Make Your Own Stream Operators

Advanced stream processing in Rust

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30 minutes + 10 minutes Q&A

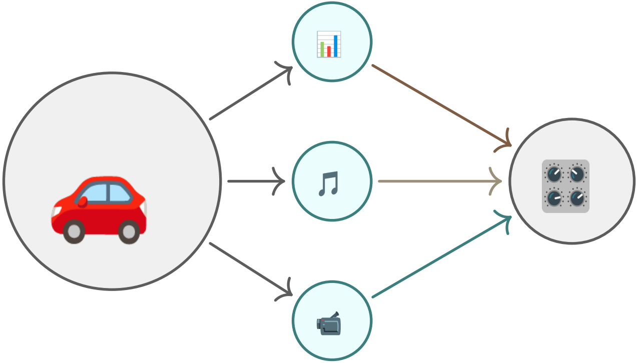
Version with clickable links:
github.com/wvhulle/streams-eurorust-2025

Plan

Motivation 3
Rust's `Stream` trait 9
Using the `Stream` API 12
Example 1: One-to-One Operator 15
Example 2: One-to-N Operator 24
General principles 34
Bonus slides 38

Motivation

Processing data from moving vehicles



Kinds of streams

Physical streams
Electronic signals
GPIO interrupts • UART frames • Network packets

OS abstraction ↓

Requires an async runtime
(see 'leaf future' by *Carl Fredrik Samson*)

Leaf streams
OS/kernel constraints
`tokio::fs::File` • `TcpListener` • `UnixStream` • `Interval`

Stream operators ↓

In this presentation →

Stream operators
Pure software transformations
`map()` • **`double()`** • **`fork()`** • **`latency()`** • **`hysteresis()`**

Data

Streams

Operators

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:**

```
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!

Functional `Stream` *usage 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

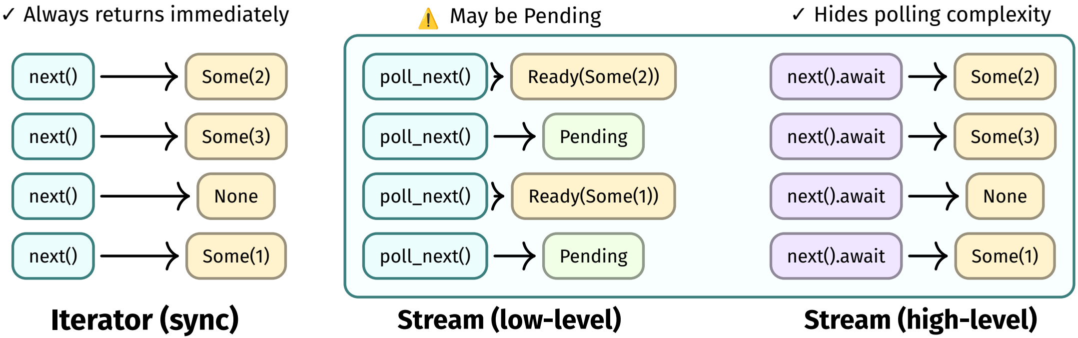
Similar to `Future`, but yields multiple items over time (when queried / **pulled**):

```
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)

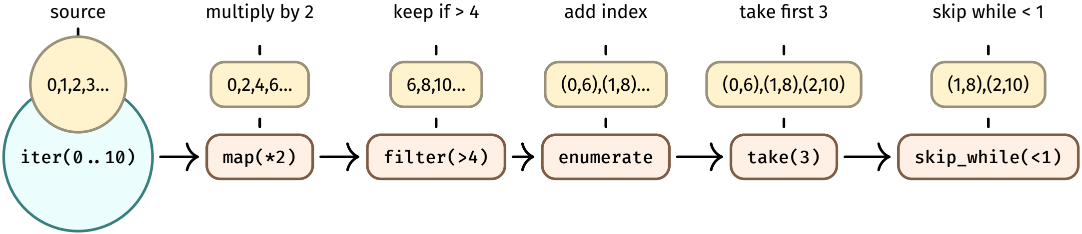
Moving from `Iterator` *to* `Stream`



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 lesser-known `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)
```

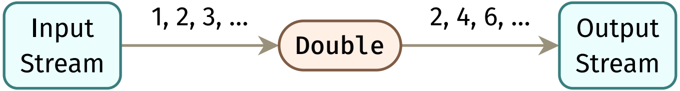
Option 3 (recommended): Wrap sync output with `std::future::ready()`

