Make Your Own Stream Operators

Transforming asynchronous data streams in Rust

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EuroRust 2025 • Paris, France

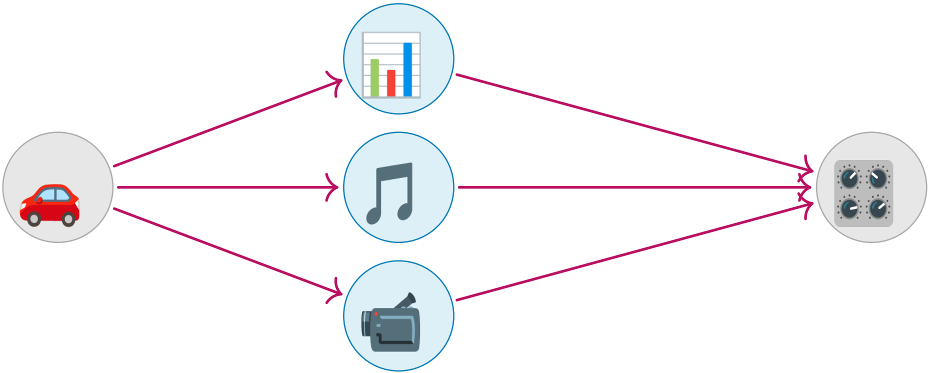
30 minutes + 10 minutes Q&A

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

Process TCP connections and collect 5 long messages

```rust
let mut results = Vec::new(); let mut count = 0;

while let Some(connection) = tcp_stream.next().await {
    match connection {
        Ok(stream) if should_process(&stream) => {
            match process_stream(stream).await {
                Ok(msg) if msg.len() > 10 => {
                    results.push(msg);
                    count += 1;
                    if count >= 5 { break; }
                }
                Ok(_) => continue,
                Err(_) => continue,
            }
        }
        Ok(_) => continue,
        Err(_) => continue,
    }
}
```

Problems:

- Deeply nested
- Hard to read
- Cannot test pieces indepen-dently

`Stream` *operators: declarative & composable*

Same logic with stream operators:

```
let results: Vec<String> = tcp_stream
    .filter_map(|conn| ready(conn.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;
```

Benefits:

- Each operation is isolated
- Testable
- Reusable

“Programs must be written **for people to read**”

— Abelson & Sussman

Rust’s `Stream` trait

The `Stream` trait: async iterator

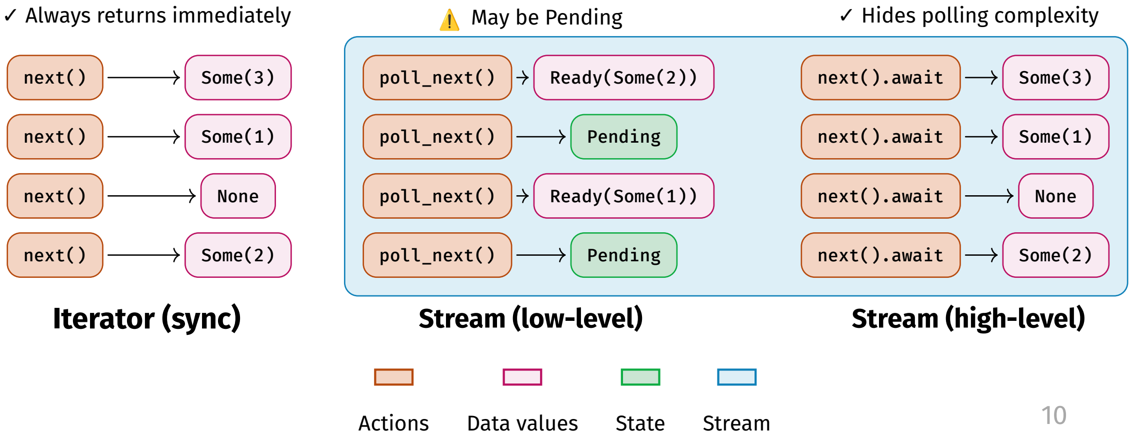
Like `Future`, but yields **multiple items** over time when polled:

```
trait Stream {
    type Item;

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

The `Poll<Option<Item>>` return type:

- `Poll::Pending` - not ready yet, try again later
- `Poll::Ready(Some(item))` - here's the next item
- `Poll::Ready(None)` - stream is exhausted (no more items **right now**)

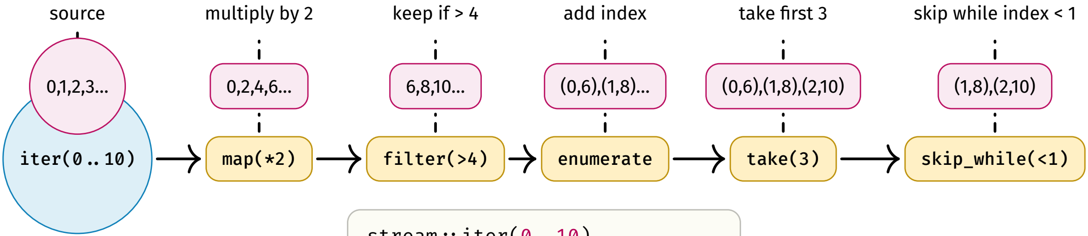
***Moving from* `Iterator` *to* `Stream`**



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))
```

