Transforming `Streams`

Advanced stream processing in Rust

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1980-01-01

1.1. Me

Motivation

Processing data from moving vehicles

1. Vehicle generates multiple data streams
2. All streams converge to control system

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Lives in Ghent, Belgium:

- Studied mathematics, physics and computer science
- Biotech automation (fermentation)
- Distributed systems (trains)

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Latest projects (github.com/wvhulle):

- SysGhent.be: social network for systems programmers in Ghent (Belgium)
- Clone-stream: lazy stream cloning library for Rust

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2. All streams converge to control system

1.2. Kinds of streams

Physical streams

Electronic signals

GPIO interrupts • UART frames • Network packets

1.2. Kinds of streams

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

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1.2. Kinds of streams

In this presentation →

Stream operators

Pure software transformations

`map()` • **`double()`** • **`fork()`** • **`latency()`** • **`hysteresis()`**

↑ Stream operators

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Operators

Streams

Data

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Operators

Streams

Data

Hardware signals are abstracted by the OS

Software operators transform the streams

1.3. Streams in Rust are not new

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1960s

Dataflow Programming
Hardware-level stream processing
Early dataflow architectures

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1960s	**Dataflow Programming** Hardware-level stream processing *Early dataflow architectures*

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1.3. Streams in Rust are not new

2019

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

2009

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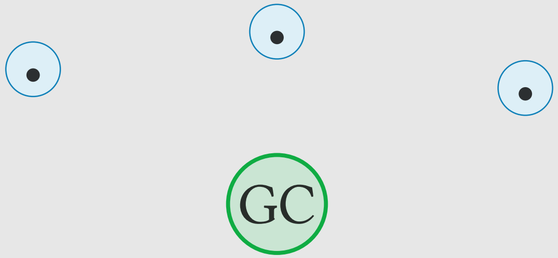
1.4. Why does Rust need special treatment?

Stream operators must wrap and own their input by value

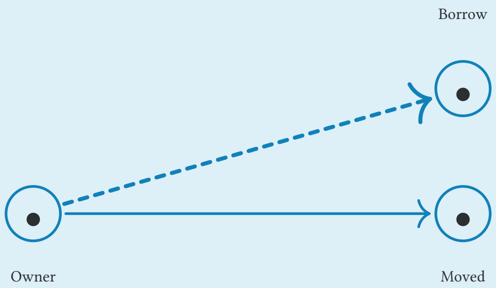
Data flows freely,
GC handles cleanup



GC Languages

vs

Explicit ownership,
tracked at compile time



Rust

1.5. Process TCP connections and collect long messages

Rust

```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 independently

1.6. Stream operators: declarative & composable

Same logic with stream operators:

Rust

```rust
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**"

2.1. Moving from `Iterator` to `Stream`

✓ Always returns immediately

⚠️ May be Pending

✓ Hides polling complexity

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`next()` → `Some(3)`

`next()` → `Some(1)`

`next()` → `None`

`next()` → `Some(2)`

Iterator (sync)

2.1. Moving from `Iterator` to `Stream`

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⚠️ May be Pending

✓ Hides polling complexity

`next()` → `Some(3)`

`next()` → `Some(1)`

`next()` → `None`

`next()` → `Some(2)`

Iterator (sync)

`poll_next()` → `Ready(Some(2))`

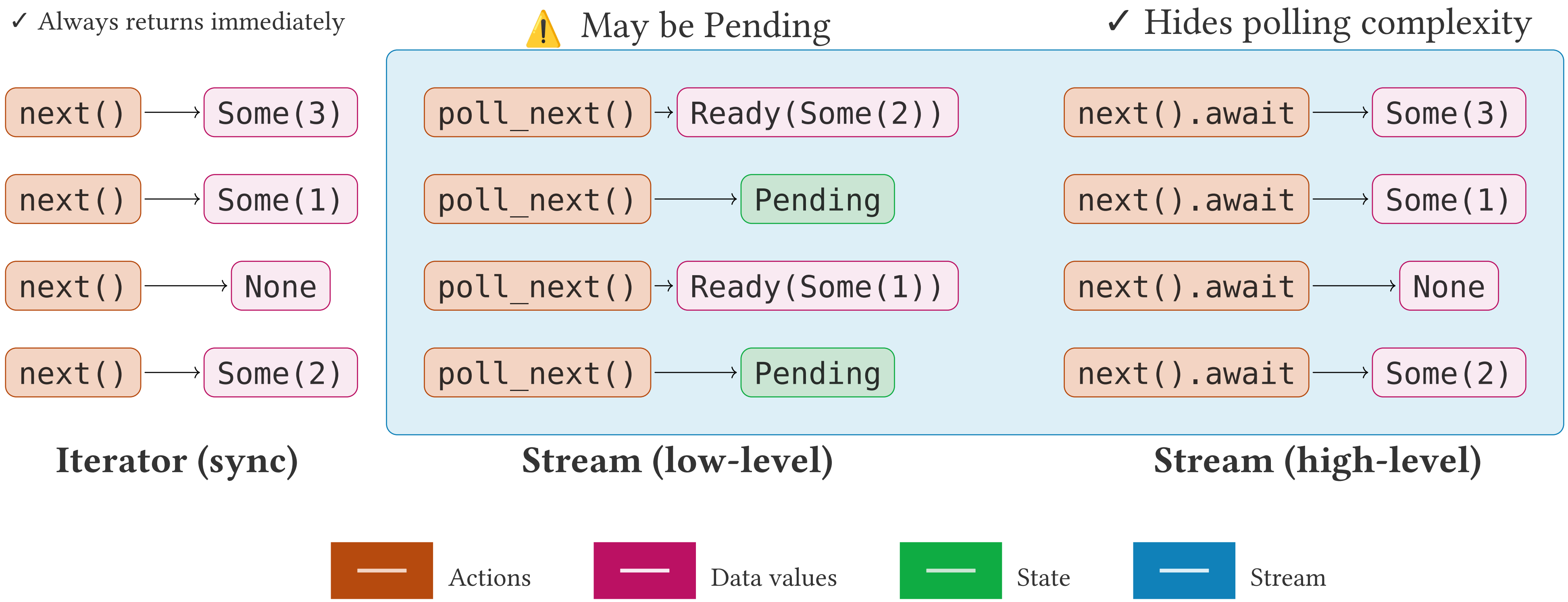
`poll_next()` → `Pending`

`poll_next()` → `Ready(Some(1))`

`poll_next()` → `Pending`

Stream (low-level)

2.1. Moving from `Iterator` to `Stream`



2.2. The `Stream` trait: async iterator

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

Rust

```rust
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**)

2.3. Possible inconsistency

Rust

```rust
trait Stream {
    type Item;

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

Warning

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.

