Make Your Own Stream Operators

Transforming asynchronous data streams in Rust

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EuroRust 2025 • Paris, France

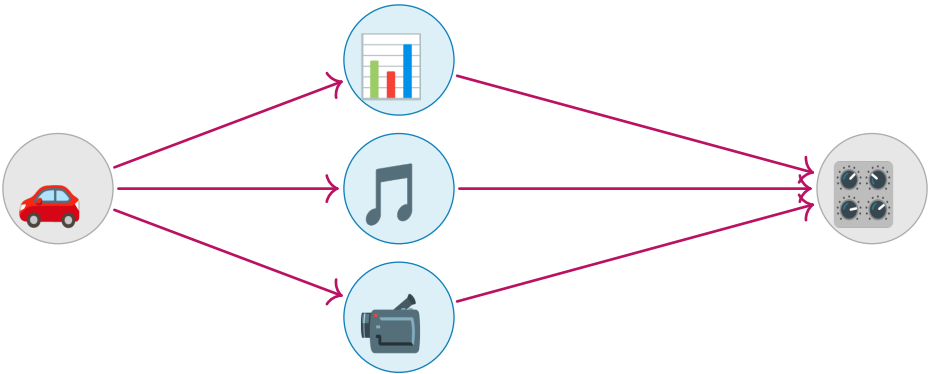
30 minutes + 10 minutes Q&A

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

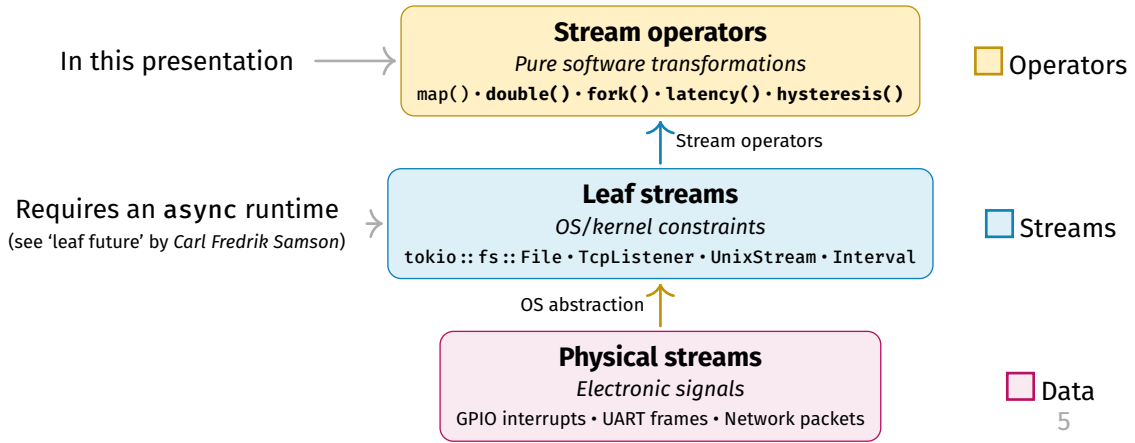
Plan

Motivation

Processing data from moving vehicles



Kinds of streams



Process TCP connections and collect 5 long messages

```
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 independently

`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:

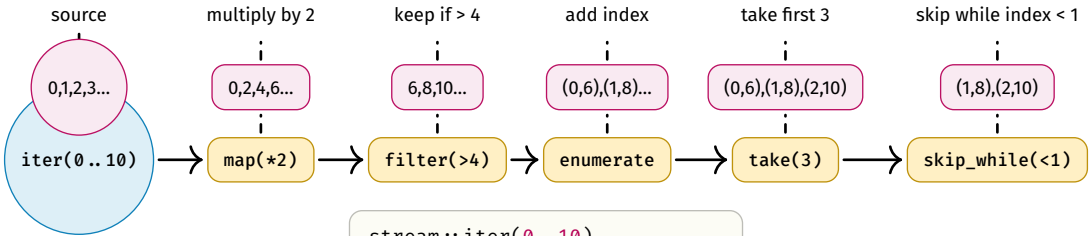
```
trait Stream {
    type Item;

