Engineering Robust Server Software

API/Protocol/Server Design Ideas

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Brian Rogers / Duke ECE
Used with permission from Drew Hilton

Important API/Protocol/Server Design Ideas

- Design for failure
- Design for asynchronous interfaces
  - What does this mean?
- Don't trust anyone or anything

How You Want Things: Synchronous

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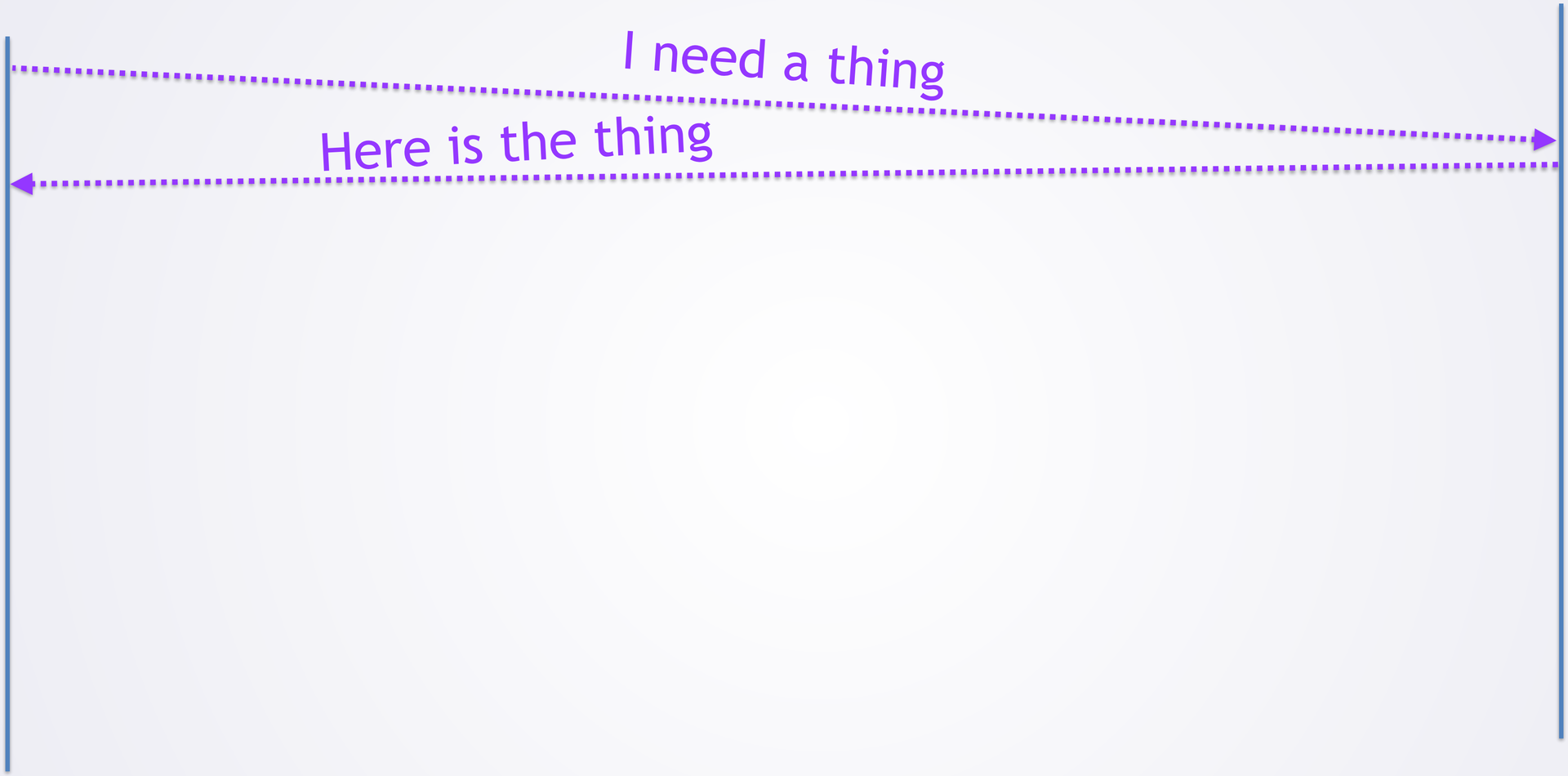
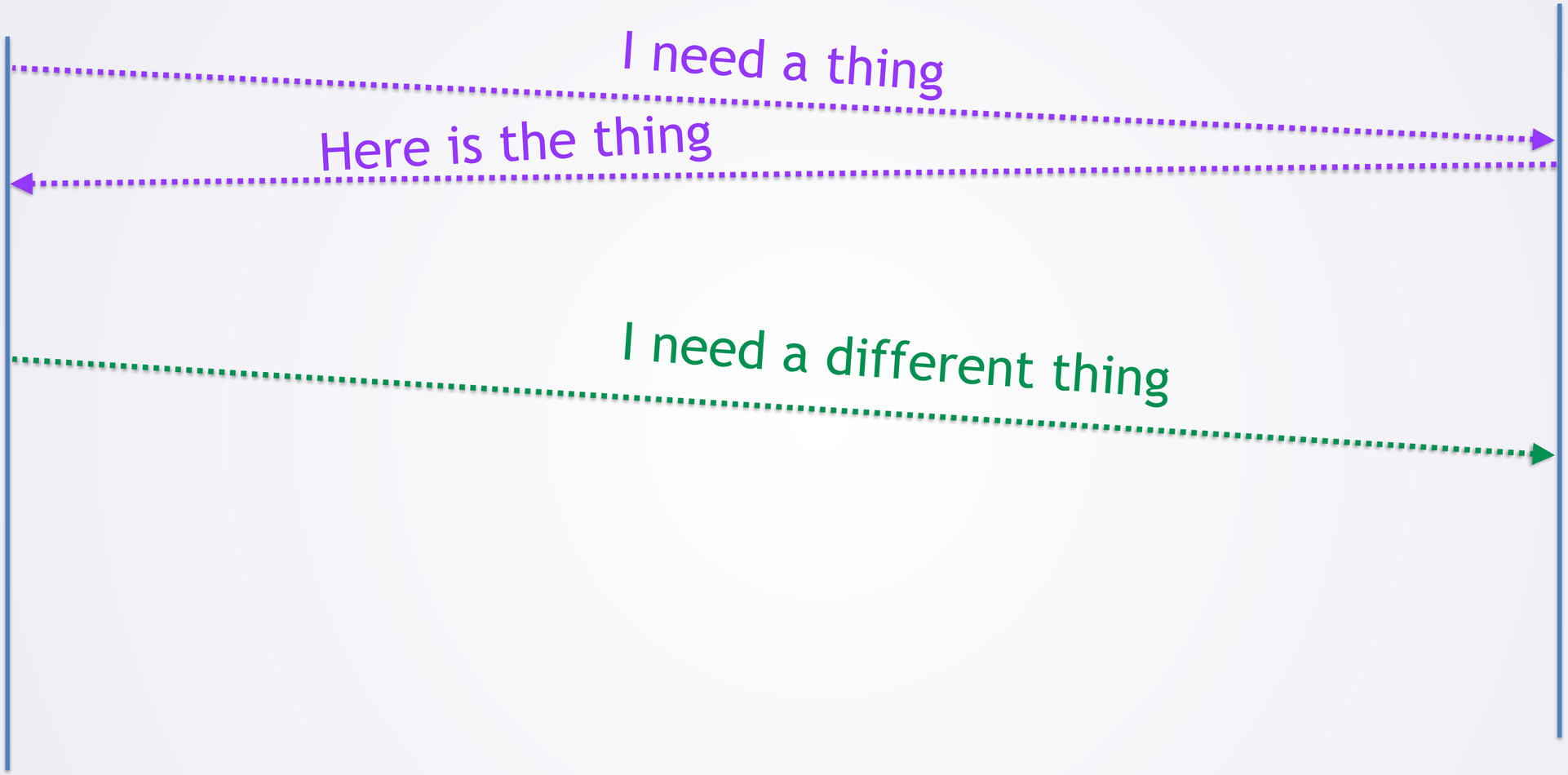
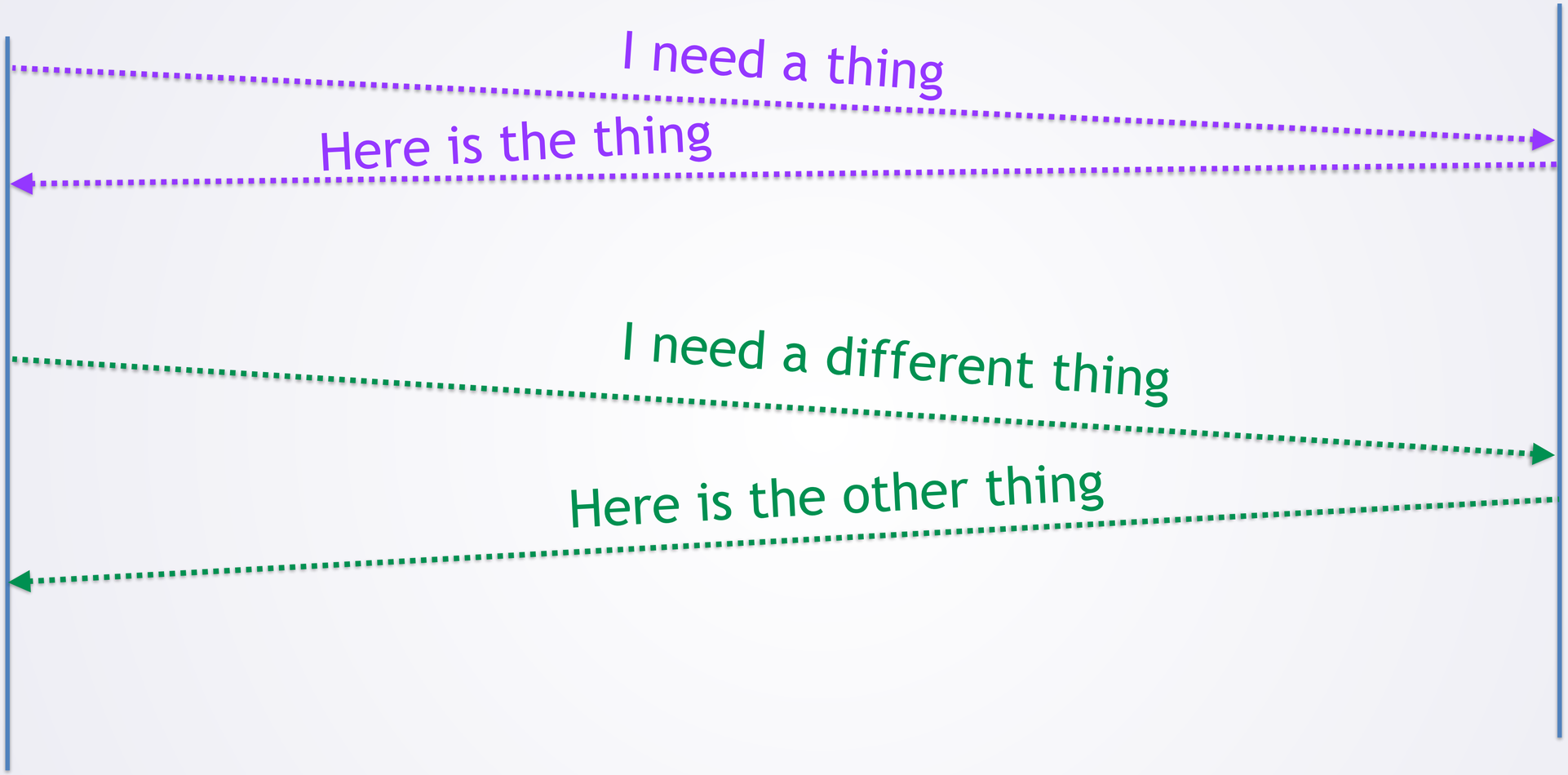


How You Want Things: Synchronous



How You Want Things: Synchronous



Synchronous Processing

- Synchronous processing is straight forward:

```
connection.send_message(request);
response = connection.read_response();
do_whatever(response);
```

but…

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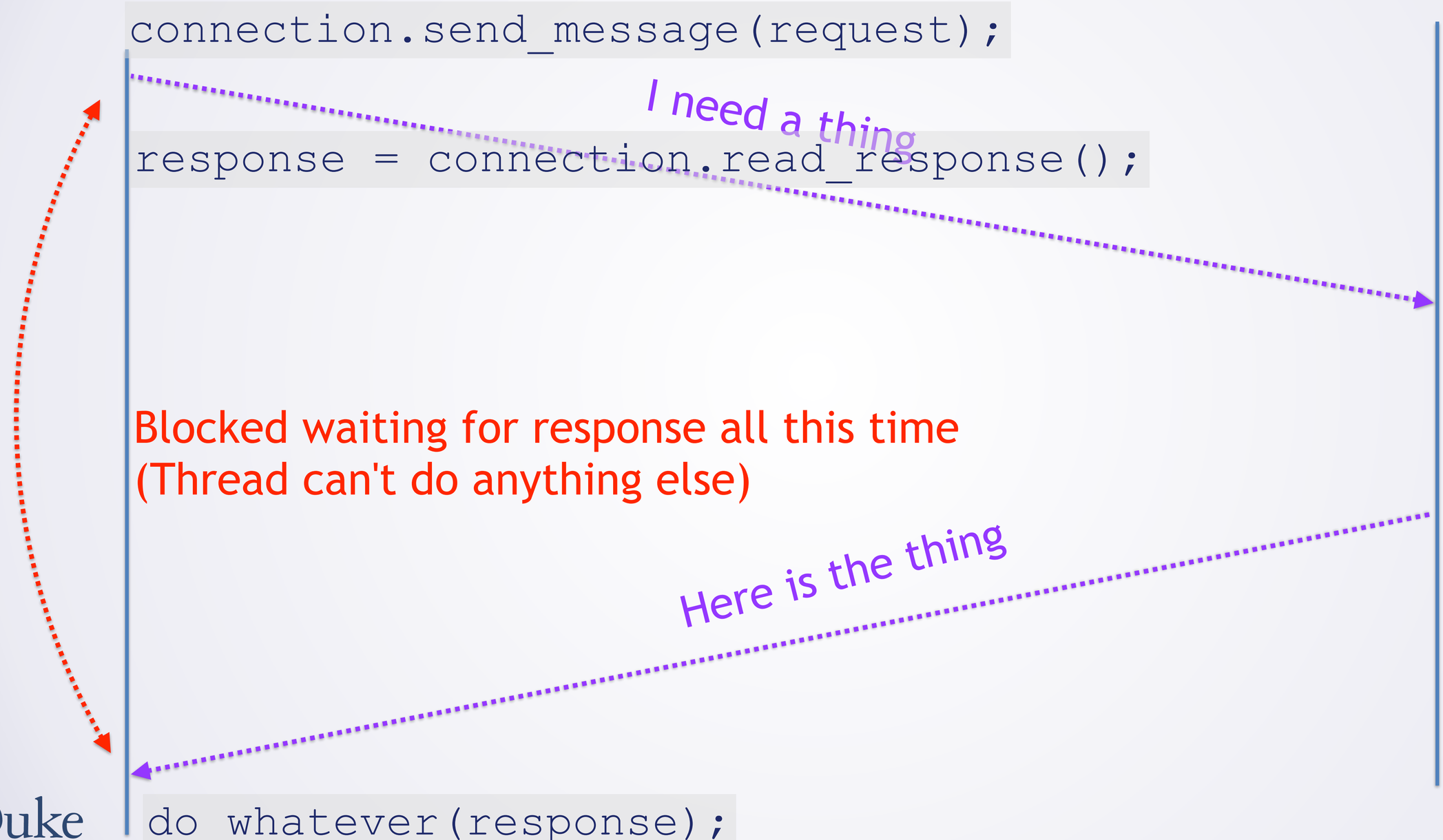
Difficulty With Synchronous Behavior



Also May Not Get Response

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Stop & Think

- Send + Receiving:
  - Take a moment to think up approaches for how we can receive data
    - **Constraint**: cannot block this thread waiting for response!
    - **Pros and Cons** of approach?
    - **Bonus**: ties to names/concepts from 550?

