Transforming `Streams`

Advanced stream processing in Rust

Willem Vanhulle

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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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Processing data from moving vehicles

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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()`**

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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

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

1.3. Streams in Rust are not new

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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
Microsoft Reactive Extensions
ReactiveX brings streams to mainstream
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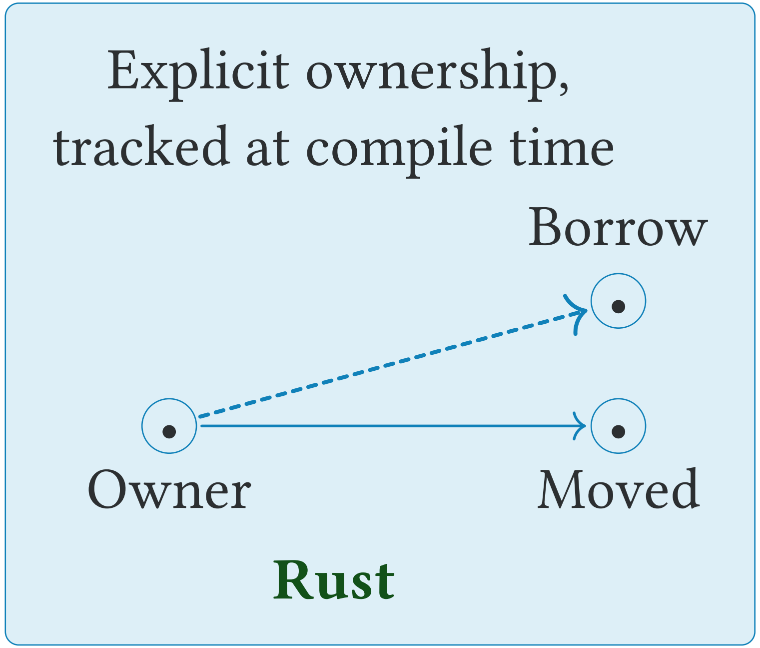
1.4. Why does Rust need special treatment?

Stream operators must wrap and own their input by value

vs



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
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)

⚠️ May be Pending

✓ Hides polling complexity

2.1. Moving from `Iterator` to `Stream`

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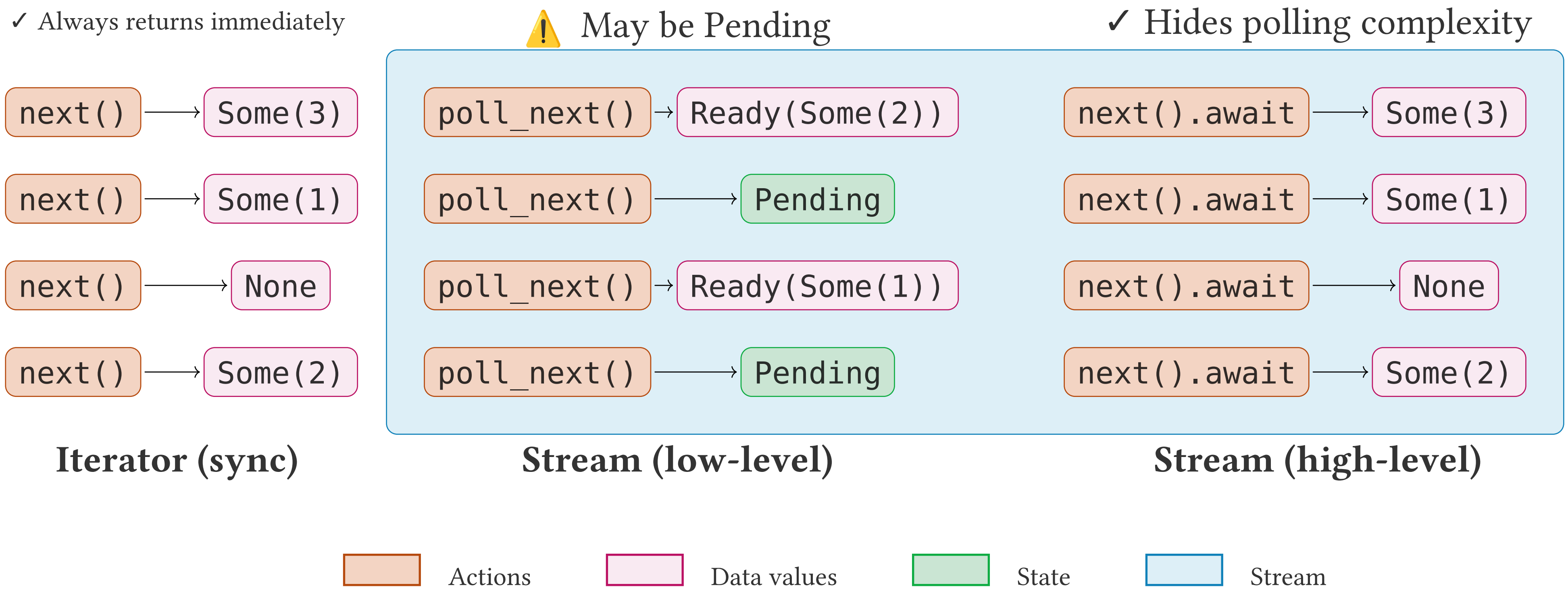
`next()` → `Some(3)`
`next()` → `Some(1)`
`next()` → `None`
`next()` → `Some(2)`

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
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
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**"

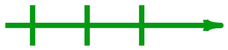
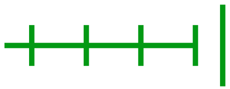
(*Stream might yield more later*)

Fused Stream

"No items **ever again**"

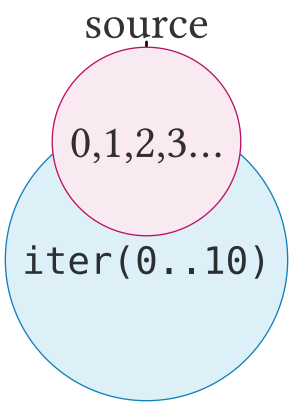
(*Stream is permanently done*)

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`



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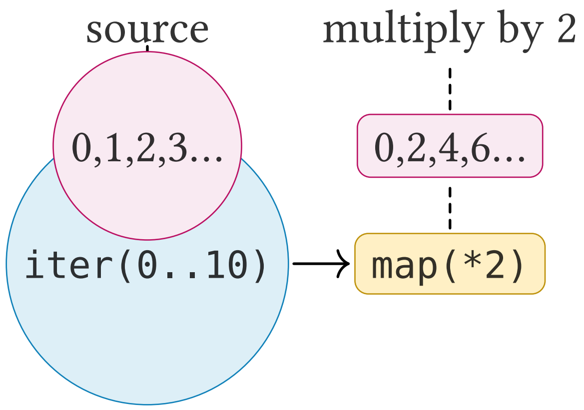

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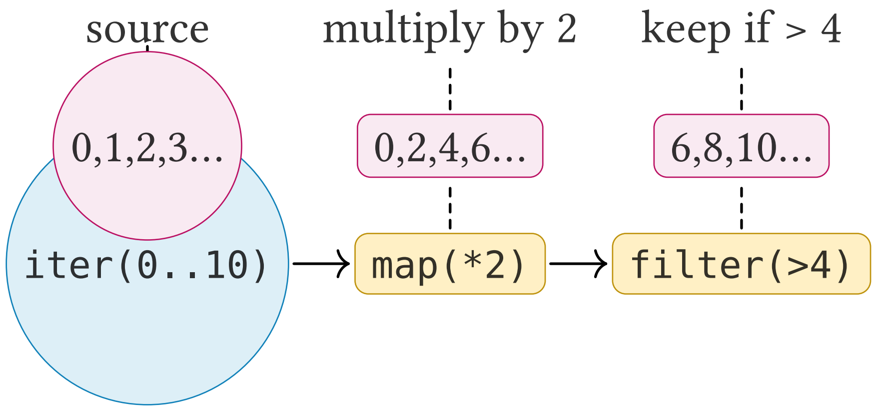

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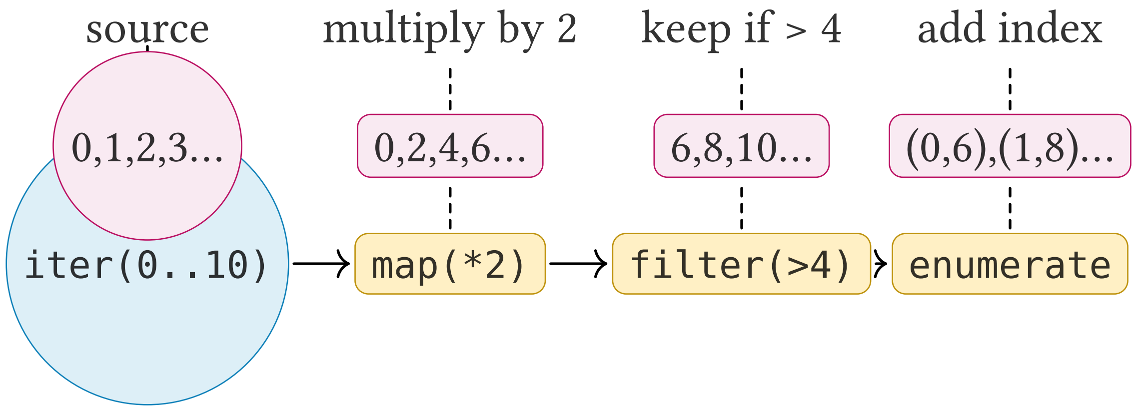