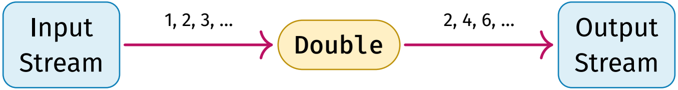
- `ready(value)` creates a `Future` that immediately resolves to `value`.
- `ready(value)` is `Unpin`

`ready` keeps pipelines `Unpin`: *easier to work with*

Example 1: $1 \to 1$ Operator

Doubling stream operator

Very simple `Stream` operator that **doubles every item** in an input stream:



Input stream **needs to yield integers**.

Building a stream operator: structure

Step 1: Define a struct that wraps the input stream

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

- Generic over stream type (works with any backend)
- Stores input stream by value

Step 2: Implement `Stream` trait with bounds

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

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

Naive implementation of `poll_next`

Focus on the implementation of the `poll_next` method

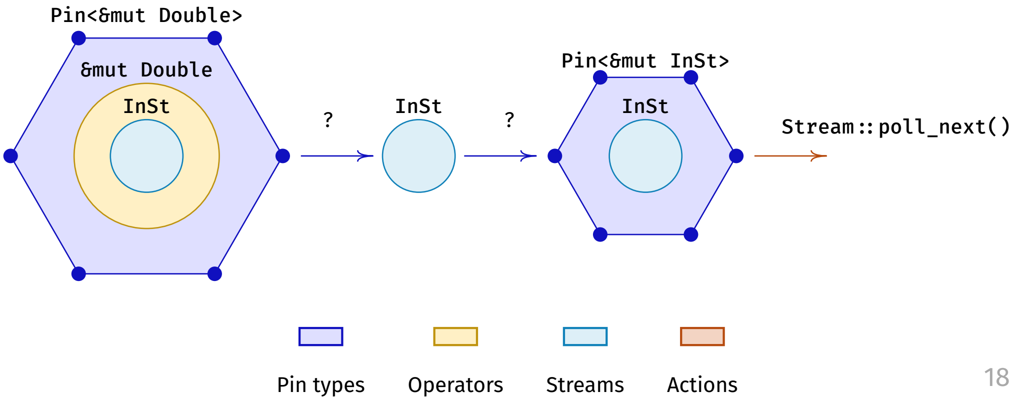
(Remember that `Self = Double<InSt>` with field `in_stream: InSt`):

```
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`)!

The projection problem: accessing pinned fields

We have `Pin<&mut Double>`, but need `Pin<&mut InSt>` to call `poll_next()`. How?



The naive solution fails

Can we use `Pin::get_mut()` to unwrap and re-wrap?

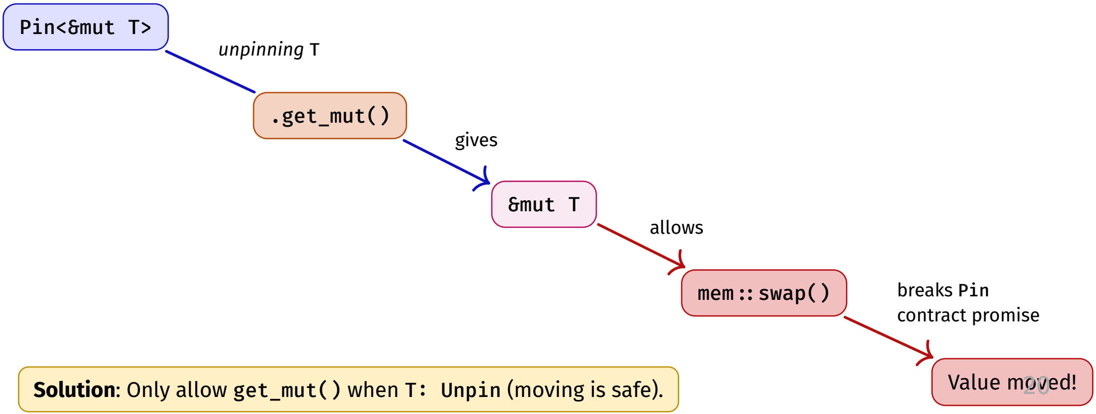
```
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {
  type Item = InSt::Item;

  fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
      -> Poll<Option<Self::Item>> {
    let this = self.get_mut();  // Error!
    let pinned_in = Pin::new(&mut this.in_stream);
    pinned_in.poll_next(cx).map(|p| p.map(|x| x * 2))
  }
}
```

Problem: `Pin::get_mut()` requires `Double<InSt>: Unpin`

But **`Double<InSt>`** ***is*** **`!Unpin`** *when* `InSt: !Unpin`!

