Make Your Own Stream Operators

Transforming asynchronous data streams in Rust

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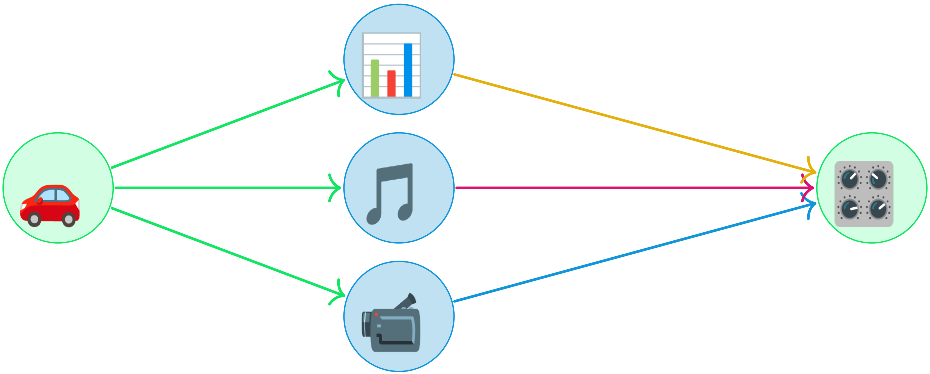
30 minutes + 10 minutes Q&A

Version with clickable links:
github.com/wvhulle/streams-eurorust-2025

Plan

Motivation

Processing data from moving vehicles



Kinds of streams

In this presentation →

Stream operators

Pure software transformations

`map()` • **`double()`** • **`fork()`** • **`latency()`** • **`hysteresis()`**

↑ Stream operators

Requires an async runtime
(see ‘leaf future’ by *Carl Fredrik Samson*) →

Leaf streams

OS/kernel constraints

`tokio::fs::File` • `TcpListener` • `UnixStream` • `Interval`

↑ OS abstraction

Physical streams

Electronic signals

GPIO interrupts • UART frames • Network packets

Operators

Streams

Data

Naive stream processing

The challenge: Process TCP connections, filter messages, and collect 5 long ones

```rust
let mut filtered_messages = Vec::new(); let mut count = 0; let mut = 0;
let mut tcp_stream = tokio::net::TcpListener::bind("127.0.0.1:8080")
      .await?
      .incoming();
while let Some(connection) = tcp_stream.next().await {
    match connection {
        Ok(stream) => {
            if should_process(&stream) {
                // More nested logic needed...
            }
        }
        Err(e) => {
            total_errors += 1;
            log_connection_error(e);
            if total_errors > 3 { break; }
        } } }
```

Complexity grows with each requirement

Inside the processing block, **even more nested logic:**

```
match process_stream(stream).await {
    Ok(msg) if msg.len() > 10 => {
        filtered_messages.push(msg);
        count += 1;
        if count >= 5 { break; }  // Break from outer loop!
    }
    Ok(_) => continue,  // Skip short messages
    Err(e) => {
        total_errors += 1;
        log_error(e);
        if total_errors > 3 { break; }  // Another outer break!
    }
}
```

Problems: hard to read, trace or test!

`Stream` *operators preview*

Same logic, much cleaner with stream operators:

```rust
let filtered_messages: Vec<String> = tcp_stream
    .filter_map(|connection| ready(connection.ok()))
    .filter(|stream| ready(should_process(stream)))
    .then(|stream| process_stream(stream))
    .filter_map(|result| ready(result.ok()))
    .filter(|msg| ready(msg.len() > 10))
    .take(5)
    .collect()
    .await;
```

"Programs must be written **for people to read**, and only incidentally for machines to execute." — *Harold Abelson & Gerald Jay Sussman*

