

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

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Motivation

My interest in stream processing (with Rust)

The problem: Processing incoming (streaming) data from moving vehicles

What I observed:

- *Inconsistent error handling* across the codebase
- Hard to reason about *data flow* and state
- Code duplication and boilerplate



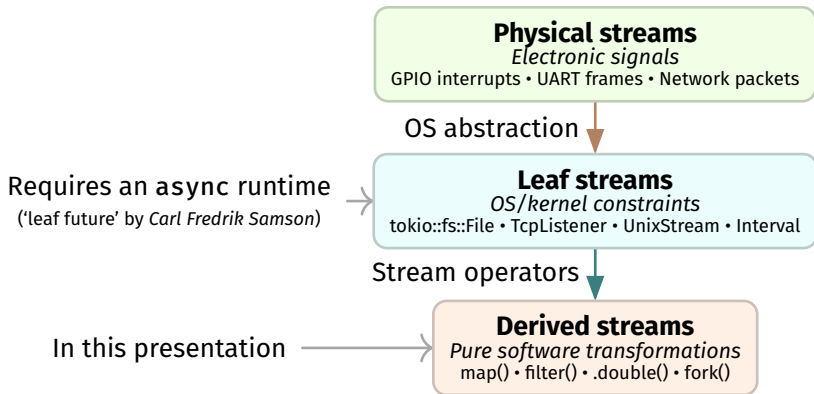
streaming data



Streams in Rust are not new



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: testing, coordination, control flow jumping around

Functional Stream usage preview

Same logic, much cleaner with stream operators:

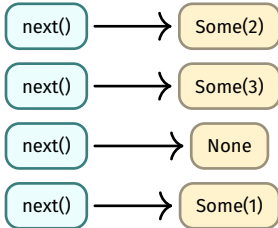
```
let filtered_messages: Vec<String> = tcp_stream
    .filter_map(|connection| ready(connection.ok()))
    .filter(|stream| ready(should_process(stream)))
    .then(|stream| process_stream(stream))
    .filter_map(|result| ready(result.ok()))
    .filter(|msg| ready(msg.len() > 10))
    .take(5)
    .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

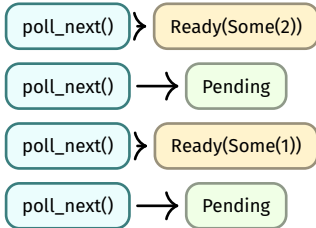
Moving from Iterator to Stream

✓ Always returns immediately



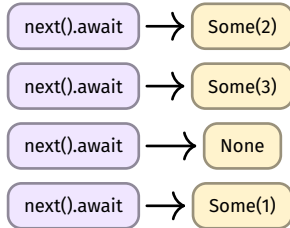
Iterator (sync)

⚠ May be Pending



Stream (low-level)

✓ Hides polling complexity



Stream (high-level)

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>>;  
}
```

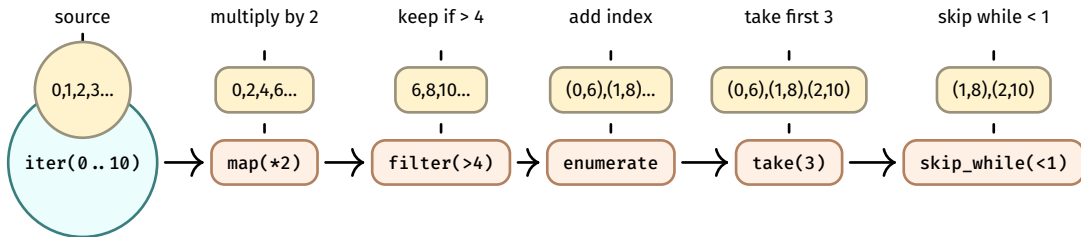
Returns Poll enum:

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)

Consumption of streams

Building pipelines

The basic stream operators of futures :: StreamExt:



```
stream::iter(0..10)
    .map(|x| x * 2)
    .filter(|&x| ready(x > 4))
    .enumerate().take(3).skip_while(|&(i, _)| i < 1)
```

The less-known futures :: ready function

Filter needs an **async closure** (or closure returning Future):

Option 1: Async block

```
stream.filter(|&x| async move {  
    x % 2 == 0  
})
```

Option 2: Async closure (Rust 2025+)

```
stream.filter(async |&x| x % 2 == 0)
```

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

```
stream.filter(|&x| ready(x % 2 == 0))
```

ready(value) creates a Future that immediately resolves to value.

