Make Your Own Stream Operators

Transforming asynchronous data streams in Rust

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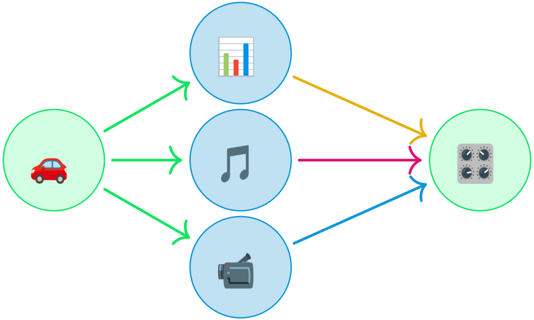
30 minutes + 10 minutes Q&A

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

```
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:**

```rust
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

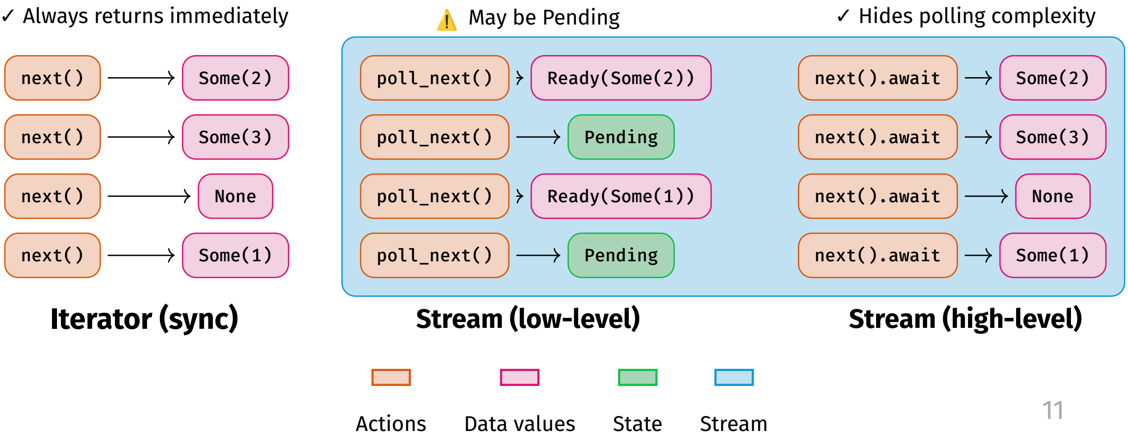
Similar to `Future`, but yields multiple items over time (when queried / **pulled**):

```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)

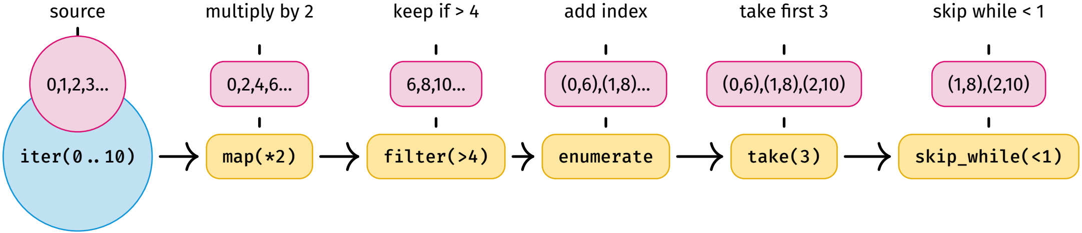
Moving from `Iterator` *to* `Stream`



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)
```