Receiving

- (1) Polling:
  - Send just does:

```
connection.send_message(request);
connections.push_back(connection);
```

  - Then we periodically try to receive:

```
for (auto &c: connections) {
        if (c.is_response_ready()) {
            response = connection.read_response();
            do_whatever(response);
        }
}
```

Pros and Cons?

Receiving

- (2) Interrupts?
  - What is user-land equivalent of interrupts?

Receiving

- (2) Interrupts?
  - What is user-land equivalent of interrupts? **Signals**
  - This is not something you can do easily.
  - TCP supports urgent data (delivers SIGURG)
    - Sender must mark data urgent
    - Not commonly used
      - You could have sender do this
      - but don't expect to e.g., have web clients mark all data urgent
  - …but similar idea?

Receiving

- (3) Spawn Another Thread To Receive:

  Pros and Cons?

  - Send just:

```
connection.send_message(request);
spawn_thread(receive_data, connection);
```

  - Receive is done in receive_data on other thread:

```
//blocking, but on its own thread
response = connection.read_response();
do_whatever(response);
```

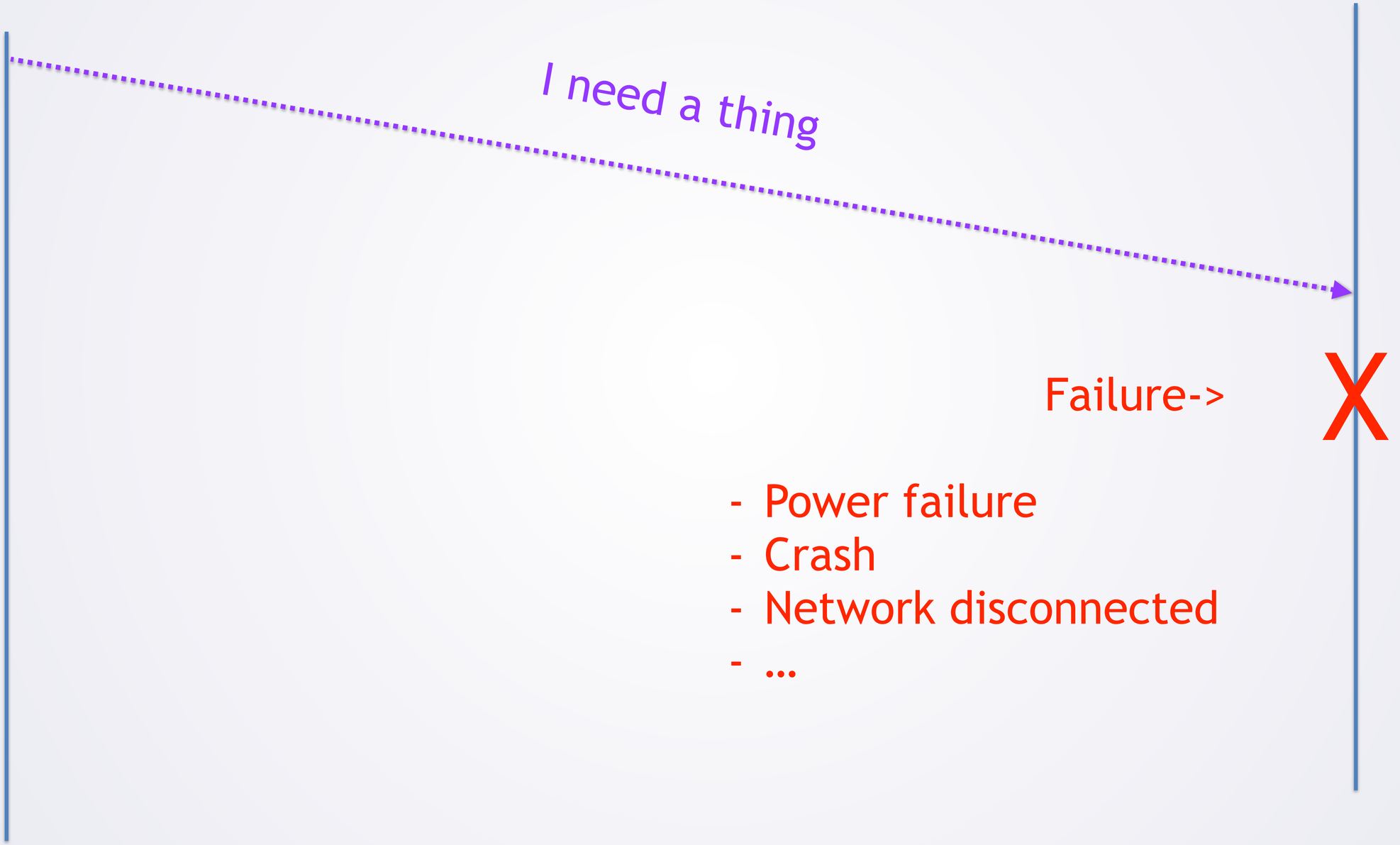
Receiving

- (3) Dedicated receive threads?

  Pros and Cons?

  - Pre-spawn some threads to receive
  - Sender communicates state (what to do) to these threads

Also May Not Get Response



- Power failure
- Crash
- Network disconnected
- …

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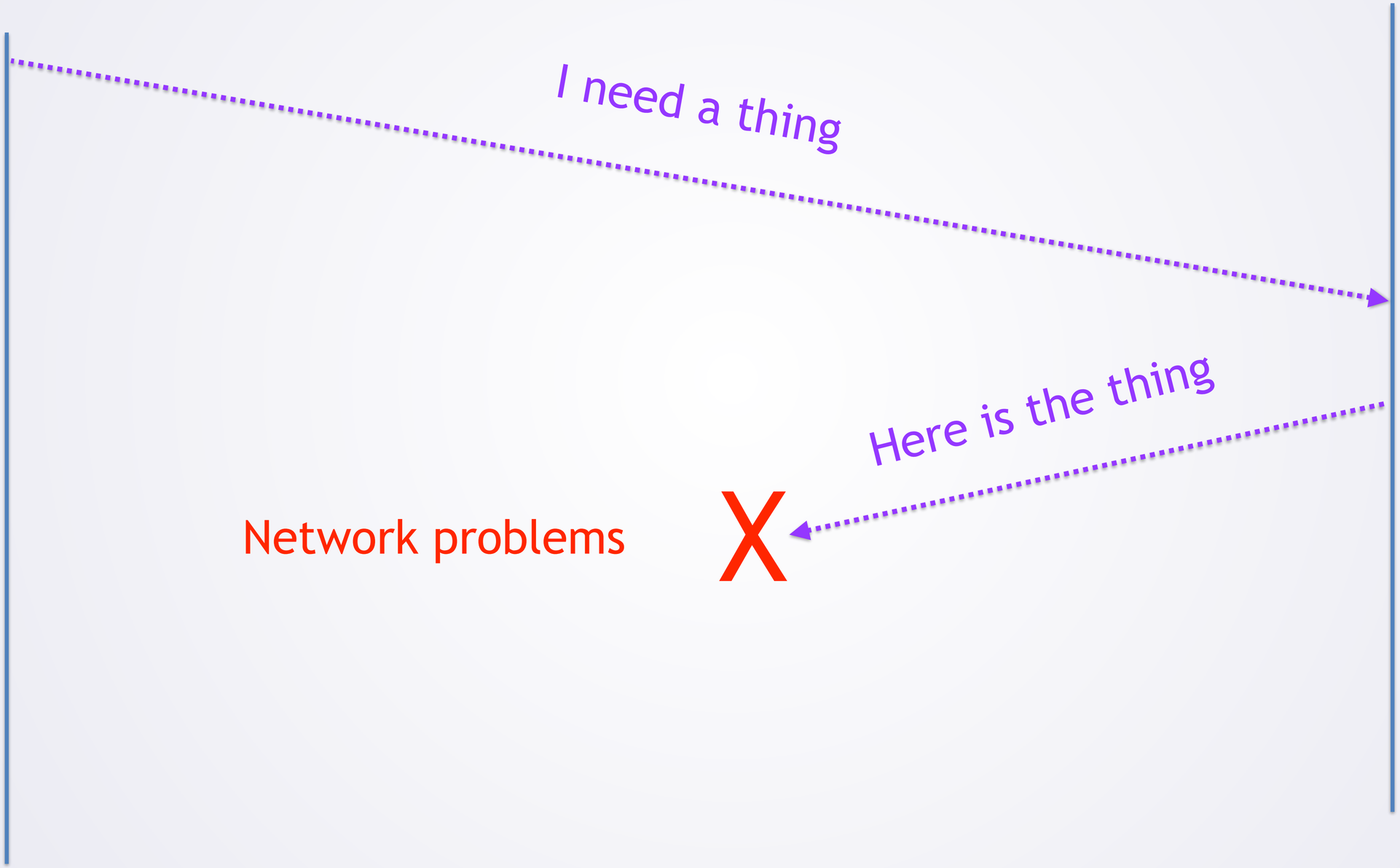
Also May Not Get Response



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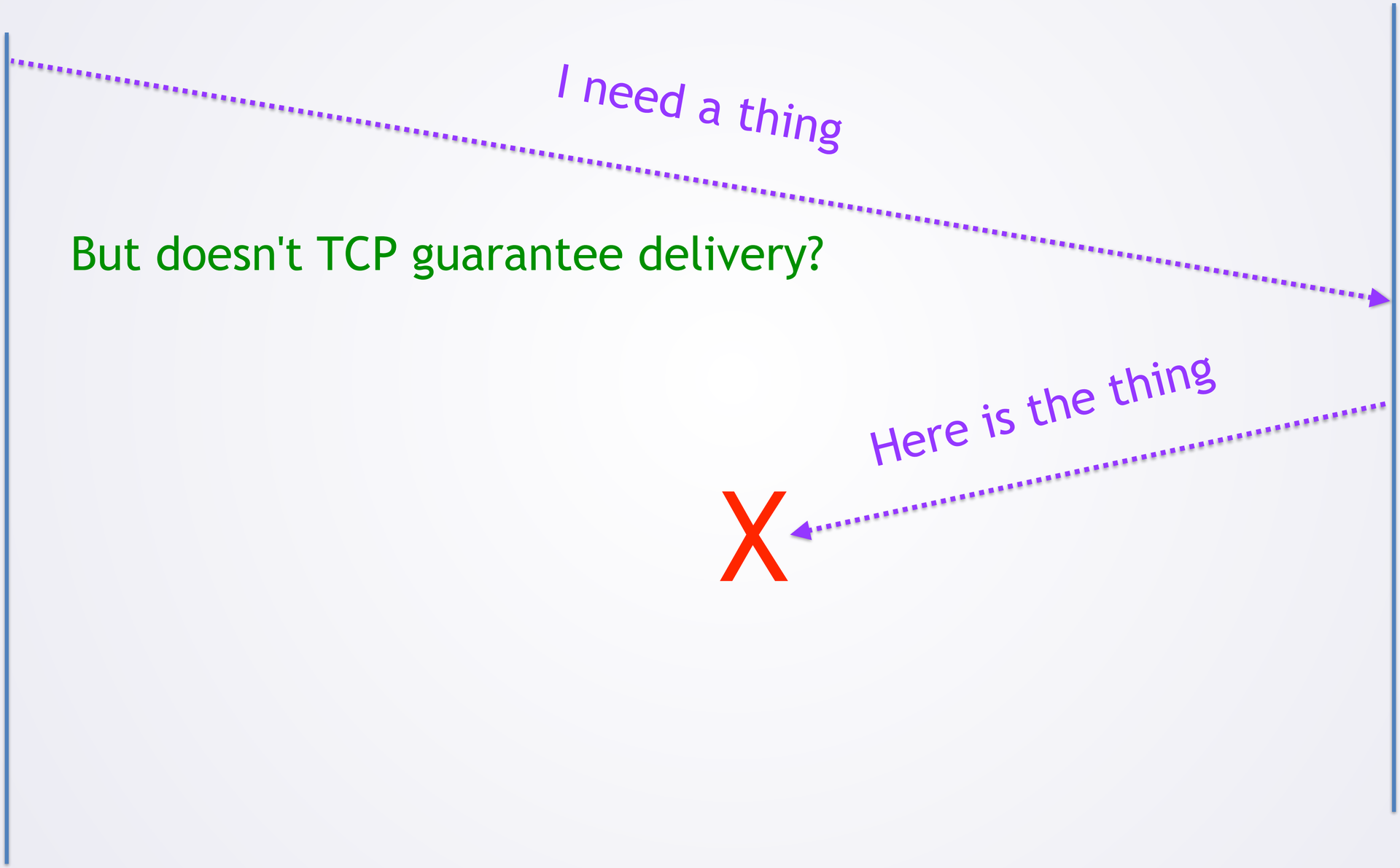
Also May Not Get Response