2.4. The meaning of `Ready(None)`

Regular Stream

"No items **right now**"

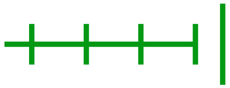
(*Stream might yield more later*)

Fused Stream

"No items **ever again**"

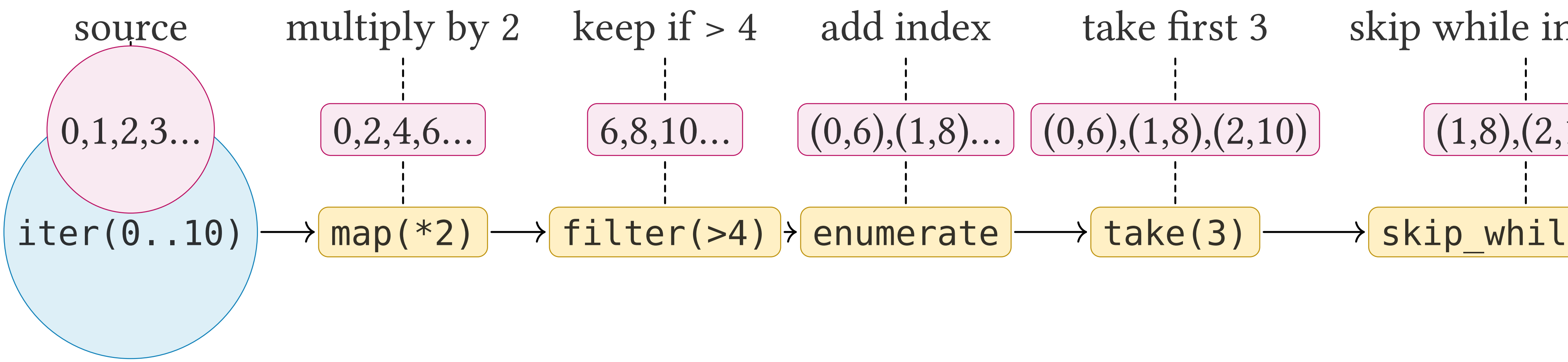
(*Stream is permanently done*)

2.5. '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

3.1. Pipelines with `futures::StreamExt`

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



Rust

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

3.2. The handy `std::future::ready` function

The `futures::StreamExt::filter` expects an **async closure** (or closure returning `Future`):

Option 1: Async block (not `Unpin`!)

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

Rust

Option 2: Async closure (not `Unpin`!)

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

Rust

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

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

Rust

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

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

3.3. Flatten a finite collection of `Streams`

A finite collection of `Streams` = `IntoIterator<Item: Stream>`

Rust

```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

3.4. Flattening an infinite stream

Beware!: `flatten()` on a stream of infinite streams will never complete!

```rust
let infinite_streams = stream::unfold(0, |id| async move {
    Some((stream::iter(id..), id + 1))
});
let flat = infinite_streams.flatten();
```

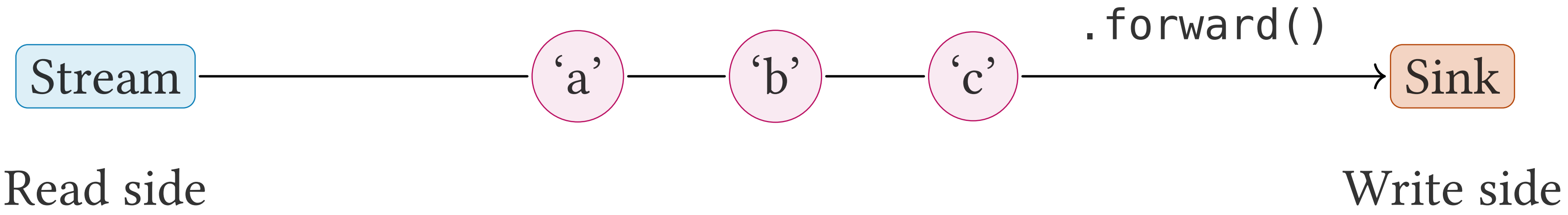
Instead, **buffer streams** concurrently with `flatten_unordered()`.

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

3.5. More Stream features to explore

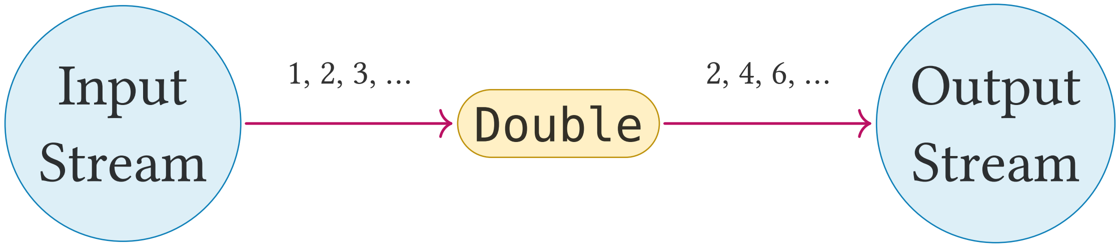
Many more advanced topics await:

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



4.1. Concept: Doubling stream operator

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



Input stream **needs to yield integers**.

4.2. Building a stream operator: structure

Step 1: Define a struct that wraps the input stream

Rust

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

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

4.3. Implementing the `Stream` trait

Step 2: Implement `Stream` trait with bounds

Rust

