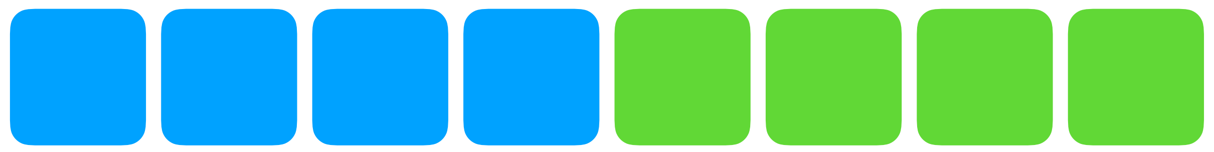
Verifying concurrent software using movers in CSPEC

Tej Chajed, Frans Kaashoek, Butler Lampson*, Nickolai Zeldovich
MIT CSAIL and *Microsoft

Concurrent software is difficult to get right

Programmer cannot reason
about code in sequence…



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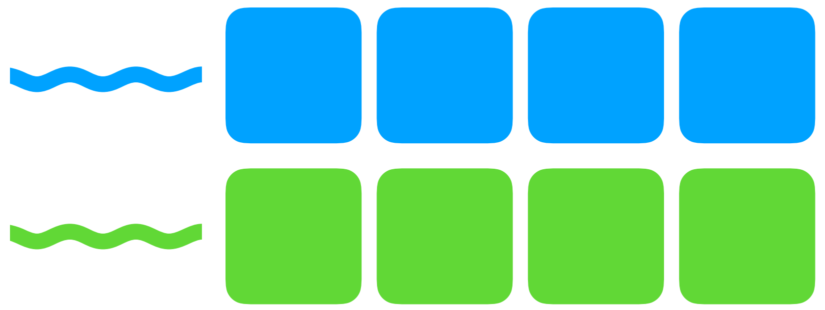

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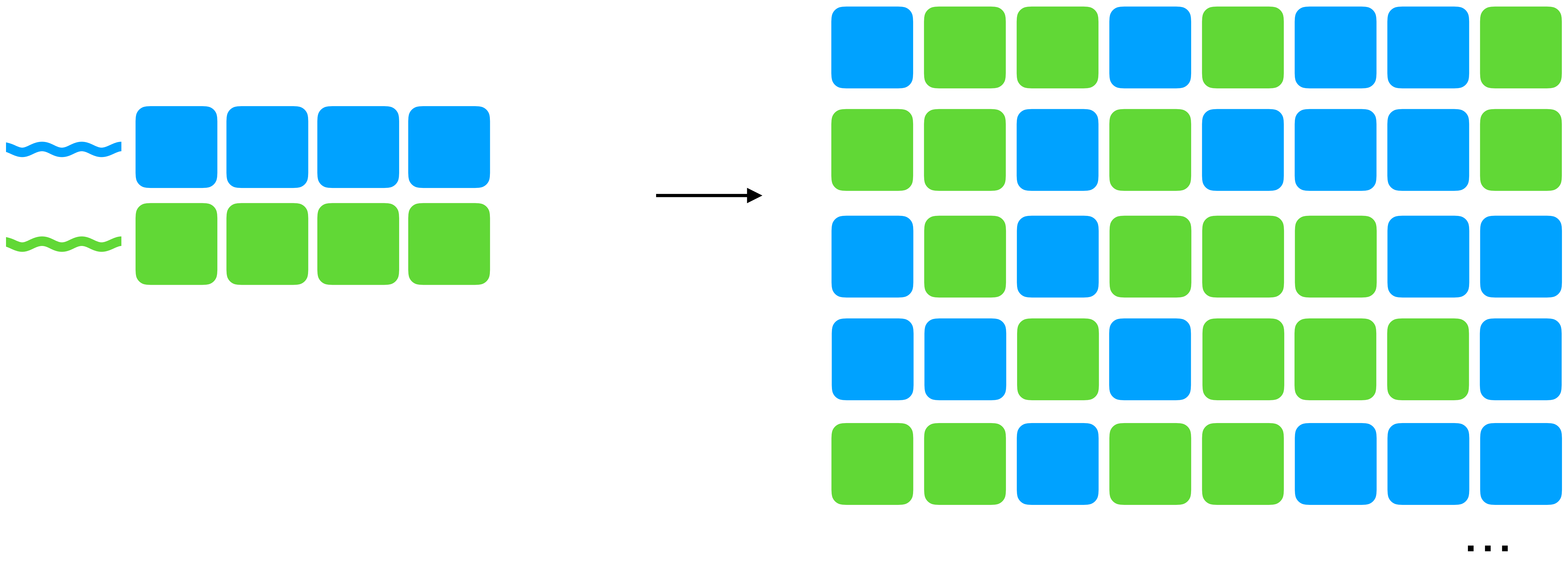

Goal: verify concurrent software

Challenge for formal verification

- Proofs must also cover every execution
- Many approaches to managing this complexity
  - movers [Lipton, 1975]
  - rely-guarantee [1983]
  - RGSep [CONCUR 2007]
  - FCSL [PLDI 2015]
  - Iris [POPL 2017, LICS 2018, others]
  - many others

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- This work: our experience using **movers**

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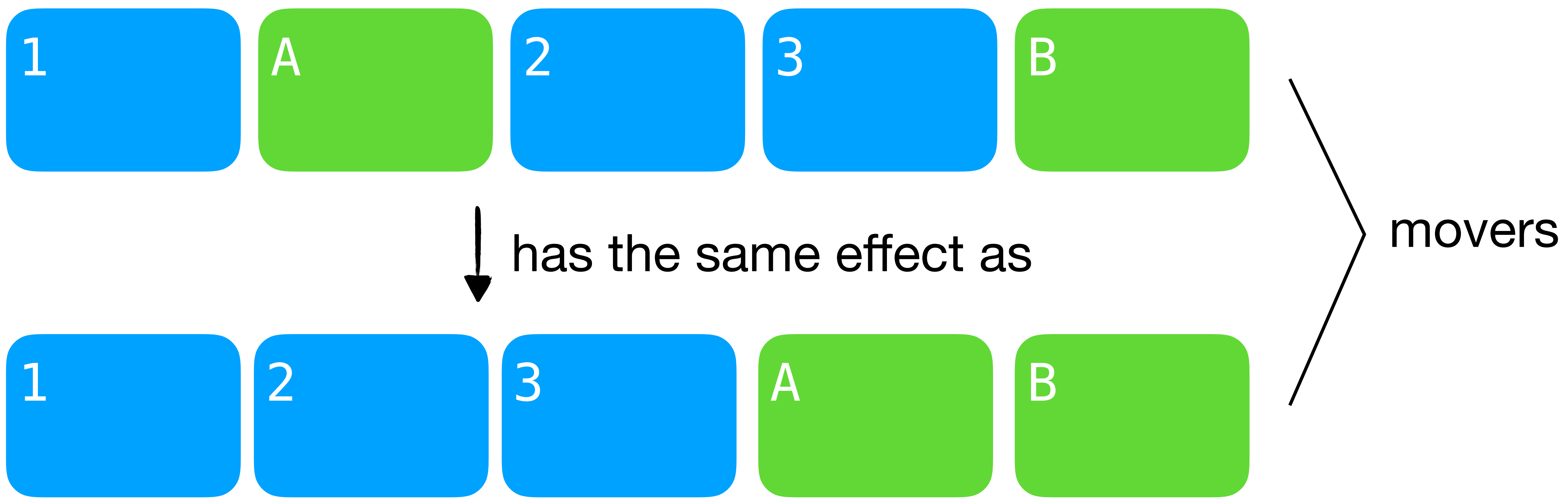

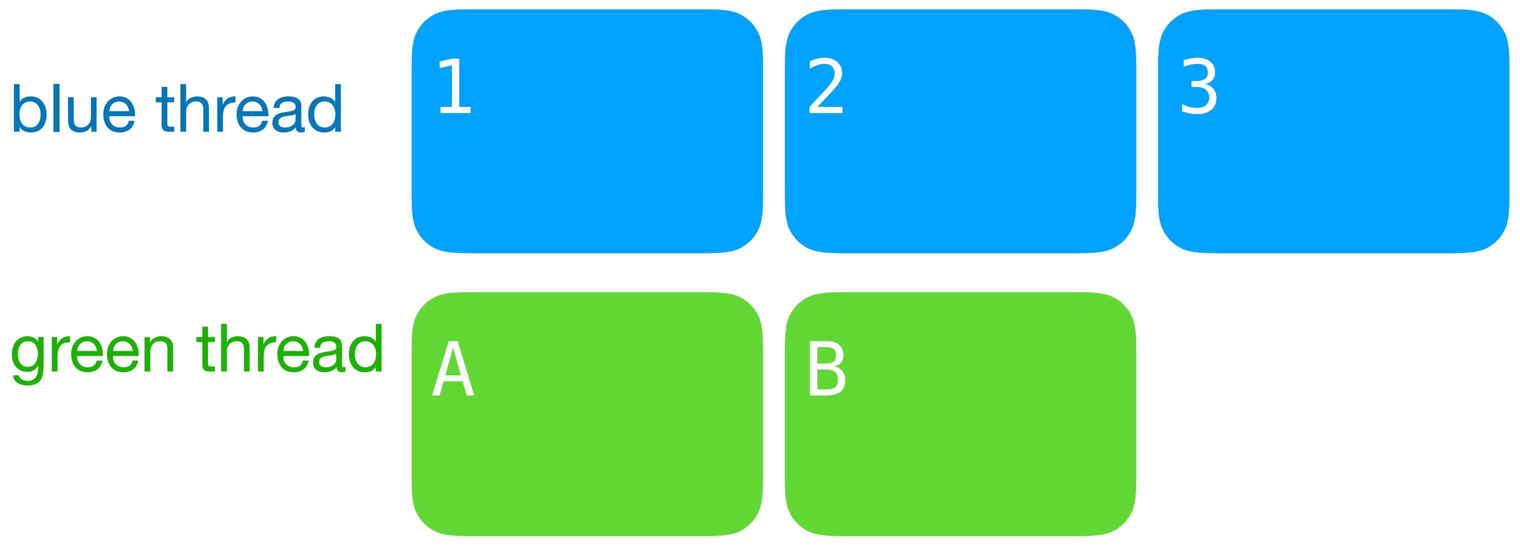

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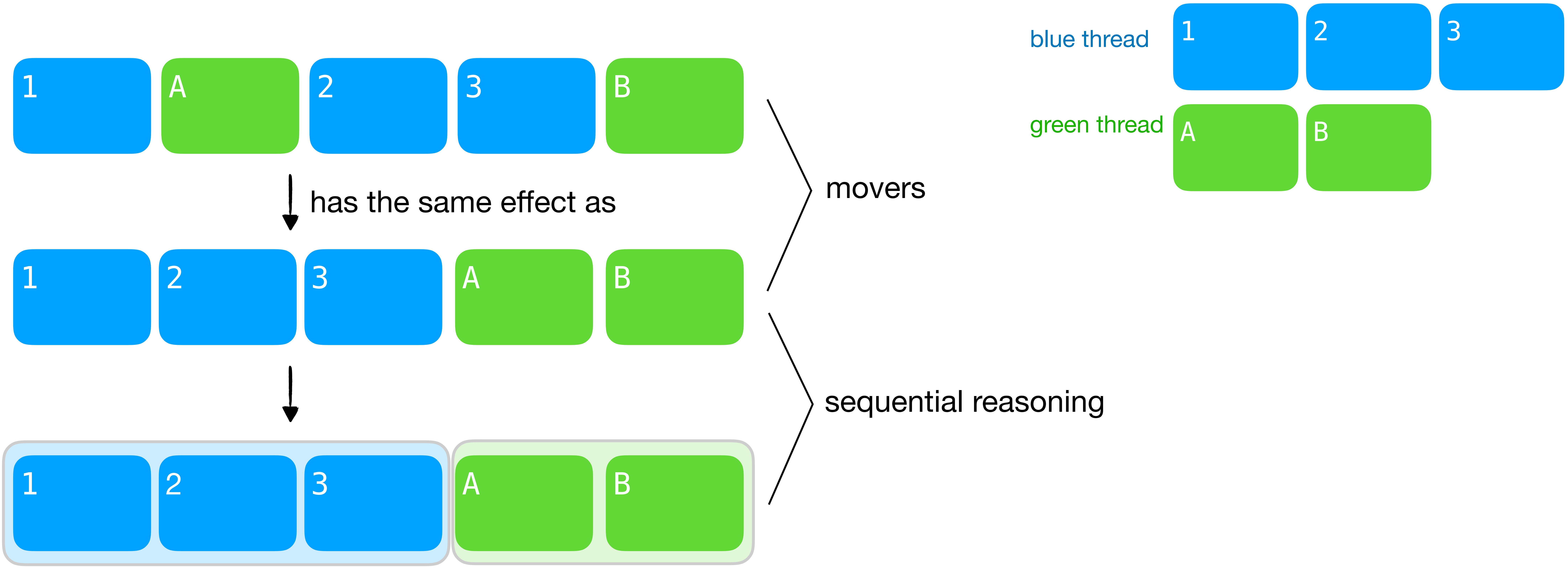