    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**)

Pipelines with `futures::StreamExt`

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




```rust
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))
```

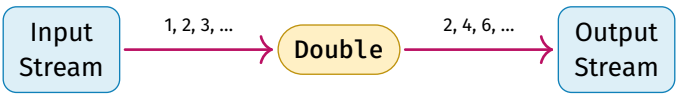
- `ready(value)` creates a `Future` that immediately resolves to `value`.
- `ready(value)` is `Unpin`

`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

```
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

```
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

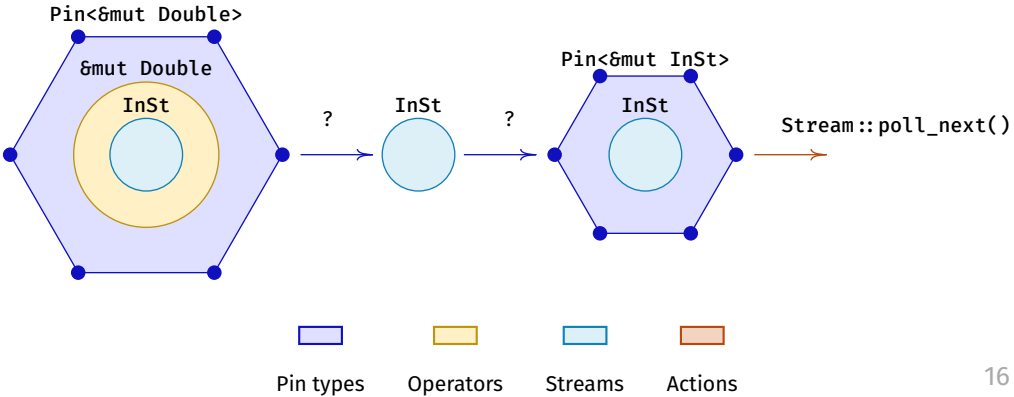
(Remember that **`Self = Double<InSt>`** with field **`in_stream: InSt`**):

```
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?

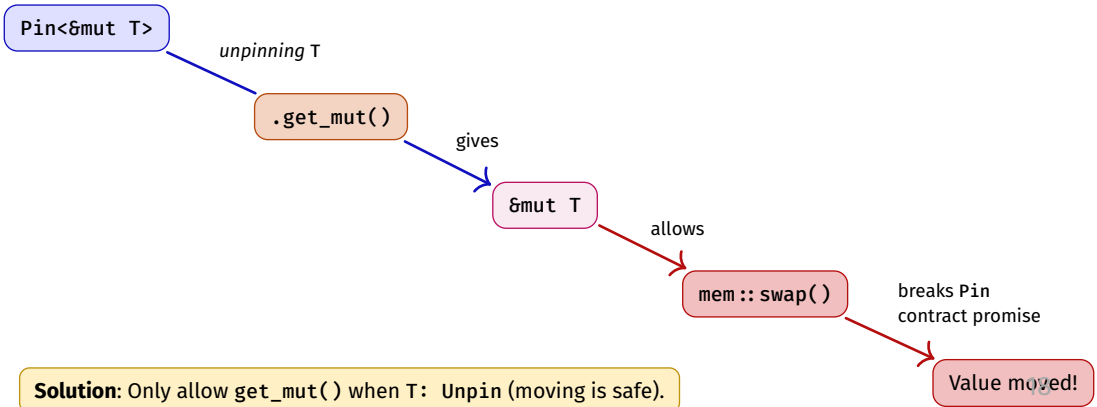
```
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {
  type Item = InSt::Item;

  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`!