```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
    }
}
```

4.4. Naive implementation of `poll_next`

Focus on the implementation of the `poll_next` method

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

```rust
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)
  }
```

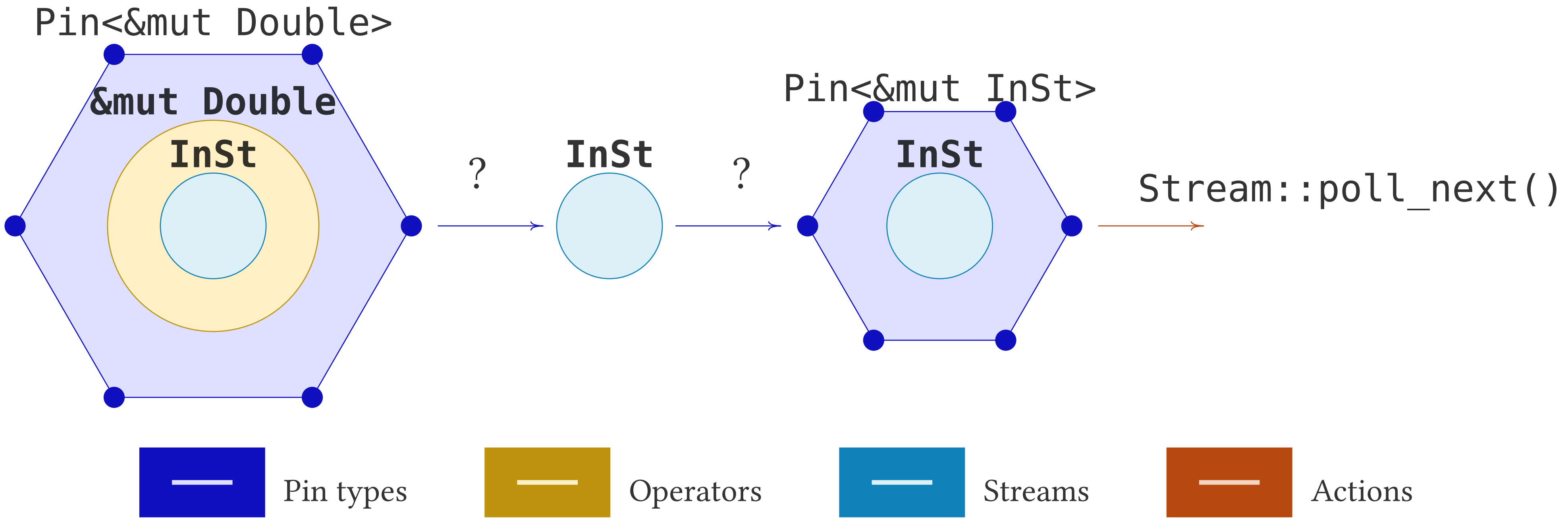
`Pin<&mut Self>` **blocks access to `self.in_stream`** (when `Self: !Unpin`)!

4.5. Accessing pinned fields

Warning

We have `Pin<&mut Double>`.

How can we obtain `Pin<&mut InSt>` to call `poll_next()`?



4.6. The naive solution fails

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

Rust

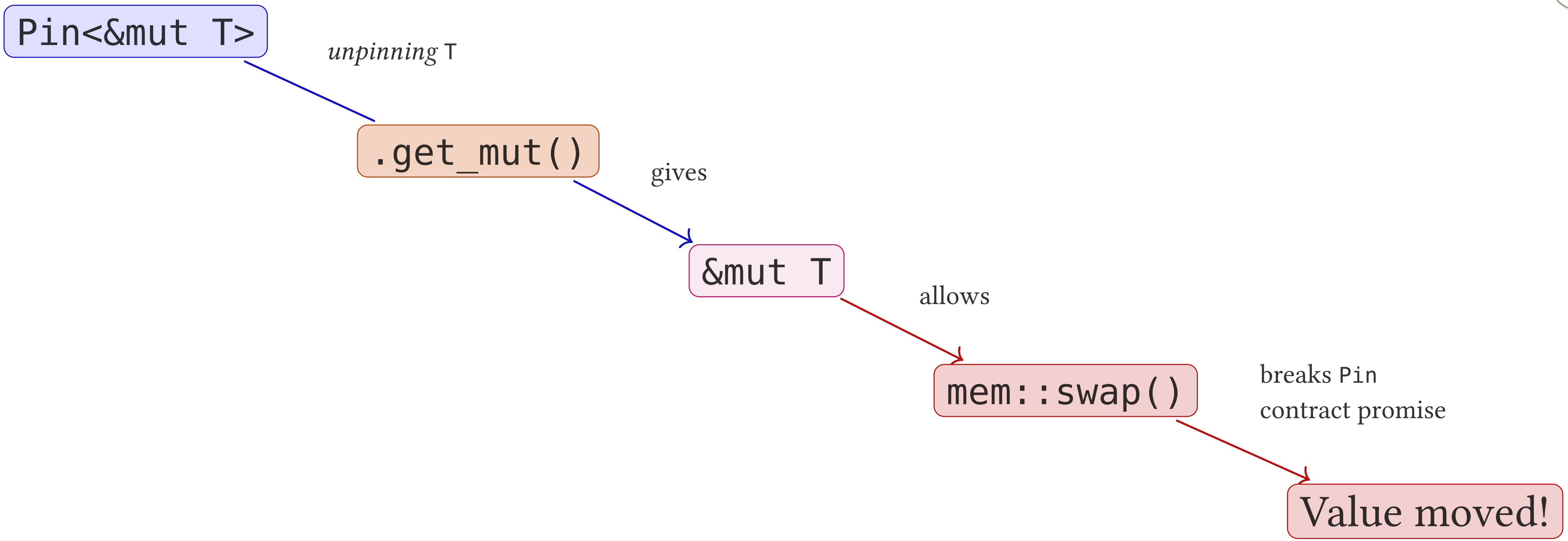
```rust
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {

  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`*!