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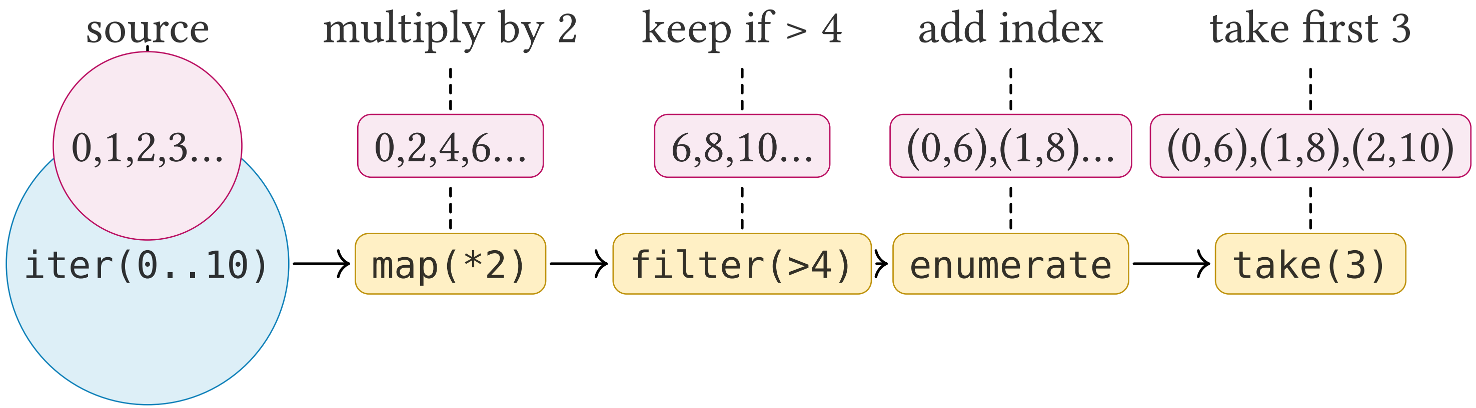

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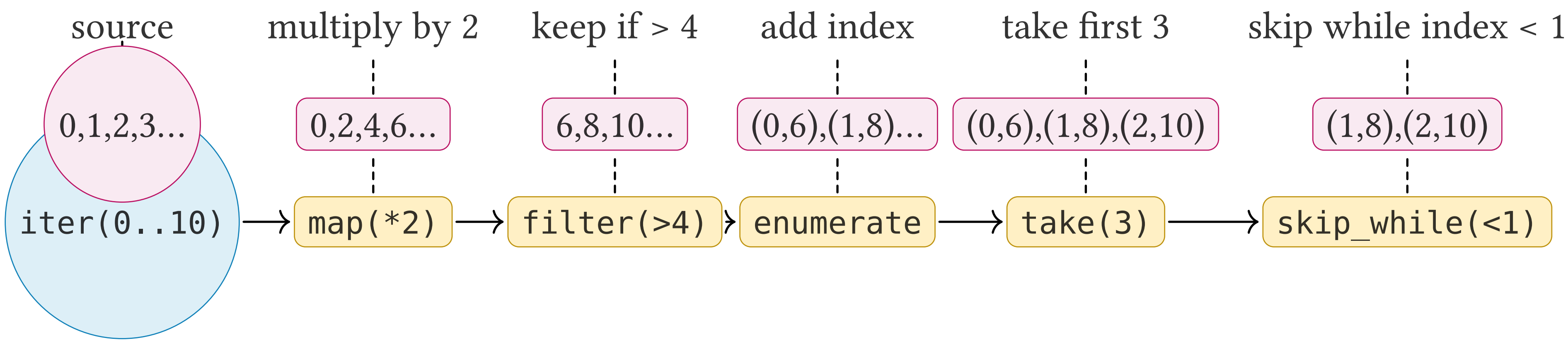



```rust
stream::iter(0..10)
    .map(|x| x * 2)
    .filter(|&x| ready(x > 4))
    .enumerate()
    .take(3)
    .skip_while(|&(i, _)| i < 1)
```

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`

The ready trick

`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
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();
```

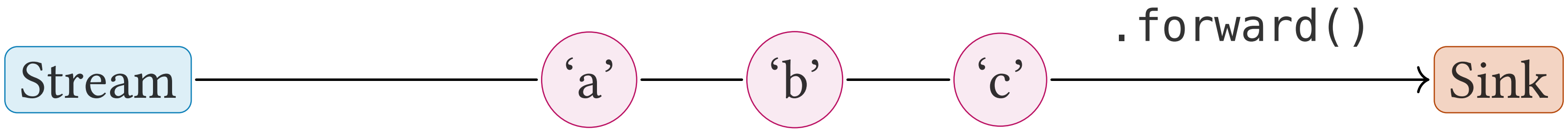
Instead, **buffer streams** concurrently with `flatten_unordered()`.

```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`

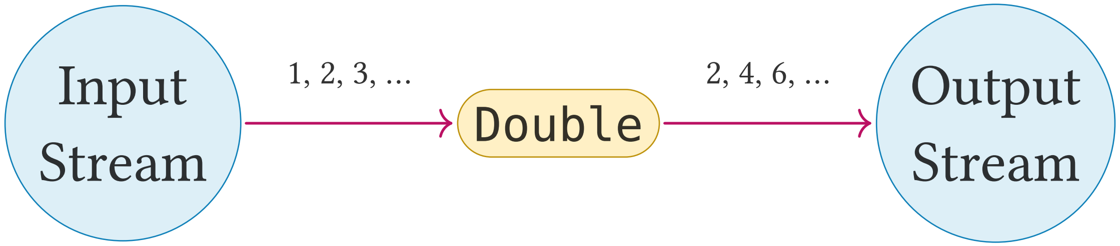


Read side

Write side

4.1. Doubling stream operator

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



Input stream **needs to yield integers**.

4.1. Doubling stream operator

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

4.1. Doubling stream operator

Step 2: Implement `Stream` trait with bounds

```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
    }
}
```

4.2. Naive implementation of poll_next

Focus on the implementation of the `poll_next` method

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

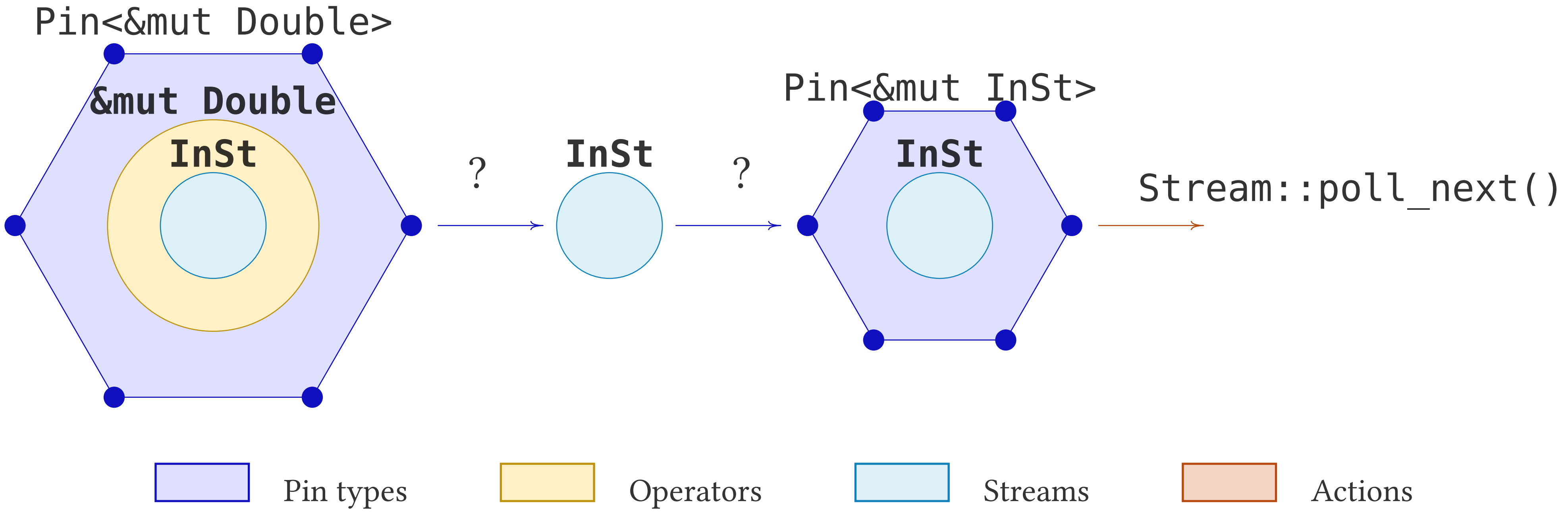
```rust
fn poll_next(self: Pin<&mut Self>, cx: &mut Context<'_>)
    -> Poll<Option<Self::Item>> {
        // Cannot access self.in_stream!
        Pin::new(&mut self.in_stream) // Not possible!
            .poll_next(cx)
            .map(|x| x * 2)
}
```