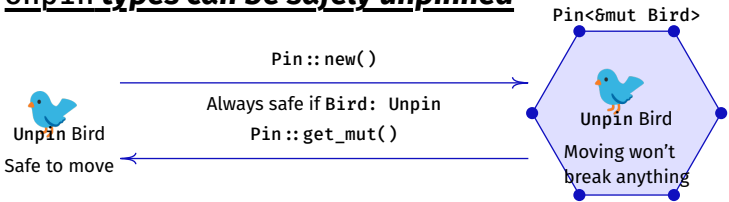
Why does `Pin::get_mut()` ***require*** `Unpin`***?***

`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*

`!Unpin` Tiger

Dangerous to move

~~`Pin::get_mut()` gives `&mut T`~~

Would break pin promise!

`Pin<&mut Tiger>`

`!Unpin` Tiger

Moving would cause UB

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***

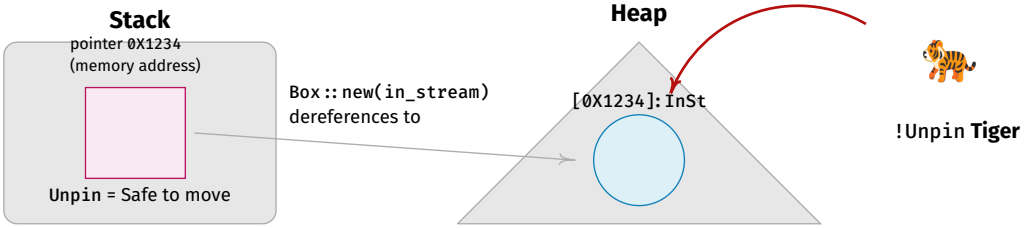
The compiler error suggests adding `InSt: Unpin`:

```
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>>`**:

```
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

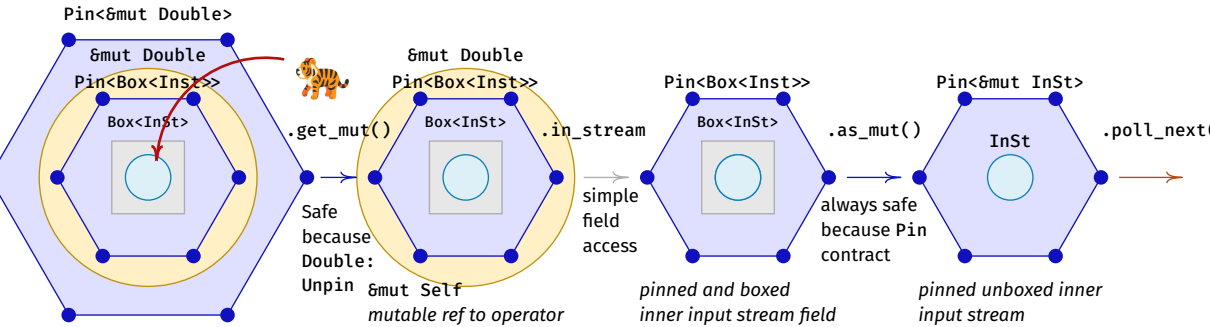
Projection in `poll_next`:

```
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**:

```
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: $1 \rightarrow N$ Operator

Complexity $1 \rightarrow N$ ***operators***

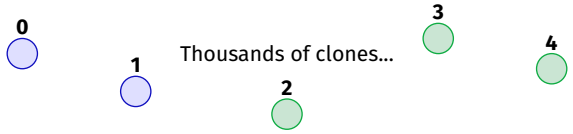
Challenges for `Stream` operators are combined from:

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!