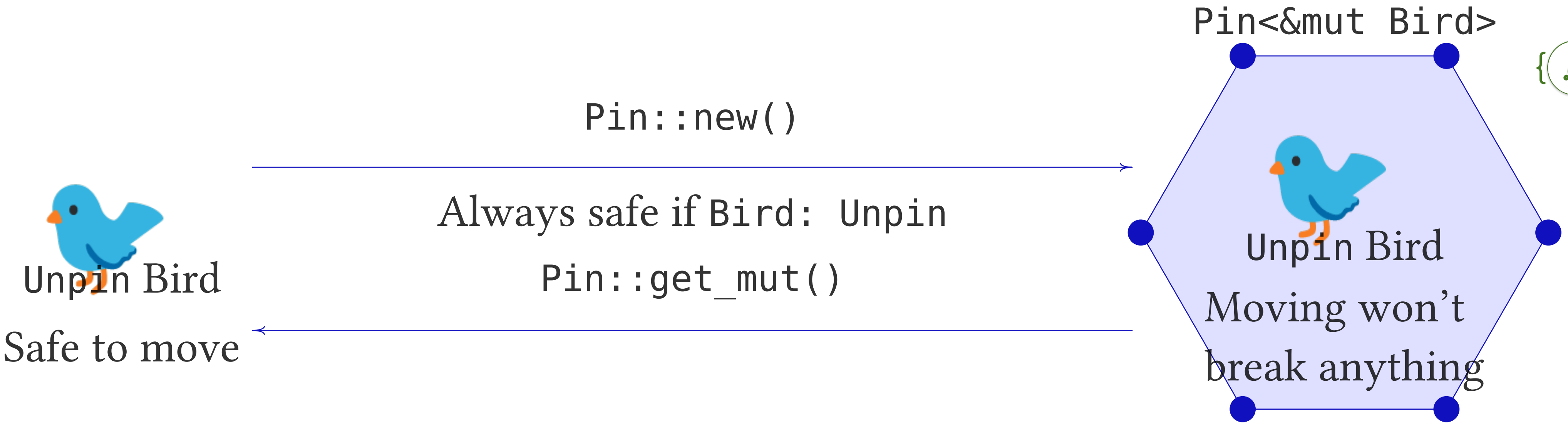
4.7. Why does `Pin::get_mut()` require `Unpin`?

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



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

4.8. `Unpin` types can be safely unpinned



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

4.9. More `Unpin` types

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!

4.10. `!Unpin` types cannot be safely unpinned

`!Unpin` Tiger

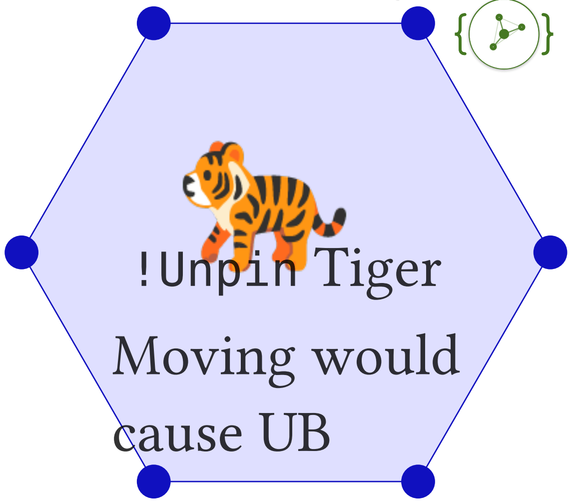
Dangerous to move

~~`Pin::get_mut()`~~

~~gives `&mut T`~~

Would break pin promise!

`Pin<&mut Tiger>`



4.11. More `!Unpin` types

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.

4.12. One workaround: add the `Unpin` bound

The compiler error suggests adding `InSt: Unpin`:

Rust

```rust
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))
  }
}
```

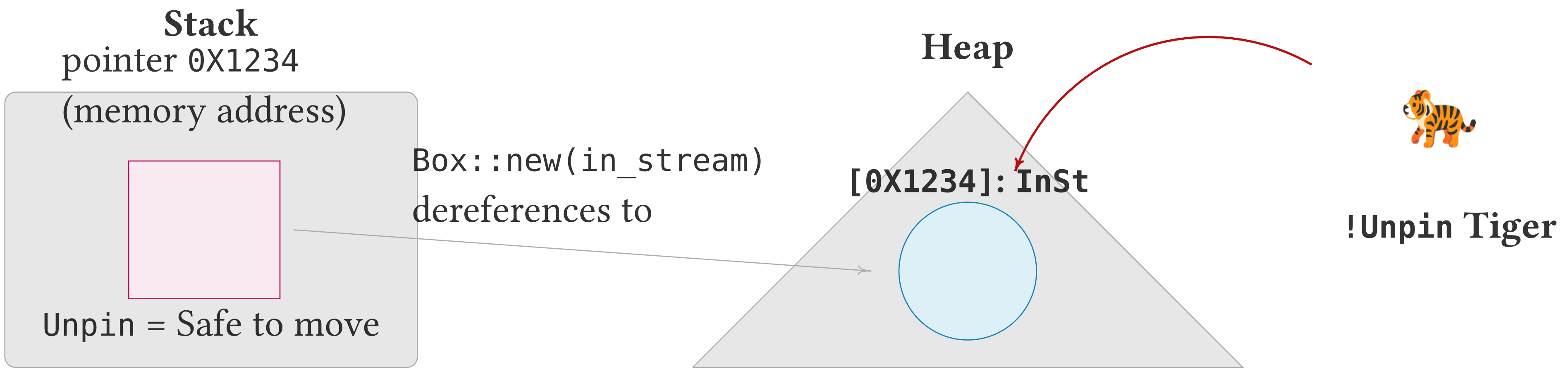
Warning

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

4.12. One workaround: add the `Unpin` bound

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

4.13. 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()`

4.14. 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

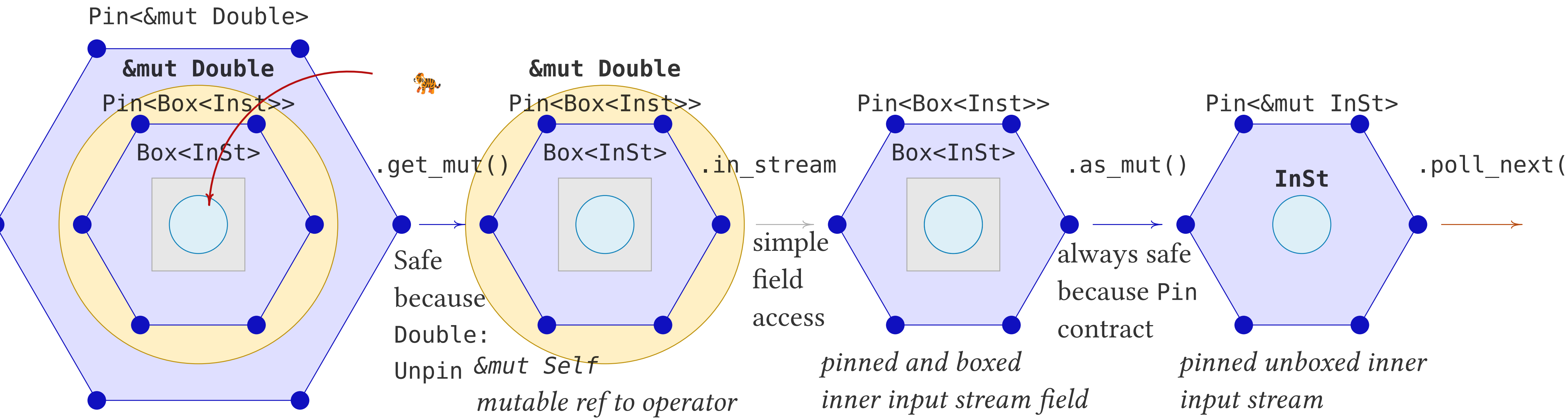
Projection in `poll_next`:

```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`**!

4.15. Projecting visually

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



4.16. Complete boxed `Stream` implementation

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

Rust

```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.in_stream.as_mut()
            .poll_next(cx)
            .map(|r| r.map(|x| x * 2))
    }
}
```

4.17. Two ways to handle `!Unpin` fields

Approach 1: Use `Box<_>`

Rust

```rust
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`

Rust

```rust
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

4.18. Approach 3: Projection with `pin-project`

Projects like Tokio use the `pin-project` crate:

Rust

```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 macros underneath.

4.19. Distributing your operator

Define a constructor and turn it into a method of an **extension trait**:

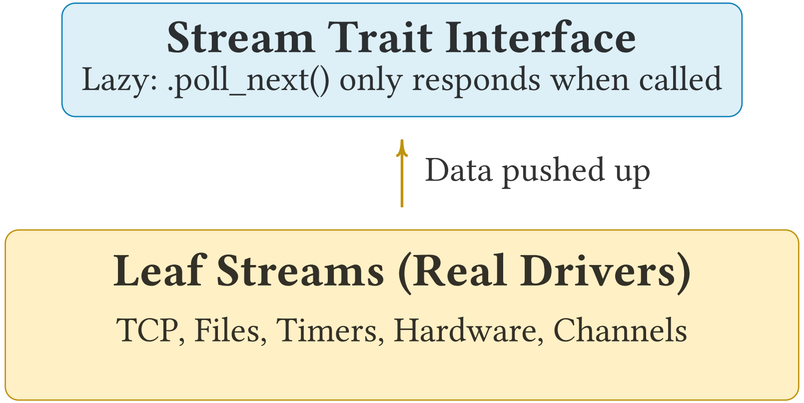
Rust

```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

4.20. The *'real'* stream drivers



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

4.21. 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

5.1. Complexity $1 \to N$ operators

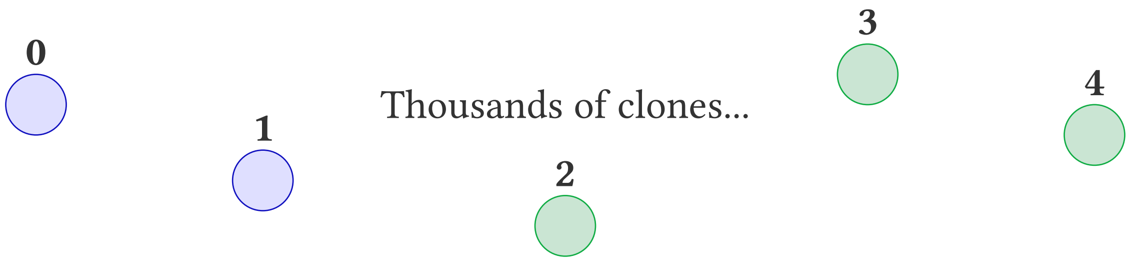
Challenges for `Stream` operators are combined from:

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

5.2. Sharing latency between tasks

Latency may need to processed by different async tasks:

```rust
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.

Warning

We need a way to clone the latency stream!

