Channels

Ryan Eberhardt and Armin Namavari
May 14, 2020

Logistics

- Congrats on making it through week 6!
- Week 5 exercises due Saturday
- Project 1 due Tuesday
- Let us know if you have questions! We have OH after class

Reconsidering multithreading

Characteristics of multithreading

- Why do we like multithreading?
  - It’s fast (lower context switching overhead than multiprocessing)
  - It’s easy (sharing data is straightforward when you share memory)
- Why do we not like multithreading?
  - It’s easy to mess up: data races

Radical proposition

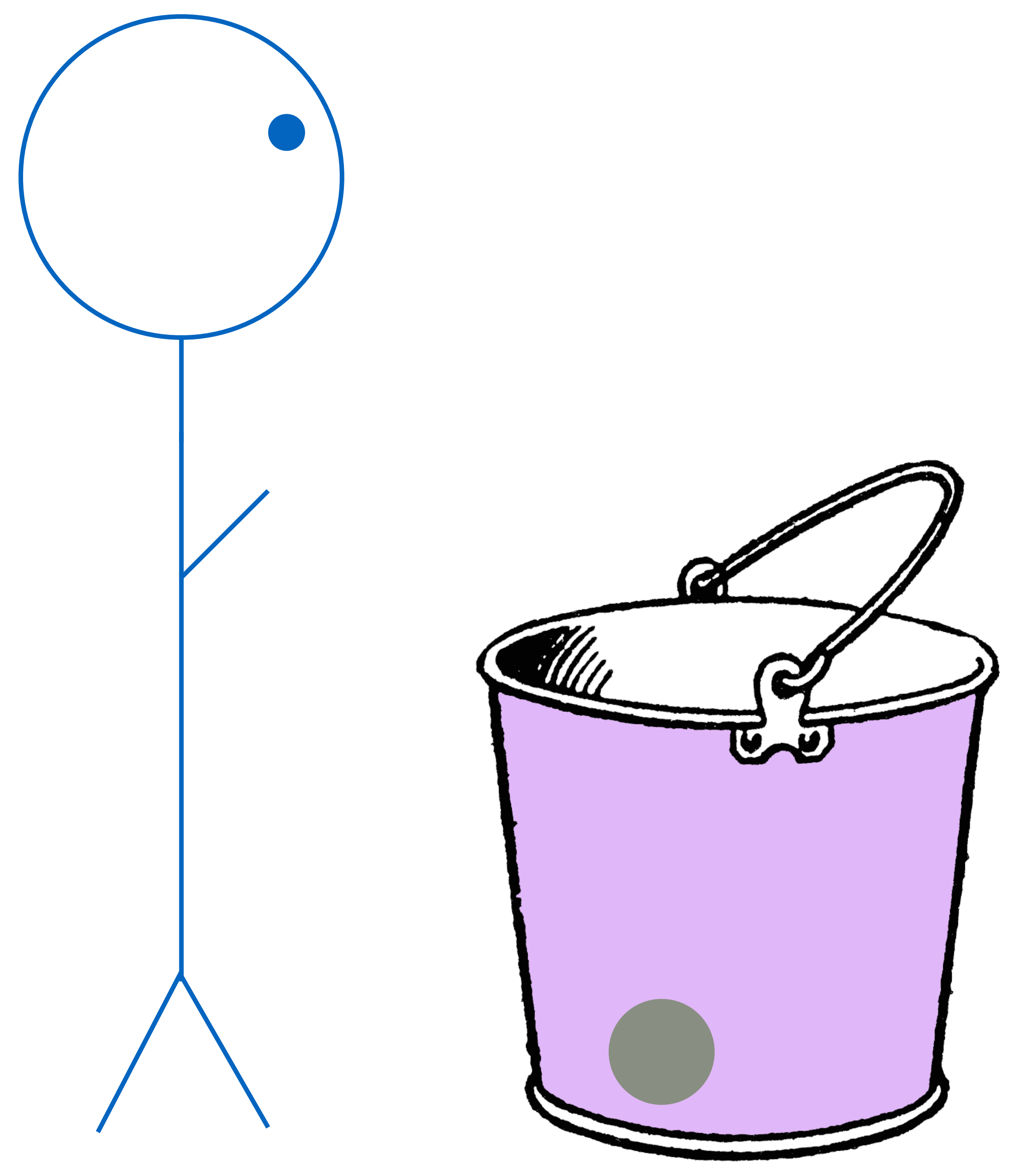
- What if we didn’t share memory?
    - Could we come up with a way to do multithreading that is just as fast and just as easy?
- If threads don’t share memory, how are they supposed to work together when data is involved?
- Golang concurrency slogan: *“Do not communicate by sharing memory; instead, share memory by communicating.”* (Effective Go)
- Message passing: Independent threads/processes collaborate by exchanging messages with each other
    - Can’t have data races because there is no shared memory

Communicating Sequential Processes

- Theoretical model introduced in 1978: sequential processes communicate via by sending messages over “channels”
    - Sequential processes: easy peasy
    - No shared state -> no data races!
- Serves as the basis for newer systems languages such as Go and Erlang
- Also served as an early model for Rust!
    - Channels used to be the *only* communication/synchronization primitive
- Channels are available in other languages as well (e.g. Boost includes an implementation for C++)

Channels: like semaphores

Semaphores

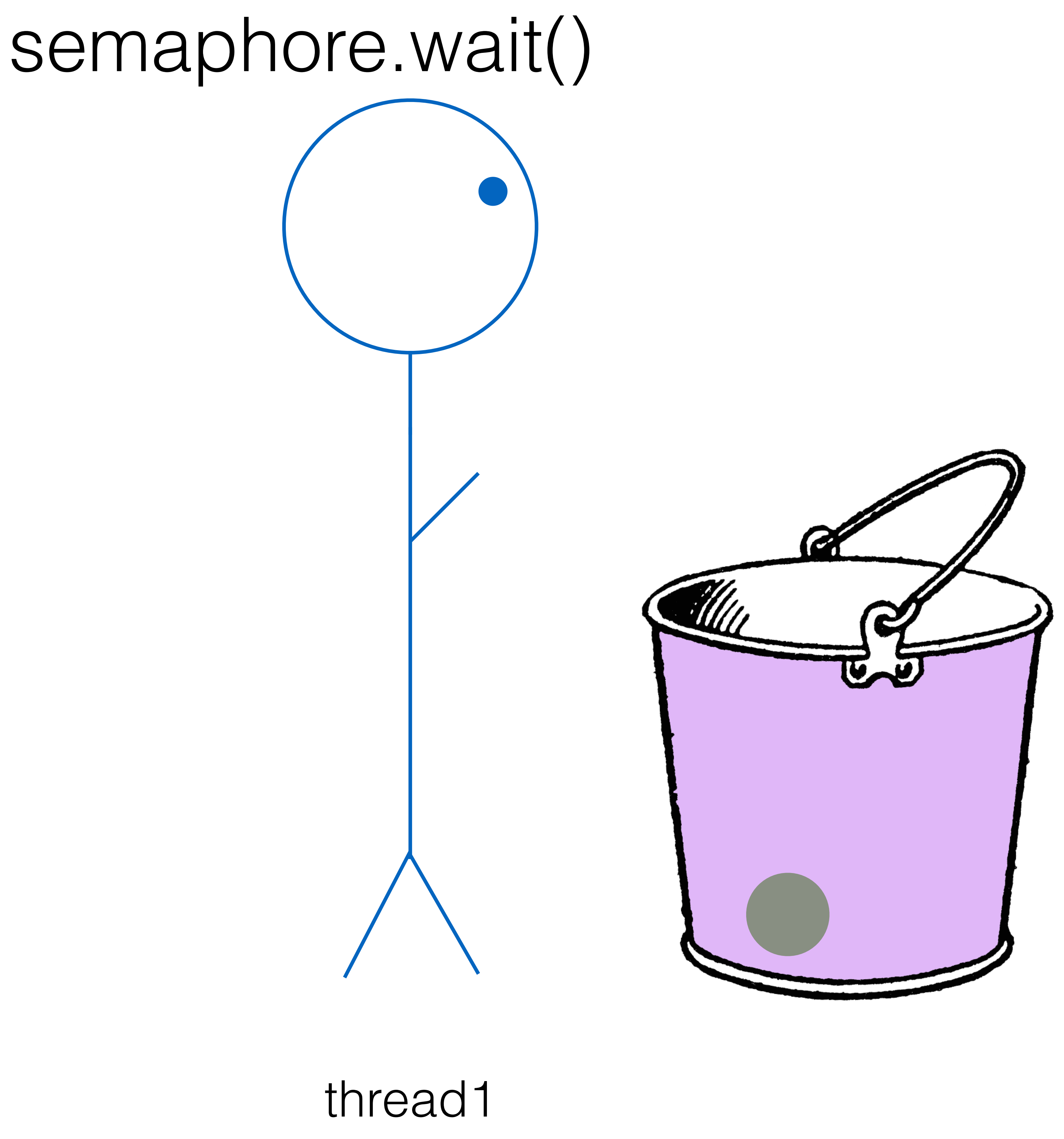


Mutex: Unlocked

Buffer:

SomeStruct { … }			

Semaphores



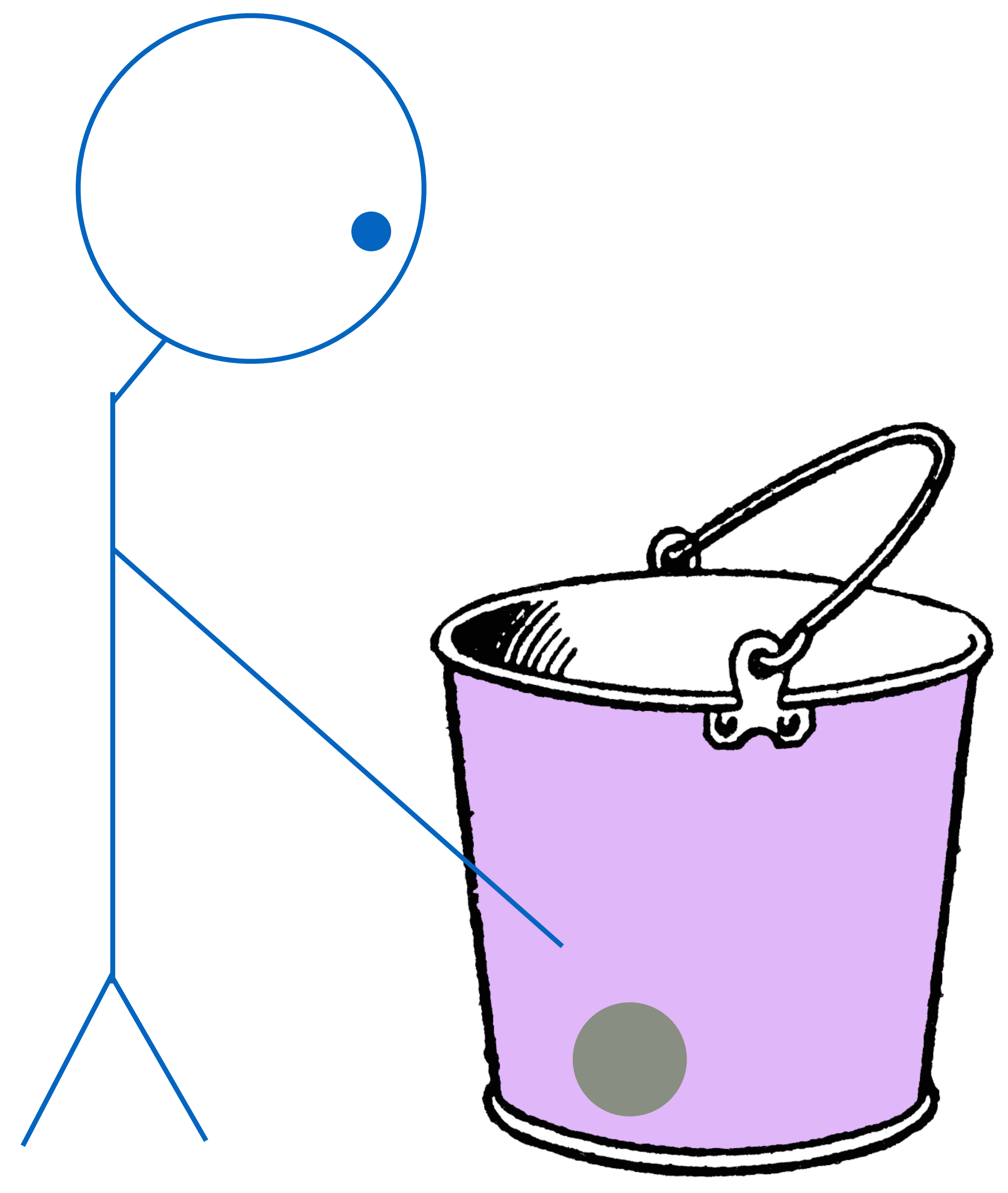
Mutex: Unlocked

Buffer:

SomeStruct {
…
}			

Semaphores

semaphore.wait()



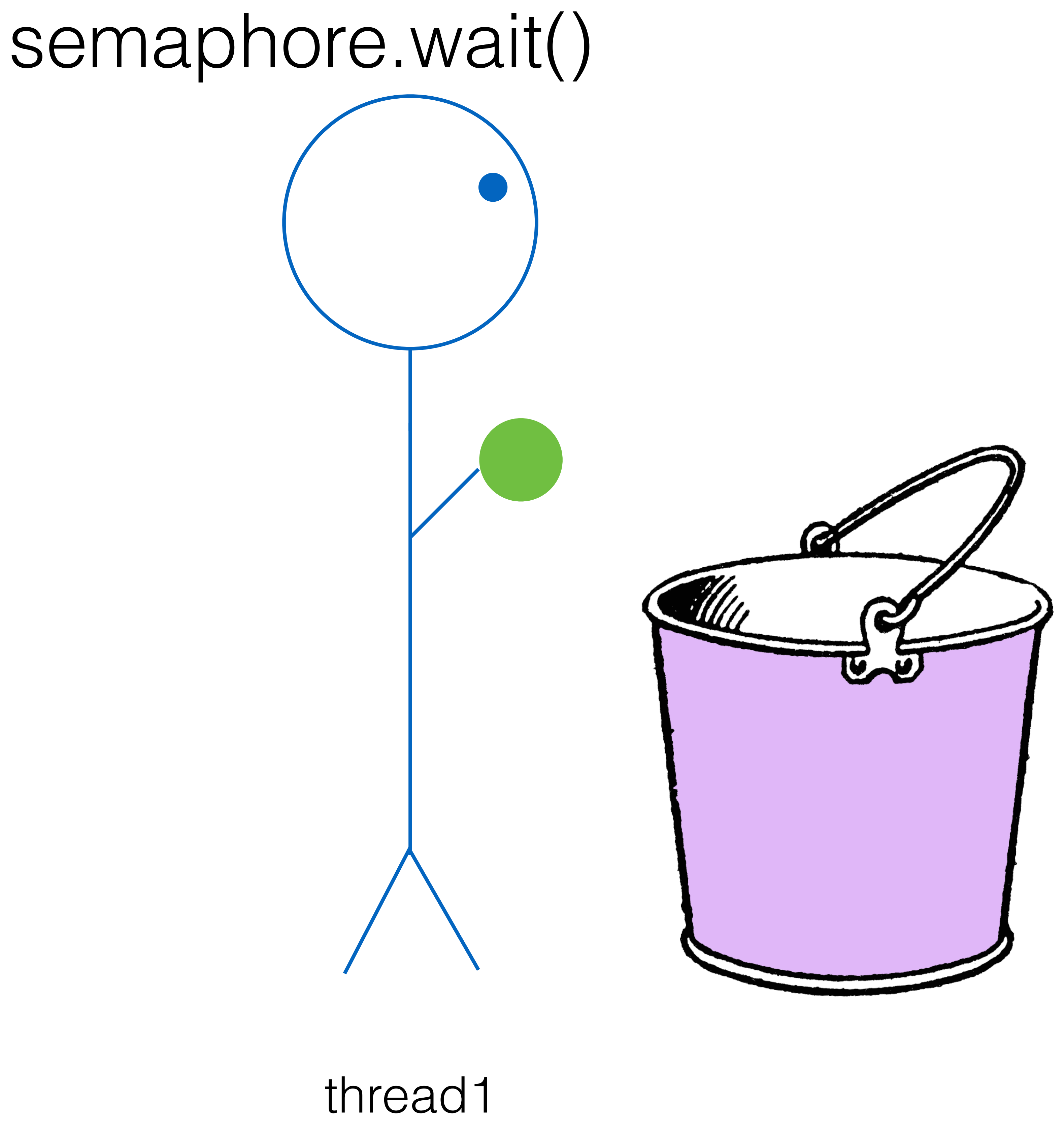
thread1

Mutex: Unlocked

Buffer:

SomeStruct { … }			

Semaphores

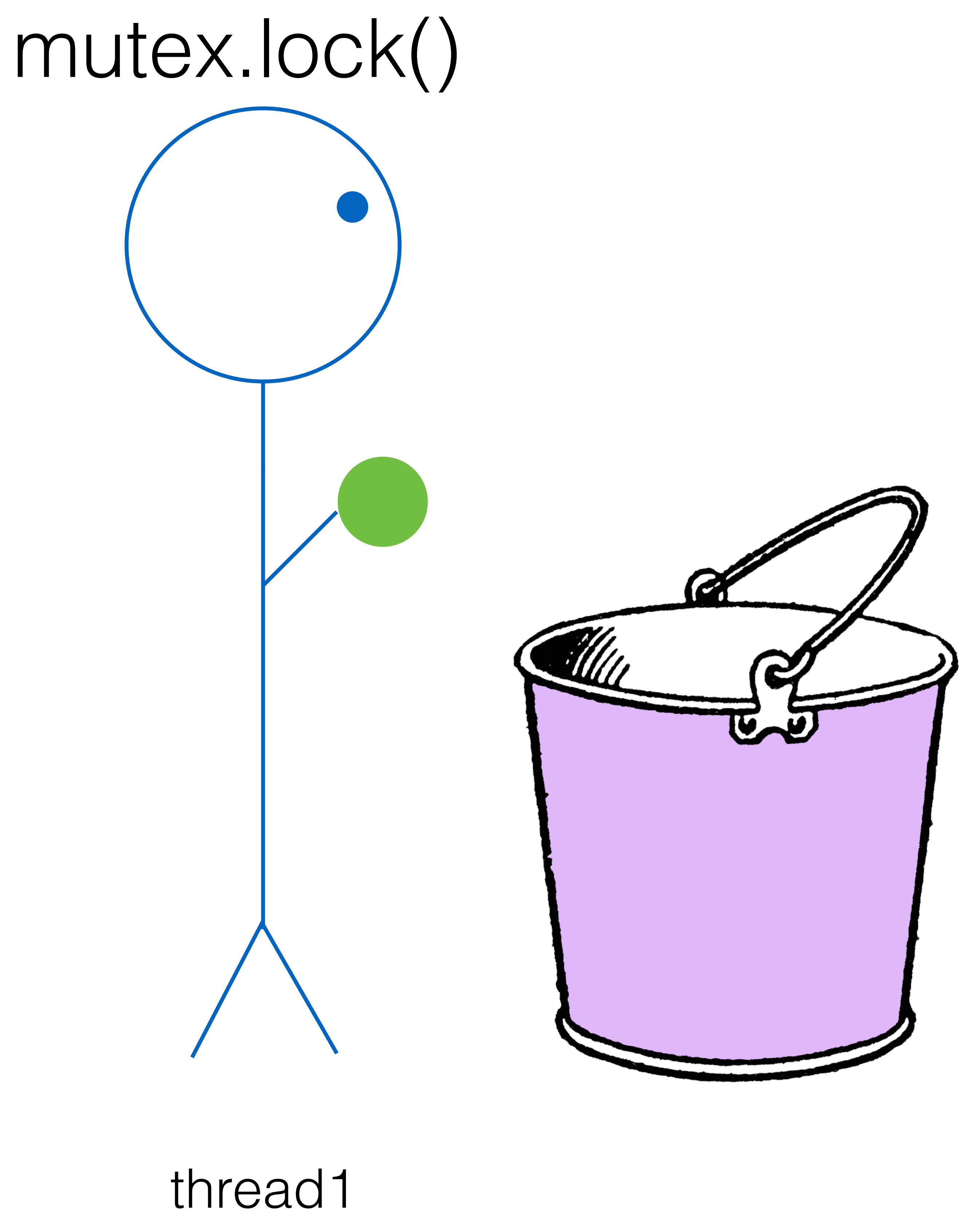


Mutex: Unlocked

Buffer:

SomeStruct { … }			

Semaphores

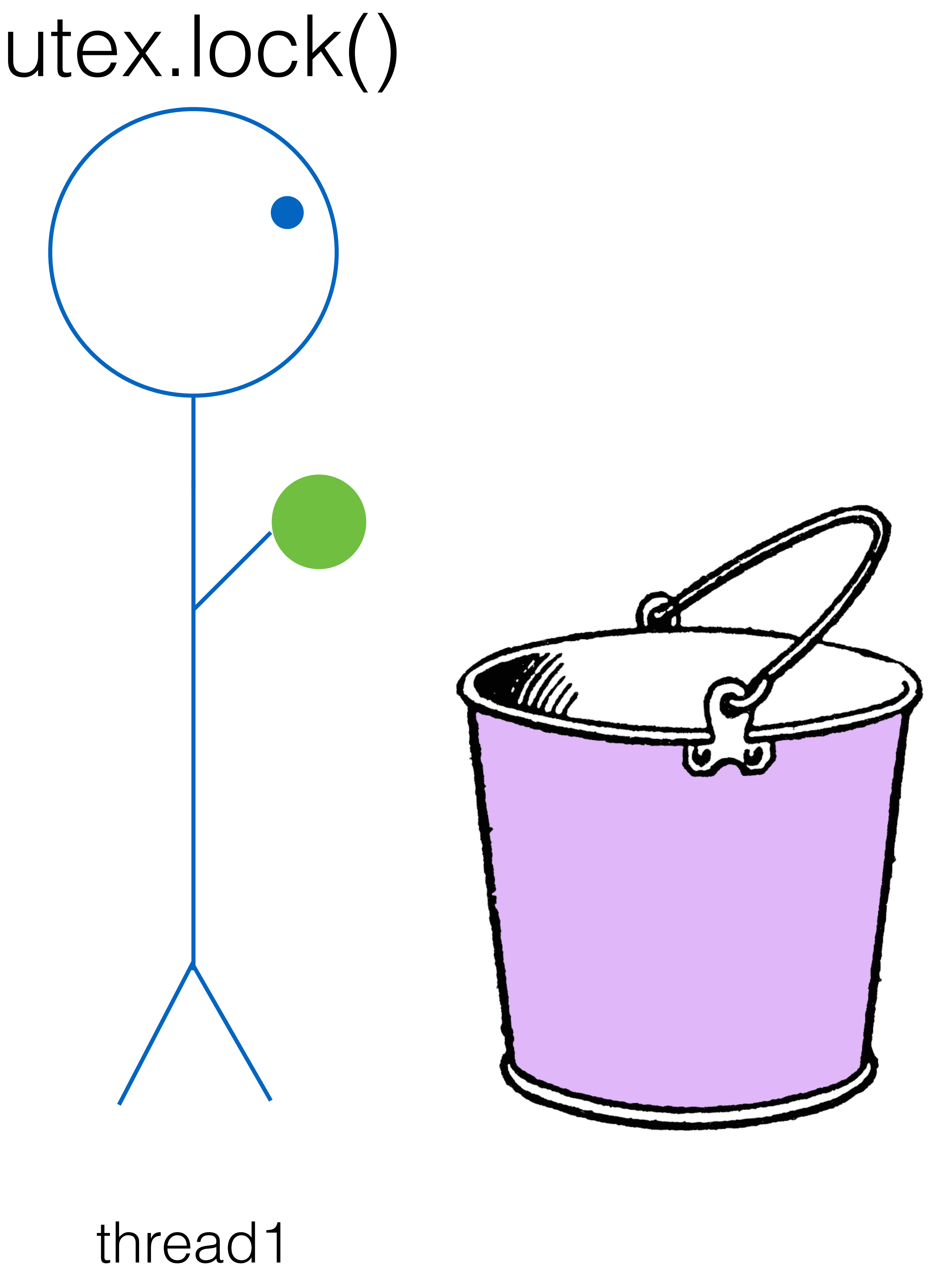


Mutex: Unlocked

Buffer:

SomeStruct { … }			

Semaphores



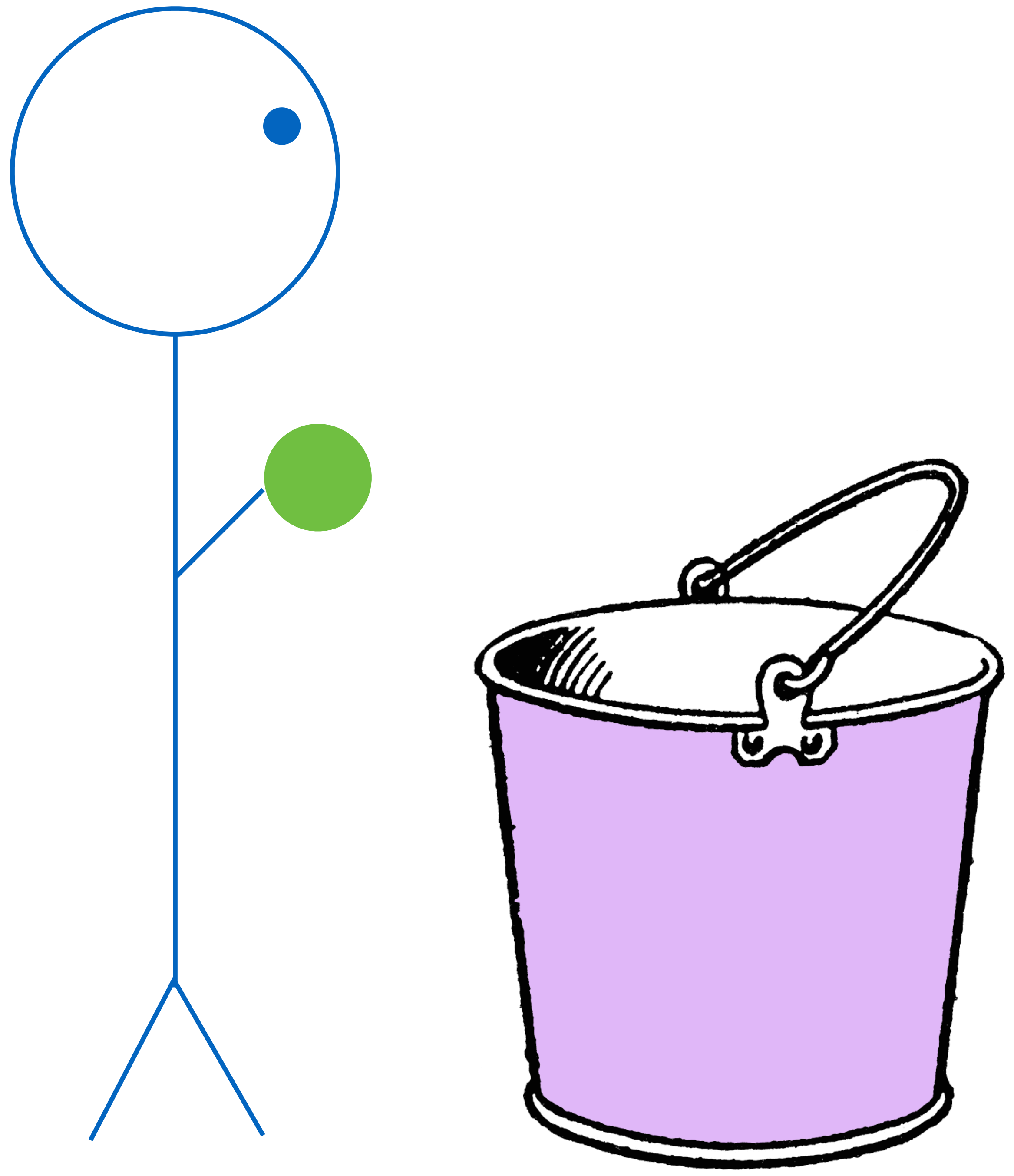
Mutex: Locked

Buffer:

