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# A Pattern Language for Expressing Concurrency

LUCIAN RADU TEODORESCU



# A Pattern Language for Expressing Concurrency

[lucteo.ro/pres/2022-cppcon/](https://lucteo.ro/pres/2022-cppcon/)



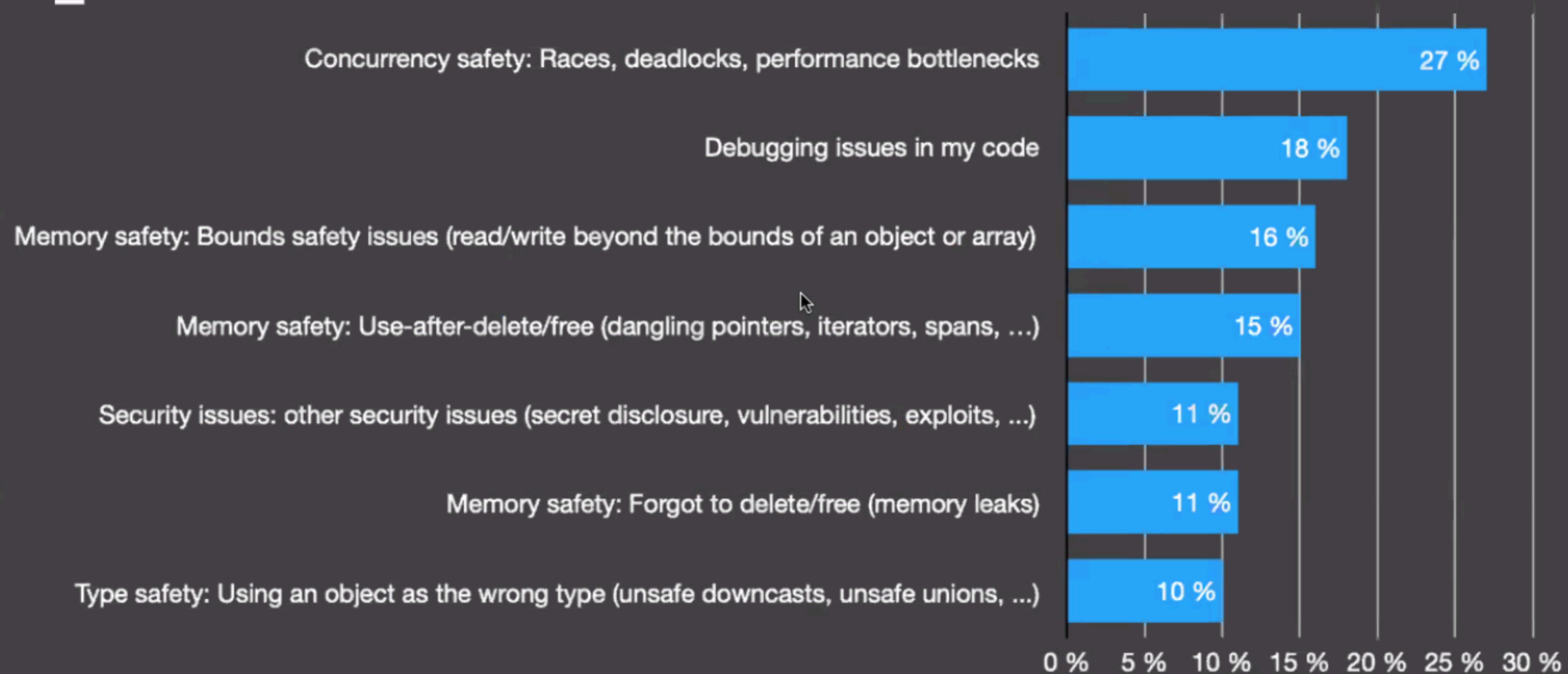
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GARMIN



concurrency is **HARD**



# C++ development frustration: safety & security



we want

safety

performance

structured approach



# P2300 — `std::execution` (senders and receivers)

C++ proposal  
did not make it to C++23



approach

abstractions

shapes

solving the puzzle

spea**k** concurrency

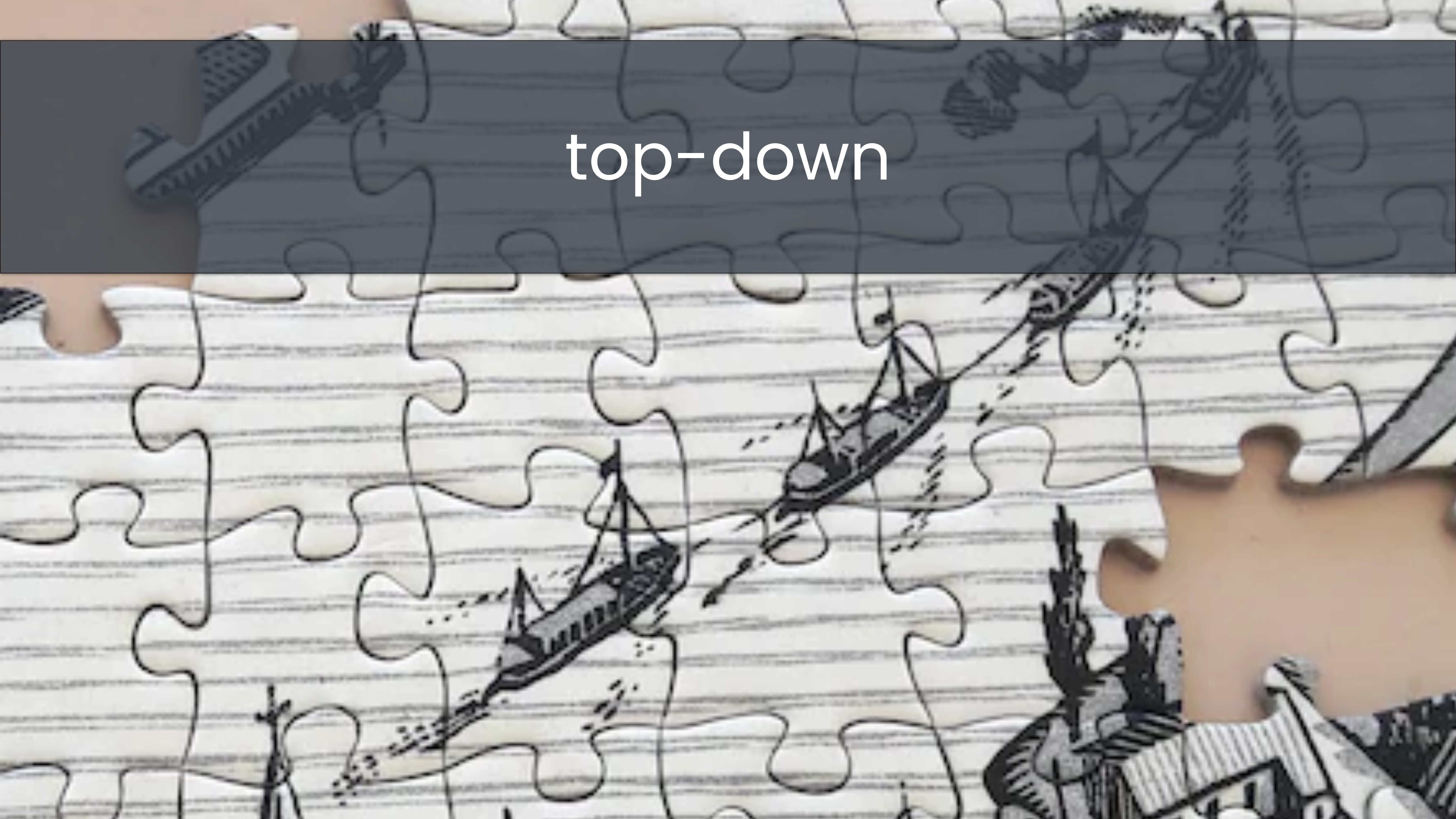




top-down



top-down



# Agenda

Structured  
Concurrency

Introductory  
Examples

Starting with  
Patterns

Extending the  
Patterns  
Repertoire

Composition  
with Patterns



# Structured Concurrency



An Introduction

# Structured **Concurrency**

extending the ideas from **Structured Programming**

# what is **Structured Programming**?

1. abstractions as building blocks
2. recursive decomposition
3. local reasoning
4. single entry, single exit point
5. soundness and completeness

no GOTOs

functions

sequence, selection, repetition

APIC Studies in Data Processing No. 8

# STRUCTURED PROGRAMMING

O.-J. Dahl, E. W. Dijkstra and C. A. R. Hoare

Academic Press  
London New York San Francisco  
*A Subsidiary of Harcourt Brace Jovanovich, Publishers*



# concurrency with **threads**

primitives: threads & mutexes



# concurrency with threads: **structured?**



<del>abstractions as building blocks</del>	no
<del>recursive decomposition</del>	no
<del>local reasoning</del>	no
<u>single entry, single exit point</u>	-
<del>soundness and completeness</del>	1/2

# concurrency with **raw tasks**

primitives: tasks  
(independent units of work)



# raw tasks — **structured?**

partial

abstractions as building blocks	yes
<del>recursive decomposition</del>	no
local reasoning	yes
<del>single entry, single exit point</del>	no
soundness and completeness	yes

# P2300 — `std::execution` (senders and receivers)

primitives: senders

# P2300 — **Structured Concurrency**



CHECK

1. abstractions as building blocks
2. recursive decomposition
3. local reasoning
4. single entry, single exit point
5. soundness and completeness



senders

ACCU  
2022

# STRUCTURED CONCURRENCY

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<https://www.youtube.com/watch?v=Xq2IMOPjPs0>



senders describe **computations**

any chunk of work,  
with one entry and one exit point

# computations

a task

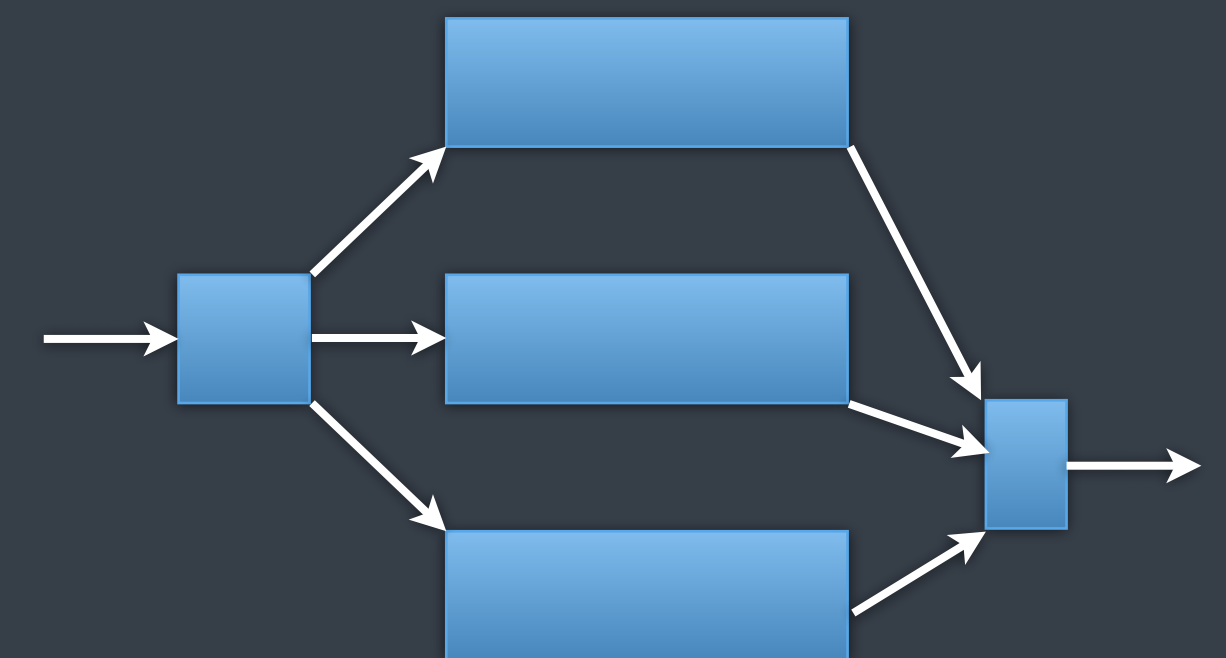




# computations

a task

tasks over multiple threads



# computations

a task

tasks over multiple threads

group of computations



# computations

a task

tasks over multiple threads

group of computations

the entire application



# computations

a task

tasks over multiple threads

group of computations

the entire application

any chunk of work,  
with one entry and one exit point

# functions

same thread

# computations

entry thread  $\neq$  exit thread

# computations

## generalisation of functions

**computations** are for **concurrency**  
what functions are for **Structured** Programming

senders model computations

what about **coroutines**?



# coroutines — **Structured Concurrency**

CHECK

1. abstractions as building blocks
2. recursive decomposition
3. local reasoning
4. single entry, single exit point
5. soundness and completeness

coroutine tasks

coroutine tasks

≡

senders

# Introductory Examples

2



# Hello, concurrent world!

```
namespace ex = std::execution;

auto say_hello() {
    return ex::just() // just a signal
        | ex::then([] {
            std::printf("Hello, concurrent world!\n");
            return 0;
        });
}

int main() {
    auto [r] = std::this_thread::sync_wait(say_hello().value());
    return r;
}
```

# shapes of the functions

just	$() \rightarrow sender$
then	$(sender, ftor) \rightarrow sender$
sync_wait	$(sender) \rightarrow optional<tuple<vals...>>$

# sender

describes work  
eventually produces a result

(similar to a future)

# Hello, concurrent world!

```
namespace ex = std::execution;

auto say_hello() {
    return ex::just() // just a signal
        | ex::then([] {
            std::printf("Hello, concurrent world!\n");
            return 0;
        });
}

int main() {
    auto [r] = std::this_thread::sync_wait(say_hello().value());
    return r;
}
```