Rust's `Stream` trait

A lazy interface

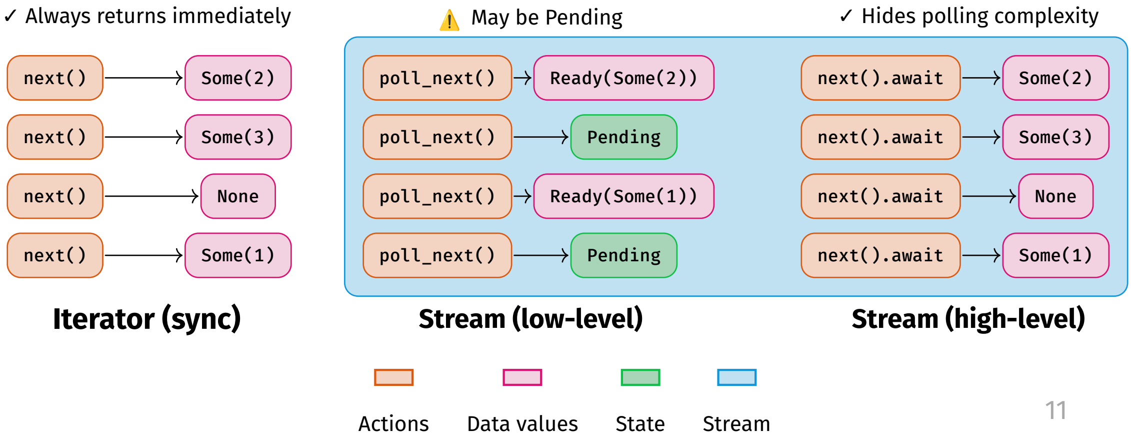
Similar to `Future`, but yields multiple items over time (when queried / **pulled**):

```rust
trait Stream {
    type Item;

    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
        -> Poll<Option<Self::Item>>;
}
```

Returns `Poll` enum:

1. `Poll::Pending`: not ready (like `Future`)
2. `Poll::Ready(_)`:
    - `Ready(Some(item))`: new data is made available
    - `Ready(None)`: currently exhausted (not necessarily the end)

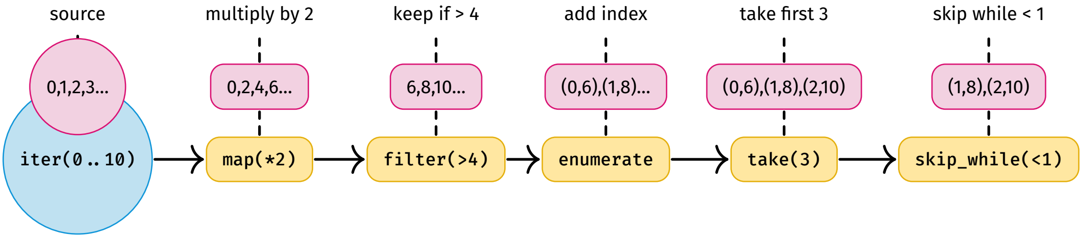
Moving from `Iterator` *to* `Stream`



Using the `Stream` API

Pipelines with `futures::StreamExt`

All basic stream operators are in `futures::StreamExt`




```
stream::iter(0..10)
  .map(|x| x * 2)
  .filter(|&x| ready(x > 4))
  .enumerate().take(3).skip_while(|&(i, _)| i < 1)
```

The handy `std::future::ready` *function*

The `futures::StreamExt::filter` expects an **async closure** (or closure returning `Future`):

Option 1: Async block (not `Unpin`!)

```
stream.filter(|&x| async move {
  x % 2 == 0
})
```

Option 2: Async closure (not `Unpin`!)

```
stream.filter(async |&x| x % 2 == 0)
```

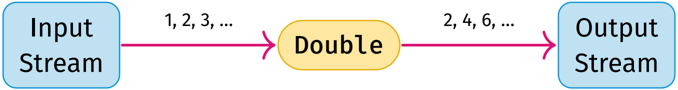
Option 3 (recommended): Wrap sync output with `std::future::ready()`

```
stream.filter(|&x| ready(x % 2 == 0))
```

- `ready(value)` creates a `Future` that immediately resolves to `value`.
- `ready(value)` is `Unpin` and **keeps pipelines `Unpin`**: ***easier to work with***, see later.

Example 1: One-to-One Operator

Doubling stream operator



Wrapping the original stream

All stream operators start by:

- **wrapping input stream by value**
- and being **generic over stream type**

(No trait bounds yet):

```
struct Double<InSt> { in_stream: InSt, }
```

And implementing the `Stream` trait for it (**with trait bounds**):

```
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {
  type Item = InSt::Item;

  fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>) -> Poll<Option<Self::Item>> {
          ...
  }
}
```

