

Make Your Own Stream Operators

Advanced stream processing in Rust

Willem Vanhulle

EuroRust 2025 • Paris, France

30 minutes + 10 minutes Q&A

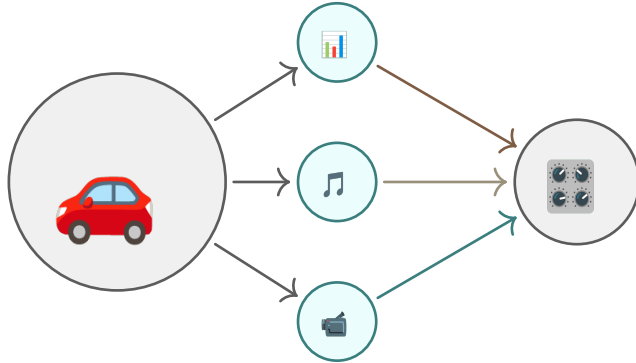
Version with clickable links:
github.com/wvhulle/streams-eurorust-2025

Plan

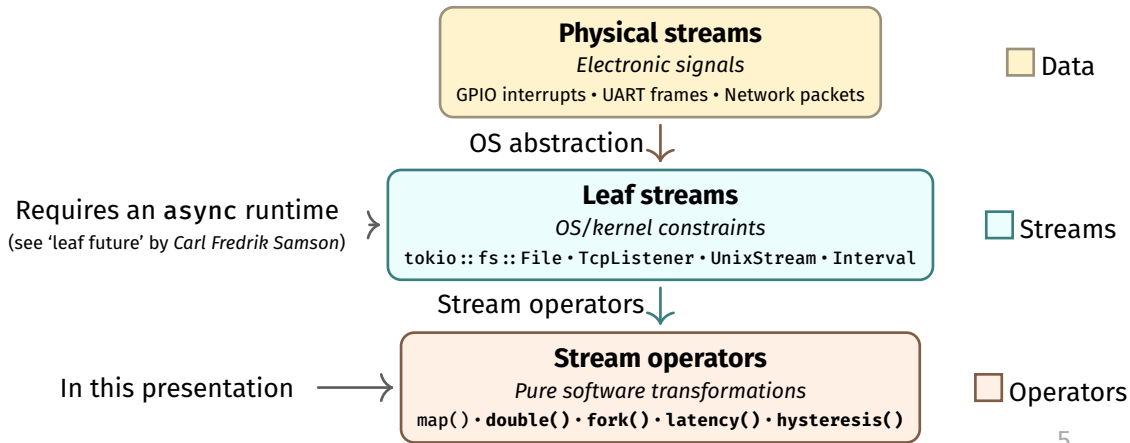
Motivation	3
Rust's <code>Stream</code> trait	9
Using the <code>Stream</code> API	12
Example 1: One-to-One Operator	15
Example 2: One-to-N Operator	24
General principles	34
Bonus slides	38

Motivation

Processing data from moving vehicles



Kinds of streams



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:

```
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**):

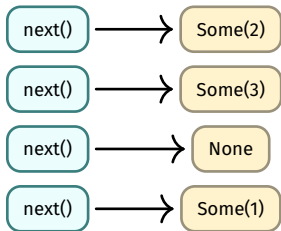
```
trait Stream {  
    type Item;  
  