# Hello, concurrent world! (2)

```
task<int> say_hello() {
    std::printf("Hello, concurrent world!\n");
    co_return 0;
}

int main() {
    auto [r] = std::this_thread::sync_wait(say_hello());
    return r;
}
```



coroutine tasks

≡

senders

rock, paper, scissors

2 players doing work in parallel

# rock, paper, scissors

```
enum class shape { rock, paper, scissors };

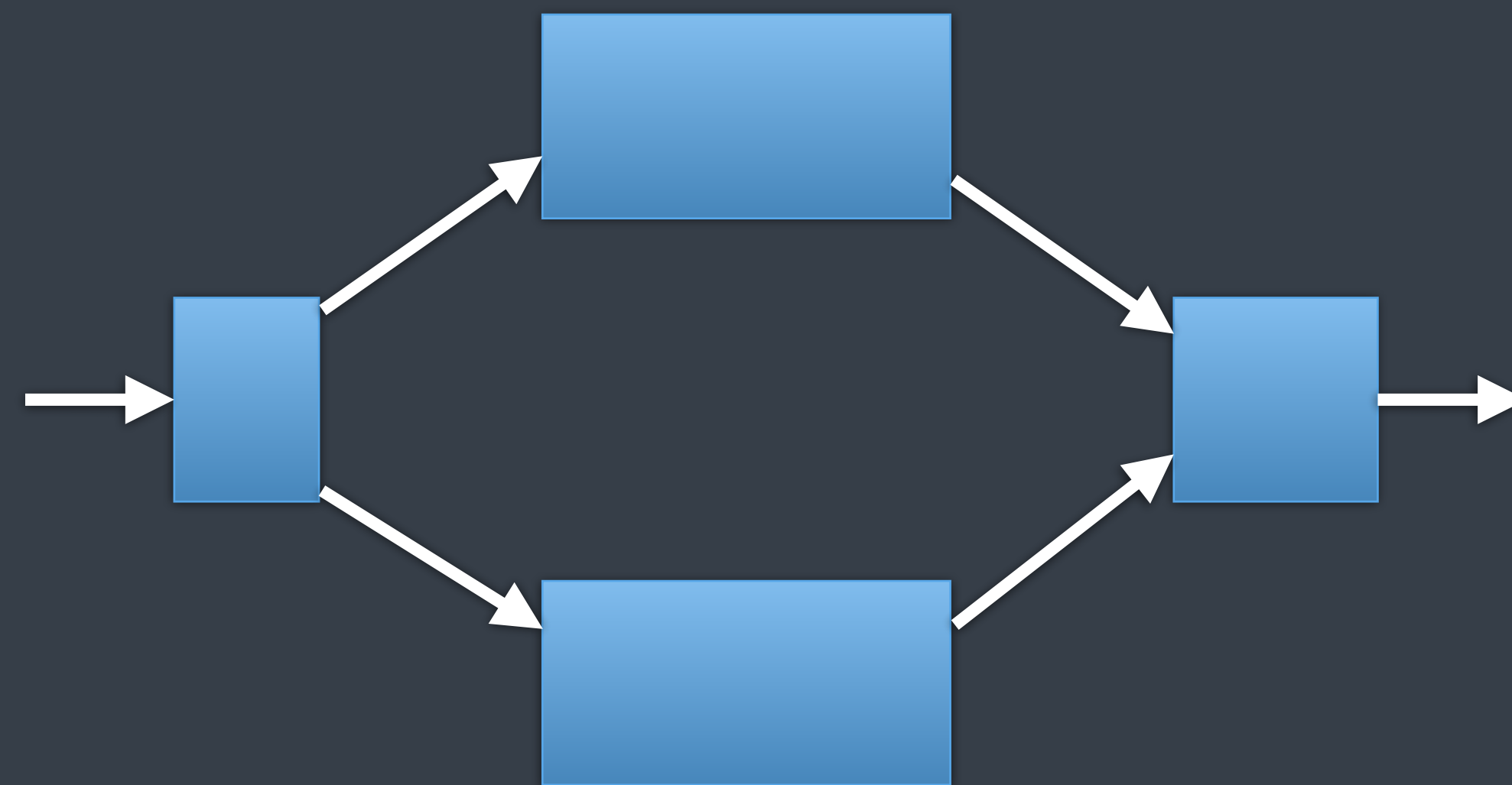
shape player_choose() { return static_cast<shape>(rand() % 3); }

void print_result(shape r1, shape r2) { ... }

void play_rock_paper_scissors() {
    static_thread_pool pool{8};
    ex::scheduler auto sched = pool.get_scheduler();

    ex::sender auto game_work = ex::when_all( //
        ex::schedule(sched) | ex::then(player_choose), //
        ex::schedule(sched) | ex::then(player_choose) //
    );
    auto [r1, r2] = sync_wait(std::move(game_work)).value();
    print_result(r1, r2);
}
```

# rock, paper, scissors



# concurrency analysis

threads are hidden  
expressed concurrency as a graph  
no explicit synchronization  
framework ensures efficiency

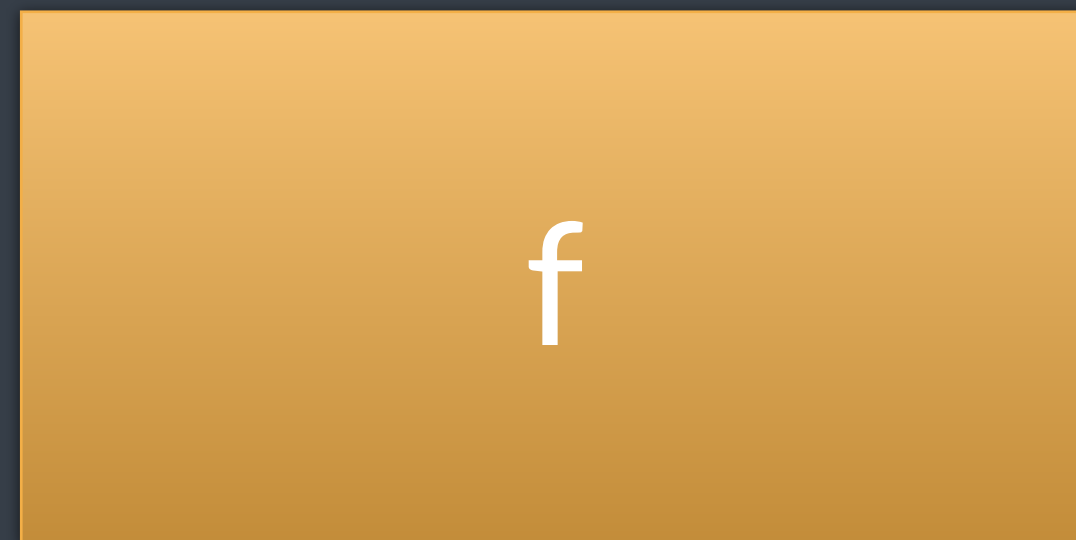
how to **describe**  
*concurrency* ?

# Starting with Patterns

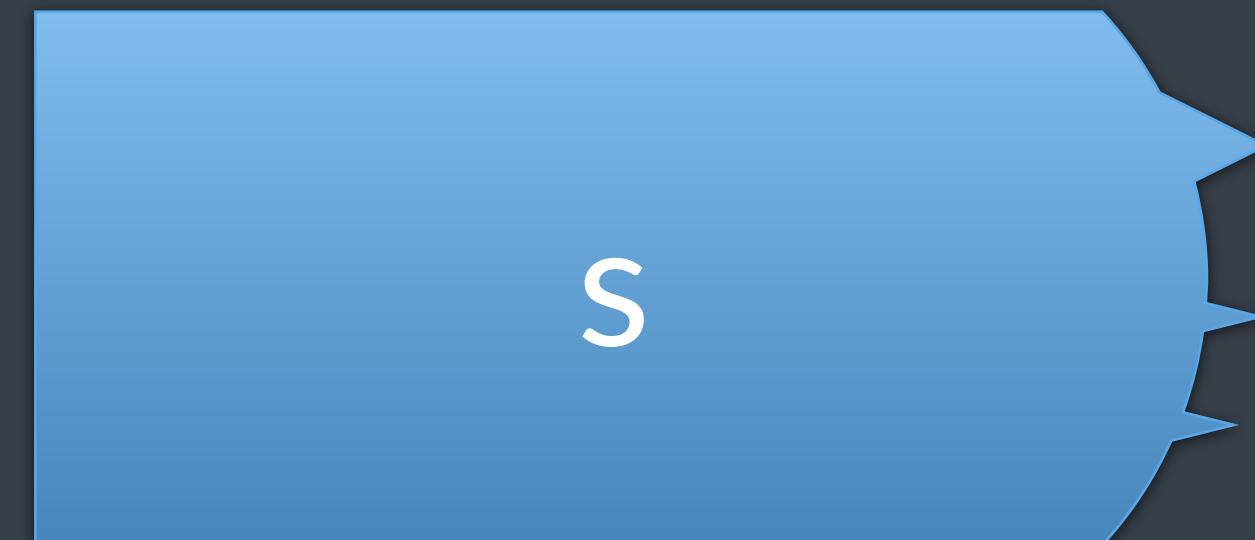
3



# functions



# senders





# exit point for **functions**

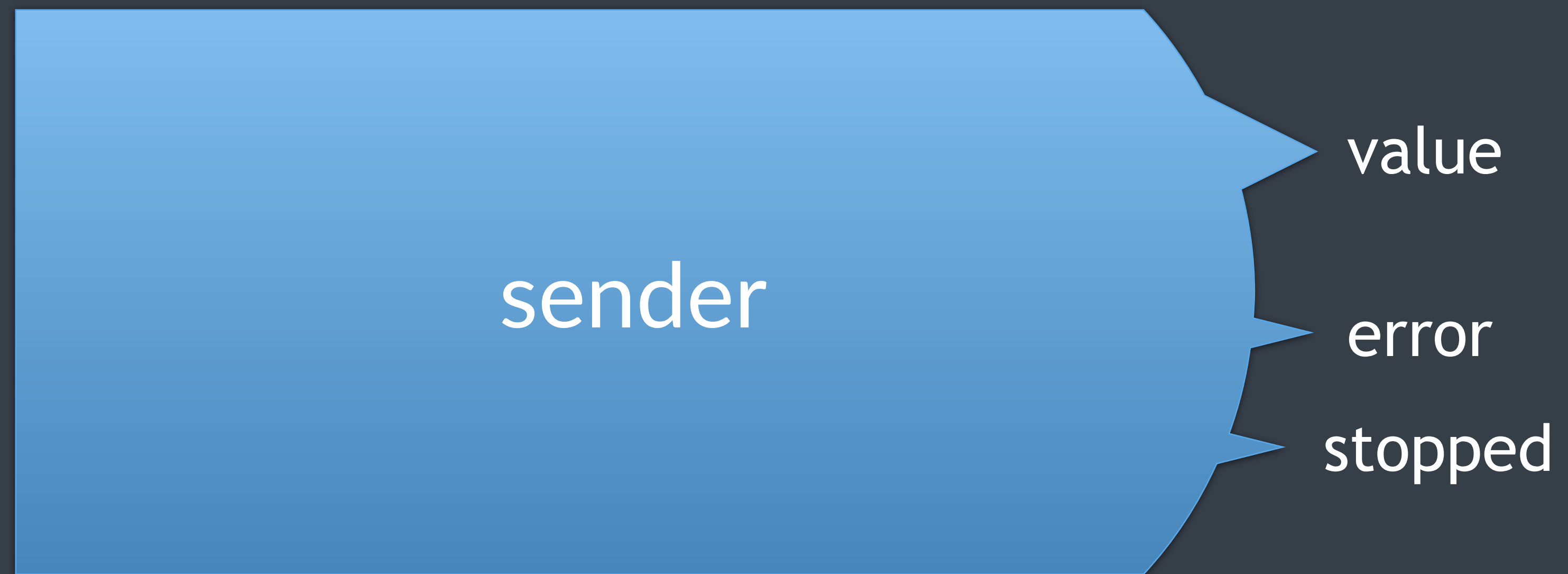
return value (or void)

exceptions

stopped — i.e., `exit( )` called

# exit point for **senders**

```
set_value(vals...)  
set_error(err)  
set_stopped( )
```



# P1: create value

## when to use:

- transform a value into a sender
- inject a value into a sender flow
- start a sender flow

# creating value

```
void create_value_example() {  
    ex::sender auto s = ex::just(13);  
  
    auto [r] = sync_wait(s).value();  
    assert(r == 13);  
    std::printf("%d\n", r);  
}
```

# multiple values

```
void create_value_example2() {  
    ex::sender auto s = ex::just(17, 19);  
  
    auto [a, b] = sync_wait(s).value();  
    assert(a == 17);  
    assert(b == 19);  
    std::printf("%d, %d\n", a, b);  
}
```

# no value, just a signal

```
void create_value_example3() {  
    ex::sender auto s = ex::just();  
  
    sync_wait(s); // finishes immediately  
}
```

`just(val...)`

`val...`



# variations

`just_error(e)`  
`just_stopped()`

`just_error(e)`  $e$

`just_stopped()`

# P2: synchronous wait

## when to use:

- wait for a sender to complete

## when NOT to use:

- too often (blocking the thread)

# creating value

```
void create_value_example() {  
    ex::sender auto s = ex::just(13);  
  
    auto [r] = sync_wait(s).value();  
    assert(r == 13);  
    std::printf("%d\n", r);  
}
```



`sync_wait()`

`just(val...)`

`sync_wait()`

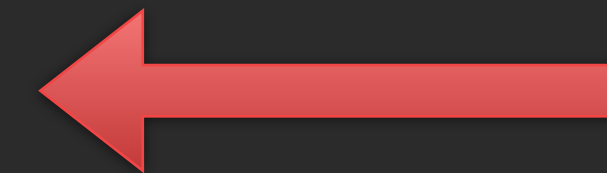
# P3: transforming values

## when to use:

- when needing to perform actions on a sender
- when values need to be transformed

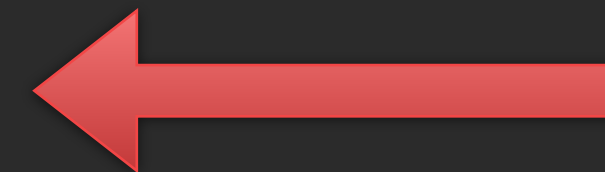
# transforming values

```
int process_value(int x) {  
    std::printf("I've got value: %d\n", x);  
    return x*x;  
}  
void then_example() {  
    ex::sender auto s = ex::just(13);  
    ex::sender auto s2 = ex::then(s, process_value);  
  
    auto [r] = sync_wait(std::move(s2)).value();  
    assert(r == 169);  
    std::printf("%d\n", r);  
}
```