Naive implementation of `poll_next`

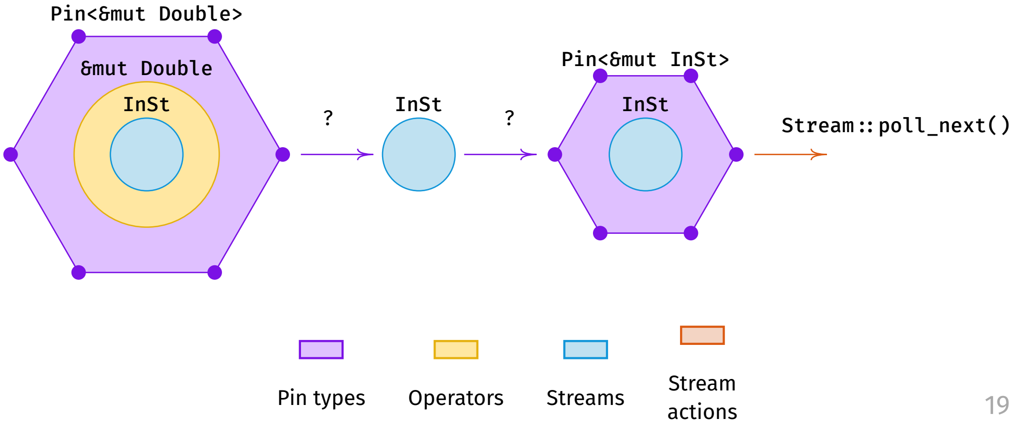
Focus on the implementation of the `poll_next` method

(Remember that `Self = Double<InSt>` with field `in_stream: InSt`):

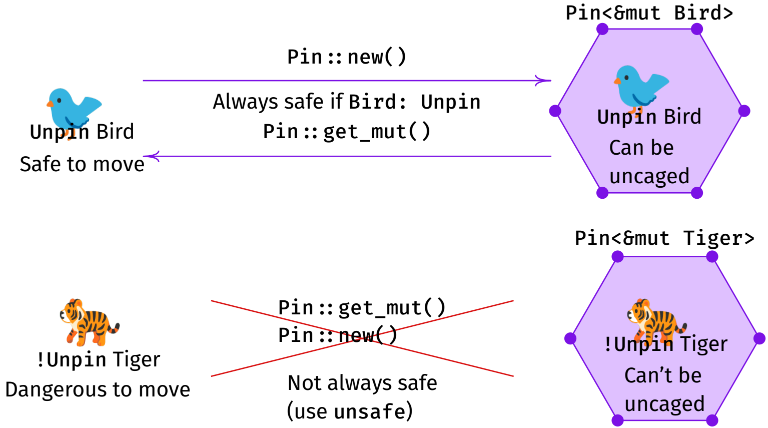
```
fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
    -> Poll<Option<Self::Item>> {
        // Cannot access self.in_stream!
        Pin::new(&mut self.in_stream) // Not possible!
            .poll_next(cx)
            .map(|x| x * 2)
}
```

`Pin<&mut Self>` **blocks access to `self.in_stream`** (when `Self: !Unpin`)!

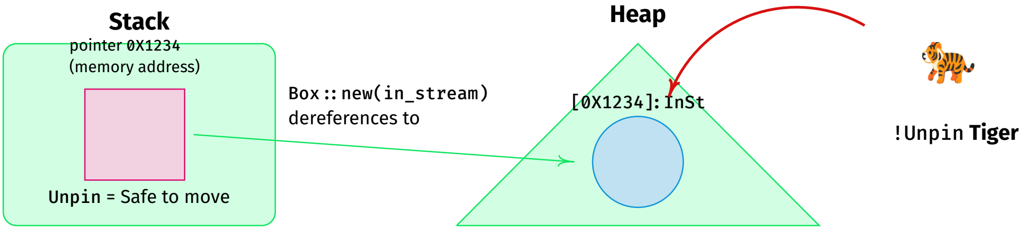
How to access `self.in_stream`*?*



`!Unpin` ***defends against unsafe moves***



Put your `!Unpin` type on the heap



Nice to have:

1. `Box::new(tiger)` produces just a pointer on the stack
   - Moving pointers is always safe
   - Therefore: **`Box<Tiger>: Unpin`**
2. Box dereferences to its contents
   - **`Box<X>: Deref<Target = X>`**

Problem: We need `Pin<&mut InSt>`, not `&mut InSt`

- Without `Pin<Box<_>>`, we'd need `InSt: Unpin` to create `Pin<&mut InSt>` (`Pin::new()` requires `Unpin`)
- This would force an `Unpin` constraint on `InSt`!