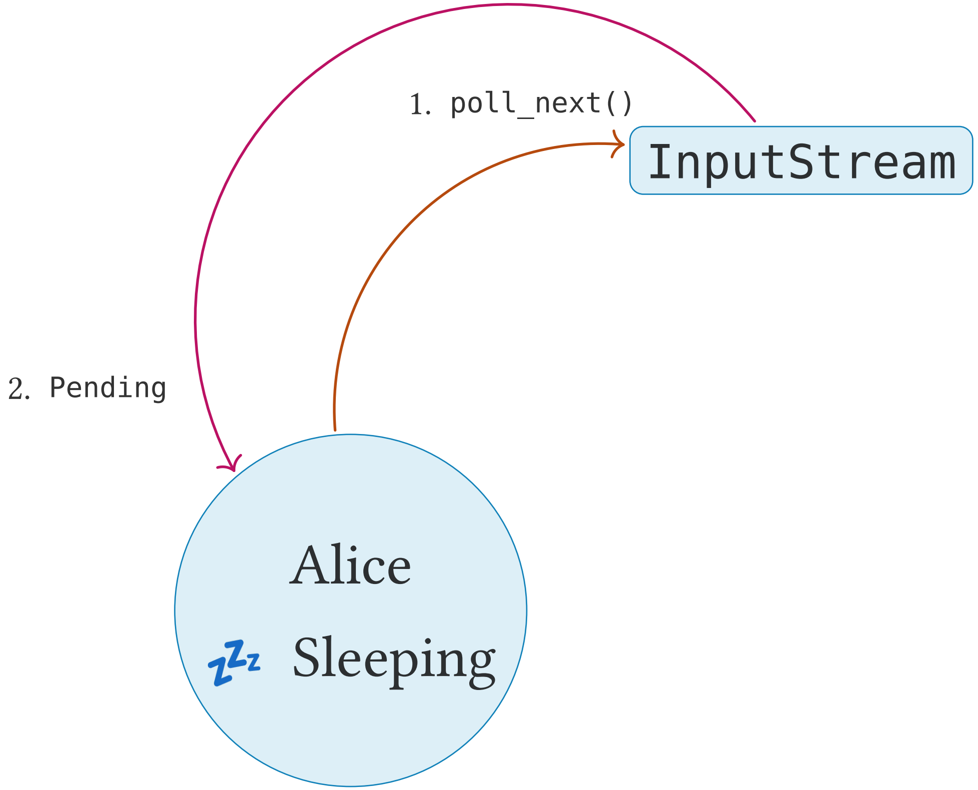
5.3. Cloning streams with an operator

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

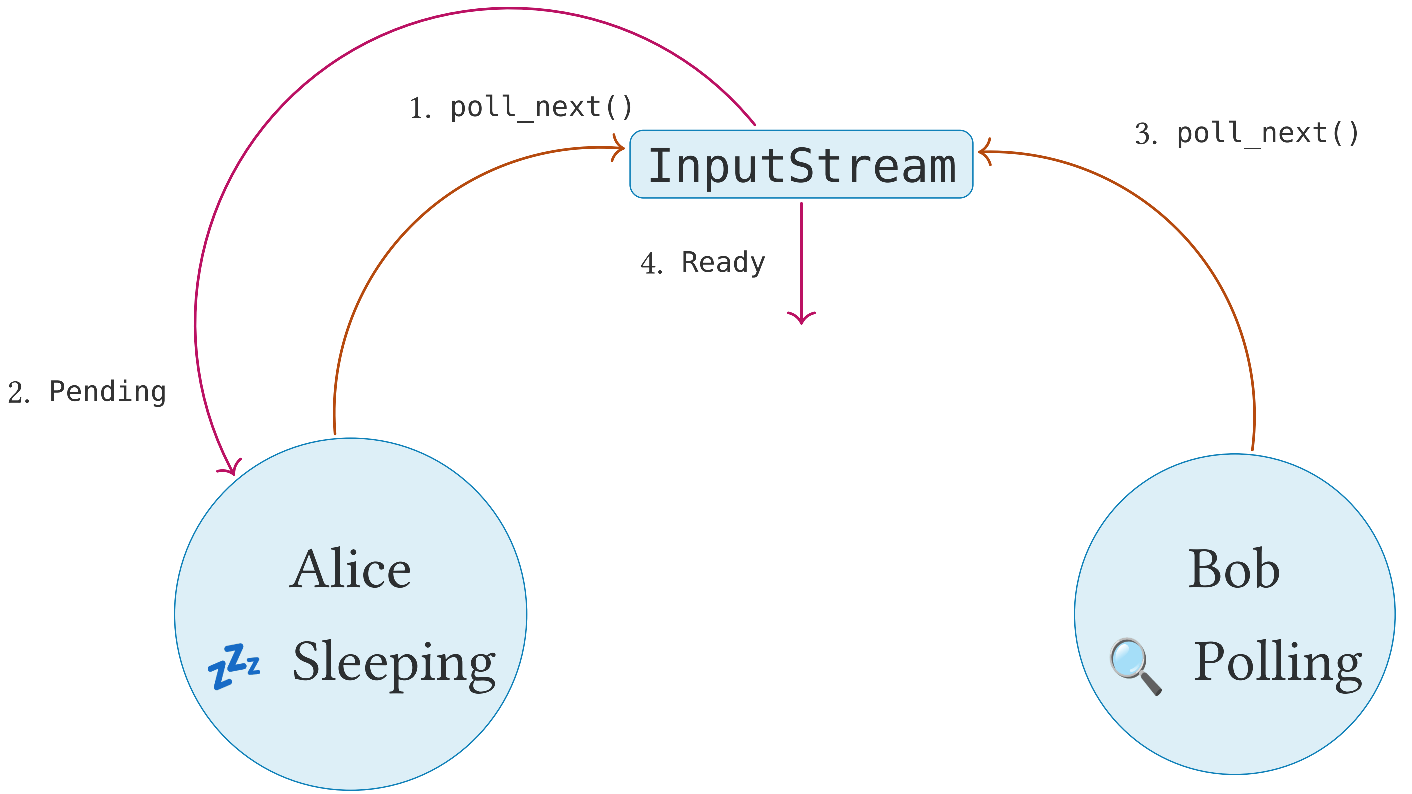
```rust
let ui_latency = tcp_stream.latency().fork();

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`)

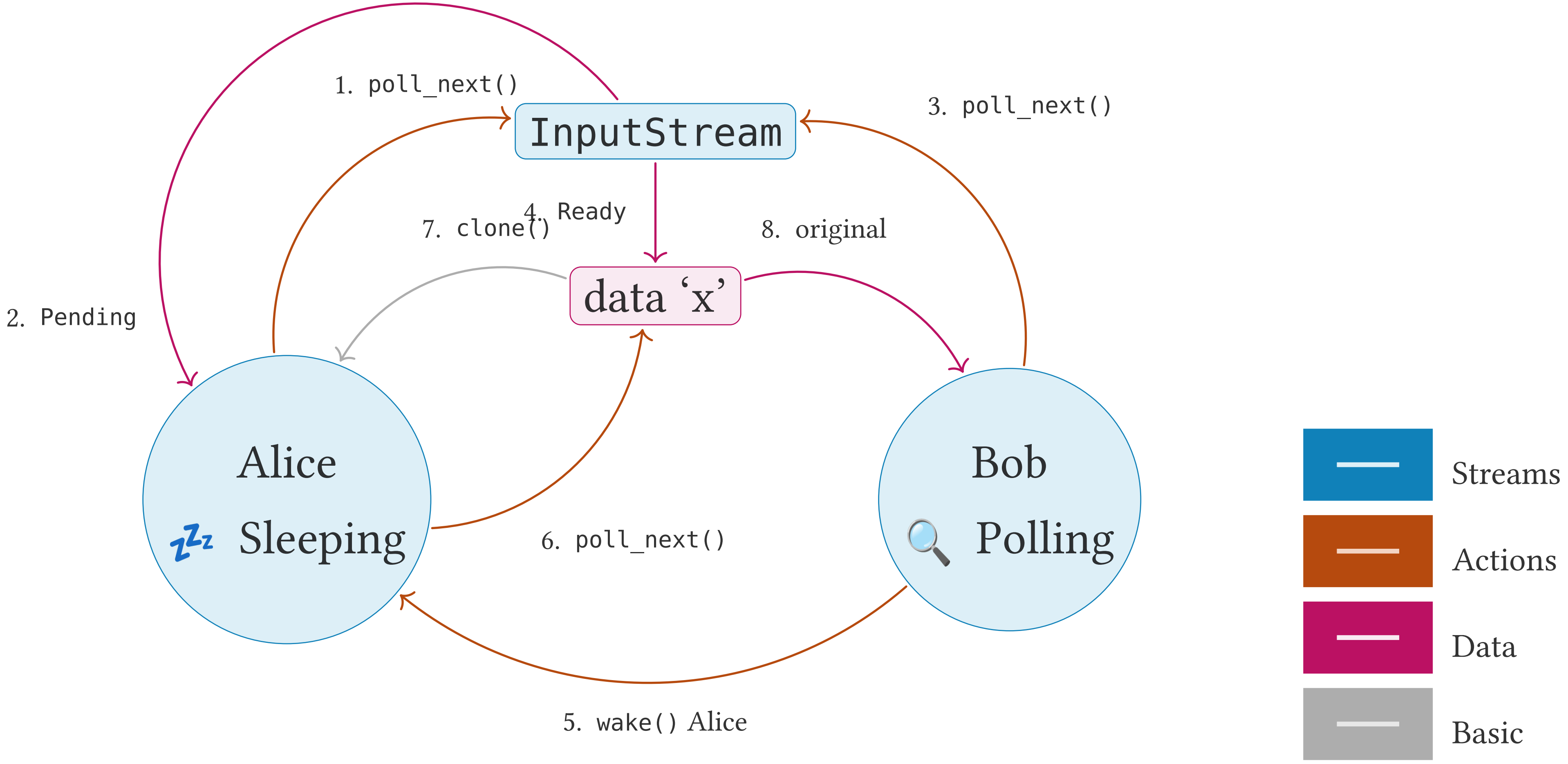