Bonus: future::ready() is Unpin, helping to keep the entire stream pipeline Unpin (if the input stream was Unpin)!

Example 1: Doubling integer streams (1-1)

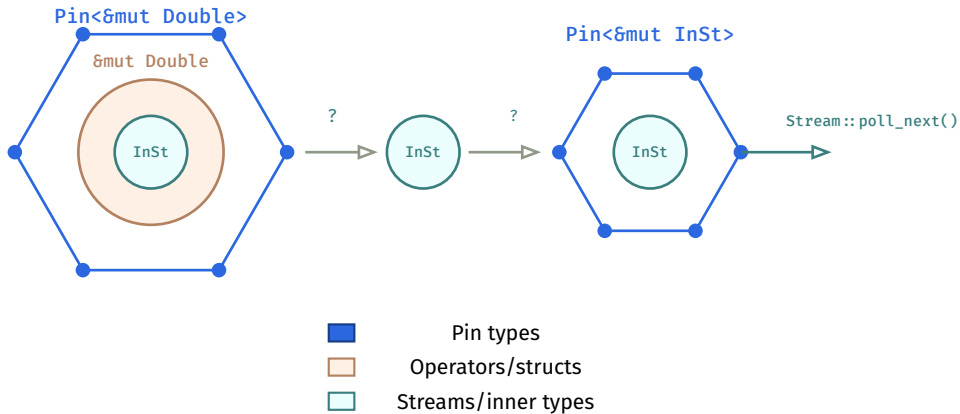
Wrapping the original stream by value

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

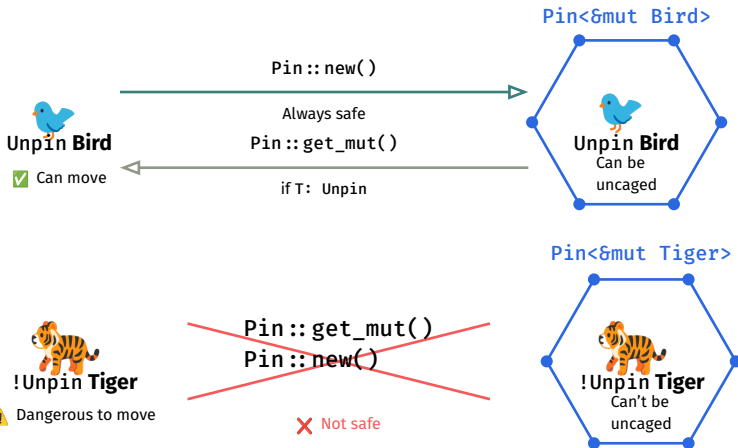
impl<InSt> Stream for Double<InSt> where Stream: Stream<Item = i32> {
    type Item = InSt::Item;
    fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
        → Poll<Option<Self::Item>> {
        Pin::new(self.in_stream) // ▲ Will not compile!
            .poll_next(cx)
            .map(|x| x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

1. Pin<&mut Self> blocks access to self.in_stream
2. Poll::new() requires InSt: Unpin

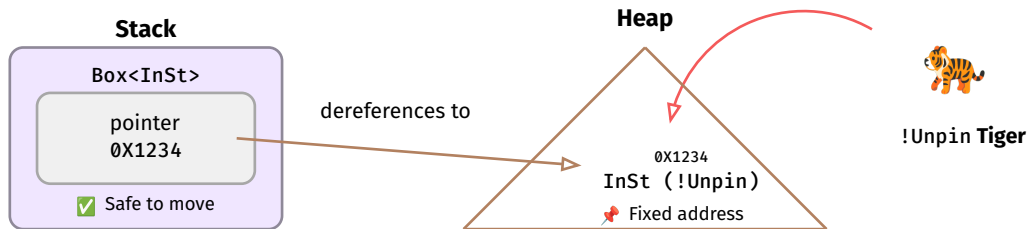
How to **project** to access `self.in_stream`?



!Unpin *defends against unsafe moves*



Why Box<T>: Unpin?

