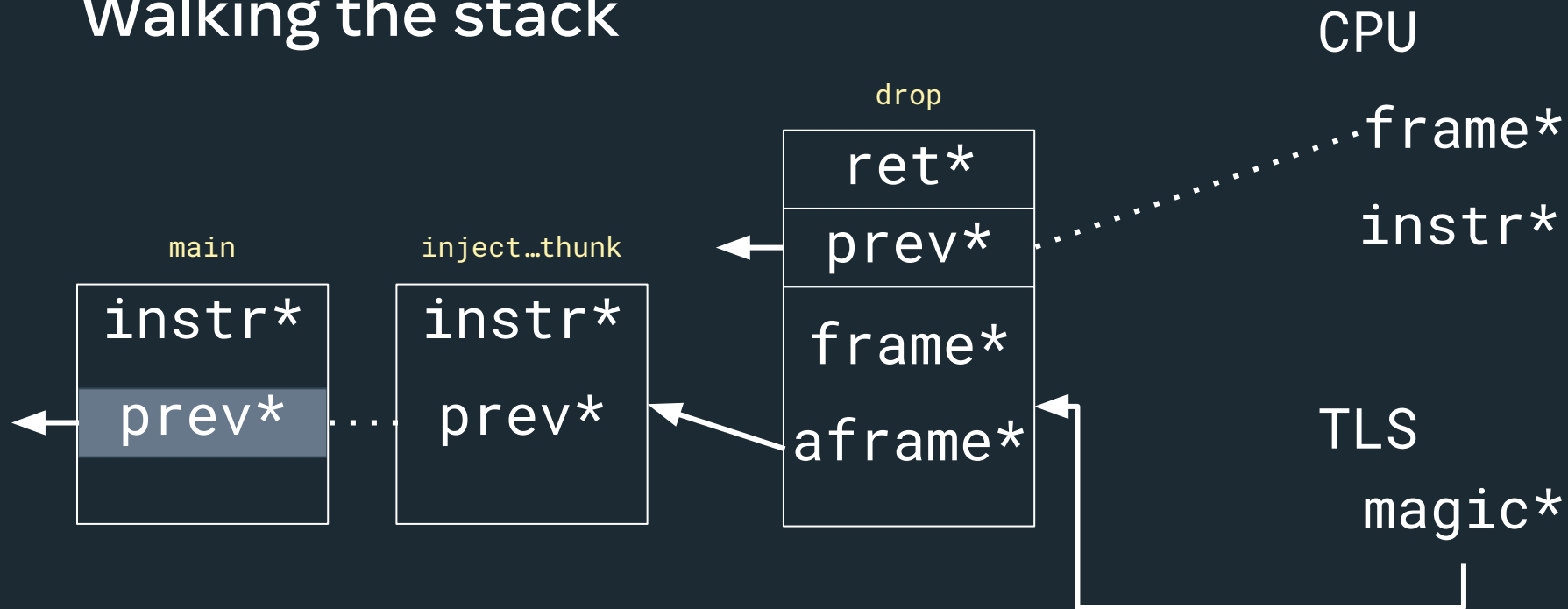
Walking the stack



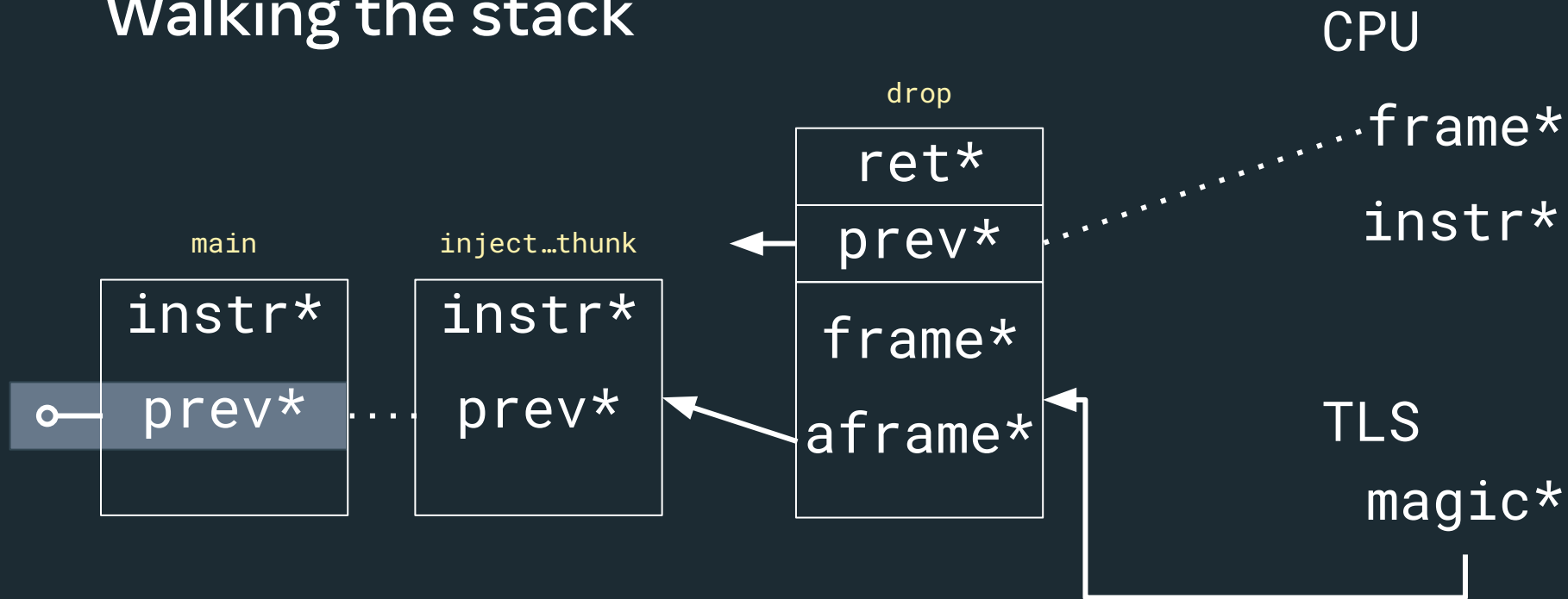
Walking the stack



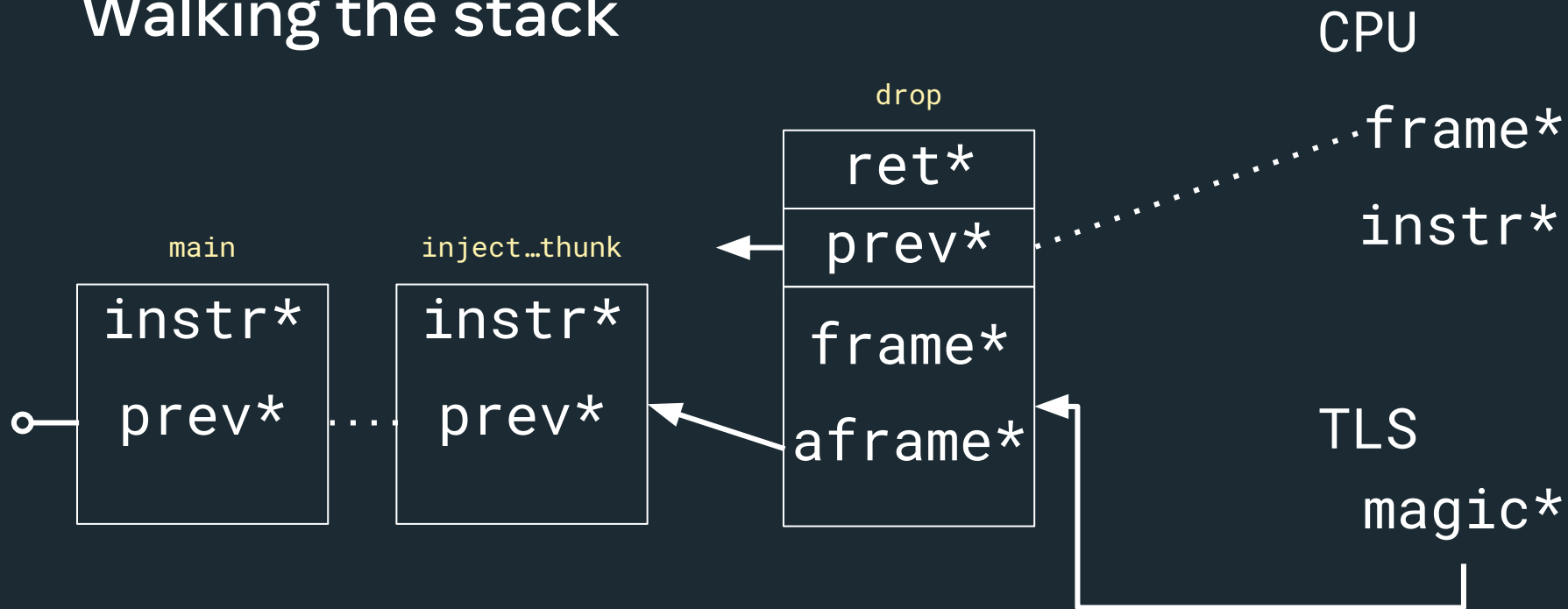
Walking the stack