```
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

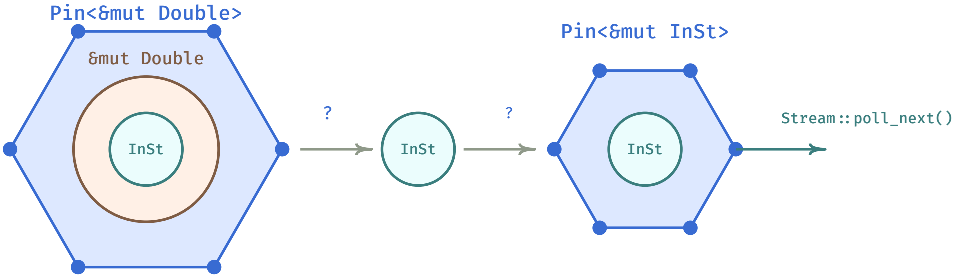


Wrapping the original stream by value

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

impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {
  type Item = InSt::Item;
  // Self = Double<InSt>
  fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
       -> Poll<Option<Self::Item>> {
           // Project onto self.in_stream...
           Pin::new(&mut self.in_stream) // Not possible!
               .poll_next(cx) // Unreachable ...
               .map(|x| x * 2)
  }
}
```

`Pin<&mut Self>` blocks access to `self.in_stream`!

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

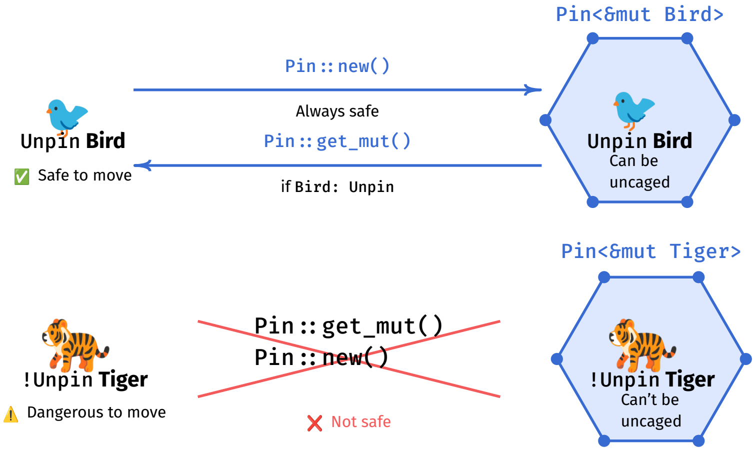


Pin types

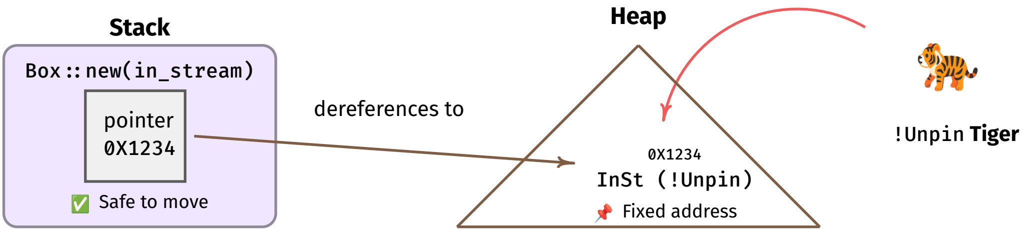
Operators/structs

Streams/inner types

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



Put your `!Unpin` type on the heap



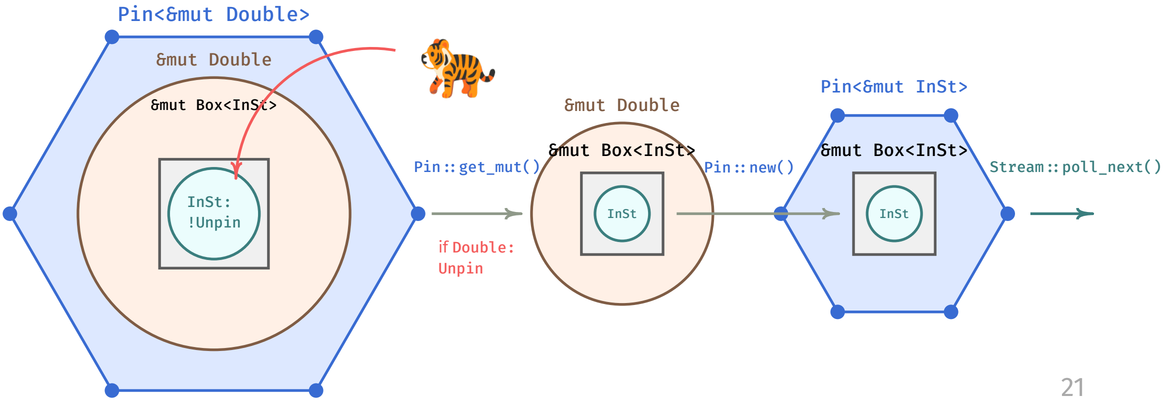
1. The output of `Box::new(tiger)` is just a pointer
   Moving pointers is safe, so **`Box: Unpin`**
2. Box behaves like what it contains: **`Box<X>: Deref<Target = X>`**

Result:

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

Putting it all together visually

... and wrapping it around the boxed stream:



Complete `Stream` trait implementation

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