Prior systems with mover reasoning

CIVL [CAV ’15, CAV ’18]	framework relies pen & paper proofs
IronFleet [SOSP ’15]	only move network send/receive

Contribution: CSPEC

- Framework for verifying concurrency in systems software
    - **general-purpose movers**
    - **patterns** to support mover reasoning
    - **machine checked** in Coq to support extensibility

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- Framework for verifying concurrency in systems software
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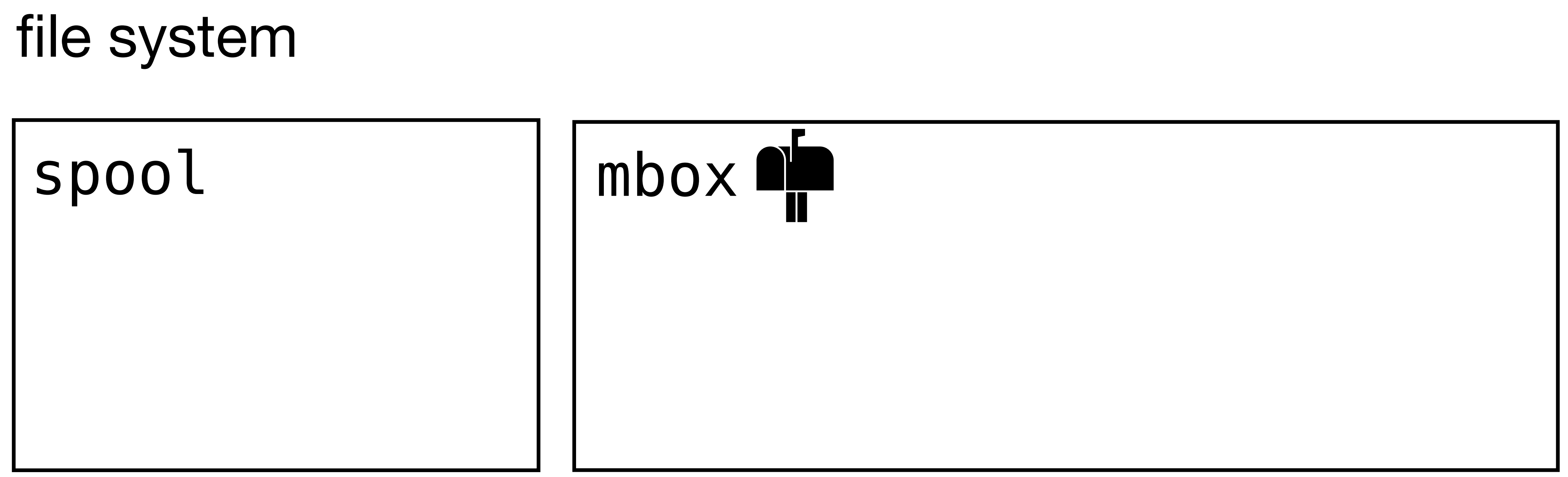
  - **patterns** to support mover reasoning
  - **machine checked** in Coq to support extensibility
- Case studies using CSPEC
  - Lock-free file-system concurrency
  - Spinlock on top of x86-TSO (see paper)

Case study: mail server using file-system concurrency



Mail servers exploit file-system concurrency

```
# accept
def deliver(msg):
  # spool
  create("/spool/$TID")
  write("/spool/$TID", msg)
  # store
  while True:
    t = time.time()
    if link("/spool/$TID",
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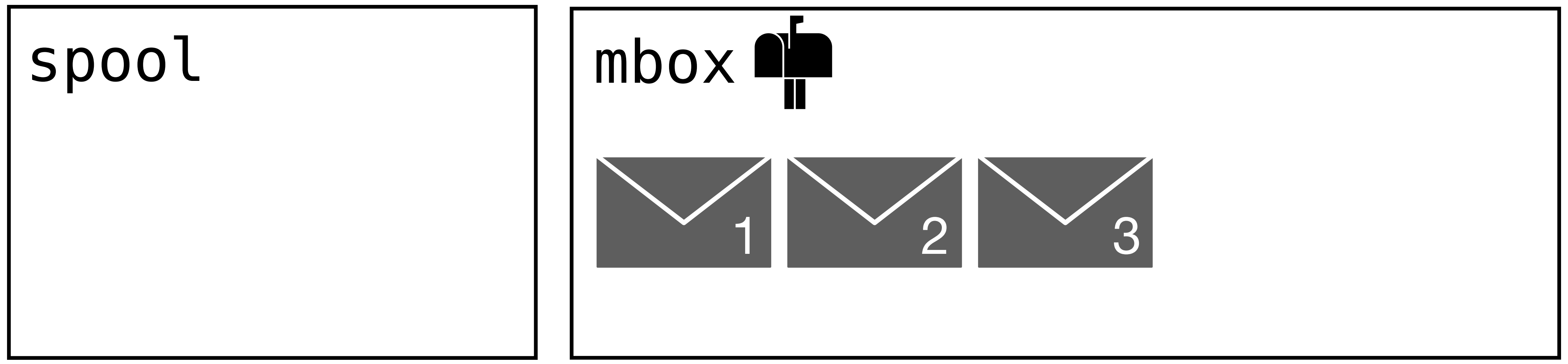
      break
  # cleanup
  unlink("/spool/$TID")
```

file system



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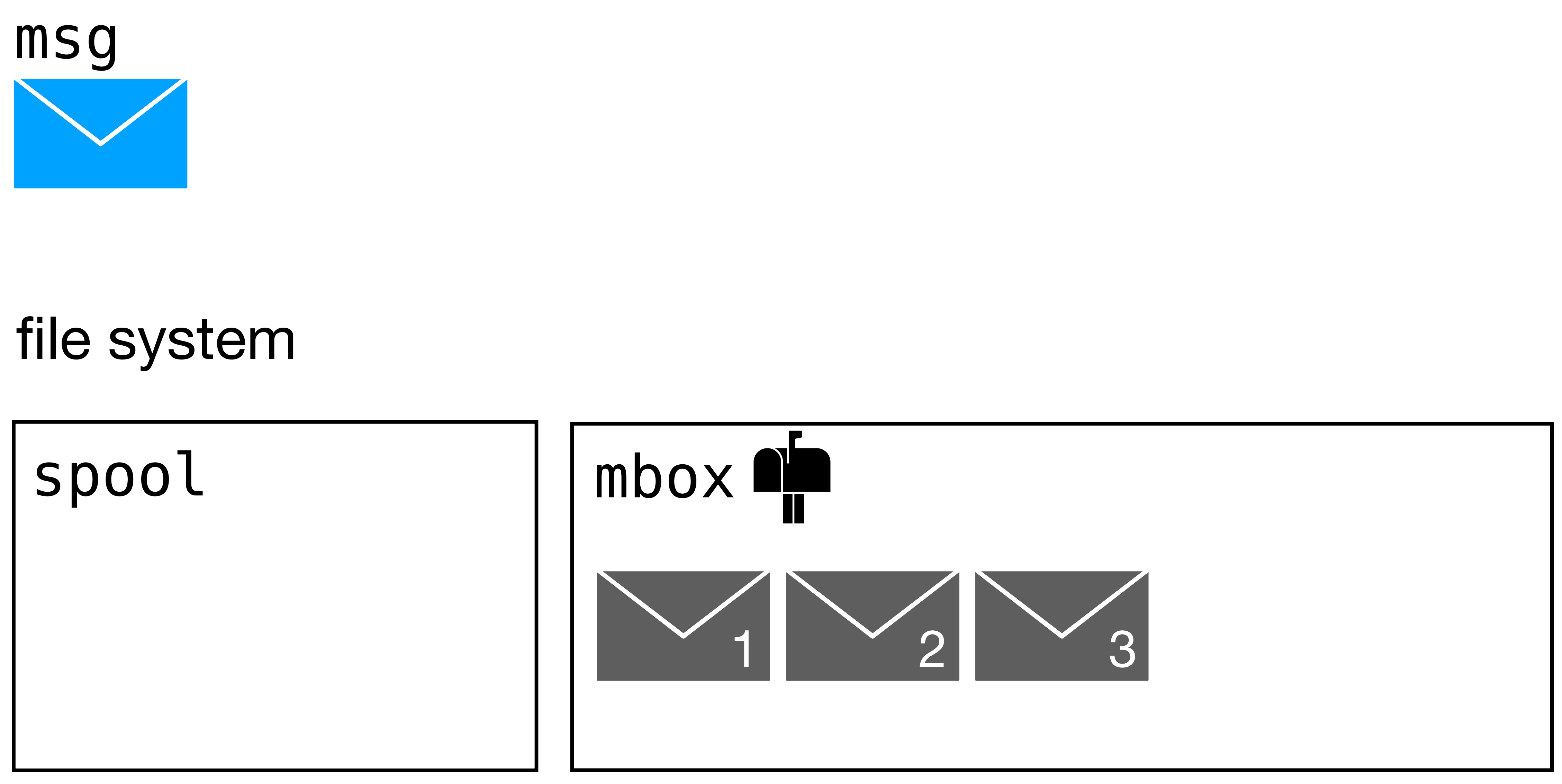

Spooling avoids reading partially-written messages

$TID =10

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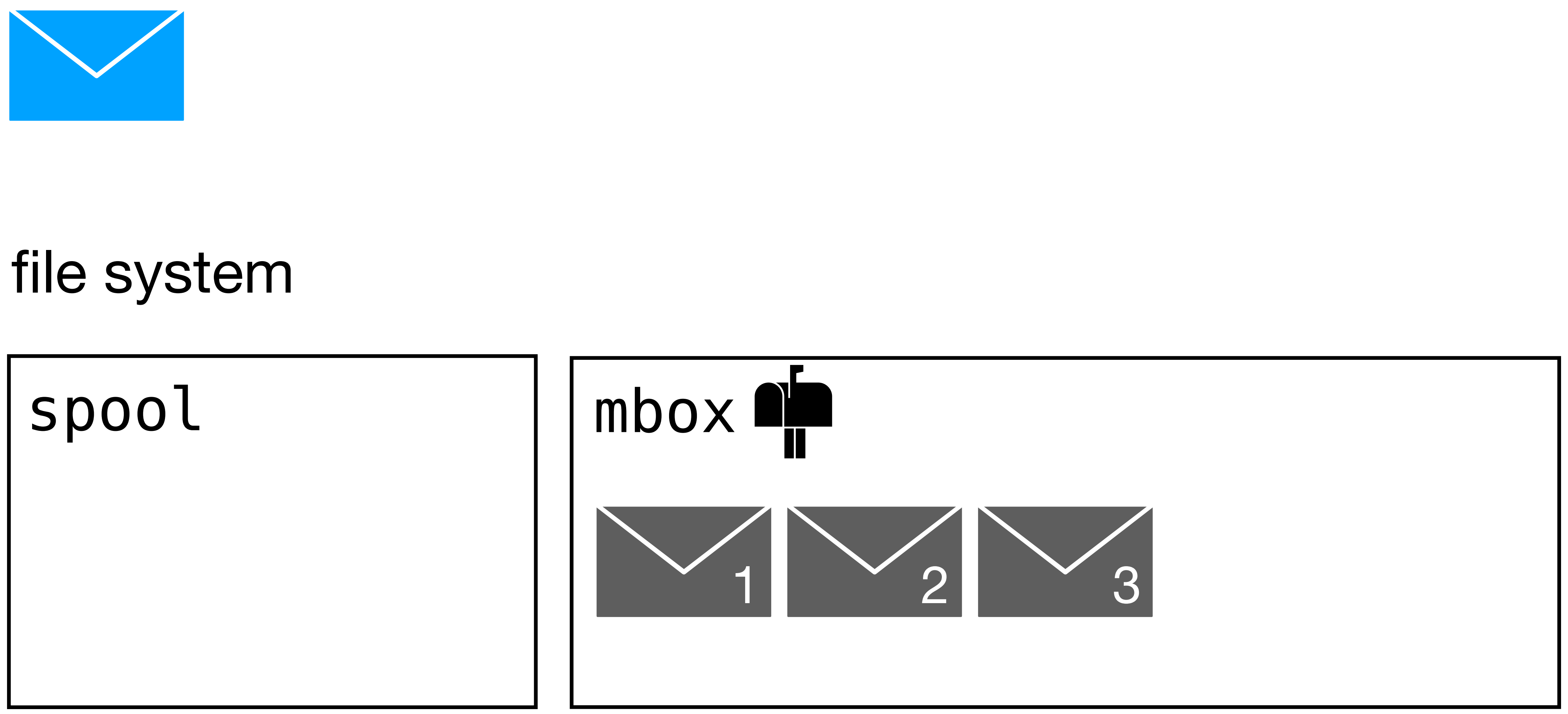