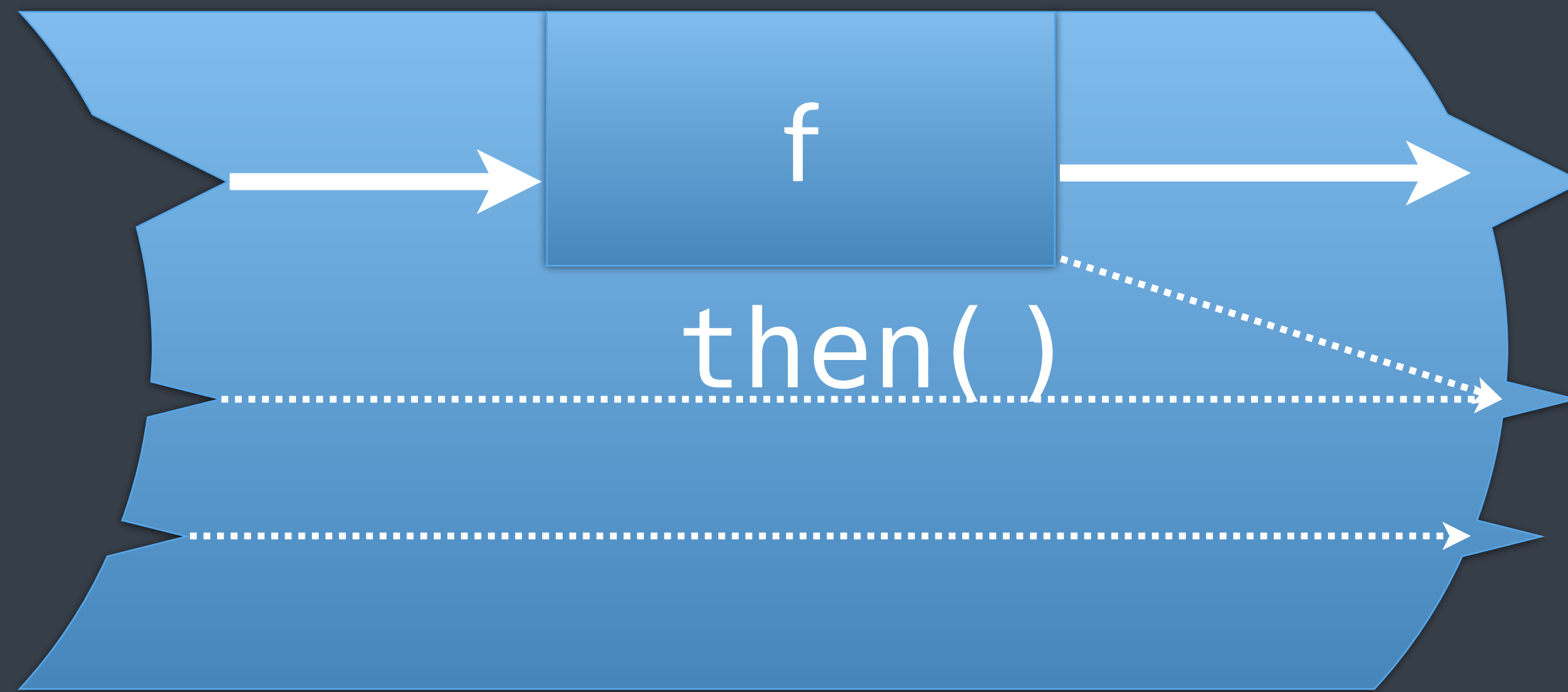


# transforming values

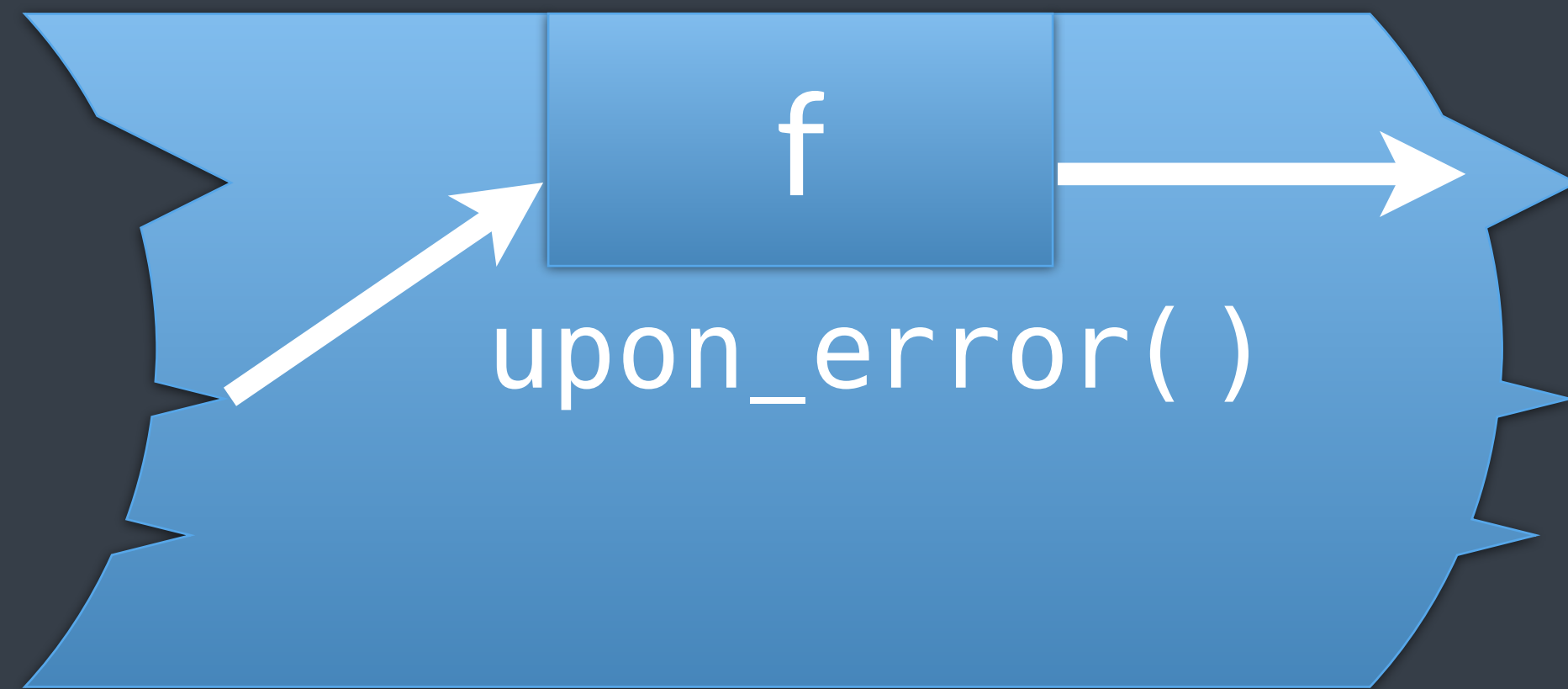
```
int process_value(int x) {  
    std::printf("I've got value: %d\n", x);  
    return x*x;  
}  
void then_example2() {  
    ex::sender auto s = ex::just(13)  
        | ex::then(process_value);  
  
    auto [r] = sync_wait(std::move(s)).value();  
    assert(r == 169);  
    std::printf("%d\n", r);  
}
```







# variations



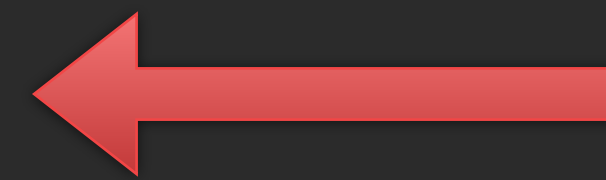
# P4: joining

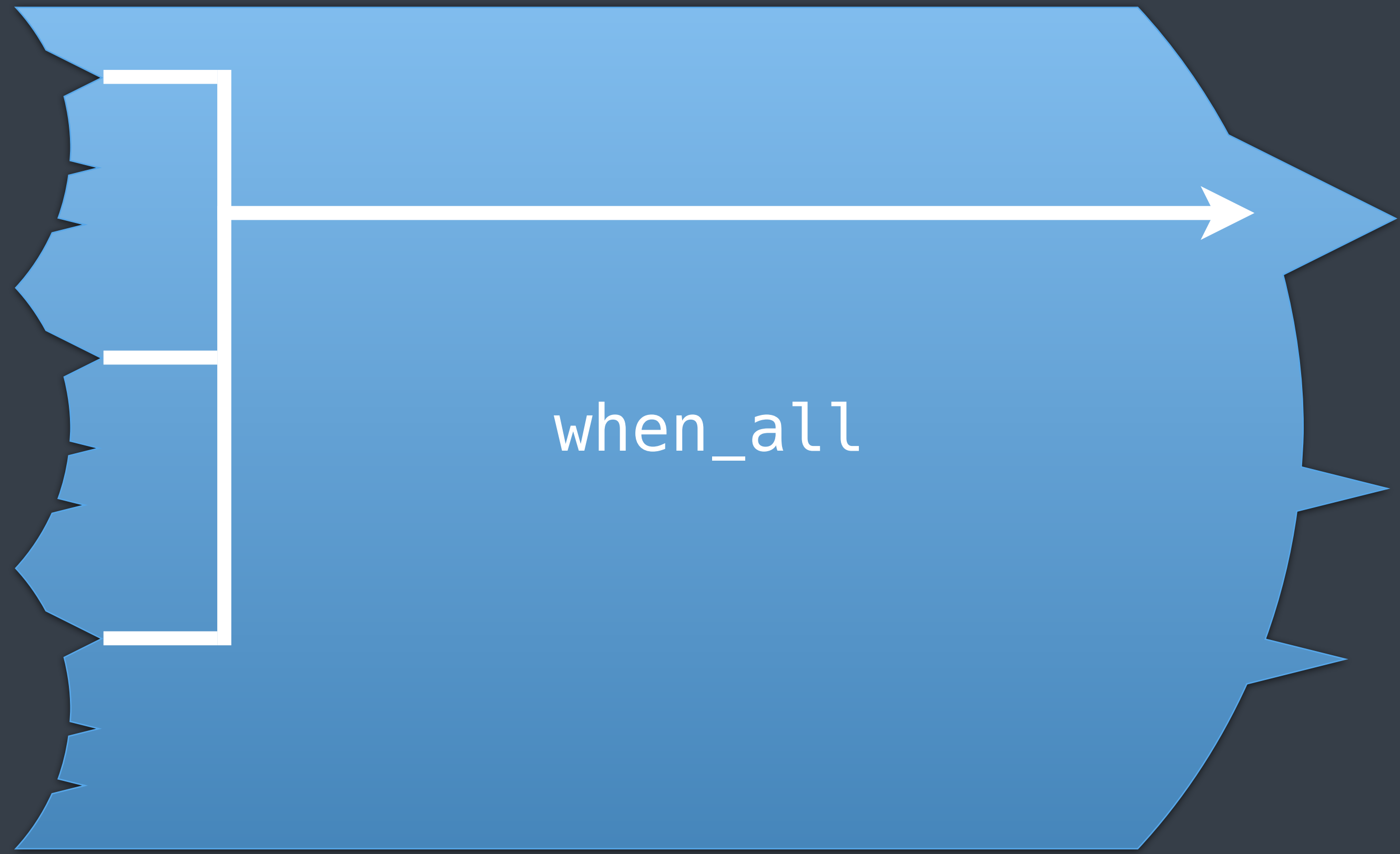
## when to use:

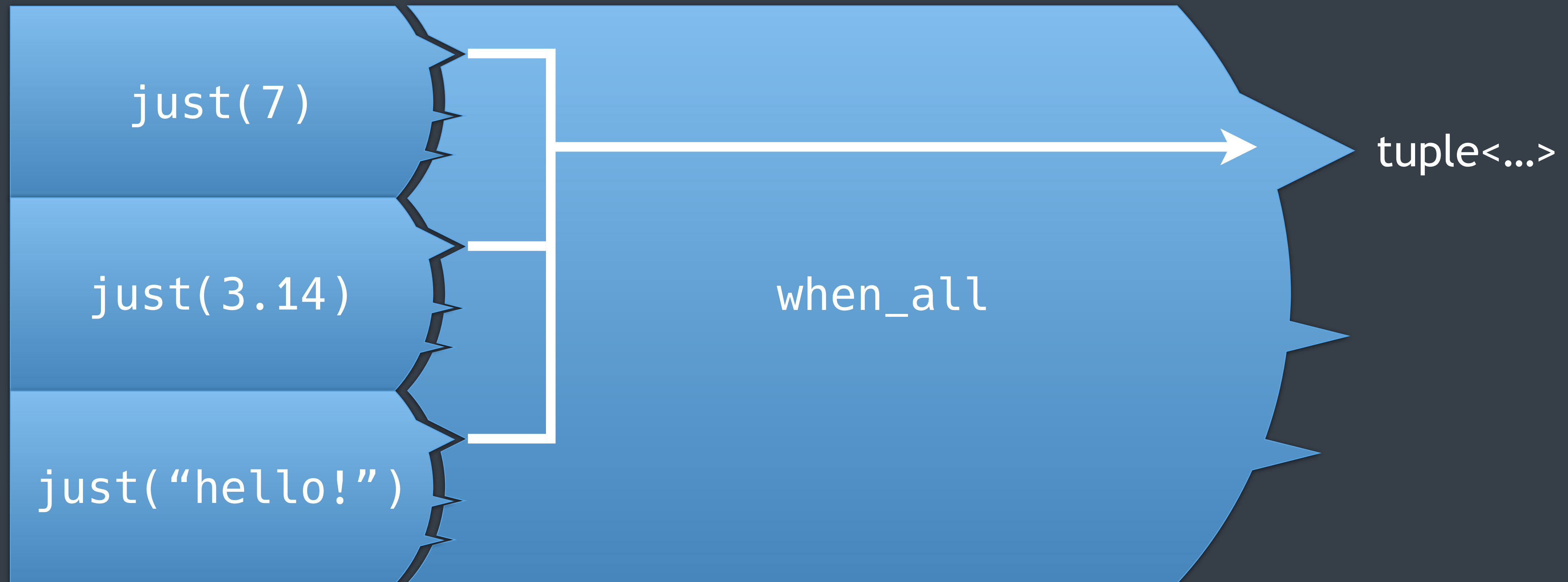
- combine parallel work
- detect the finish of multiple execution paths

# joining senders

```
void join_example() {  
    ex::sender auto s = ex::when_all( //  
        ex::just(7), //  
        ex::just(3.14), //  
        ex::just("hello!") //  
    );  
  
    auto [i, d, str] = sync_wait(std::move(s)).value();  
    std::printf("%d, %g, %s\n", i, d, str);  
}
```








# P5: scheduling

## when to use:

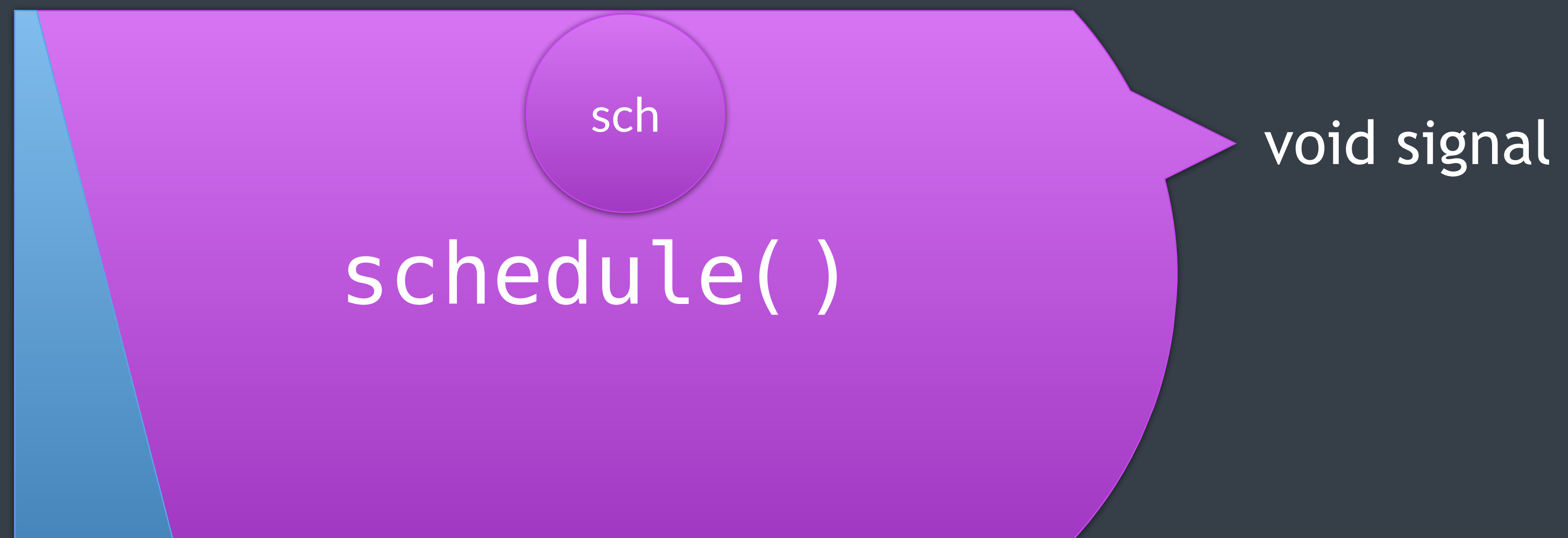
- start parallel work chain
- start work on a different execution context
- transform a scheduler into a sender

# scheduling work

```
void schedule_example() {  
    static_thread_pool pool{8};  
    ex::scheduler auto sch = pool.get_scheduler();  
  
    ex::sender auto s = ex::schedule(sch)  
        | ex::then([]{std::printf("Hello from another thread!");});  
  
    sync_wait(std::move(s));  
}
```