Solution: Add a `Pin` layer around `Box`

- Use `Pin<Box<InSt>>` instead of `Box<InSt>`
- Enables to go directly from `Pin<&mut Double>` to `Pin<&mut InSt>` with `Pin::as_mut()`

Projecting the `Doubled` *stream*

Create a `Doubled` stream (works with `!Unpin` streams!)

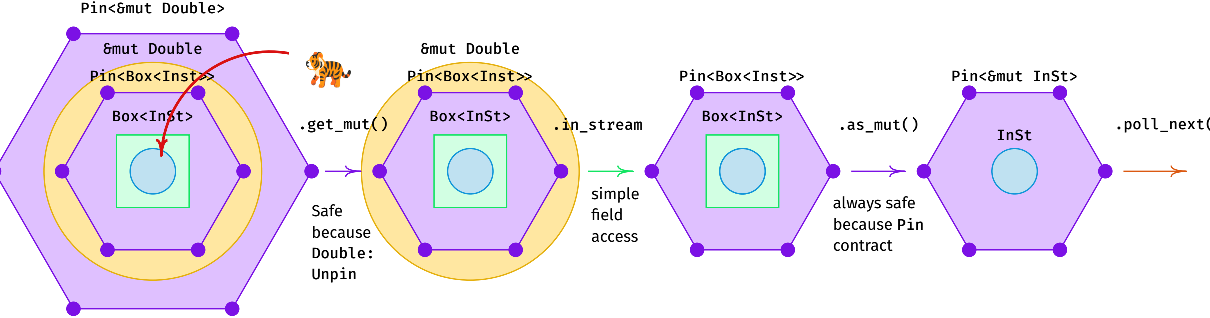
```
let double = Double {
    in_stream: Pin::new(Box::new(in_stream)) // Box::pin()
};
```

Inside `poll_next`, project to `Pin<&mut InSt>`:

```
let in_stream: Pin<&mut InSt> = double
  .get_mut() // Pin<&mut Double<InSt>> -> &mut Double<InSt>
  .in_stream // &mut Double<InSt> -> Pin<Box<InSt>>
  .as_mut(); // Pin<Box<InSt>> -> Pin<&mut InSt>
```

Projecting visually

From `Pin<&mut Double>` to `Pin<&mut InSt>` in a few **safe steps**:



`Pin` does not take up space, it functions more like a gatekeeper.

Complete boxed `Stream` implementation

We can call `Pin::get_mut()` to get `&mut Double<InSt>` safely from `Pin<&mut Double<InSt>>`

```rust
impl<InSt> Stream for Double<InSt>
where InSt: Stream<Item = i32>
{
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
        -> Poll<Option<Self::Item>>
    {
        // We can project because `Self: Unpin`
        let this: &mut Double<InSt> = self.get_mut();
        // `this` = a conventional name for `get_mut` output
        this.in_stream.as_mut()
            .poll_next(cx)
            .map(|r| r.map(|x| x * 2))
    }
}
```

Two ways to handle `!Unpin` fields

Approach 1: Use Box<_>

```
struct Double<InSt> {
  in_stream: Pin<Box<InSt>>
}

impl<InSt> Stream for Double<InSt>
  where InSt: Stream
```

✓ Works with `InSt`

Approach 2: Require Unpin

```
struct Double<InSt> {
  in_stream: InSt
}

impl<InSt> Stream for Double<InSt>
  where InSt: Stream + Unpin
```

✗ Imposes `Unpin` constraint

Approach 3: Projection with `pin-project`

Projects like Tokio use the `pin-project` crate:

```rust
#[pin_project]
struct Double<InSt> {
    #[pin]
    in_stream: InSt,
}

impl<InSt: Stream> Stream for Double<InSt> {
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
        -> Poll<Option<Self::Item>>
    {
        // pin-project generates a safe projection method `project()`
        self.project().in_stream.poll_next(cx)
            .map(|r| r.map(|x| x * 2))
    }
}
```

Uses a lot of macros underneath (a bit out-of-scope).