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)  
        → Poll<Option<Self::Item>>;  
}
```

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)

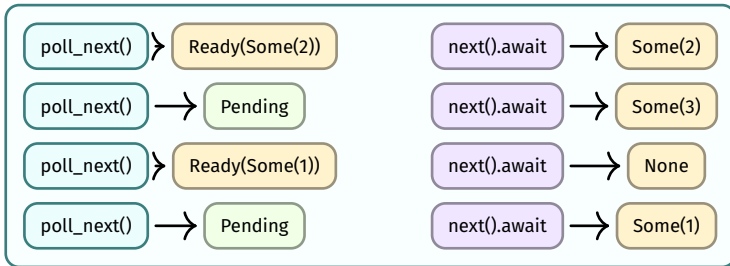
Moving from Iterator to Stream

✓ Always returns immediately



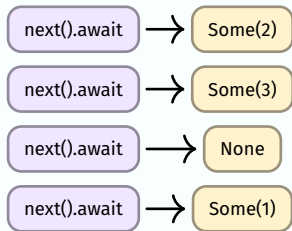
Iterator (sync)

⚠ May be Pending



Stream (low-level)

✓ Hides polling complexity

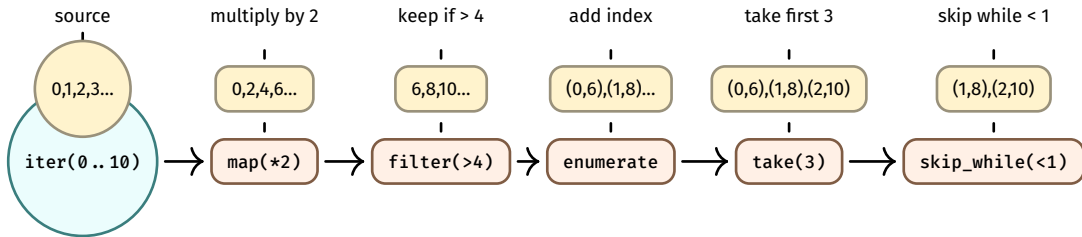


Stream (high-level)

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)
```

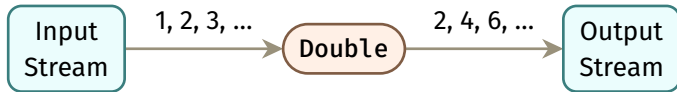
Option 3 (recommended): Wrap sync output with `std::future::ready()`

```
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



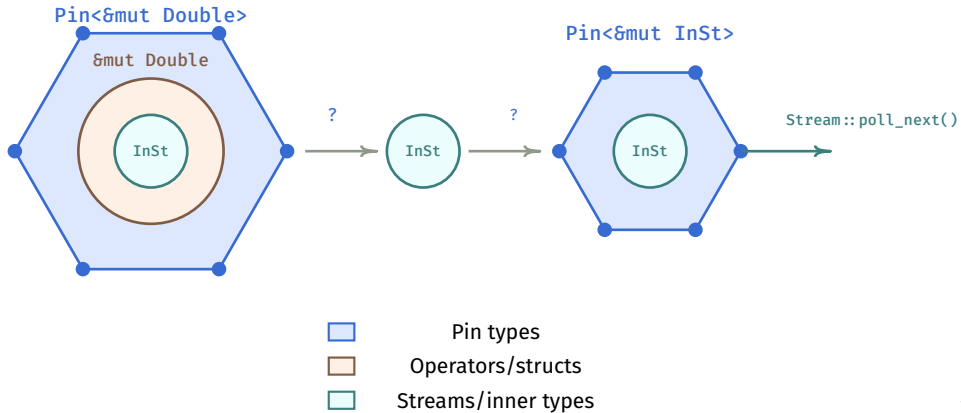
Wrapping the original stream by value

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

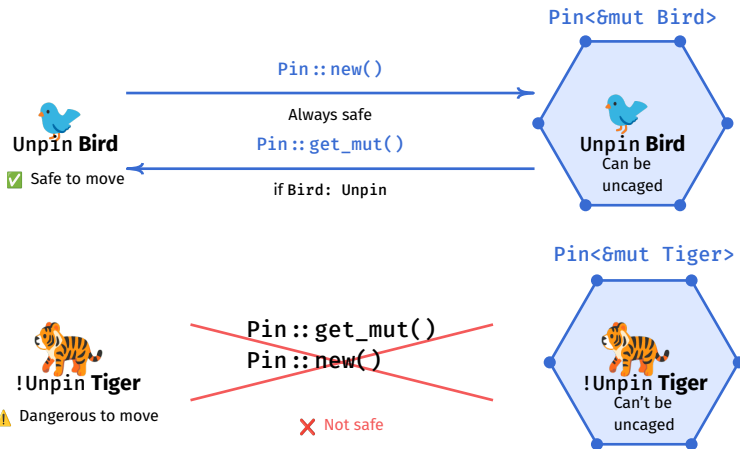
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {
    type Item = InSt::Item;
    // Self = Double<InSt>
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
        → Poll<Option<Self::Item>> {
        // Project onto self.in_stream...
        Pin::new(&mut self.in_stream)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

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

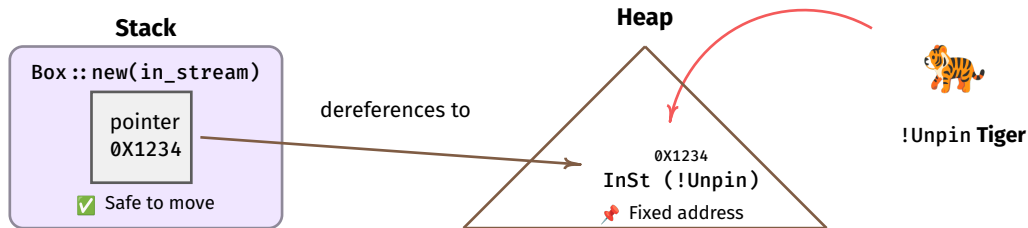
How to project to access self.in_stream?



!Unpin *defends against unsafe moves*



Put your !Unpin type on the heap



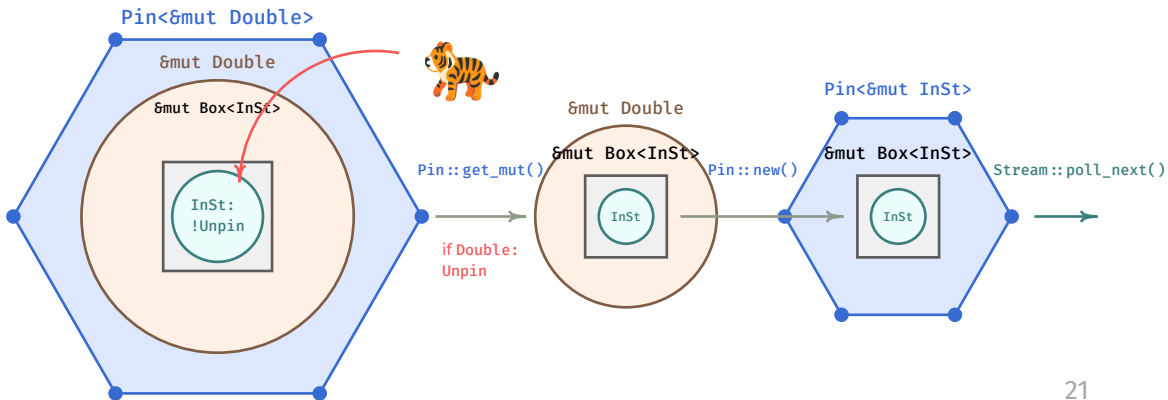
1. The output of `Box :: new(tiger)` is just a pointer
Moving pointers is safe, so **Box: Unpin**
2. Box behaves like what it contains: **Box<X>: Deref<Target = X>**

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:

```
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**:

```
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

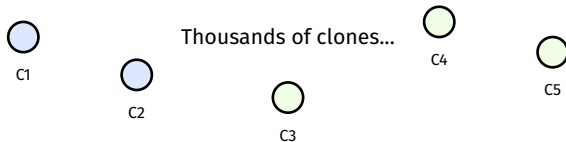
Challenges for Stream operators are combined from:

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 be 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?;

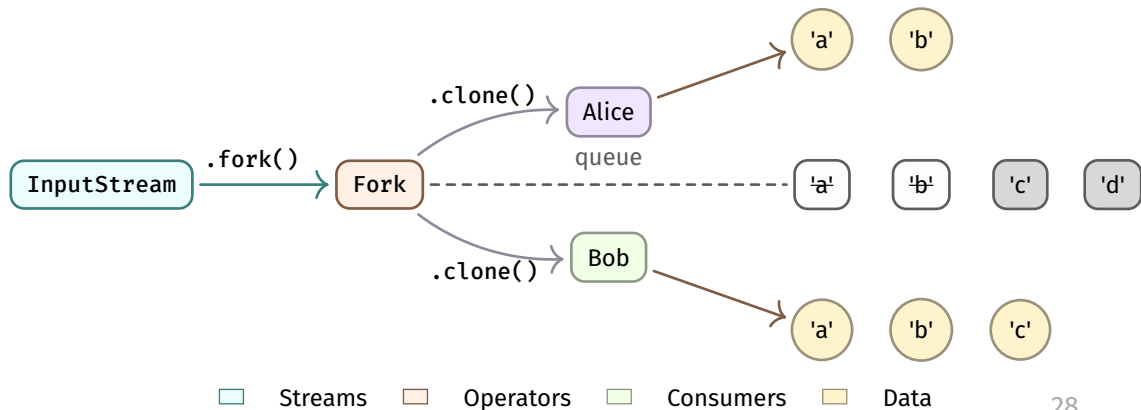
// Fork makes the input stream cloneable
let ui_latency = tcp_stream.latency().fork();

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

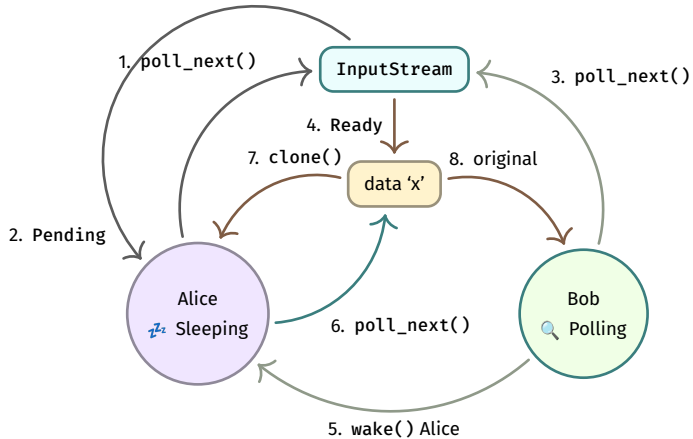
spawn(async move { display_ui(ui_latency).await; });
spawn(async move { engage_breaks(breaks_latency_clone).await; });
```