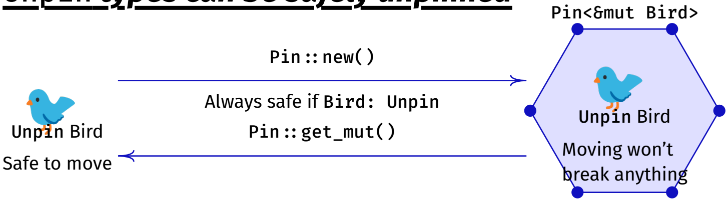
Why does `Pin::get_mut()` ***require*** `Unpin`***?***

`Pin<P>` makes a promise: **the pointee will never move again**.



Solution: Only allow `get_mut()` when `T: Unpin` (moving is safe).

`Unpin` *types can be safely unpinned*



If `T: Unpin`, then `Pin::get_mut()` is safe because moving `T` doesn't cause UB.

Examples of `Unpin` types:

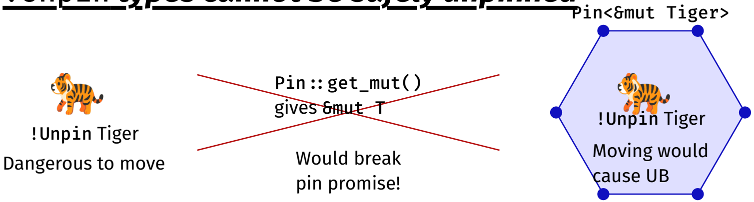
- `i32`, `String`, `Vec<T>` - all primitive and standard types
- `Box<T>` - pointers are safe to move
- `&T`, `&mut T` - references are safe to move

Why safe?

These types don't have self-referential pointers. Moving them in memory doesn't invalidate any internal references.

Almost all types are `Unpin` by default!

`!Unpin` *types cannot be safely unpinned*



Examples of `!Unpin` types:

- `PhantomPinned` - explicitly opts out of `Unpin`
- Most `Future` types (self-ref. state machines)
- Types with self-referential pointers
- `Double<InSt>` where `InSt: !Unpin`

Why unsafe?

These types may contain pointers to their own fields. Moving them in memory would invalidate those internal pointers, causing use-after-free.

`!Unpin` is rare and usually intentional for async/self-referential types.

One workaround: add the `Unpin` ***bound***

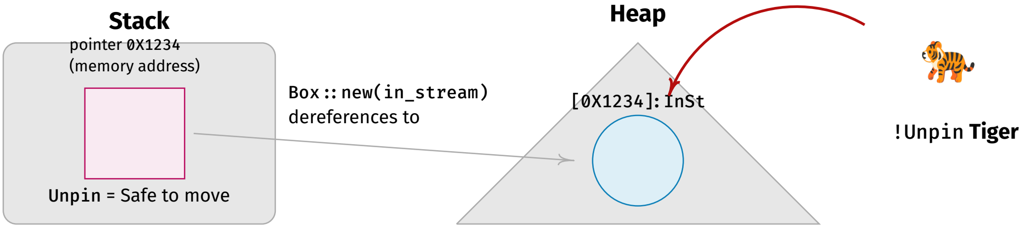
The compiler error suggests adding **`InSt: Unpin`**:

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

  fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>) -> Poll<Option<Self::Item>> {
    // `this` = a conventional name for `get_mut` output
    let mut this = self.get_mut();
    let pinned_in = Pin::new(&mut this.in_stream);
    pinned_in
      .poll_next(cx)
      .map(|p| p.map(|x| x * 2))
  }
}
```