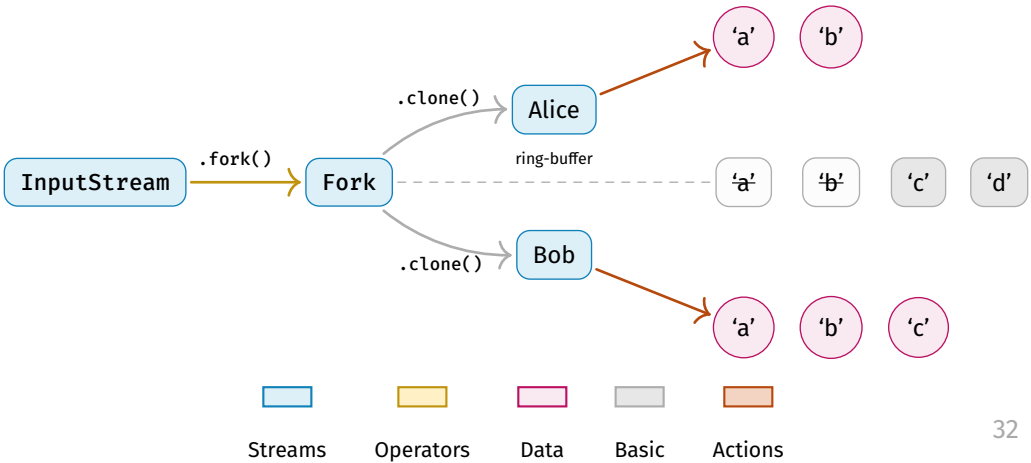
Cloning streams with an operator

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

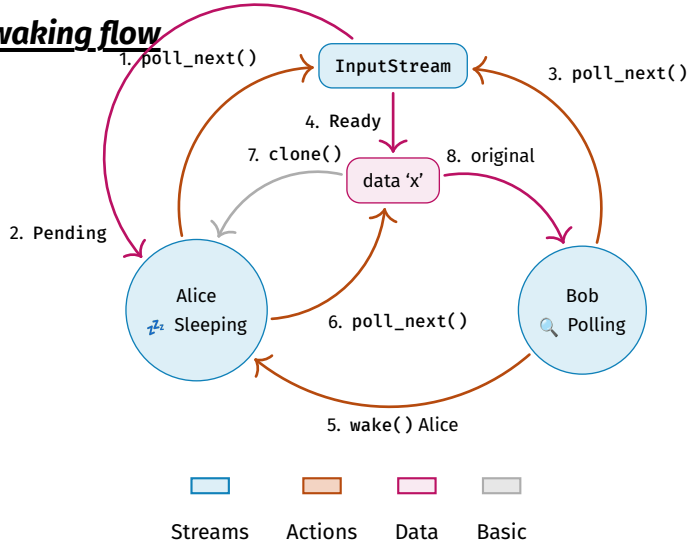
```
let ui_latency = tcp_stream.latency().fork();

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

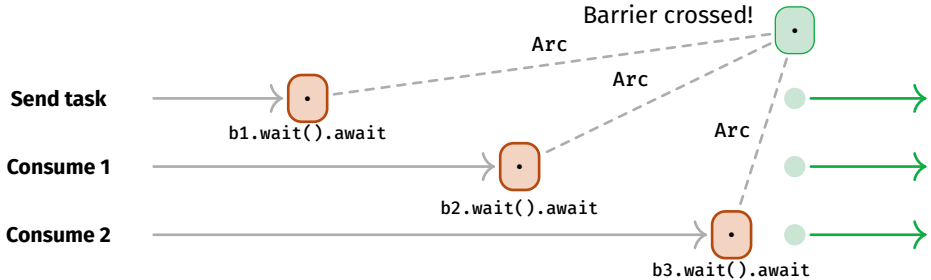


`Barrier`s *for task synchronization checkpoints*

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 `Barrier`s.

Including `Barrier`*s 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 (`criterion`)

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

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

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"***

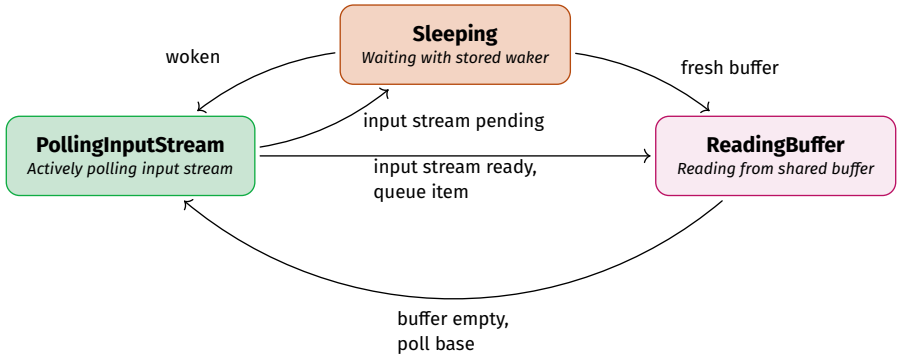
- Location: Ghent (Belgium)
- Date: starting 4th of November 2025.

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

Bonus slides

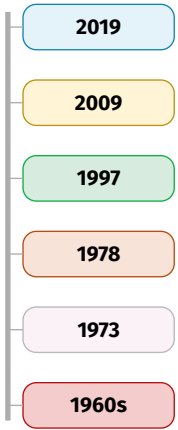
Simplified state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**:



Each clone maintains its own state

`Stream`*s in Rust are not new*



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

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

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

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

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

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' `Stream`**s** ***and*** `Future`**s**

	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();
```