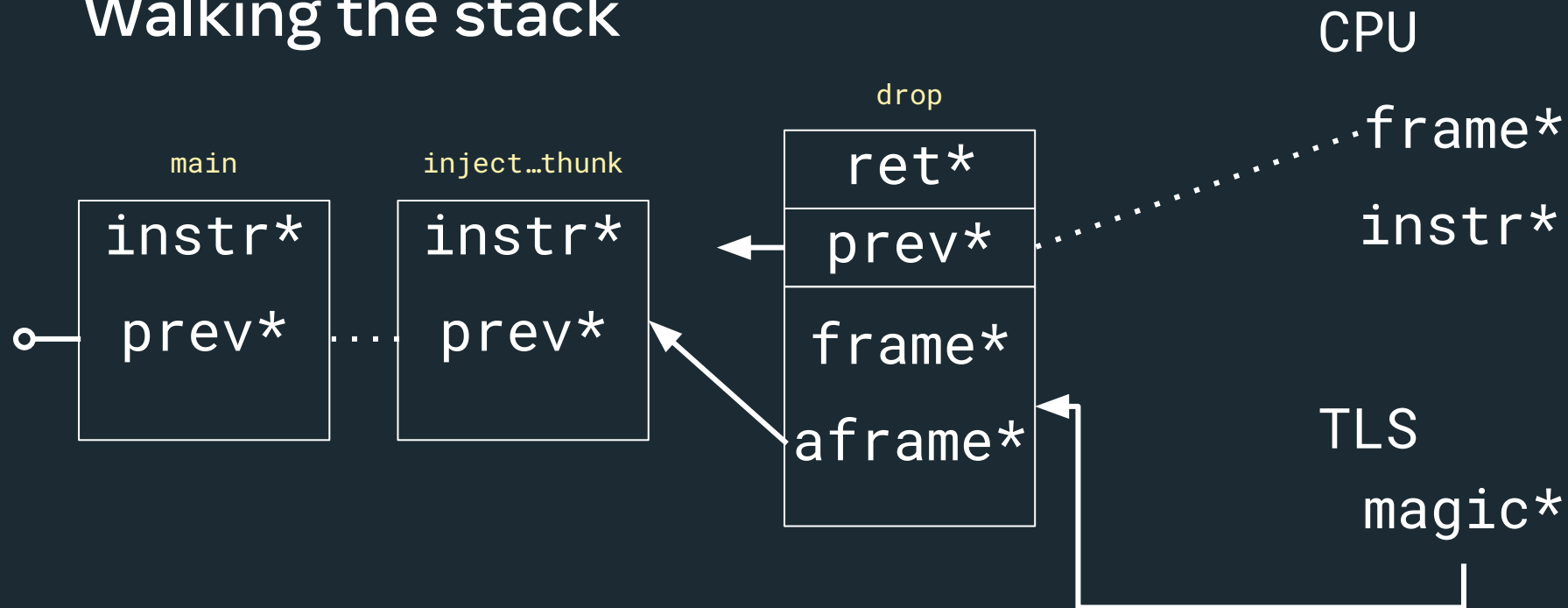
Walking the stack



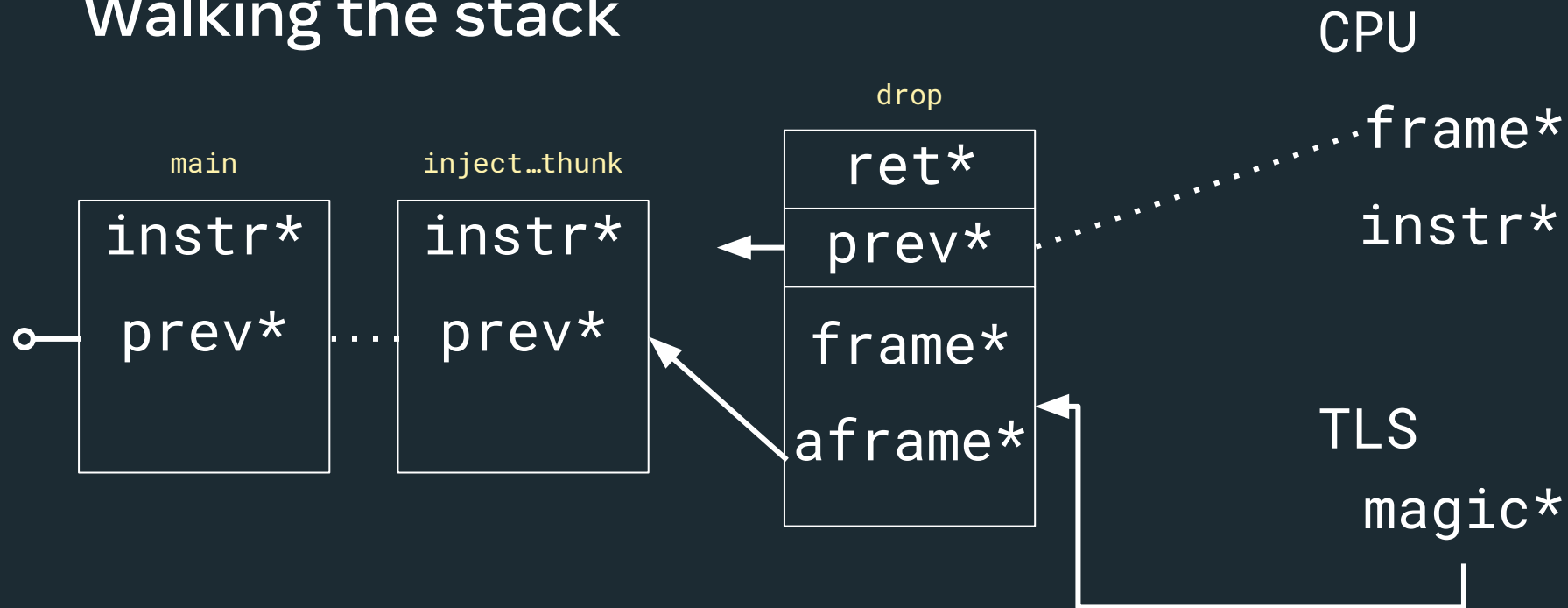
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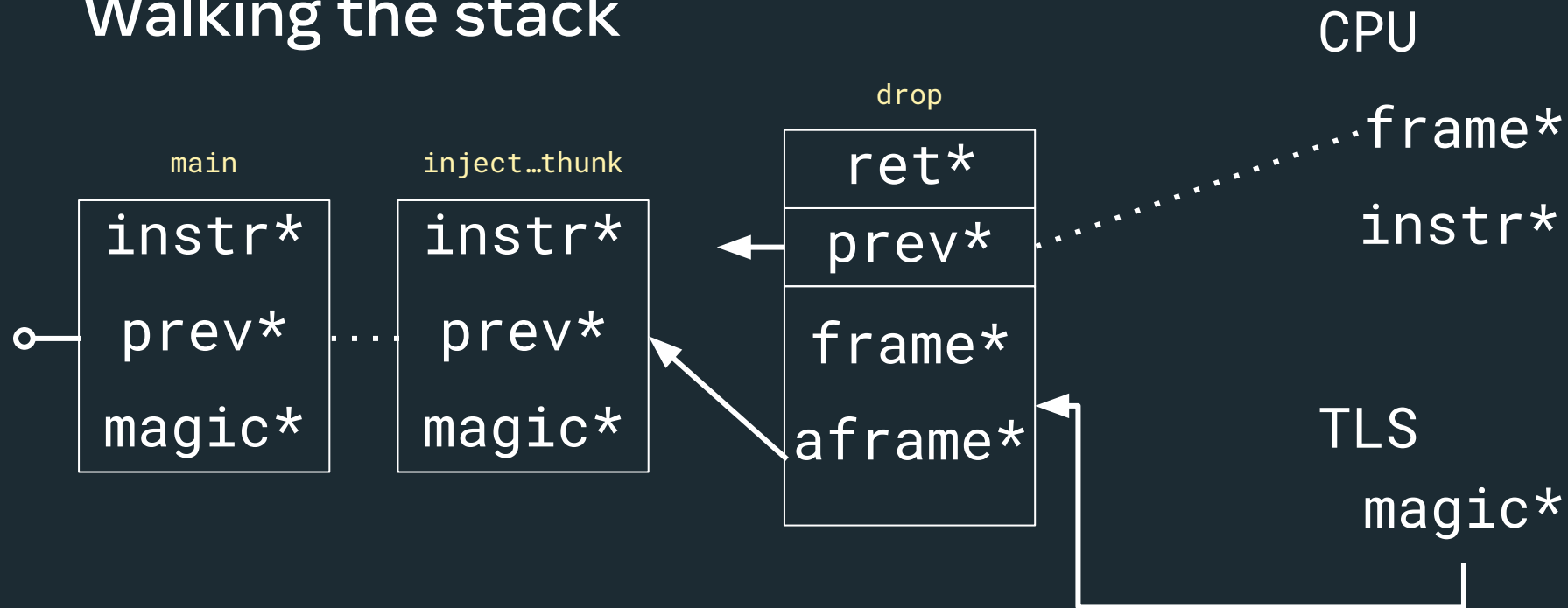
Walking the stack