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

4.2. Naive implementation of `poll_next`

We have `Pin<&mut Double>`

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



4.2. Naive implementation of `poll_next`

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

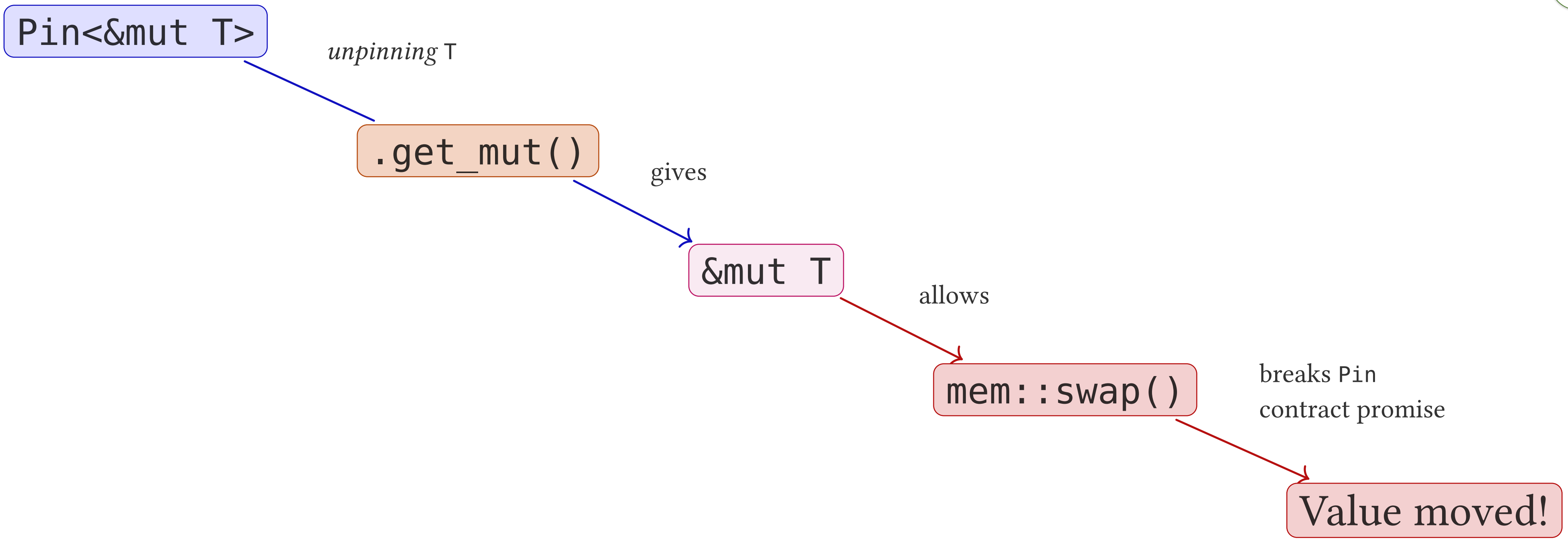
```rust
impl<InSt> Stream for Double<InSt> where InSt: Stream<Item = i32> {

    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`*!

4.3. 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).

4.4. `Unpin` types can be safely unpinned

`Unpin` Bird

Safe to move

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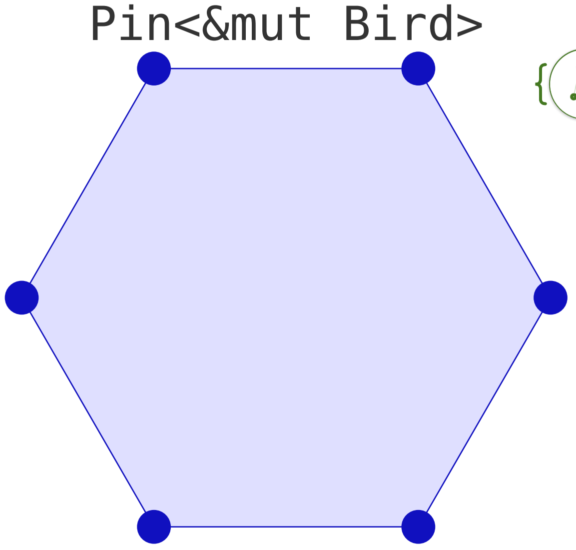
Safe to move



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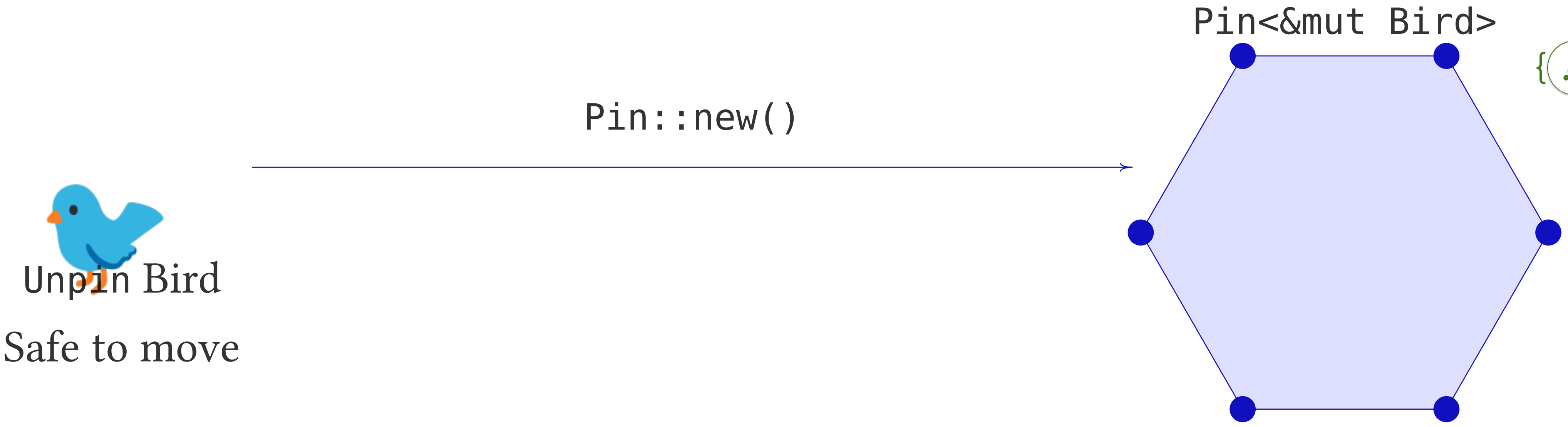

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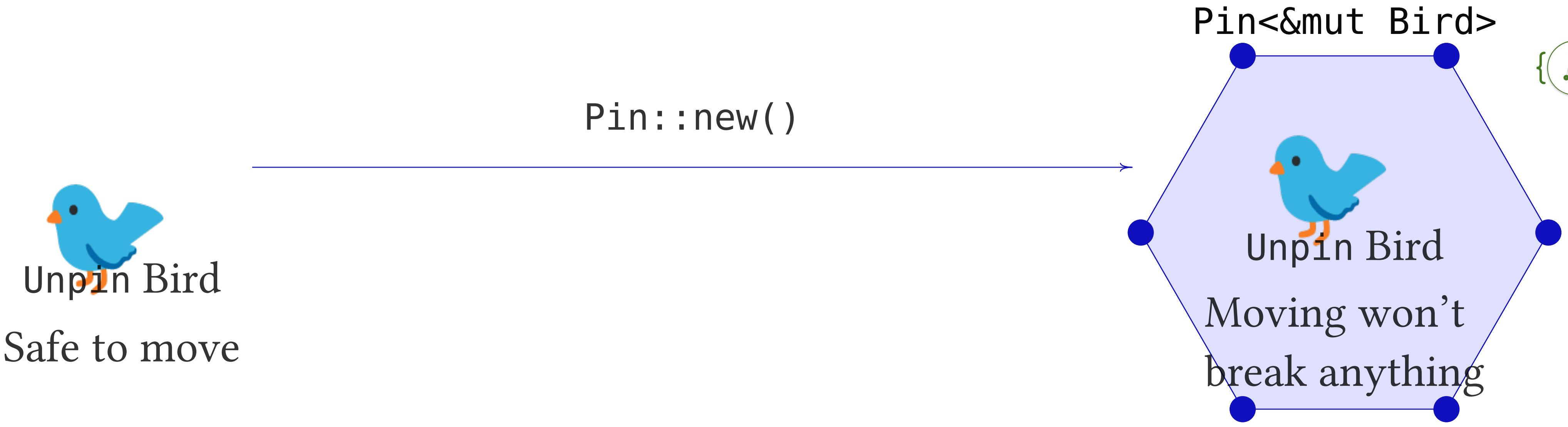

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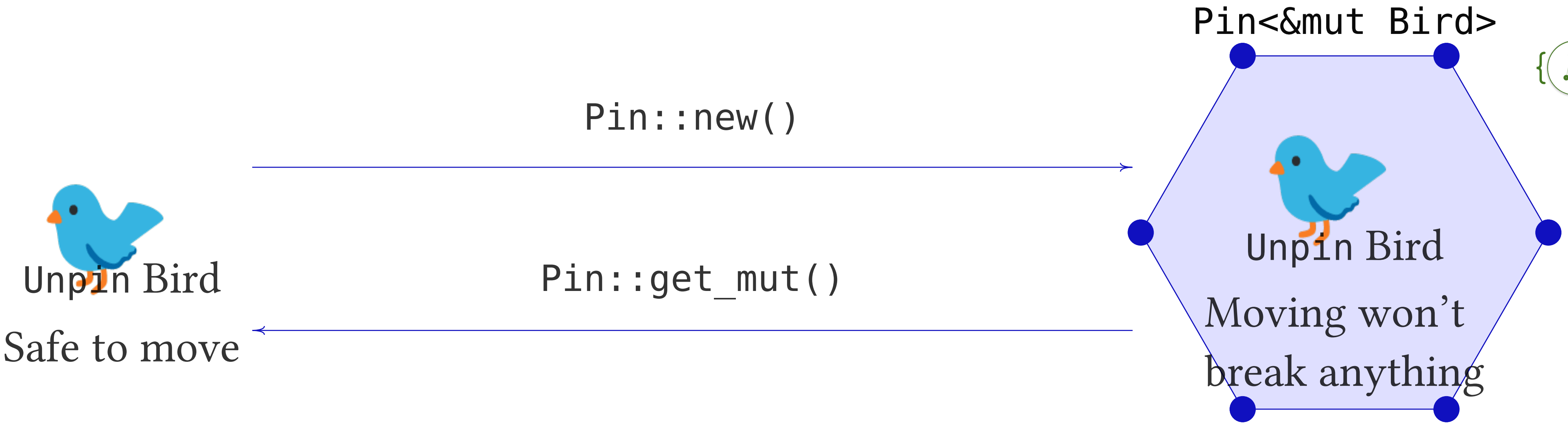

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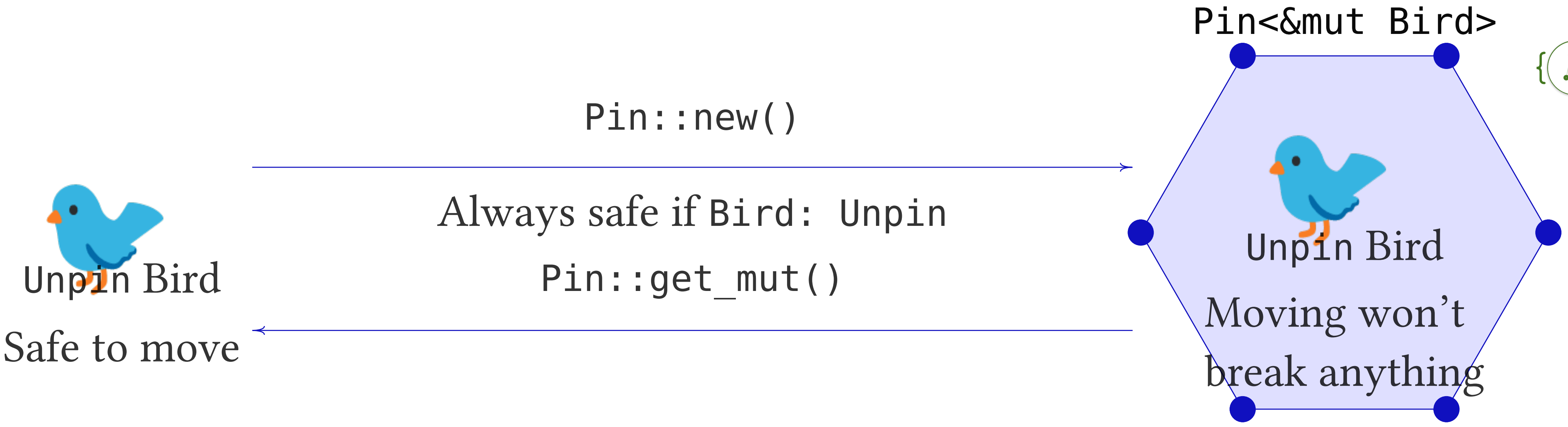

If `T: Unpin`, then `Pin::get_mut()` is safe because moving `T` doesn't cause UB.

4.4. `Unpin` types can be safely unpinned

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.

Info

Almost all types are `Unpin` by default!

4.5. `!Unpin` types cannot be 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

4.5. `!Unpin` types cannot be unpinned

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.

Info

`!Unpin` is rare and usually intentional for async/self-referential types.

4.6. Following compiler hints

The compiler error suggests adding `InSt: Unpin`:

```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))
  }
}
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      .map(|p| p.map(|x| x * 2))
  }
}
```

Warning

This is a common, misleading compiler hint and **not the right solution**!

4.6. Following compiler hints

Instead of mindlessly following the compiler suggestion:

Info

Accept that `!Unpin` things are a fact of life and ask your users to pin stream operators (or futures and other raw `!Unpin` types):

- On the stack with the `pin!` macro
- On the heap with `Box::new()`

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Instead of forcing customers of our API to know what `Unpin` means, I decided to "fix" the problem upstream and pin on the heap.

4.6. Following compiler hints

Instead of mindlessly following the compiler suggestion:

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Accept that `!Unpin` things are a fact of life and ask your users to pin stream operators (or futures and other raw `!Unpin` types):

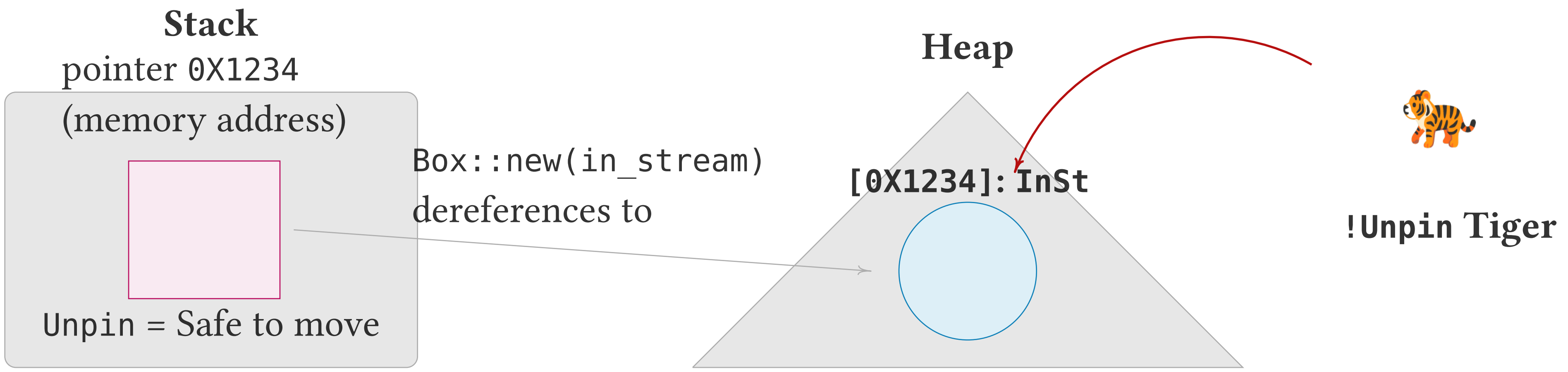
- On the stack with the `pin!` macro
- On the heap with `Box::new()`

Instead of forcing customers of our API to know what `Unpin` means, I decided to "fix" the problem upstream and pin on the heap.

Warning

Pinning the original stream on the heap is not a **real** / idiomatic Rust solution!
(-0-30% runtime performance)

4.7. 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()`

4.7. Turning `!Unpin` into `Unpin` with boxing

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

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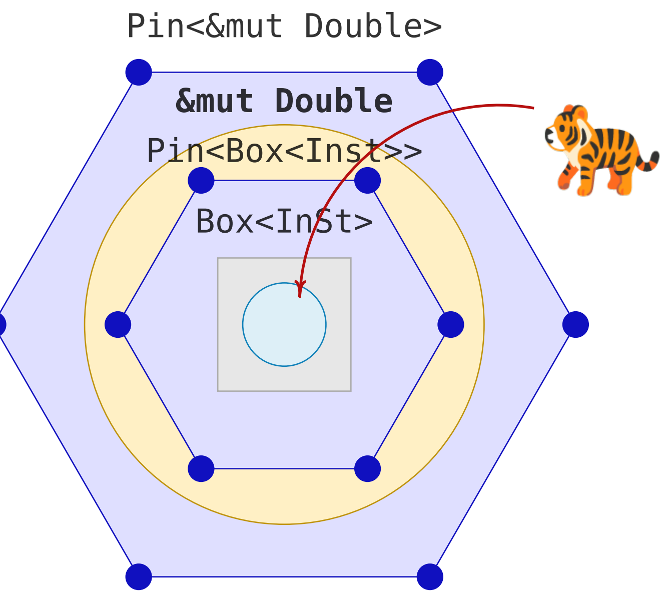
Projection in `poll_next`:

```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`**!