SomeStruct { … }			

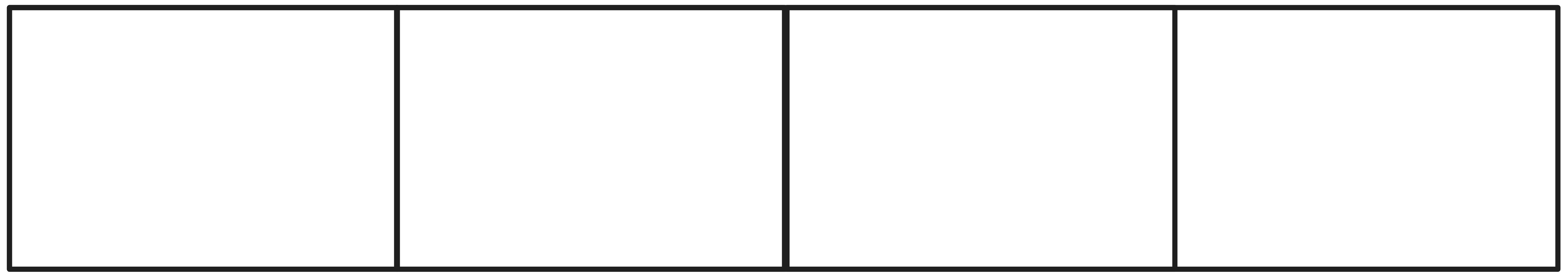
Semaphores

```
SomeStruct {
    ...
}
```



Mutex: Locked

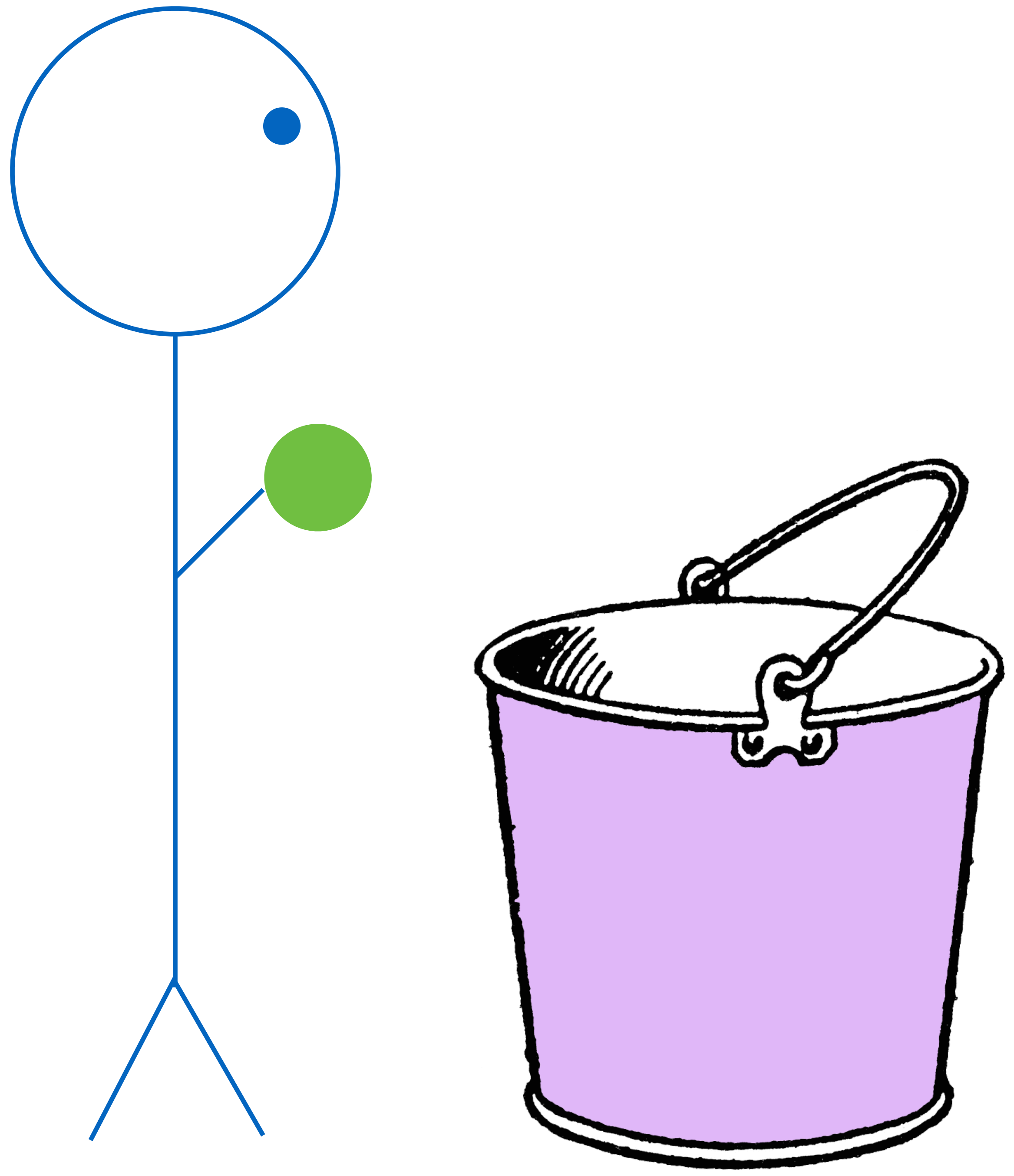
Buffer:



Semaphores

mutex.unlock()

```
SomeStruct {
    ...
}
```



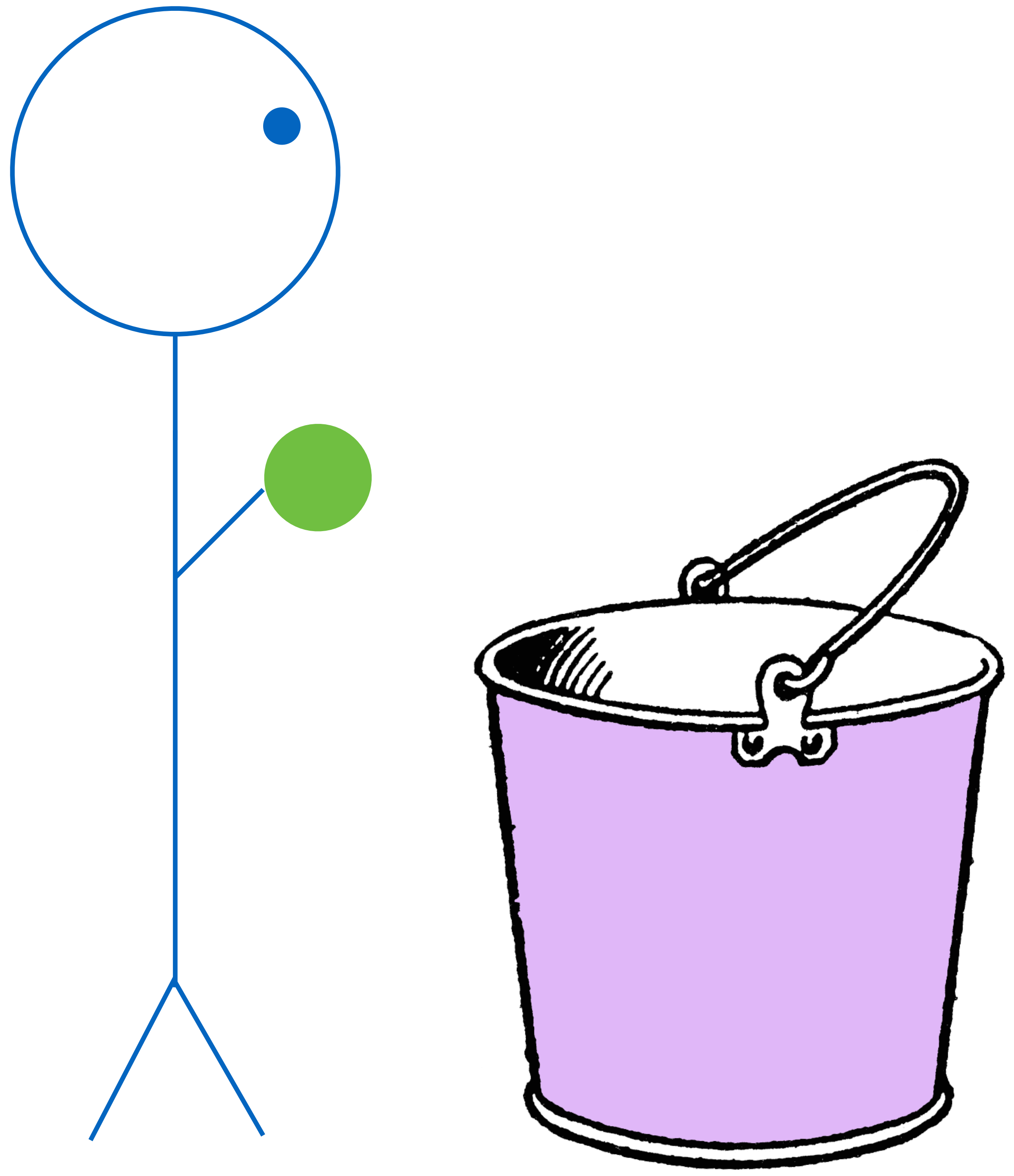
Mutex: Locked

Buffer:

Semaphores

mutex.unlock()

```
SomeStruct {
    ...
}
```



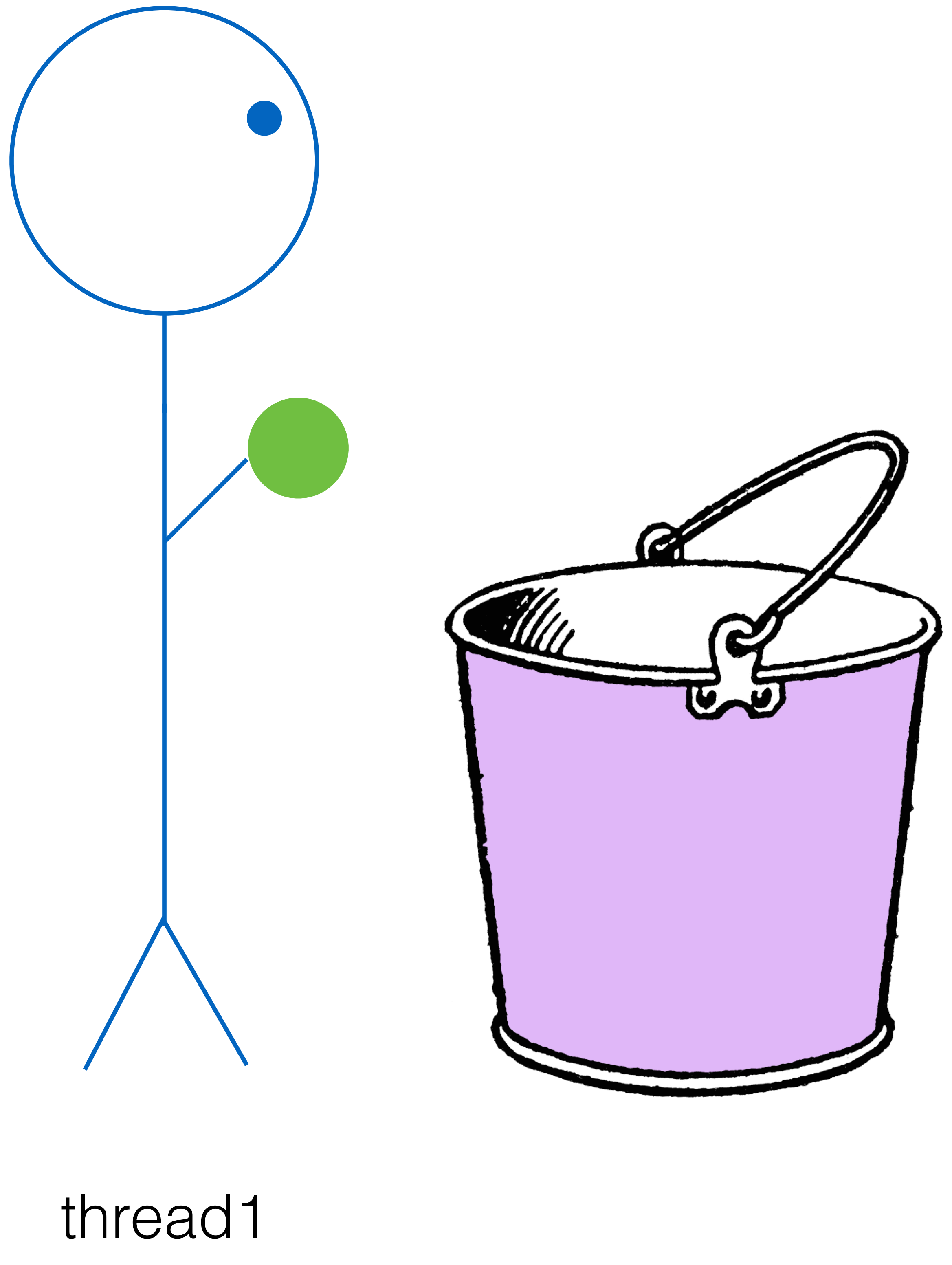
Mutex: Unlocked

Buffer:

Semaphores

semaphore.wait() (again)

```
SomeStruct {
    ...
}
```



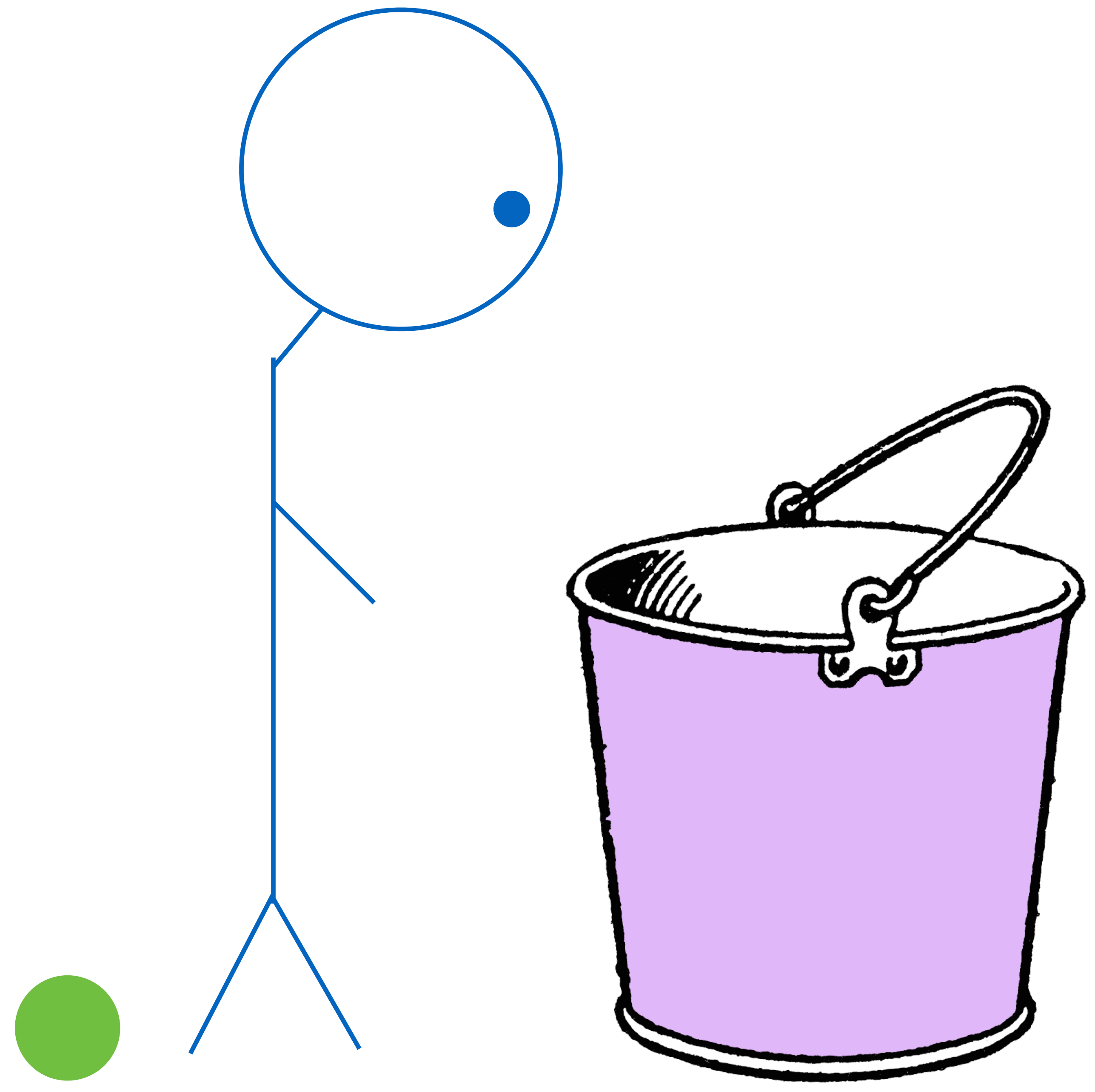
Mutex: Unlocked

Buffer:

Semaphores

semaphore.wait() (again)

```
SomeStruct {
    ...
}
```



thread1 (blocked)

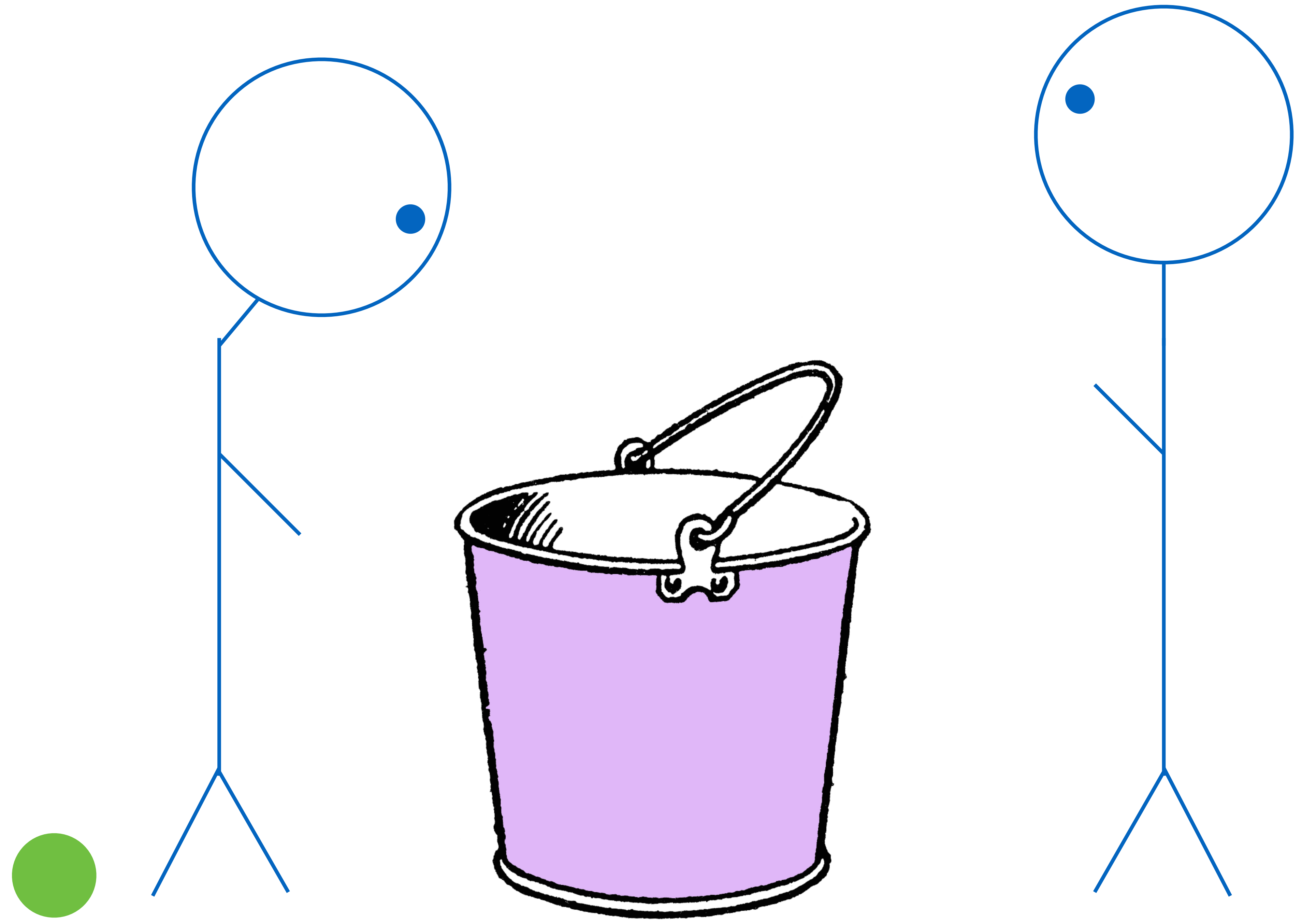
Mutex: Unlocked

Buffer:

Semaphores

semaphore.wait() (again)

SomeStruct {
    …
}



thread1 (blocked)

thread2

SomeStruct {
    …
}

Mutex: Unlocked

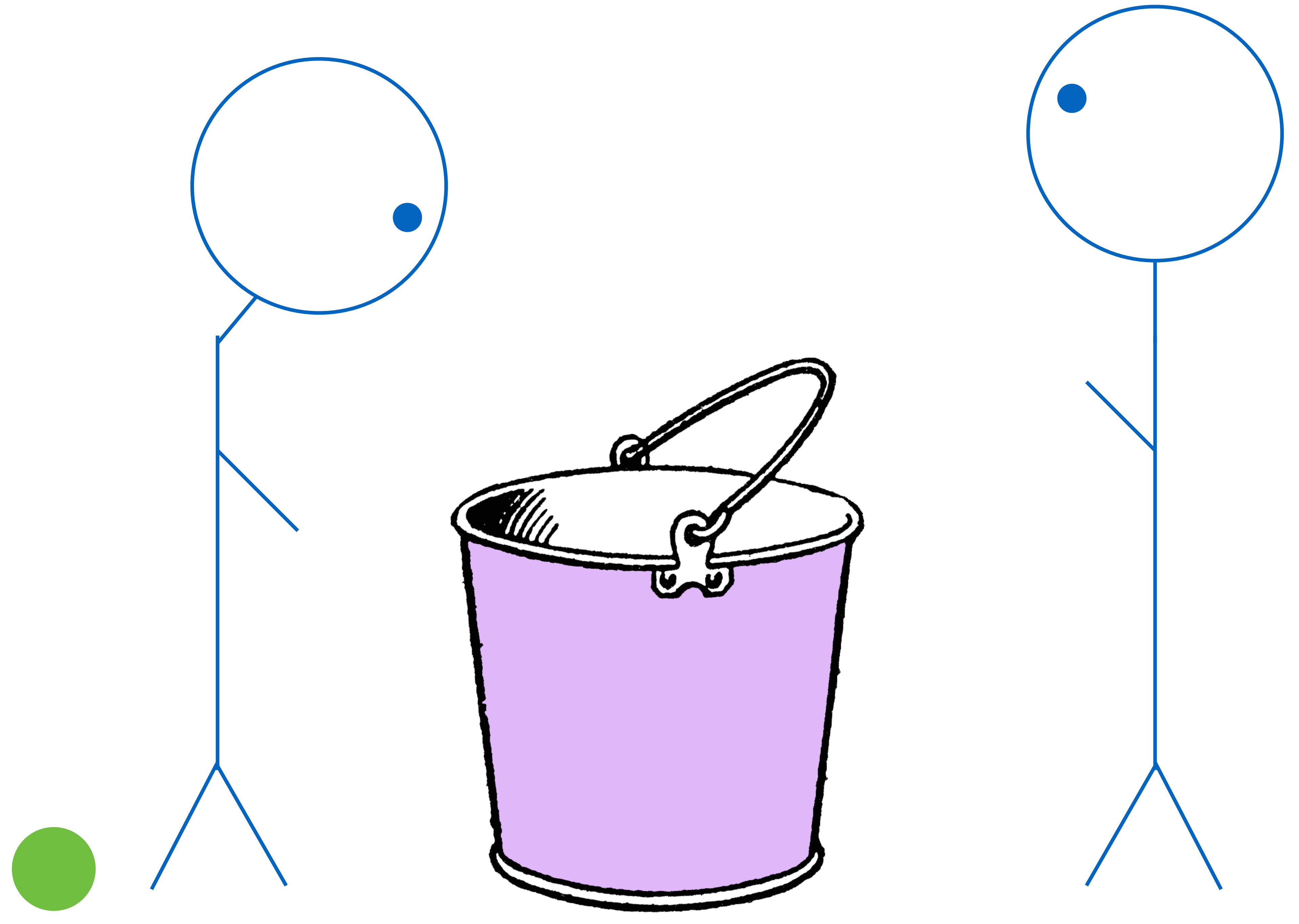
Buffer:

Semaphores

semaphore.wait() (again)

mutex.lock()

SomeStruct {
    ...
}



thread1 (blocked)

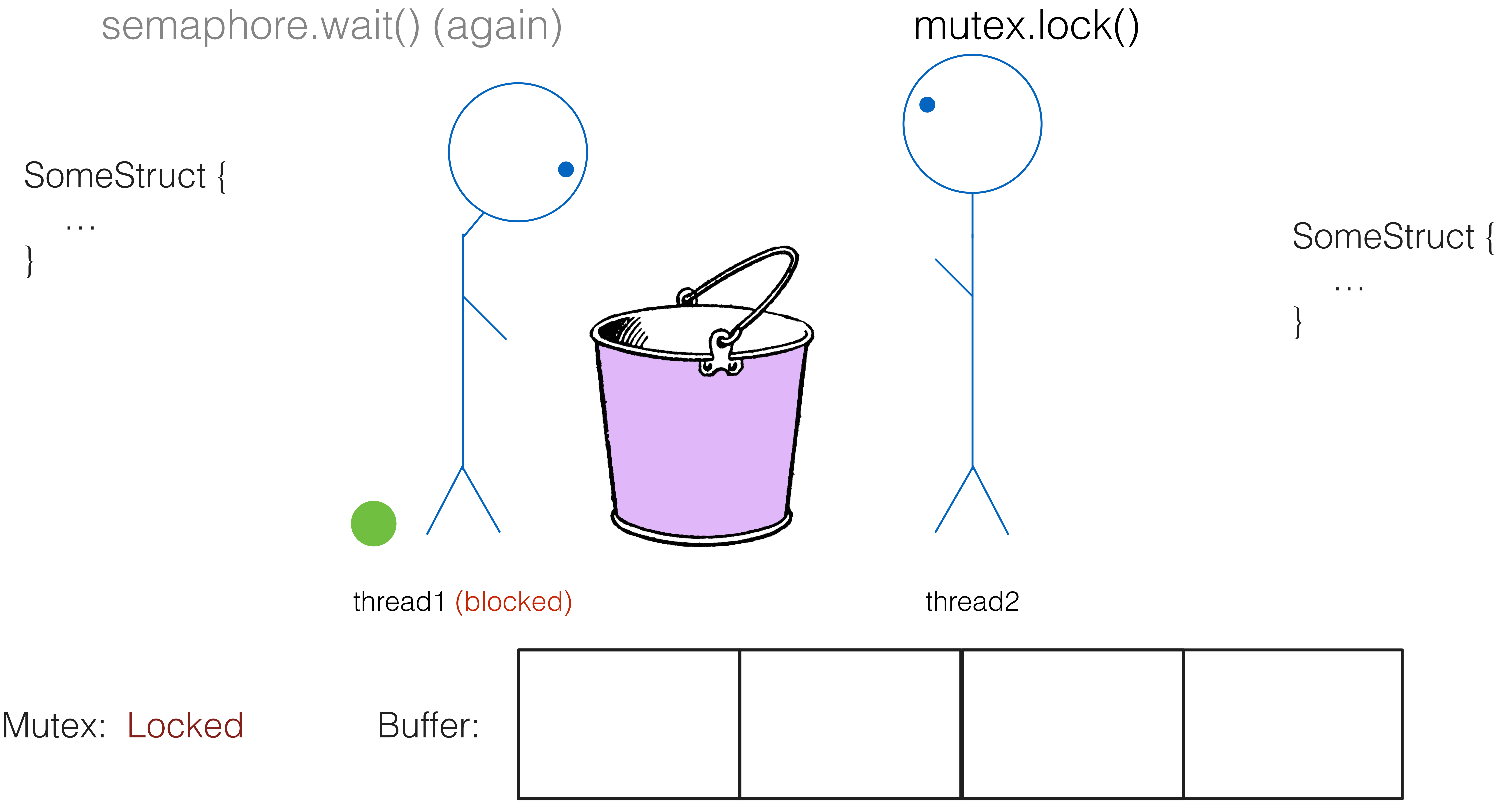
thread2

SomeStruct {
    ...
}

Mutex: Unlocked

Buffer:

Semaphores

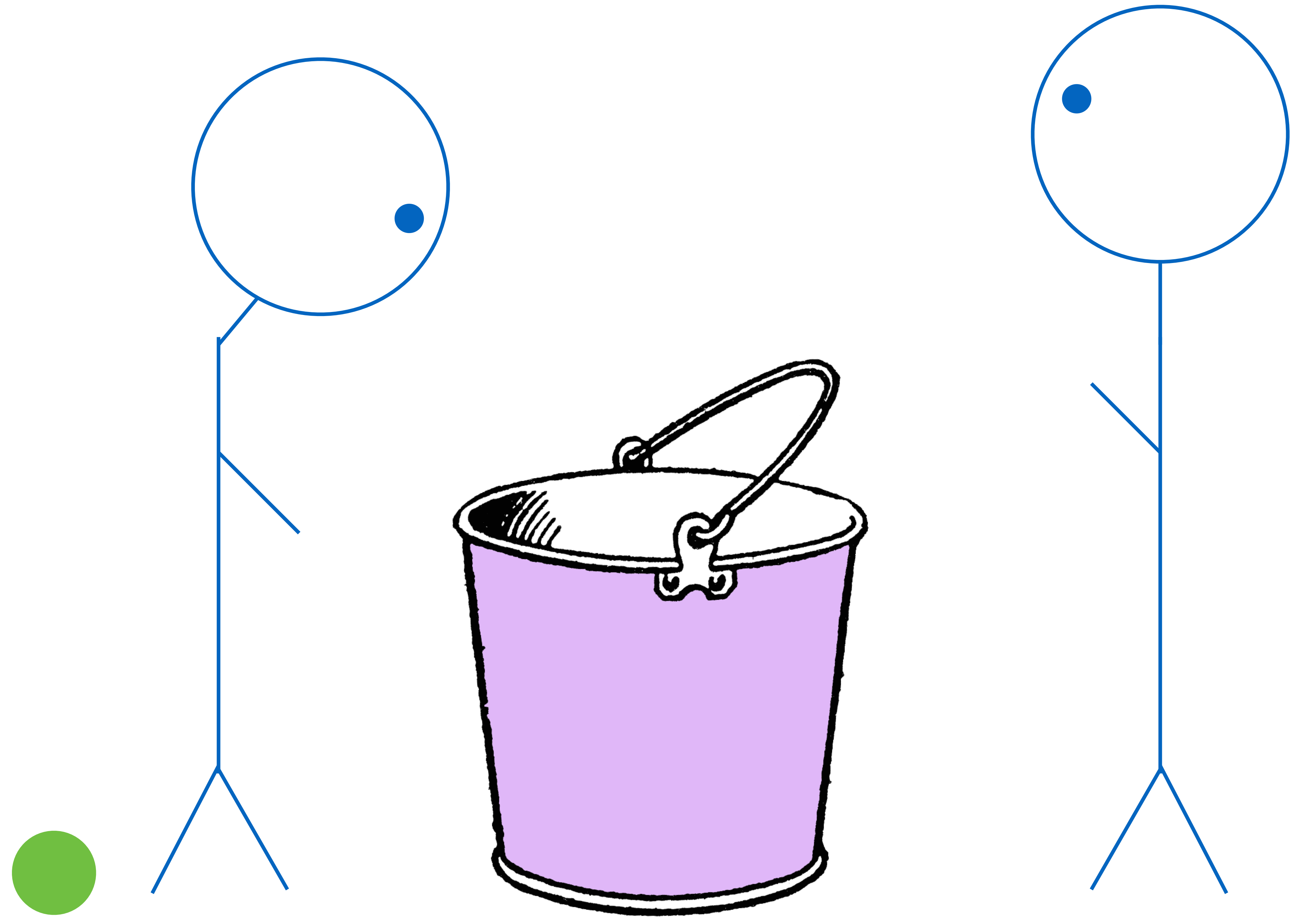


semaphore.wait() (again)
mutex.lock()
SomeStruct {
…
}
SomeStruct {
…
}
thread1 (blocked)
thread2
Mutex: Locked
Buffer:

Semaphores

semaphore.wait() (again)

```
SomeStruct {
    …
}
```



Mutex: Locked

Buffer:

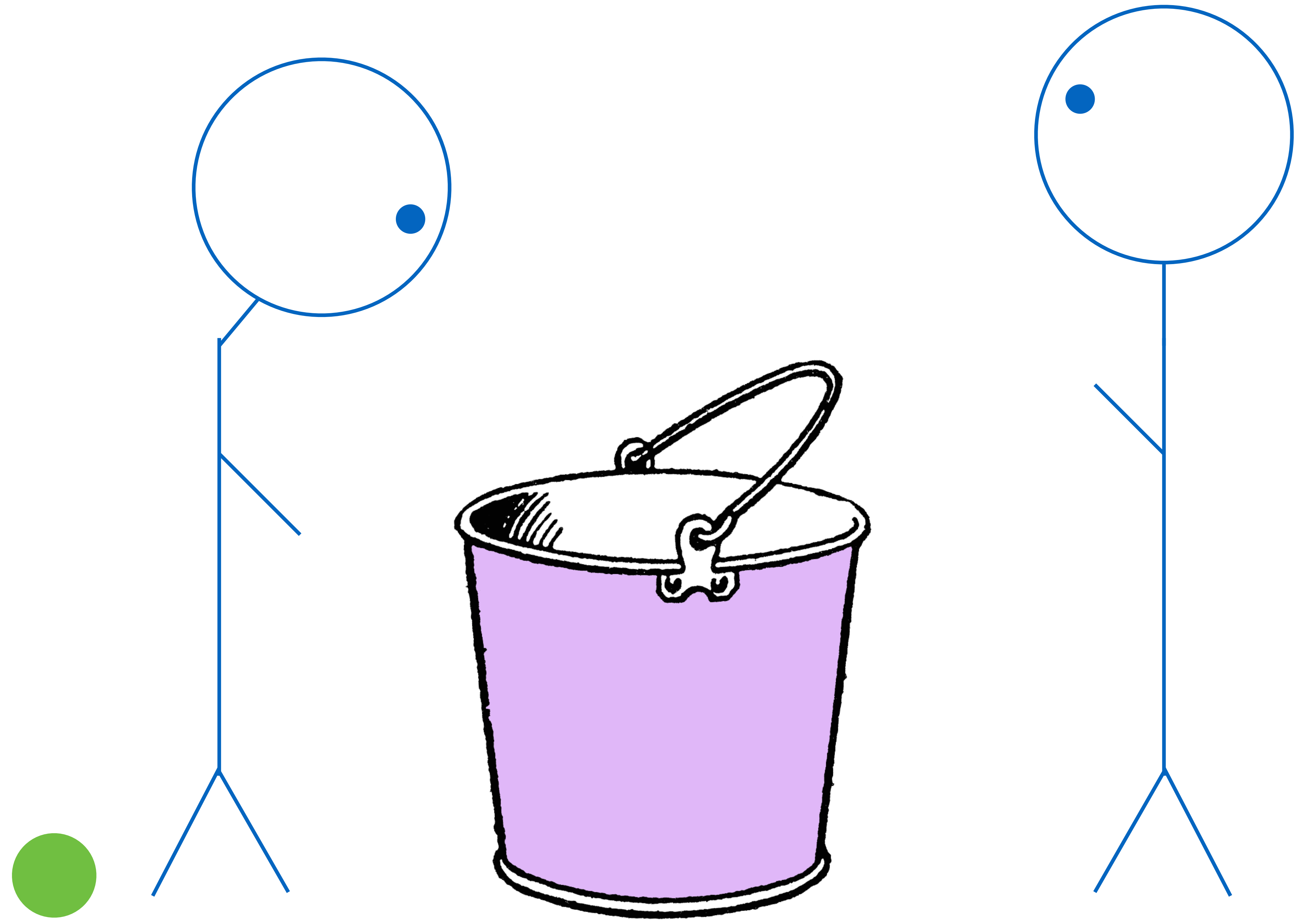
SomeStruct { … }			

Semaphores

semaphore.wait() (again)

mutex.unlock()

SomeStruct {
    …
}



thread1 (blocked)

thread2

Mutex: Locked

Buffer:

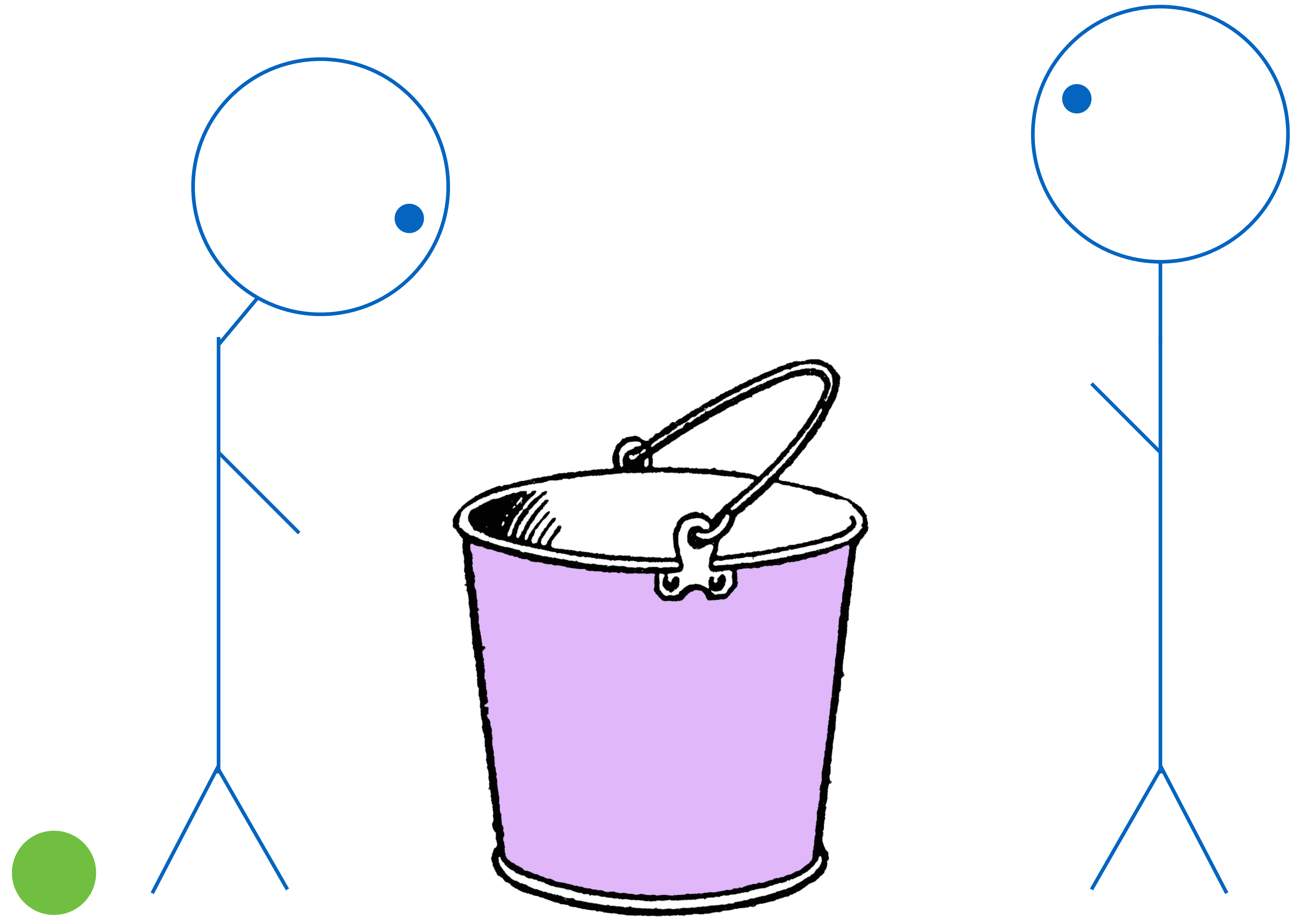
SomeStruct { … }			

Semaphores

semaphore.wait() (again)

mutex.unlock()

SomeStruct {
    …
}



thread1 (blocked)

thread2

Mutex: Unlocked

Buffer:

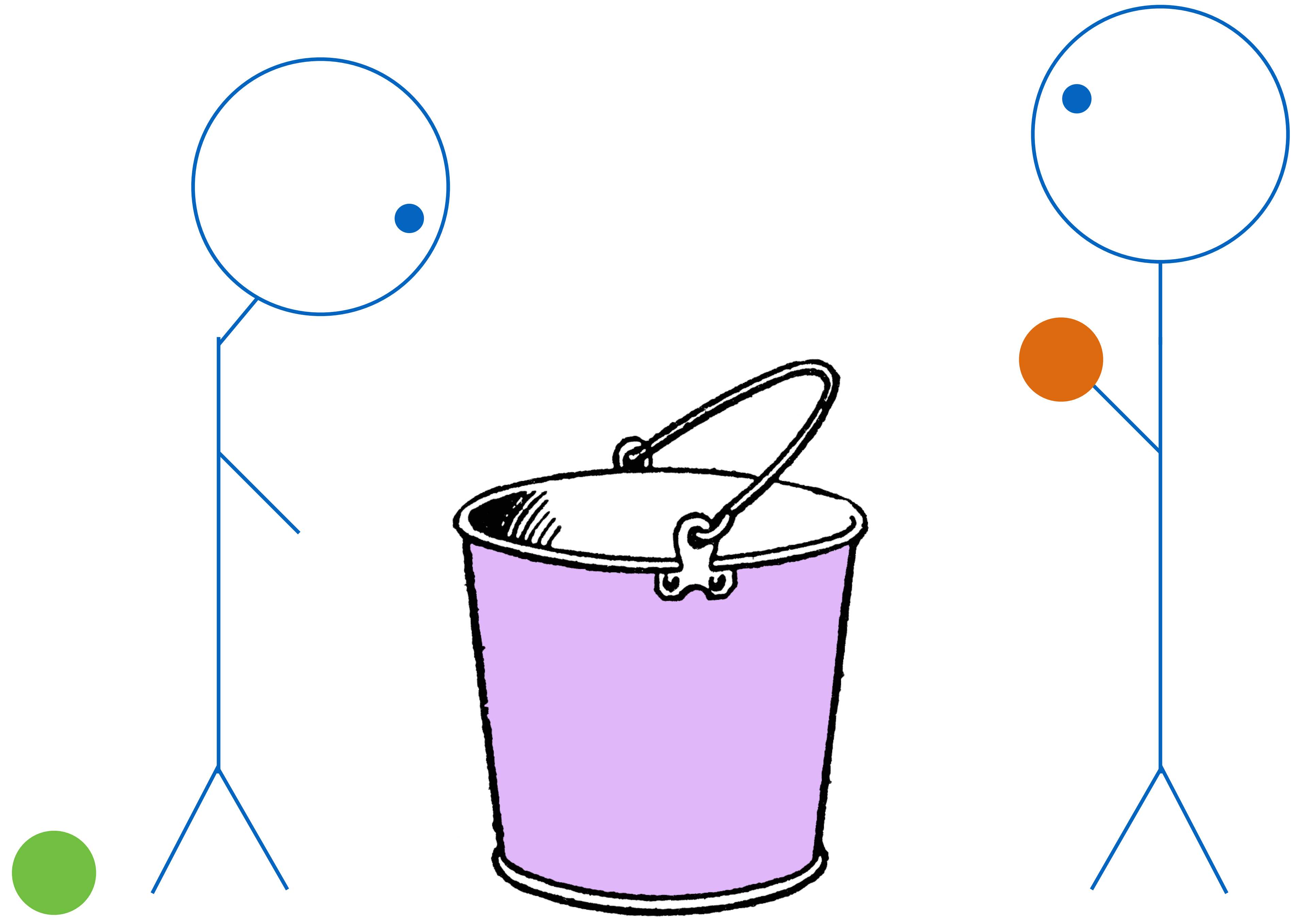
SomeStruct { … }			

Semaphores

semaphore.wait() (again)

semaphore.signal()

```
SomeStruct {
    …
}
```



thread1 (blocked)

thread2

Mutex: Unlocked

Buffer:

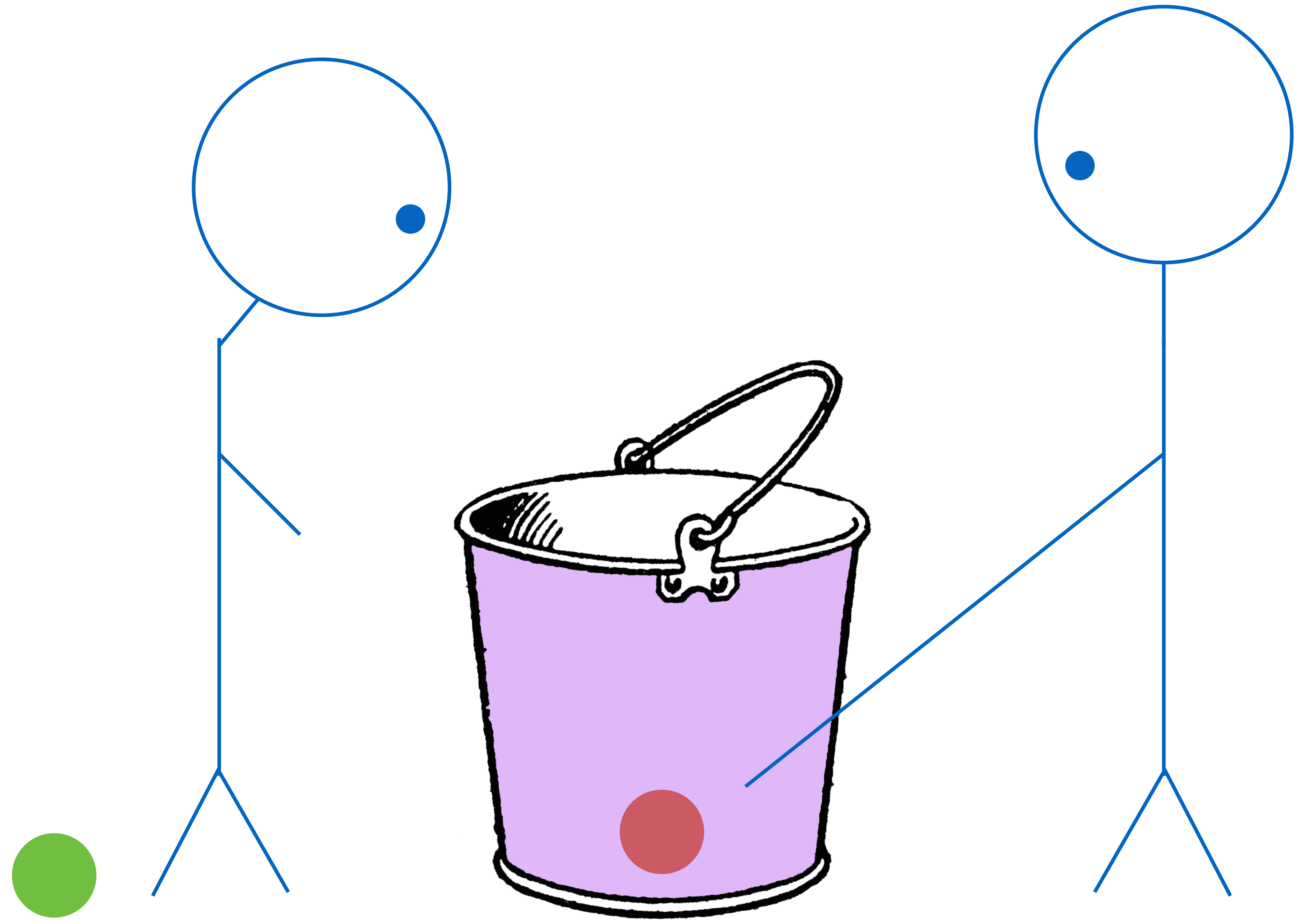
SomeStruct { … }			

Semaphores

semaphore.wait() (again)

semaphore.signal()

```
SomeStruct {
    …
}
```



thread1 (blocked)

thread2

Mutex: Unlocked

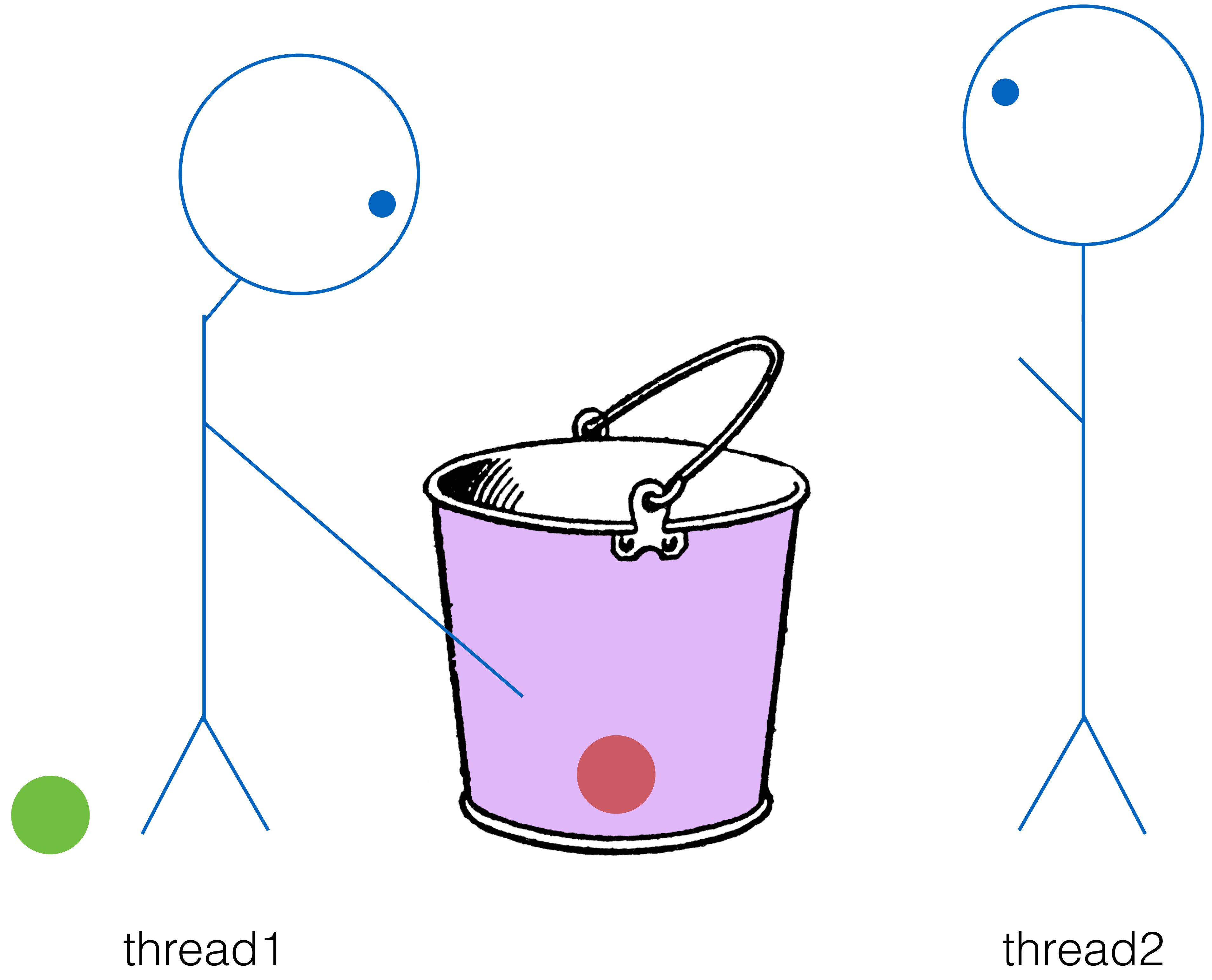
Buffer:

SomeStruct { … }			

Semaphores

semaphore.wait() (again)

SomeStruct {
    …
}



Mutex: Unlocked

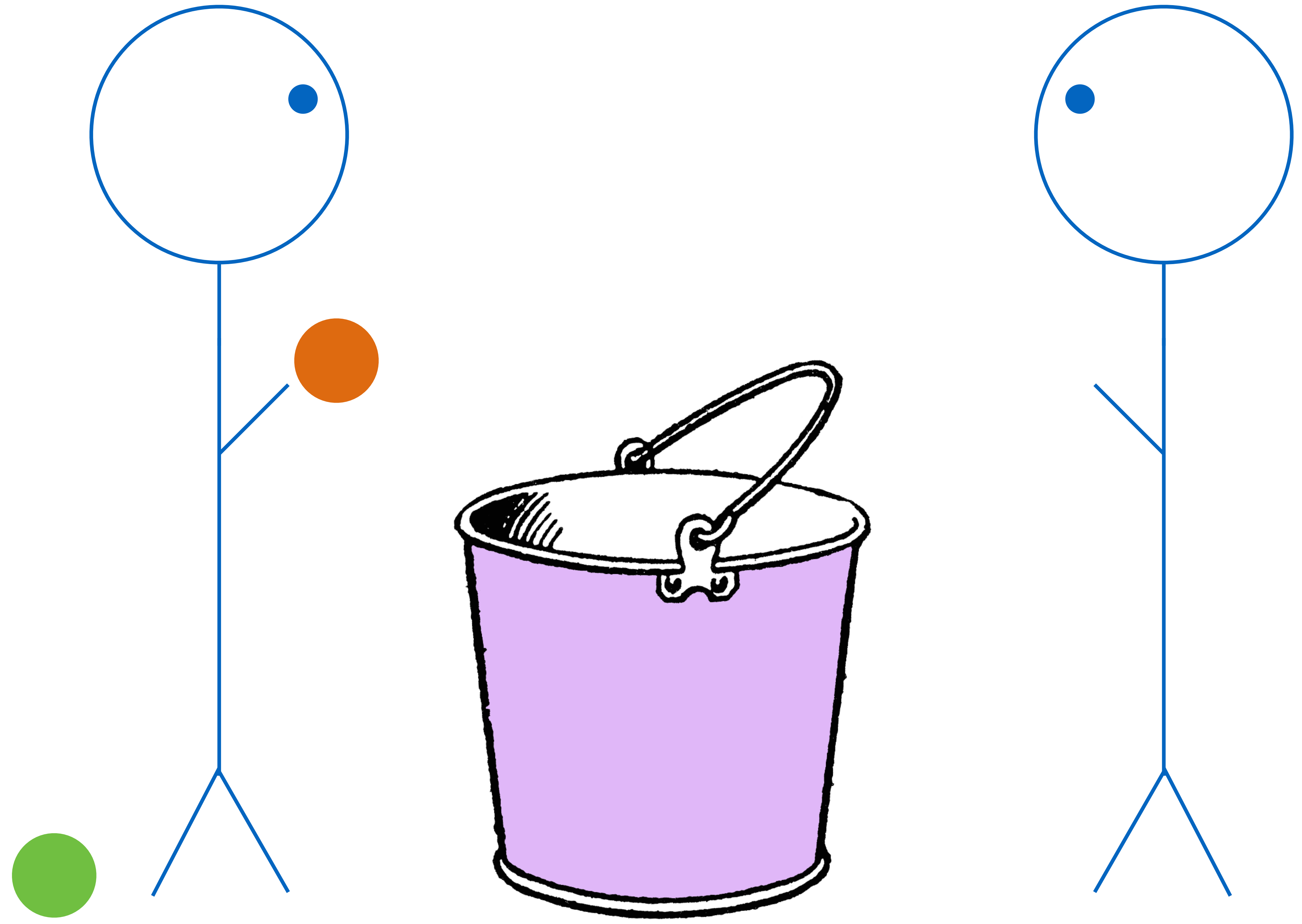
Buffer:

SomeStruct { … }			

Semaphores

semaphore.wait() (again)