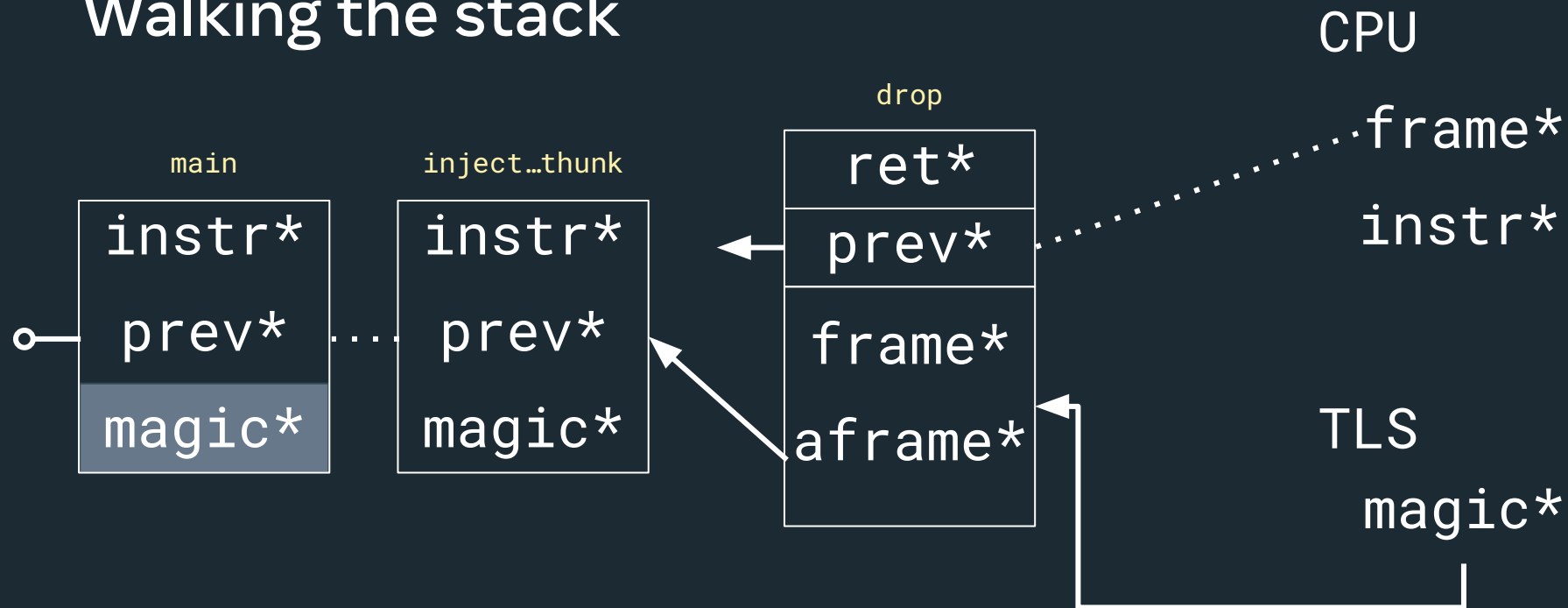
Walking the stack



Walking the stack



Walking the stack



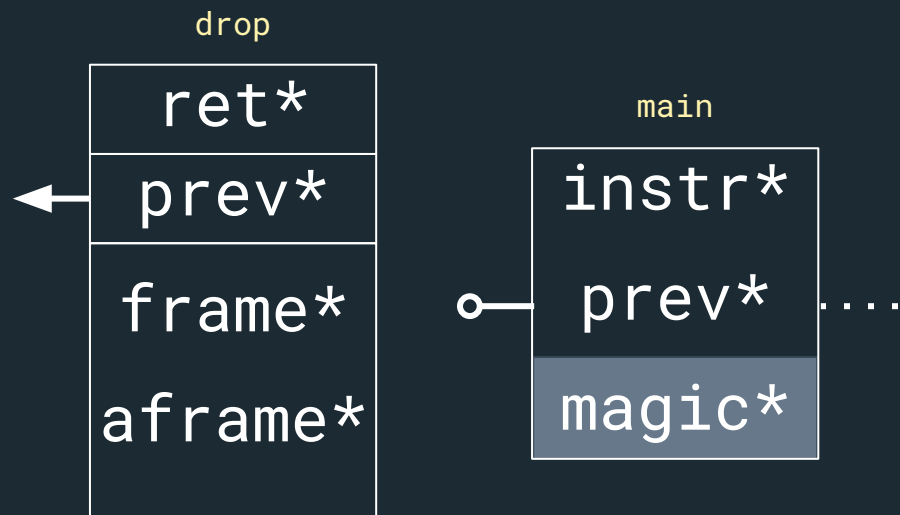
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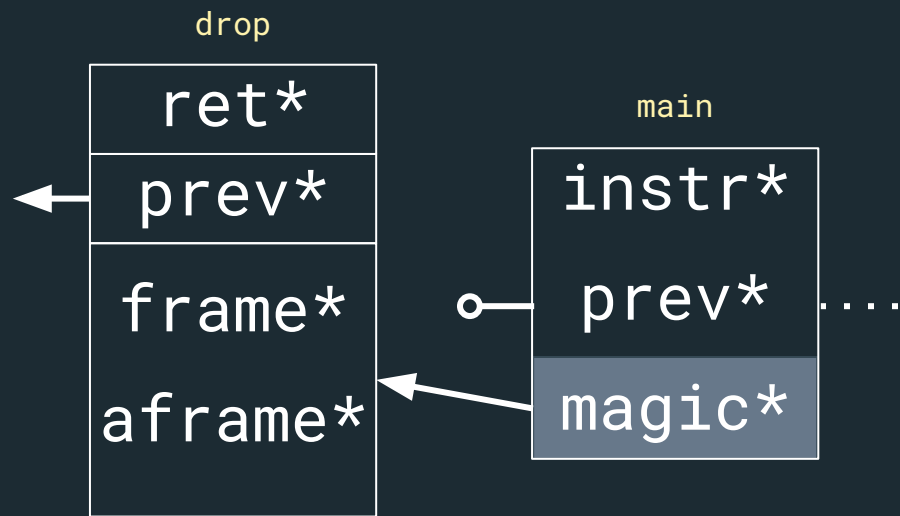
Walking the stack