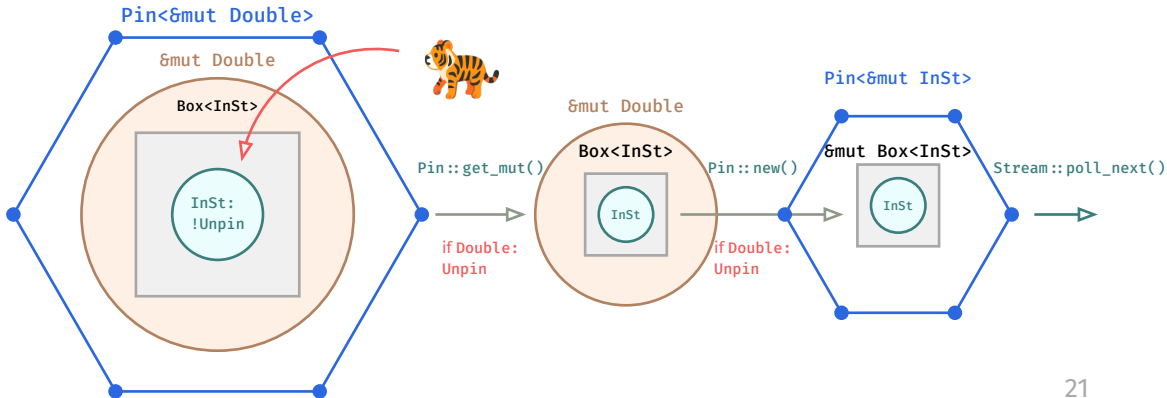


1. Put your !Unpin type on the heap with `Box :: new()`
(Heap content stays at fixed address)
2. The output of `Box :: new(tiger)` is just a pointer
(Moving pointers is safe)
3. `Box<X>: Deref<Target = X>`, so `Box<InSt>` **behaves like InSt**

```
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>>
    {
        // this: &mut Double<InSt>
        let this = self.get_mut(); // Safe because Double is Unpin
        match Pin::new(&mut this.in_stream).poll_next(cx) {
            Poll::Ready(r) ⇒ Poll::Ready(r.map(|x| x * 2)),
            Poll::Pending ⇒ Poll::Pending,
        }
    }
}
```

Distributing your operator

Create an extension trait to add `.double()` method to any integer stream:

```
trait DoubleStream: Stream {  
  fn double(self) → Double<Self>  
  where Self: Sized + Stream<Item = i32>,  
    { Double::new(self) }  
}
```

Add a **blanket impl** that automatically implements `DoubleStream` for any `Stream<Item = i32>`:

```
impl<S> DoubleStream for S where S: Stream<Item = i32> {}
```

Important: A blanket implementation should be provided by you!

Users just add dependency + import

Super simple for users to adopt your custom operators:

```
[dependencies]  
double-stream = "1.0"
```

The DoubleStream trait must be in scope to use `.double()`:

```
use double_stream::DoubleStream; // Trait in scope  
  
let doubled = stream::iter(1..=5).double(); // Now works!
```

Compositionality of traits (versus traditional OOP) shines!

Example 2: Cloning streams at run-time (1-N)