SomeStruct {
    …
}

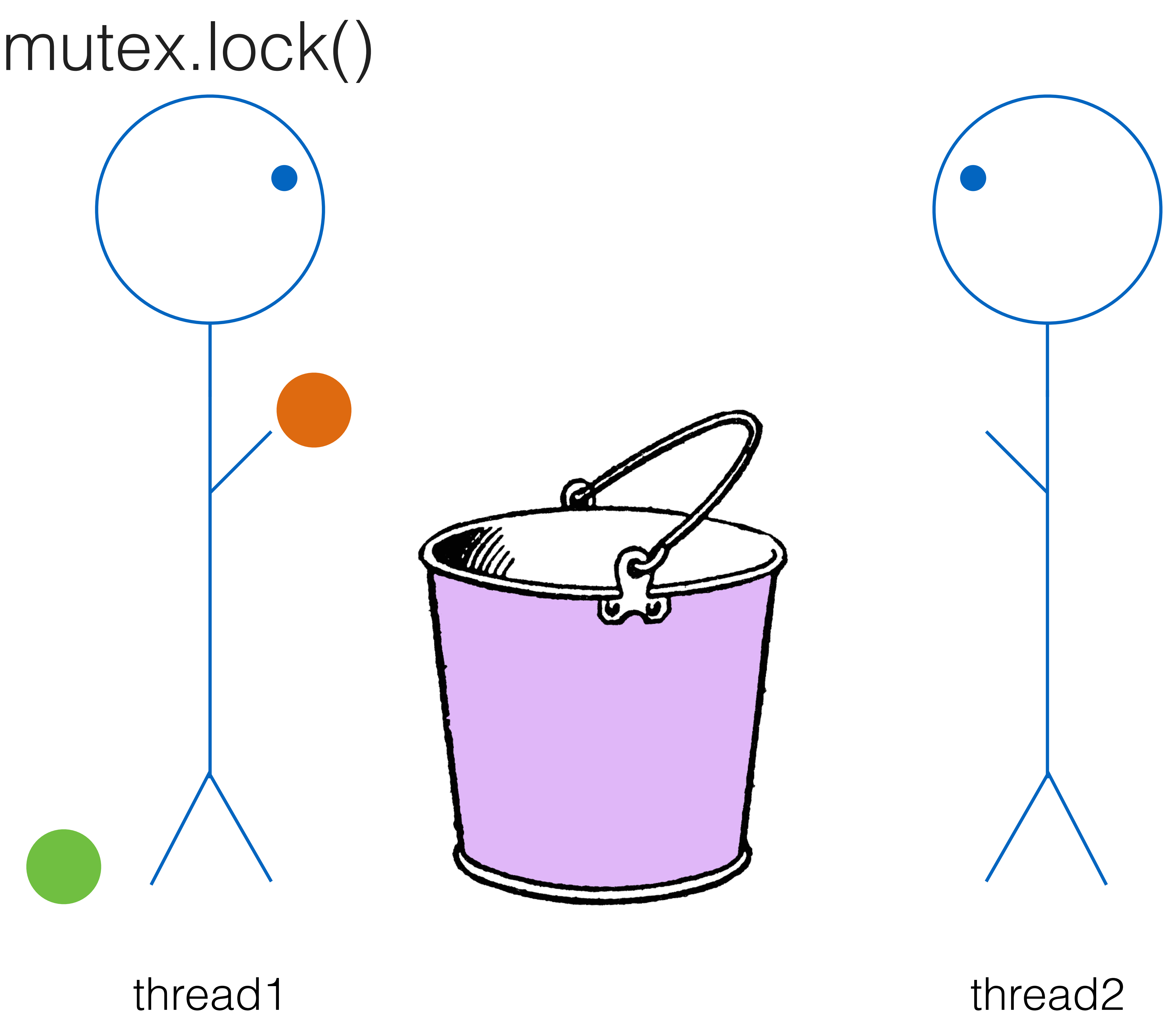


Mutex: Unlocked

Buffer:

SomeStruct { … }			

Semaphores



```
SomeStruct {
    …
}
```

Mutex: Unlocked

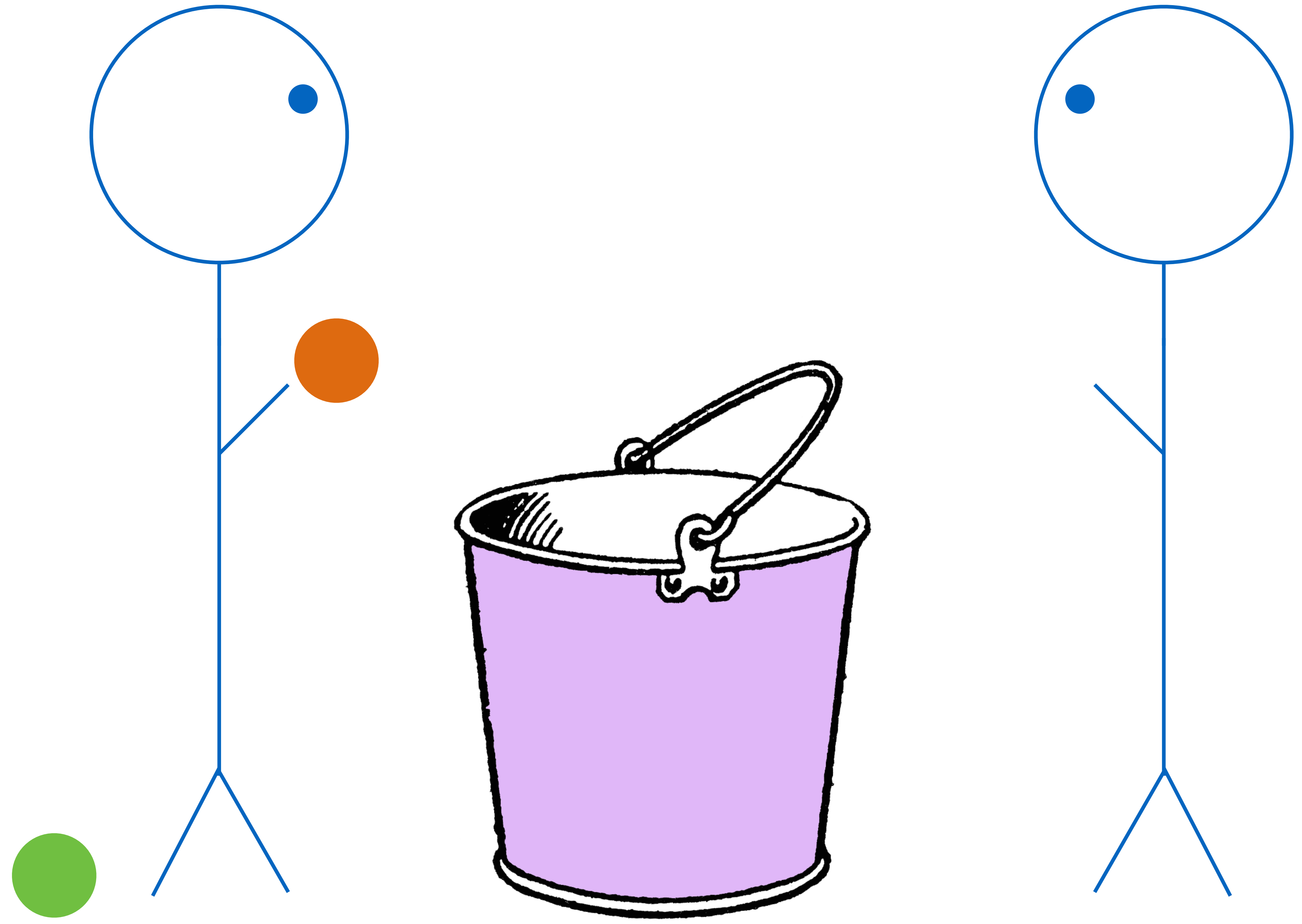
Buffer:

SomeStruct { … }			

Semaphores

mutex.lock()

SomeStruct {
    …
}



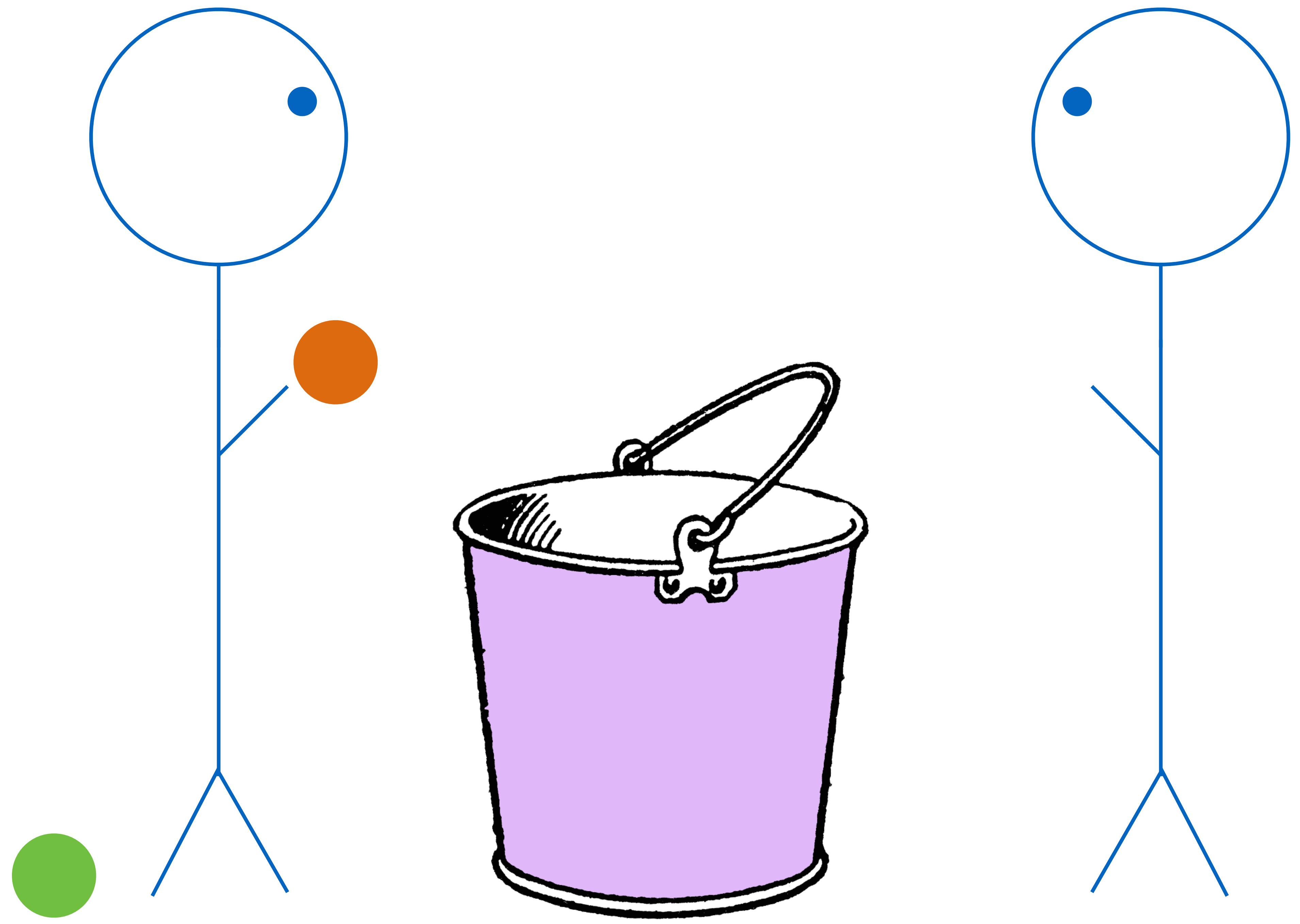
Mutex: Locked

Buffer:

SomeStruct { … }			

Semaphores

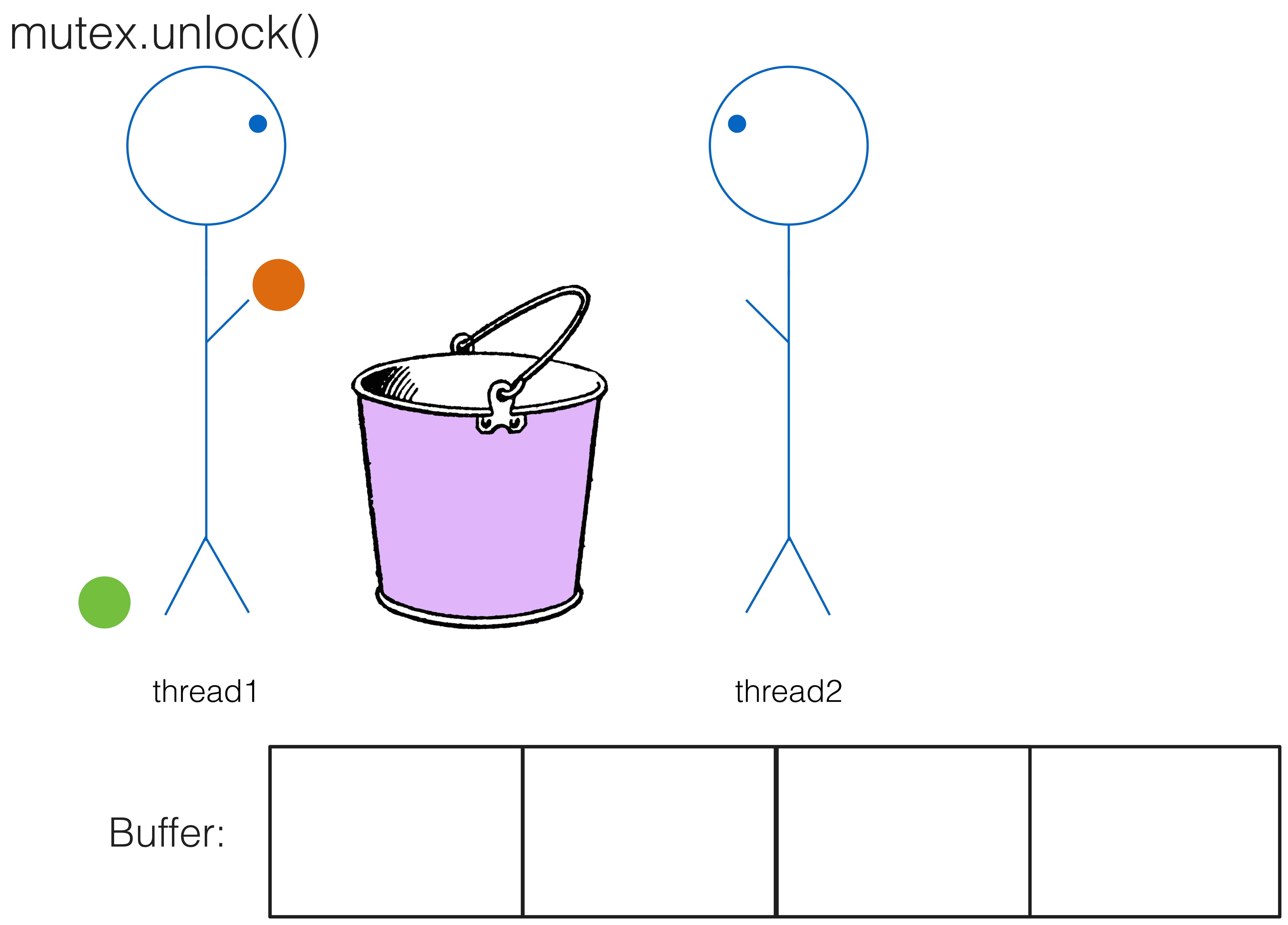
```
SomeStruct {
    ...
}

SomeStruct {
    ...
}
```



Mutex: Locked

Buffer:

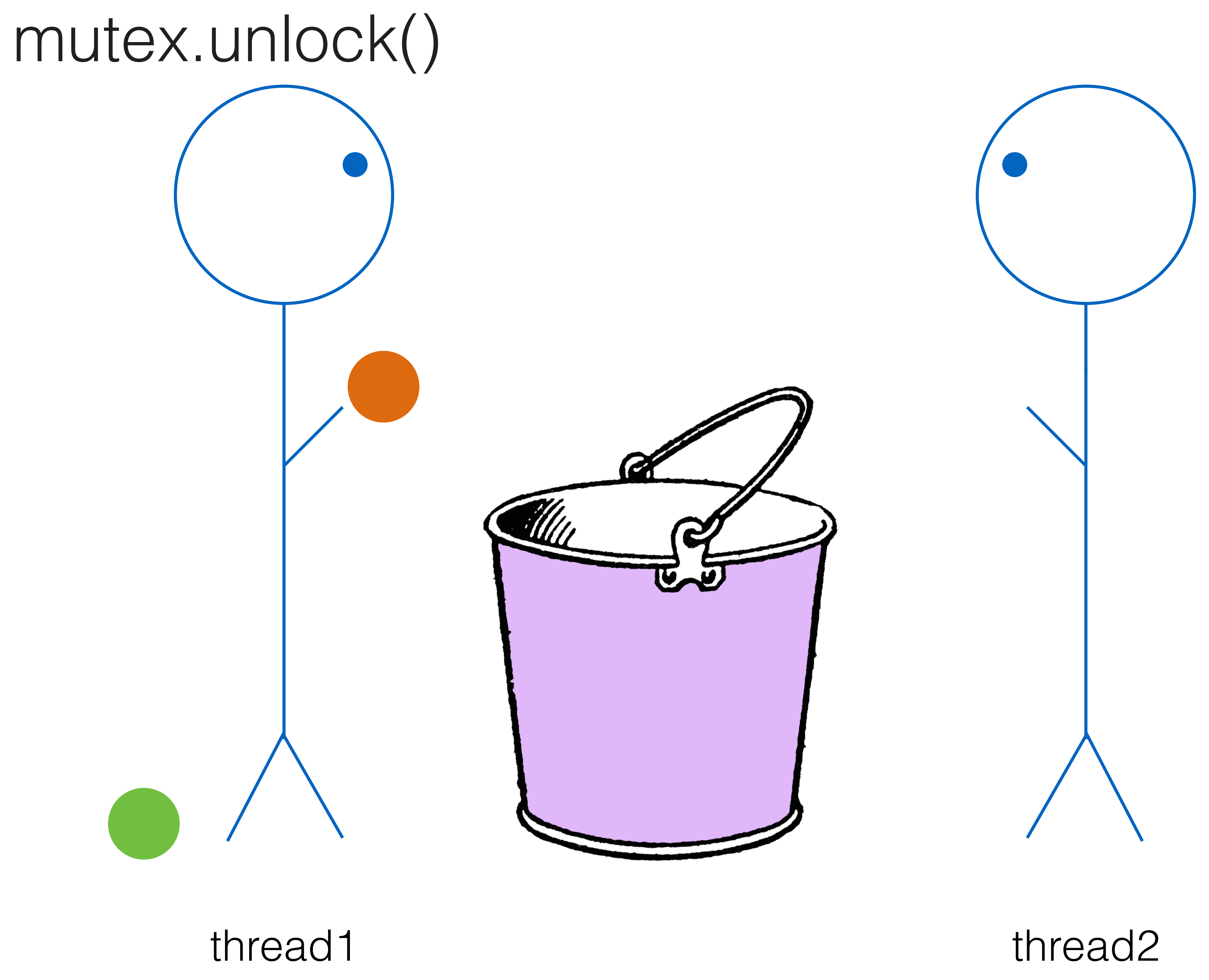
Semaphores


mutex.unlock()
SomeStruct {
...
}
SomeStruct {
...
}
thread1
thread2
Mutex: Locked
Buffer:

Semaphores

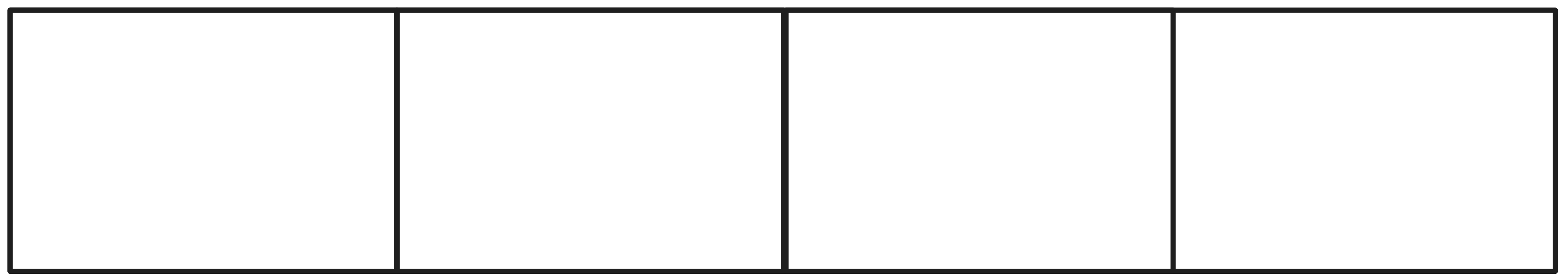
SomeStruct {
    ...
}

SomeStruct {
    ...
}

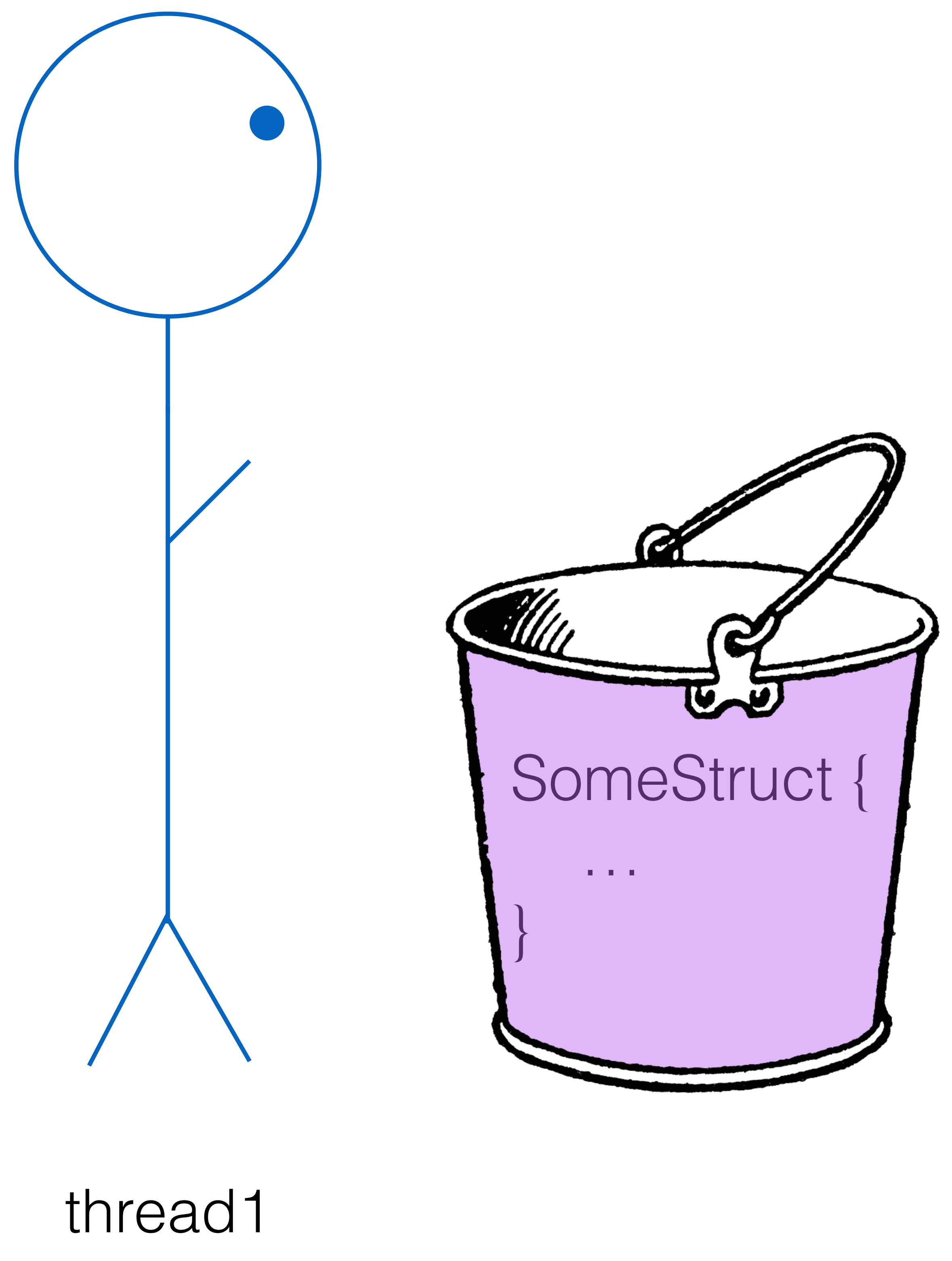


Mutex: Unlocked

Buffer:

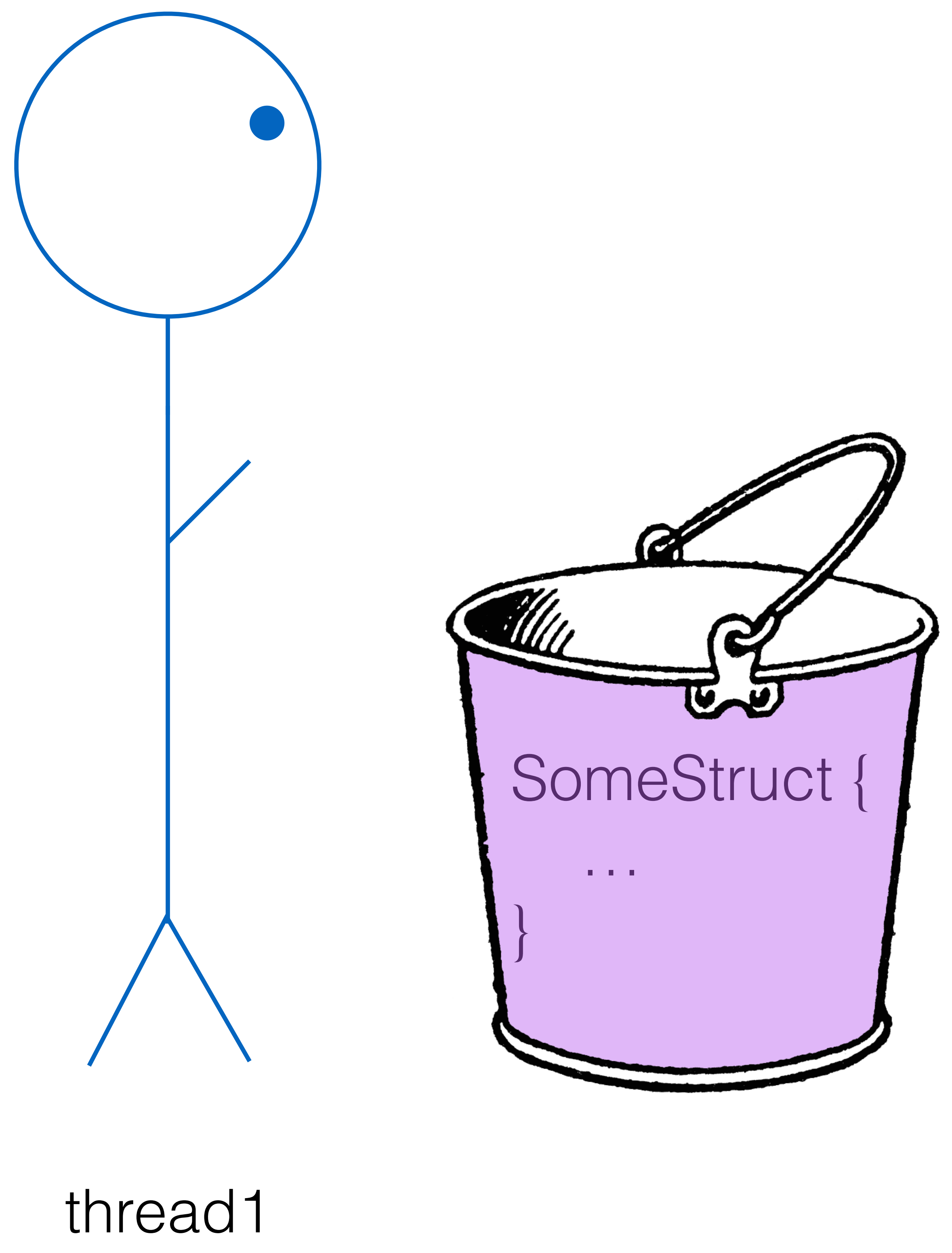


Channels



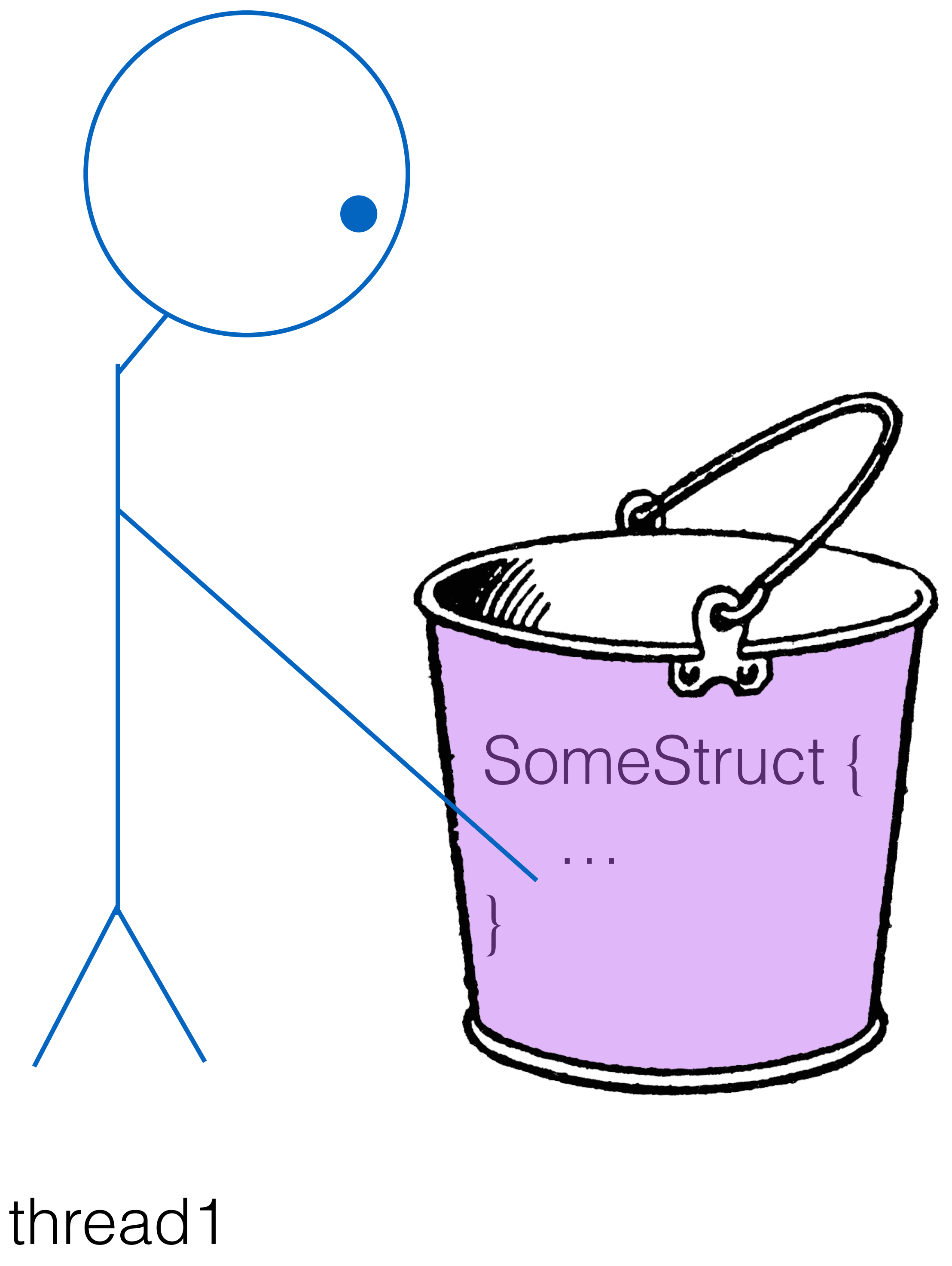
Channels

let struct = receive_end.recv().unwrap()