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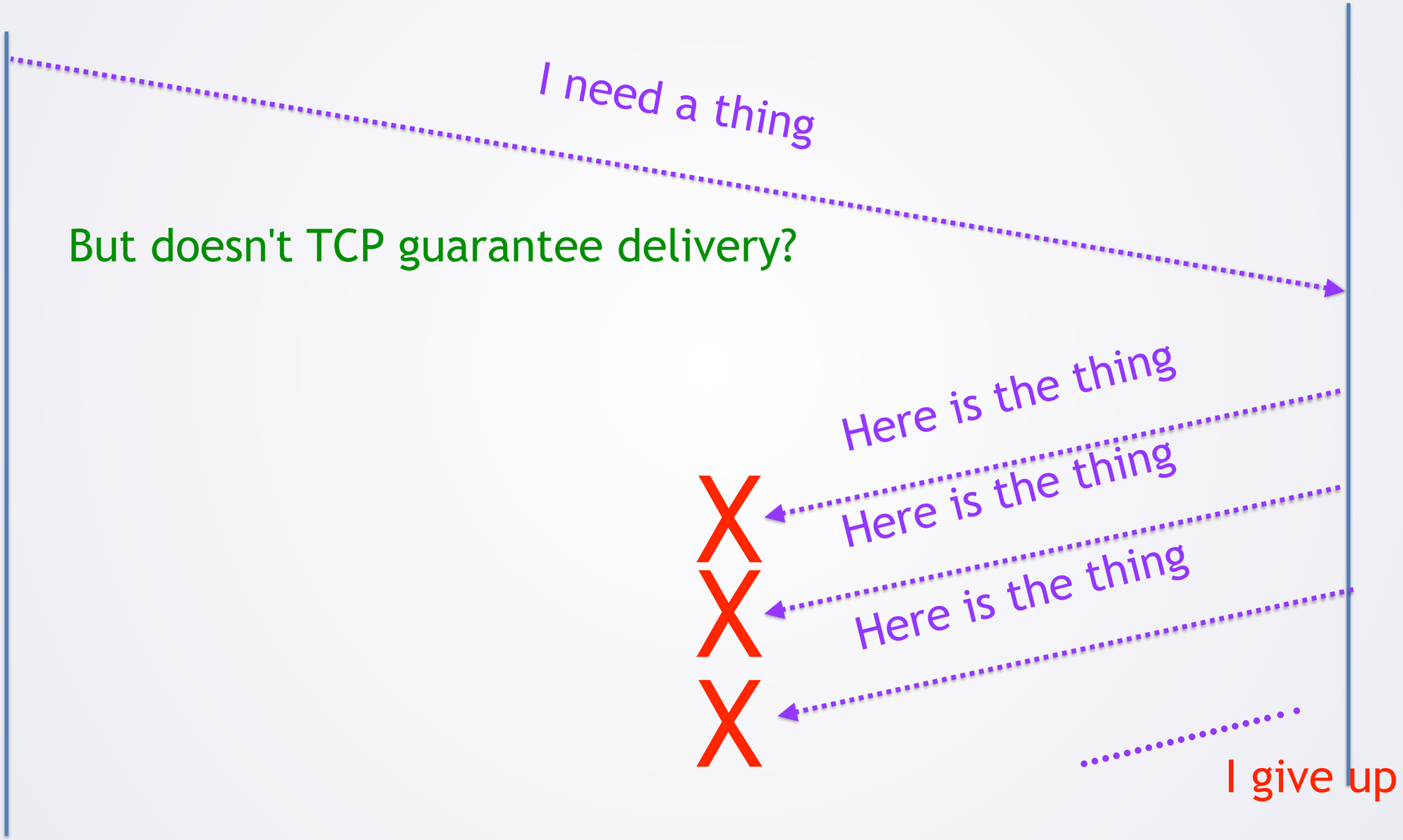
Also May Not Get Response



No Way To Tell Where Failure Happened

- We cannot tell the difference between
  - Data not reaching the receiver
  - Data reaching the receiver, but ACK not reaching us
- Is that a big deal?

Data Did Not Reach Receiver

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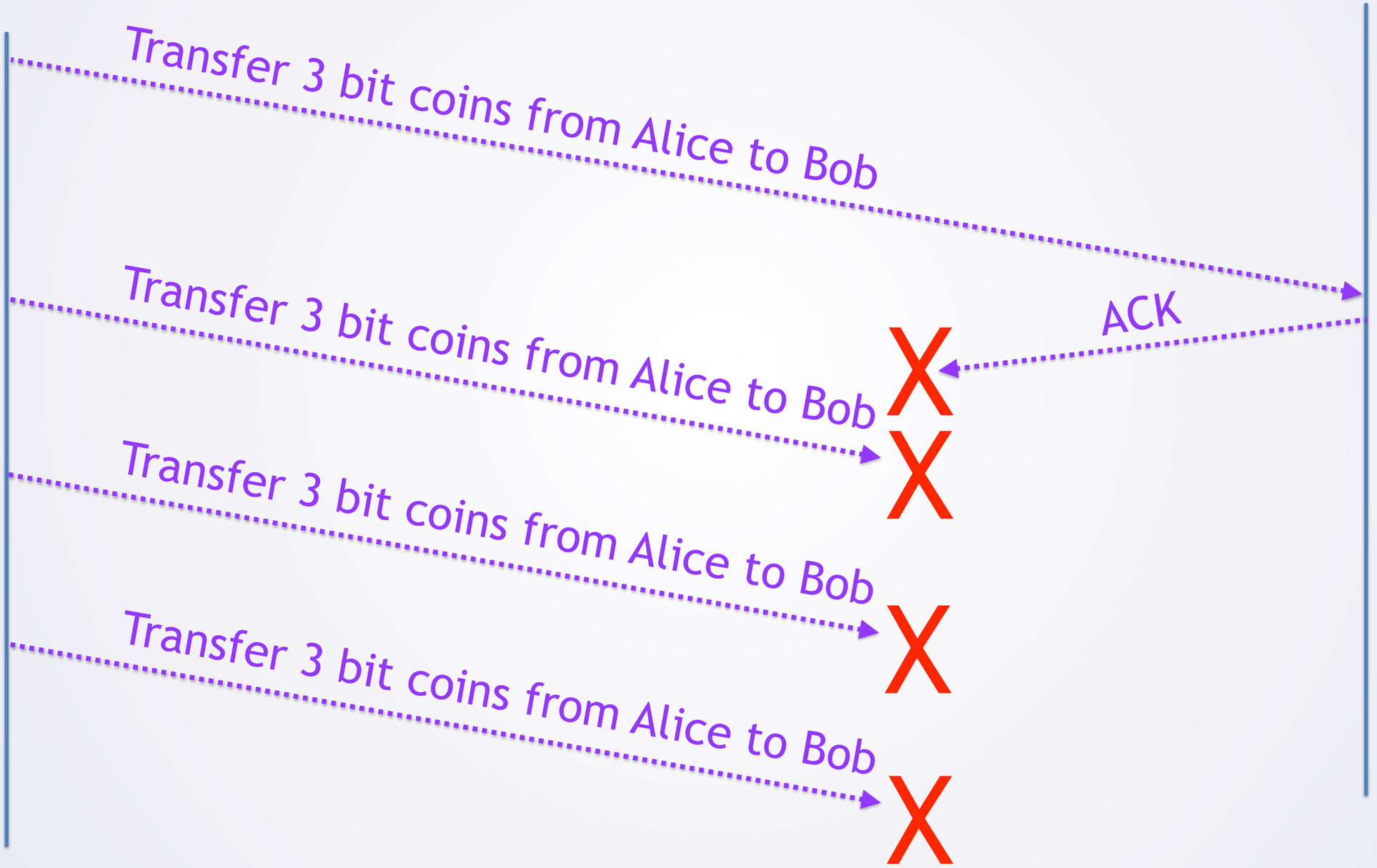
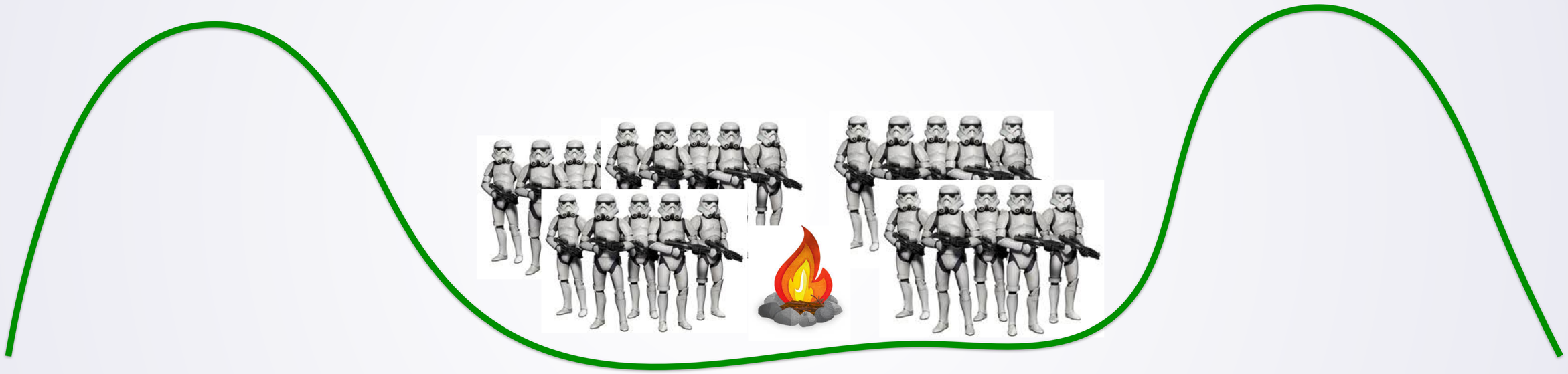
ACK Did Not Reach Sender



Two Generals Problem

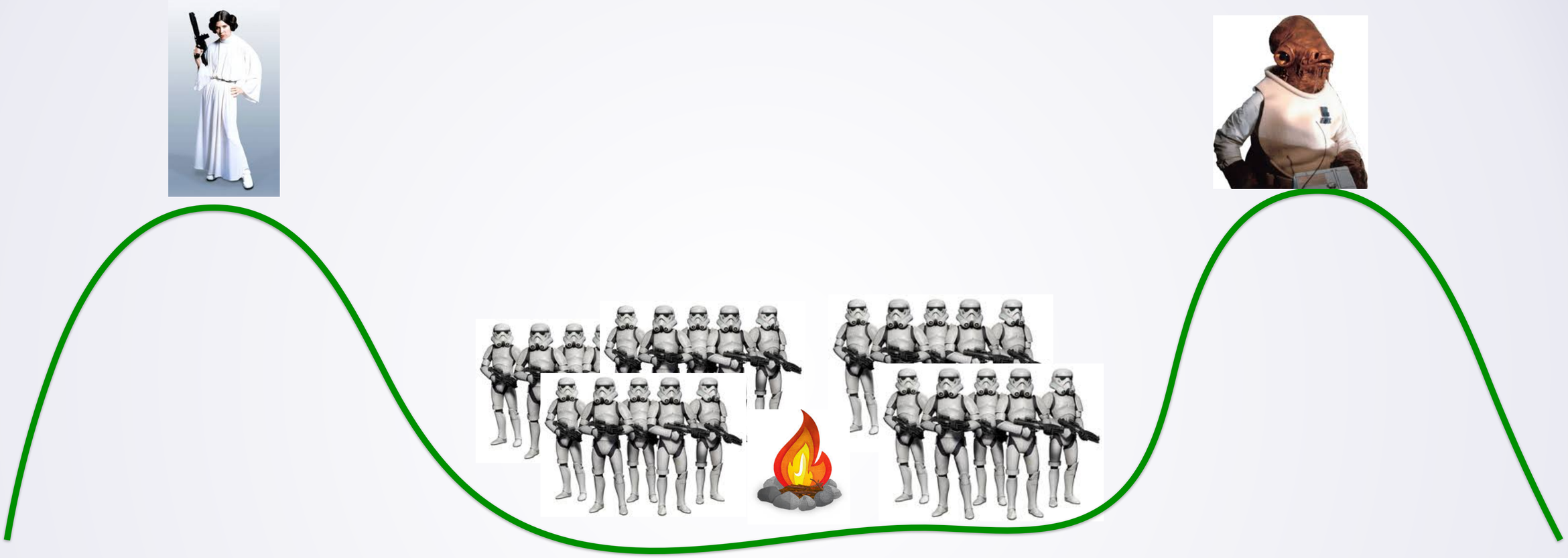
- Famous problem: two generals

Two Generals Problem



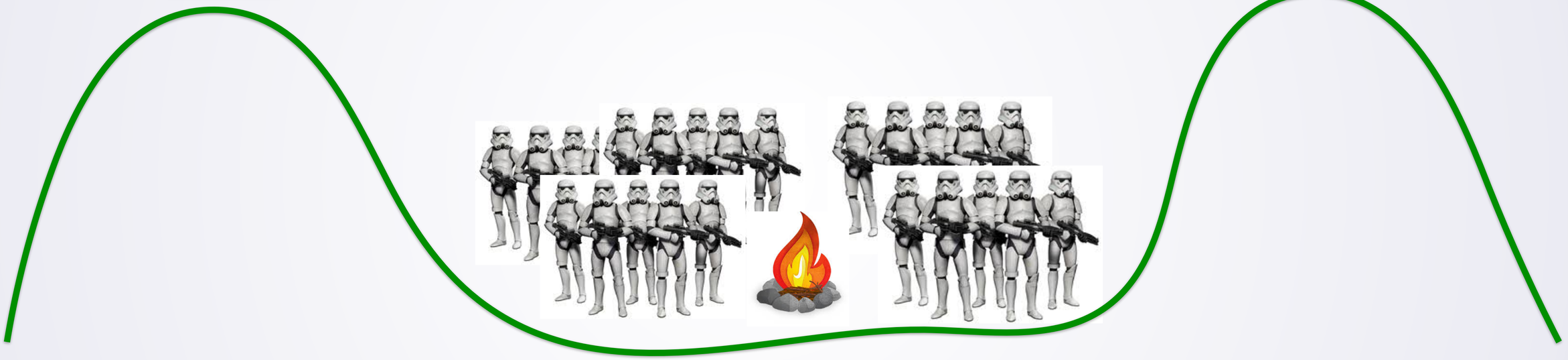
- I have a valley with the enemy army camped in it

Two Generals Problem



- We have an army camped on each side, each with its own general

Two Generals Problem



- If both generals attack together, they win
- If either attacks alone, they lose

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Two Generals Problem

A,
I will attack
at dawn if
you will
—L

- One wants to send a message to the other to attack

Two Generals Problem

A,
I will attack at dawn if you will
—L

- But that messenger might get captured…

Two Generals Problem

A,
I will attack at dawn if you will
—L

L,
Yes, I will attack
—A

- So now we need an acknowledgement…

Two Generals Problem

A,
I wil
at da
you will
—L

L,
Yes, I will
attack
—A

- But the ACK could get lost…

Two Generals Problem

I never got an ACK. My message was lost. I should **NOT** attack

I ACKed her message. I **MUST** attack.

- Now our armies will be defeated…

Two Generals Problem

I never got an ACK. My message was lost. I should **NOT** attack

I ACKed her message. I **MUST** attack.

- Problem: we can never tell if our ACK got through
  - ACK the ACKs? Need infinite number…

No Way To Tell Where Failure Happened

- We cannot tell the difference between
  - Data not reaching the receiver
  - Data reaching the receiver, but ACK not reaching us
- **Why is this such a big deal?**
  - We don’t know whether the requested action was taken or not

Would Like "Exactly Once,"...but...

- We can **never** ensure "exactly once" semantics
  - Which is what we would really like:
    - Ensure that receiver gets our message exactly once
- So what choices do we have?

At Least Once / At Most Once

- At least once:
  - We can know if receiver has gotten message at least once
  - Receive an ACK—got it at least once
  - May send need to send multiple times, may receive multiple times
- At most once:
  - Send it once
  - May or may not get it—-at most once semantics.