Distributing your operator

Define a constructor and turn it into a method of an **extension trait**:

```rust
trait DoubleStream: Stream {
    fn double(self) -> Double<Self>
    where Self: Sized + Stream<Item = i32>,
    { Double::new(self) }
}
// A blanket implementation should be provided by you!
impl<S> DoubleStream for S where S: Stream<Item = i32> {}
```

Now, users **don't need to know how** `Double` is implemented, just

1. import your extension trait: `DoubleStream`
2. call `.double()` on any compatible stream

Example 2: One-to-N Operator

Complexity $1 - N$ ***operators***

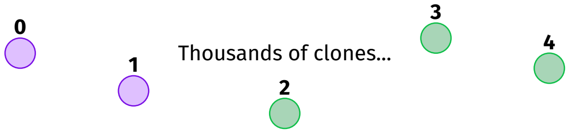
Challenges for `Stream` operators are combined from:

Inherent `Future` challenges:

- Clean up orphaned wakers
- Cleanup when tasks abort
- Task coordination complexity

Inherent `Iterator` challenges:

- Ordering guarantees across consumers
- Backpressure with slow consumers
- Sharing mutable state safely
- Avoiding duplicate items



All in different states

Sharing latency between tasks

Latency may need to processed by different async tasks:

```
let tcp_stream = TcpStream::connect("127.0.0.1:8080").await?;
let latency = tcp_stream.latency(); // Stream<Item = Duration>

spawn(async move { display_ui(latency).await; });
spawn(async move { engage_breaks(latency).await; }); // Error!
```

Error: `latency` is moved into the first task, so the second task can't access it.

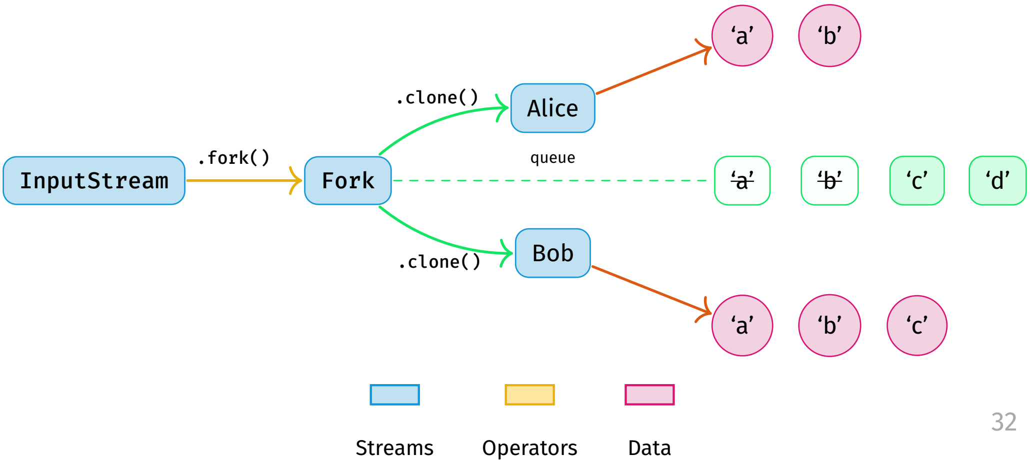
Cloning streams with an operator

Solution: Create a ***stream operator*** `fork()` makes the input stream `Clone`.

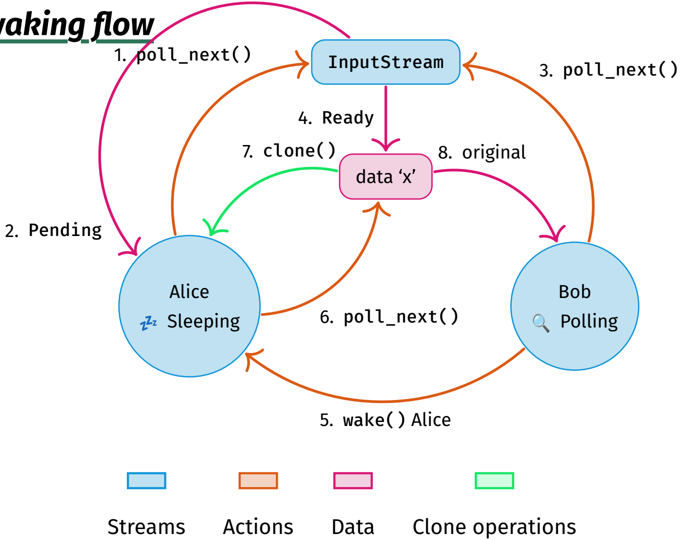
```
let tcp_stream = TcpStream::connect("127.0.0.1:8080").await?;

// Fork makes the input stream cloneable
let ui_latency = tcp_stream.latency().fork();

let breaks_latency_clone = ui_latency.clone();
// Warning: `Clone` needs to be implemented!

spawn(async move { display_ui(ui_latency).await; });
spawn(async move { engage_breaks(breaks_latency_clone).await; });
```