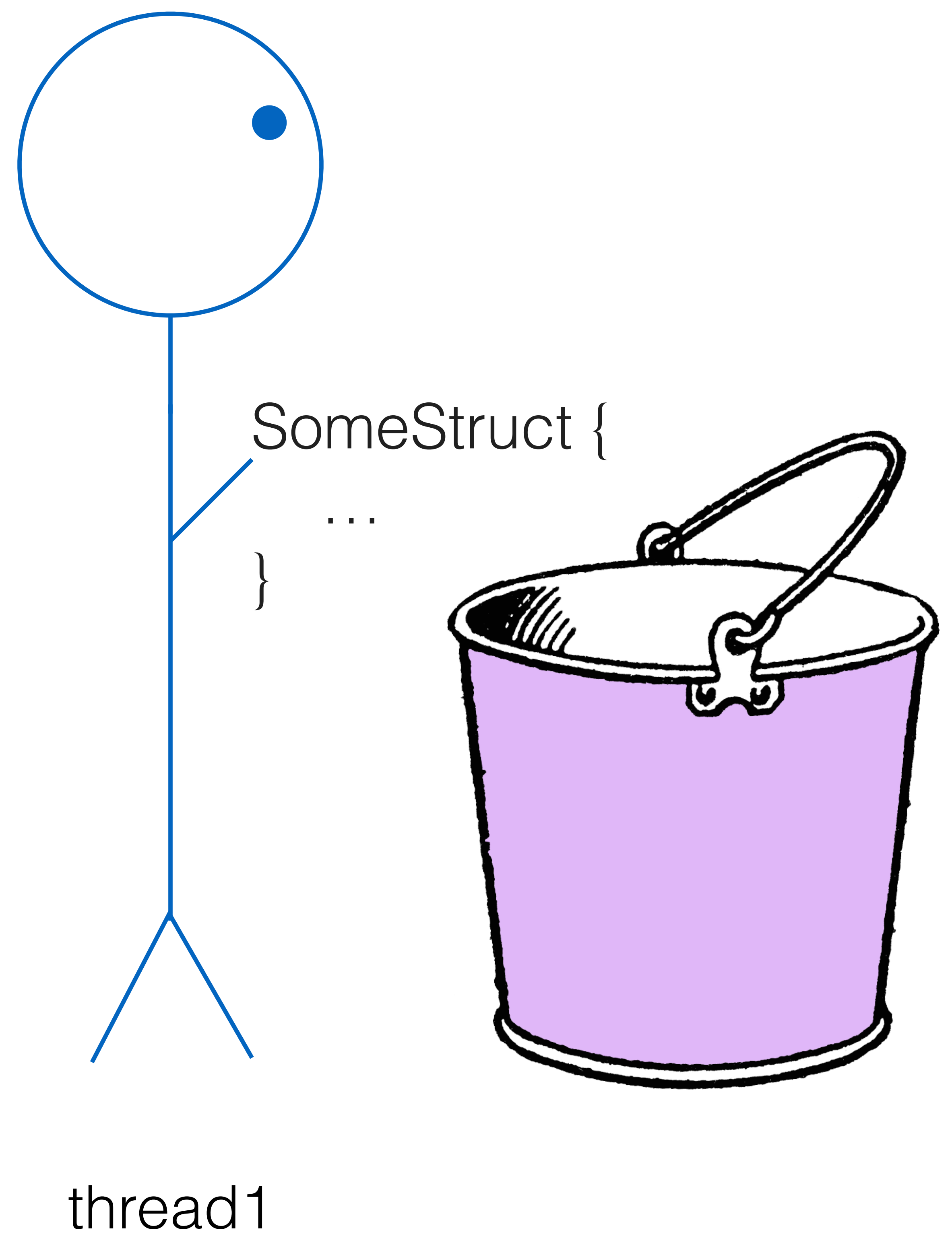
Channels

let struct = receive_end.recv().unwrap()



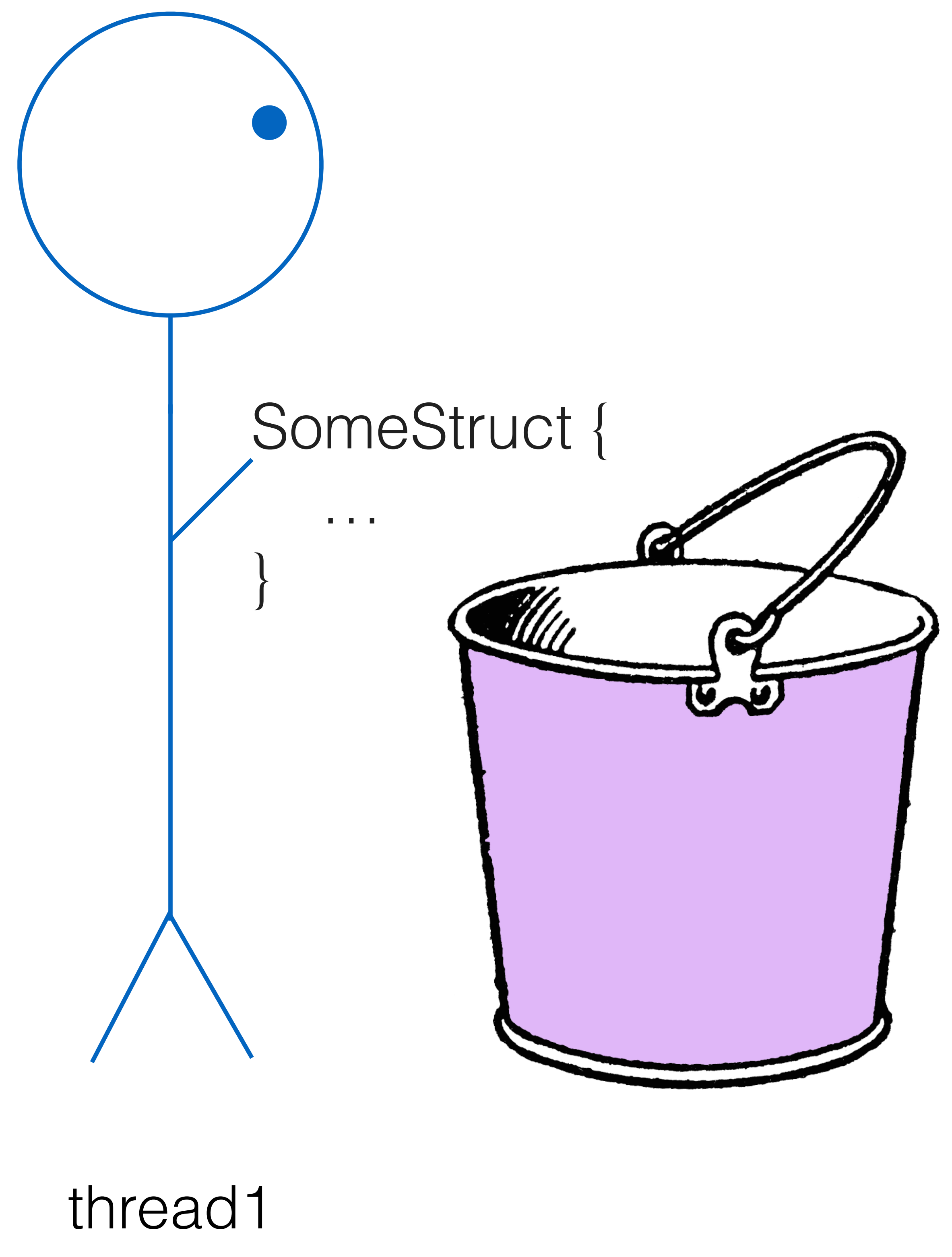
Channels

let struct = receive_end.recv().unwrap()



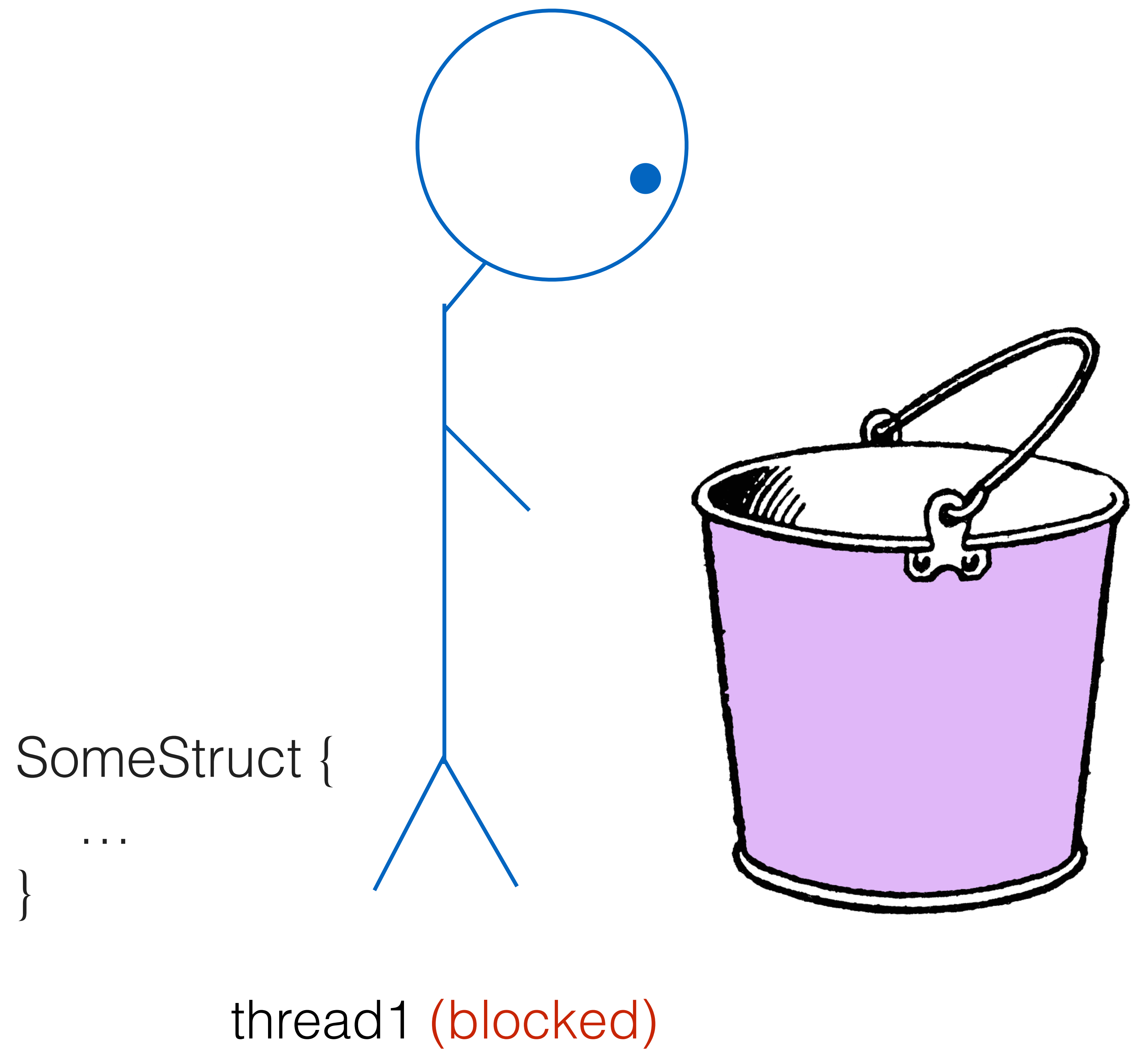
Channels

let struct2 = receive_end.recv().unwrap() (again)



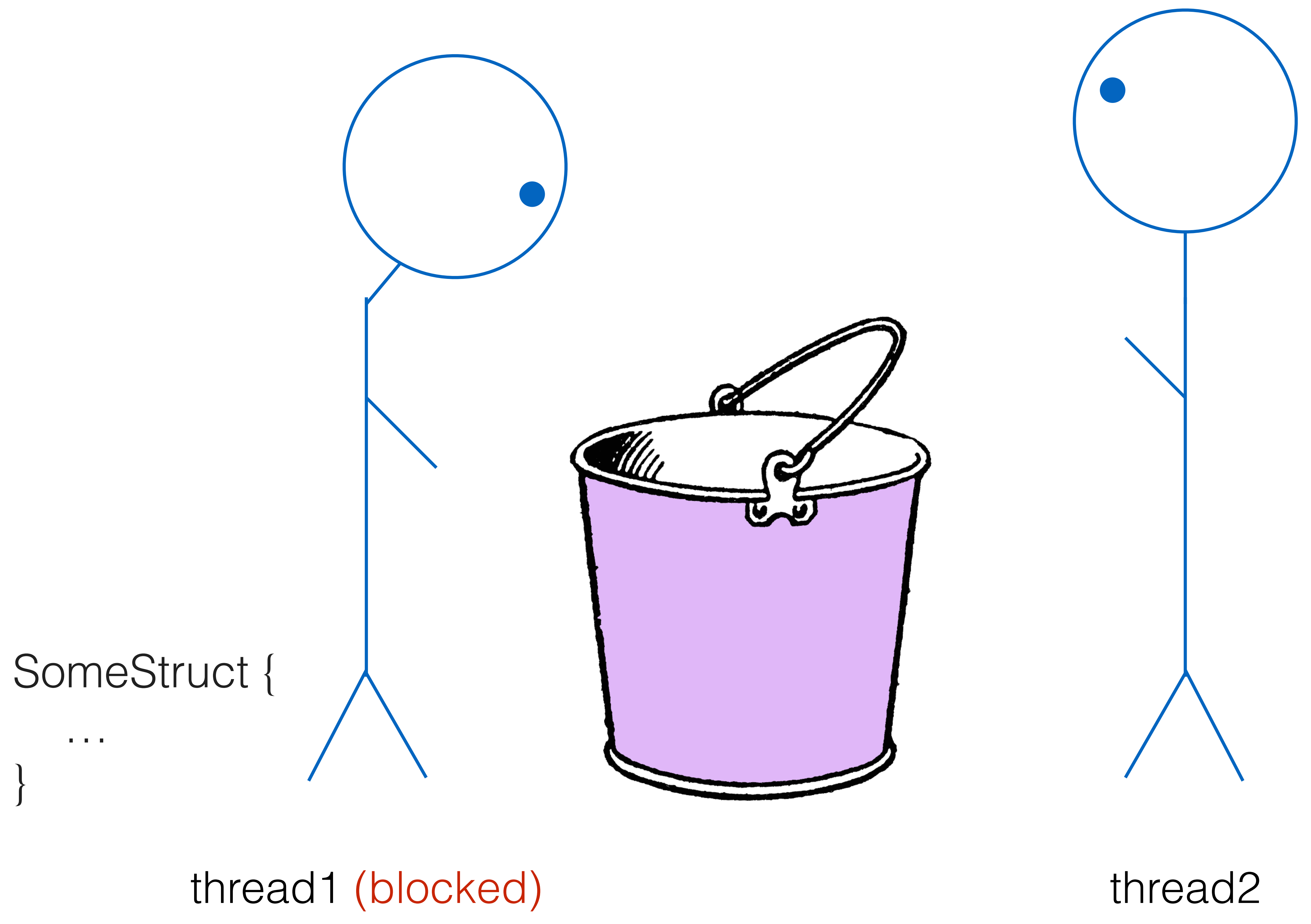
Channels

let struct2 = receive_end.recv().unwrap() (again)



Channels

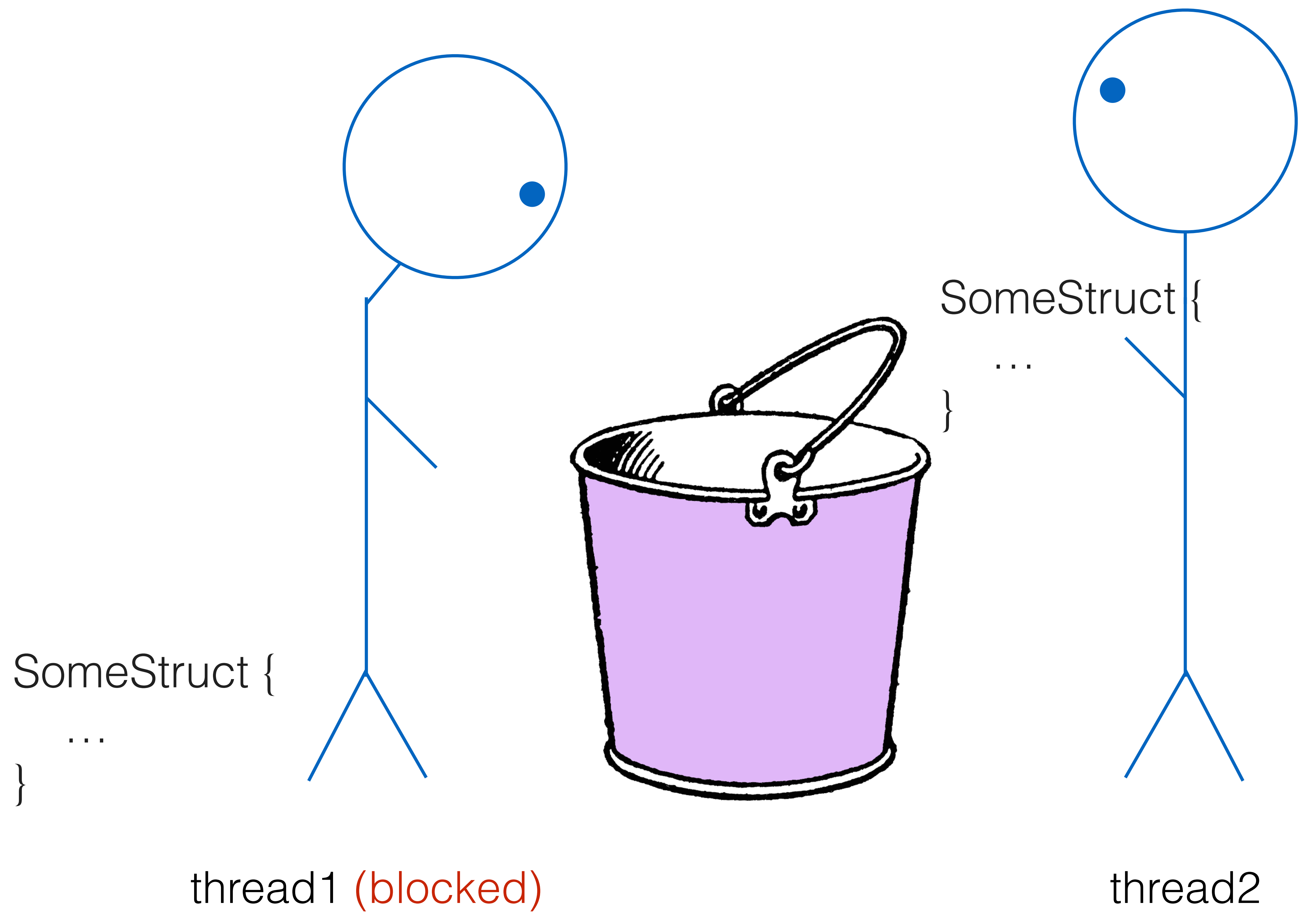
let struct2 = receive_end.recv().unwrap() (again)



Channels

let struct2 = receive_end.recv().unwrap() (again)

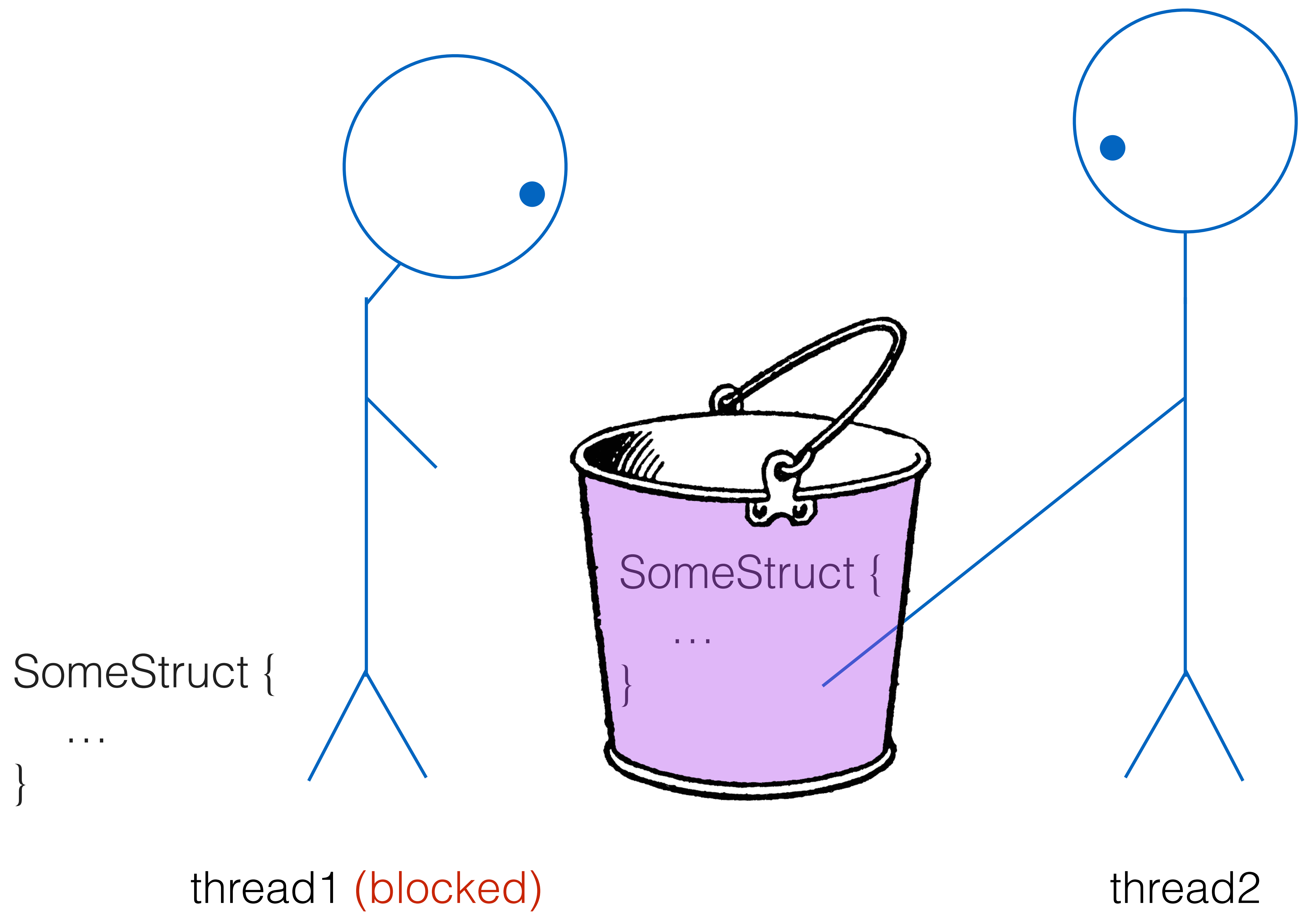
send_end.send(struct).unwrap()



Channels

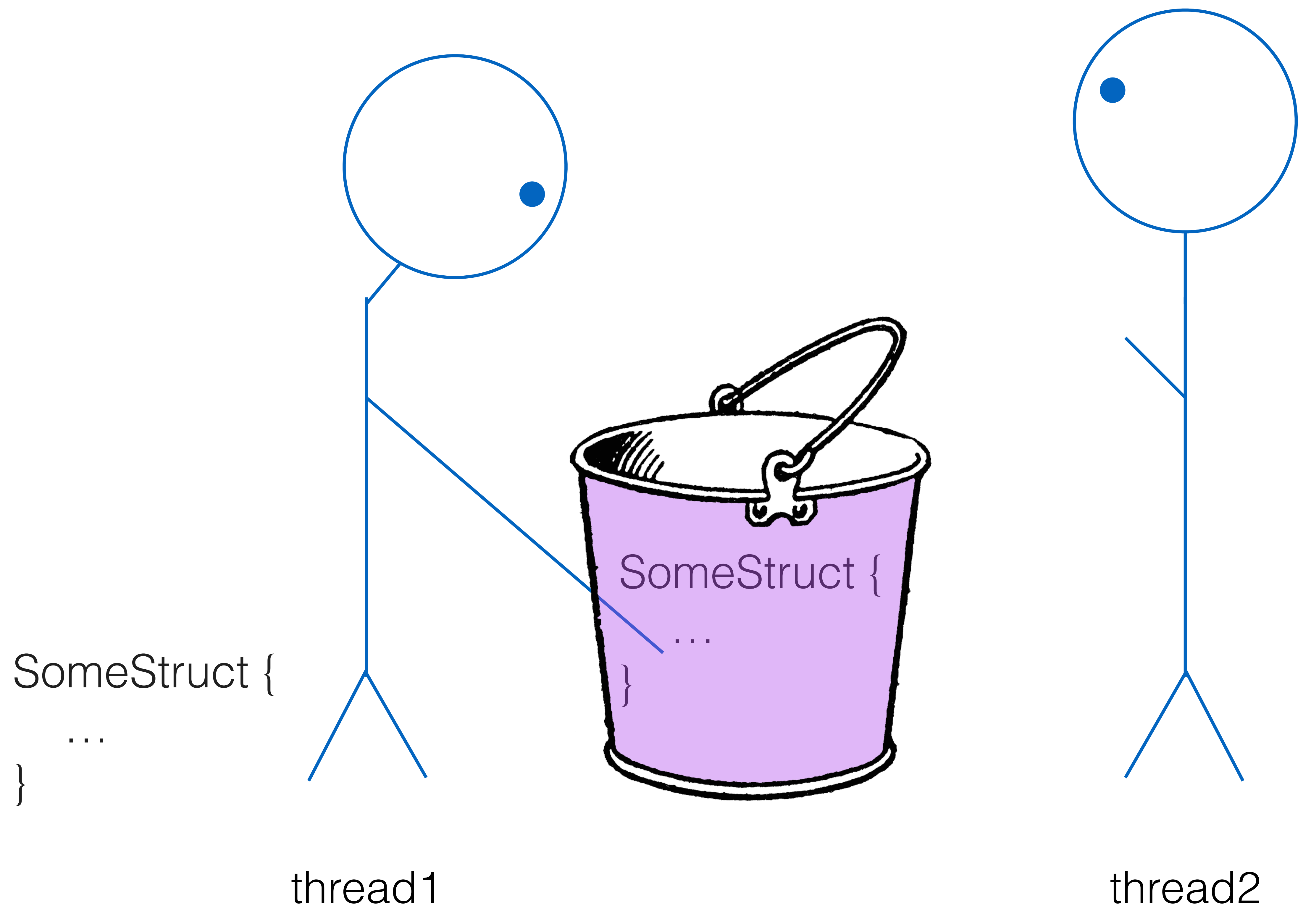
let struct2 = receive_end.recv().unwrap() (again)

send_end.send(struct).unwrap()