At Least Once / At Most Once

- At least once:
  - We can know if receiver has gotten message at least once
  - Receive an ACK—got it at least once
  - May send need to send multiple times, may receive multiple times
- At most once:
  - Send it once
  - May or may not get it—-at most once semantics.

"But wait" you say...

At Least vs At Most Once

- TCP may send data multiple times (no ACK -> retransmission)
  - We said multiple sending goes with **at least once**
- But **application** receives any piece of data **at most once**
  - Once, unless connection fails

At Least vs At Most Once

- TCP may send data multiple times (no ACK -> retransmission)
  - We said multiple sending goes with **at least once**
- But **application** receives any piece of data **at most once**
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- TCP layer has sequence numbers
  - Can identify duplicates, only passes data to application once

At Least vs At Most Once

- TCP may send data multiple times (no ACK -> retransmission)
  - We said multiple sending goes with **at least once**
- But **application** receives any piece of data **at most once**
  - Once, unless connection fails
- TCP layer has **sequence numbers**
  - Can identify duplicates, only passes data to application once
- This idea is key:
  - Can receive same data multiple times
  - But only act on it once

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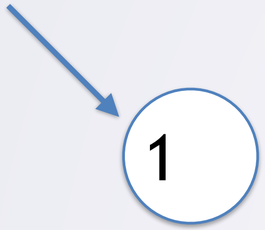
FSMs + Idempotent Operations

- Two ideas that work together to handle asynchronous + failures
  - Build protocols/APIs around **idempotent operations**
    - Applying an operation multiple times is the same as applying it once (i.e. ignore duplicates)
  - Build implementations with **FSMs**
    - Computation model where system keeps track of current ‘state’ during operations and transitions to a next state based on an action/event.

Example: Buy 5 widgets

- Online store, user asks to buy 5 widgets
  - What do we need to do to fulfill this request?

Buy 5 widgets



1. We accept the request + give it a unique ID

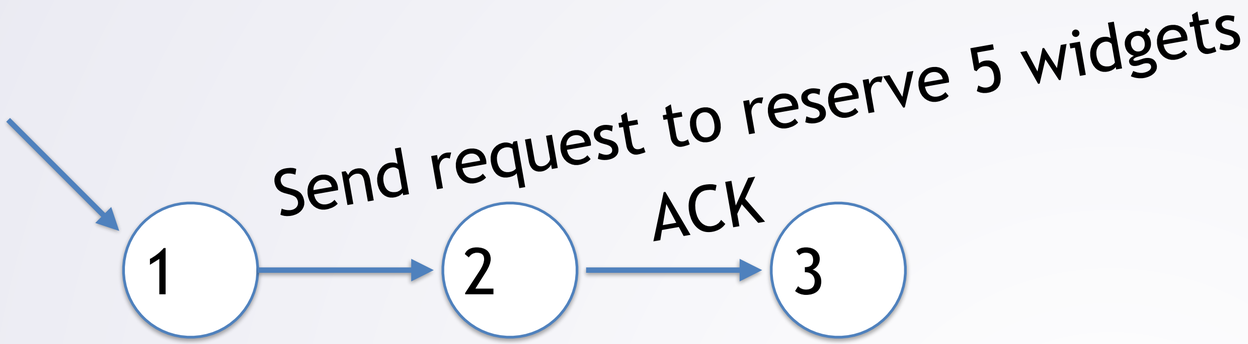
   E.g., 123456789

Buy 5 widgets

2. Send a request to our inventory management system

"req 87654: Reserve 5 widgets for transaction 123456789"

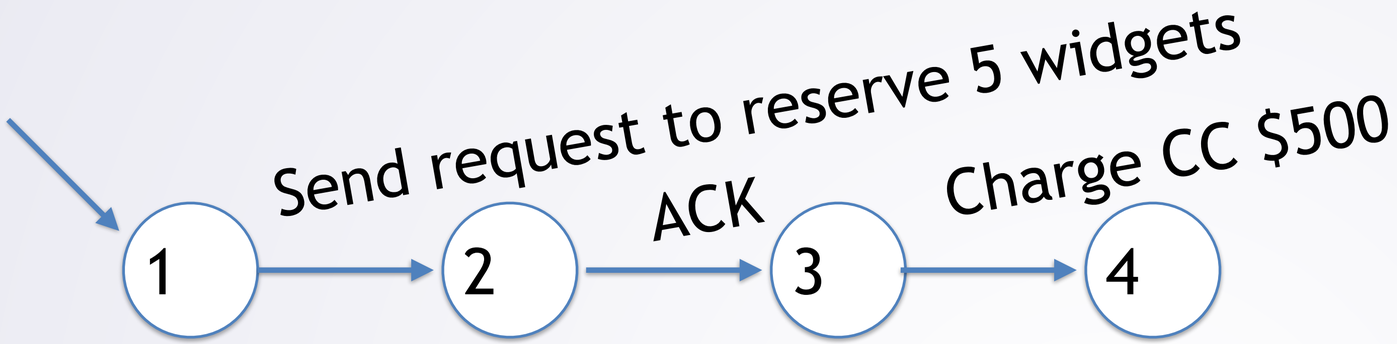
Buy 5 widgets



3. Receive successful acknowledgement

"ack 87654: 5 widgets reserved for 123456789"

Buy 5 widgets



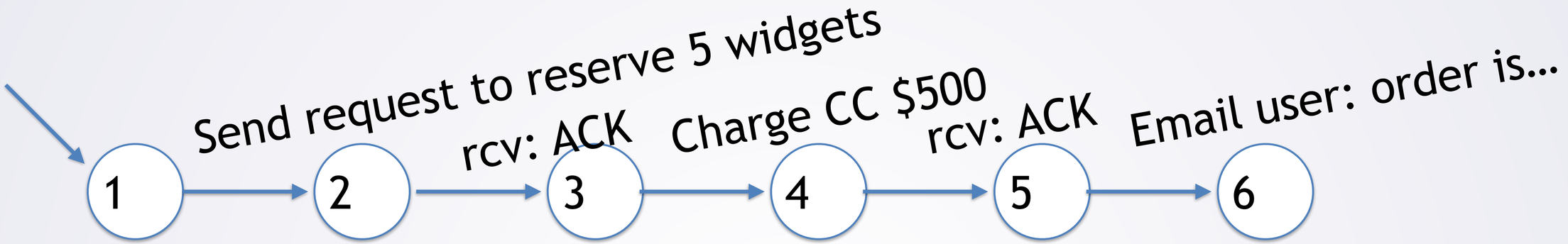
4. Send Credit Card Charge request

External service: probably has its own unique ID?

Buy 5 widgets

5. Receive confirmation of successful card charge

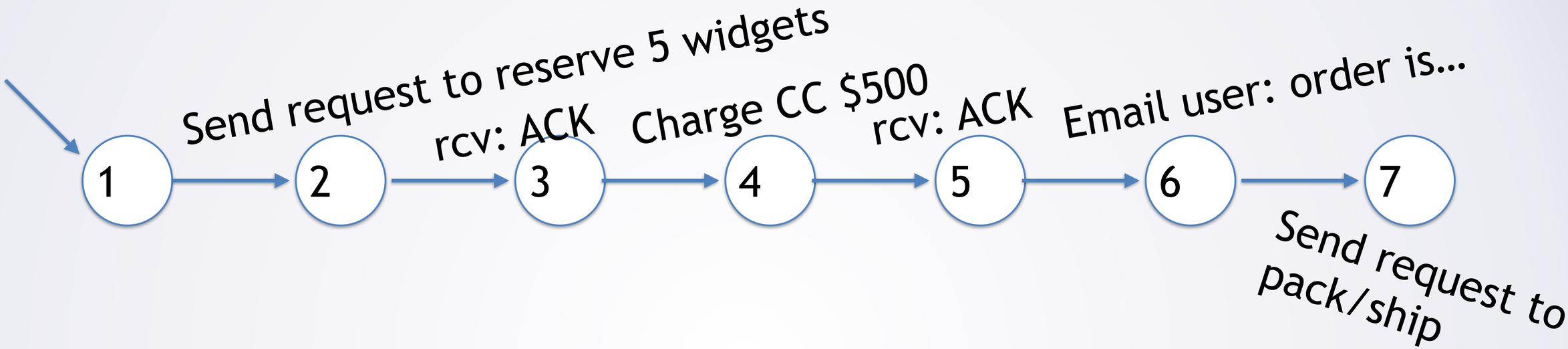
Buy 5 widgets



6. Inform user of successful purchase

E.g., send email?

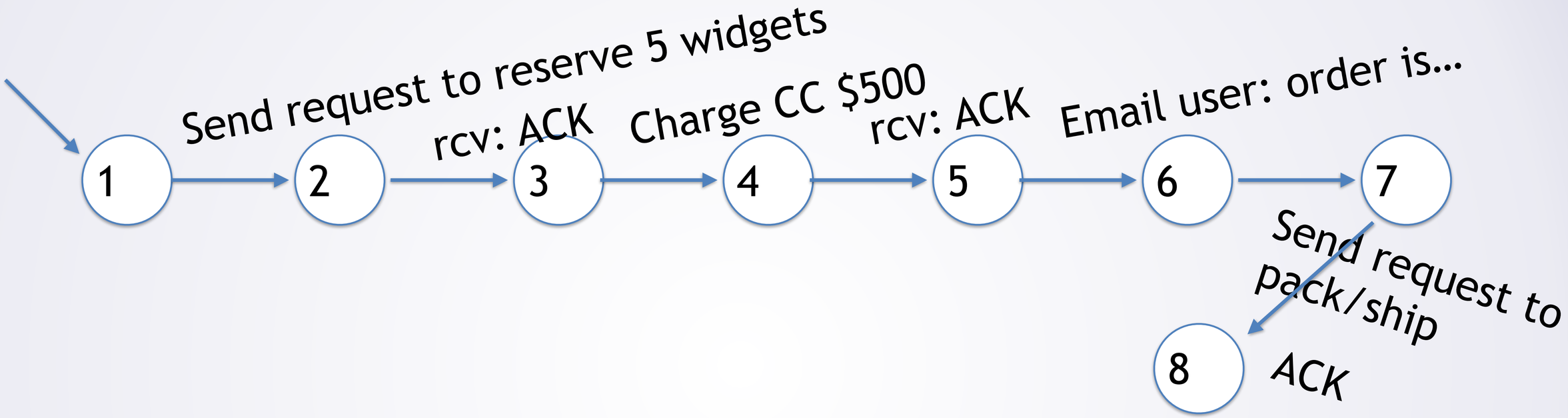
Buy 5 widgets



7. Send request to warehouse to pack/ship

req: 8888 Send 5 widgets to 123 Fake St for order 123456789

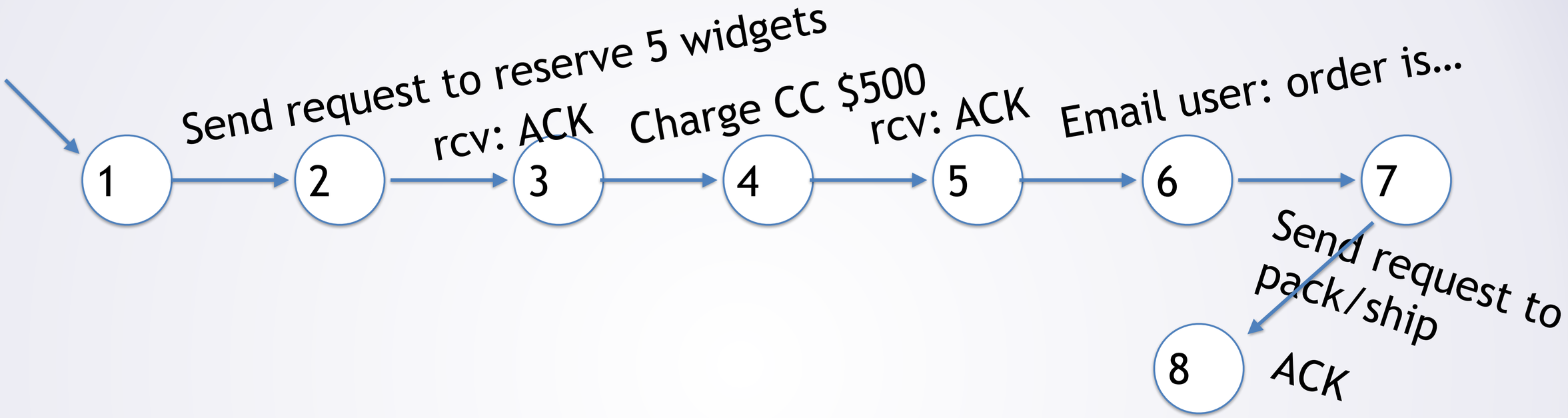
Buy 5 widgets



8. Receive ACK

Now done (other systems may still deal with things)

Buy 5 widgets

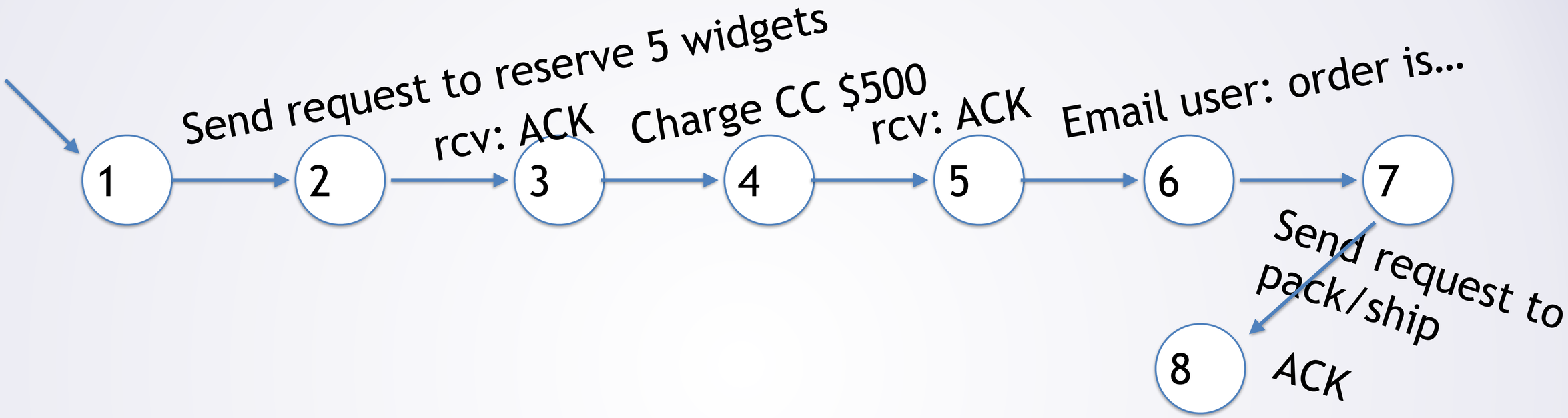


But is that all there is to it?