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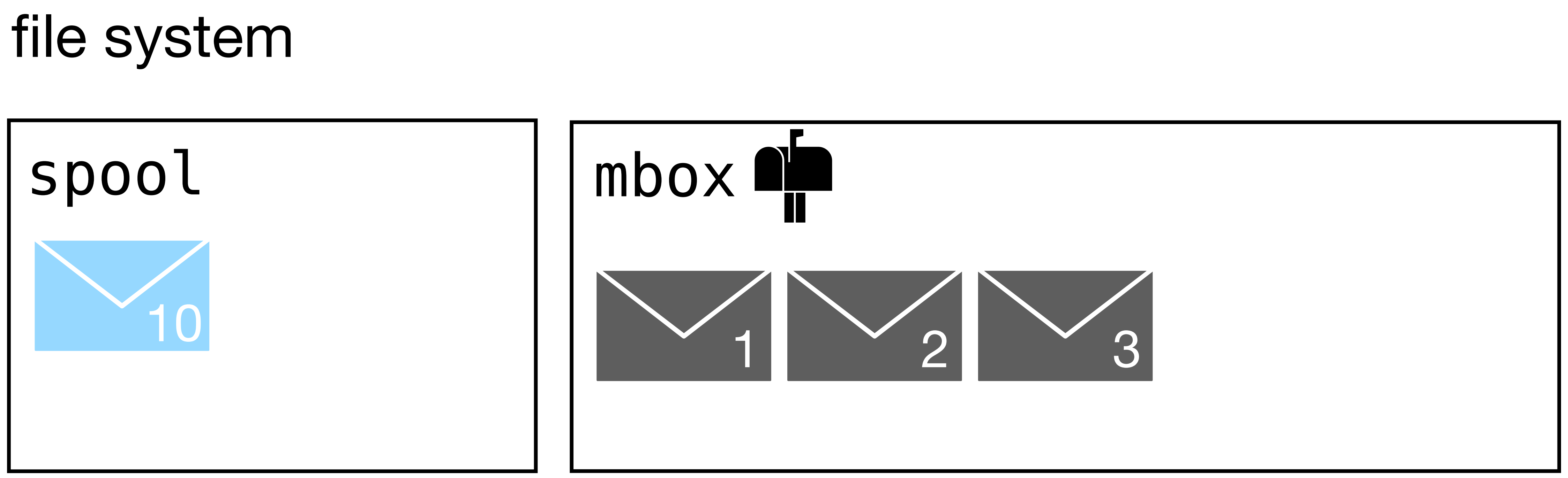

Threads use unique IDs to avoid conflicts

$TID =10 $TID =11

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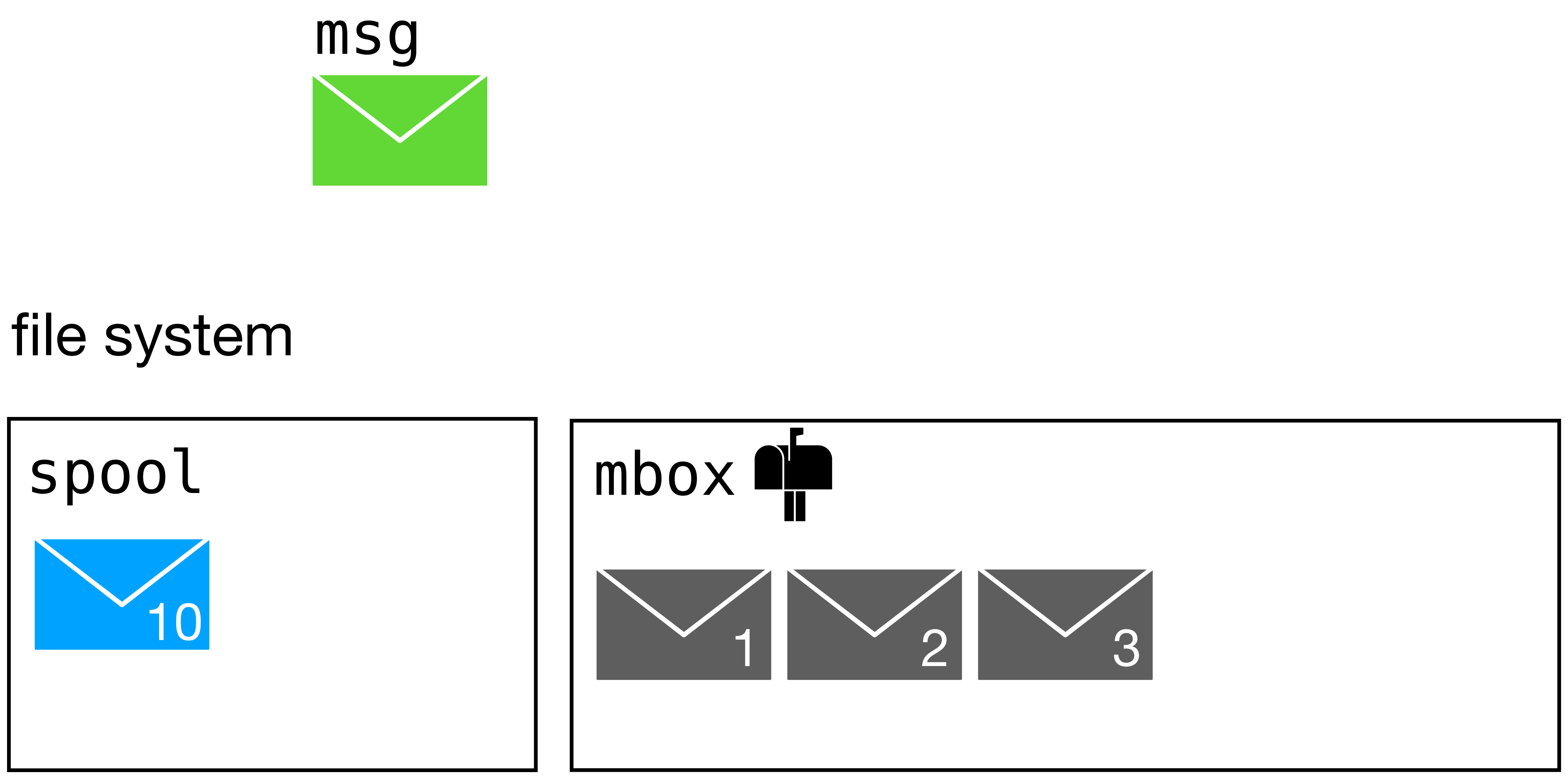

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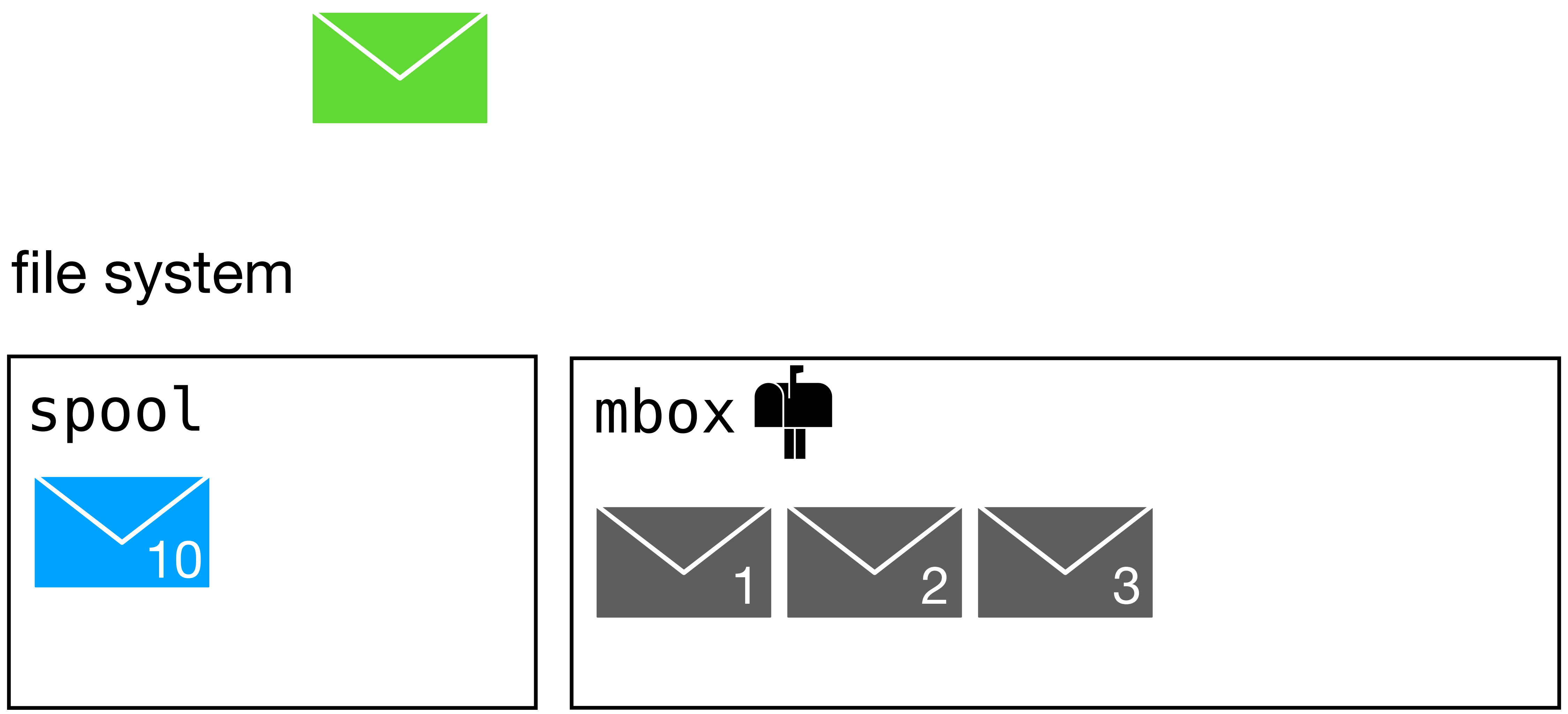