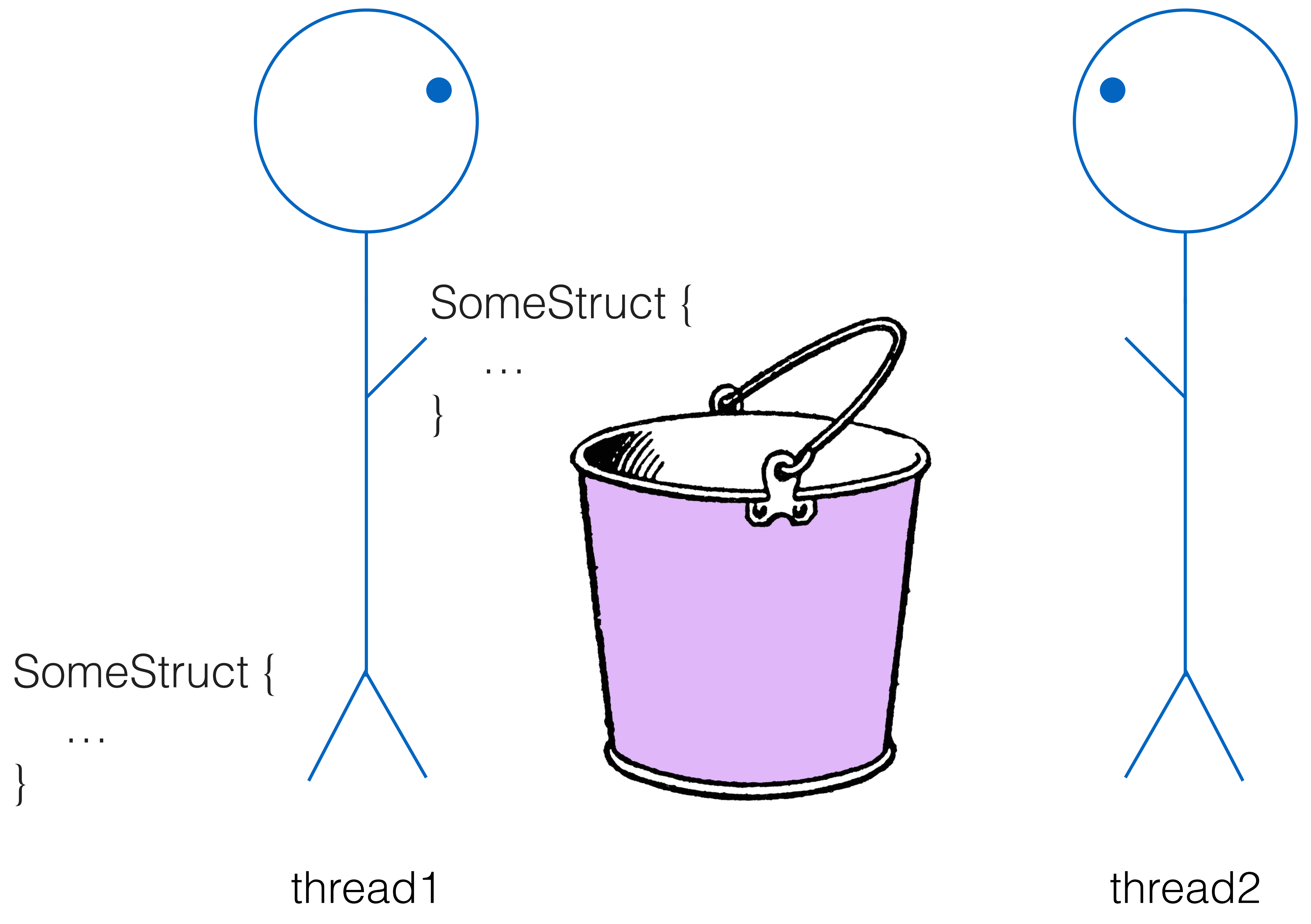
Channels

let struct2 = receive_end.recv().unwrap() (again)



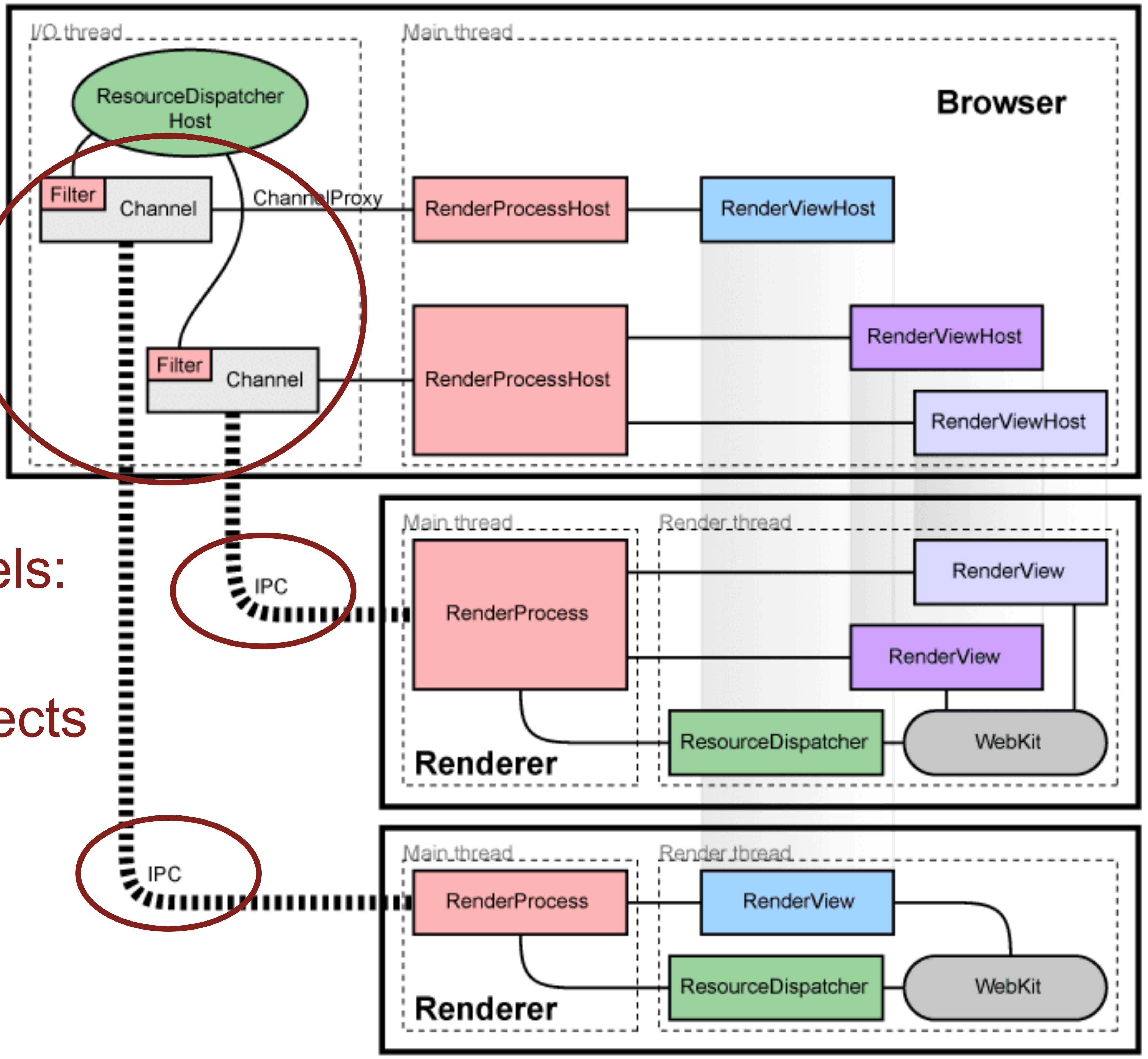
Channels

let struct2 = receive_end.recv().unwrap() (again)



Channels: like strongly-typed pipes

Chrome architecture diagram



Inter-Process Communication channels: Pipes, but with an extra layer of abstraction to serialize/deserialize objects

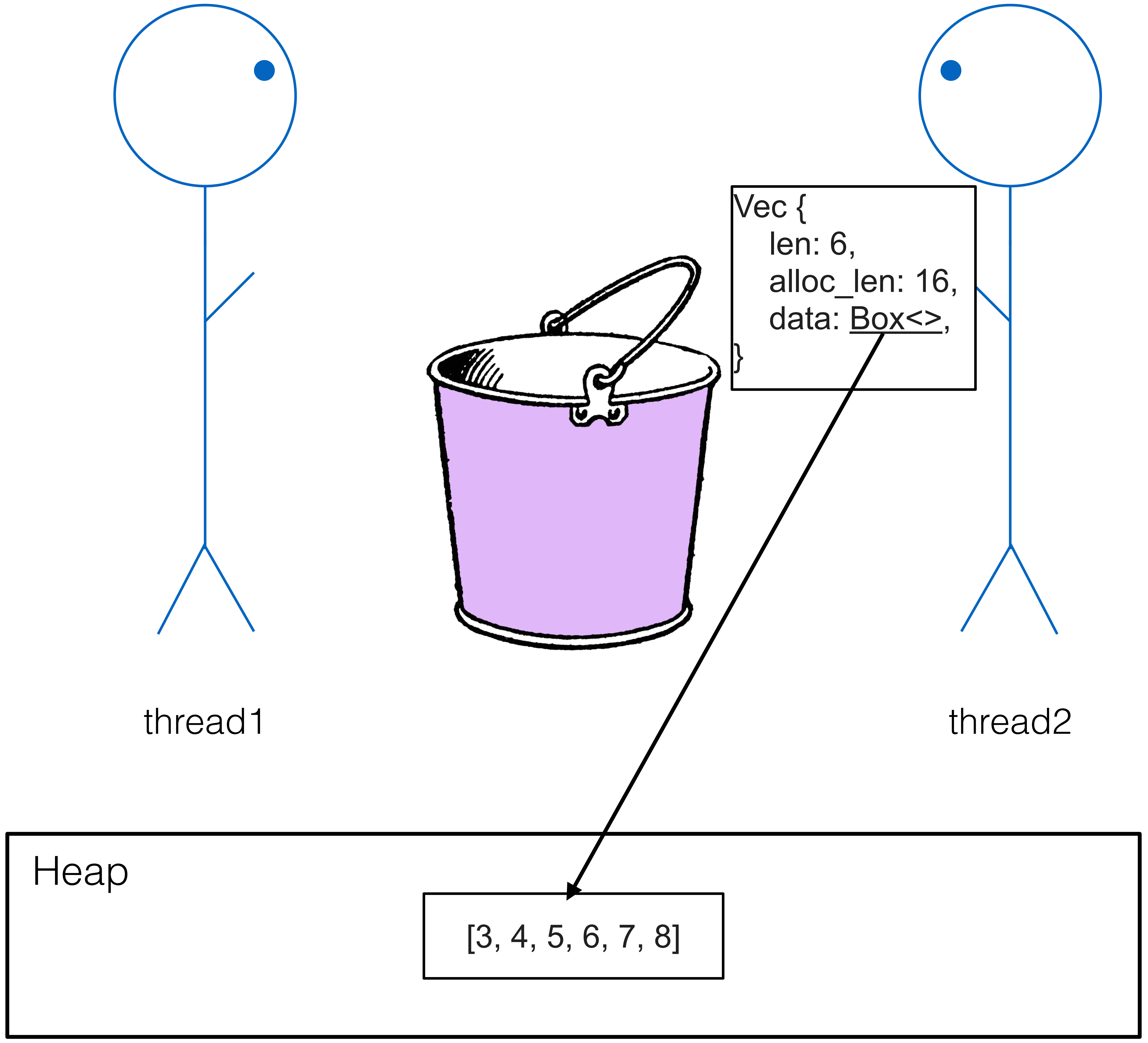
https://www.chromium.org/developers/design-documents/multi-process-architecture (slightly out of date)

Using channels

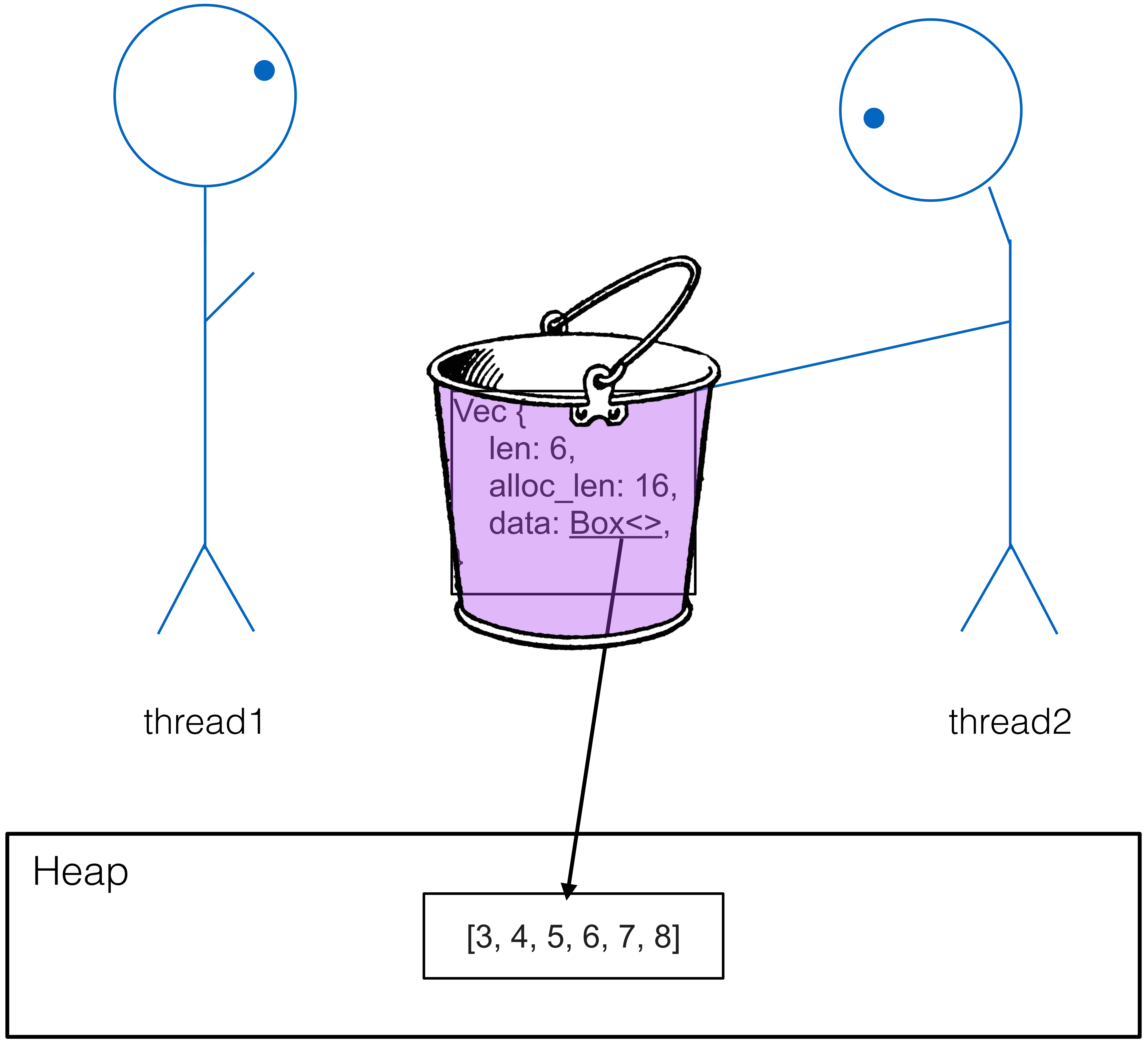
Isn’t message passing bad for performance?

- If you don’t share memory, then you need to copy data into/out of messages. That seems expensive. What gives?
- Theory != practice
    - We share *some* memory (the heap) and only make shallow copies into channels

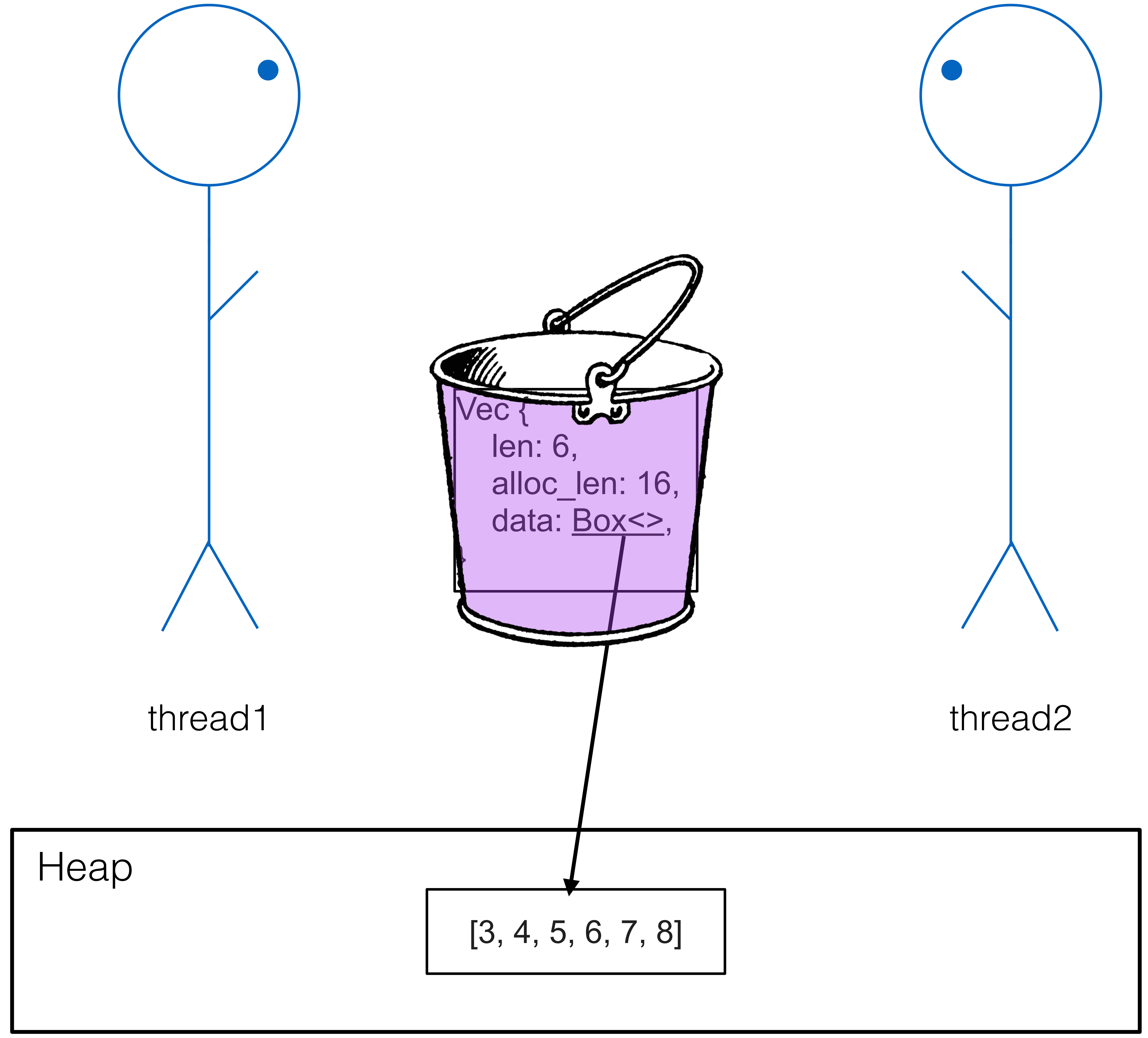
Partly-shared memory (shallow copies only)



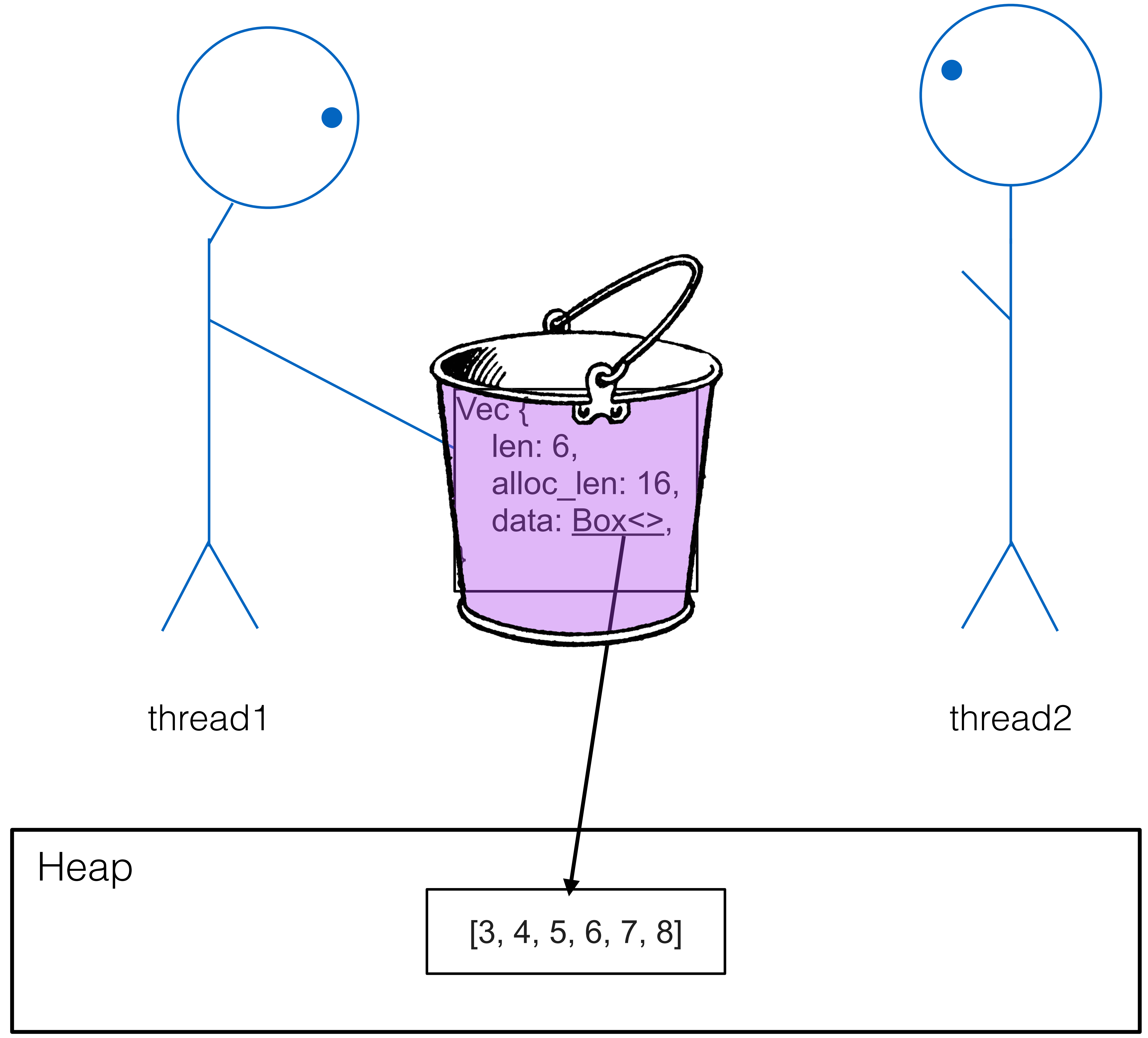
Partly-shared memory (shallow copies only)



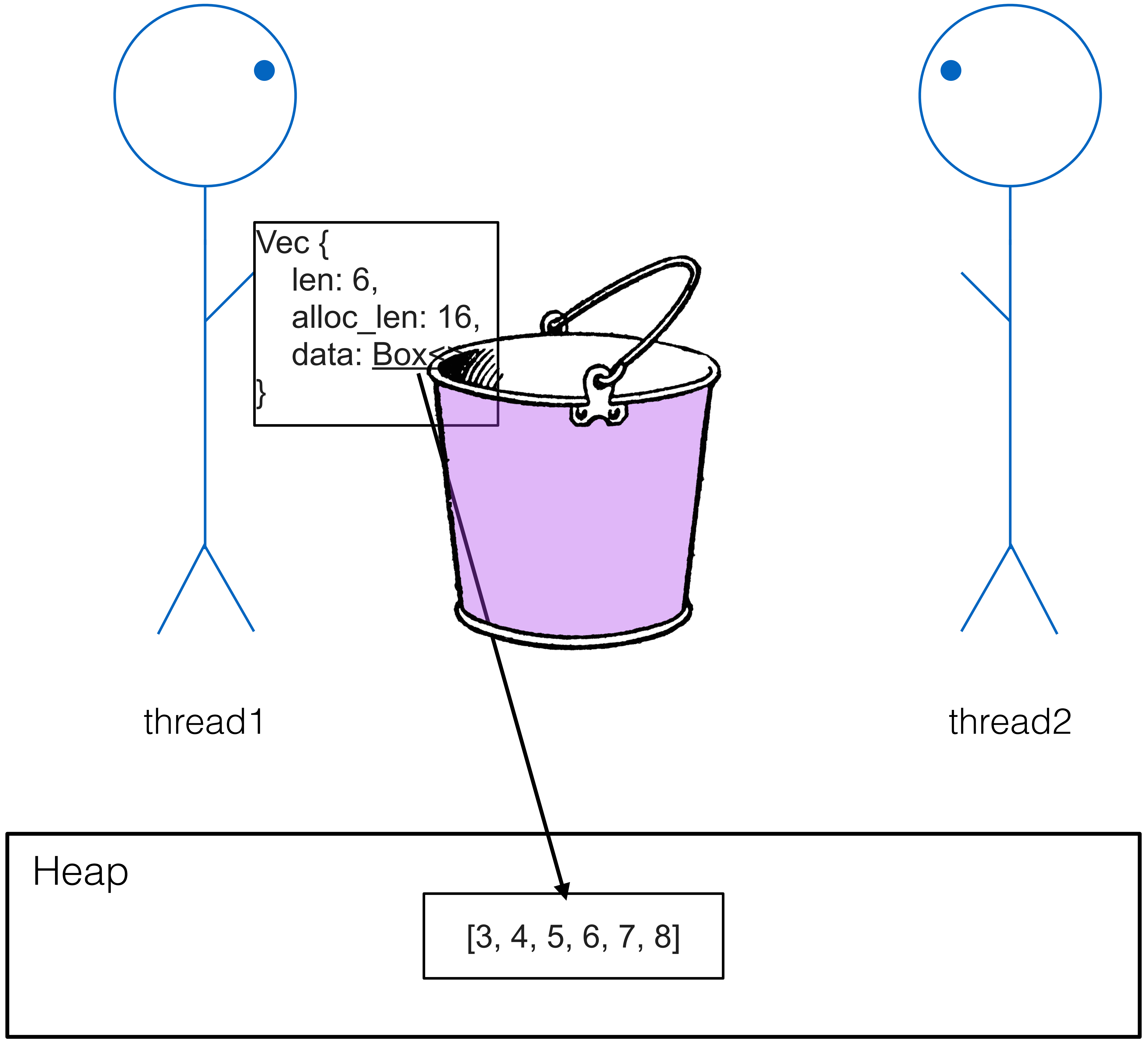
Partly-shared memory (shallow copies only)



Partly-shared memory (shallow copies only)



Partly-shared memory (shallow copies only)



Isn’t message passing bad for performance?