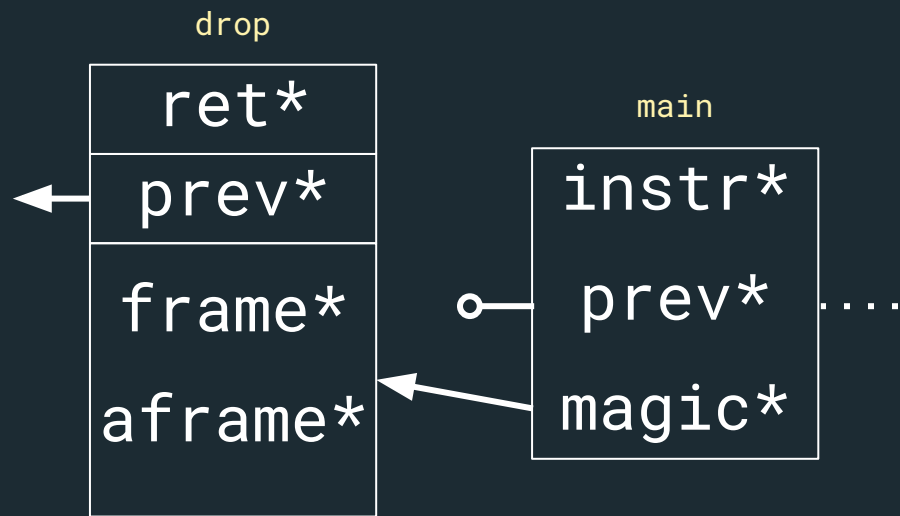
Walking the stack



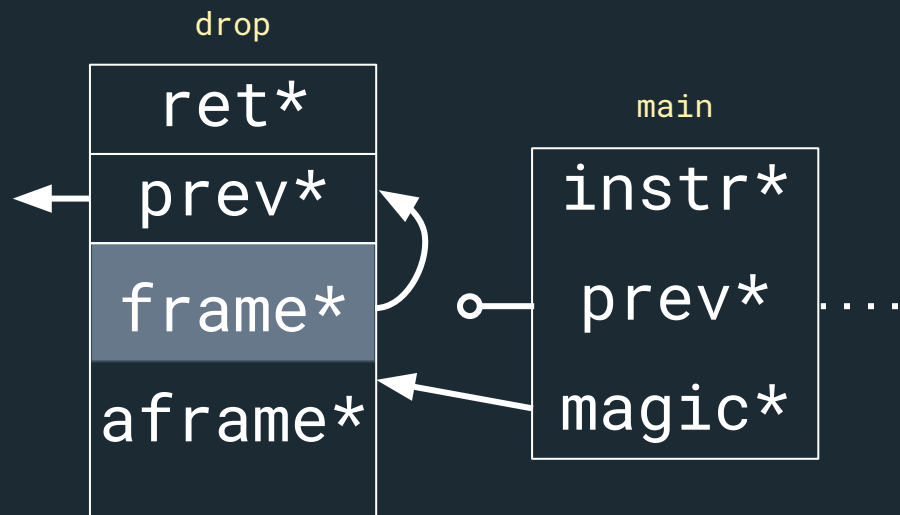
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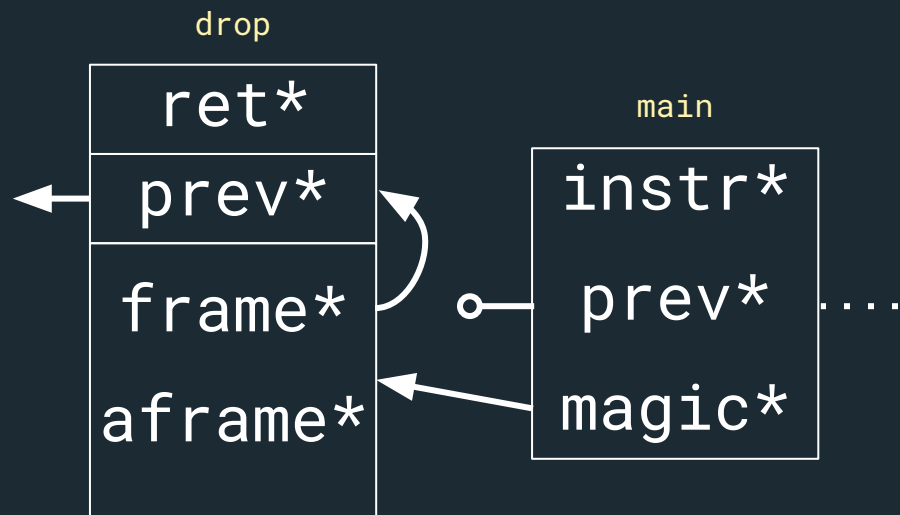
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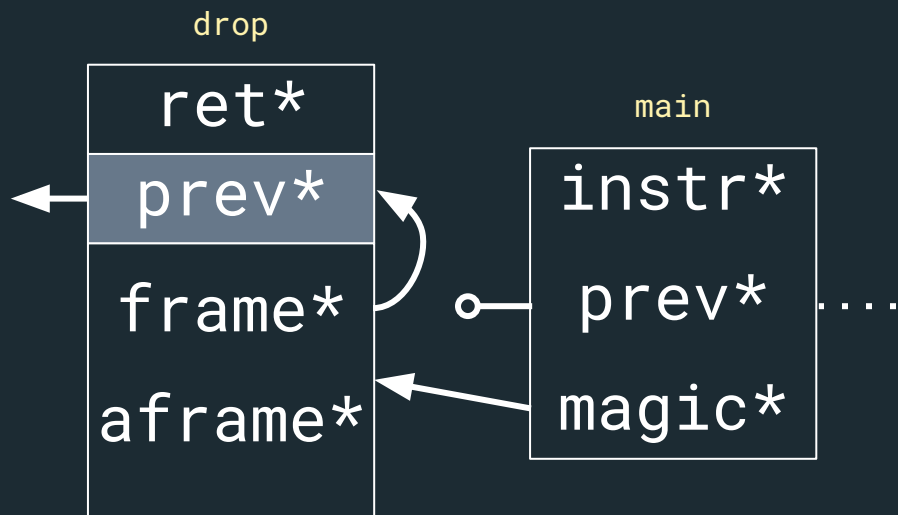
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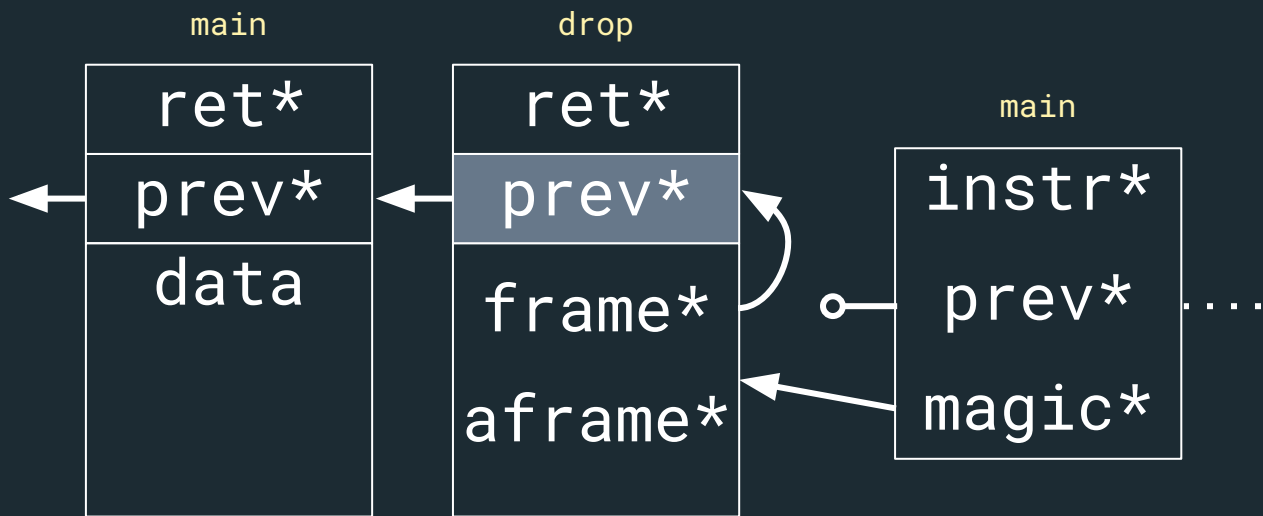
Walking the stack