sch

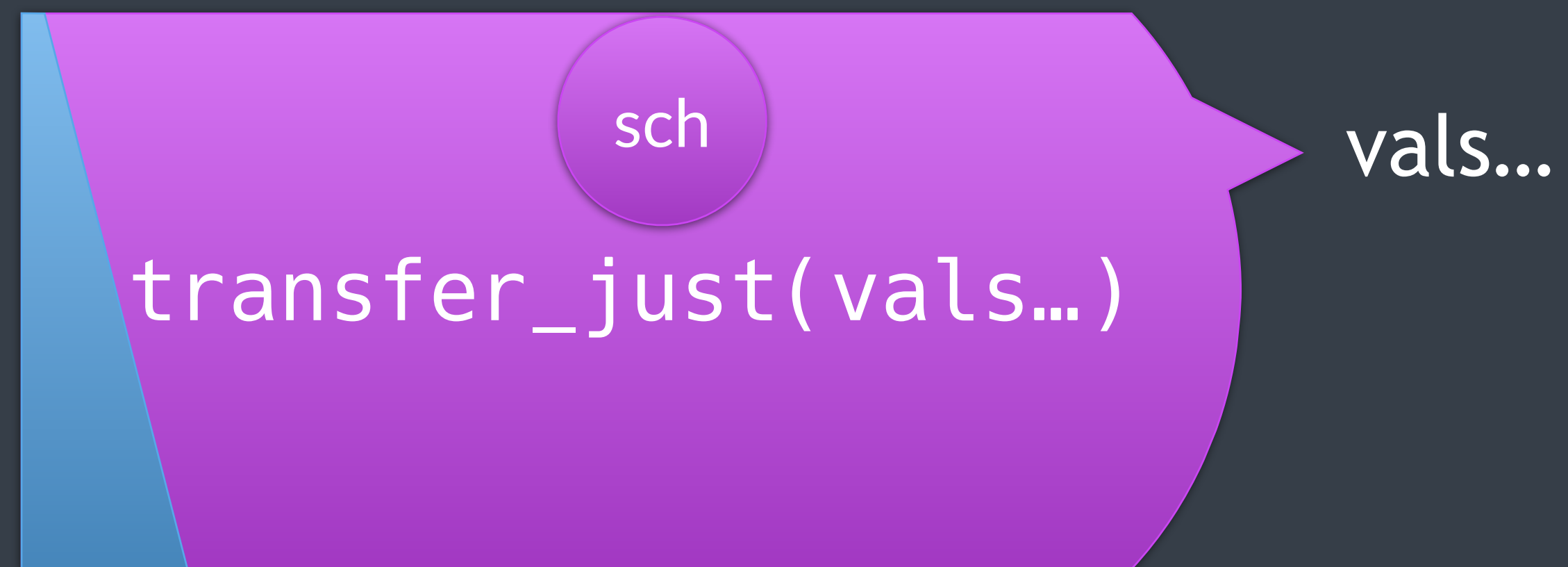
`schedule()`

f

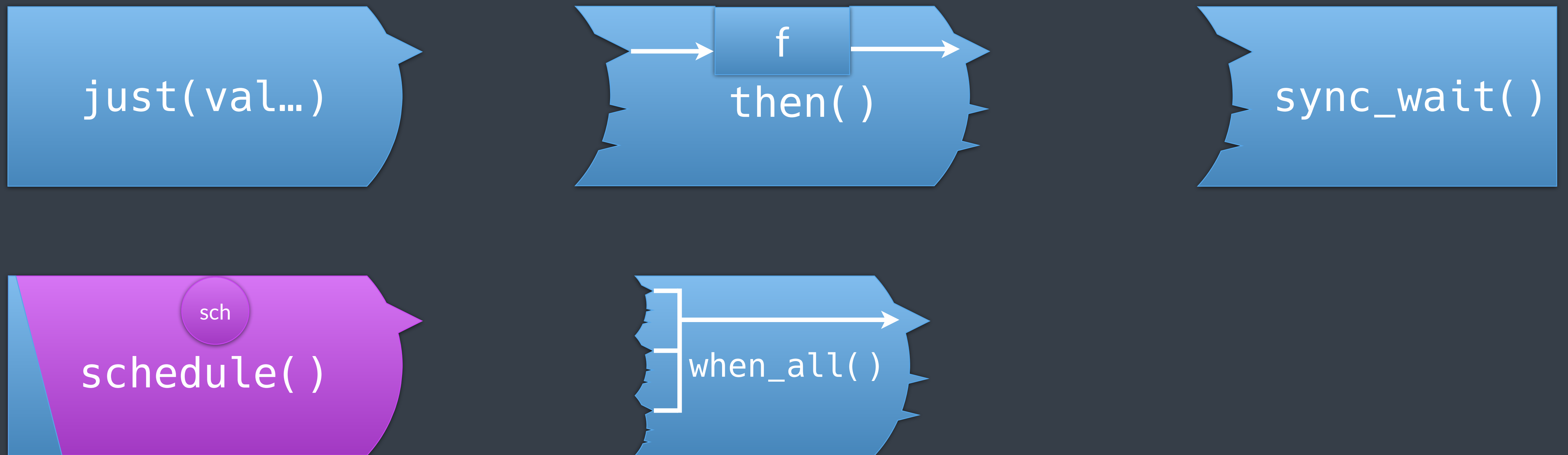
`then()`

`sync_wait()`

# variation



# patterns so far



# Extending the Patterns Repertoire



# P6: composing senders

## when to use:

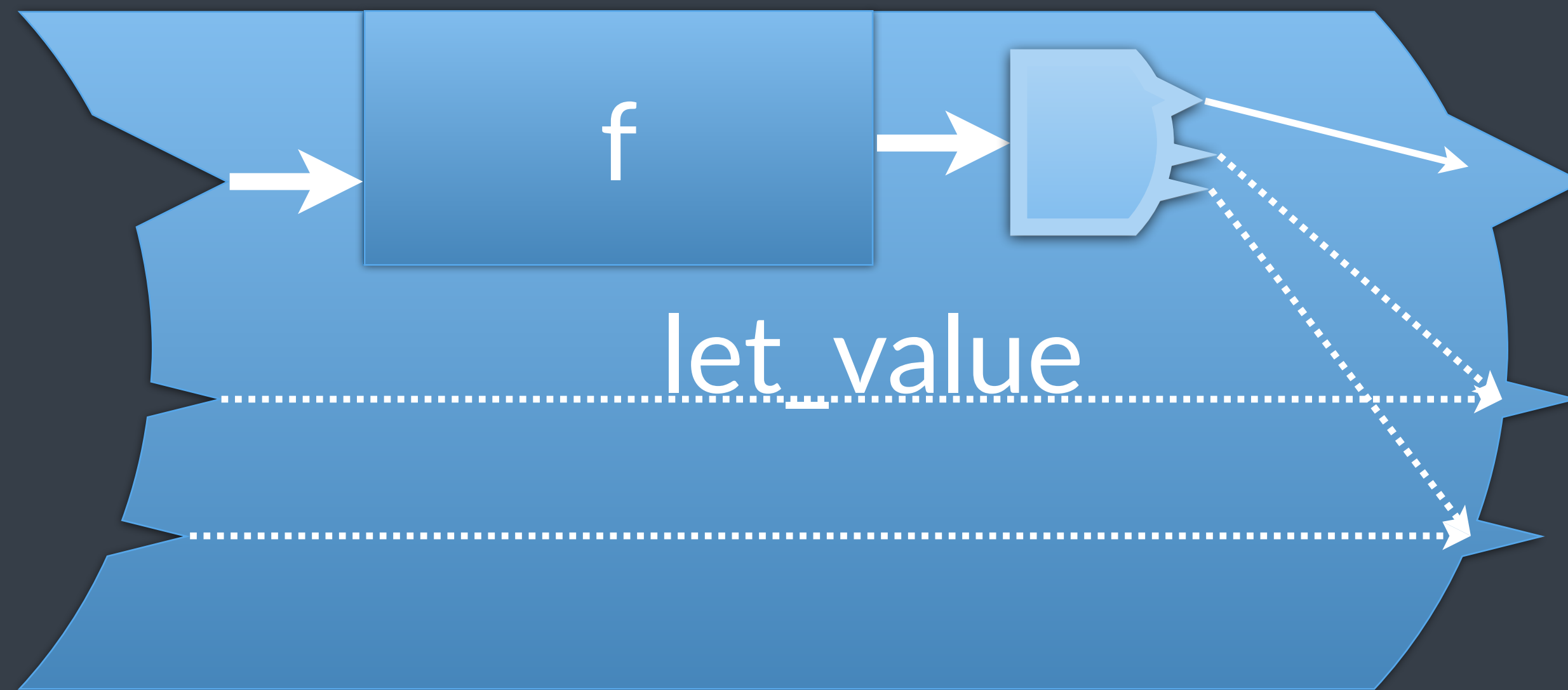
- compose senders (monadic bind usecases)
- ensure data is alive for the entire lifetime of a sender

# the problem of composition

snd 1



snd 2





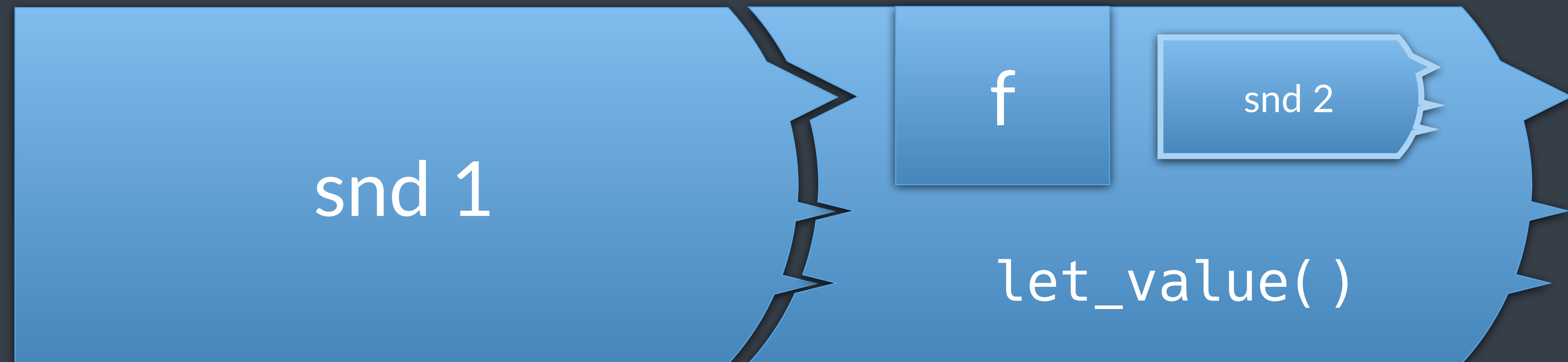
# how composition works



# how composition works



# how composition works

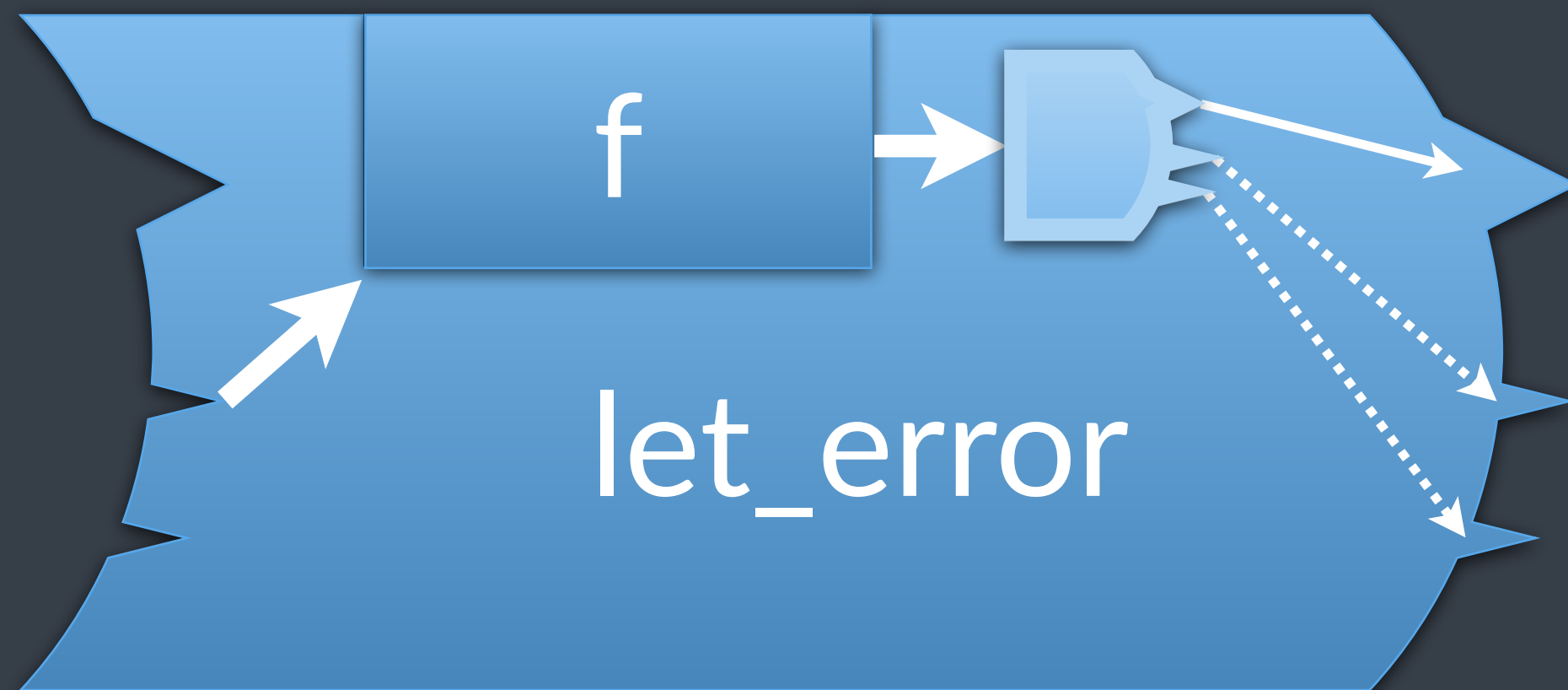


# composing senders

```
ex::sender auto schedule_request_start(read_requests_ctx ctx) { ... }
ex::sender auto validate_request(const http_request& req) { ... }
ex::sender auto handle_request(const http_request& req) { ... }
ex::sender auto send_response(const http_response& resp) { ... }

ex::sender auto request_pipeline(read_requests_ctx ctx) {
    return
        schedule_request_start(ctx)
        | ex::let_value(validate_request)
        | ex::let_value(handle_request)
        | ex::let_value(send_response)
        ;
}
```

# variants



# graphical alternative



# P7: starting senders in other contexts

## **when to use:**

- start a sender on a different execution context
- work needs to start in a specified scheduler

# start sender in a new context

```
ex::sender auto do_read_from_socket() { ... }
```

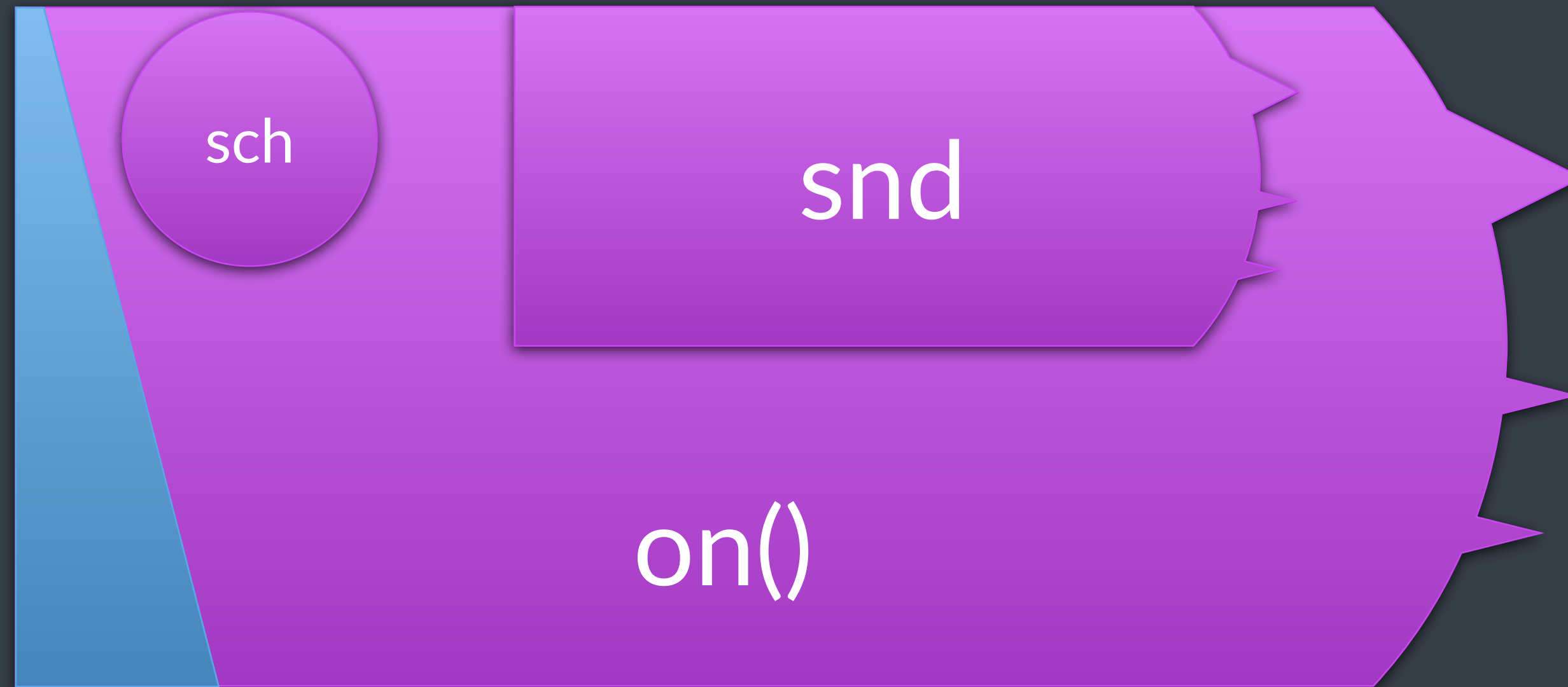
```
io_context io_threads;  
ex::scheduler auto sch = io_threads.get_scheduler();
```

```
ex::sender auto snd = ex::on(sch, do_read_from_socket());
```

```
sync_wait(std::move(snd));
```