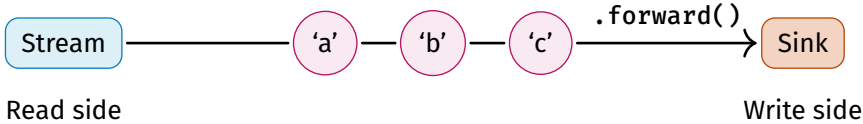
Instead, **buffer streams** concurrently with `flatten_unordered()`.

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

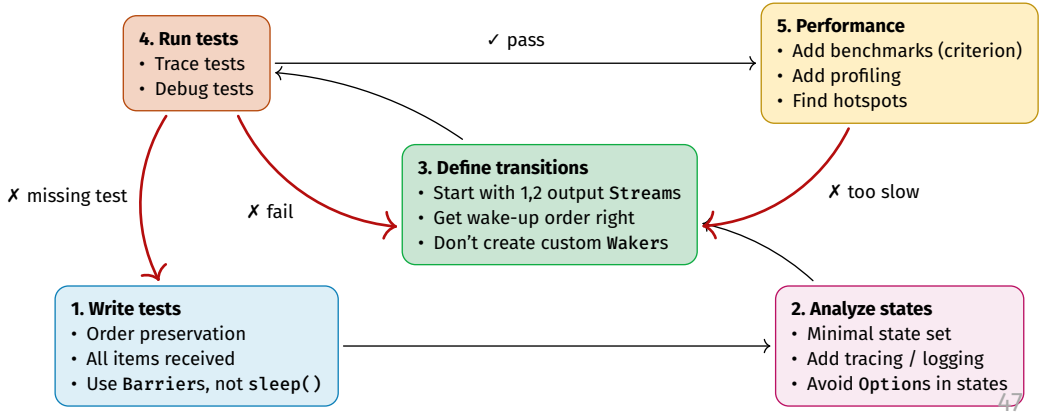
More `Stream` ***features to explore***

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.