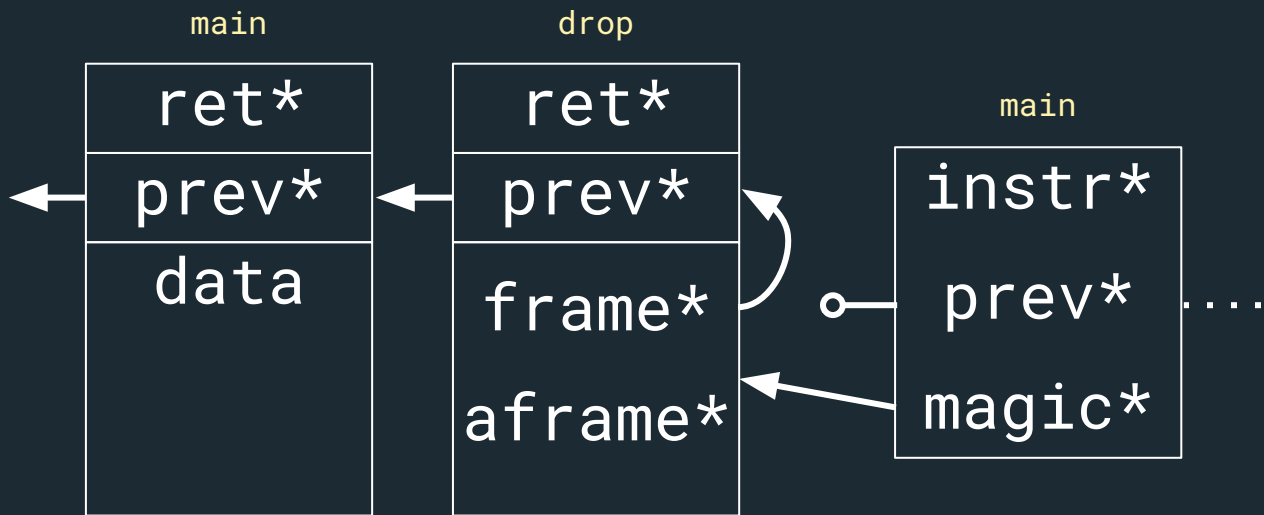
Walking the stack



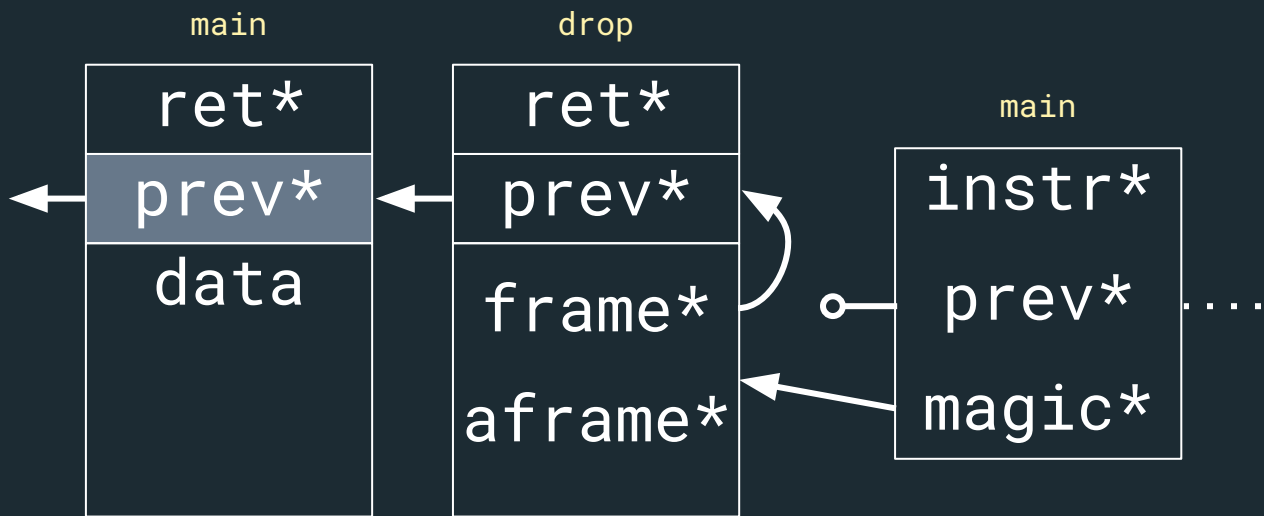
Walking the stack



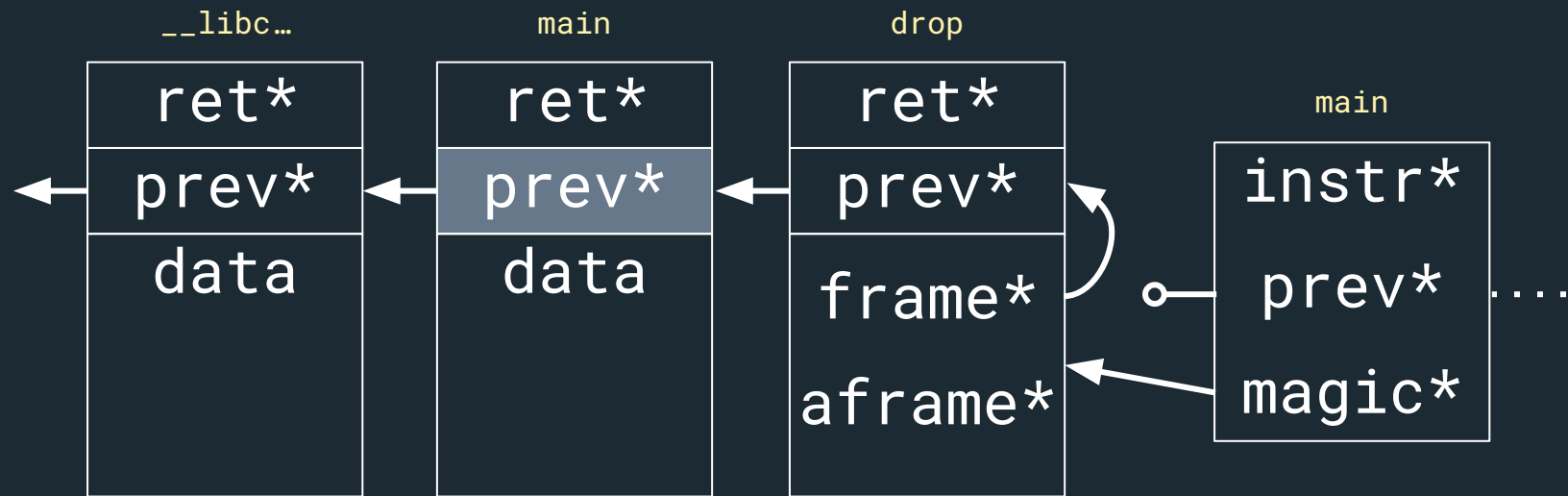
Walking the stack



Walking the stack

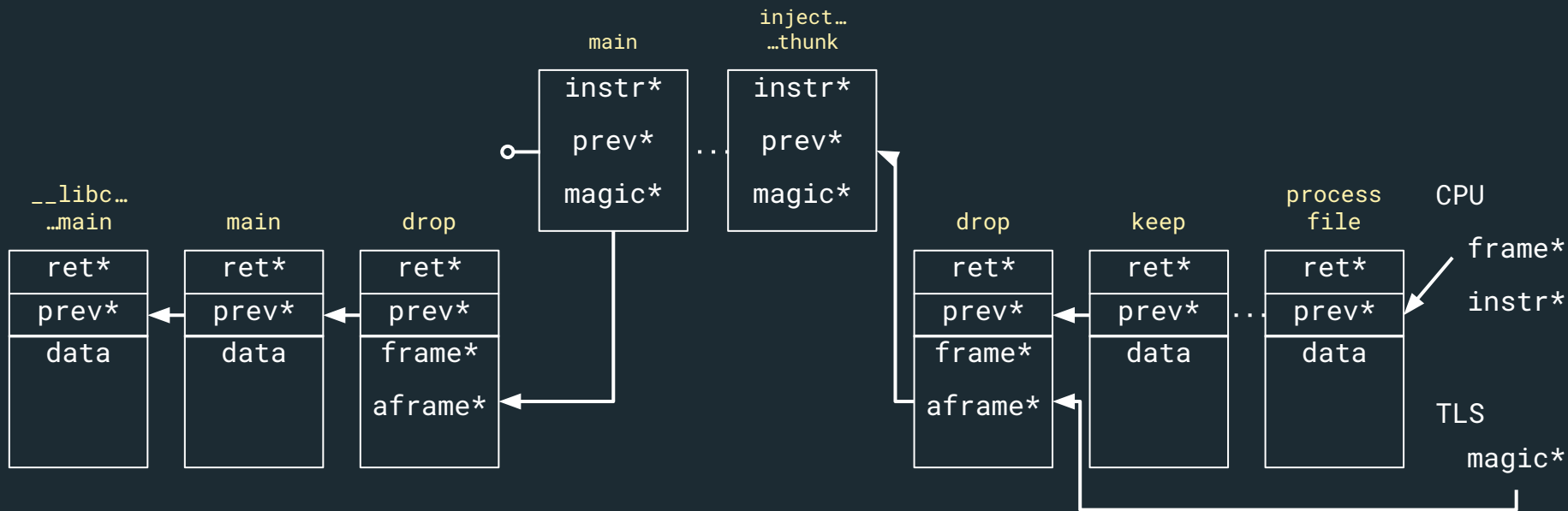


Walking the stack

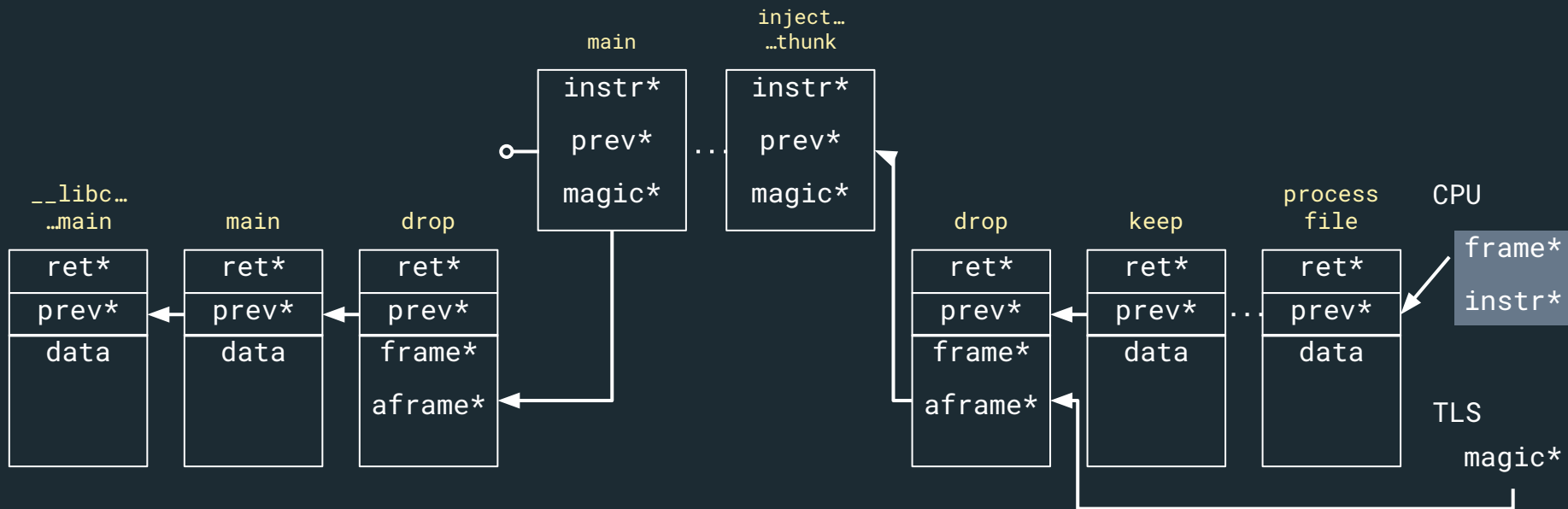


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15: main () at main.cpp:103