# equivalence

`on(sch, snd)`

≡

`ex::schedule(sch) | ex::let_value([], { return snd; })`

# P8: transfer between contexts

## when to use:

- work needs to change execution context
- add new work on the same execution context

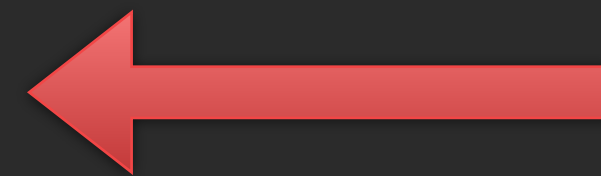


# transfer between contexts

```
ex::sender auto read_from_socket() { ... }  
ex::sender auto process(in_data) { ... }  
ex::sender auto write_output(out_data) { ... }
```

```
io_ontext io_threads;  
static_thread_pool work_pool{8};  
ex::scheduler auto sch_io = io_threads.get_scheduler();  
ex::scheduler auto sch_cpu = work_pool.get_scheduler();
```

```
ex::sender auto snd  
    = ex::on(sch_io, read_from_socket())  
    | ex::transfer(sch_cpu)  
    | ex::let_value(process)  
    | ex::transfer(sch_io)  
    | ex::let_value(write_output)  
    ;
```

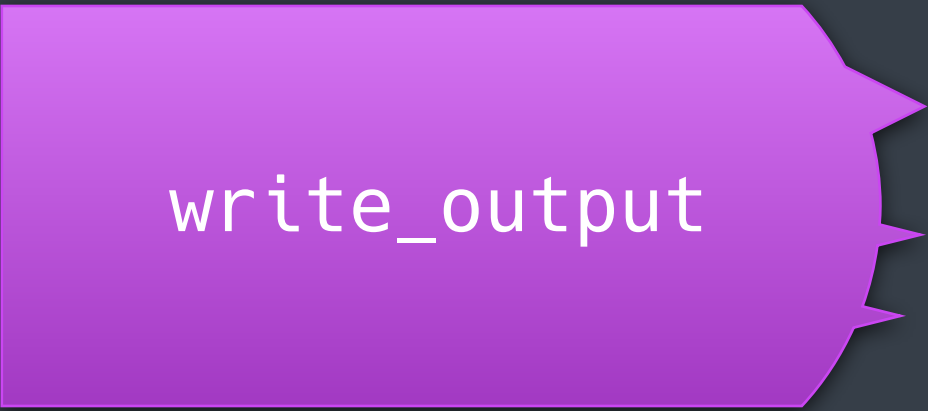


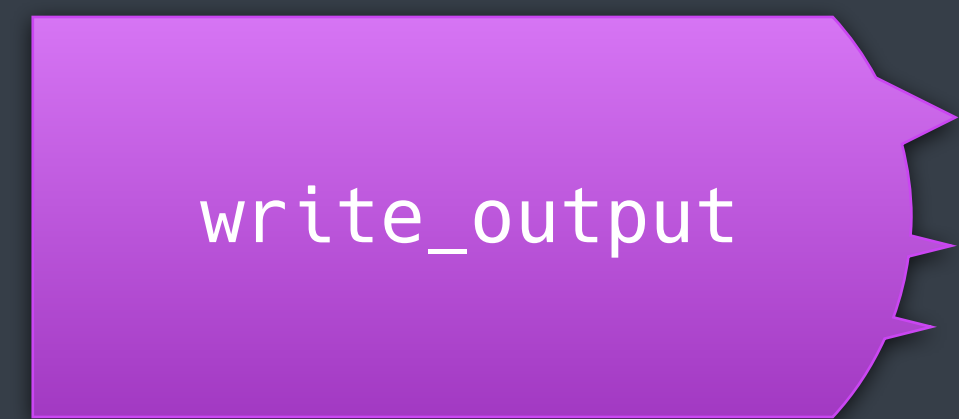
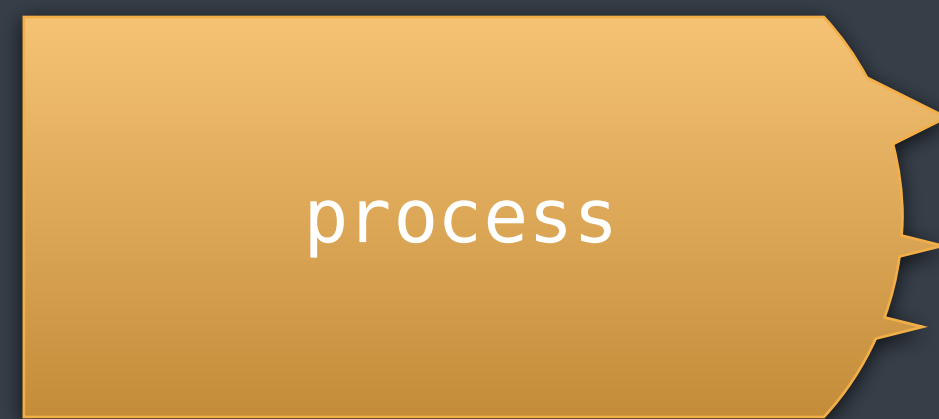
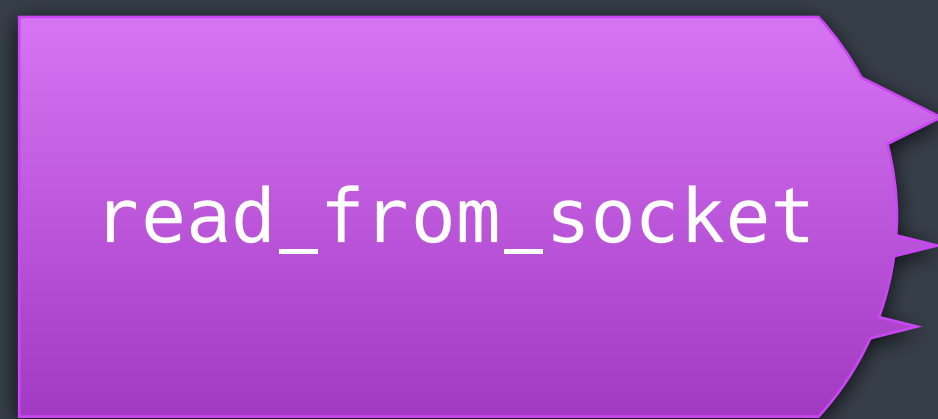
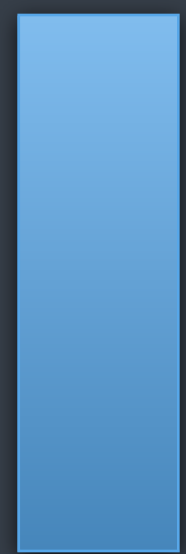
```
sync_wait(std::move(snd));
```

read\_from\_socket

process

write\_output

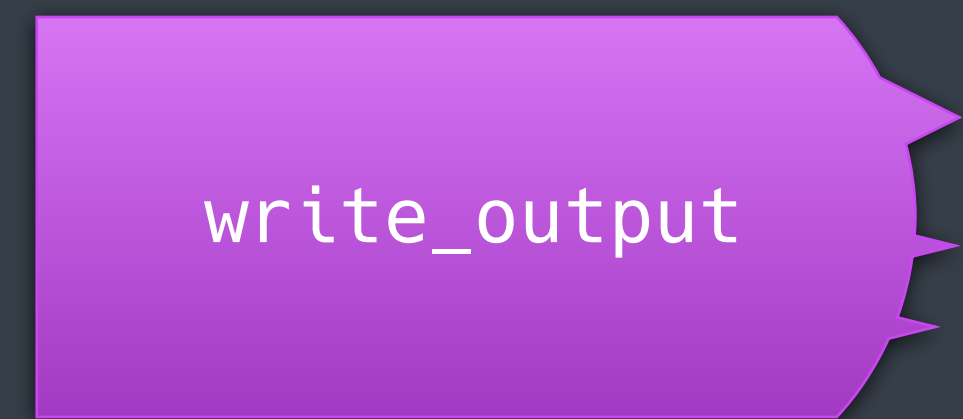
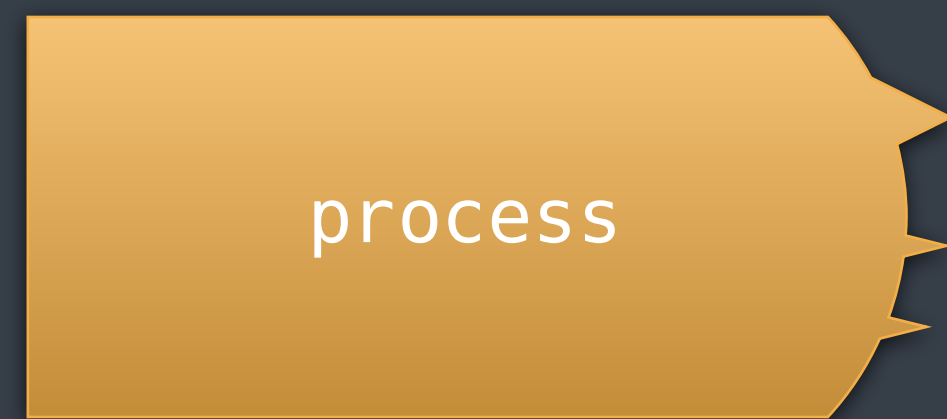