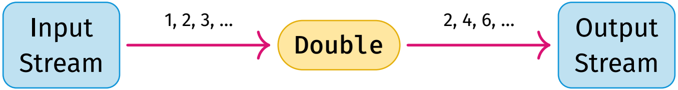
Option 3 (recommended): Wrap sync output with `std::future::ready()`

```
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`

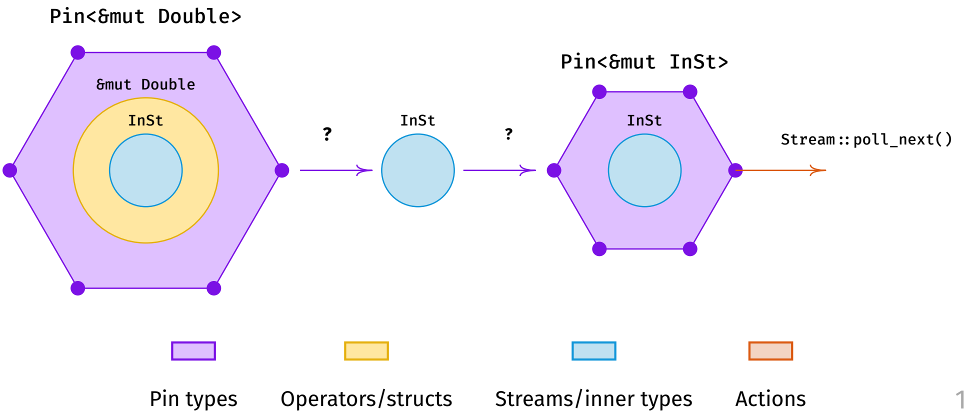
Focus on the implementation of the `poll_next` method

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

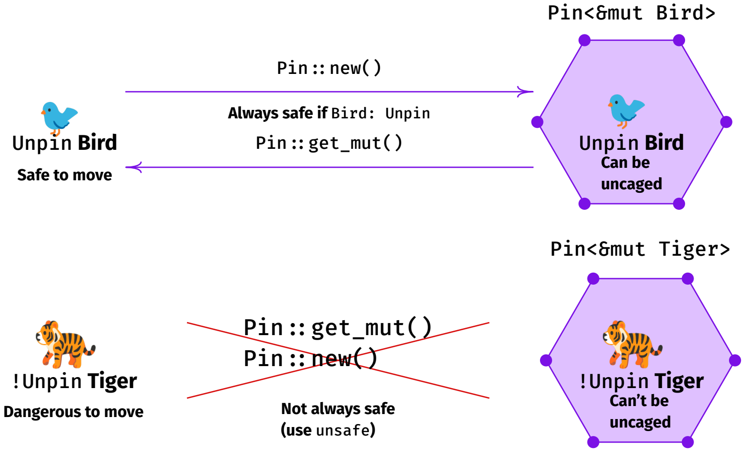
```
fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
    -> Poll<Option<Self::Item>> {
        // Cannot access self.in_stream!
        Pin::new(&mut self.in_stream) // Not possible!
            .poll_next(cx)
            .map(|x| x * 2)
}
```

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

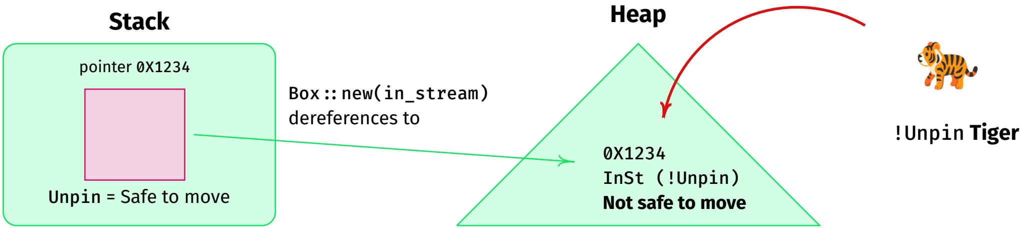
How to access `self.in_stream`***?***



`!Unpin` *defends against unsafe moves*



Put your `!Unpin` ***type on the heap***



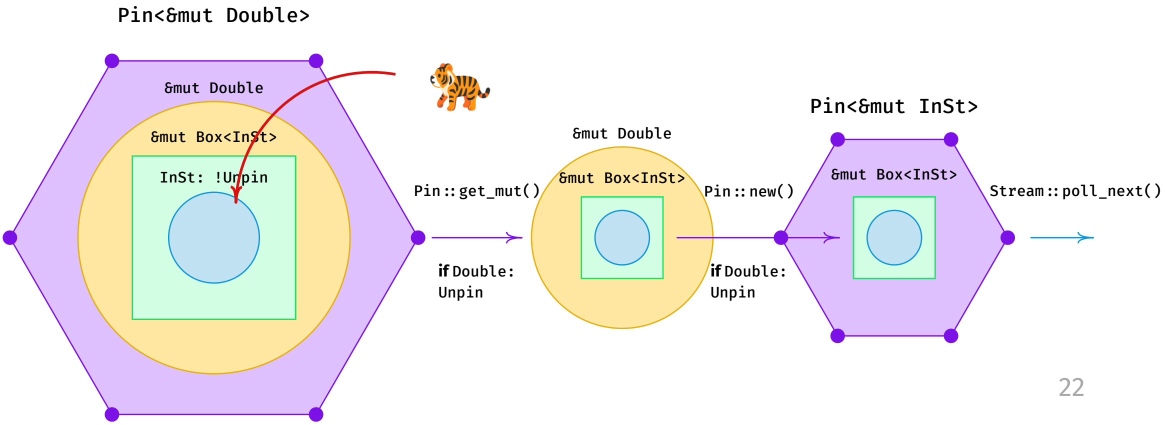
1. The output of `Box::new(tiger)` is just a pointer
   Moving pointers is safe, so **`Box<Tiger>: Unpin`**
2. Box behaves like what it contains: **`Box<X>: Deref<Target = X>`**

Result:

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

Putting it all together visually

Mapping from `Pin<&mut Double>` to `&mut InSt` is called **projection**



Complete `Stream` trait implementation

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