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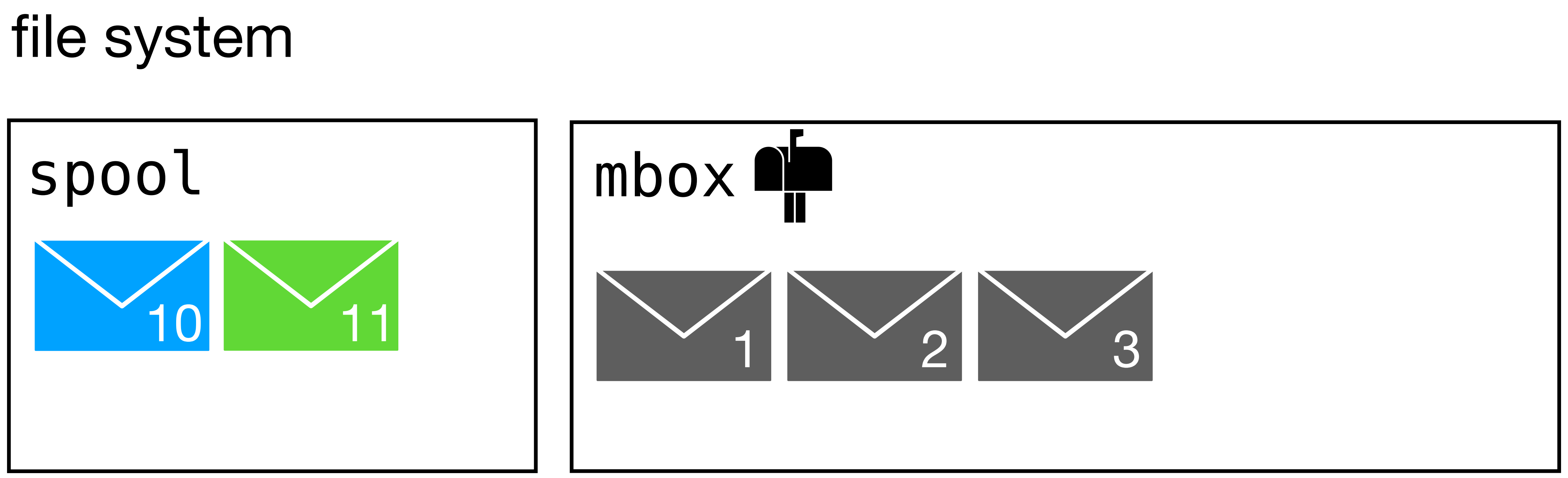

Timestamps help generate unique message names

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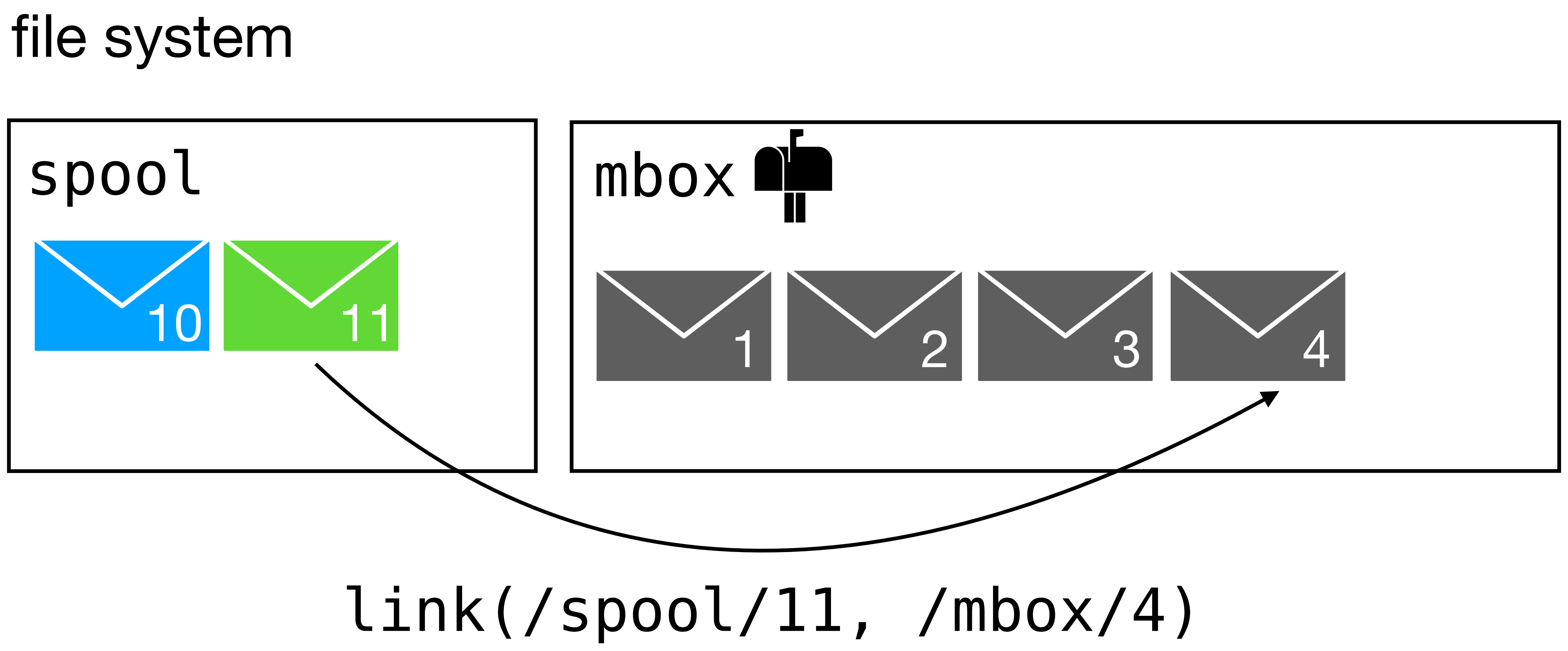

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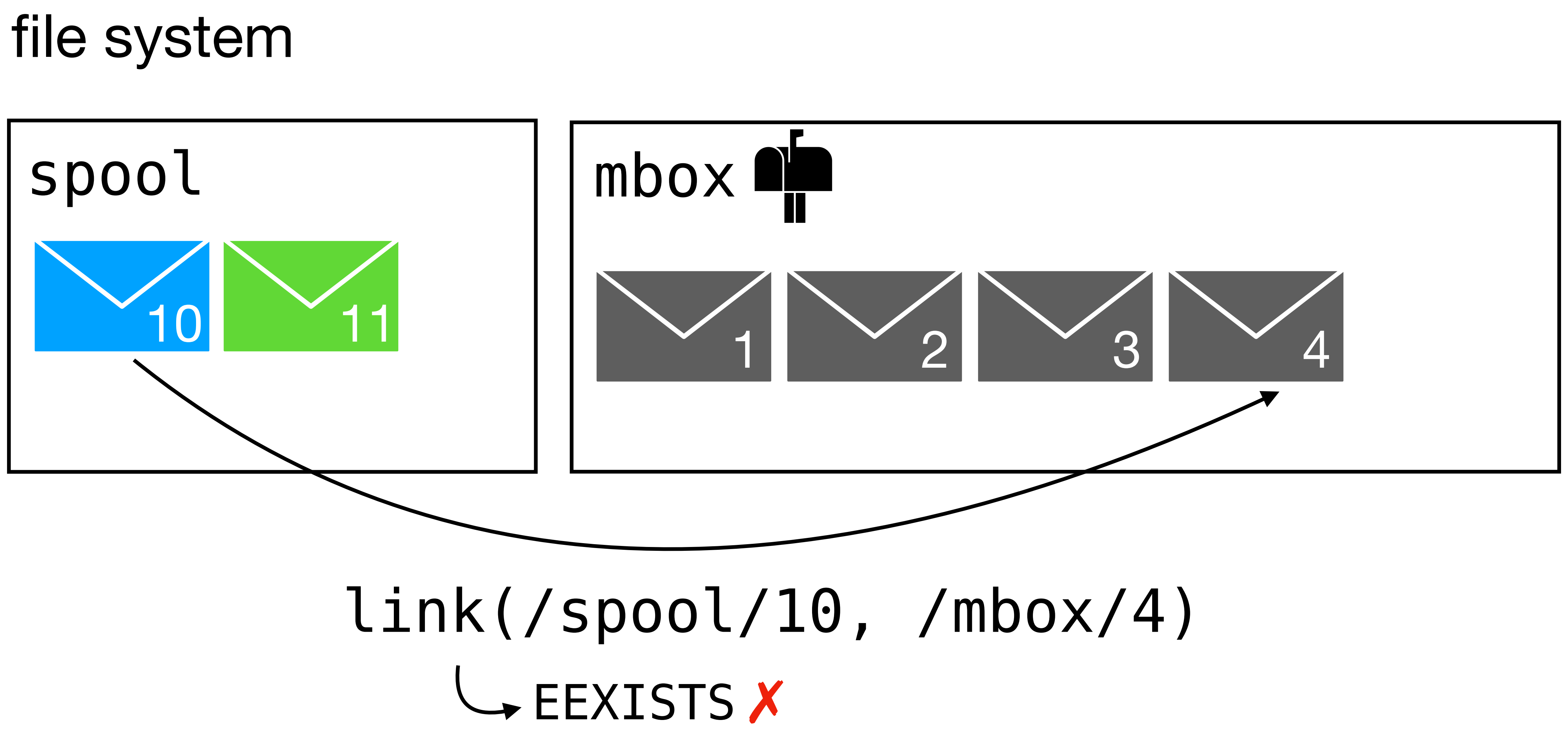

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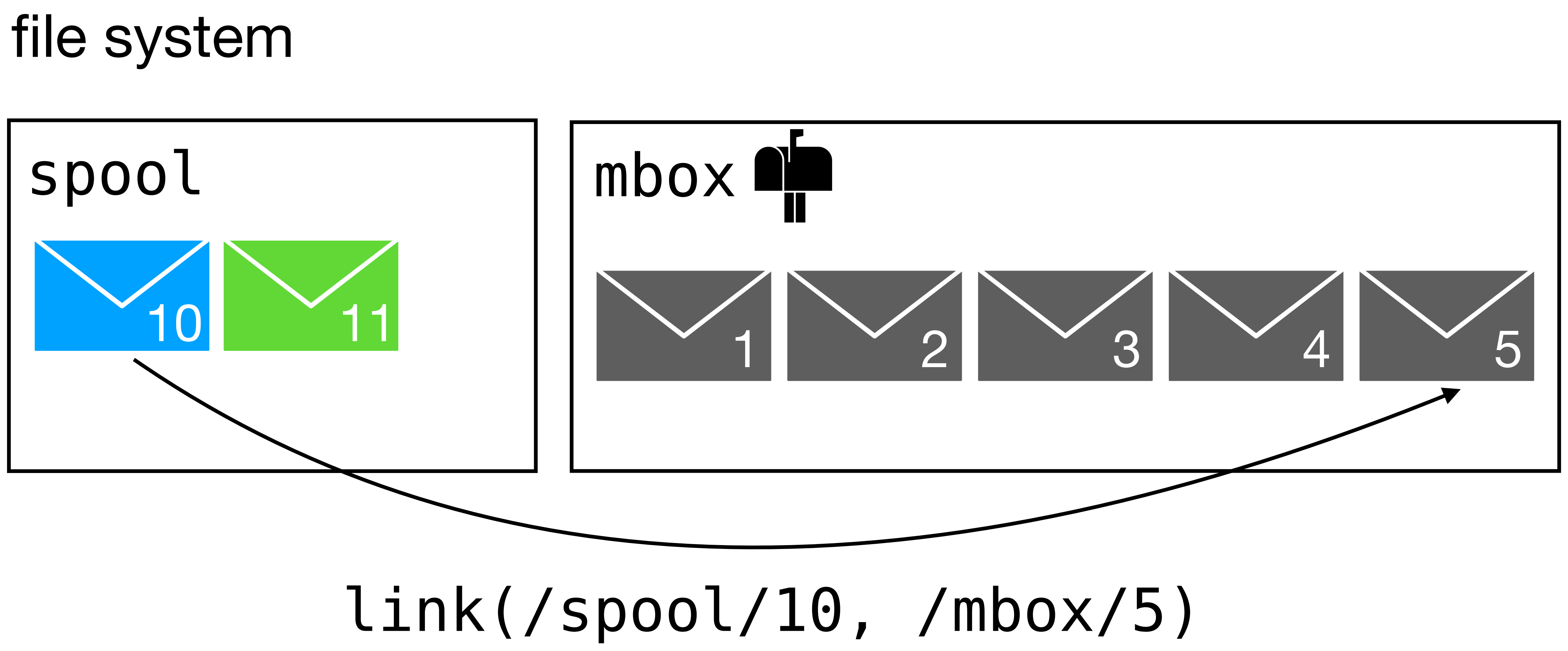