16: main () at main.cpp:103
17: main () at main.cpp:105
18: __libc_start_main () at ???:0
```

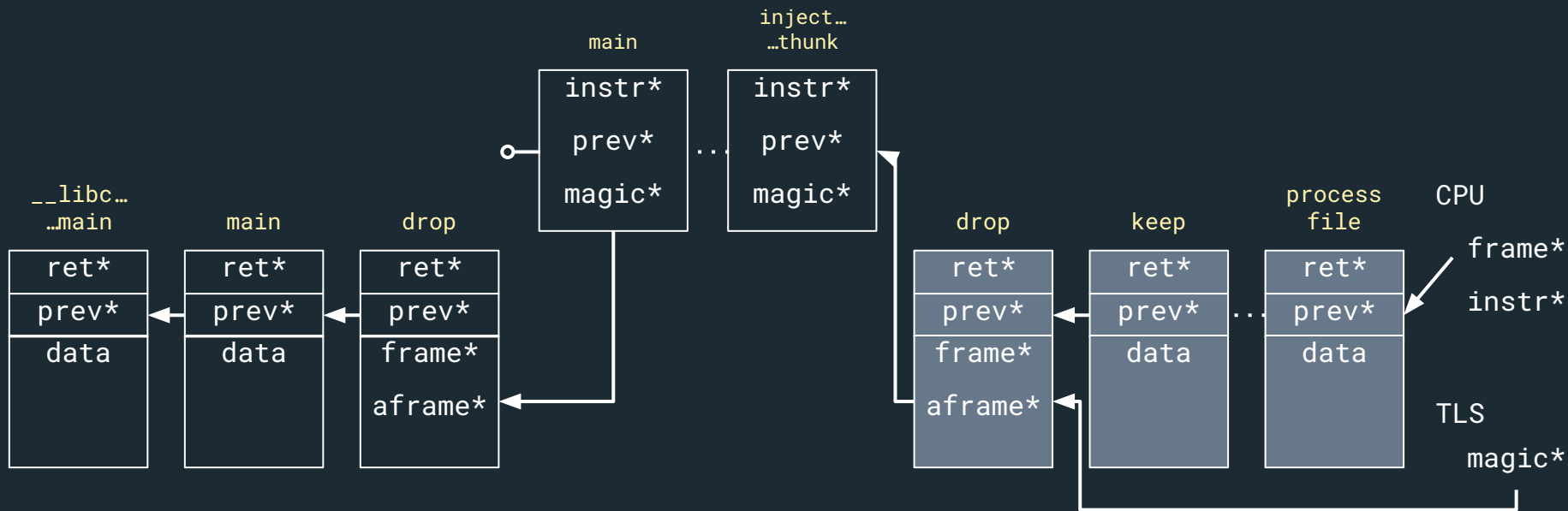
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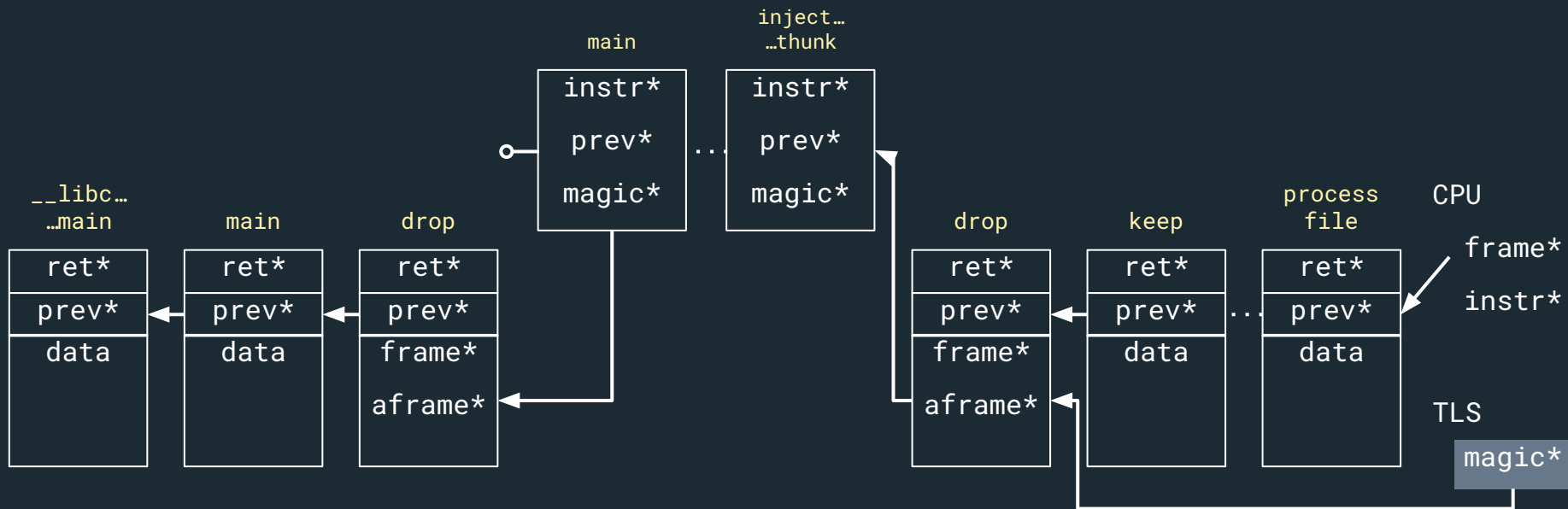
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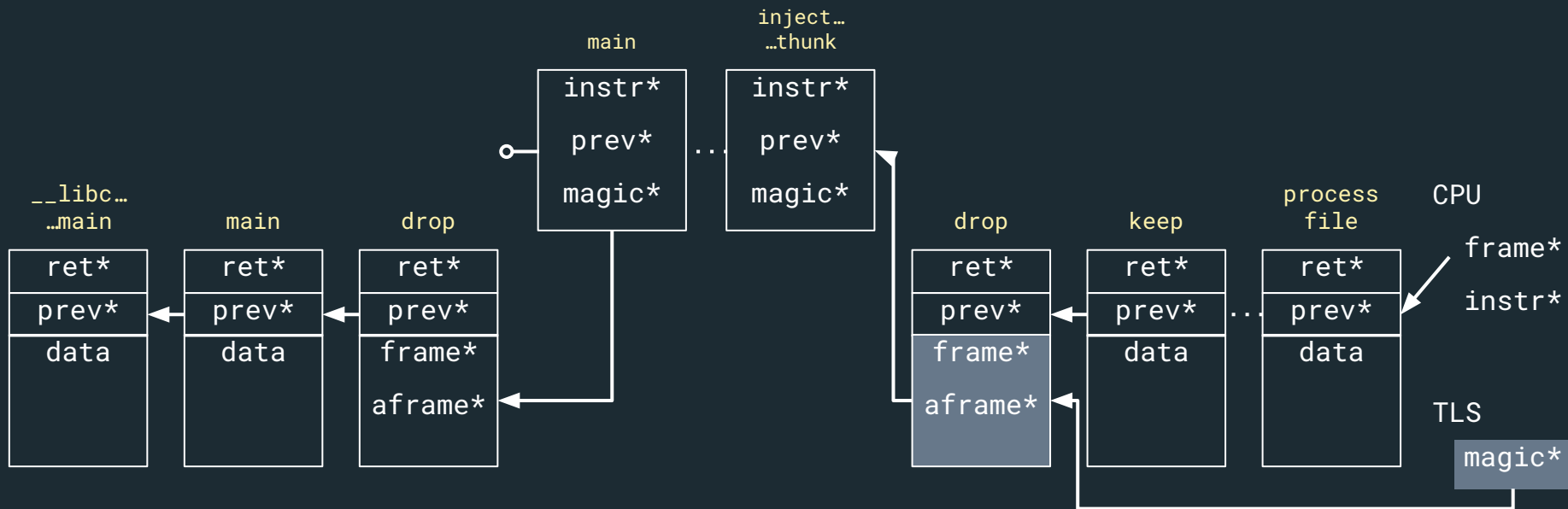
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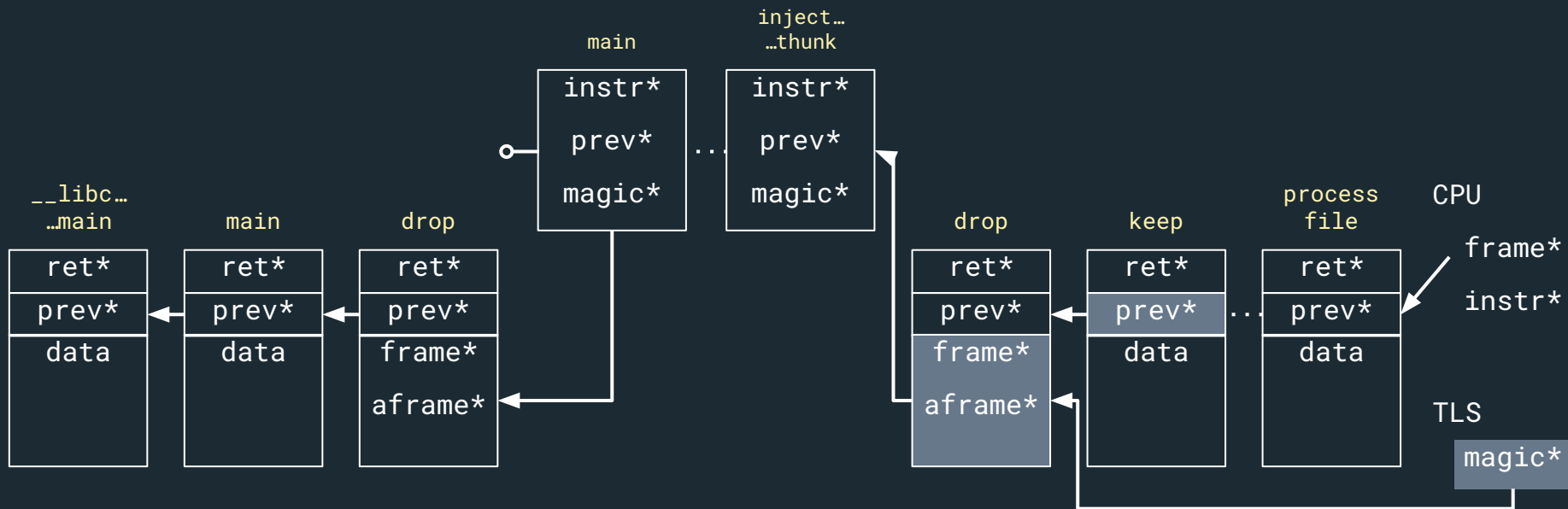