Requirement: `Stream<Item: Clone>`, so we can clone the items (`Duration` is `Clone`)

Rough architecture of `clone-stream`



Polling and waking flow

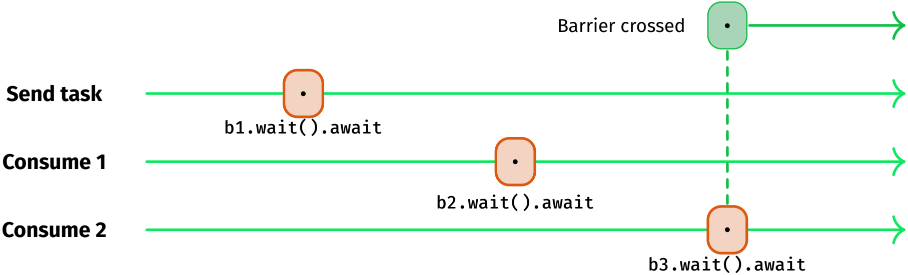


`Barriers` *for task synchronization*

For performance reasons, you may want to **ignore unpolled consumers** (init required) in 1-to-N stream operators.

Synchronisation after the “init” phase is done with a single `Barrier` ot type $N + 1$.

```
let b1 = Arc::new(Barrier::new(3)); // For input task
let b2 = b1.clone(); // First output
let b3 = b1.clone(); // For second output
```



Including `Barriers` *in your unit tests*

When you build your own:

1. Pick a **`Barrier`** crate (tokio / async-lock).
2. Define synchronization points with **`Barrier`**:

```
let b1 = Arc::new(Barrier::new(3));
let b2 = b1.clone(); // Second output
let b3 = b1.clone(); // For input
```

3. Apply your custom operator

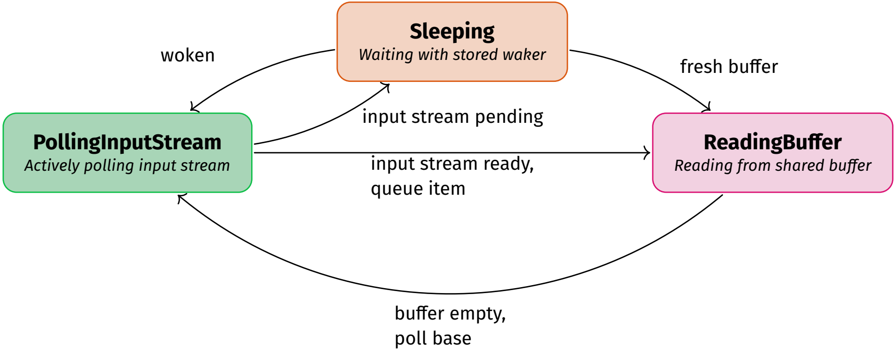
```
let out_stream1 =
create_test_stream(in_stream)
    .your_custom_operator();
let out_stream2 = out_stream1.clone();
```

4. Send your inputs and outputs to separate tasks
5. Do not use **`sleep`** and await all tasks.

```
try_join_all([
    spawn(async move {
        setup_task().await;
        b1.wait().await;
        out_stream1.collect().await;
    }),
    spawn(async move {
        setup_task().await;
        b2.wait().await;
        out_stream2.collect().await;
    }),
    spawn(async move {
        b3.wait().await;
        send_input(in_stream).await;
    })
]).await.unwrap();
```