```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` is a conventional name for projection
        Pin::new(&mut this.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

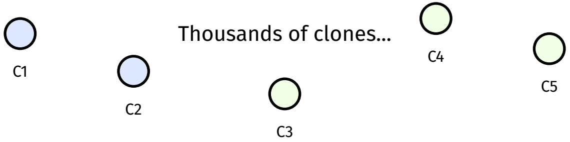
Example 2: One-to-N Operator

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:

```
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.

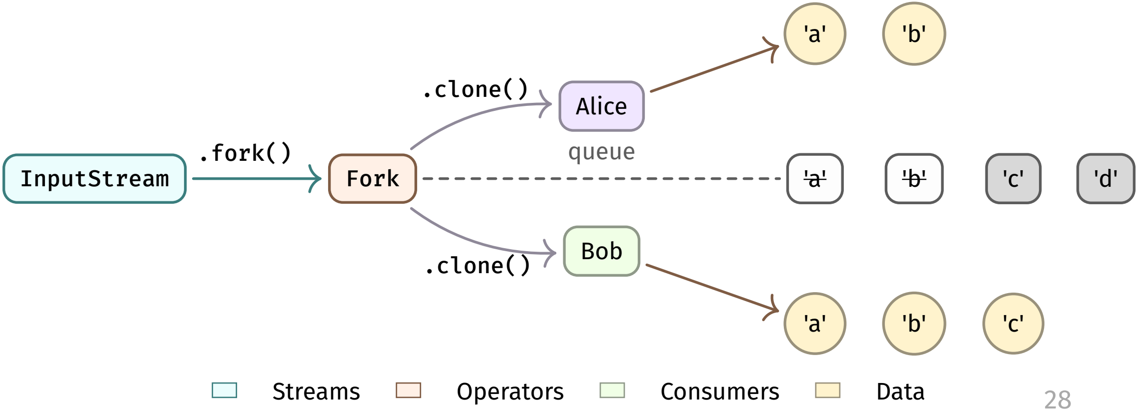
Cloning streams with an operator

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

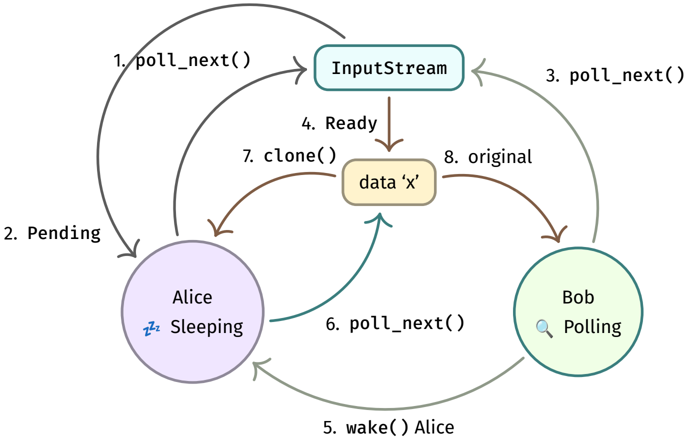
```
let tcp_stream = TcpStream::connect("127.0.0.1:8080").await?;