5.4. Polling and waking flow



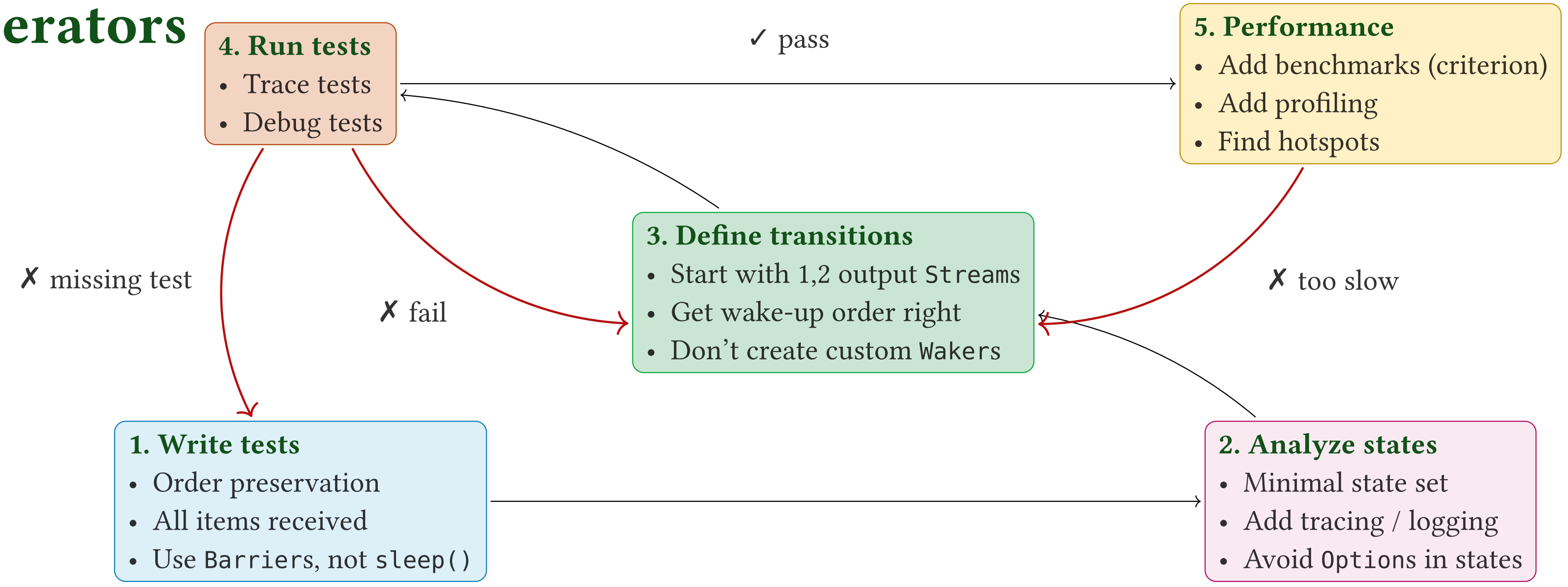
5.4. Polling and waking flow



5.4. Polling and waking flow

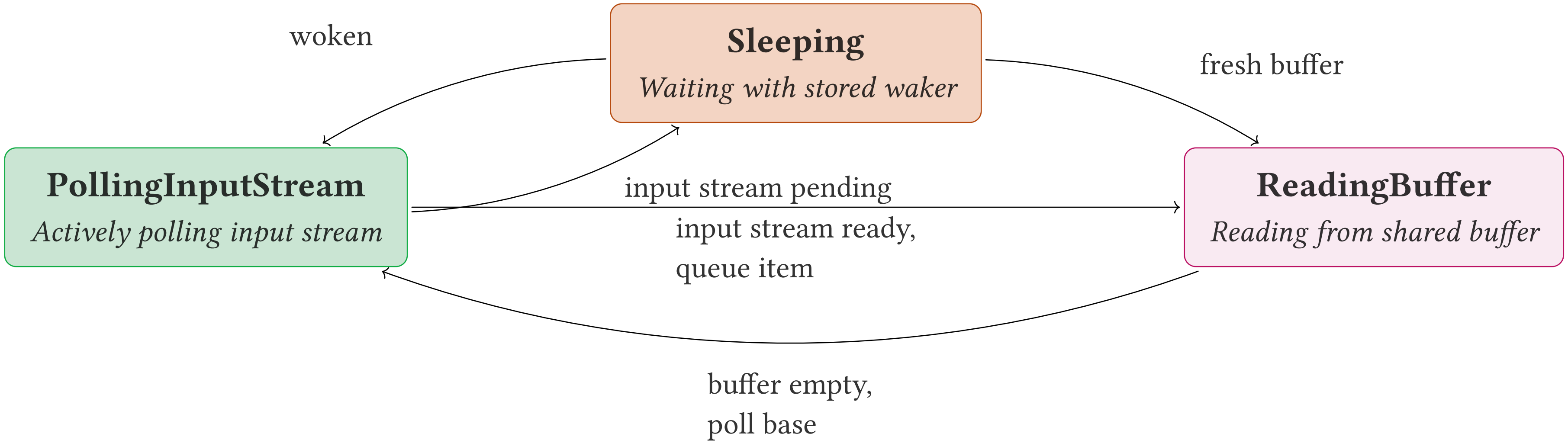


5.5. Steps for creating robust stream operators



5.6. Simplified state machine of `clone-stream`

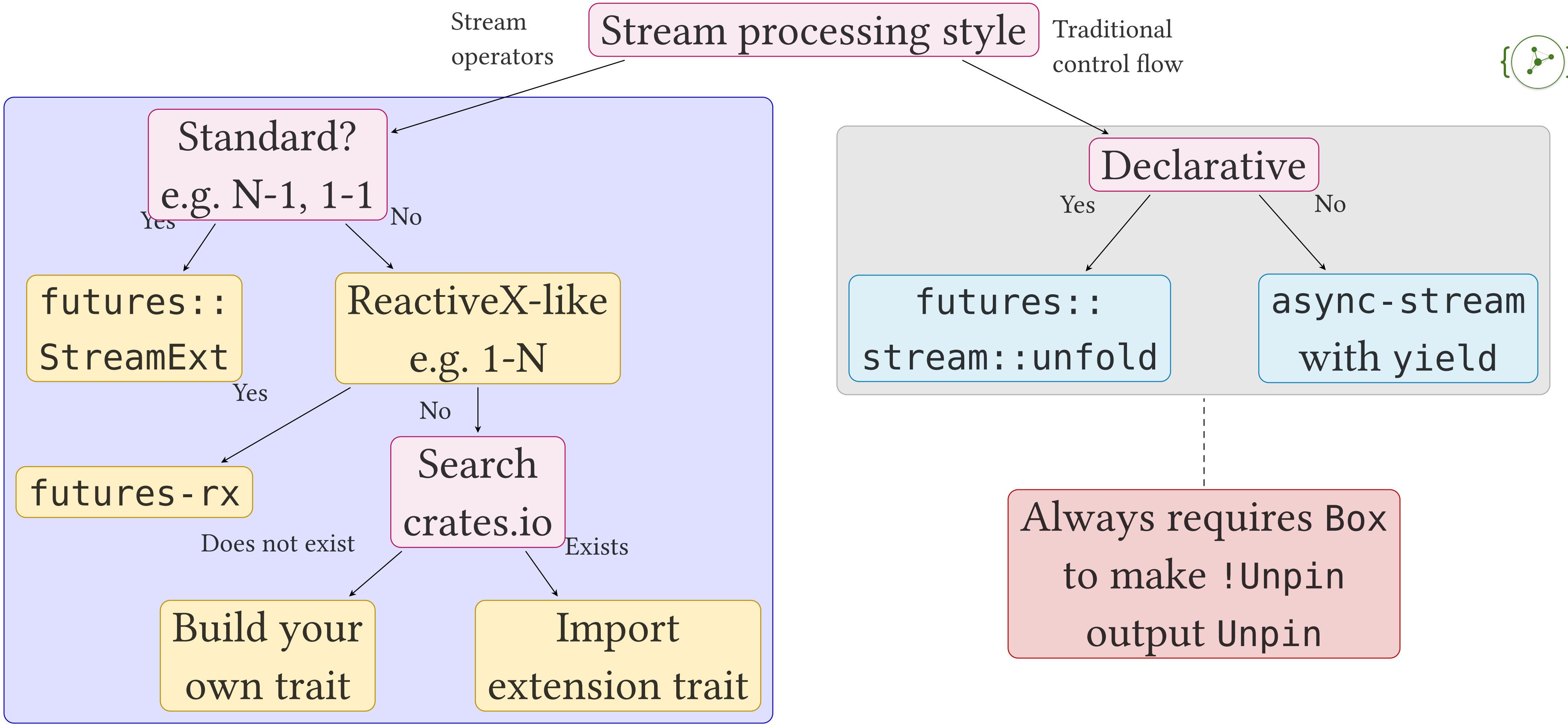
Enforcing simplicity, **correctness and performance**:



Warning

Each clone maintains its own state

6.1. Quickstart



6.2. Questions

Thank you for your attention!

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

Want to learn more?

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/