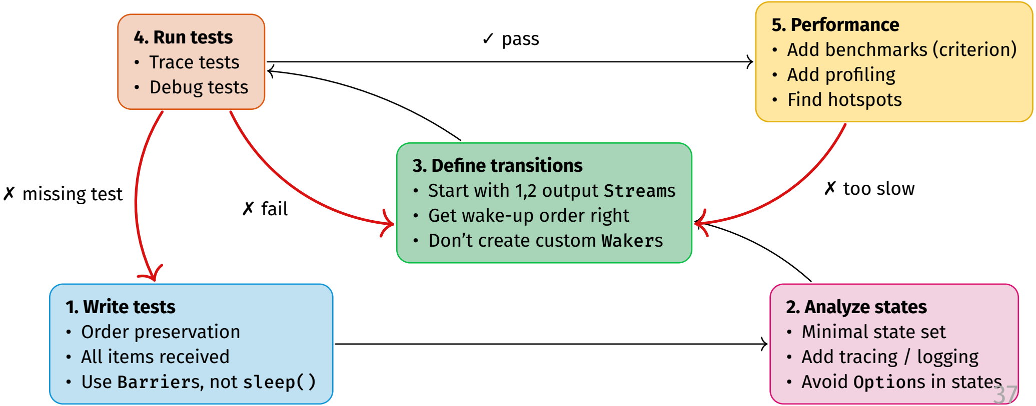
Simplified state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**:



Each clone maintains its own state:

Steps for creating robust stream operators



General principles

Rules of thumb

Separation of concerns:
- Modular functions
- Descriptive names
- Split long functions

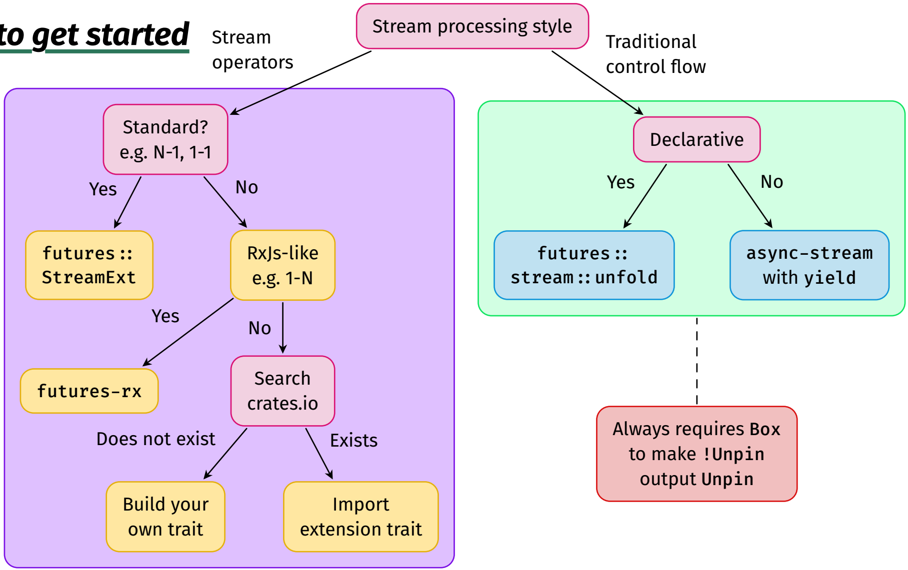
Don’t overuse streams:
- Keep pipelines short
- Only *physical async data flow*

Meaningful objective targets:
- Simple, clear unit tests
- Relevant benchmarks

Simple state machines:
1. Fewer `Options`
2. Fewer states

“Perfection is achieved, not when there is nothing more to add, but when there is **nothing left to take away**.” — *Antoine de Saint-Exupéry*

How to get started



Any questions?

Thank you!

Want to learn more in-depth?

Join my 7-week course ***“Creating Safe Systems in Rust”***

- Location: Ghent (Belgium)
- Date: starting November 2025.

Register at willemvanhulle.tech (link at bottom of page)

- Contact me: willemvanhulle@protonmail.com
- These slides: github.com/wvhulle/streams-eurorust-2025

Bonus slides

`Streams` *in Rust are not new*

2019

async/await stabilized in Rust
Stable async streams in std
RFC 2394, Rust 1.39.0

2009

Microsoft Reactive Extensions
ReactiveX brings streams to mainstream
Erik Meijer, Microsoft

1997

Functional Reactive Programming
Conal Elliott & Paul Hudak (Haskell)
ICFP '97, pp. 263-273

1978

Communicating Sequential Processes
Tony Hoare formalizes concurrent dataflow
CACM 21(8):666-677

1973

Unix Pipes
Douglas McIlroy creates `|` operator
Bell Labs, Unix v3-v4

1960s

Dataflow Programming
Hardware-level stream processing
Early dataflow architectures