8. Receive ACK

Now done (other systems may still deal with things)

Buy 5 widgets

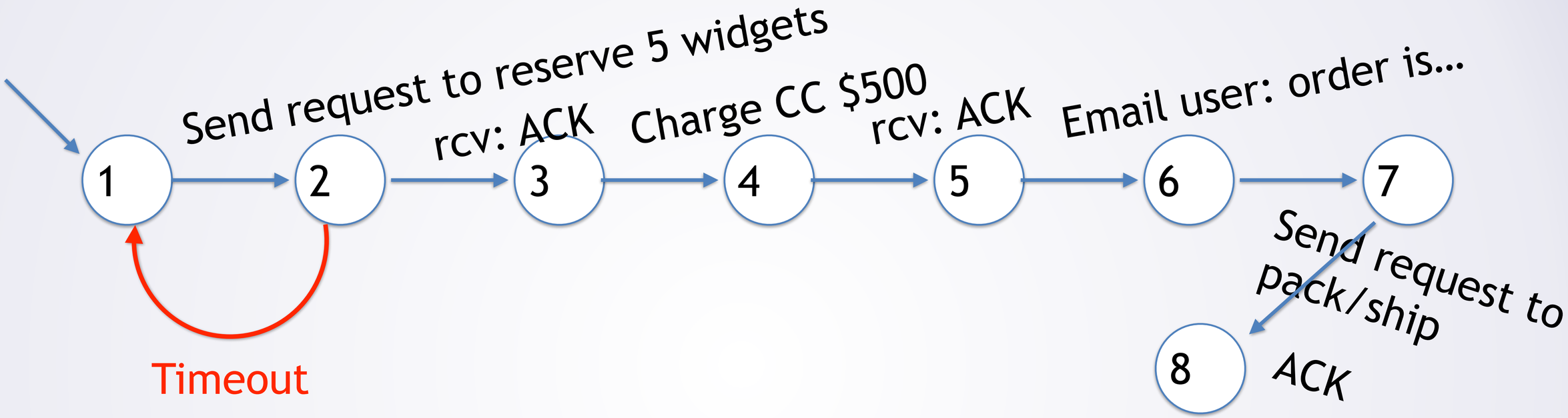


No things could go wrong at pretty much any step!

8. Receive ACK

Now done (other systems may still deal with things)

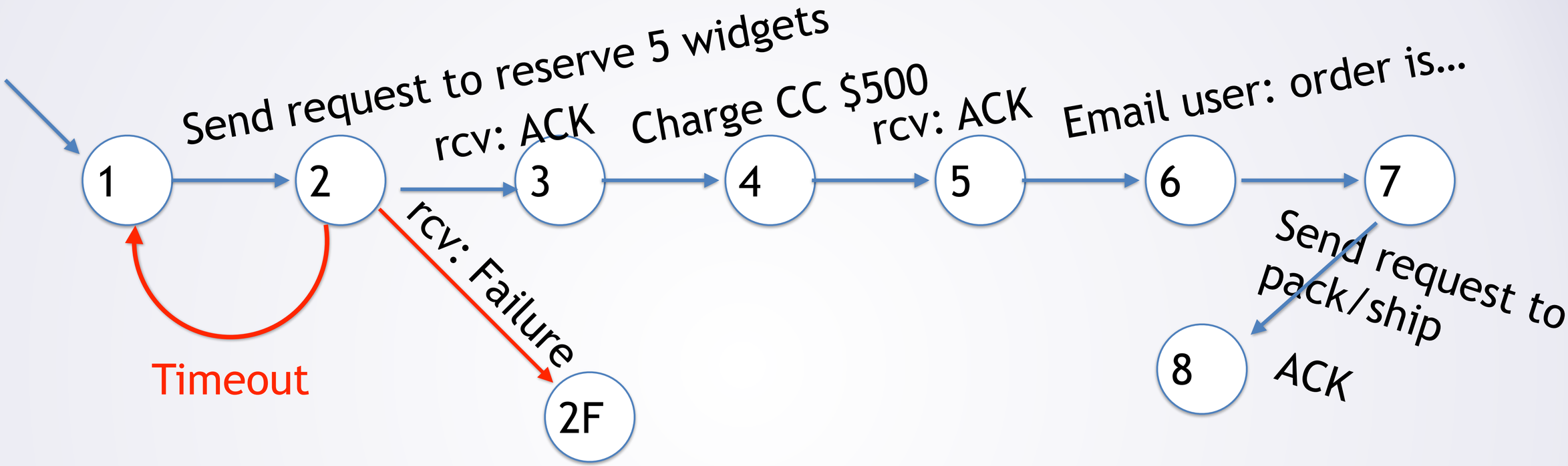
Buy 5 widgets



2. Message not ACKed? Re-send message

Receiver already has req 87654 -> Ignores message

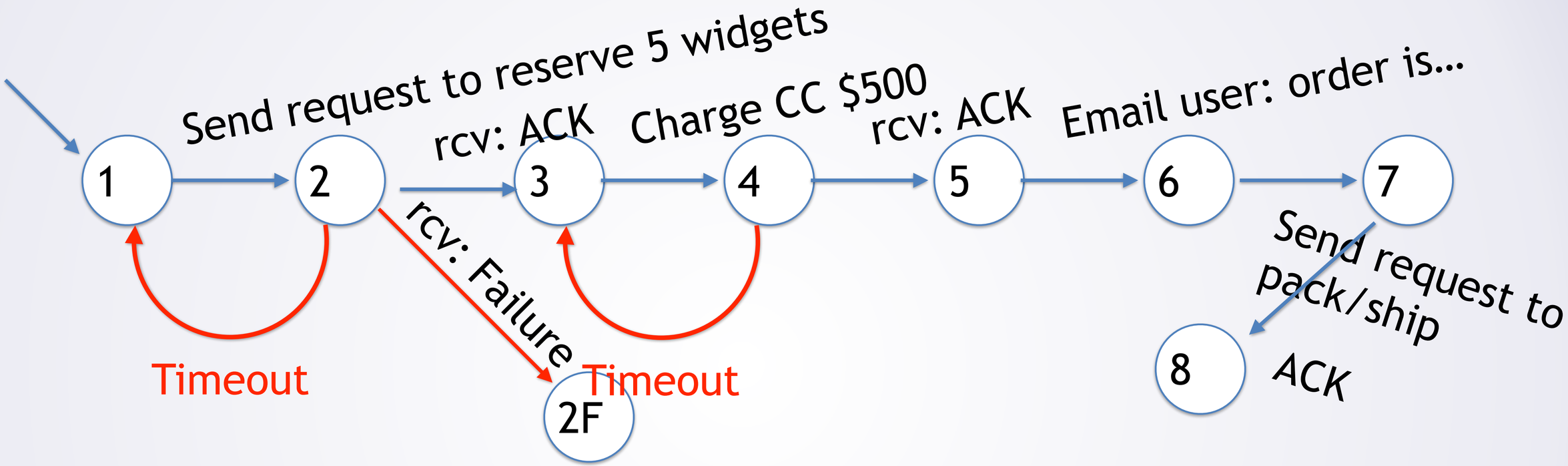
Buy 5 widgets



2. Insufficient widgets in warehouse?

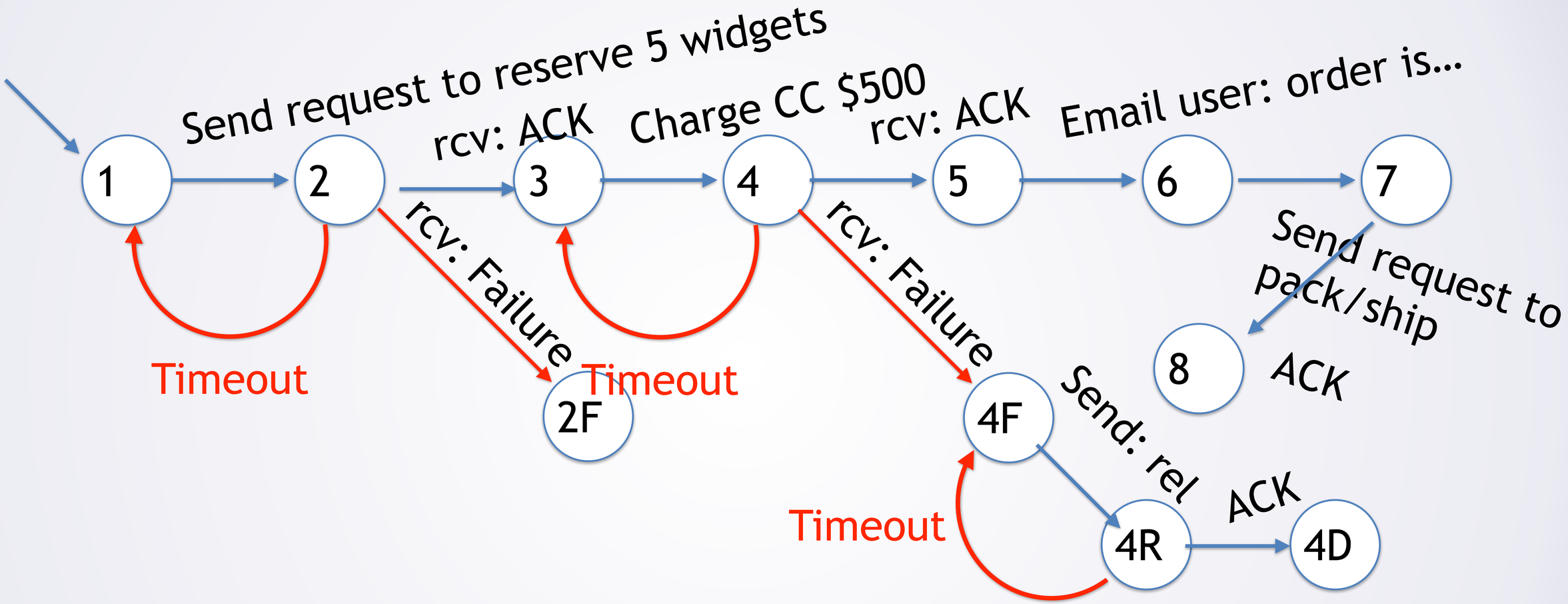
   Go to error state (inform user, retry later…)

Buy 5 widgets



4. Timeout? Retry.

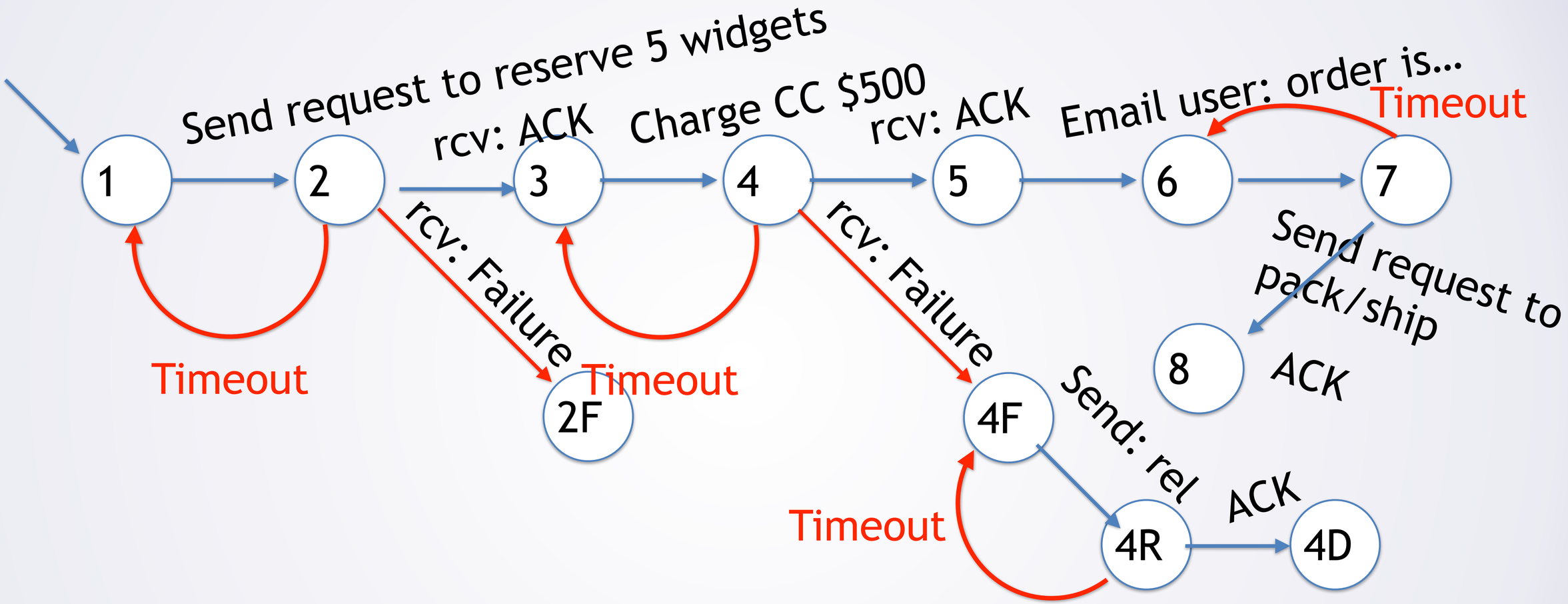
Buy 5 widgets



4. Card denied? (stolen, insufficient funds,…)

   Need to release reservation

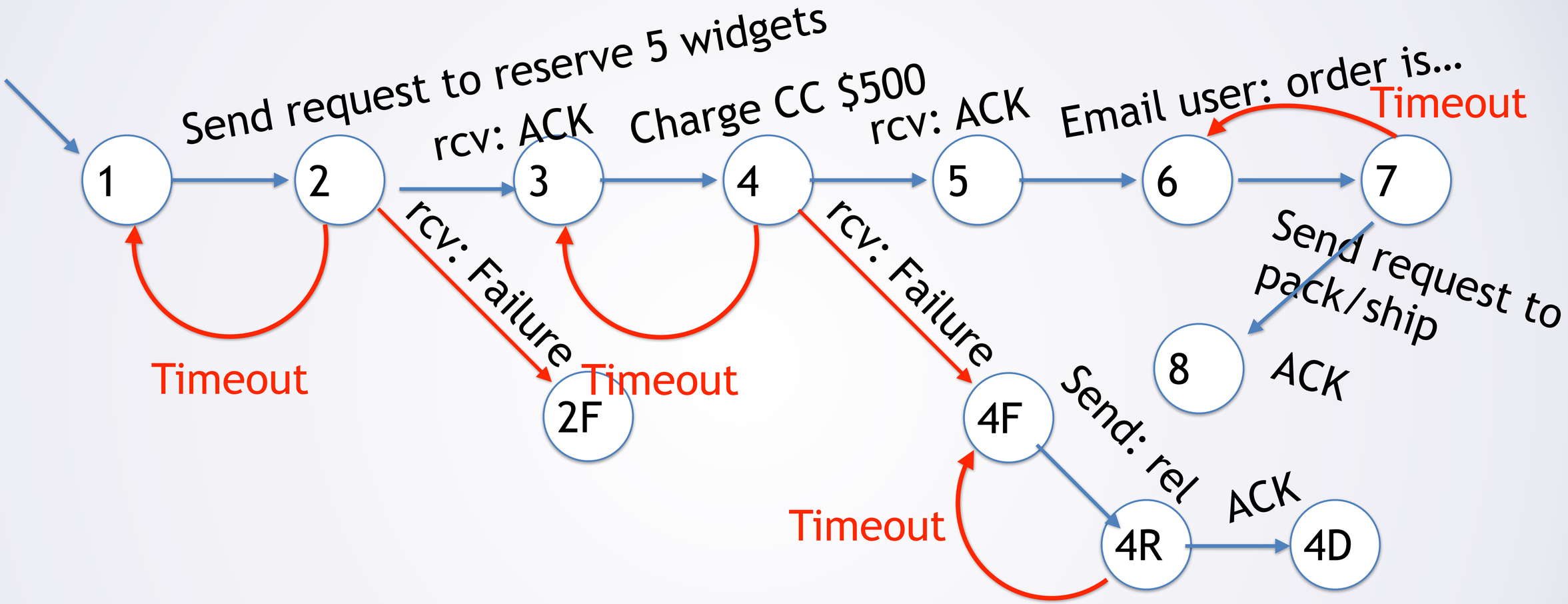
Buy 5 widgets



7. Timeout? Retry

What about other failures here?