- If you don’t share memory, then you need to copy data into/out of messages. That seems expensive. What gives?
- Theory != practice
  - We share *some* memory (the heap) and only make shallow copies into channels
- In Go, passing pointers is potentially dangerous! Channels make data races less likely but don’t preclude races if you use them wrong
- In Rust, passing pointers (e.g. Box) is always safe despite sharing memory
  - When you send to a channel, ownership of value is transferred to the channel
  - The compiler will ensure you don’t use a pointer after it has been moved into the channel

Channel APIs and implementations

- The ideal channel is an MPMC (multi-producer, multi-consumer) channel
  - We implemented one of these on Tuesday! A simple Mutex<VecDeque<>> with a CondVar
  - However, that approach is much slower than we'd like. (Why?)
- It's really, really hard to implement a fast and safe MPMC channel!
  - Go's channels are known for being slow
    - They essentially implement Mutex<VecDeque<>>, but using a "fast userspace mutex" (futex)
  - A fast implementation needs to use lock-free programming techniques to avoid lock contention and reduce latency

Channel APIs and implementations

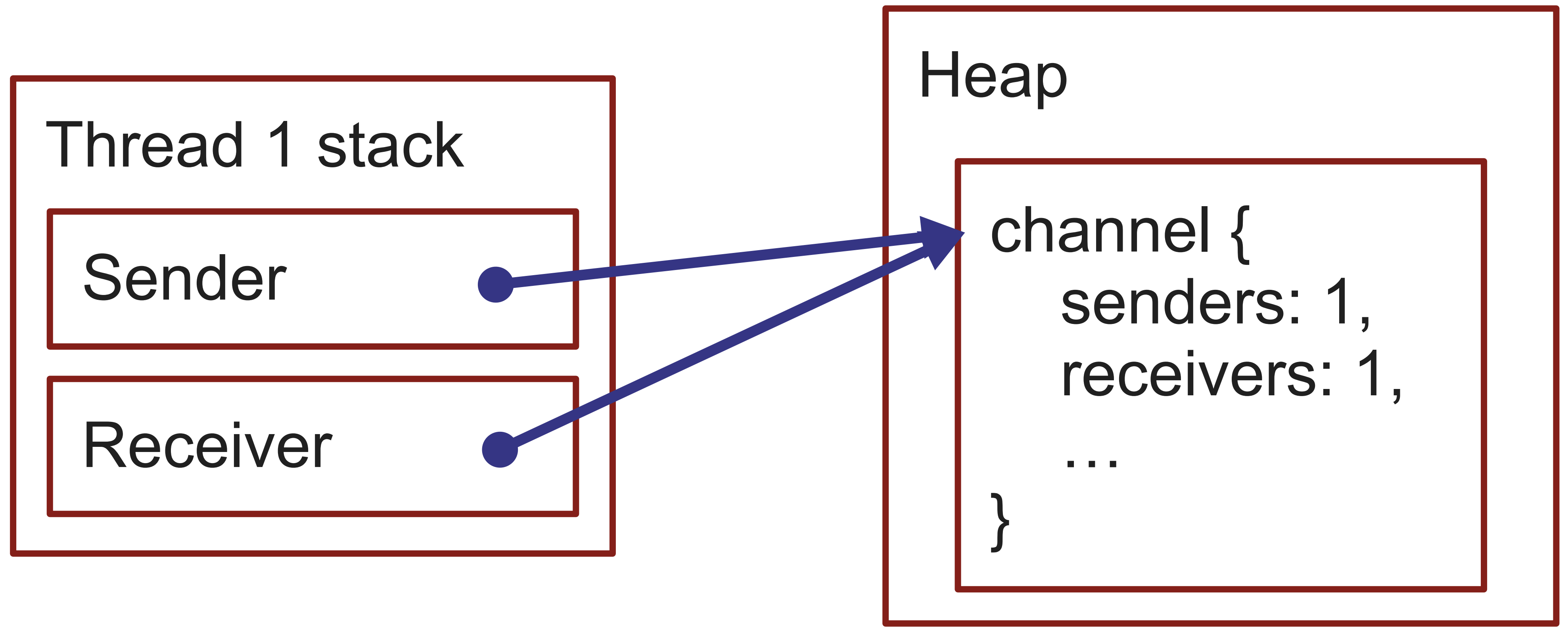
- The Rust standard library includes an MPSC (multi-producer, single-consumer) channel, but it's not ideal (one of the oldest APIs in Rust stdlib)
  - Great if you want multiple threads to send to one thread (e.g. aggregating results of an operation)
  - Also great for thread-to-thread communication (superset of SPSC)
  - Not so great if you want to distribute data/work (e.g. a work queue)
  - Additionally, the API has some oddities (great article)
  - There's a good chance this channel implementation will be replaced within the next year or two (discussion)

Channel APIs and implementations

- The crossbeam crate recently (2018) added an excellent MPMC implementation
  - “If we were to redo Rust channels from scratch, how should they look?” Much improved API
  - Mostly lock free
  - Even faster than the existing MPSC channels
  - Great read here
  - Likely to replace the stdlib channels in some capacity

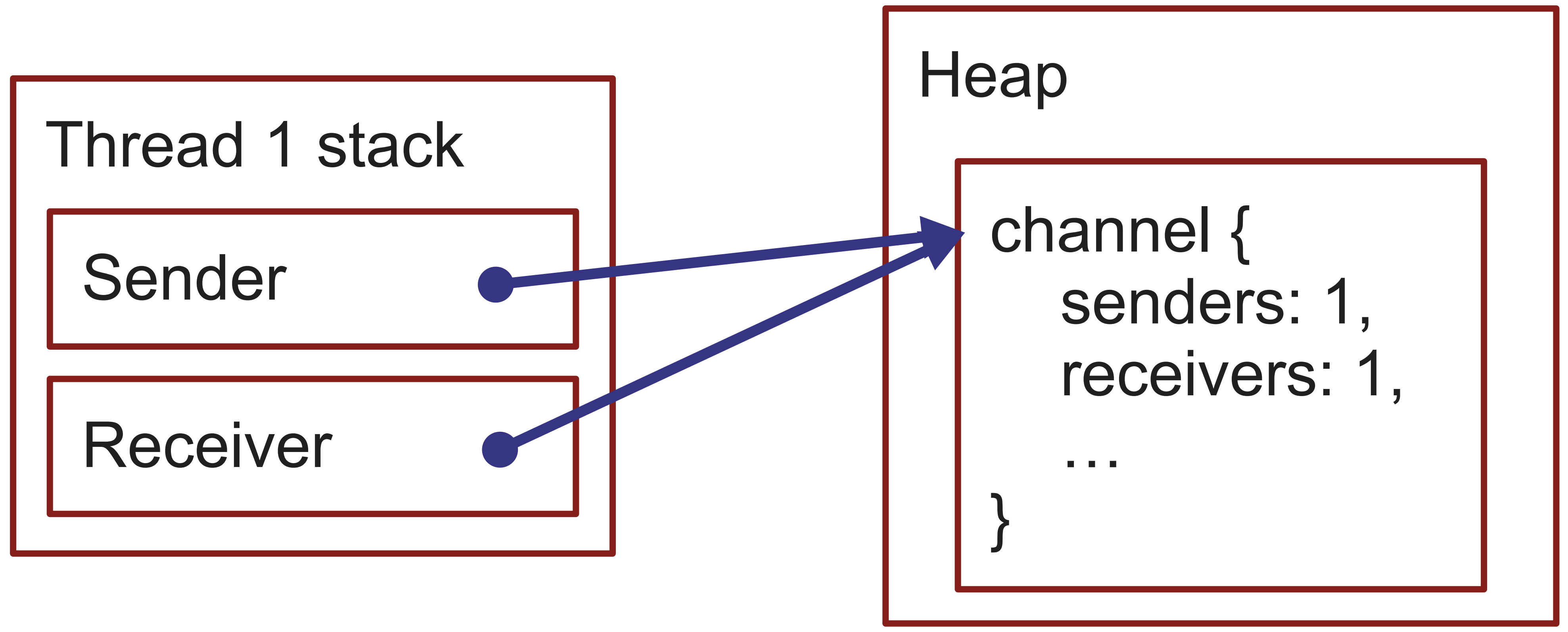
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();
```



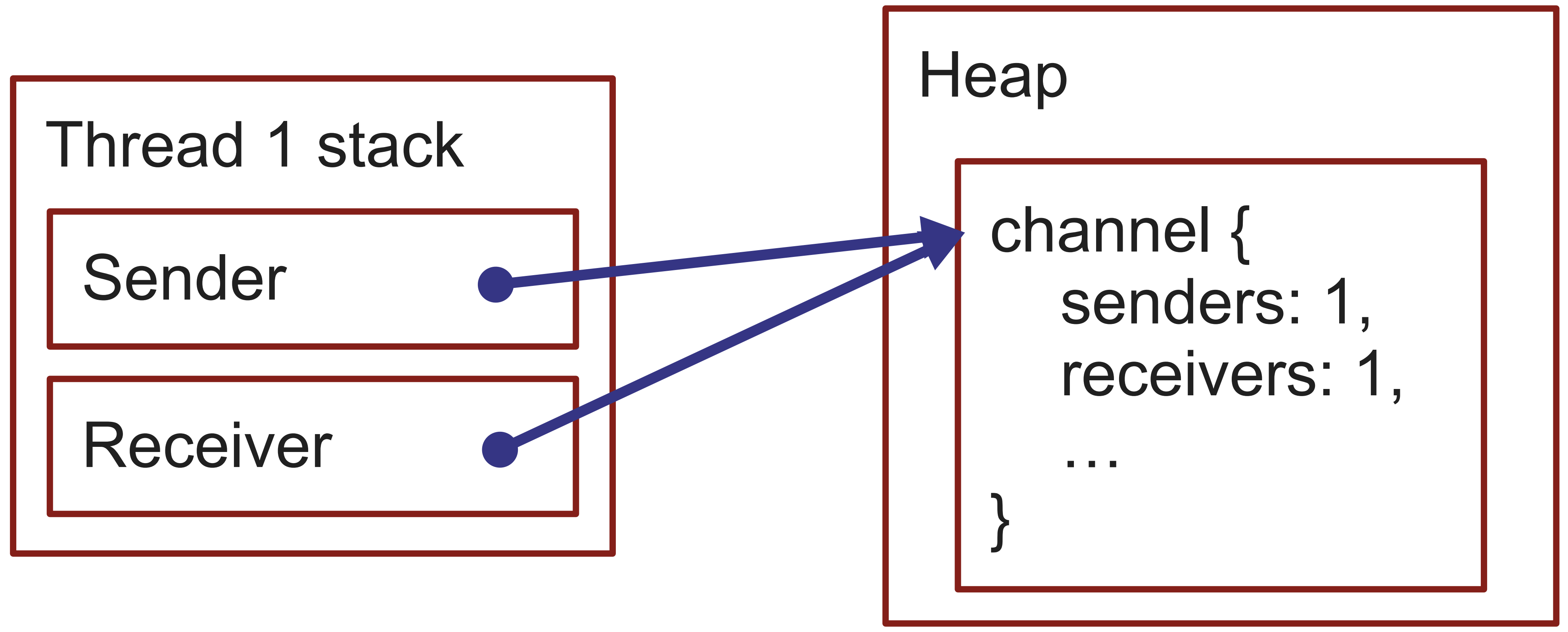
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
```



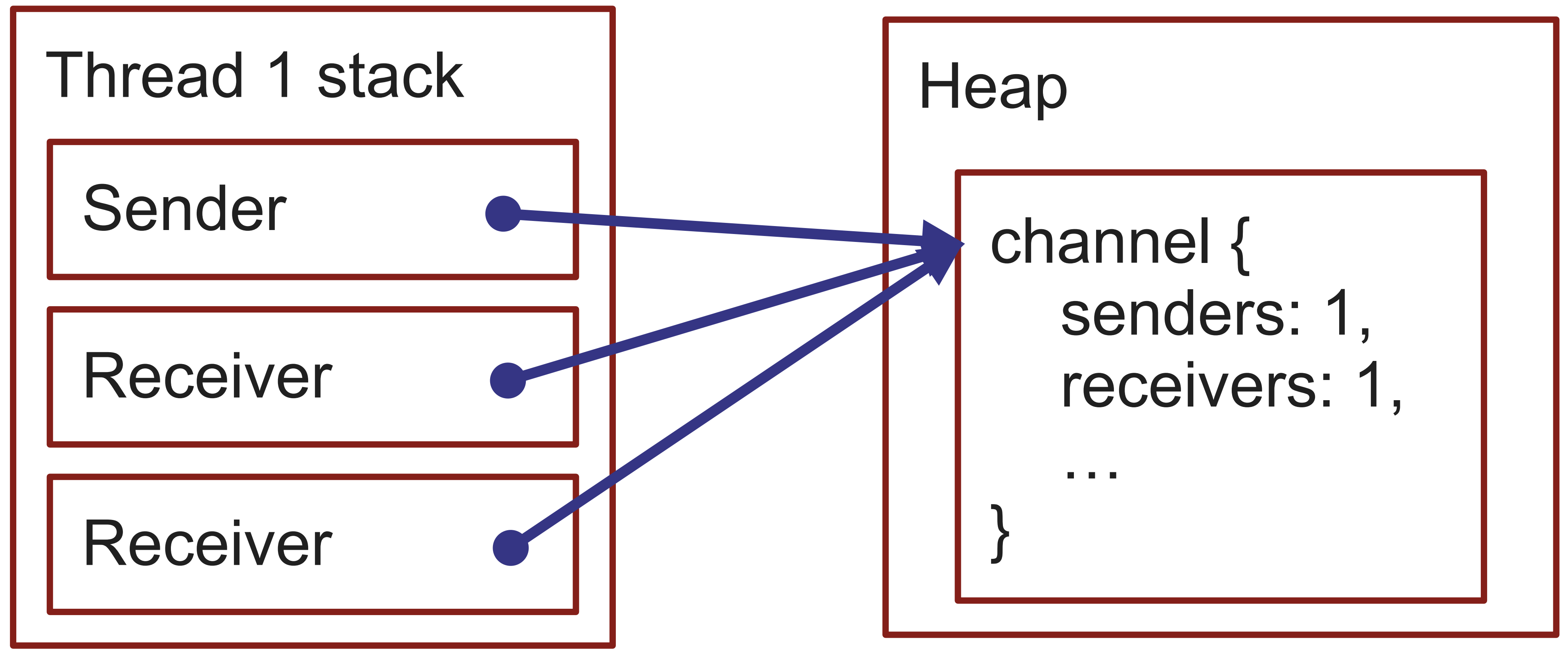
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
```



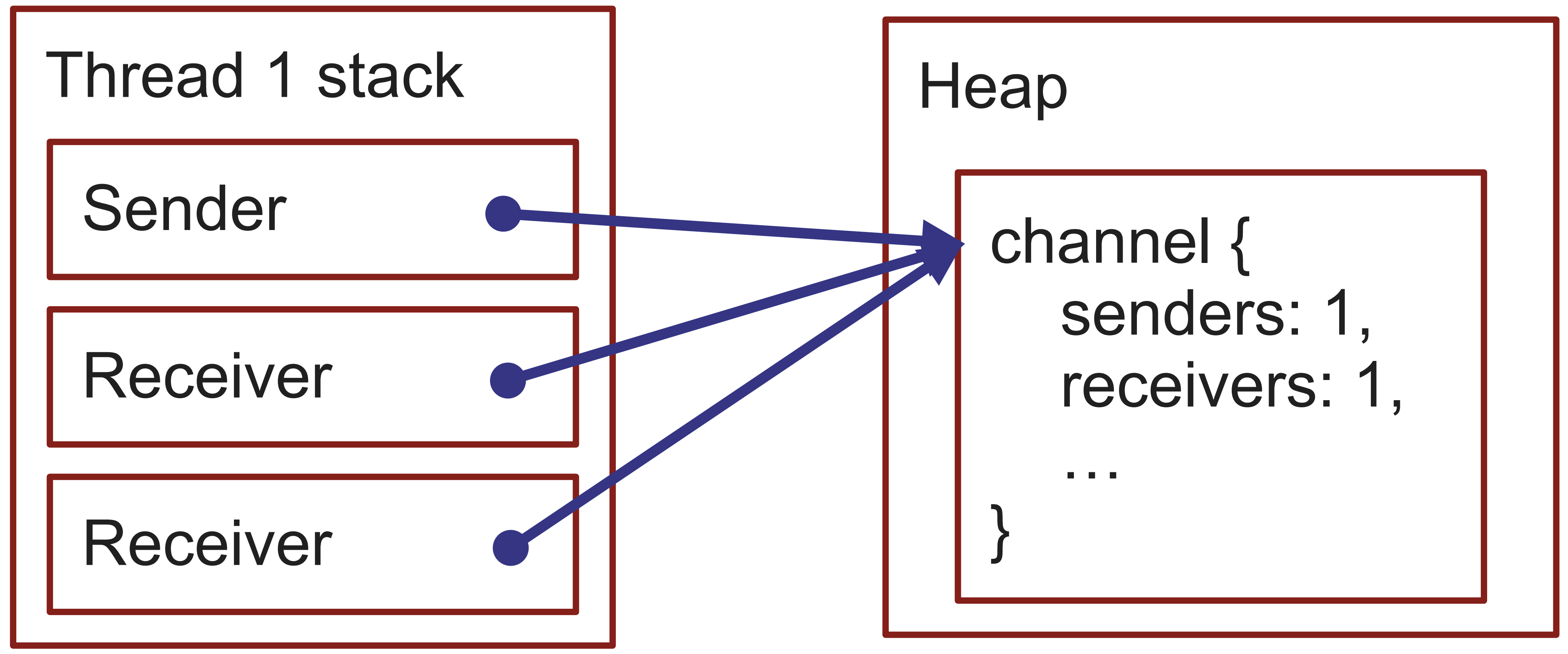
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
```



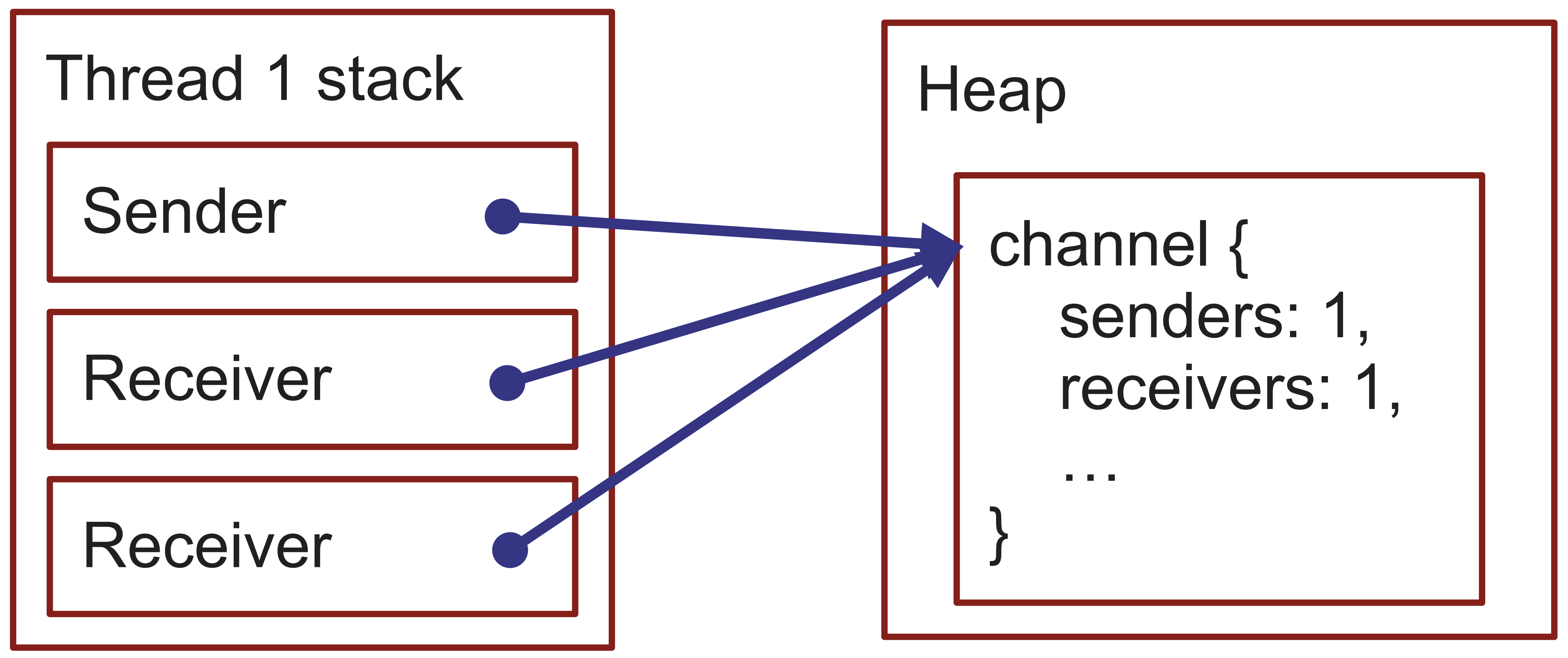
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
```



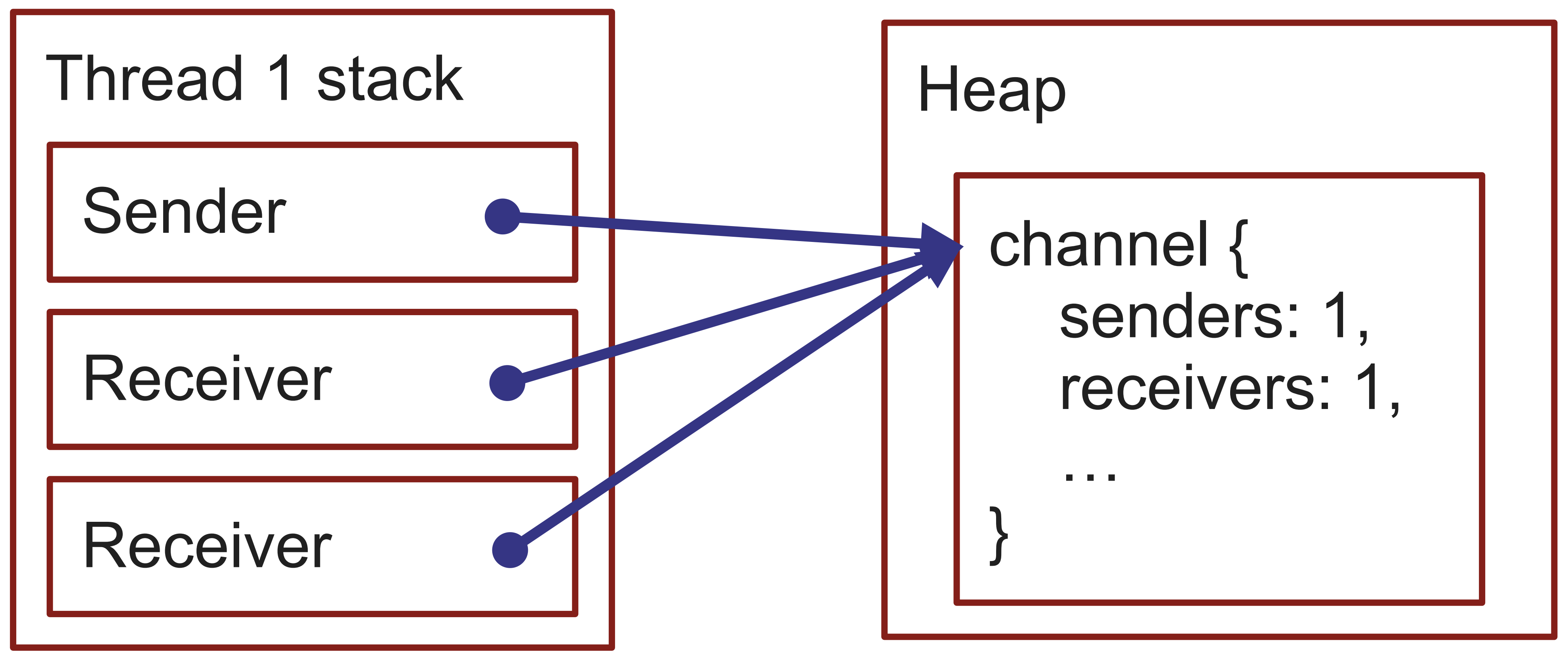
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }
```



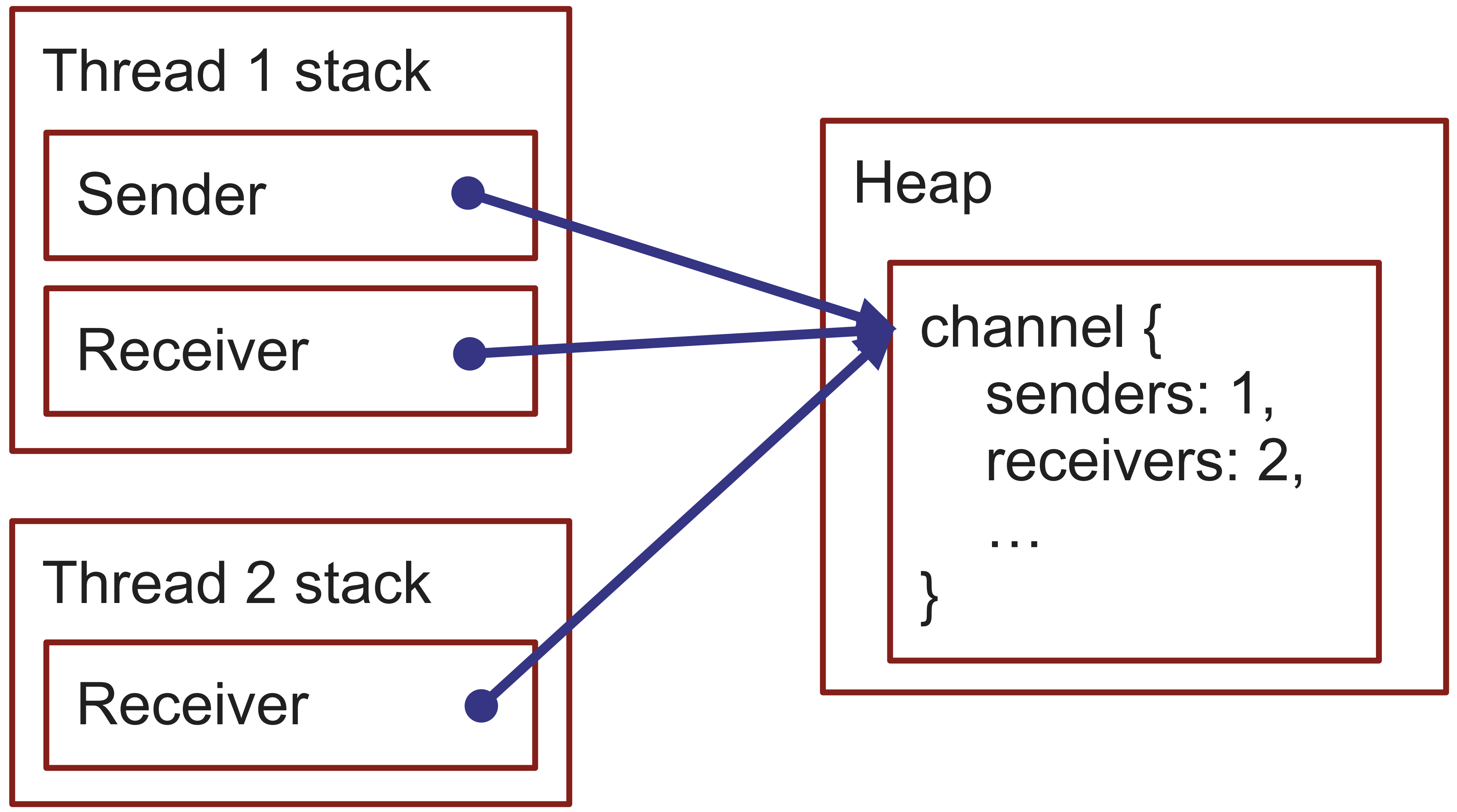
Implementing farm v3.0

```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }
```