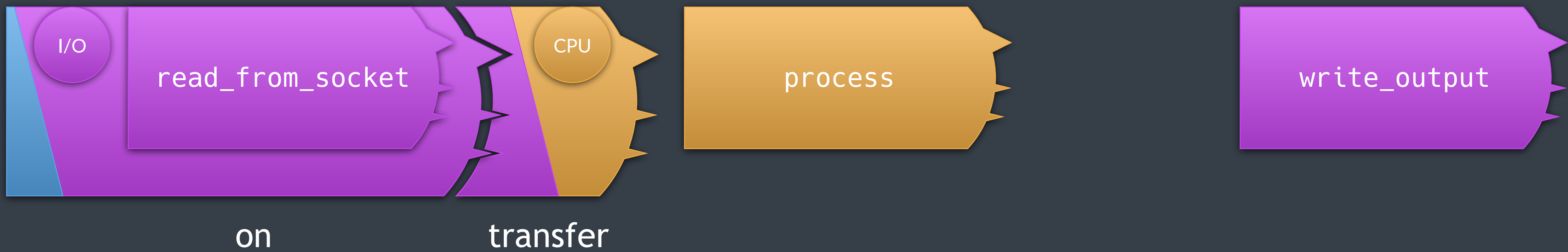


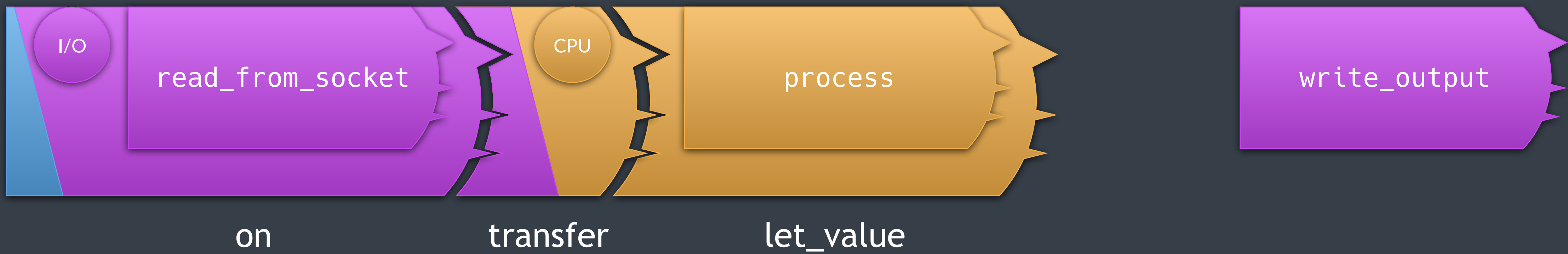


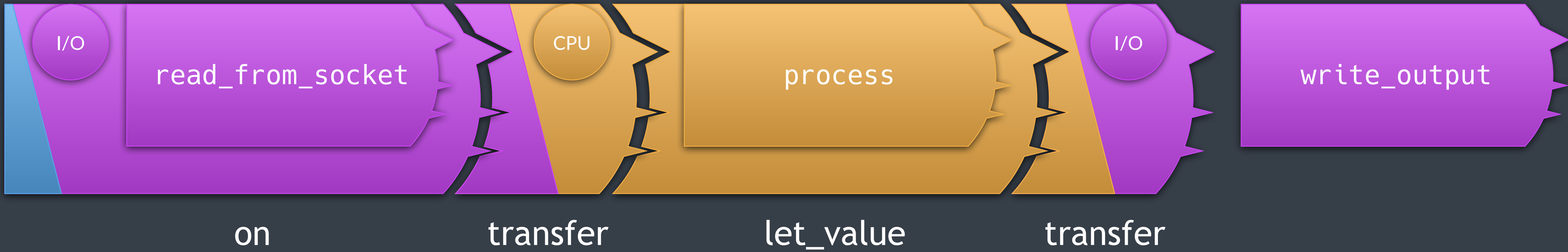


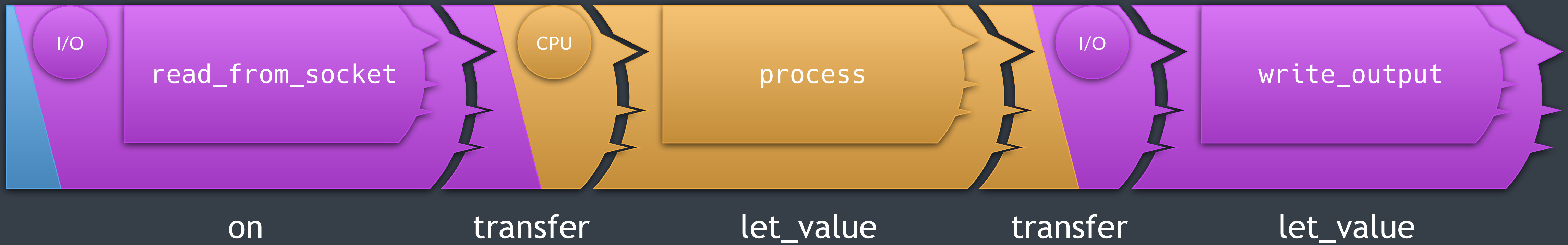
on

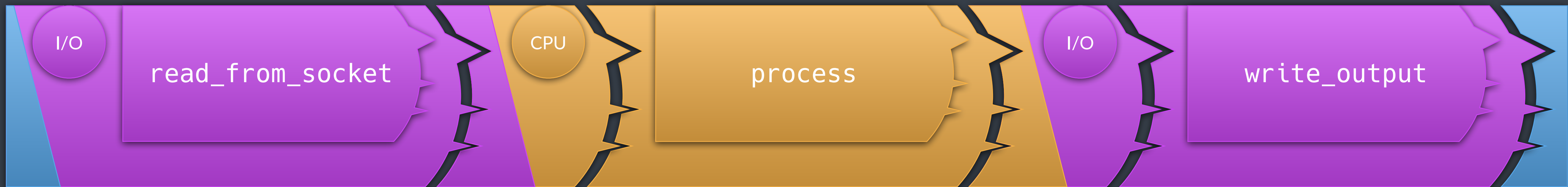












on

transfer

let\_value

transfer

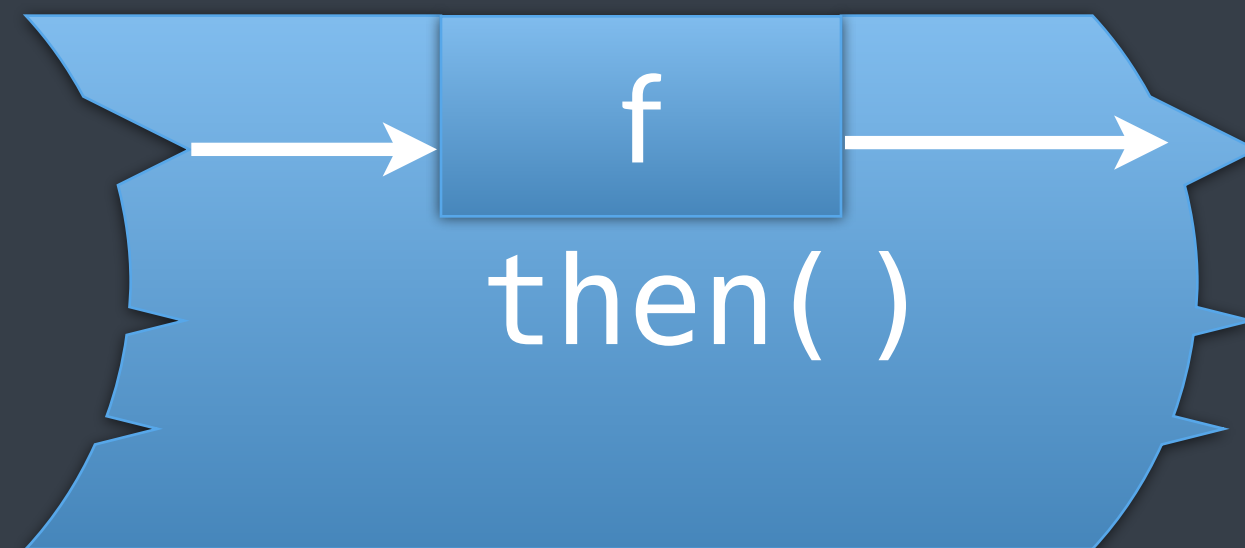
let\_value

sync\_wait

# more in P2300

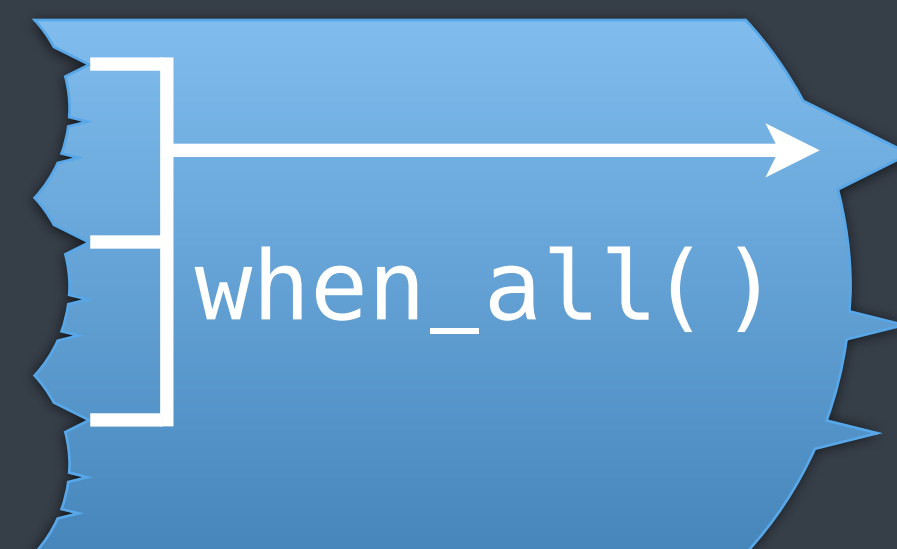
- `bulk`
- `split`, `ensure_started`
- `start_detached`
- `into_variant`, `stopped_as_optional`, `stopped_as_error`
- `read`
- coroutine support

`just(val...)`



`sync_wait()`

`sch`  
`schedule()`





`just(val...)`

`f`  
`then()`

`sync_wait()`

`sch`  
`schedule()`

`when_all()`

`sch` `snd`  
`on()`

`sch`  
`transfer()`

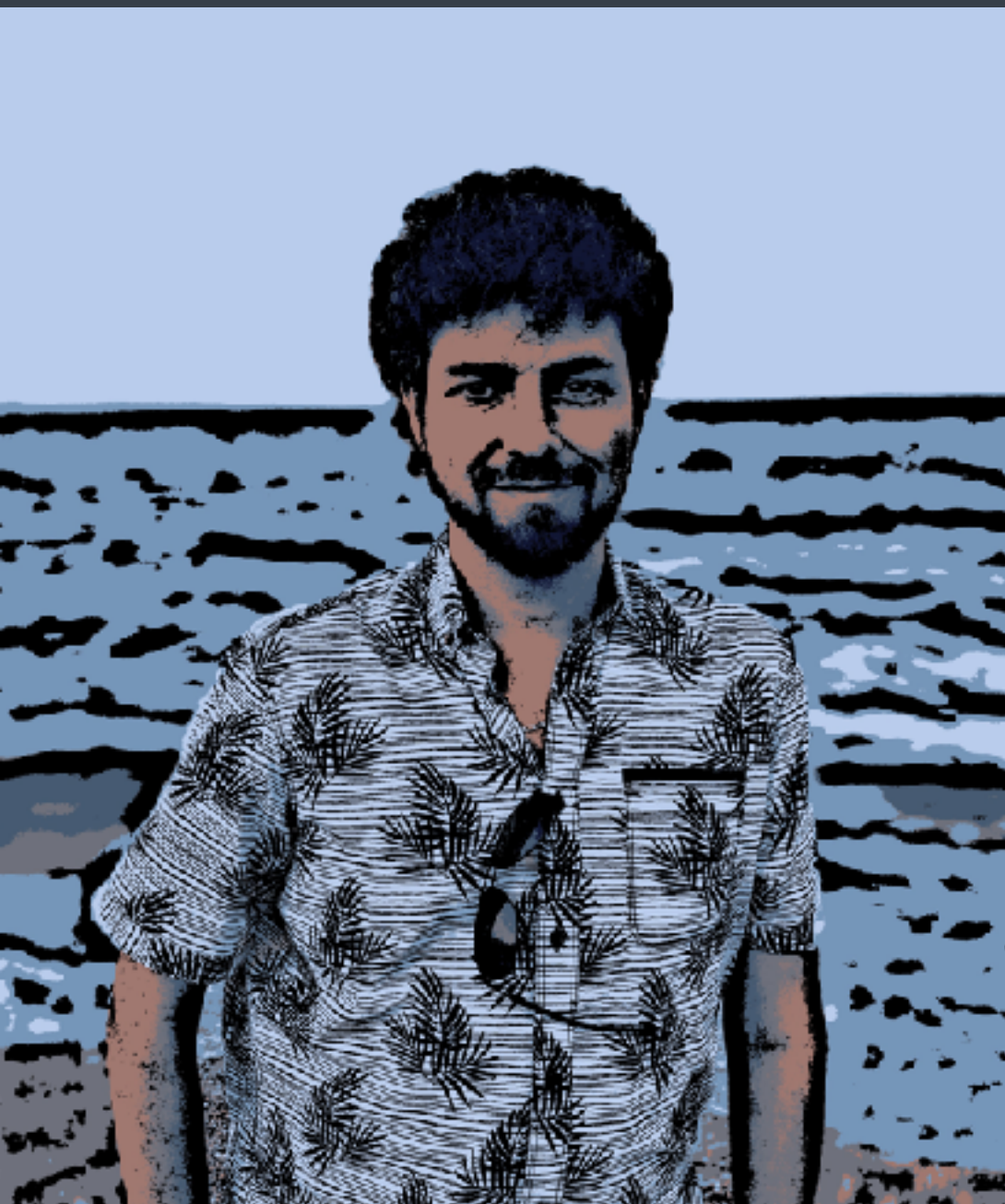
`snd`  
`let_value()`

# Composition with Patterns

5



# application



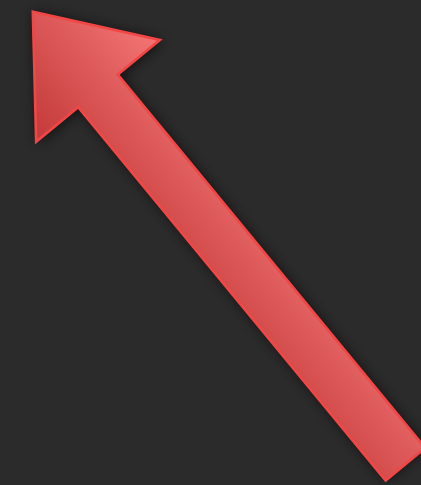
HTTP server  
image processing



# the entire app is a sender

```
auto get_main_sender() {  
    return ex::just() | ex::then([] {  
        //...  
        return 0;  
    });  
}
```

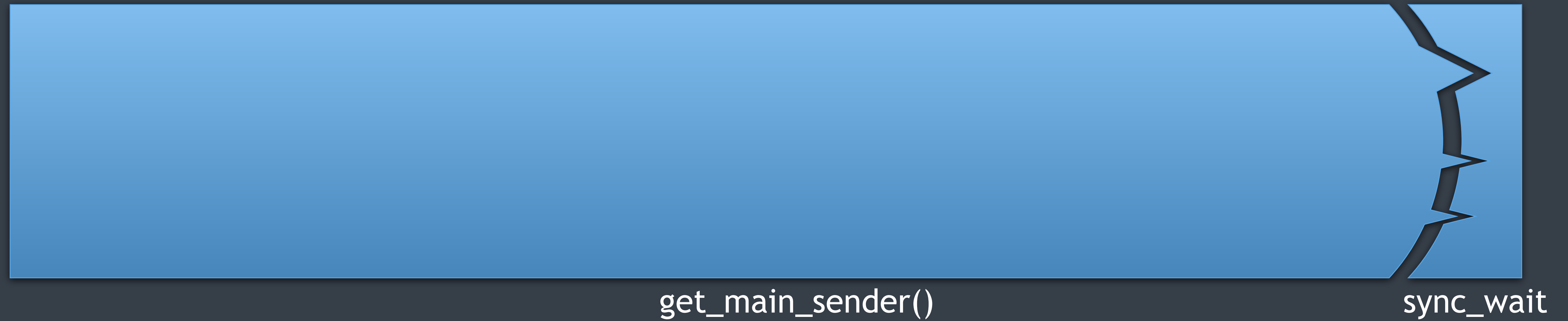
```
auto main() -> int {  
    auto [r] = std::this_thread::sync_wait(get_main_sender()).value();  
    return r;  
}
```



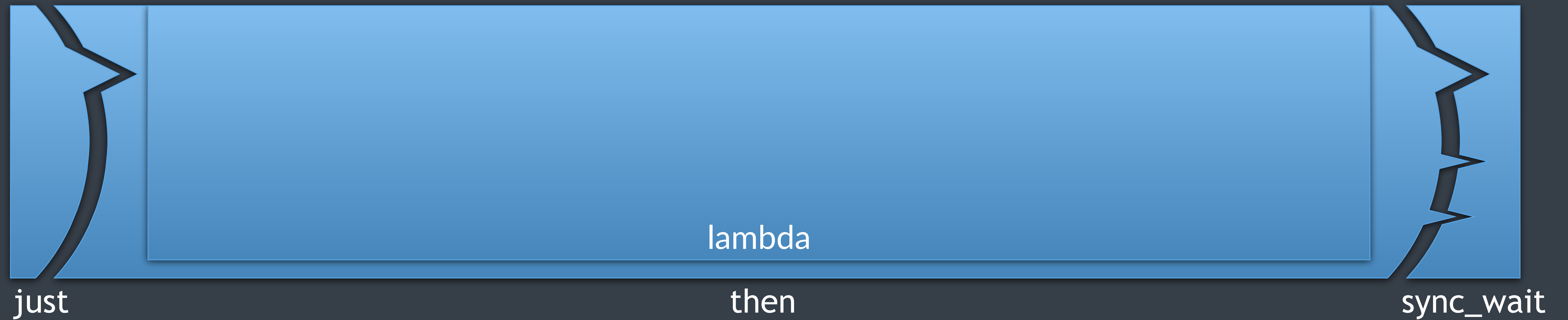
# main()



# main()

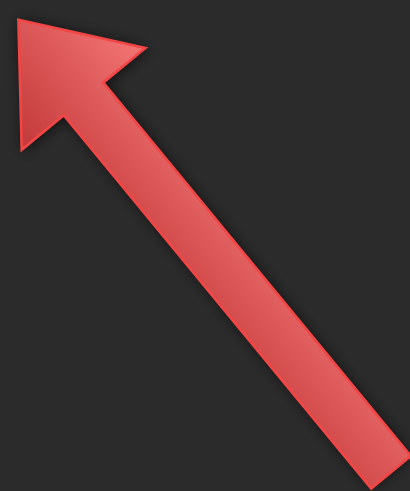


# main()



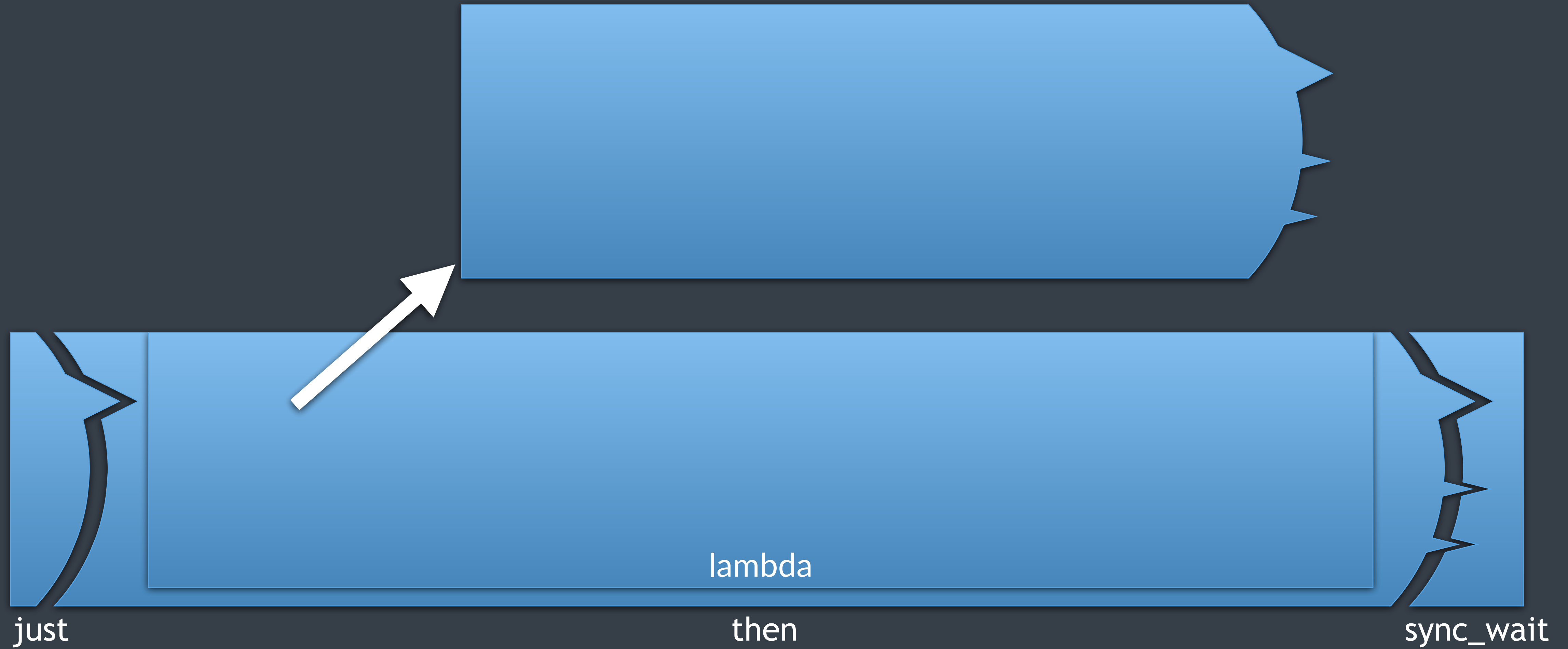
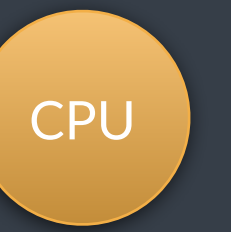
# top-level logic

```
auto get_main_sender() {  
    return ex::just() | ex::then([] {  
        int port = 8080;  
  
        static_thread_pool pool{8};  
  
        io::io_context ctx;  
        set_sig_handler(ctx, SIGTERM);  
  
        ex::sender auto snd = ex::on(ctx.get_scheduler(), listener(port, ctx, pool));  
        ex::start_detached(std::move(snd));  
  
        ctx.run();  
        return 0;  
    });  
}
```