Delivery concurrency does not use locks

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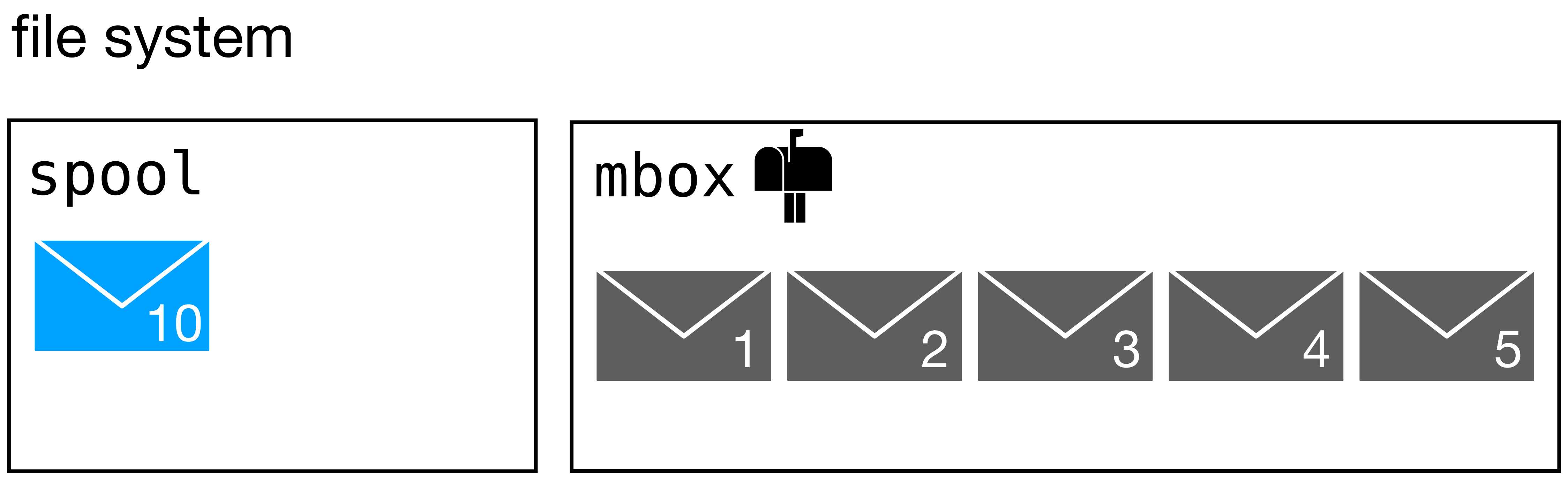

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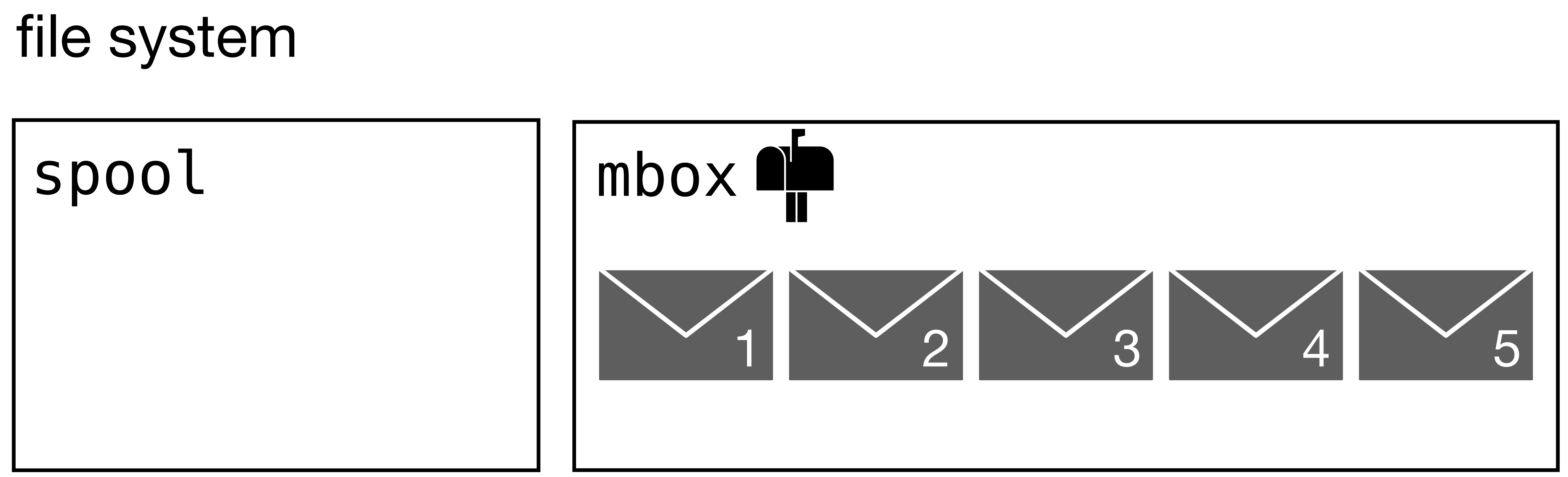
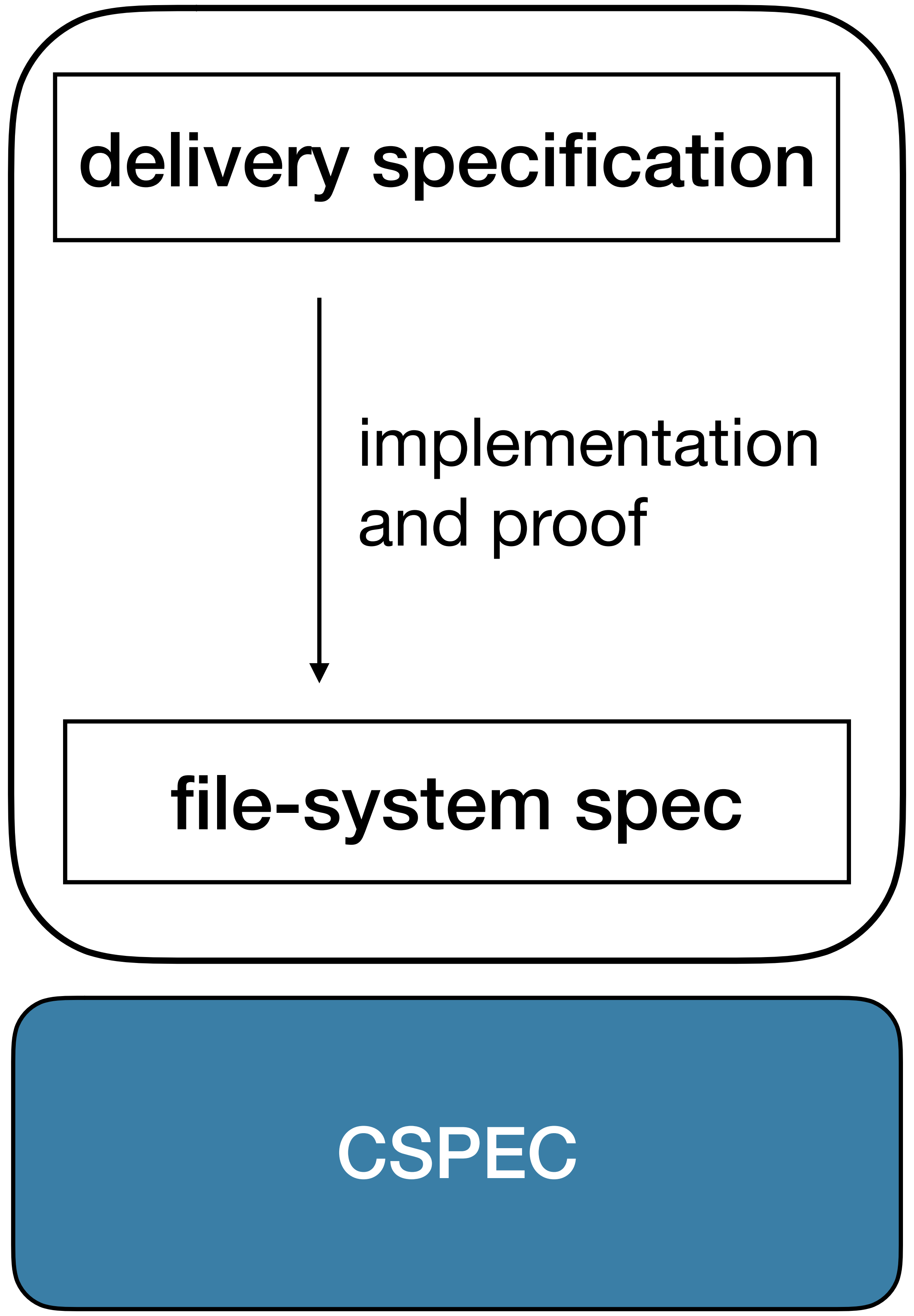


Proving delivery correct in CSPEC



CSPEC provides supporting definitions and theorems

Proof engineer reasons about file-system operations

```
def deliver(msg):
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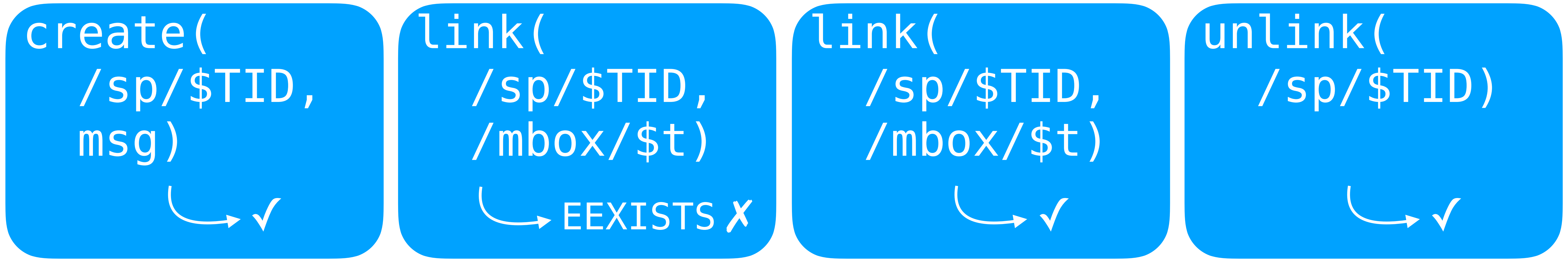

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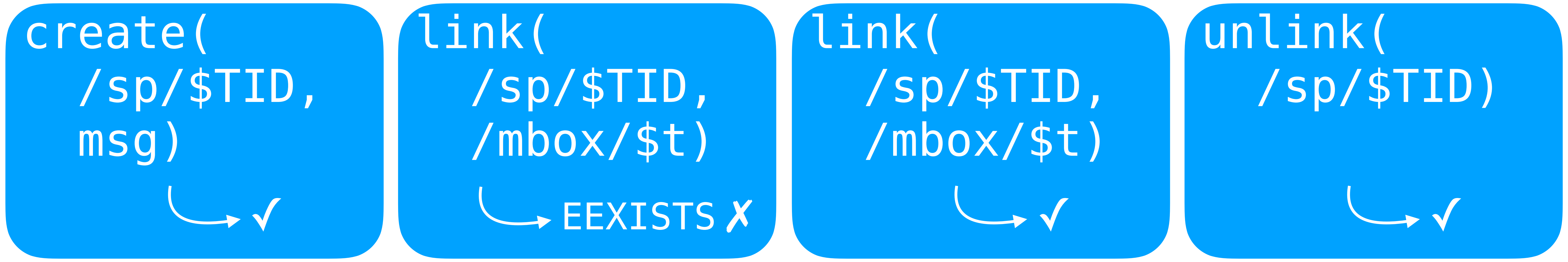
  unlink(“/spool/$TID”)
```

collapsed to one operation ←

```
create(“/spool/$TID”)
write(“/spool/$TID”, msg)
```