// 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

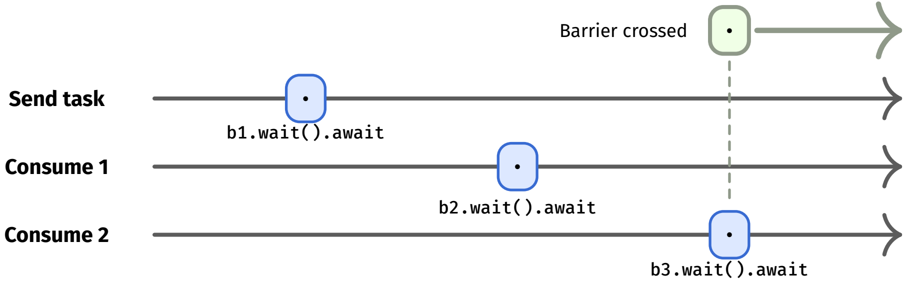


`Barriers` *for task synchronization*

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

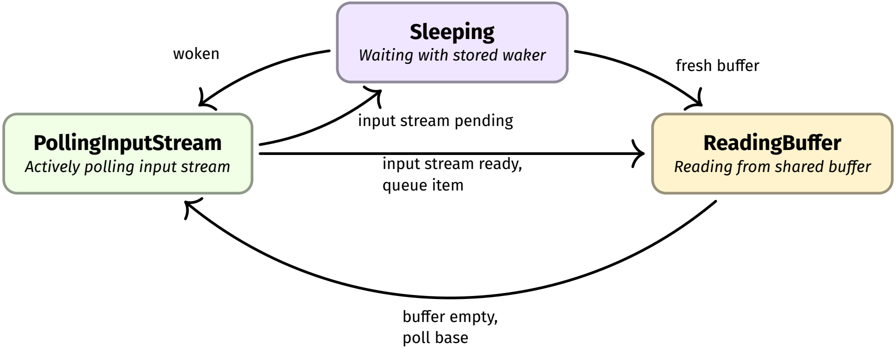
```
let out_stream1 =
create_test_stream(in_stream)
    .your_custom_operator();
let out_stream2 = out_stream1.clone();
```