We **don't want to impose `InSt: Unpin` on users** of `Double`!

How to support **`InSt: !Unpin`** streams? …

Turning `!Unpin` ***into*** `Unpin` ***with boxing***



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: Need `Pin<&mut InSt>`, but `Box<InSt>` requires `InSt: Unpin` to create it

Solution: Use `Pin<Box<InSt>>` to project from `Pin<&mut Double>` to `Pin<&mut InSt>` via `Pin::as_mut()`

Applying the solution: `Pin<Box<InSt>>`

Change the struct definition to store `Pin<Box<InSt>>`:

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

Why this works:

- `Box<InSt>` is always `Unpin` (pointers are safe to move)
- `Pin<Box<InSt>>` can hold `!Unpin` streams safely on the heap

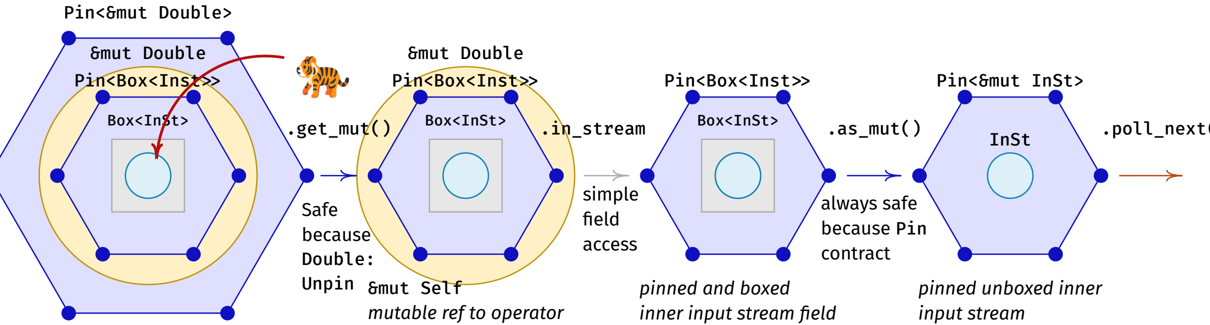
Projection in `poll_next`:

```rust
fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
    -> Poll<Option<Self::Item>> {
    let this = self.get_mut();  // Safe: Double is Unpin now
    this.in_stream.as_mut()      // Project to Pin<&mut InSt>
        .poll_next(cx)
        .map(|opt| opt.map(|x| x * 2))
}
```

This works **without requiring `InSt: Unpin`**!