Proof engineer reasons about interleaving of file-system operations

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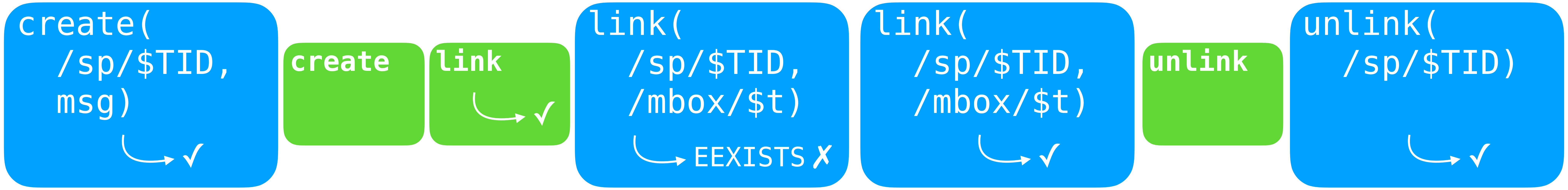
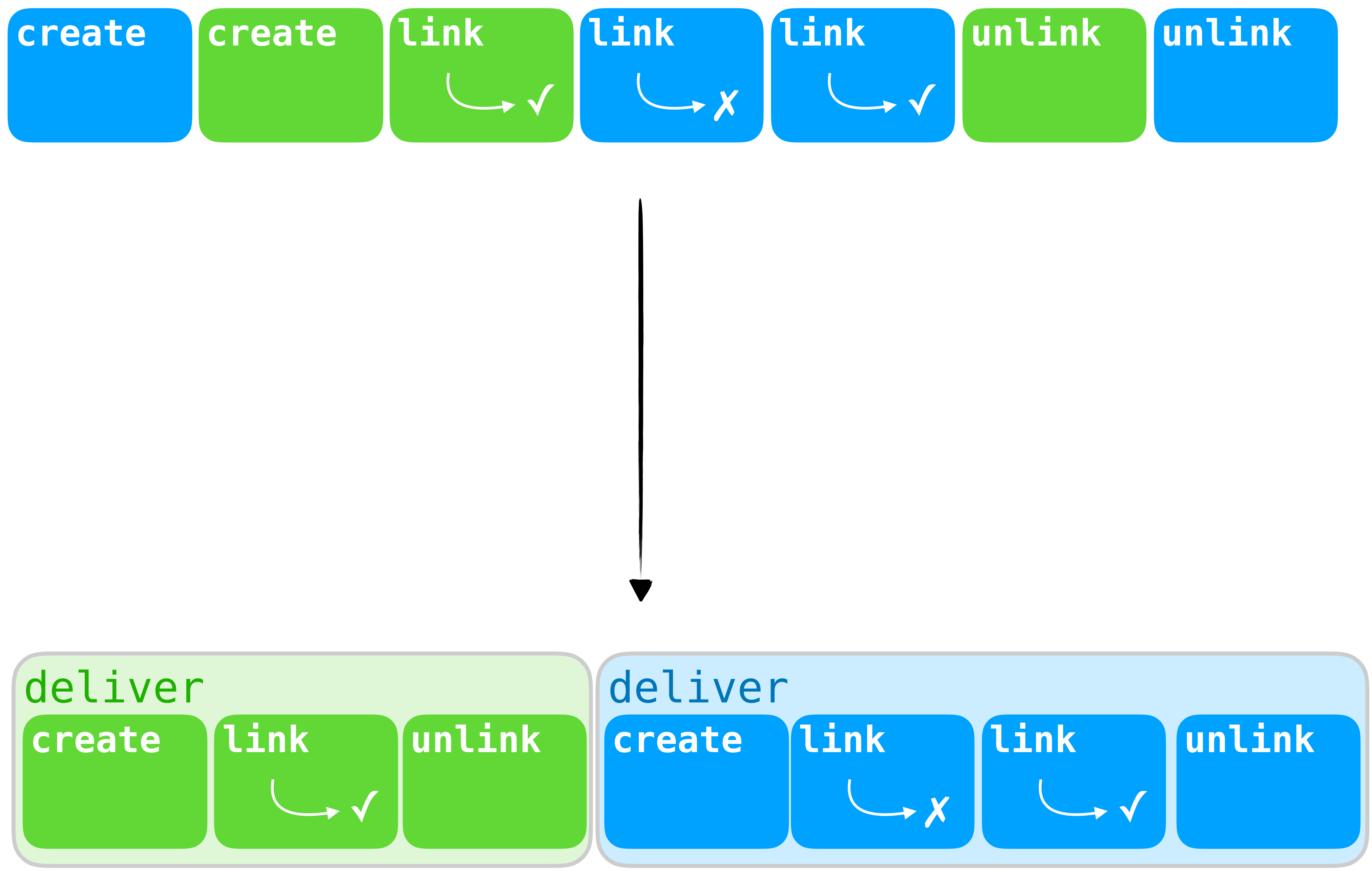


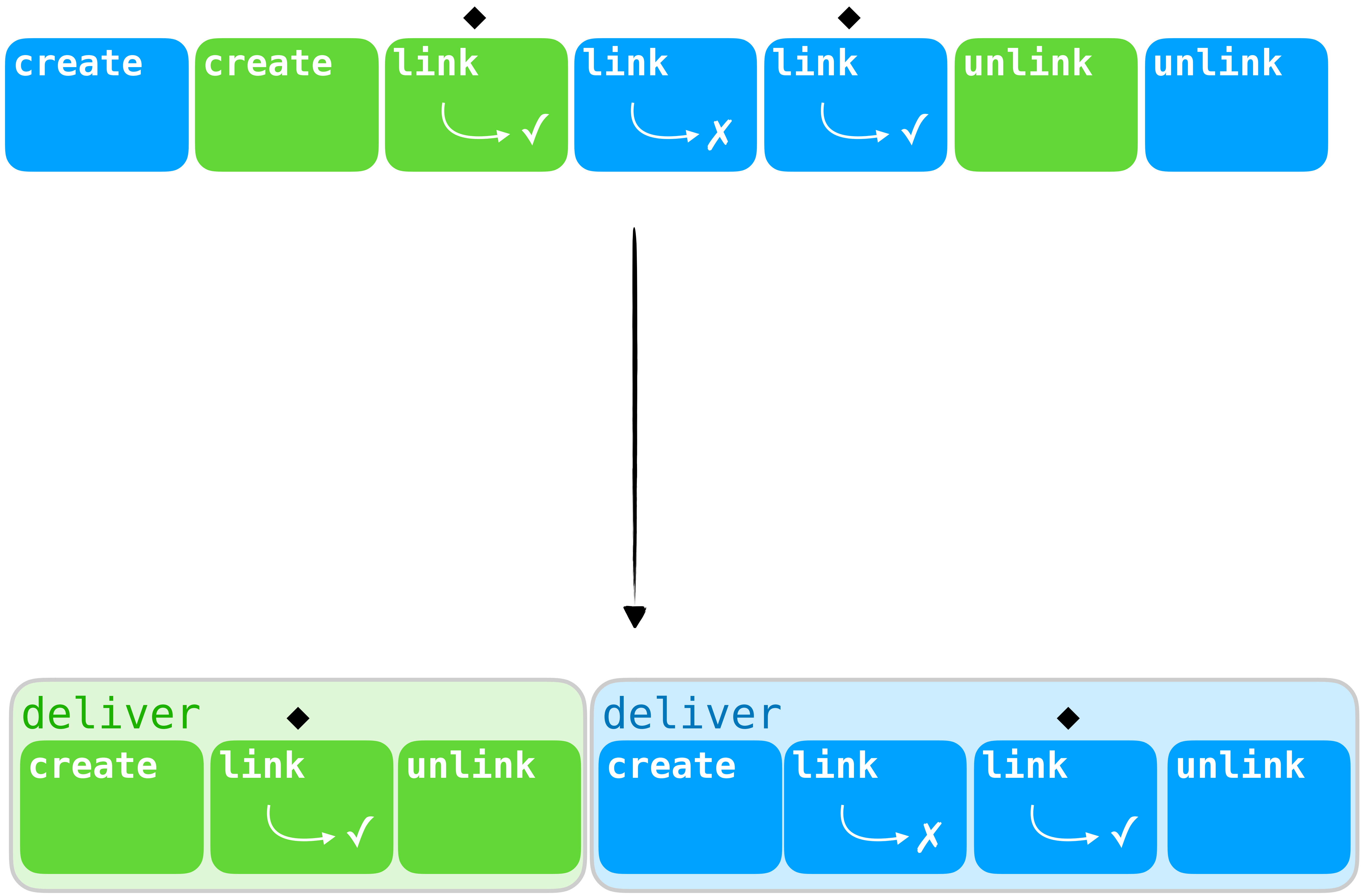
We assume file-system operations are atomic

Proving atomicity of delivery



atomicity: concurrent deliveries appear to execute all at once (in some order)

Proving atomicity of delivery



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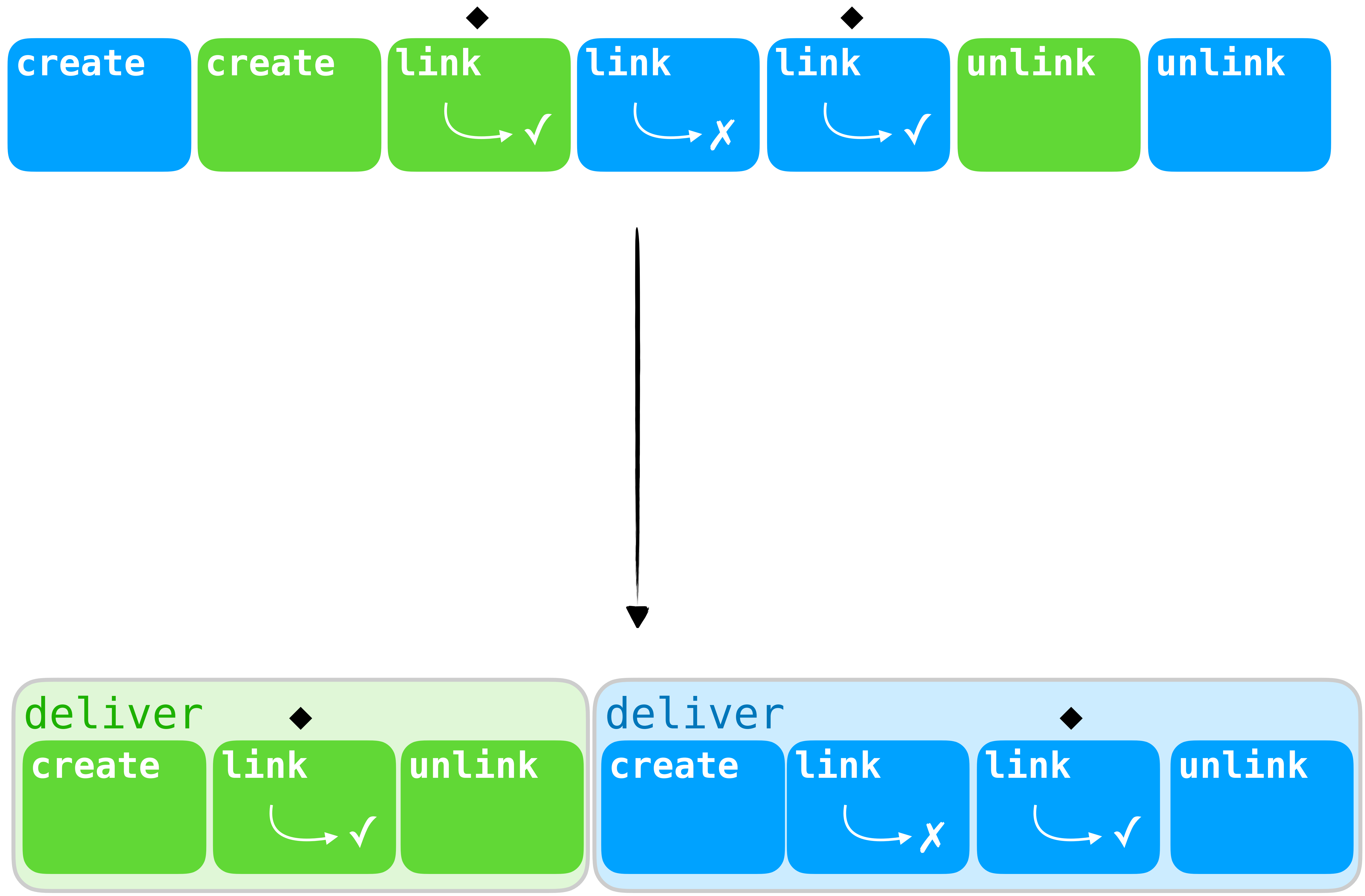
Step 1: developer identifies commit point