```
impl<InSt> Stream for Double<InSt>
where InSt: Stream<Item = i32> + Unpin
{
    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` is a conventional name for projection
        Pin::new(&mut this.in_stream)
            .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: 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: Use `pin-project`

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

Used by popular crates (Tokio, etc.)

Example usage of `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 safe projection code
        self.project().in_stream.poll_next(cx)
            .map(|r| r.map(|x| x * 2))
    }
}
```

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***

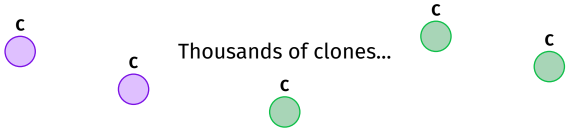
Challenges for `Stream` operators are combined from:

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



Sharing latency between tasks

Latency may need to processed by different async tasks:

```rust
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.

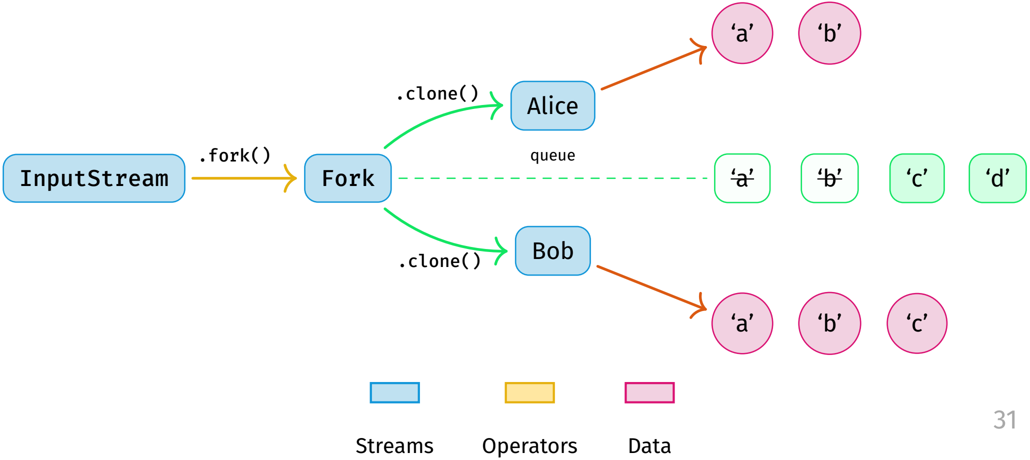
Cloning streams with an operator

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

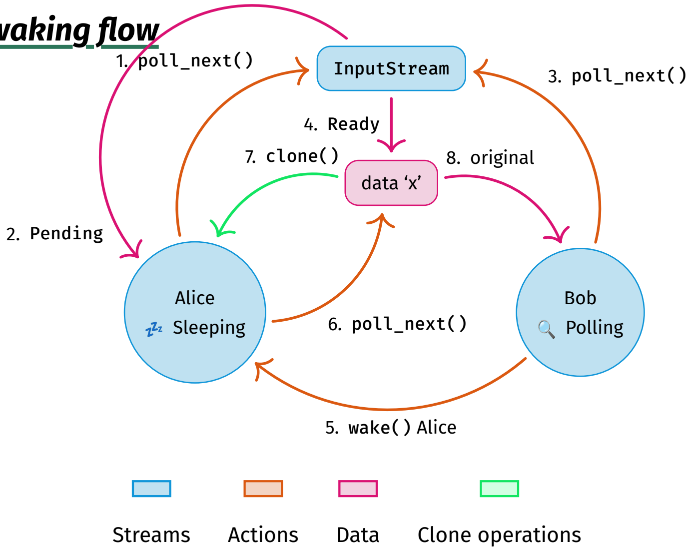
```
let tcp_stream = TcpStream::connect("127.0.0.1:8080").await?;

// 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

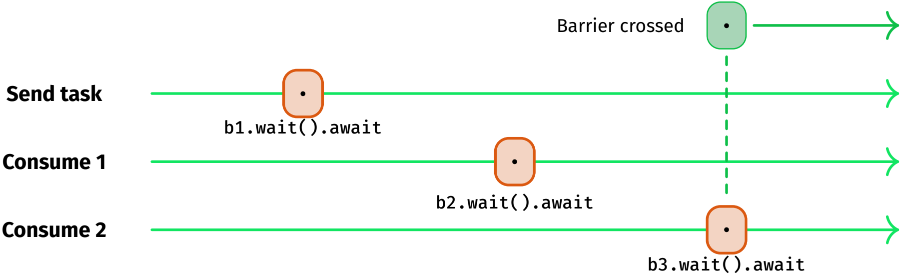


`Barriers` *for task synchronization*

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

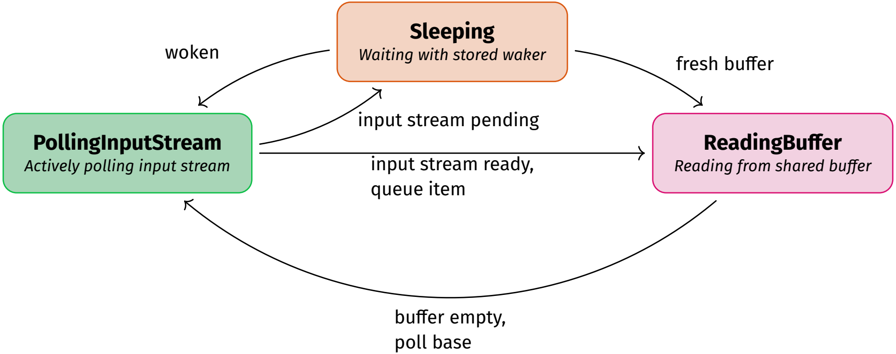
```
let out_stream1 =
create_test_stream(in_stream)
    .your_custom_operator();
let out_stream2 = out_stream1.clone();
```

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();
```

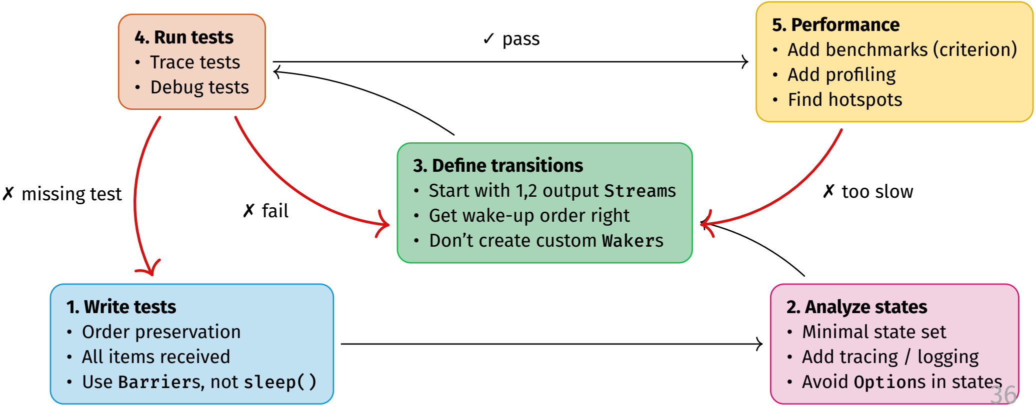
Simplified state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**:



Each clone maintains its own state:

Steps for creating robust stream operators



General principles

Rules of thumb

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

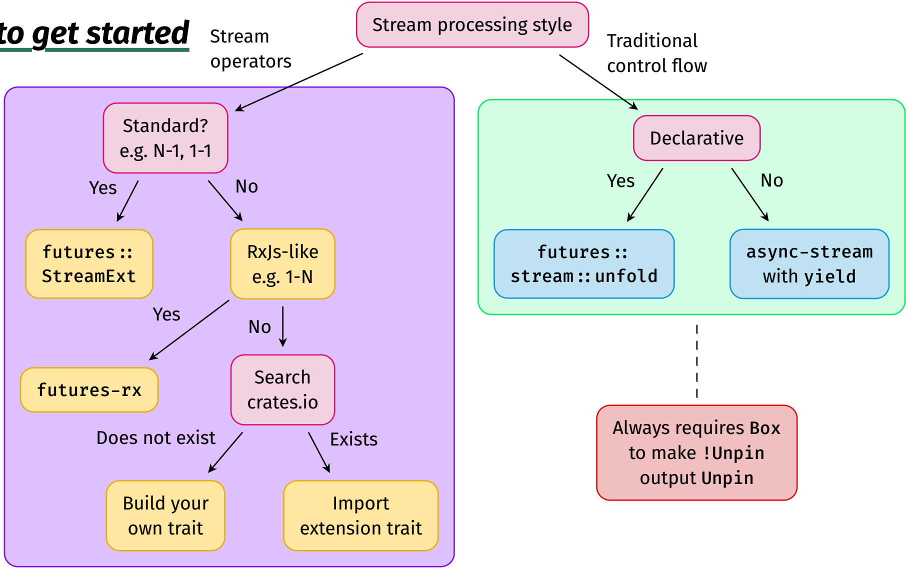
Meaningful objective targets:
- Simple, clear unit tests
- Relevant benchmarks

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

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();
```

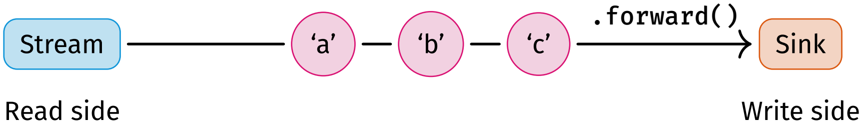
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```
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.

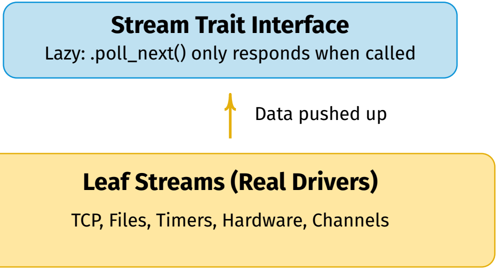
What `Stream` trait does:

- 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>>
}
```

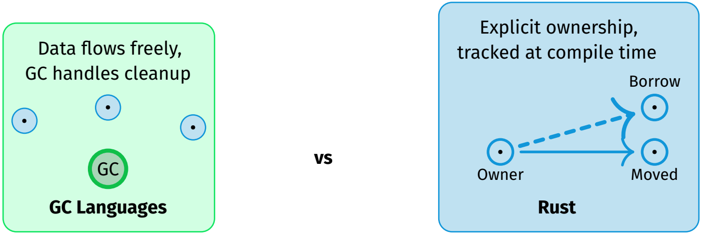
What about Rust rule `self` needs to be `Deref<Target=Self>`?

`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