The meaning of `Ready(None)`

Regular Stream

"No items **right now**"

(*Stream might yield more later*)

Fused Stream

"No items **ever again**"

(*Stream is permanently done*)

'Fusing' `Streams` *and* `Futures`

	`Future`	**`Stream`**	**Meaning**
Regular			May continue
Fused	**`FusedFuture`**	**`FusedStream`**	`is_terminated()` method
Fused			Done permanently
Fused value	`Pending`	`Ready(None)`	Final value

Flatten a finite collection of `Streams`

A finite collection of `Streams` = `IntoIterator<Item: Stream>`

```
let streams = vec![
    stream::iter(1..=3),
    stream::iter(4..=6),
    stream::iter(7..=9),
];

let merged = stream::select_all(streams);
```

1. Creates a `FuturesUnordered` of the streams
2. Polls all streams concurrently
3. Yields items as they arrive

Flattening an infinite stream

Beware!: `flatten()` on a stream of infinite streams will never complete!

```
let infinite_streams = stream::unfold(0, |id| async move {
    Some((stream::iter(id..), id + 1))
});
let flat = infinite_streams.flatten();
```

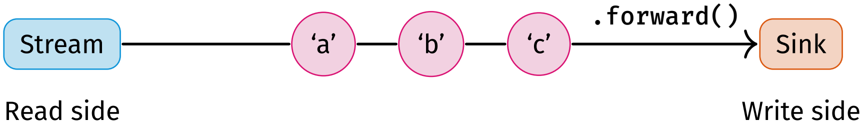
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```
let requests = stream::unfold(0, |id| async move {
    Some((fetch_stream(format!("/api/data/{}", id)), id + 1))
});
let flat = requests.flatten_unordered(Some(10));
```

More `Stream` features to explore

Many more advanced topics await:

- **Boolean operations**: `any`, `all`
- **Async operations**: `then`
- **`Sinks`**: The write-side counterpart to `Streams`



The `Stream` *trait: a lazy query interface*

The `Stream` trait is NOT the stream itself - it's just a lazy frontend to query data.

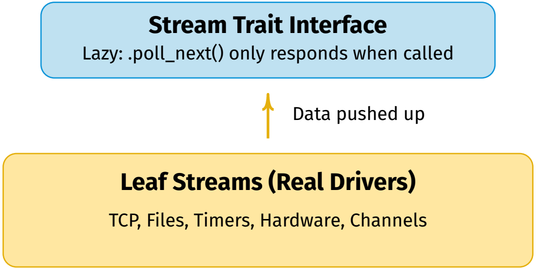
What `Stream` trait does:

- Provides uniform `.poll_next()` interface
- Lazy: only responds when asked
- Doesn't drive or produce data itself
- Just queries whatever backend exists

What actually drives streams:

- TCP connections receiving packets
- File I/O completing reads
- Timers firing
- Hardware signals
- Channel senders pushing data

The 'real' stream drivers



`Stream` trait just provides a **uniform way to query** - it doesn't create or drive data flow.

Possible inconsistency

```rust
trait Stream {
    type Item;

    fn poll_next(self: Pin<&mut Self>, cx: &mut Context)
        -> Poll<Option<Self::Item>>
}
```

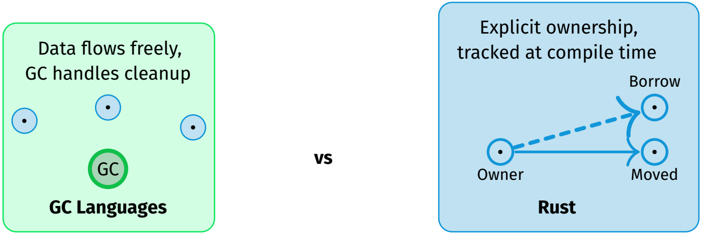
What about Rust rule `self` needs to be `Deref<Target=Self>`?

`Pin<&mut Self>` only implements `Deref<Target=Self>` for `Self: Unpin`.

Problem? No, `Pin` is an exception in the compiler.

Why does Rust need special treatment?

- Stream operators must wrap and own their input by value
- Combining `Future` (waker cleanup, coordination) and `Iterator` (ordering, backpressure) complexity
- Sharing mutable state safely across async boundaries requires careful design



Reactive patterns from GC languages require rethinking in Rust's ownership model

The end