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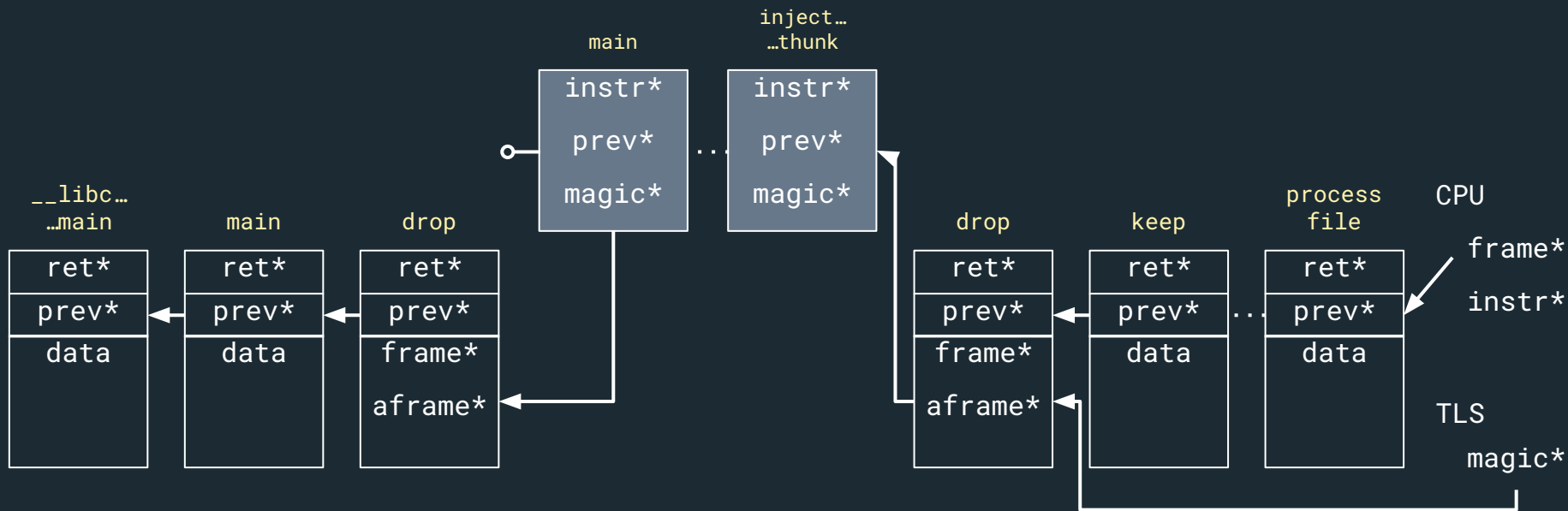
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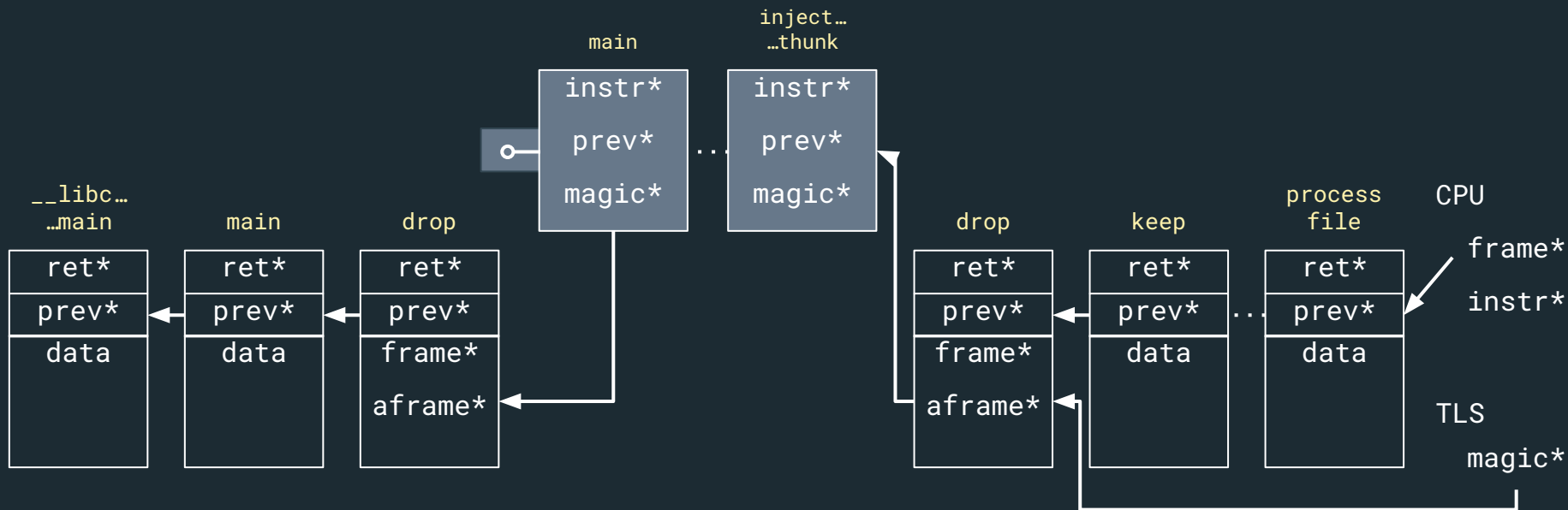
Walking the stack



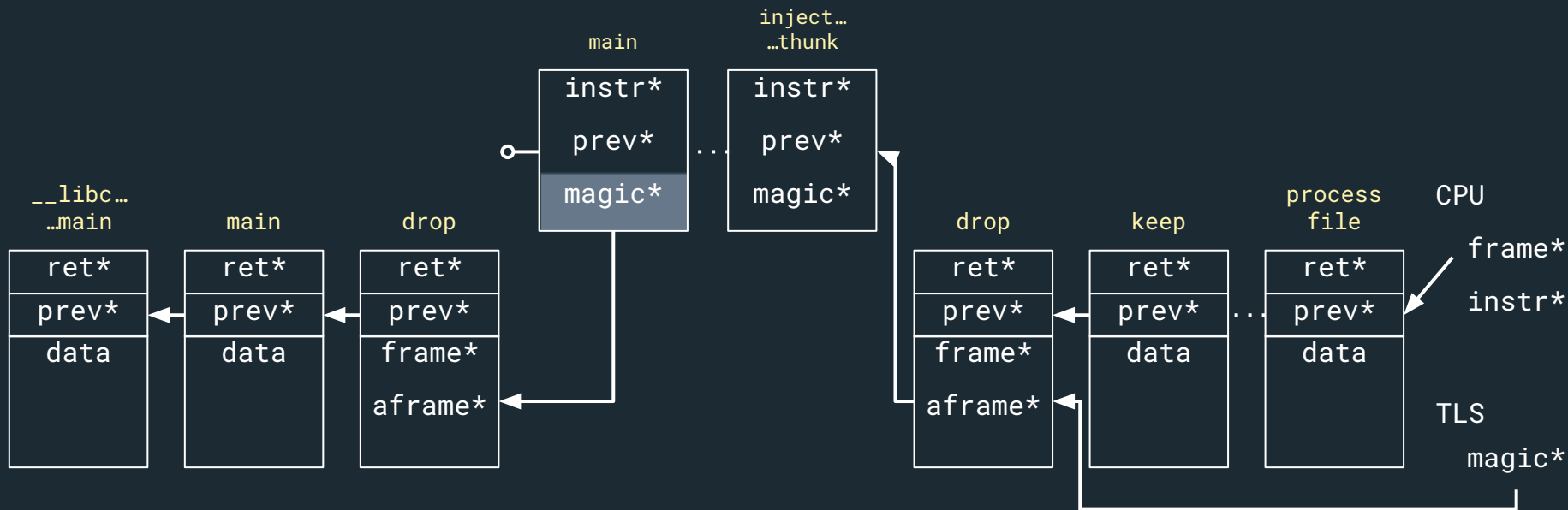
Walking the stack



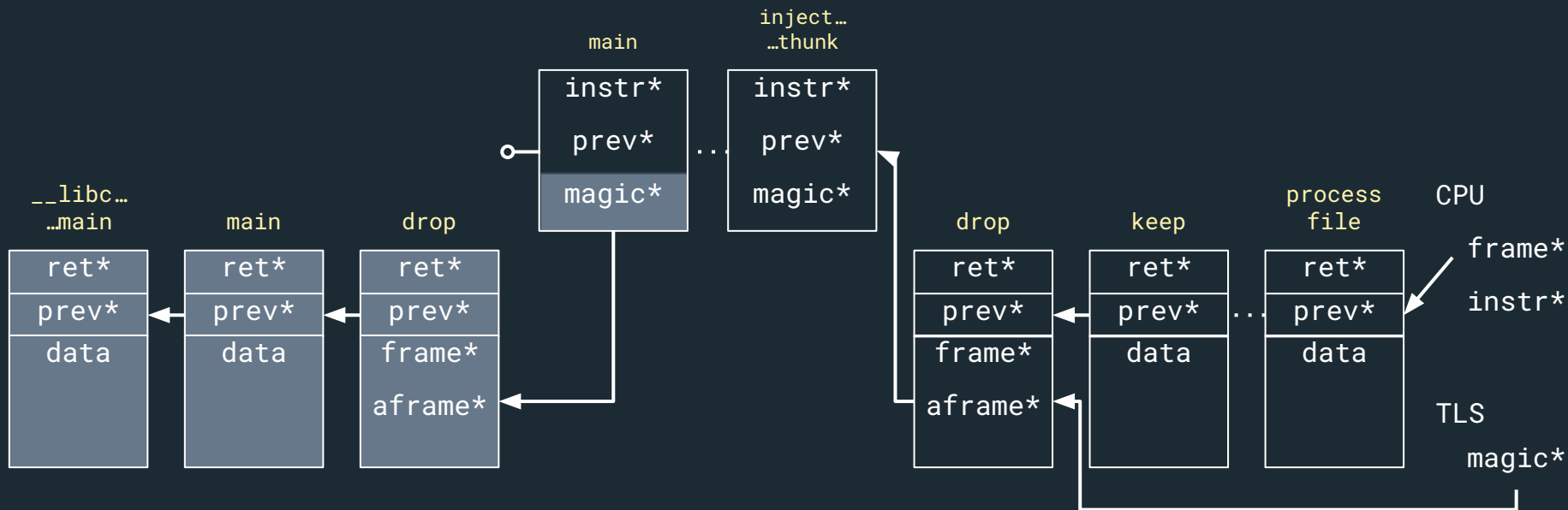
Walking the stack



Walking the stack



Walking the stack



So what was that magic*?