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();
```

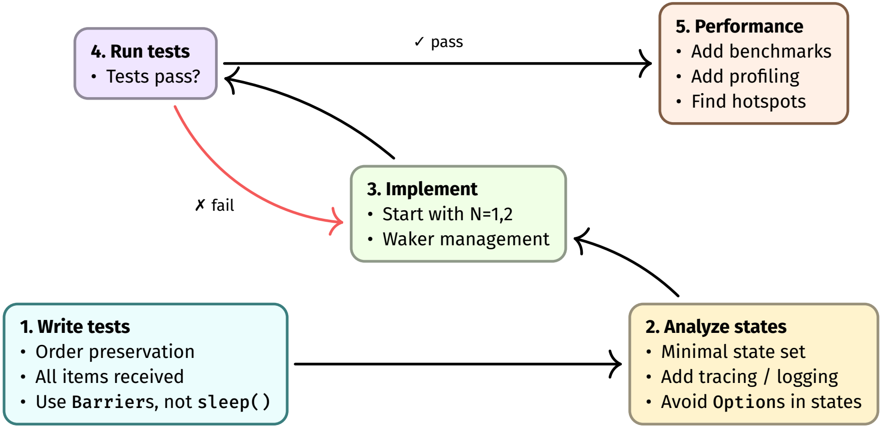
Eventual state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**, I ended up with this minimal (simplified) state machine.



Each clone maintains its own state:

Steps for developing robust operators



General principles

Principles

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

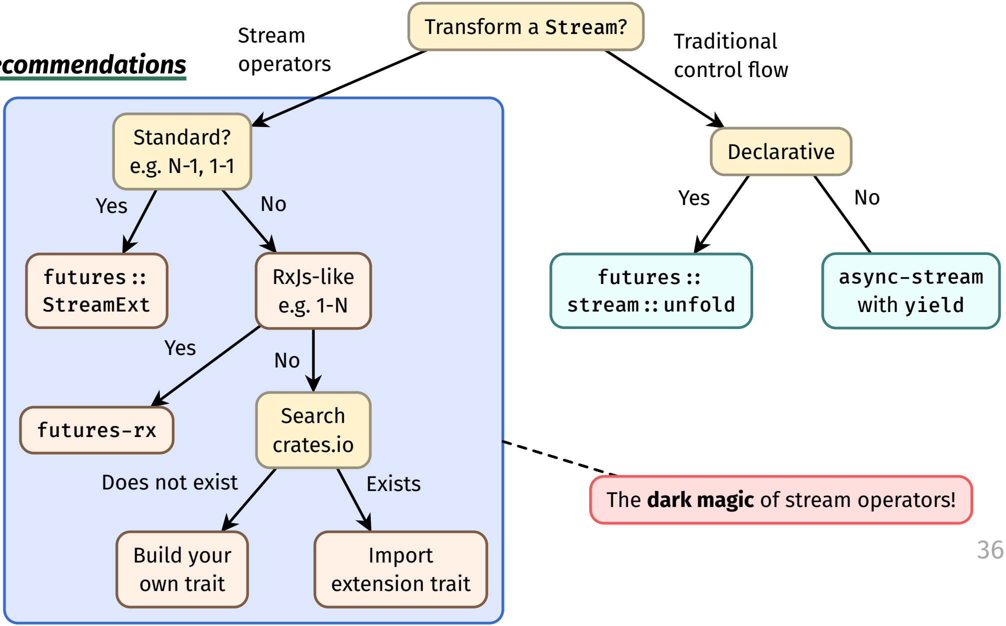
Meaningful objective targets:
- Simple, clear unit tests
- Relevant benchmarks

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*

Recommendations



Any questions?

Thank you!

Want to learn Rust in-depth?

Join my 7-week course ***"Creating Safe Systems in Rust"*** in Ghent 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();
```

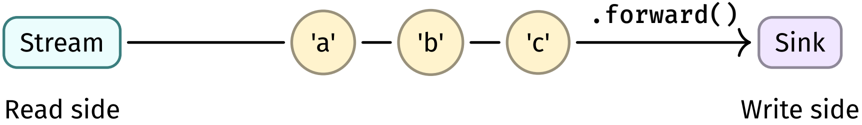
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```
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.

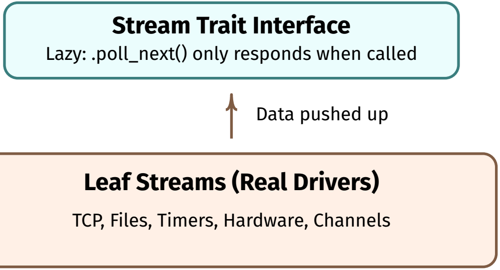
What `Stream` trait does:

- 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>`**?

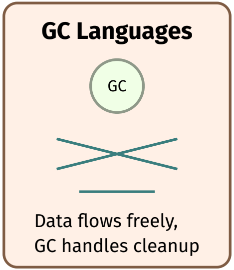
`Pin<&mut Self>` only implements **`Deref<Target=Self>`** for **`Self: Unpin`**.

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

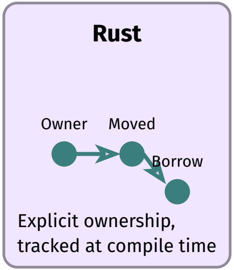
Why does Rust need special treatment?

Key challenges:

- Most mainstream languages lack functional stream operators entirely
- Rust’s ownership and borrowing rules require explicit data tracking
- Memory safety constraints force careful stream design



vs



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

The end