4.7. Turning `!Unpin` into `Unpin` with boxing

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



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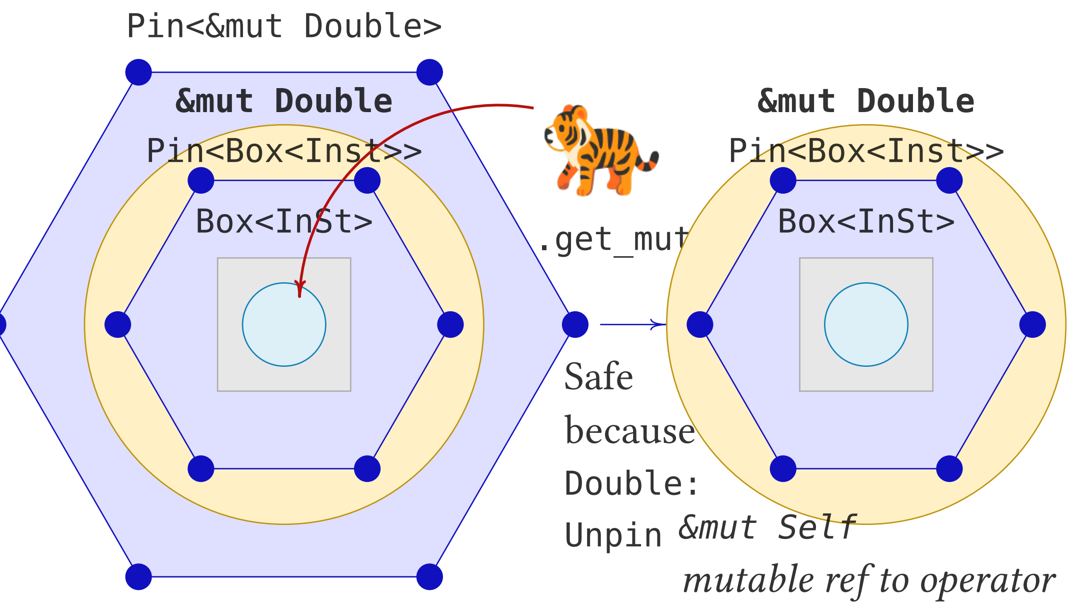

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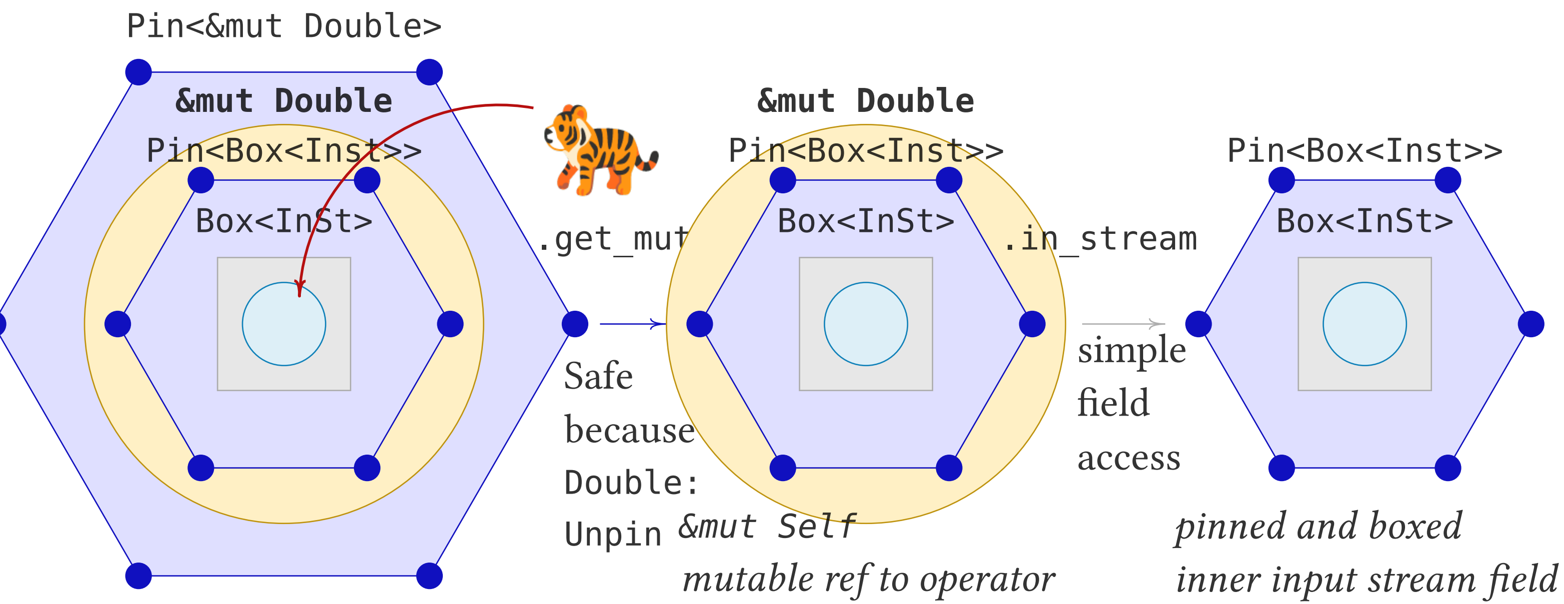

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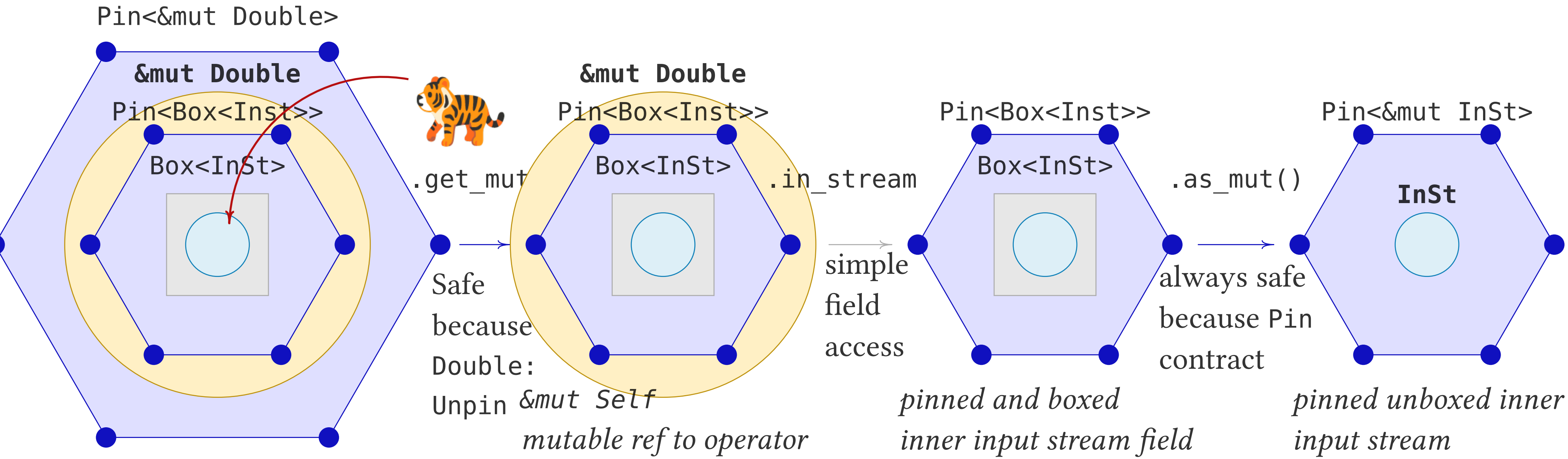