Proving atomicity of delivery

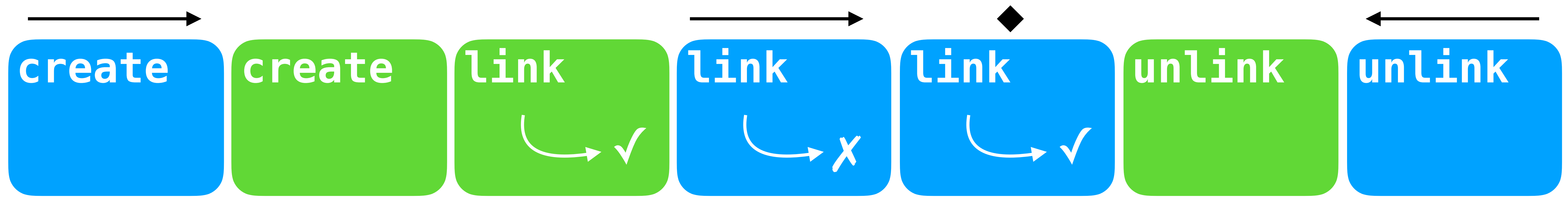


atomicity: concurrent deliveries appear to execute all at once (in some order)

Step 1: developer identifies commit point

Step 2: prove operation occurs logically at commit point

Example of movers for this execution



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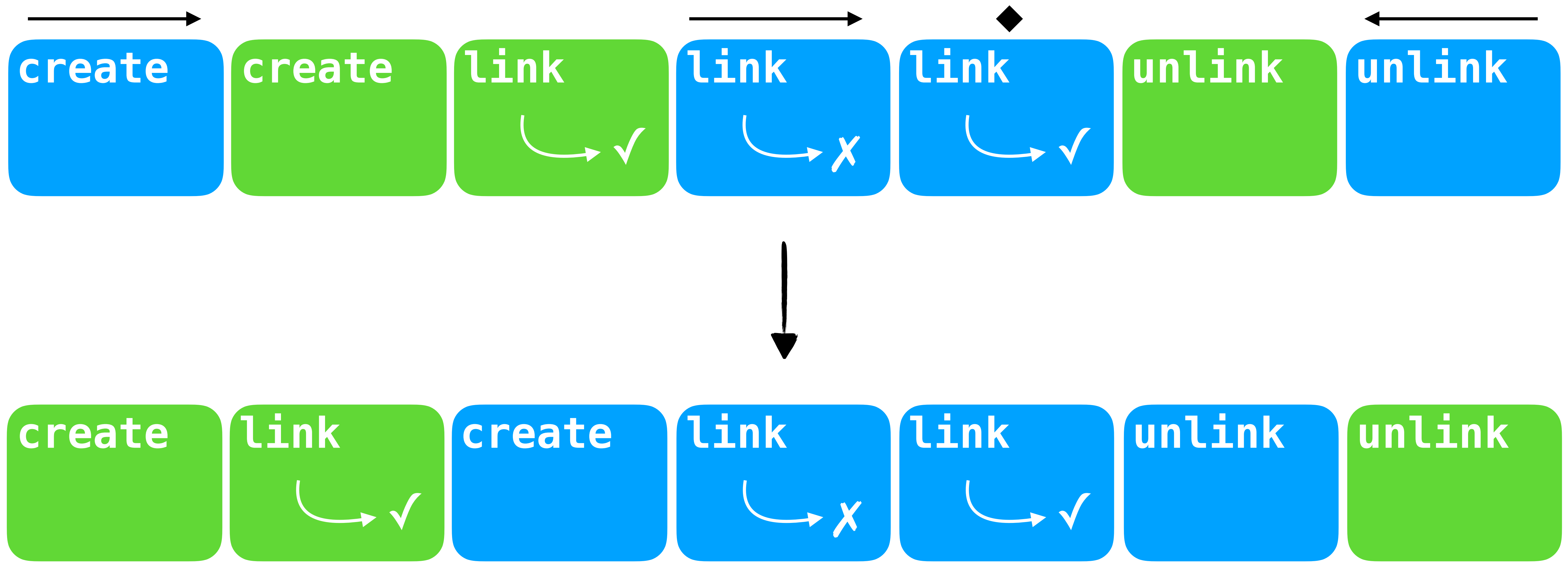

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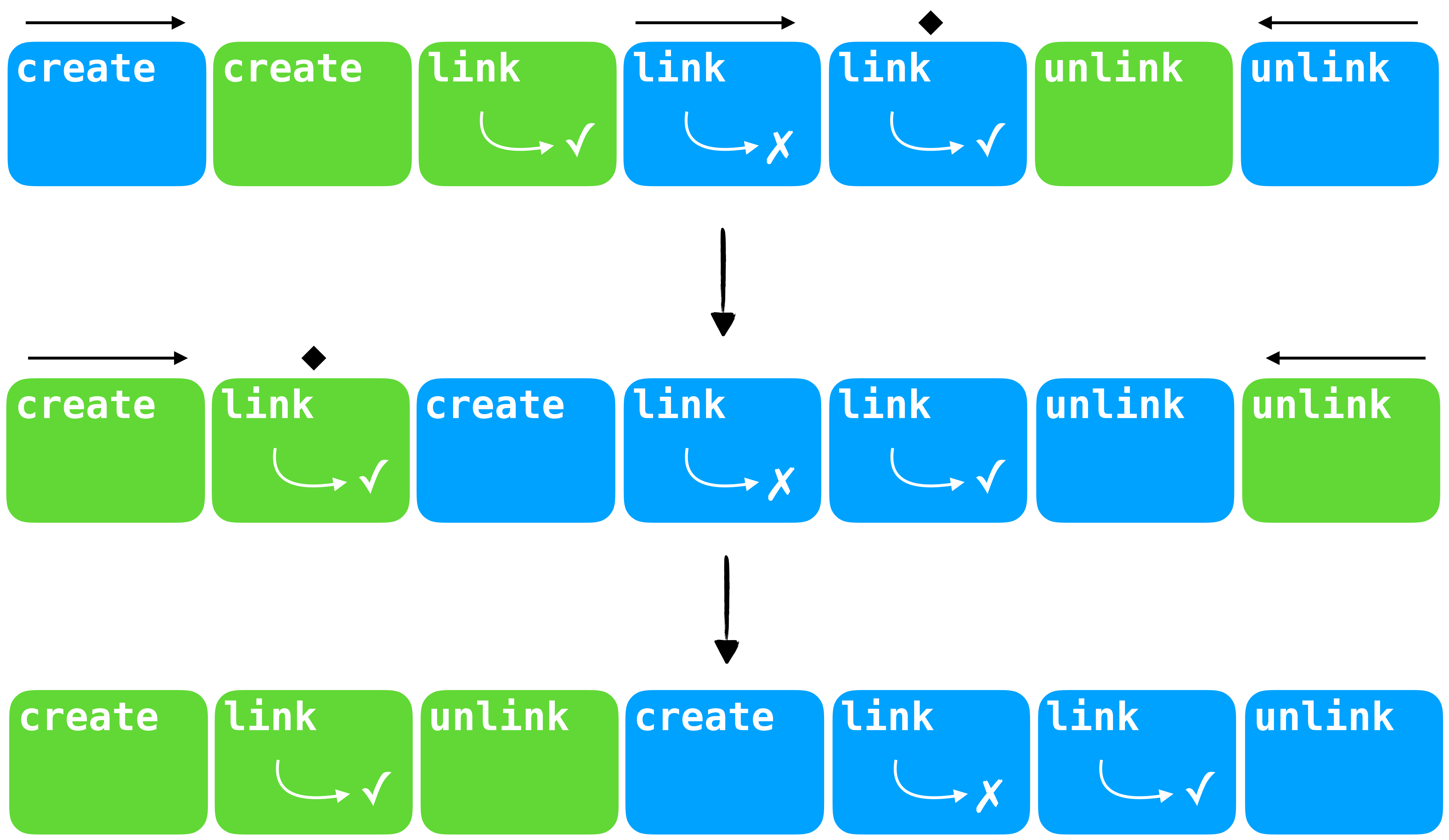
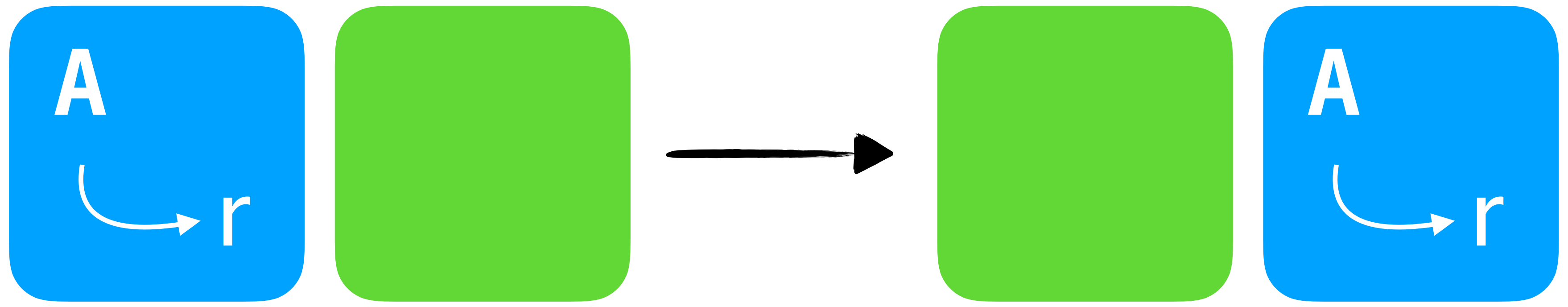


Right mover can be reordered after any green thread operation



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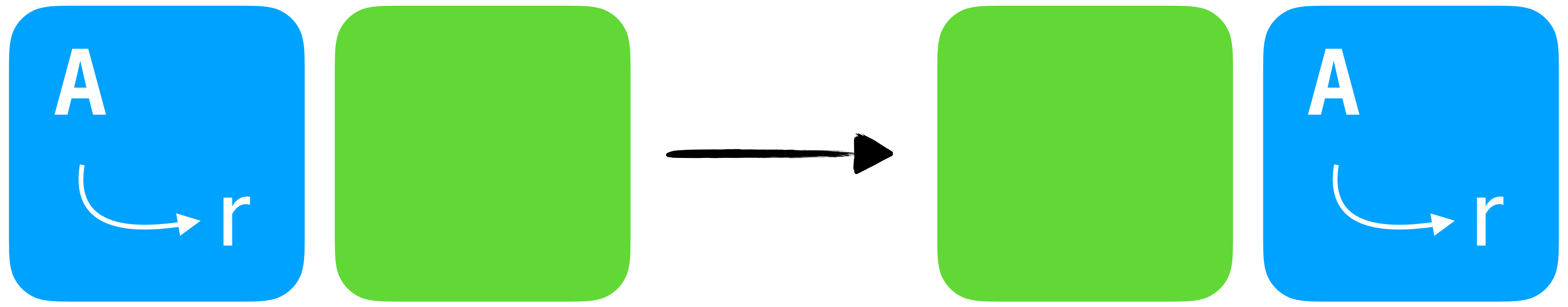
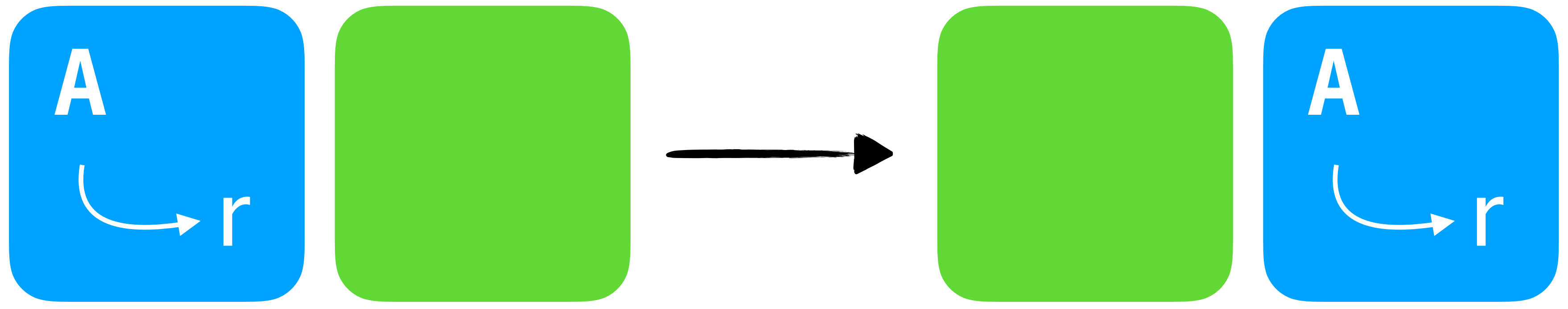


left movers are the converse

Movers need to consider only *possible* operations from other threads

A is a *right mover* if

for all green operations,



left movers are the converse

is one of

```
create(
  /sp/$TID,
  msg)
```

```
link(
  /sp/$TID,
  /mbox/$t)
```