```
struct AsyncStackRoot {  
    atomic<AsyncStackFrame*> topFrame;  
    AsyncStackRoot* nextRoot;  
    frame_ptr          stackFramePtr;  
    instruction_ptr returnAddress;  
};
```


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```

```
struct AsyncStackFrame {  
    AsyncStackFrame* parentFrame;  
    instruction_ptr  instructionPointer;  
    AsyncStackRoot*  stackRoot;  
};
```

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    AsyncStackRoot*  stackRoot;  
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```

So how did we bring async stacks to Unifex?

- Every async operation owns an `AsyncStackFrame`
- Threads executing part of an async operation have an `AsyncStackRoot` on a frame in their stack
- Every sender algorithm captures its return address

How can you use it?



Folly / Unifex

Async stacks integration is currently available in [folly](#) and [unifex](#).



LLDB Python Extension

Co_bt python extension is available in [folly](#) and can be imported to lldb.

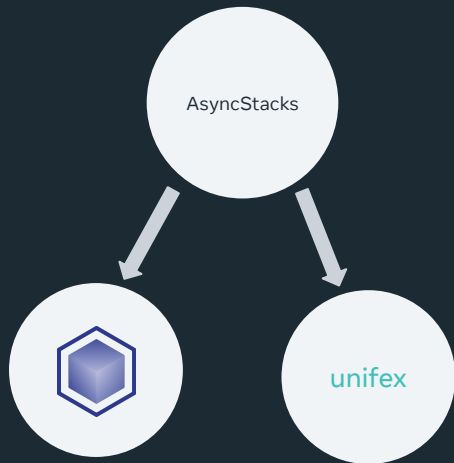
Has worked for GDB, too; needs some updating.



co_bt

Use co_bt instead of bt to view async stack trace

How you can contribute



AsyncStacks lib

Shared AsyncStacks library for folly + unifex that can be integrated into other coroutine / sender libs.

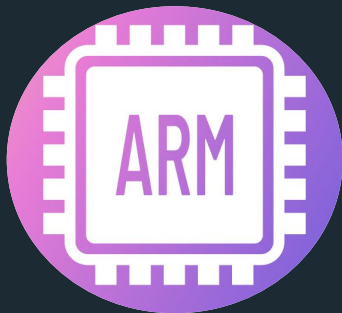


Industry adoption



AsyncStackFrame local variable inspection

Be able to inspect variables in the AsyncStackFrame



Arm64 support



Complete unifex algorithm
coverage



Visual Studio
integration

Try it yourself

- [fbsamples/cppcon24-async-demo](https://github.com/fbsamples/cppcon24-async-demo)