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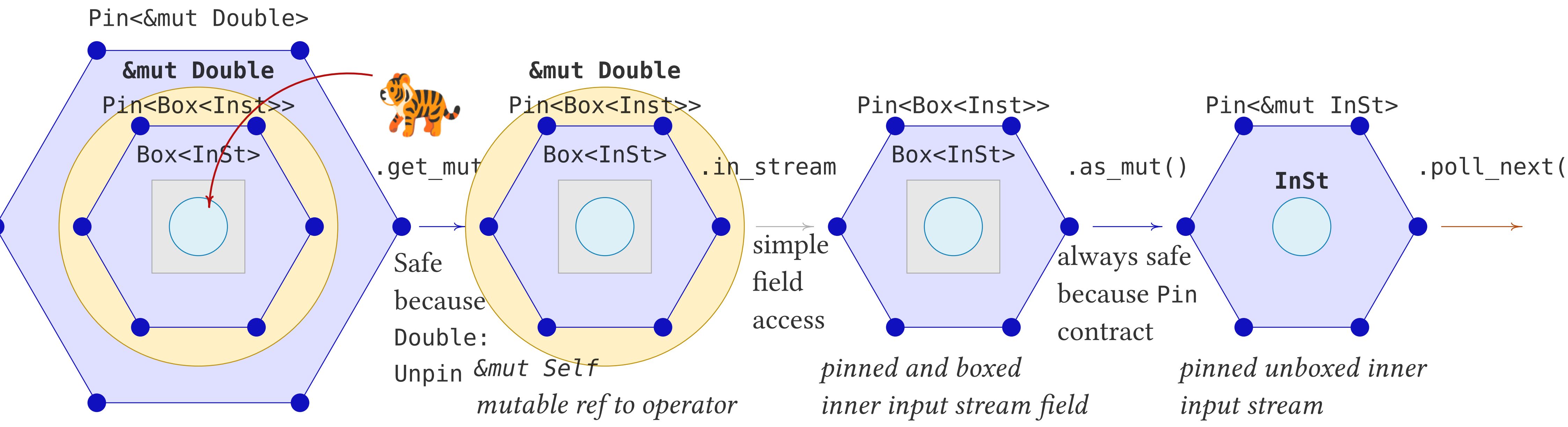

4.7. Turning !Unpin into Unpin with boxing

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

```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))
    }
}
```

4.8. Review of approaches to `!Unpin` fields

Approach 1: Use `Box<_>`

```rust
struct Double<InSt> {
    in_stream: Pin<Box<InSt>>
}

impl<InSt> Stream for Double<InSt>
    where InSt: Stream
```

✓ Works with any `InSt`, also `!Unpin`

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Approach 1: Use `Box<_>`

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struct Double<InSt> {
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impl<InSt> Stream for Double<InSt>
    where InSt: Stream
```

✓ Works with any `InSt`, also `!Unpin`

Approach 2: Require `Unpin`

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

impl<InSt> Stream for Double<InSt>
    where InSt: Stream + Unpin
```

✗ Imposes `Unpin` constraint on users

Approach 3: Use `pin-project` crate

4.8. Review of approaches to `!Unpin` fields

Approach 3: Projection with `pin-project`

Do not impose `Unpin` constraint on input stream **and** avoid heap allocation with `Box`:

```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>>
    {
        self.project().in_stream.poll_next(cx)
            .map(|r| r.map(|x| x * 2))
    }
}
```

Info

`pin-project` generates a safe projection method `project()`.

Warning

You don't have juggle with an `Unpin` constraint (**but your users have to!**)

4.9. 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> {}
```

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trait DoubleStream: Stream {
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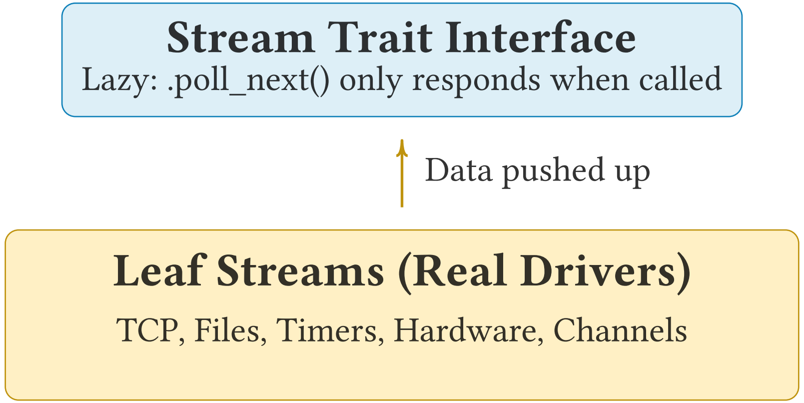
    { Double::new(self) }
}
  // A blanket implementation should be provided by you!
  impl<S> DoubleStream for S where S: Stream<Item = i32> {}
```

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

4.10. The ‘*real*’ stream drivers



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

4.10. The *'real'* stream drivers

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

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Inherent `Future` challenges:

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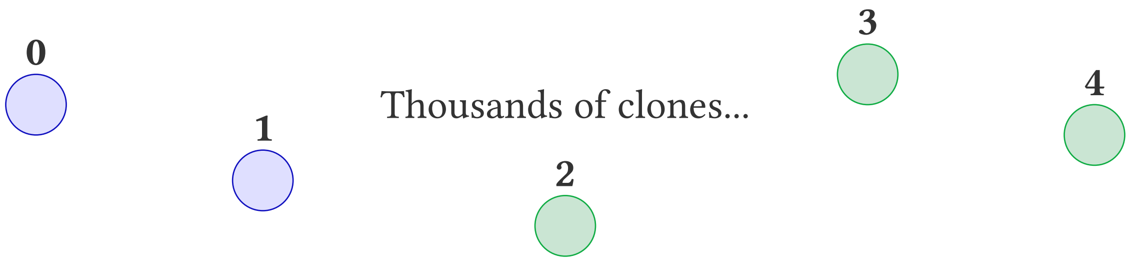
Inherent `Iterator` challenges:

- 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!