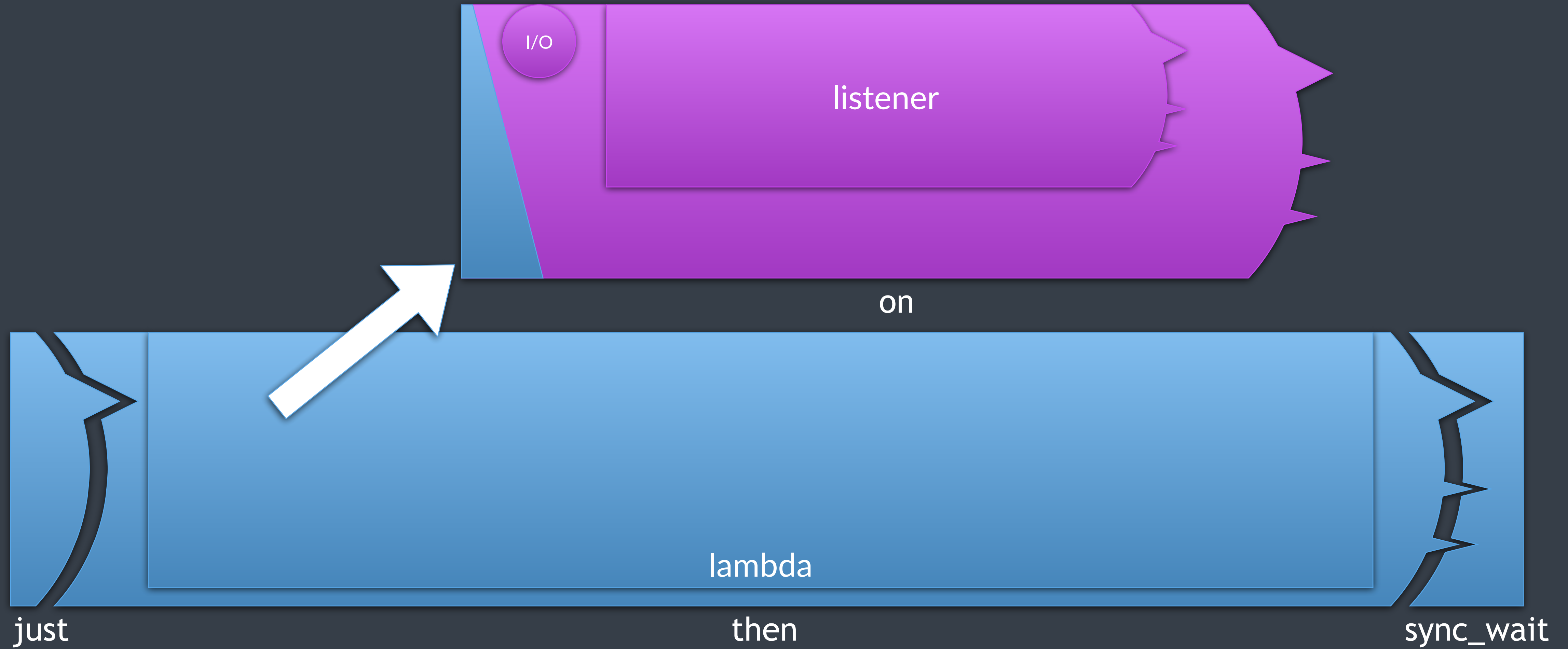
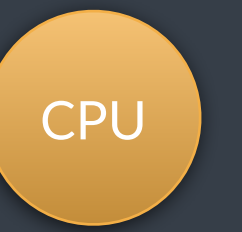




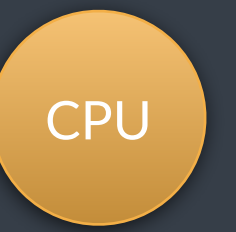
# main()



# main()

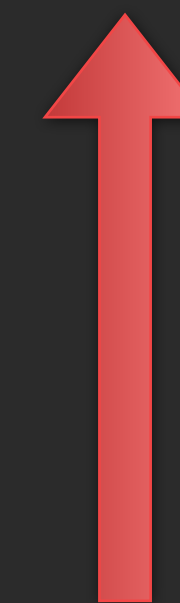


# listener



# listener

```
auto listener(int port, io::io_context& ctx, static_thread_pool& pool)-> task<bool> {  
    // ...  
    co_return true;  
}
```



# Listener

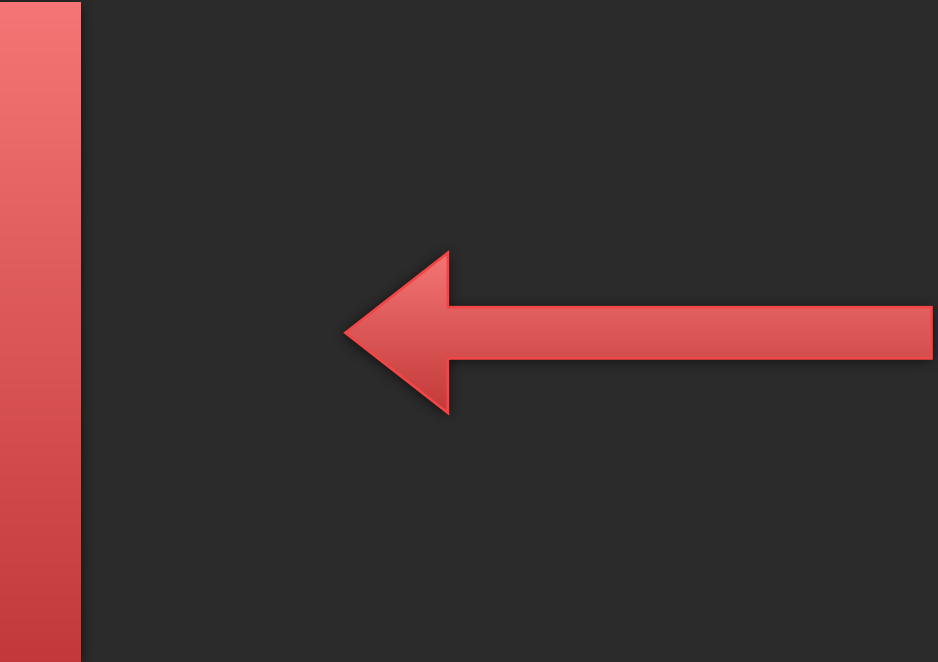
```
auto listener(int port, io::io_context& ctx, static_thread_pool& pool)-> task<bool> {
    io::listening_socket listen_sock;
    listen_sock.bind(port);
    listen_sock.listen();

    while (!ctx.is_stopped()) {
        io::connection conn = co_await io::async_accept(ctx, listen_sock);

        conn_data data{std::move(conn), ctx, pool};

        ex::sender auto snd = //
            ex::just() //
            | ex::let_value([data = std::move(data)]() { //
                return handle_connection(data);
            });
        ex::start_detached(std::move(snd));
    }

    co_return true;
}
```



# listener

I/O

CPU

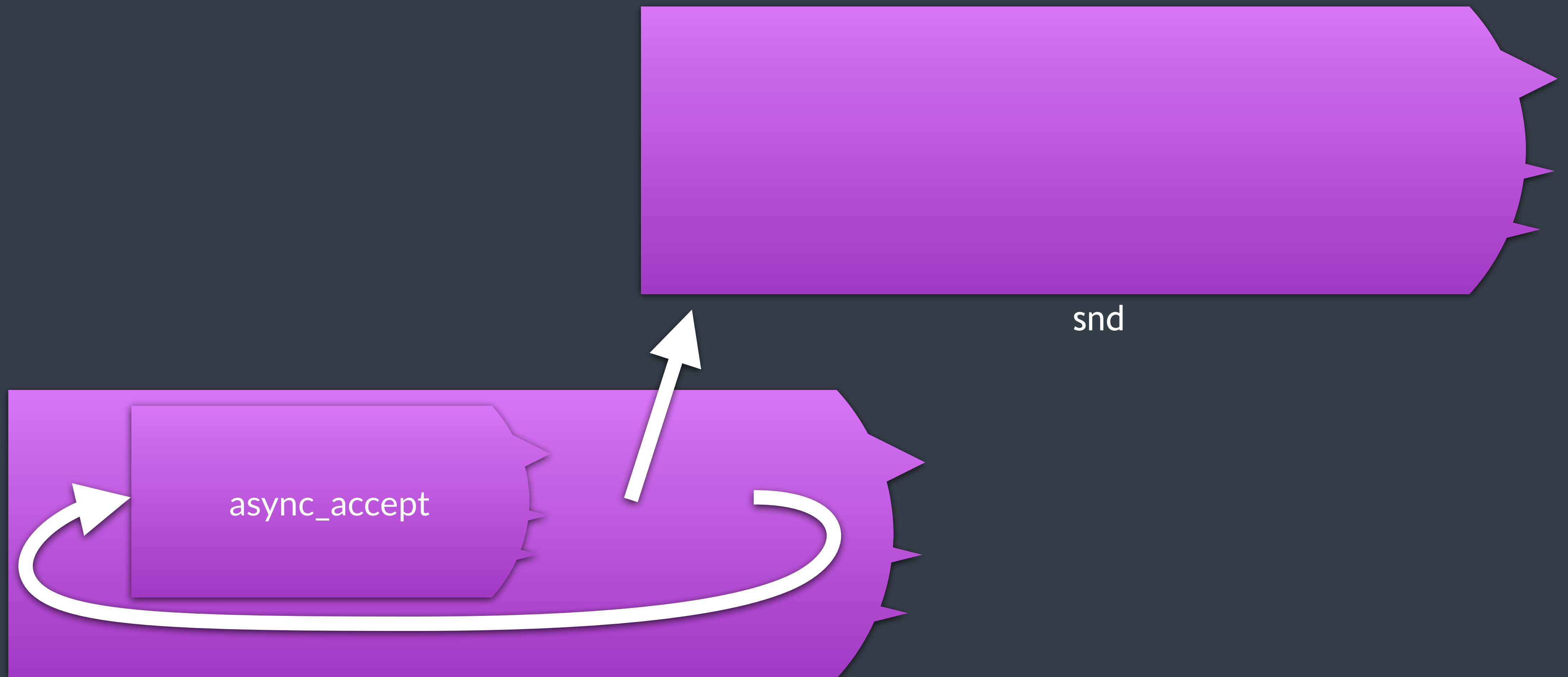


listener

# listener

I/O

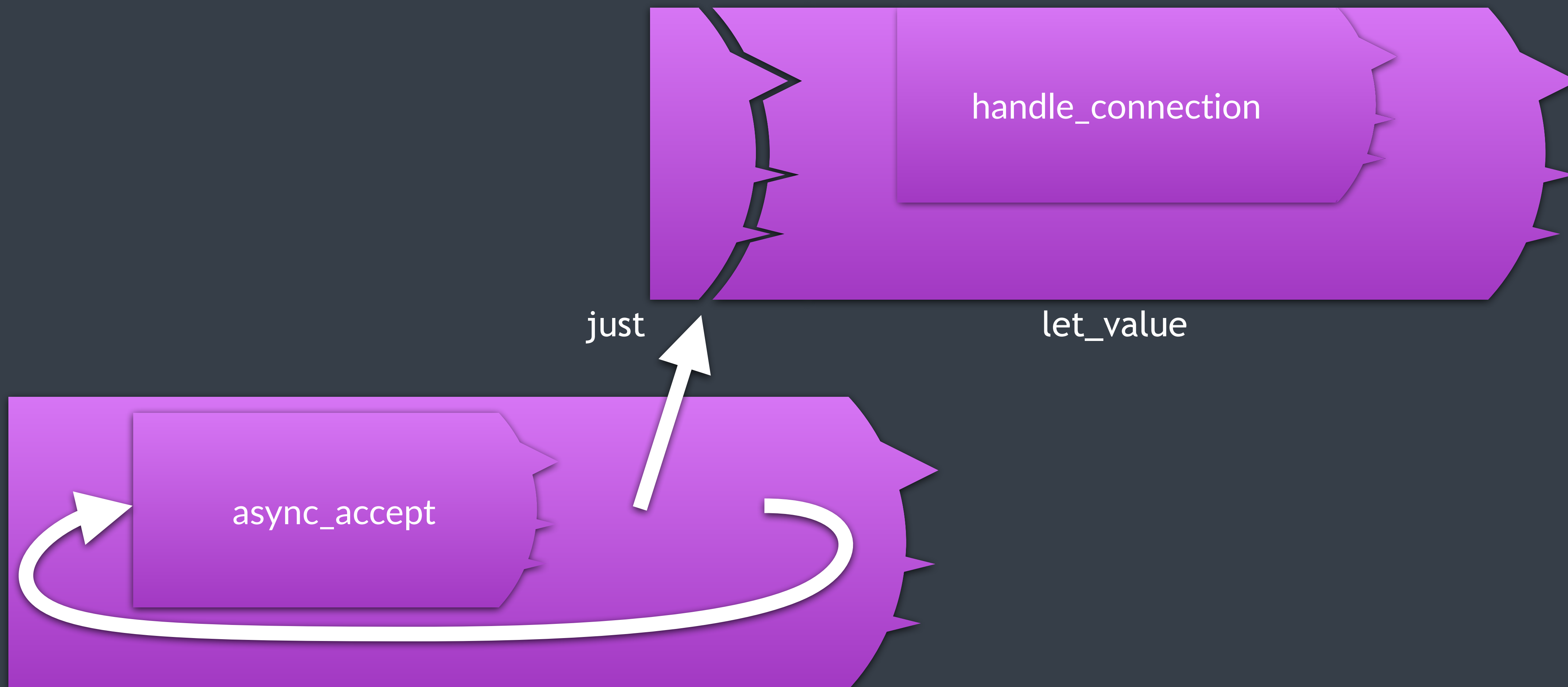
CPU



# listener

I/O

CPU





# handle\_connection

I/O

CPU



handle\_connection

# handle\_connection

```
auto handle_connection(const conn_data& cdata) {
    return read_http_request(cdata.io_ctx_, cdata.conn_)
        | ex::transfer(cdata.pool_.get_scheduler())
        | ex::let_value([&cdata](http_server::http_request req) {
            return handle_request(cdata, std::move(req));
        })
        | ex::let_error([](std::exception_ptr) { return just_500_response(); })
        | ex::let_stopped([]() { return just_500_response(); })
        | ex::let_value([&cdata](http_server::http_response r) {
            return write_http_response(cdata.io_ctx_, cdata.conn_, std::move(r));
        });
}
```

# handle\_connection




# just\_500\_response

```
auto just_500_response() {  
    auto resp = http_server::create_response(  
        http_server::status_code::s_500_internal_server_error);  
    return ex::just(std::move(resp));  
}
```