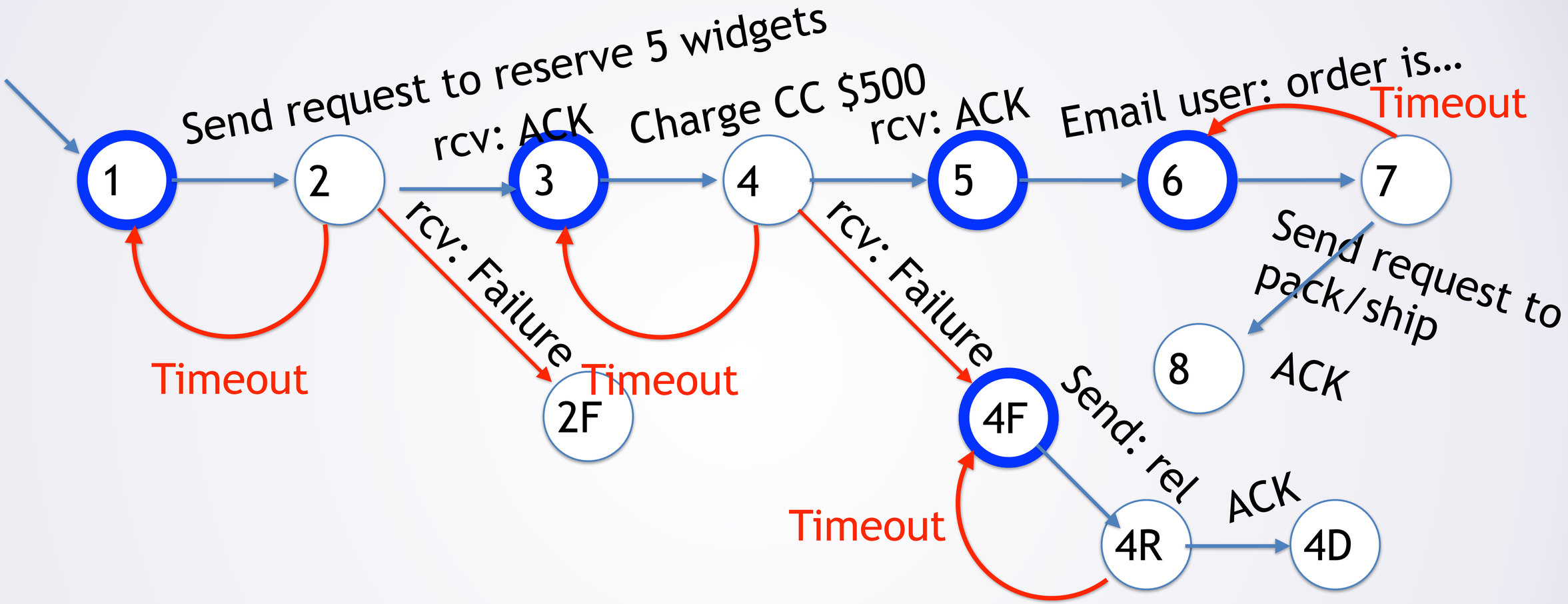
Buy 5 widgets



No other failures here:

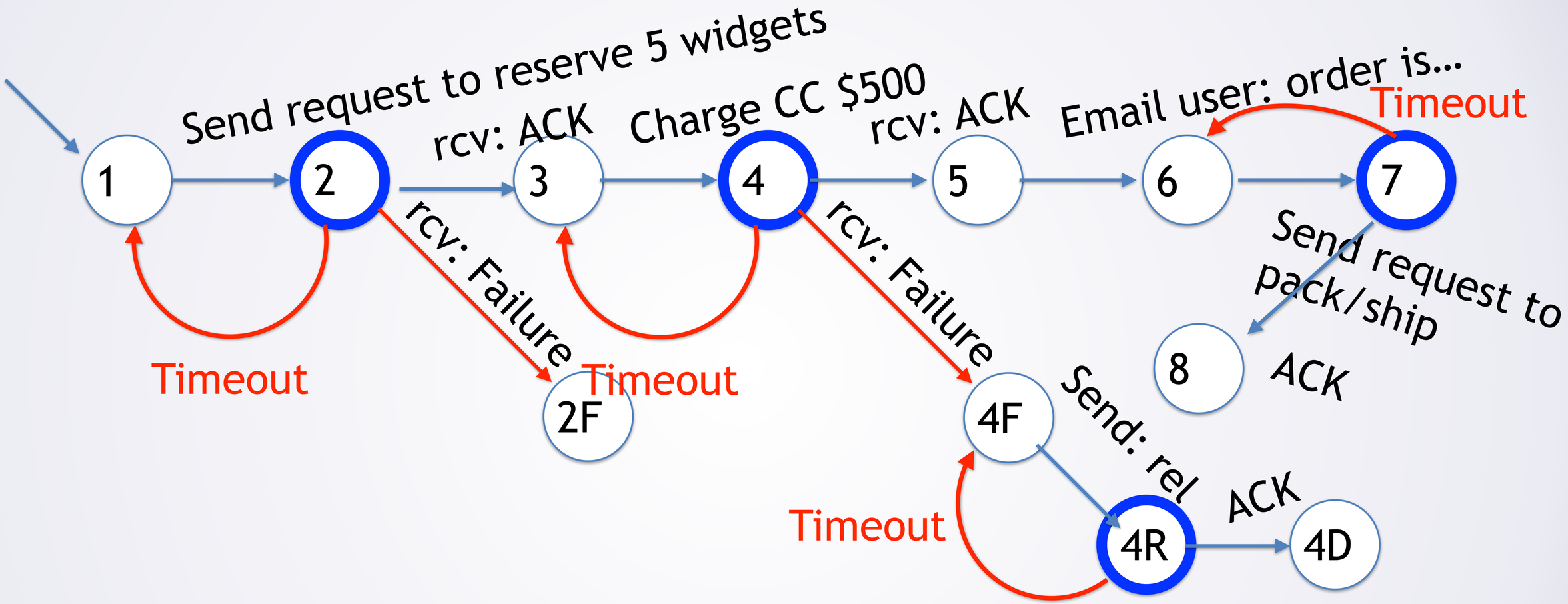
Confirmed/reserved everything in advance

Buy 5 widgets



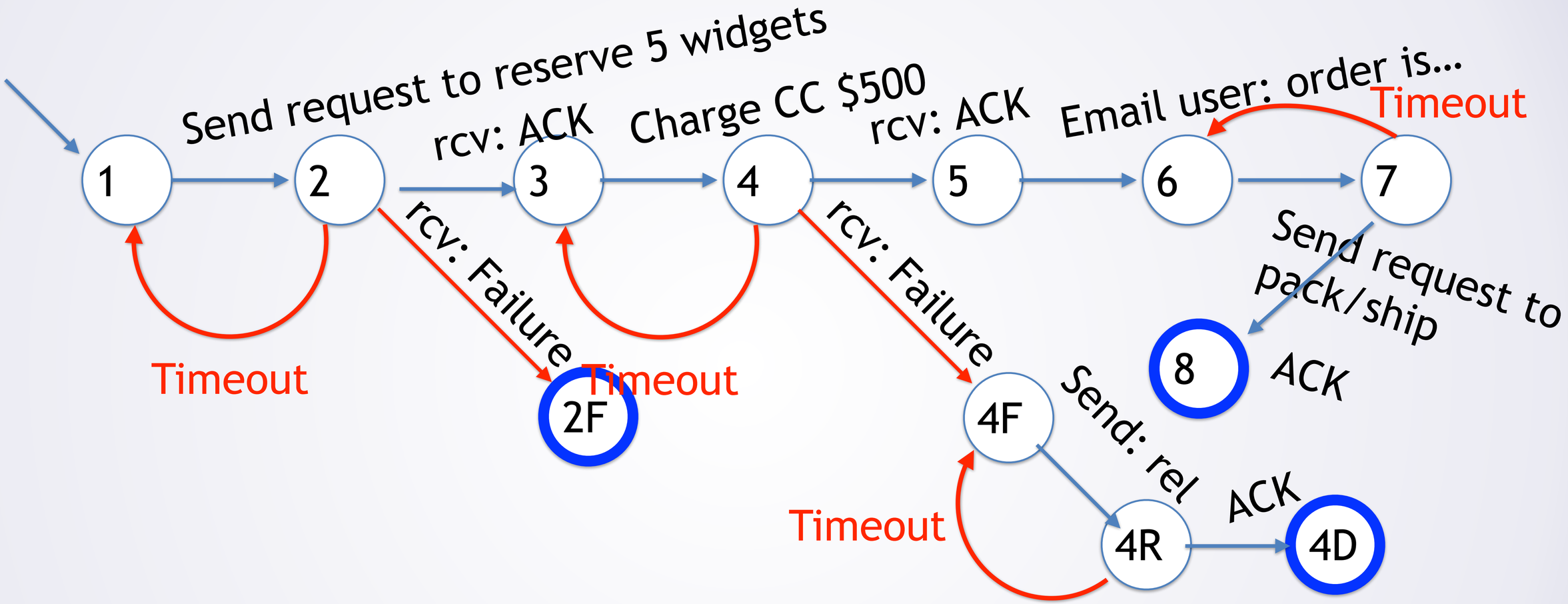
States 1, 3, 5, 6, and 4F: send message, go to next state

Buy 5 widgets



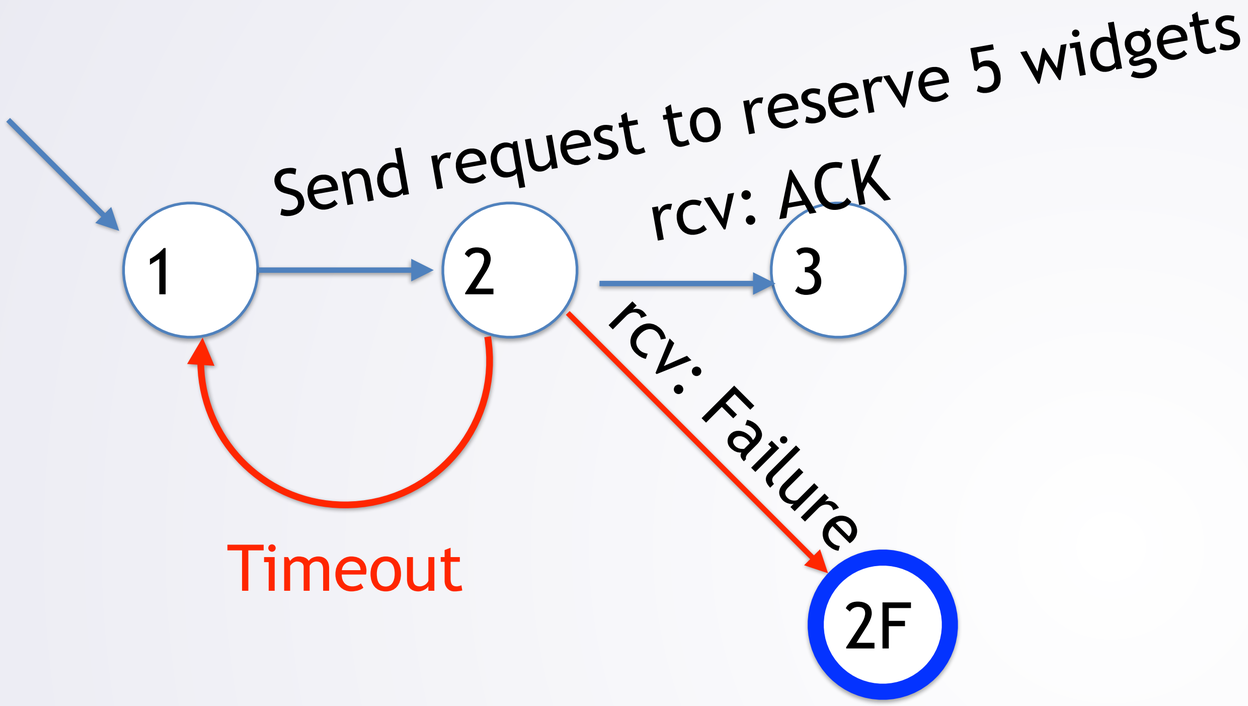
States 2, 4, 7, 4R: Wait to receive message (timeout -> retry)

Buy 5 widgets



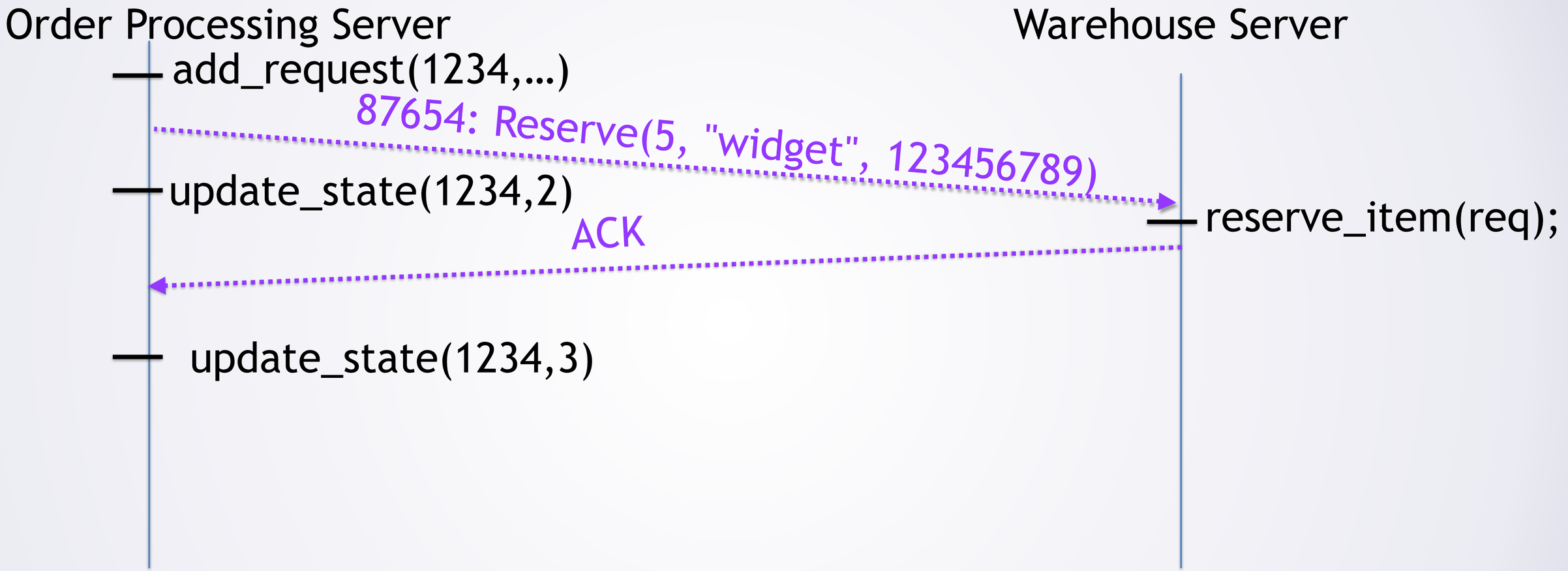
States 8, 2F, 4D: finished.