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

Rough architecture of clone-stream



Polling and waking flow

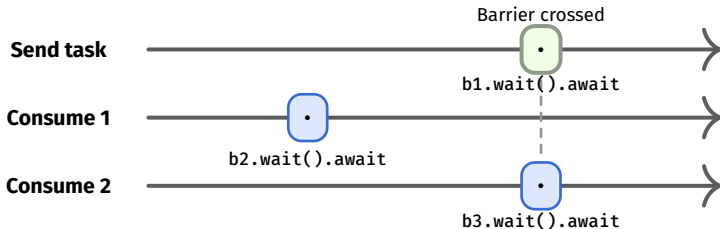


Barriers for task synchronization

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

Synchronisation after the “init” phase is done with a single Barrier of 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();
```

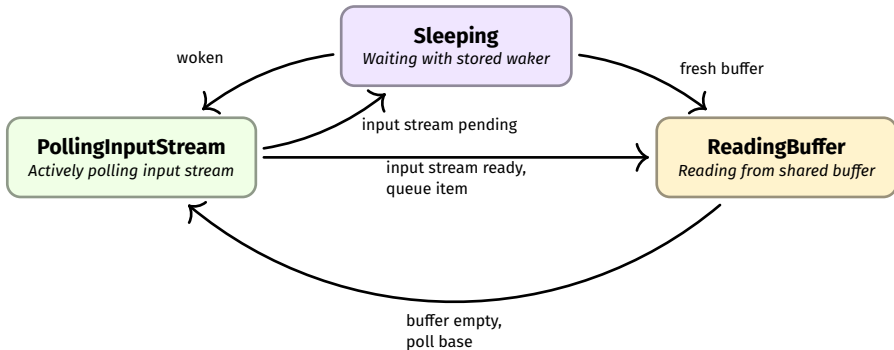
4. Send your inputs and outputs to separate tasks

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();
```

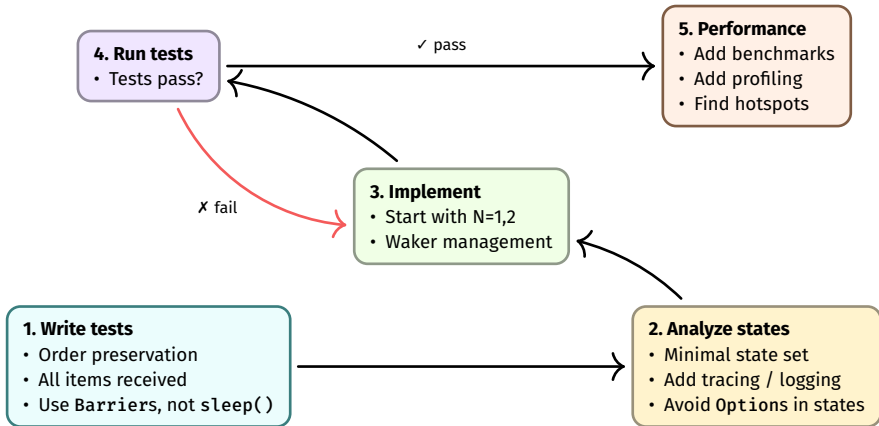
Eventual state machine of clone-stream

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:

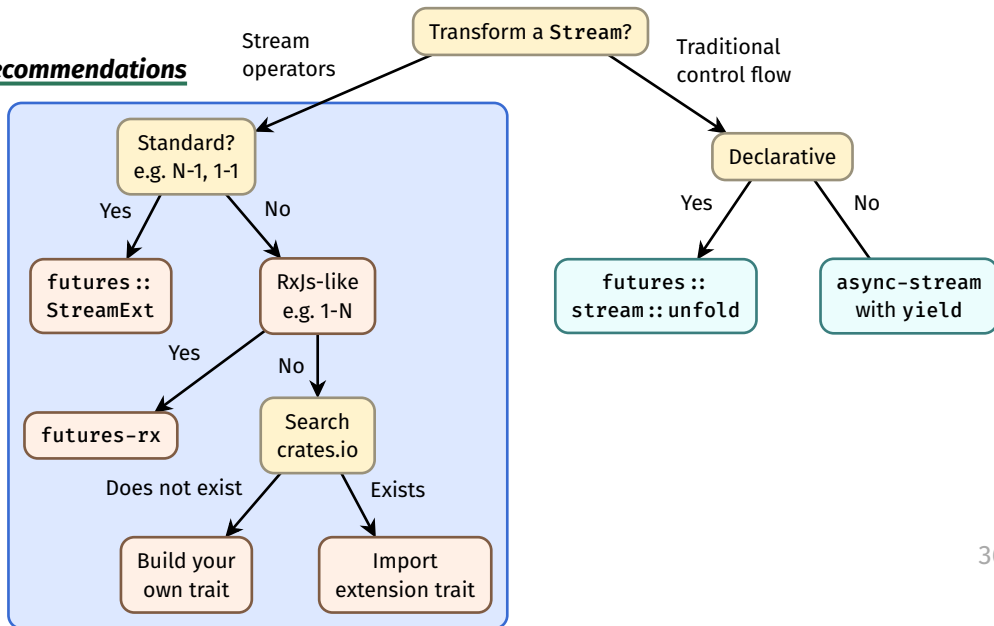
- Modular functions
- Descriptive names
- Split long functions

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



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	<code>is_terminated()</code> 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();
```

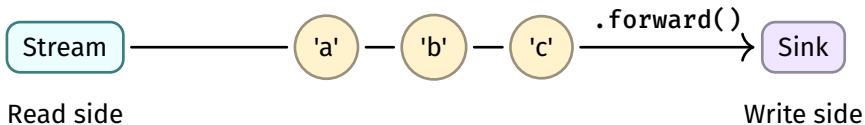
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```
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.

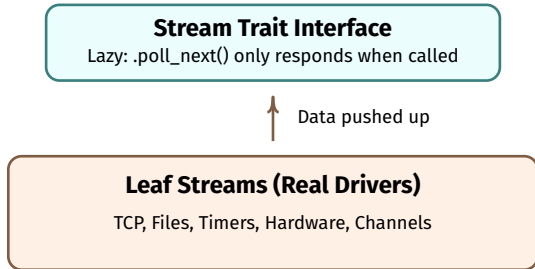
What Stream trait does:

- 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

```
trait Stream {  
    type Item;  
  
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context)  
        → Poll<Option<Self::Item>>  
}
```

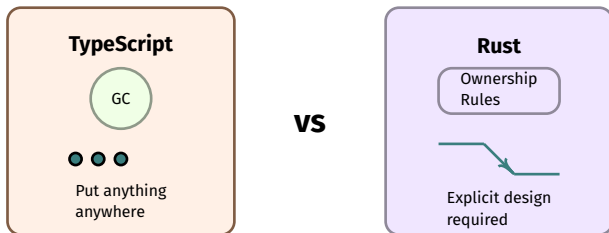
What about Rust rule `self` needs to be `Deref<Target=Self>`?

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

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

Why does Rust bring to the table?

Reactivity in garbage collected languages is **completely different** from Rust's ownership system



This fundamental difference explains why stream patterns from other languages don't translate directly

The end