# read\_http\_request

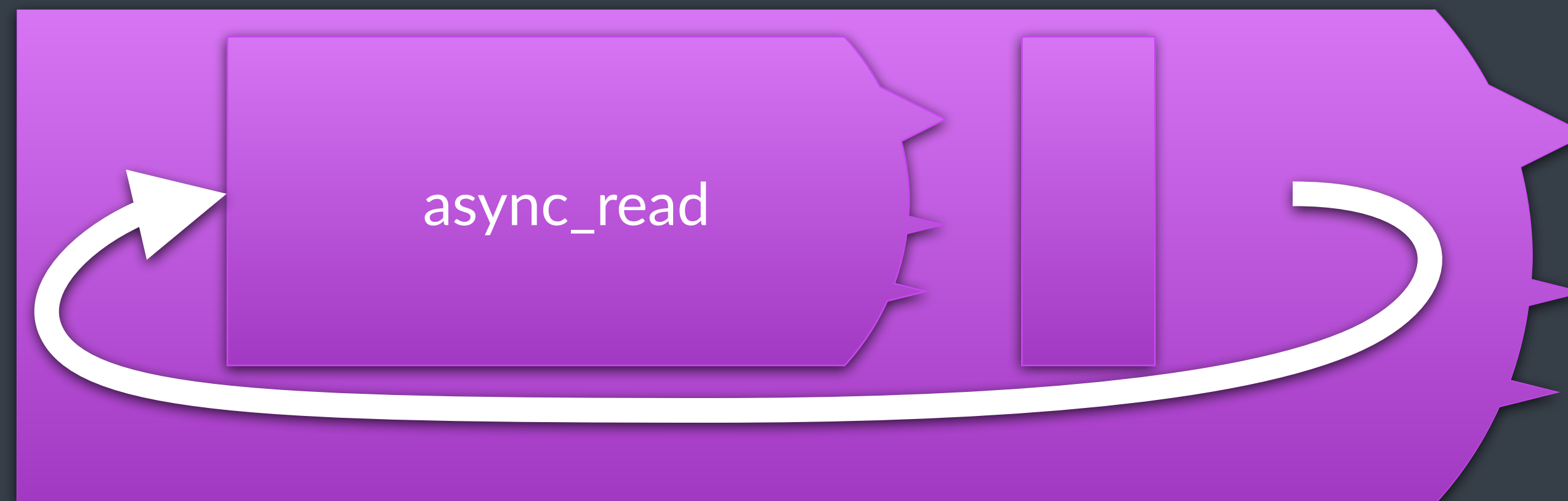
```
auto read_http_request(io::io_context& ctx, const io::connection& conn)
    -> task<http_server::http_request> {
    http_server::request_parser parser;
    std::string buf;
    buf.reserve(1024 * 1024);
    io::out_buffer out_buf{buf};
    while (true) {
        std::size_t n = co_await io::async_read(ctx, conn, out_buf);
        auto data = std::string_view{buf.data(), n};
        auto r = parser.parse_next_packet(data);
        if (r)
            co_return {std::move(r.value())};
    }
}
```



# read\_http\_request


I/O

CPU



# write\_http\_response

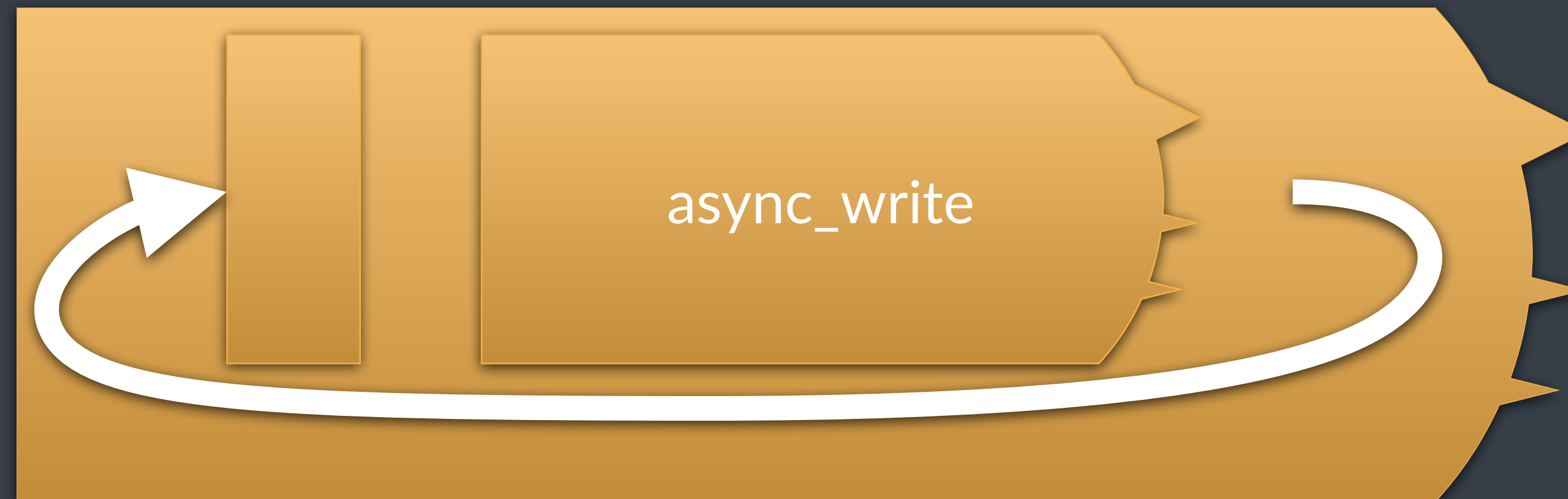
```
auto write_http_response(io::io_context& ctx, const io::connection& conn,
    http_server::http_response resp) -> task<std::size_t> {
    std::vector<std::string_view> out_buffers;
    http_server::to_buffers(resp, out_buffers);
    std::size_t bytes_written{0};
    for (auto buf : out_buffers) {
        while (!buf.empty()) {
            auto n = co_await io::async_write(ctx, conn, buf);
            bytes_written += n;
            buf = buf.substr(n);
        }
    }
    co_return bytes_written;
}
```



# write\_http\_response

I/O

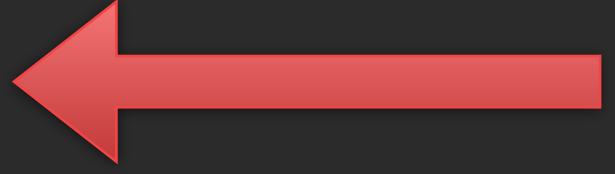
CPU



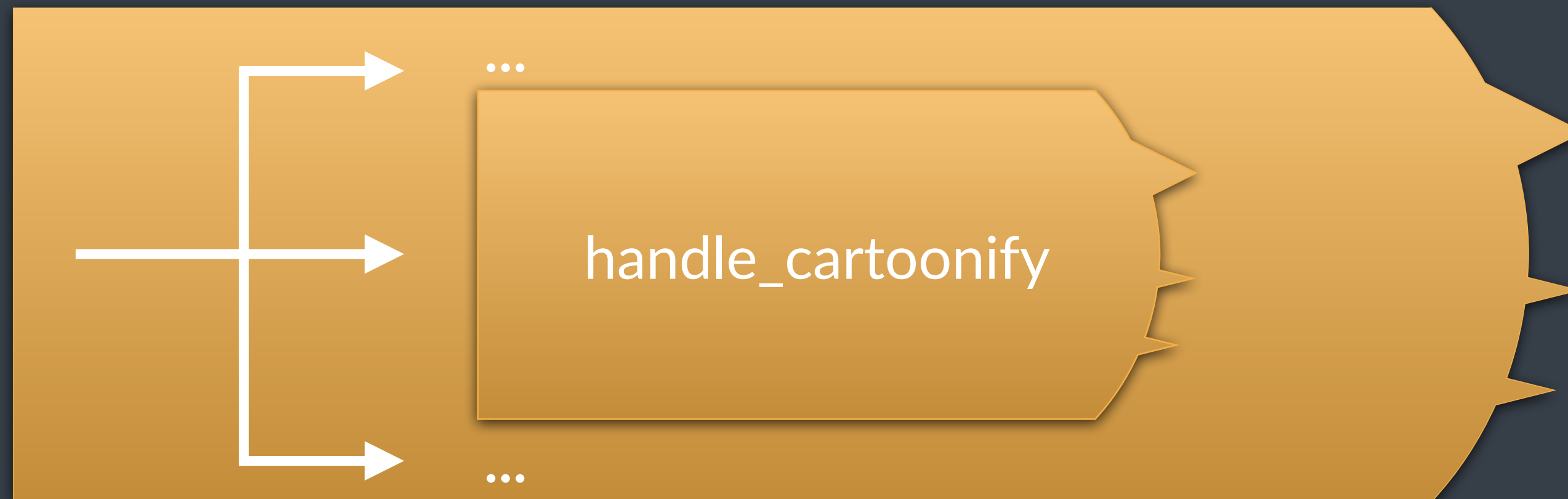


# handle\_request

```
auto handle_request(const conn_data& cdata, http_server::http_request req)
    -> task<http_server::http_response> {
    auto puri = parse_uri(req.uri_);
    if (puri.path_ == "/transform/blur")
        co_return handle_blur(cdata, std::move(req), puri);
    else if (puri.path_ == "/transform/adaptthresh")
        co_return handle_adaptthresh(cdata, std::move(req), puri);
    else if (puri.path_ == "/transform/reducecolors")
        co_return handle_reducecolors(cdata, std::move(req), puri);
    else if (puri.path_ == "/transform/cartoonify")
        co_return co_await handle_cartoonify(cdata, std::move(req), puri);
    else if (puri.path_ == "/transform/oilpainting")
        co_return handle_oilpainting(cdata, std::move(req), puri);
    else if (puri.path_ == "/transform/contourpaint")
        co_return co_await handle_contourpaint(cdata, std::move(req), puri);
    co_return http_server::create_response(http_server::status_code::s_404_not_found);
}
```



# handle\_request



```

auto handle_cartoonify(const conn_data& cdata, http_server::http_request&& req, parsed_uri puri)
    -> task<http_server::http_response> {
    int blur_size = get_param_int(puri, "blur_size", 3);
    int num_colors = get_param_int(puri, "num_colors", 5);
    int block_size = get_param_int(puri, "block_size", 5);
    int diff = get_param_int(puri, "diff", 5);
    auto src = to_cv(req.body_);
    ex::sender auto snd = ex::when_all(
        ex::transfer_just(cdata.pool_.get_scheduler(), src)
        | ex::then(=[](const cv::Mat& src) {
            auto gray = tr_to_grayscale(tr_blur(src, blur_size));
            return tr_adaptthresh(gray, block_size, diff);
        })),
        ex::transfer_just(cdata.pool_.get_scheduler(), src)
        | ex::then(=[](const cv::Mat& src) {
            return tr_reducecolors(src, num_colors);
        })
    )
    | ex::then(=[](const cv::Mat& edges, const cv::Mat& reduced_colors) {
        return tr_apply_mask(reduced_colors, edges);
    })
    | ex::then(img_to_response);
    co_return co_await std::move(snd);
}

```

# handle\_cartoonify

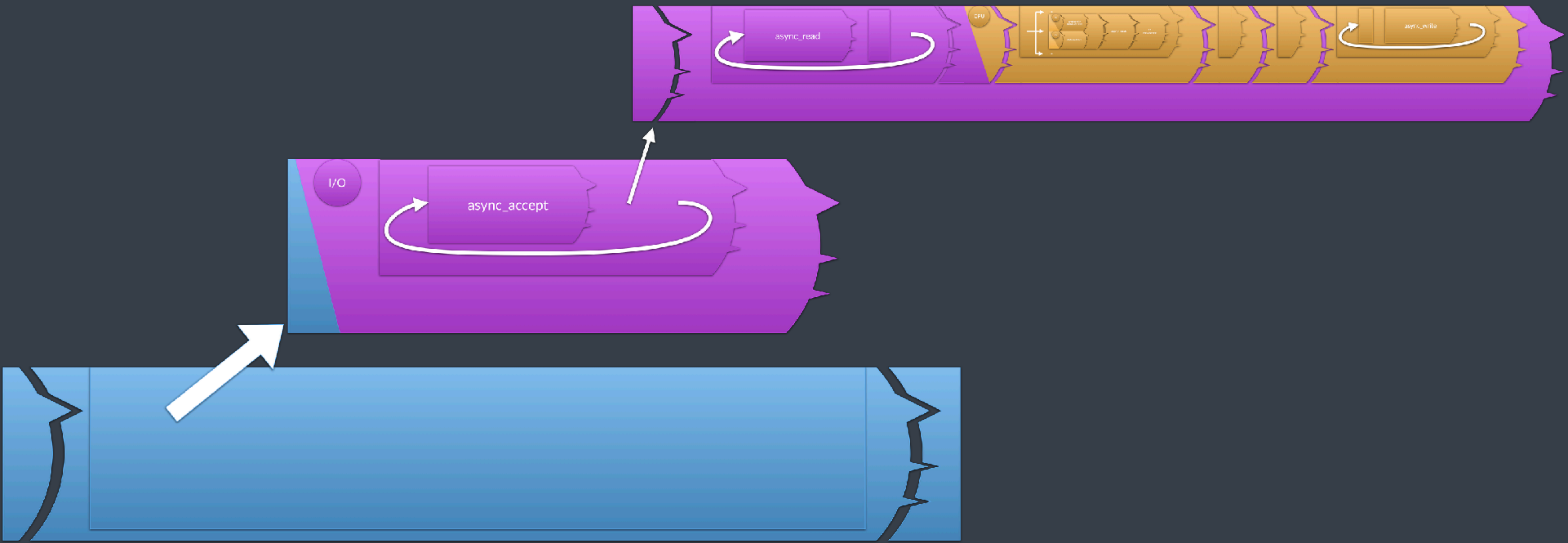
I/O

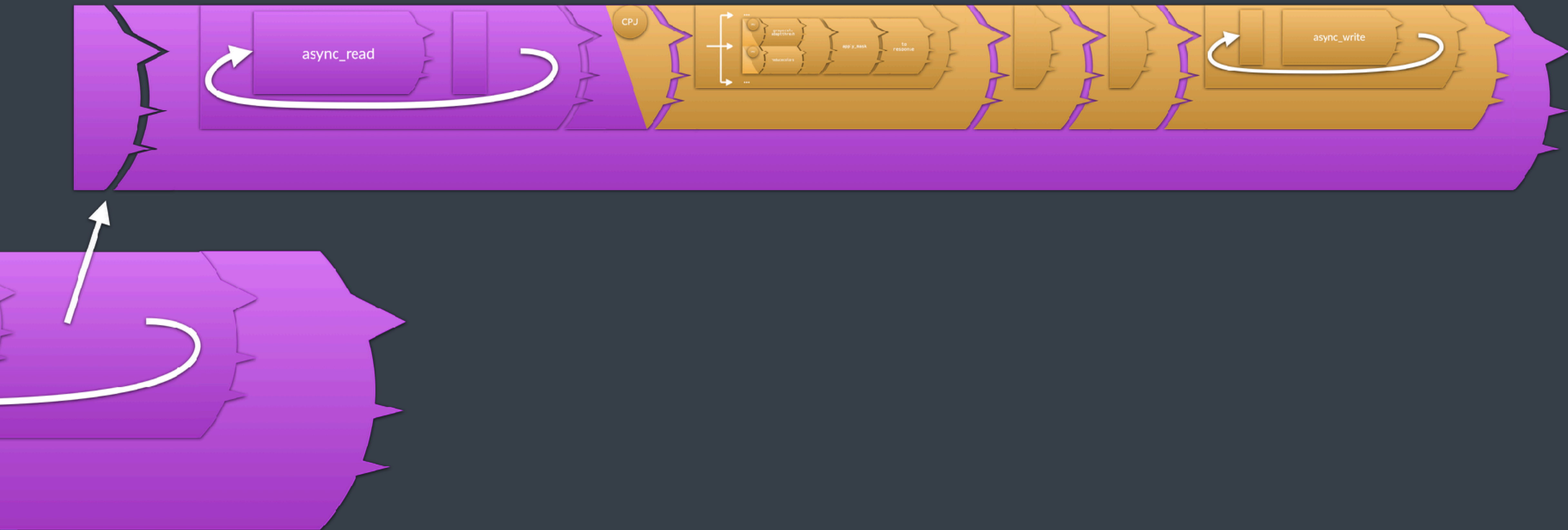
CPU



# recursive decomposition

- `get_main_sender`
  - `listener`
    - `async_accept`
    - `handle_connection`
      - `read_http_request`
        - `async_read`
      - `handle_request`
        - `handle_cartoonify`
        - ...
      - `just_500_response`
      - `write_http_response`
        - `async_write`





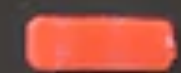




# Conclusions



DIFFICULT  
ROADS  
LEAD TO  
BEAUTIFUL  
DESTINATIONS



# senders

good abstractions for concurrency

no need for synchronization

highly composable

# a pattern language

shapes of sender algorithms -> basic patterns

patterns -> lexicon

nuances for patterns

composing patterns -> syntax

speaking **concurrency** ?

a language for **safety**  
a language for **efficiency**  
**structured** language

# Thank You



@LucT3o



lucteo.ro