Projecting visually

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



Complete boxed `Stream` implementation

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

```
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.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 any `InSt`, also `!Unpin`

Approach 2: Require Unpin

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

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

✗ Imposes `Unpin` constraint on users

… or, use `pin-project` crate

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: $1 \to N$ Operator

Complexity $1 \to N$ operators

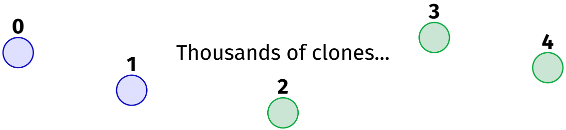
Challenges for `Stream` operators are combined from:

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.

We need a way to clone the latency stream!

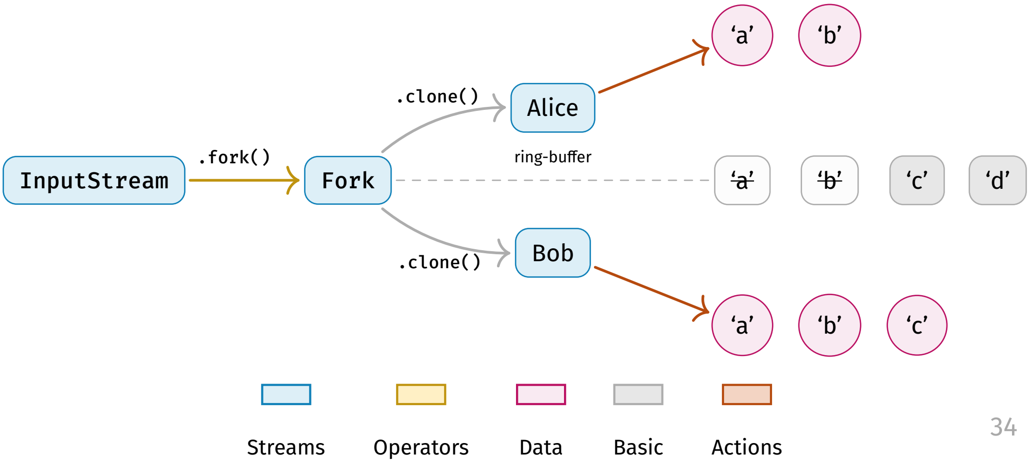
Cloning streams with an operator

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

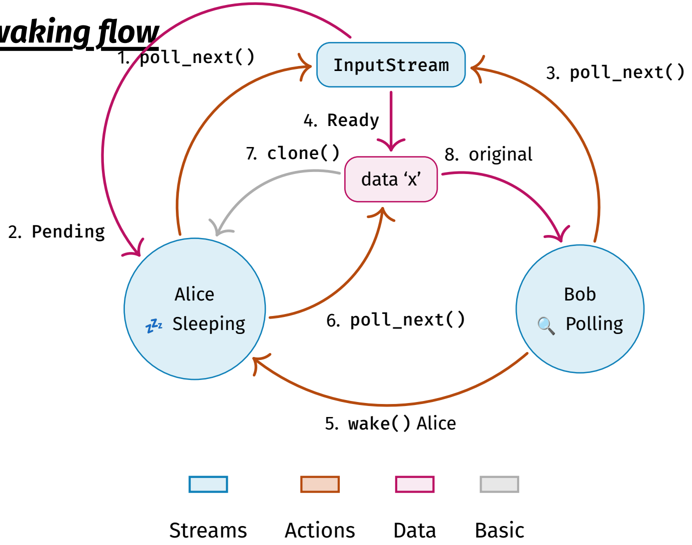
```rust
let tcp_stream = TcpStream::connect("127.0.0.1:8080").await?;