Importance of Idempotence

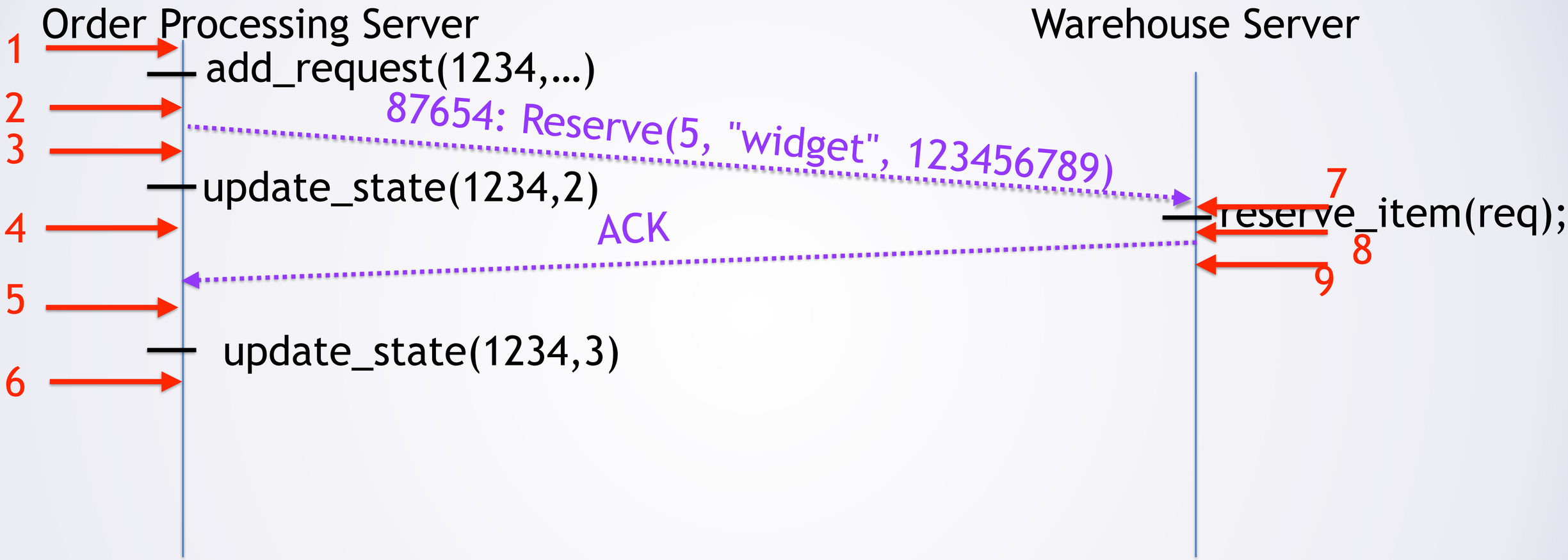


Let us look at just this part and see why idempotence is so useful

Normal Operation



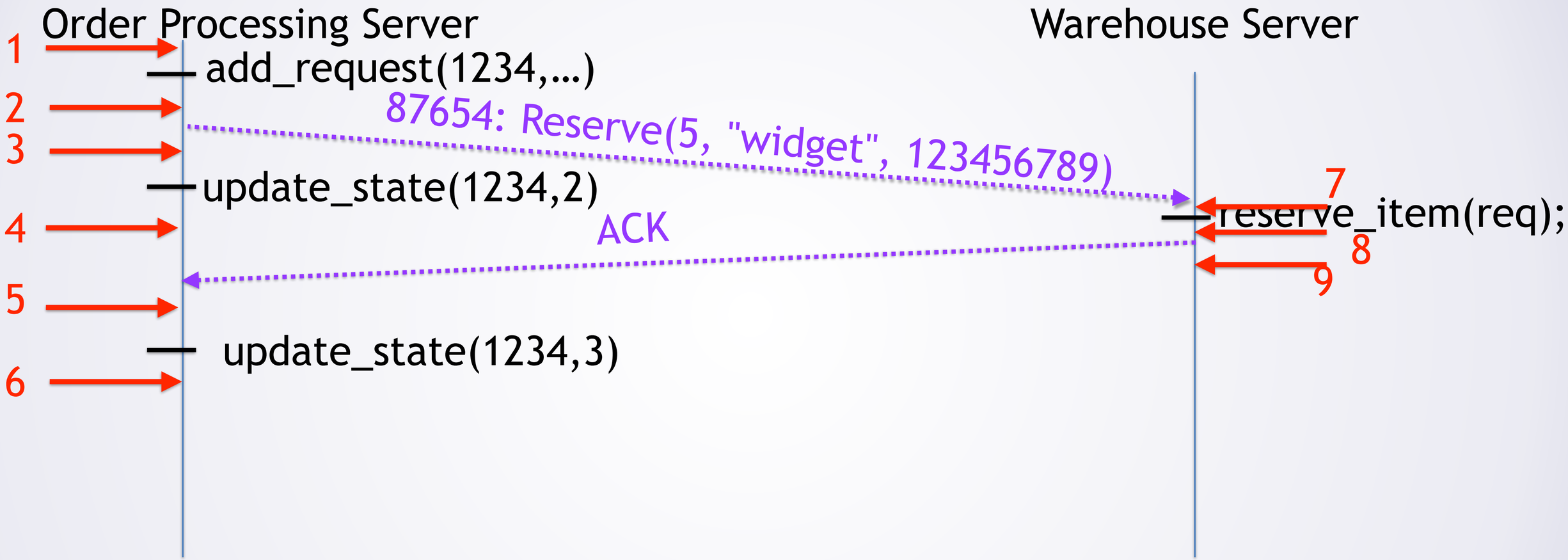
Normal Operation



What happens if server fails at any of these points?

Turned off, crashes, …

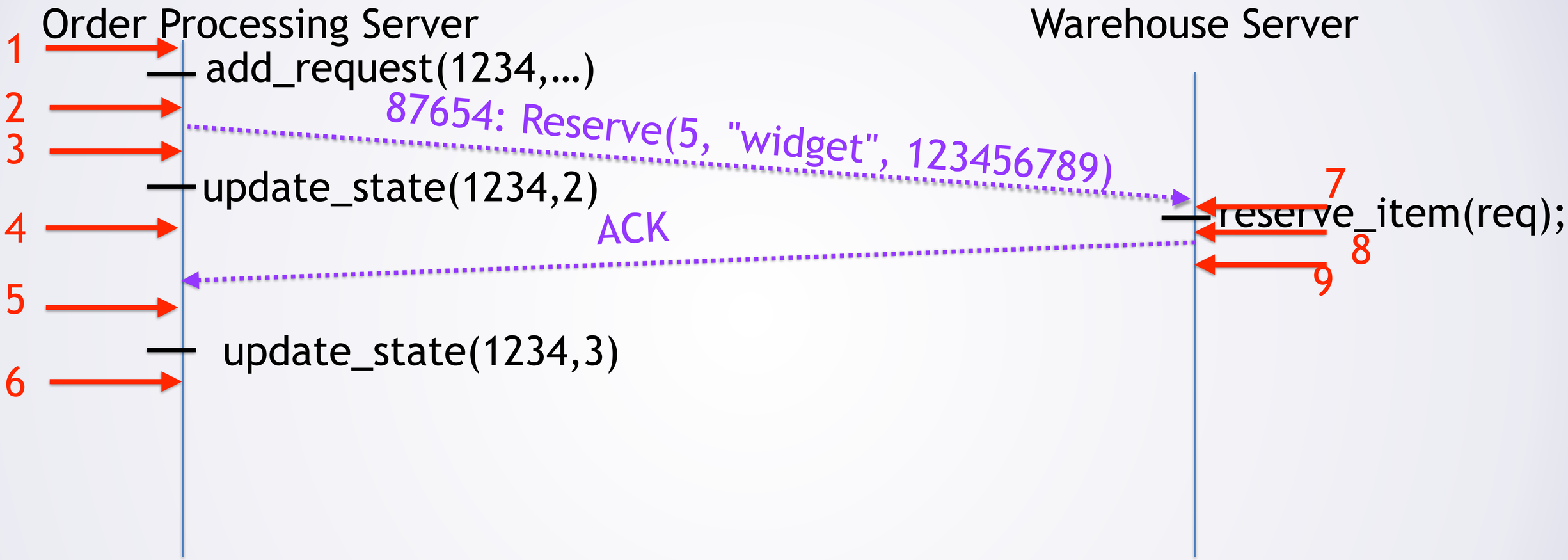
Normal Operation



1: request not yet accept (not confirmed with client)

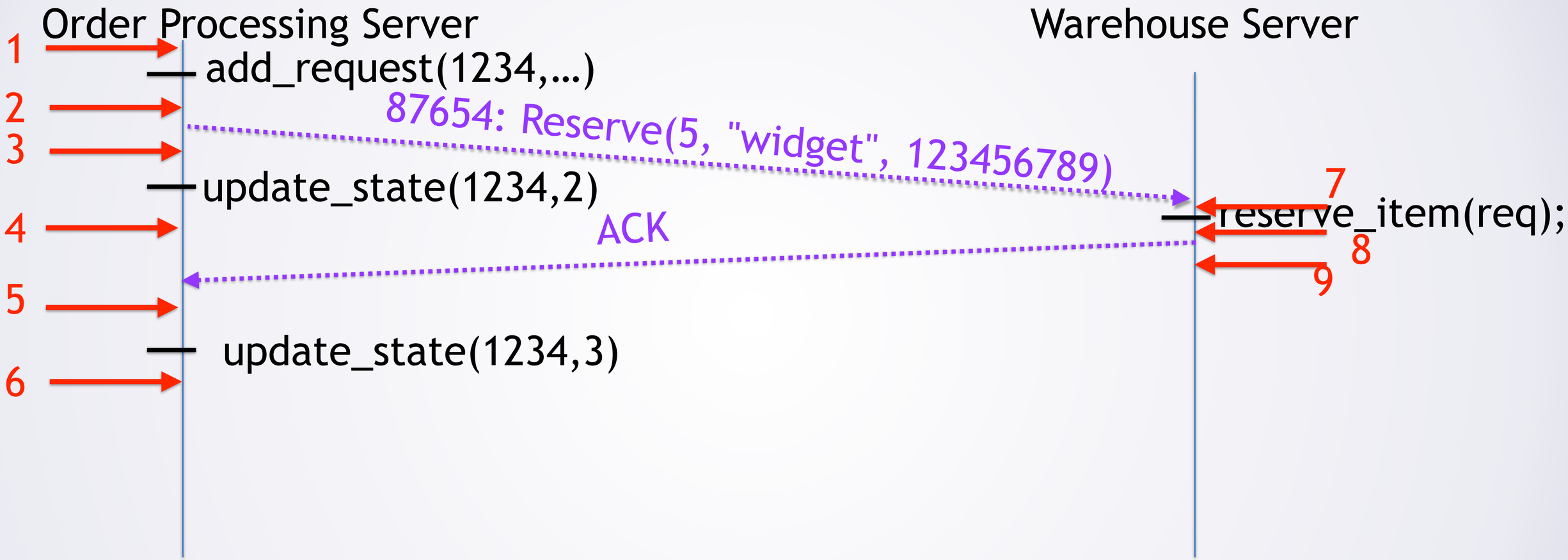
Client needs to re-send request (external API should use idempotency)

Normal Operation



2: will just send message when server returns

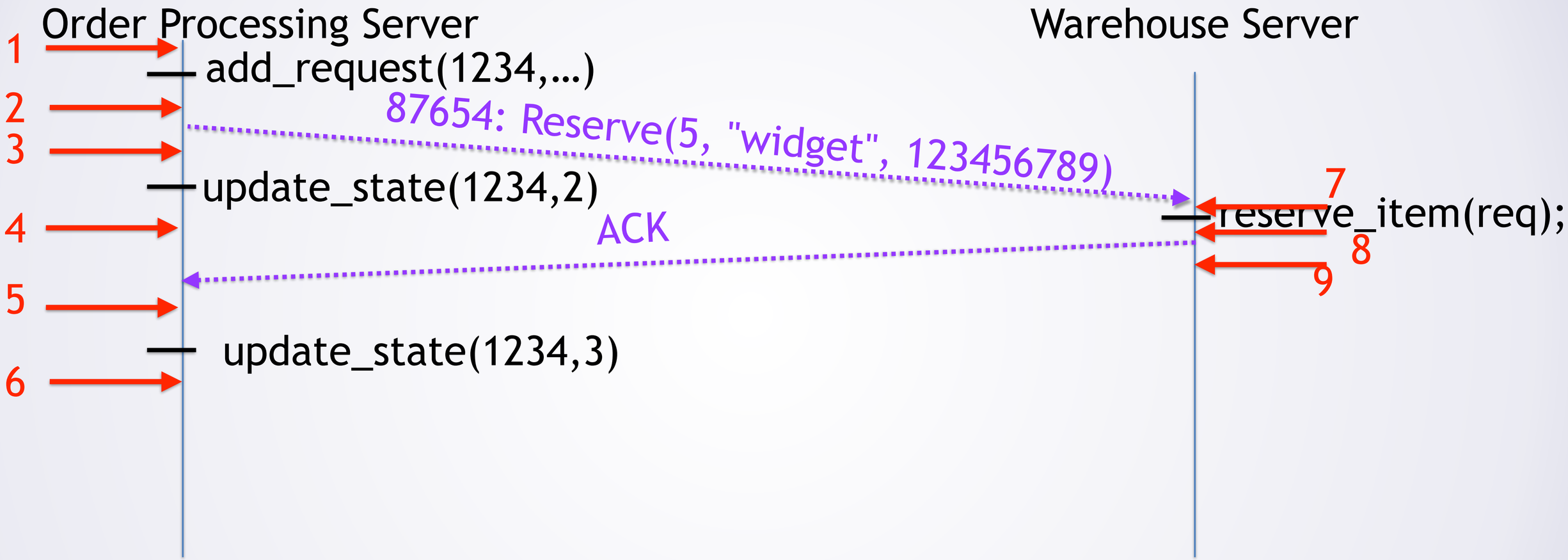
Normal Operation



3: will resend when server returns

Good thing warehouse will ignore duplicates!