5.2. Sharing latency between tasks

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

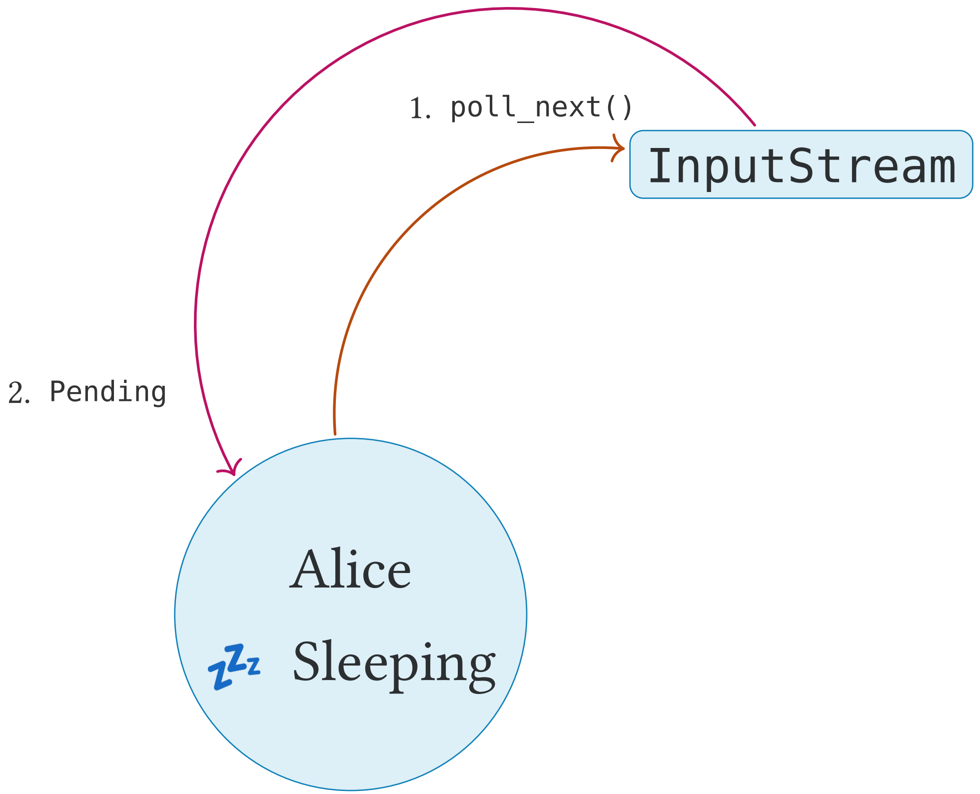
```rust
let ui_latency = tcp_stream.latency().fork();

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`)

5.3. Handling sleeping and waking



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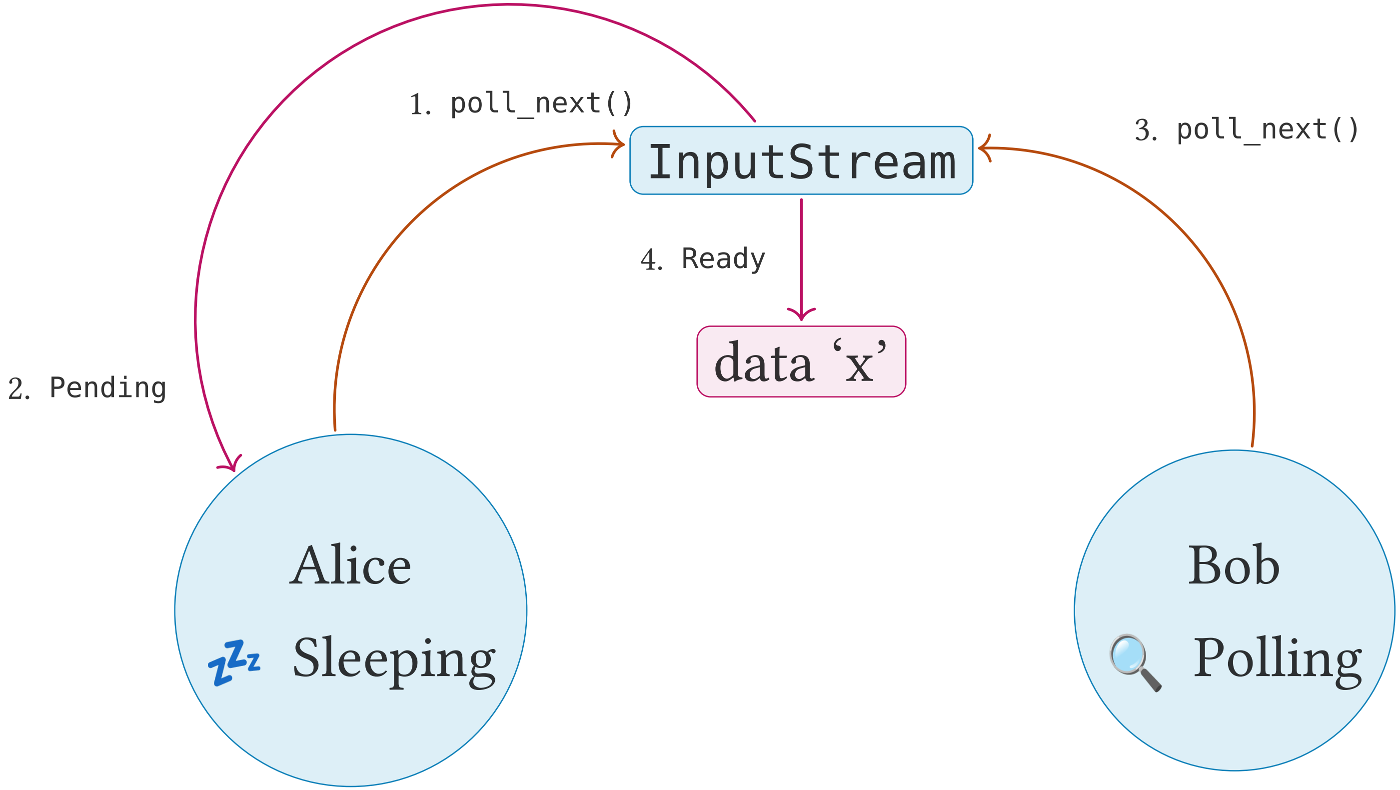

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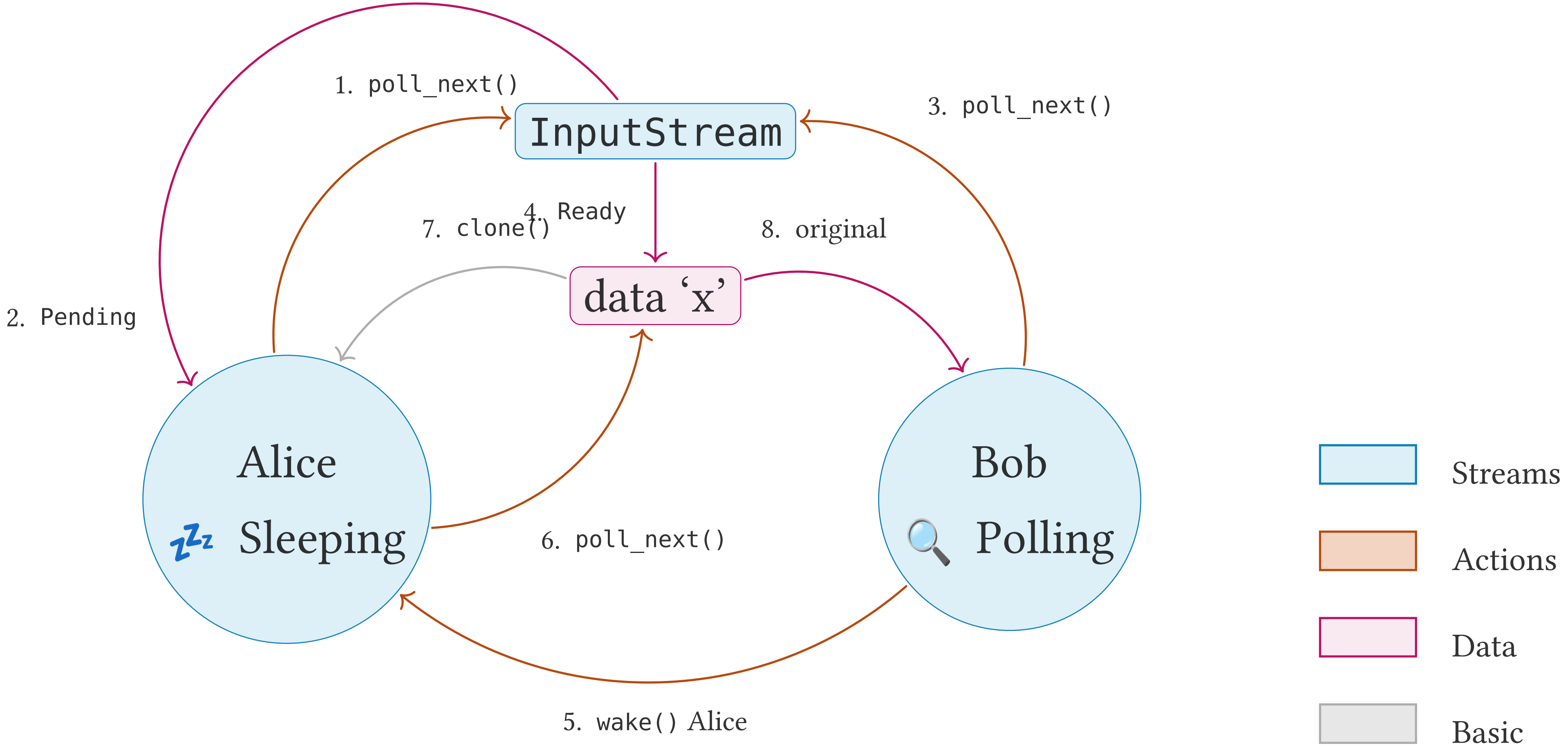
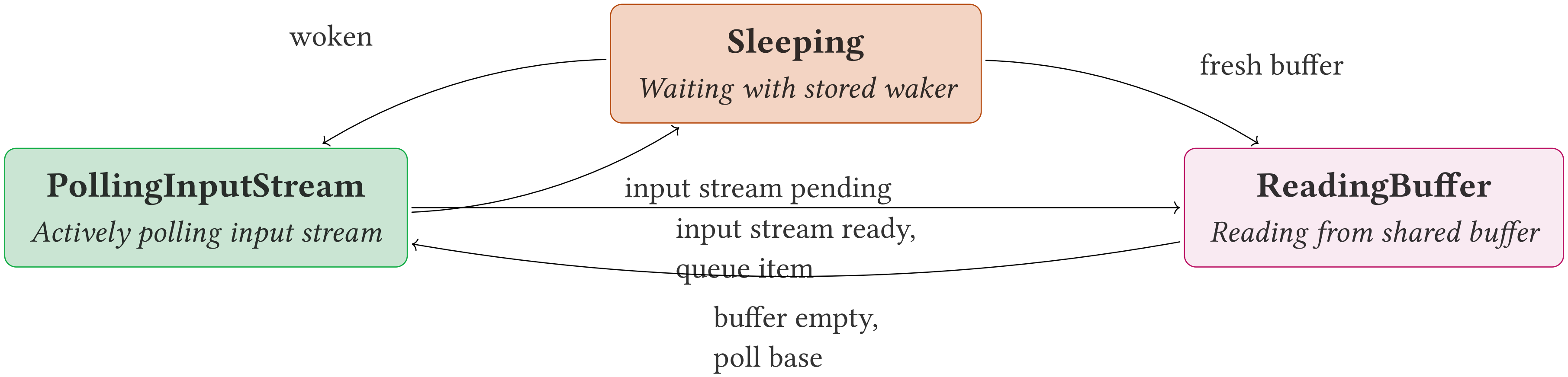


5.4. Simplified state machine of `clone-stream`

Enforcing simplicity, **correctness and performance**:

Solution