// 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`

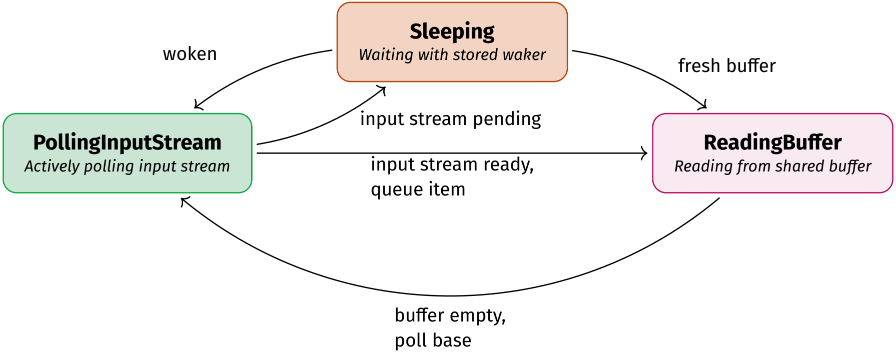


Polling and waking flow



Simplified state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**:



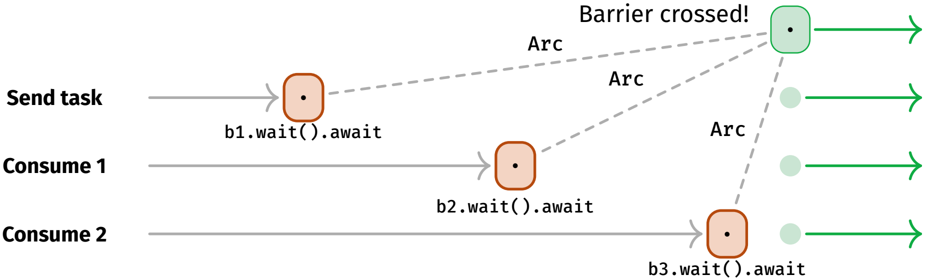
Each clone maintains its own <u>state</u>

`Barriers` *for task synchronization checkpoints*

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

Each consumer needs to signal when it is ready to receive items.

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



Multiple **synchronization points are possible** with multiple `Barriers`.

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();
```

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

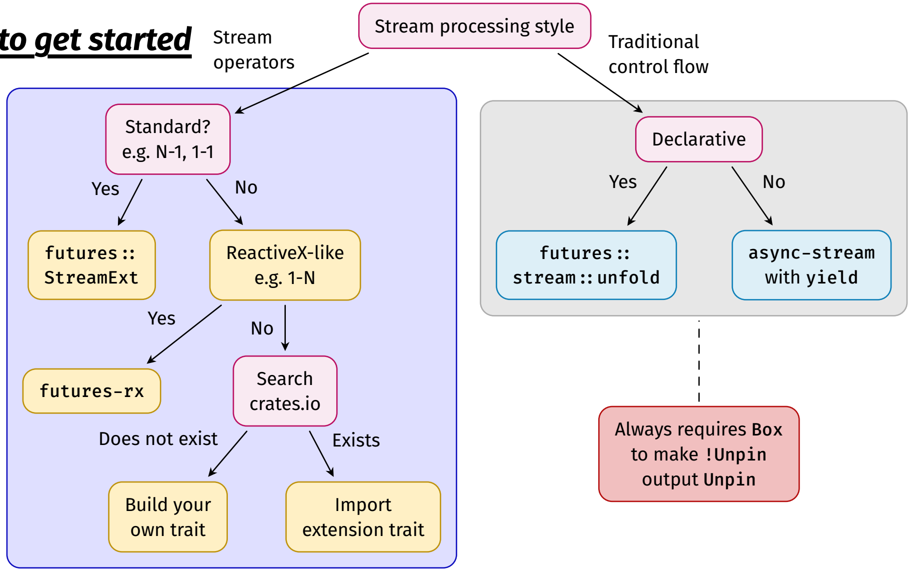
Simple state machines:

1. Fewer `Options`
2. More states

"Perfection is achieved when there is **nothing left to take away**."

— Antoine de Saint-Exupéry

How to get started



Any questions?

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

Want to learn more in-depth?

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

- Location: Ghent (Belgium)
- Date: starting 4th of November 2025.

Register at pretix.eu/devlab/rust-course/

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>`