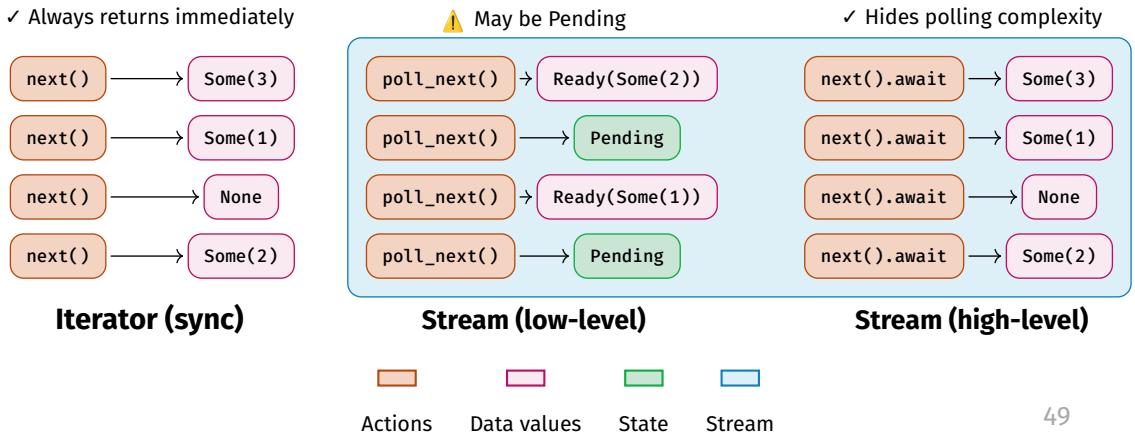
What `Stream` trait does:

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

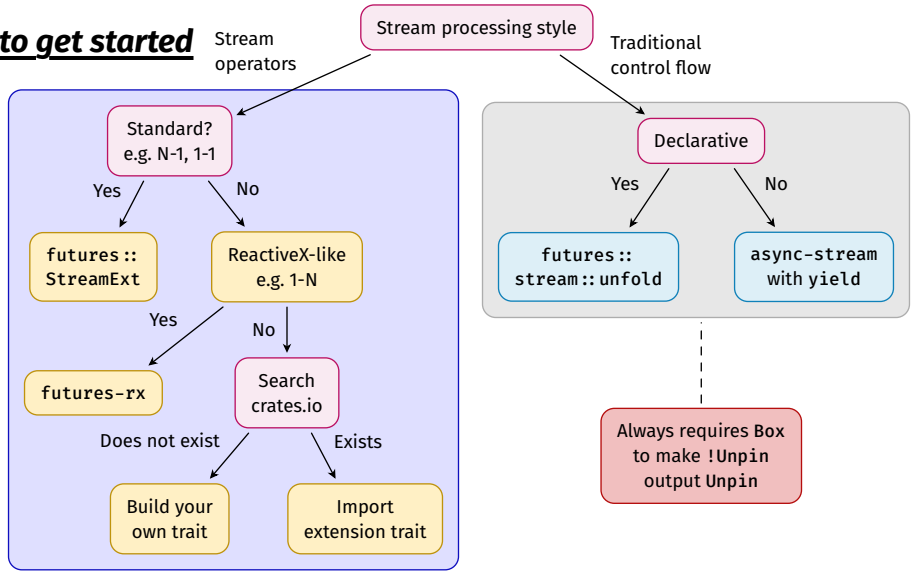
What actually drives streams:

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

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



How to get started



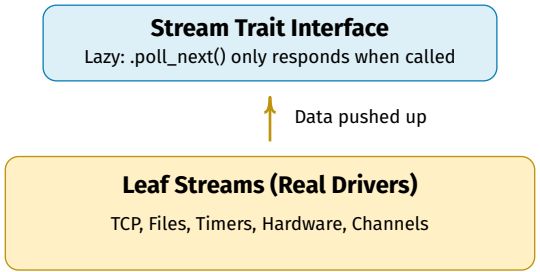
Approach 3: Projection with `pin-project`

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>>
}
```

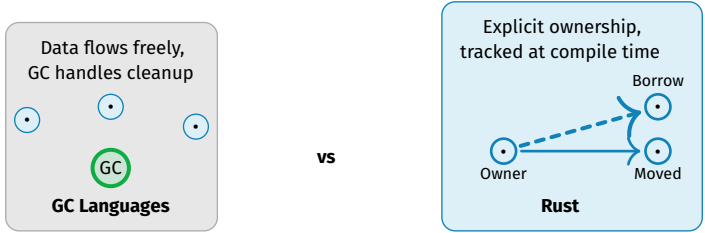
What about Rust rule `self` needs to be `Deref<Target=Self>`?

`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