Problem: most streams aren't Clone

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>  
let latency_clone = latency.clone(); // Error! Can't clone stream  
spawn(async move { process_for_alice(latency).await; });  
spawn(async move { process_for_bob(latency_clone).await; });
```

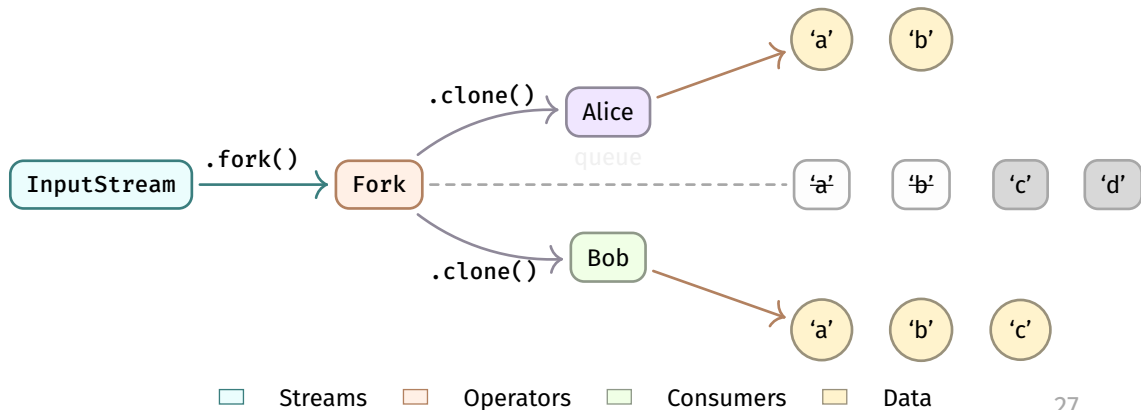
Solution: Create a **stream operator** that clones streams.

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

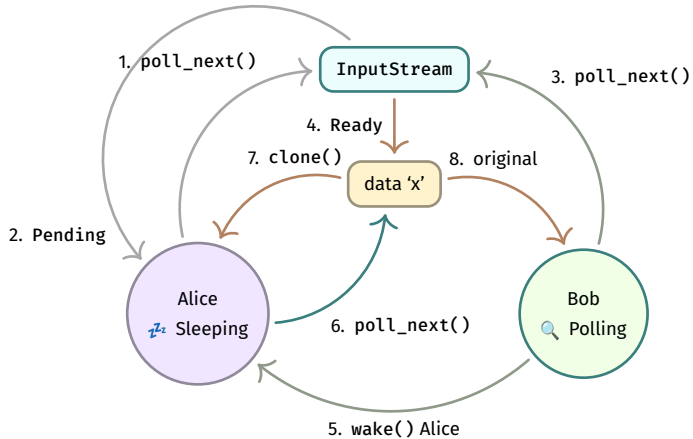
Approach:

1. Implement forking the input stream
2. Implement cloning on forked streams
3. Package as crate with blanket impl

Rough architecture of clone-stream



Polling and waking flow



Complexity grows with thousands of clones

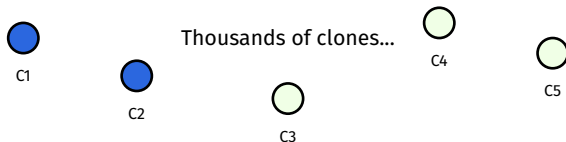
Careful state management:

Inherent async challenges:

- Dynamic clone lifecycle
- Memory leaks from orphaned wakers
- Cleanup when tasks abort
- Task coordination complexity

Stream-specific challenges:

- Ordering guarantees across clones
- Backpressure with slow consumers
- Sharing mutable state safely
- Avoiding duplicate items



Meaningful operator testing

When you build your own:

1. Pick an async run-time.
2. Define synchronization points with **Barrier**:

```
let b1 = Arc::new(Barrier::new(3)); //  
First output  
let b2 = b1.clone(); // Second output  
let b3 = b1.clone(); // For input
```

3. Apply your custom operator

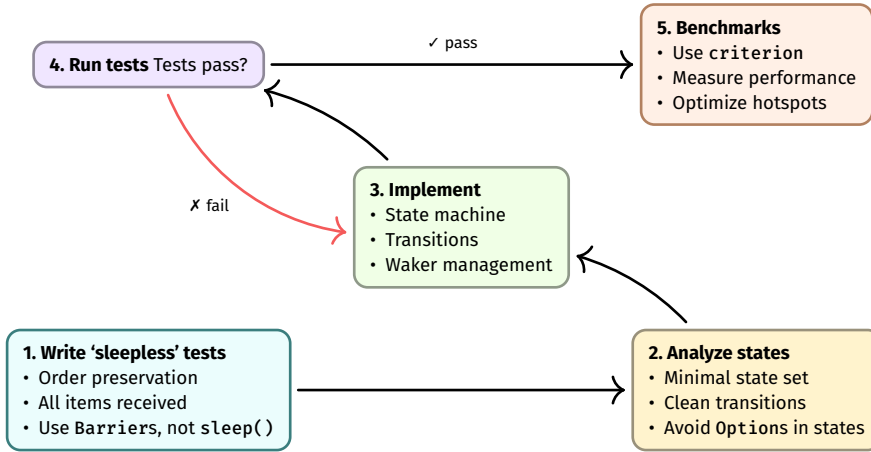
```
let stream1 = create_test_stream()  
    .your_custom_operator();  
let stream2 = stream1.clone();
```

Can be used for **benchmarks** too (use **criterion**).

Do not use `sleep(1ms)` in tests! (Use barriers!)

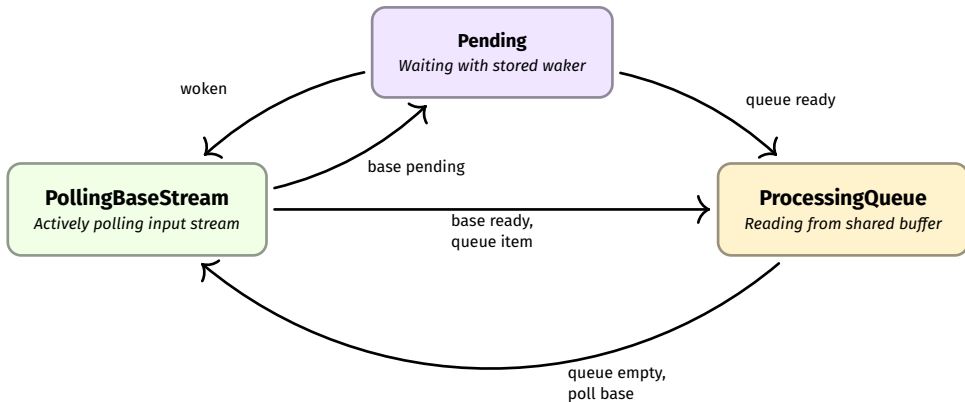
```
try_join_all([  
    spawn(async move {  
        setup_task().await;  
        b1.wait().await;  
        stream1.collect().await;  
    }),  
    spawn(async move {  
        setup_task().await;  
        b2.wait().await;  
        stream2.collect().await;  
    }),  
    spawn(async move {  
        b3.wait().await;  
        send_to_stream().await;  
    })  
]).await.unwrap();
```

State machines for physically-separated components



State machine of clone-stream

Each clone maintains its own state:



General principles

Before building your own operators

1. For simple state machines: `futures :: stream :: unfold` constructor
2. Streams from scratch: `async-stream` crate with `yield`

Otherwise, import an operator from:

Standard: futures :: StreamExt

- 5.7k ★ , 342 contributors
- Since 2016, actively maintained
- Latest: v0.3.31 (Oct 2024)

RxJs-style: futures-rx

- Reactive operators & specialized cases
- 8 ★ , small project
- Since Dec 2024, very new
- Fills gaps in `futures :: StreamExt`

Build custom operators **only when no existing operator fits!**

Last recommendation

Don't overuse streams:

- Keep pipelines short
- Only *physical async data flow*

Separation of concerns:

- Modular functions
- Descriptive names
- Split long functions

Use objective targets:

- Correctness unit tests
- Statistically relevant benchmarks

“When you have a hammer, everything looks like a nail.” — *Abraham Maslow*

“Perfection is achieved, not when there is nothing more to add, but when there is **nothing left to take away**.” — *Antoine de Saint-Exupéry*

Any questions?

Longer read: willemvanhulle.tech/blog/streams

Thank you!

Willem Vanhulle

Feel free to reach out!

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willemvanhulle.tech

github.com/wvhulle/streams-eurorust-2025

Bonus slides

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();
```

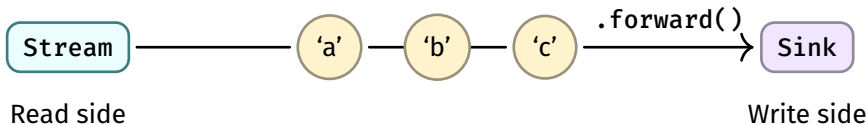
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```
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.

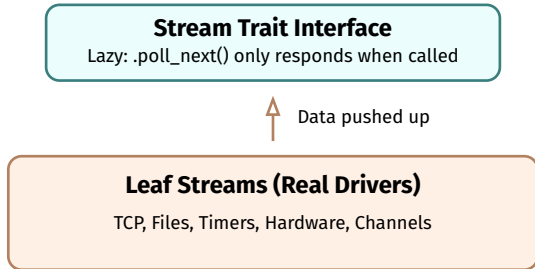
What Stream trait does:

- 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>>  
}
```

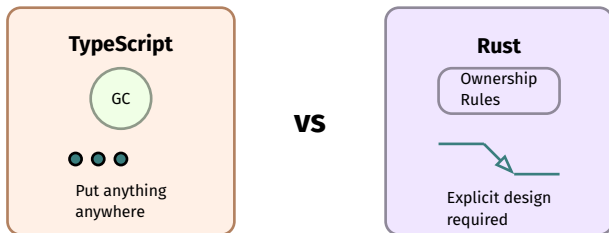
What about Rust rule `self` needs to be `Deref<Target=Self>`?

`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