```rust
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();
```

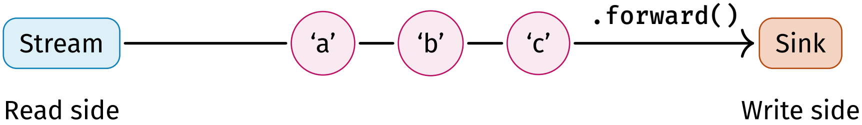
Instead, **buffer streams** concurrently with `flatten_unordered()`.

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

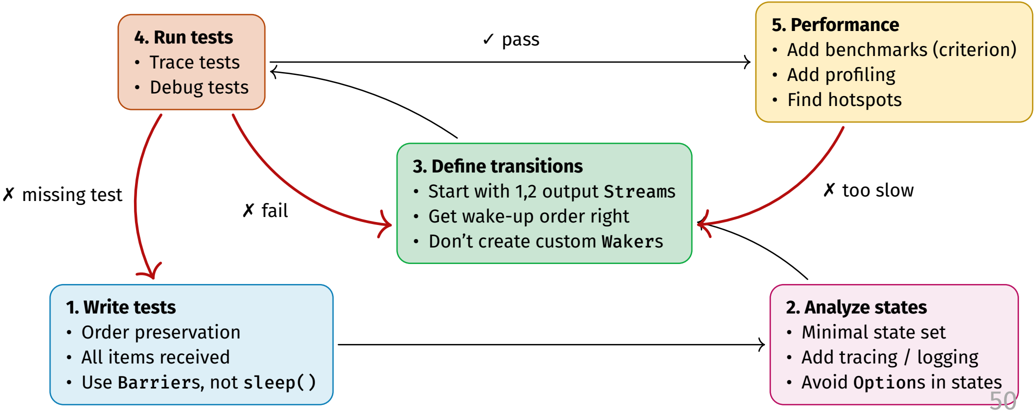
More `Stream` features to explore

Many more advanced topics await:

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



Steps for creating robust stream operators



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

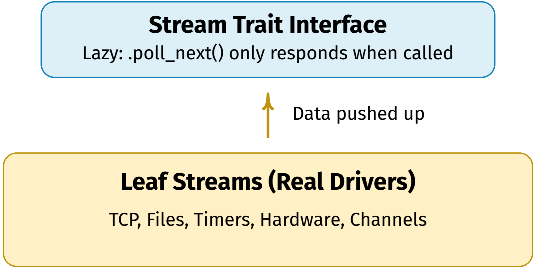
Approach 3: Projection with `pin-project`

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).

The 'real' stream drivers



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

Possible inconsistency

```
trait Stream {
    type Item;

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

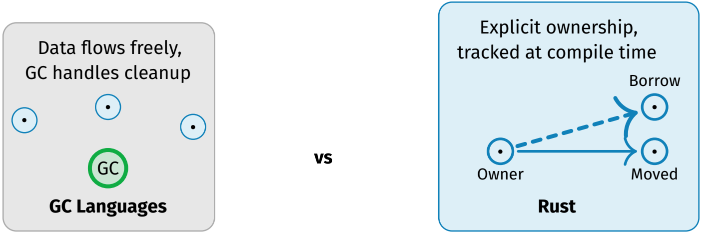
What about Rust rule `self` needs to be `Deref<Target=Self>`?

`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