Each clone maintains its own state



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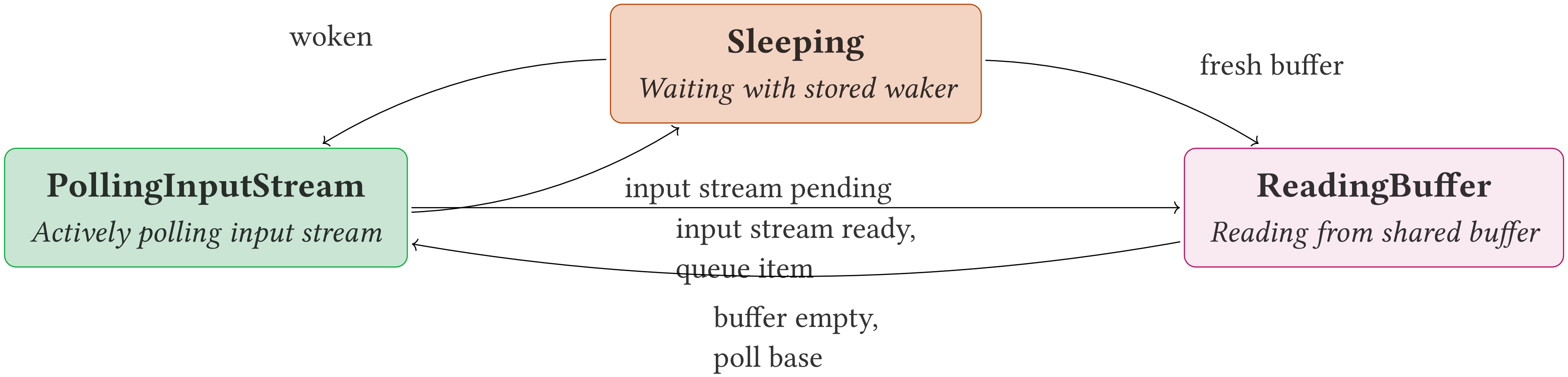
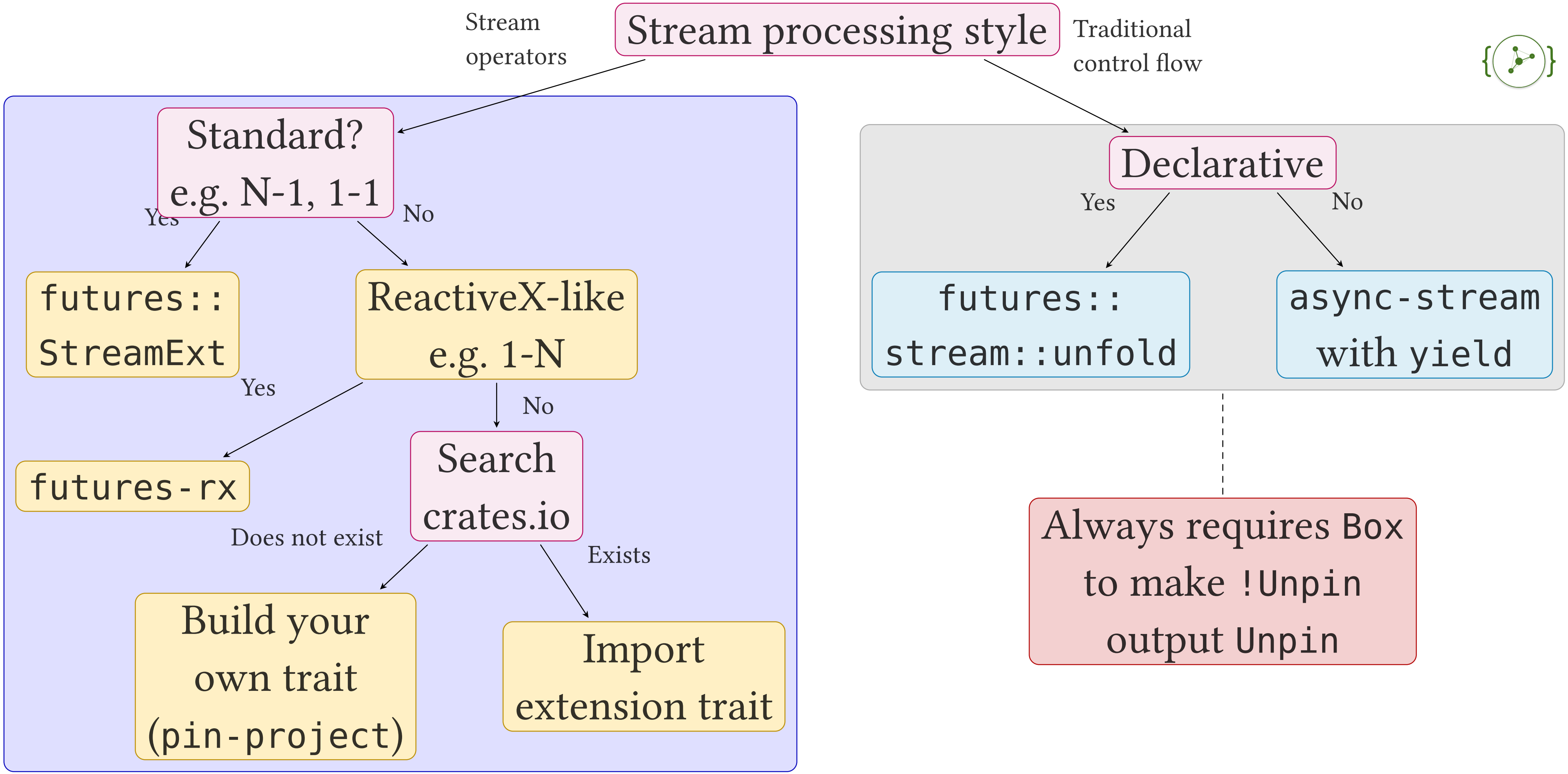


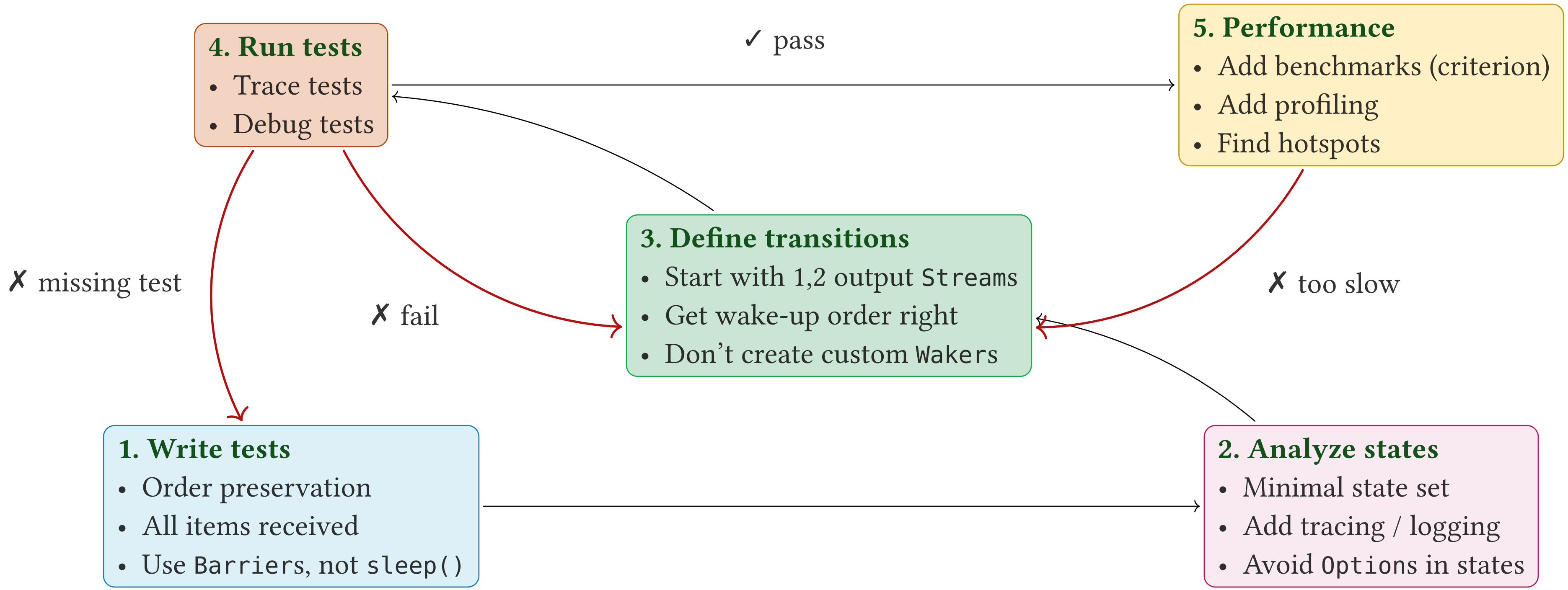
Speed

8 - 12 micro seconds per item per clone. (Using `pin-project` did not speed up.)

6.1. Quickstart



6.2. Advanced operator construction



6.3. Questions

Thank you for your attention!

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

Learn more?

Join my 7-week course ***"Creating Safe Systems in Rust"***

- Location: Ghent (Belgium)
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Register at pretix.eu/devlab/rust-course/