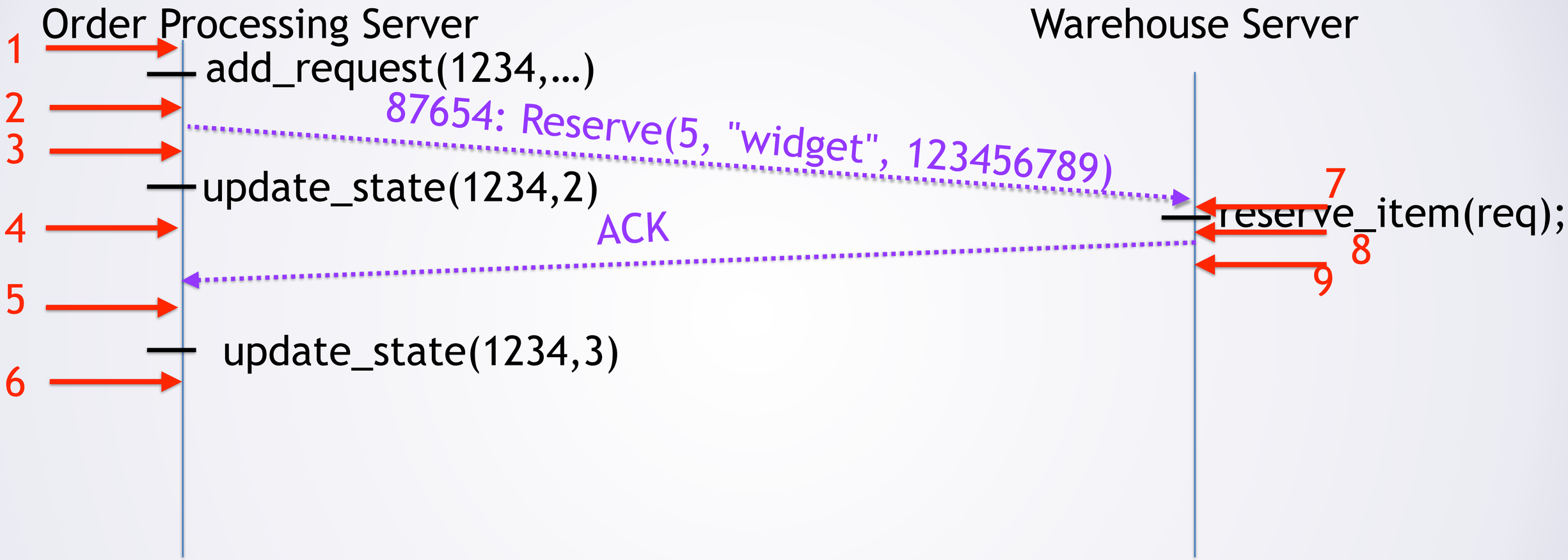
Normal Operation



4: depending on when server returns, might miss ACK.

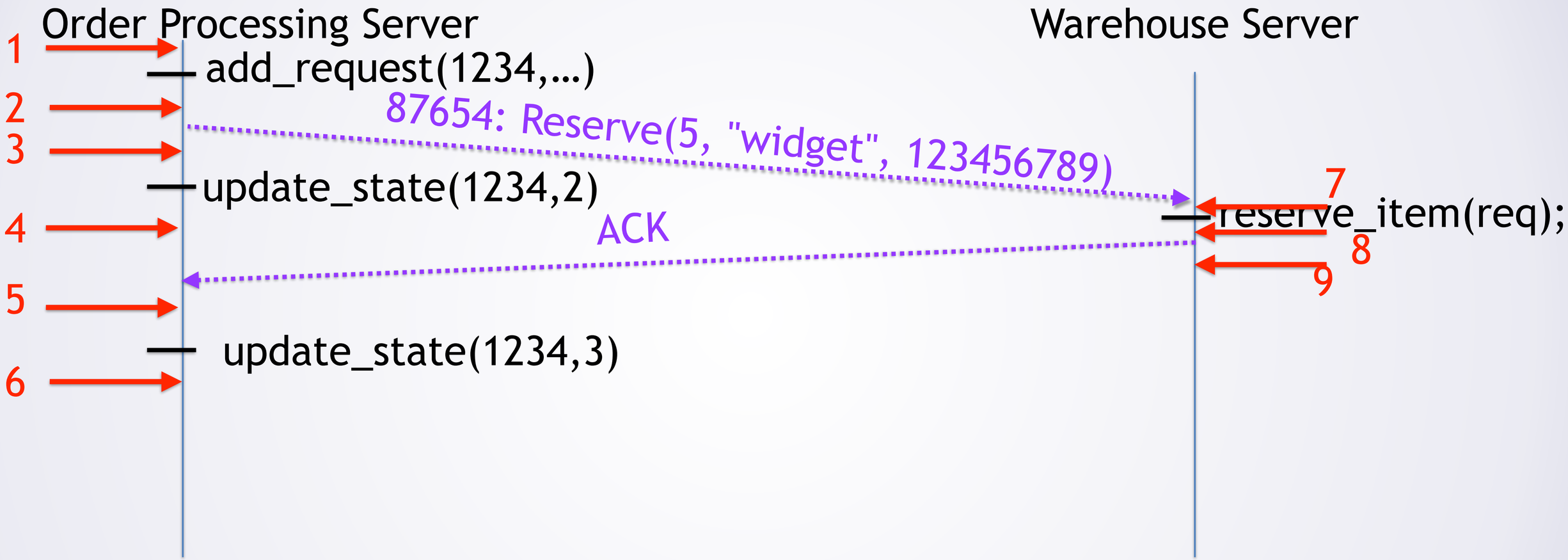
Missed ACK? Will resend after timeout—idempotency helps here!

Normal Operation



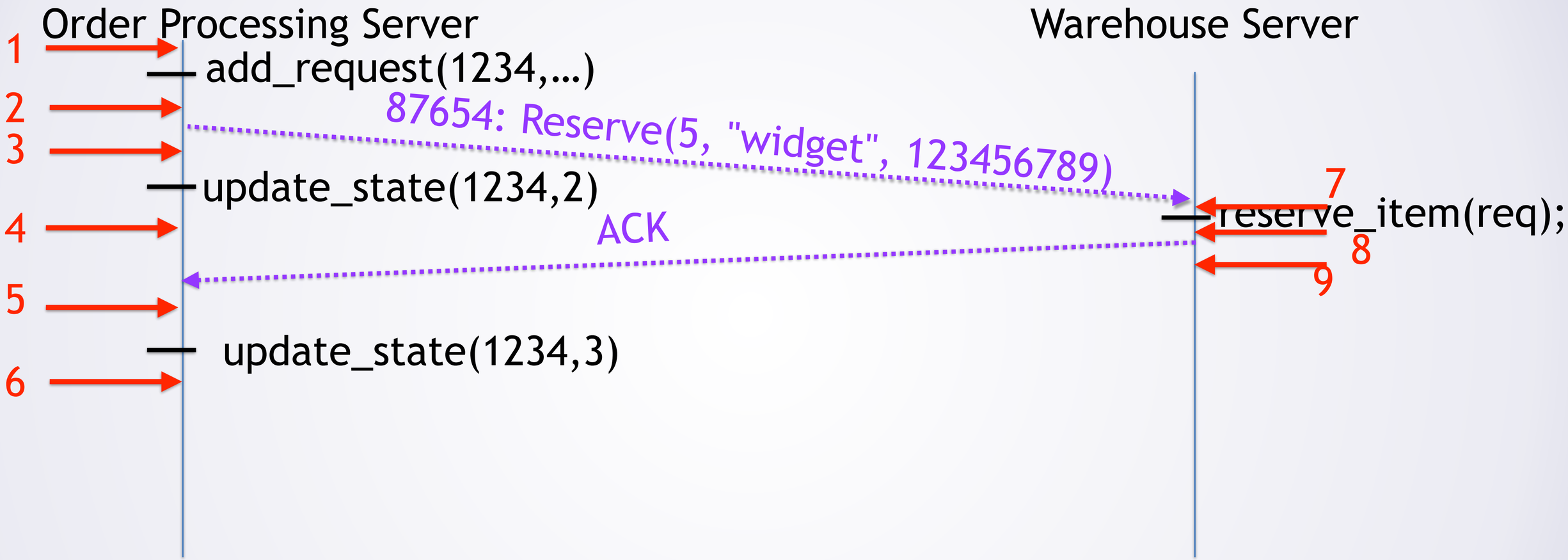
5: will resend after timeout

Normal Operation



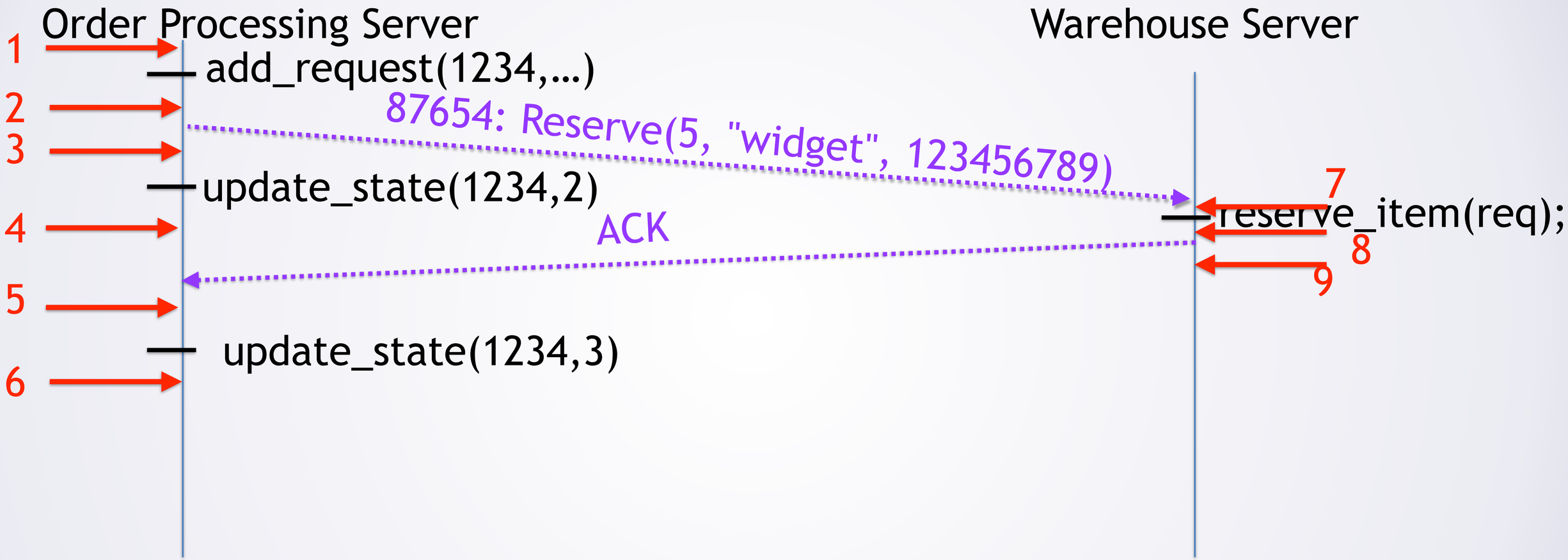
6: will just continue to next step after server returns

Normal Operation



7: will never send ACK. order processor will retry

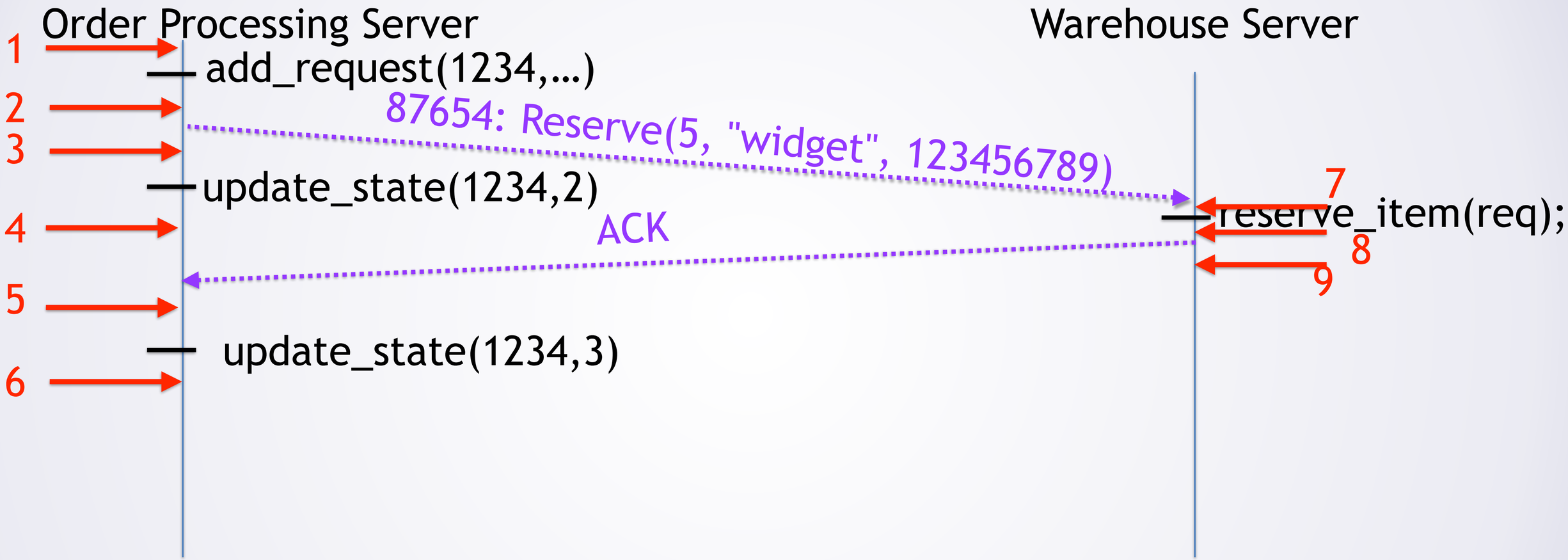
Normal Operation



8: ACK never sent, order processor will retry, duplicate will be ignored

Note order processor can't distinguish 7 vs 8

Normal Operation



9: done—nothing special happens

Trust No One

- Another important consideration:
  - Never trust clients
- Server should validate **everything**
  - Client can forge any bit of request
  - Trusting client = huge security hole!
- We will talk more about this when we get to security
  - Especially authentication.