Implementing farm v3.0

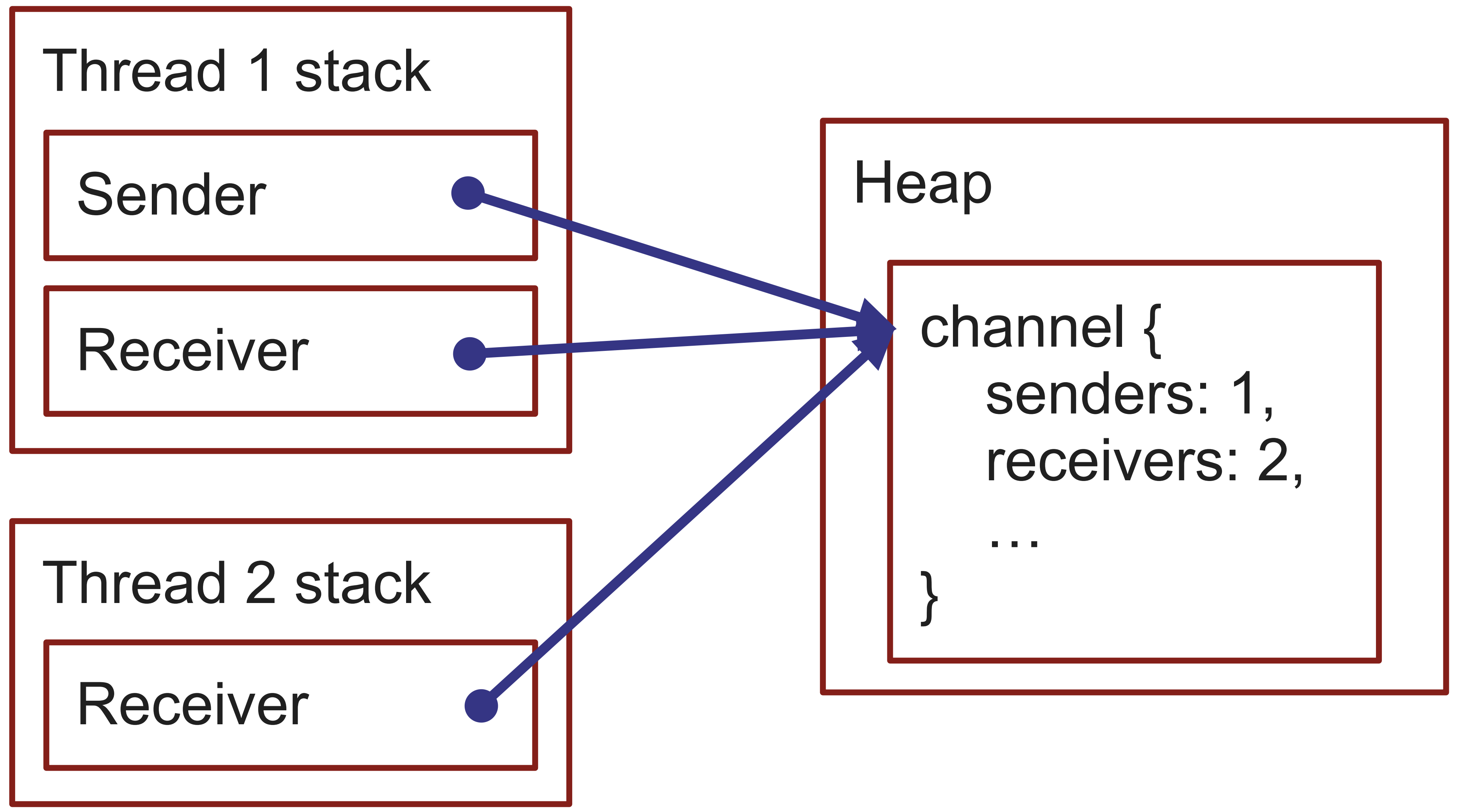
```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }
```



Implementing farm v3.0

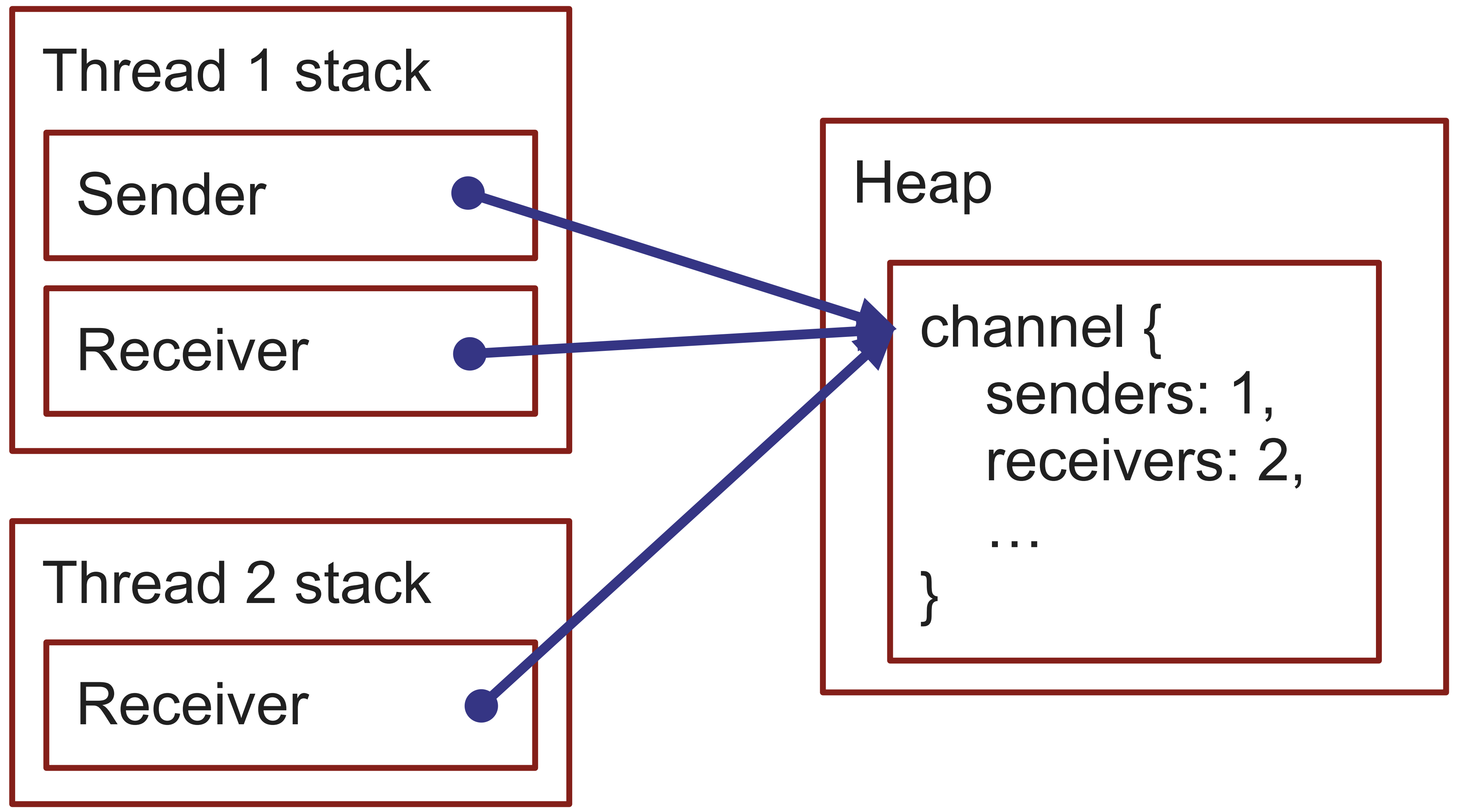
```
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }
```

Read until recv() returns Err (i.e. until the channel is closed)



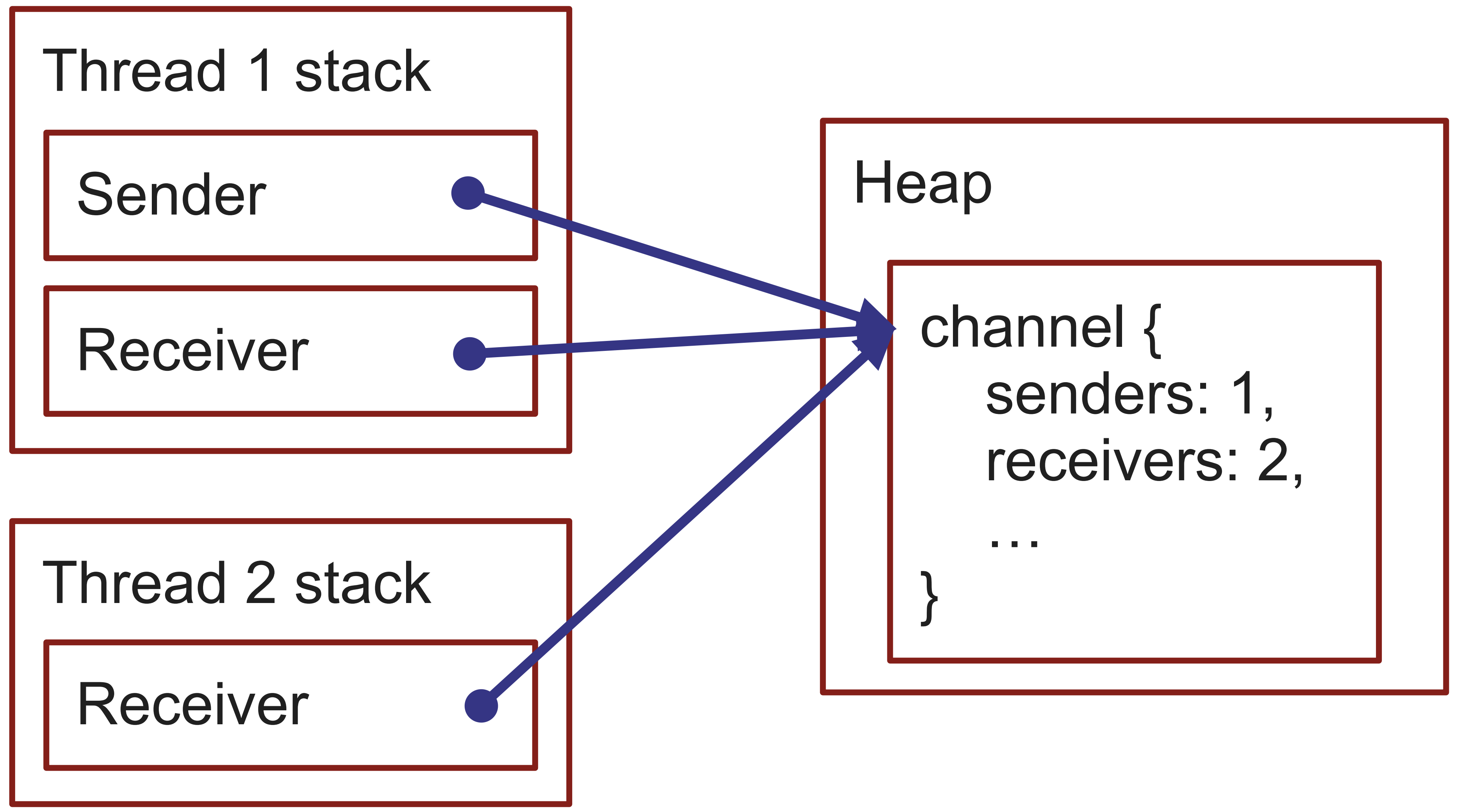
Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
```



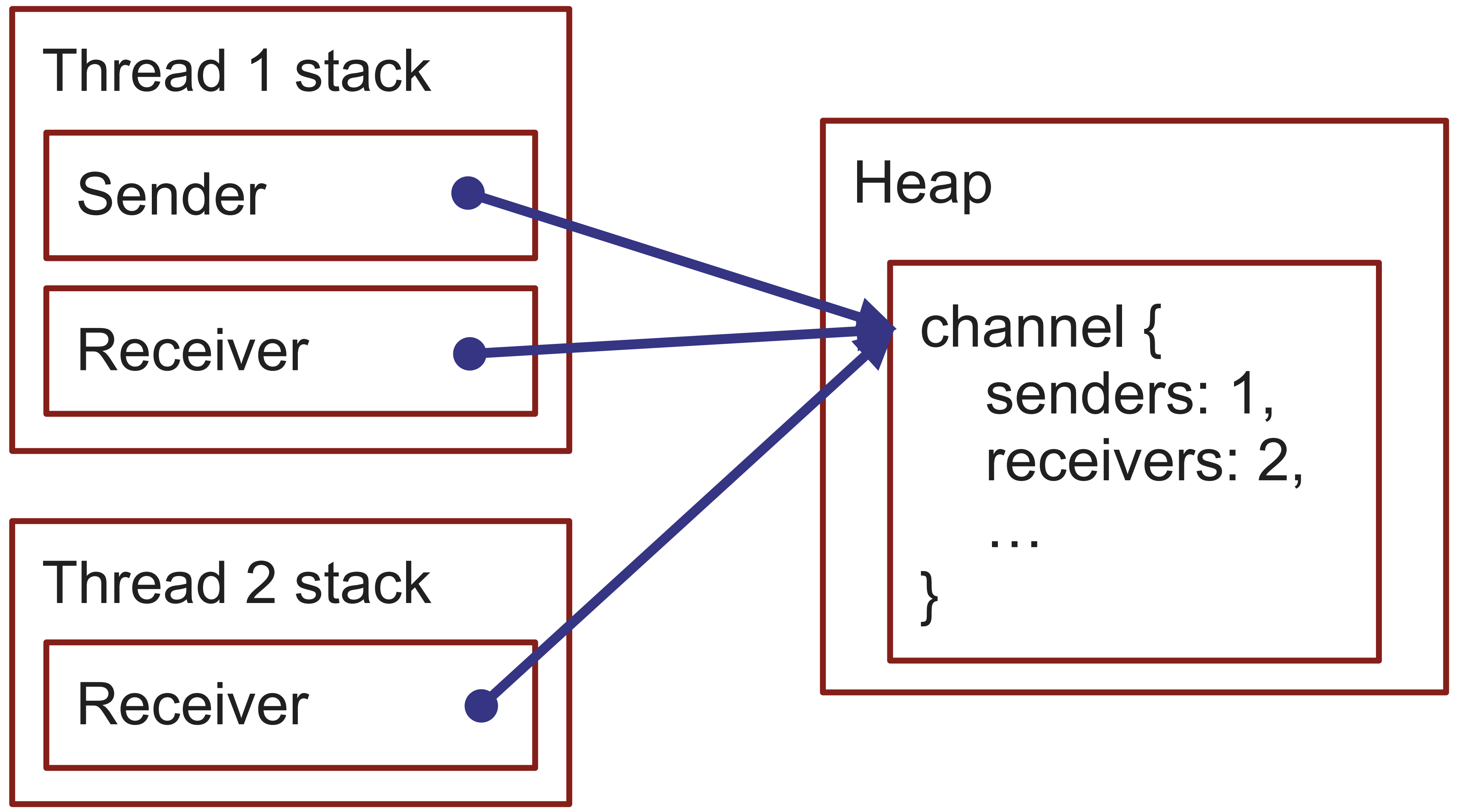
Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }
```



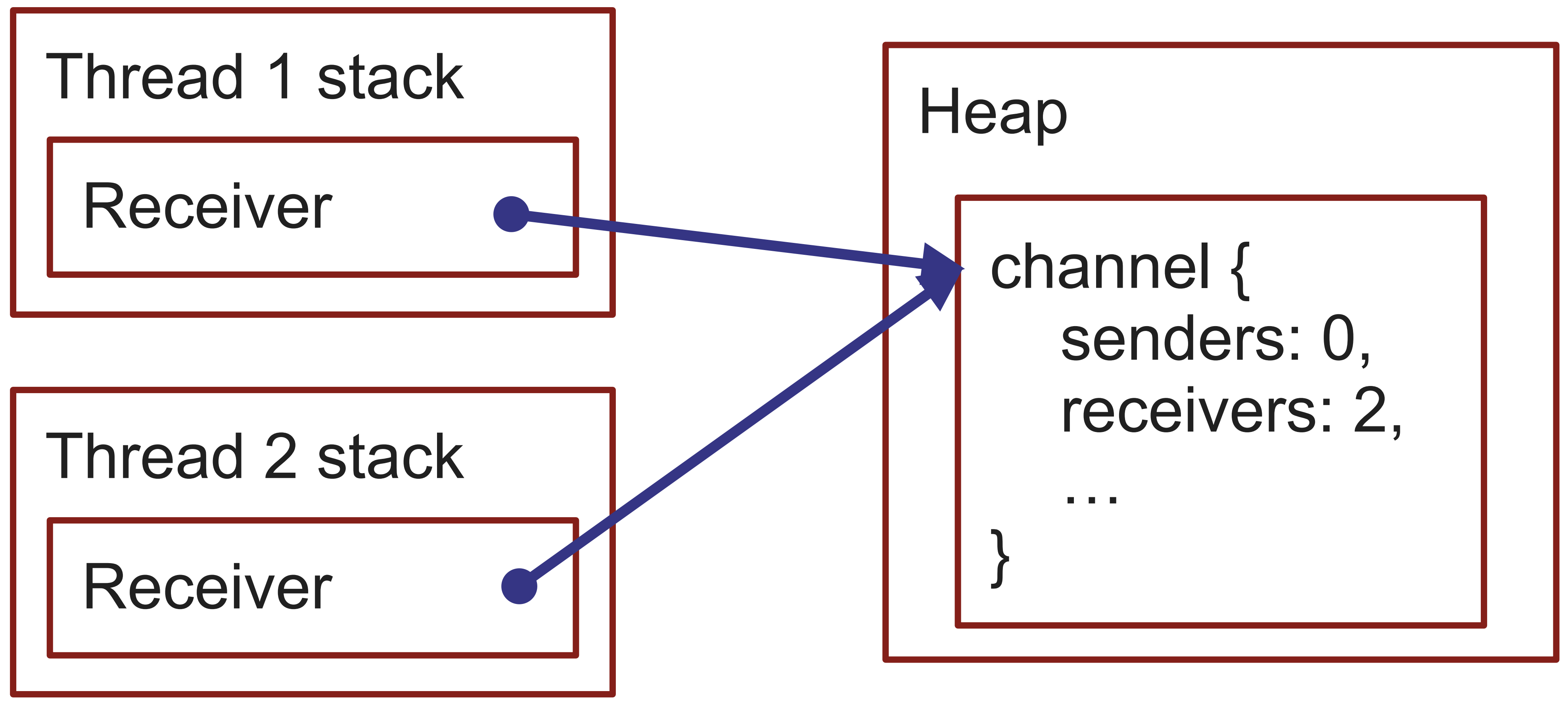
Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }

    drop(sender);
```



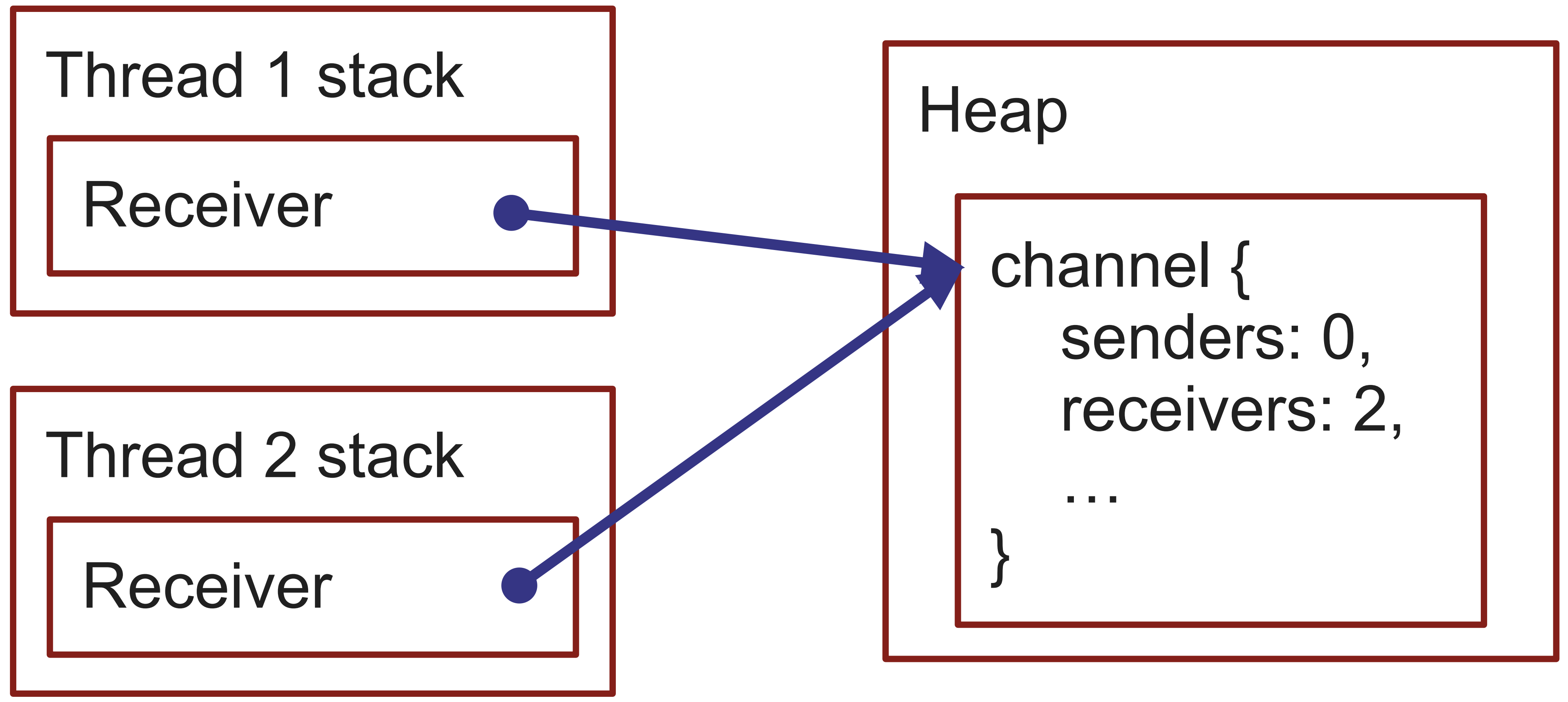
Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }

    drop(sender);
```



Implementing farm v3.0

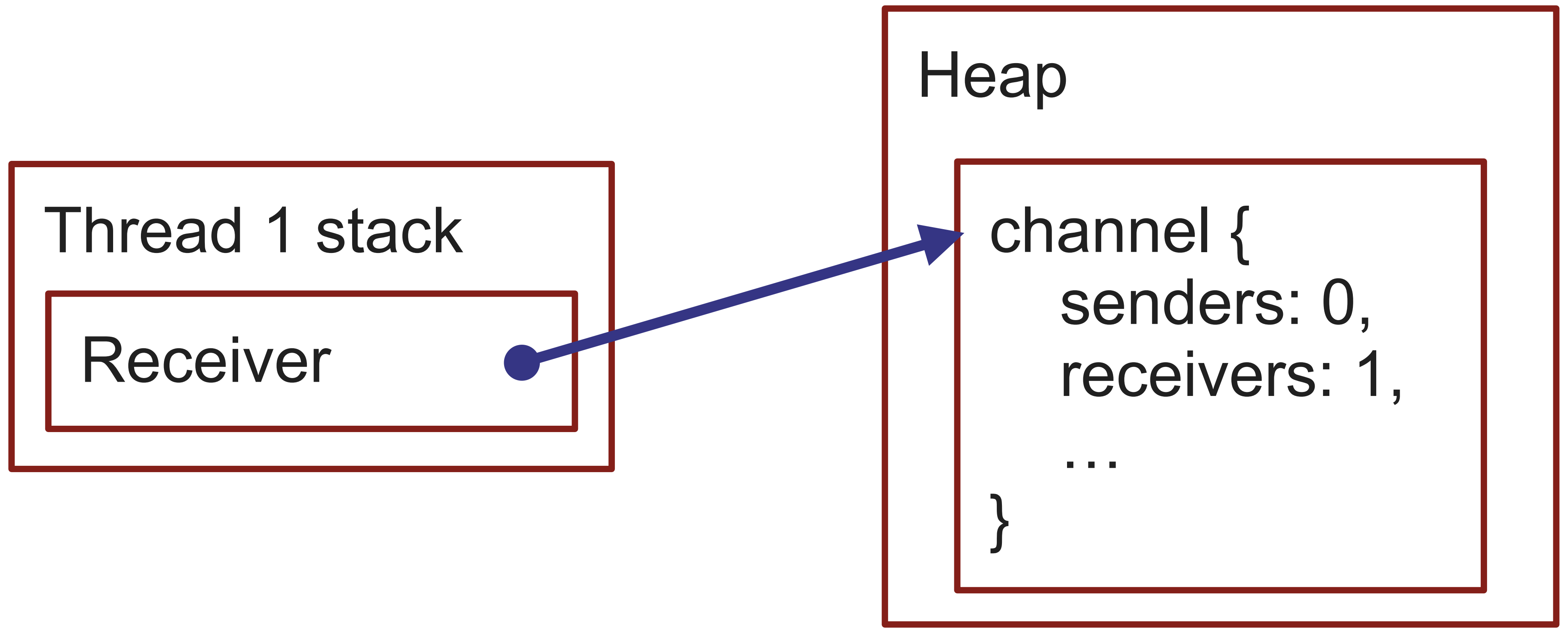
```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }

    drop(sender);
```



Channel is closed! Worker threads will break out of while loop

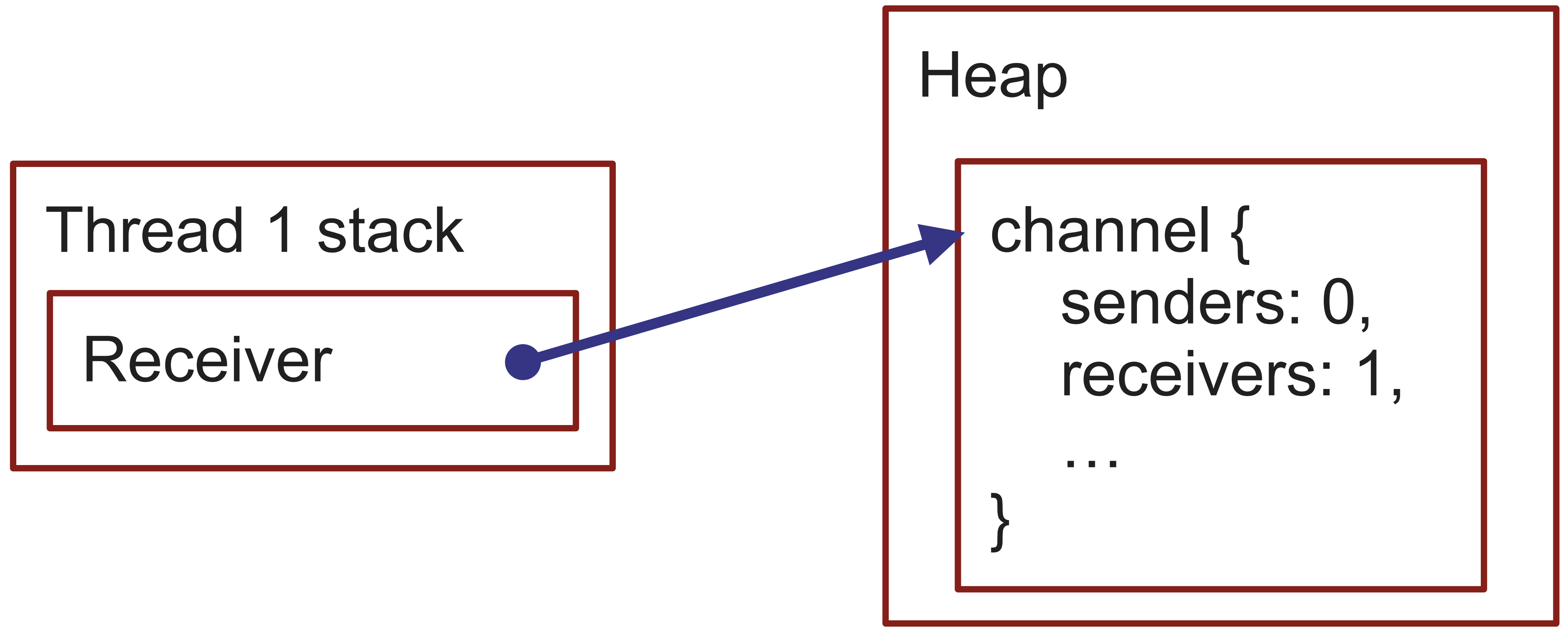
Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }

    drop(sender);
```



Implementing farm v3.0

```rust
fn main() {
    let (sender, receiver) = crossbeam::channel::unbounded();

    let mut threads = Vec::new();
    for _ in 0..num_cpus::get() {
        let receiver = receiver.clone();
        threads.push(thread::spawn(move || {
            while let Ok(next_num) = receiver.recv() {
                factor_number(next_num);
            }
        }));
    }

    let stdin = std::io::stdin();
    for line in stdin.lock().lines() {
        let num = line.unwrap().parse::<u32>().unwrap();
        sender
            .send(num)
            .expect("Tried writing to channel, but there are no receivers!");
    }

    drop(sender);

    for thread in threads {
        thread.join().expect("Panic occurred in thread");
    }
}
```



Pick the right tool for the job

- Using channels is often much simpler and safer than using mutexes + CVs
  - Even in Rust, mutexes can still cause problems if you lock/unlock at the wrong times
  - E.g. semaphore will break if you unlock after cv.wait() and then re-lock before decrementing the counter. You hold the lock while touching the counter, so the compiler doesn't complain, but there is still a race condition
- However, channels aren't always the best choice
  - Not very well suited for global values (e.g. caches or global counters)