↪ EEXISTS ✗

```
link(
  /sp/$TID,
  /mbox/$t)
```

```
unlink(
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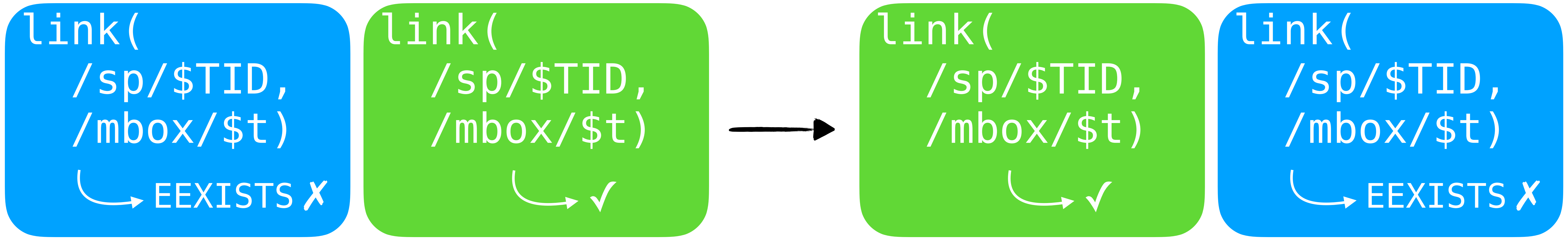
```

Example mover proof: failing `link` is a *right mover*

Proof sketch (only `link` case):



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```
link(                link(                        link(                link(
  /sp/$TID,            /sp/$TID,                    /sp/$TID,            /sp/$TID,
  /mbox/$t)            /mbox/$t)        →           /mbox/$t)            /mbox/$t)
    ↳ EEXISTS ✗          ↳ ✓                          ↳ ✓                  ↳ EEXISTS ✗
```

`$t` ≠ `$t` (otherwise `link` ↳ ✗ then `link` ↳ ✓ is impossible)

Example mover proof: failing `link` is a *right mover*

Proof sketch (only `link` case):

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  ↪ EEXISTS ✗
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```
link(
  /sp/$TID,
  /mbox/$t)
  ↪ ✓
```

→

```
link(
  /sp/$TID,
  /mbox/$t)
  ↪ ✓
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⟹ `link` operations are independent

Failing `link` does not move left

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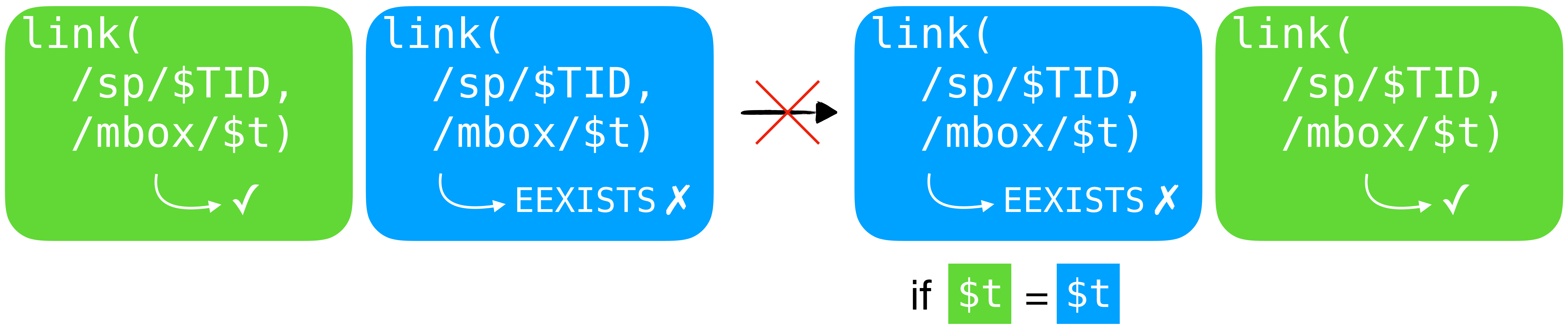
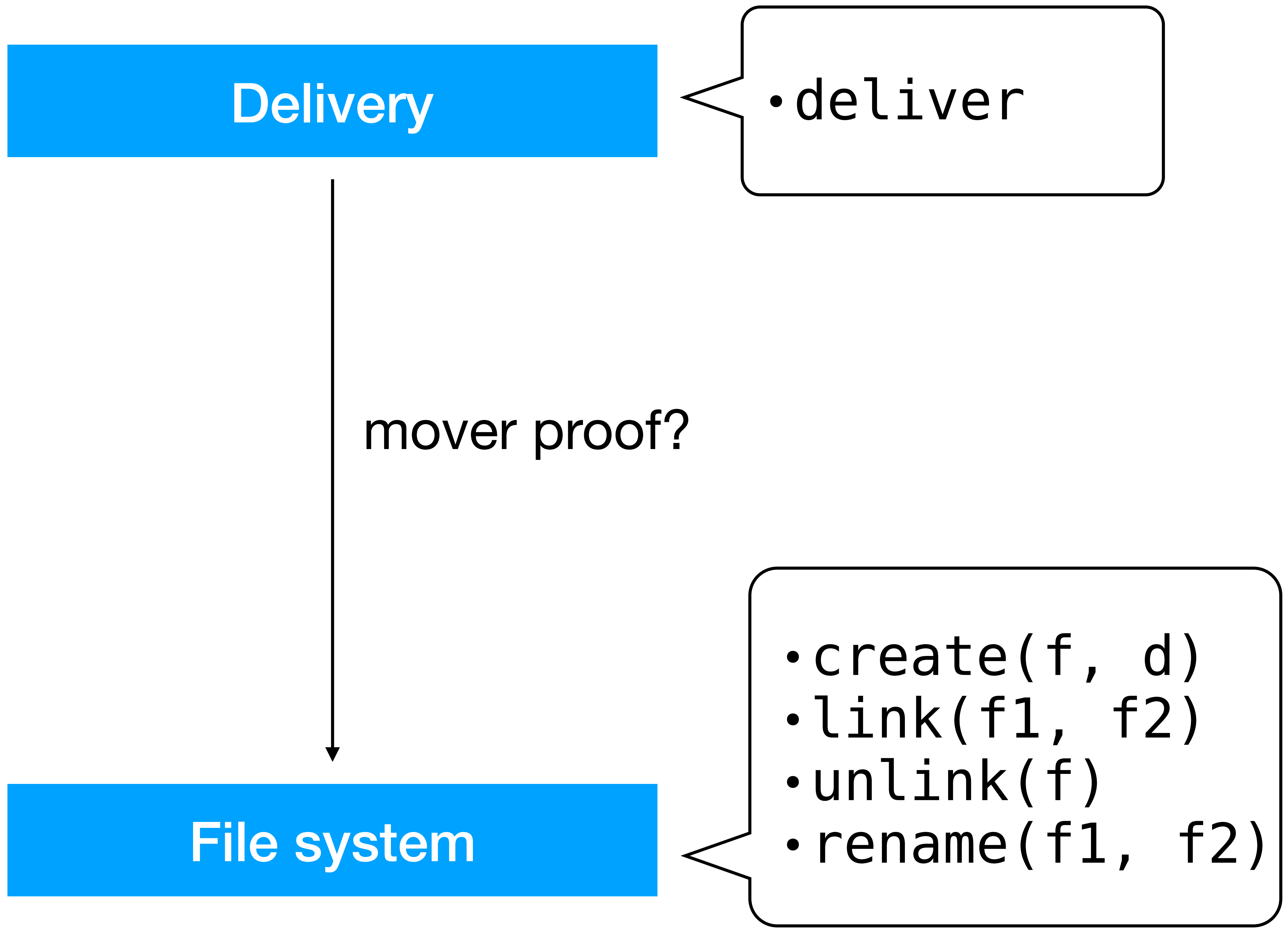


Challenge: how to limit what other operations to consider in mover proofs?



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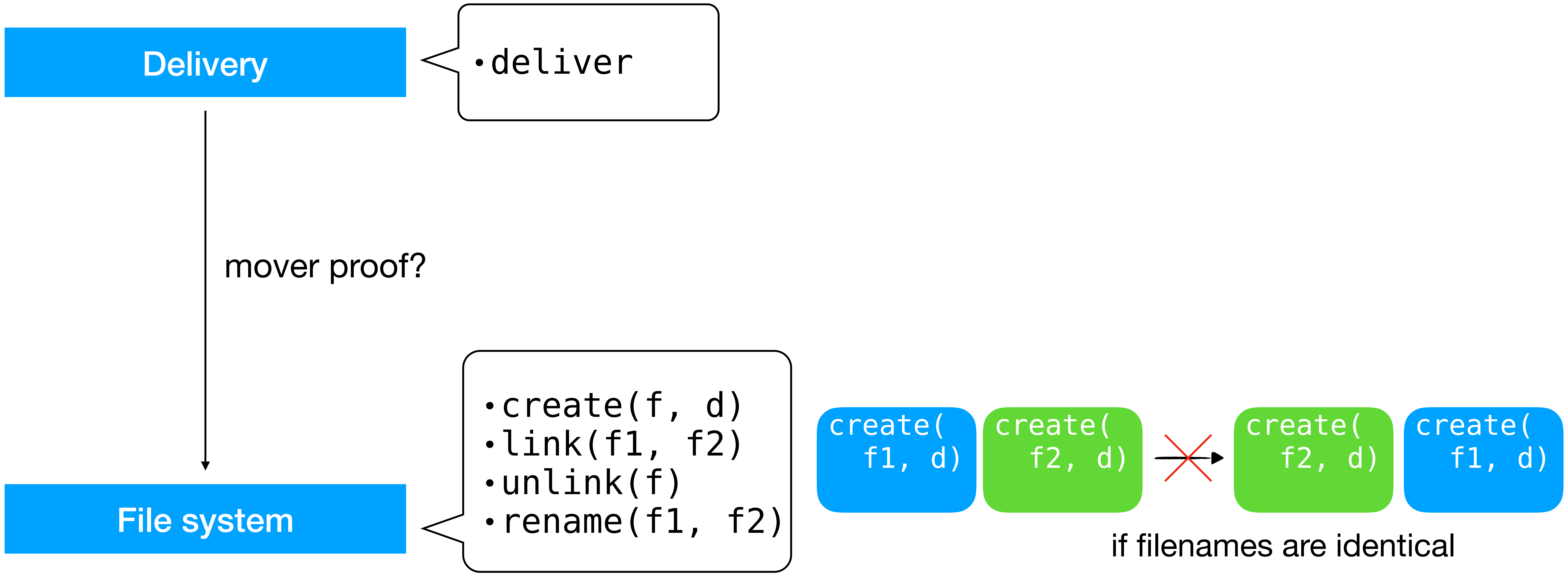
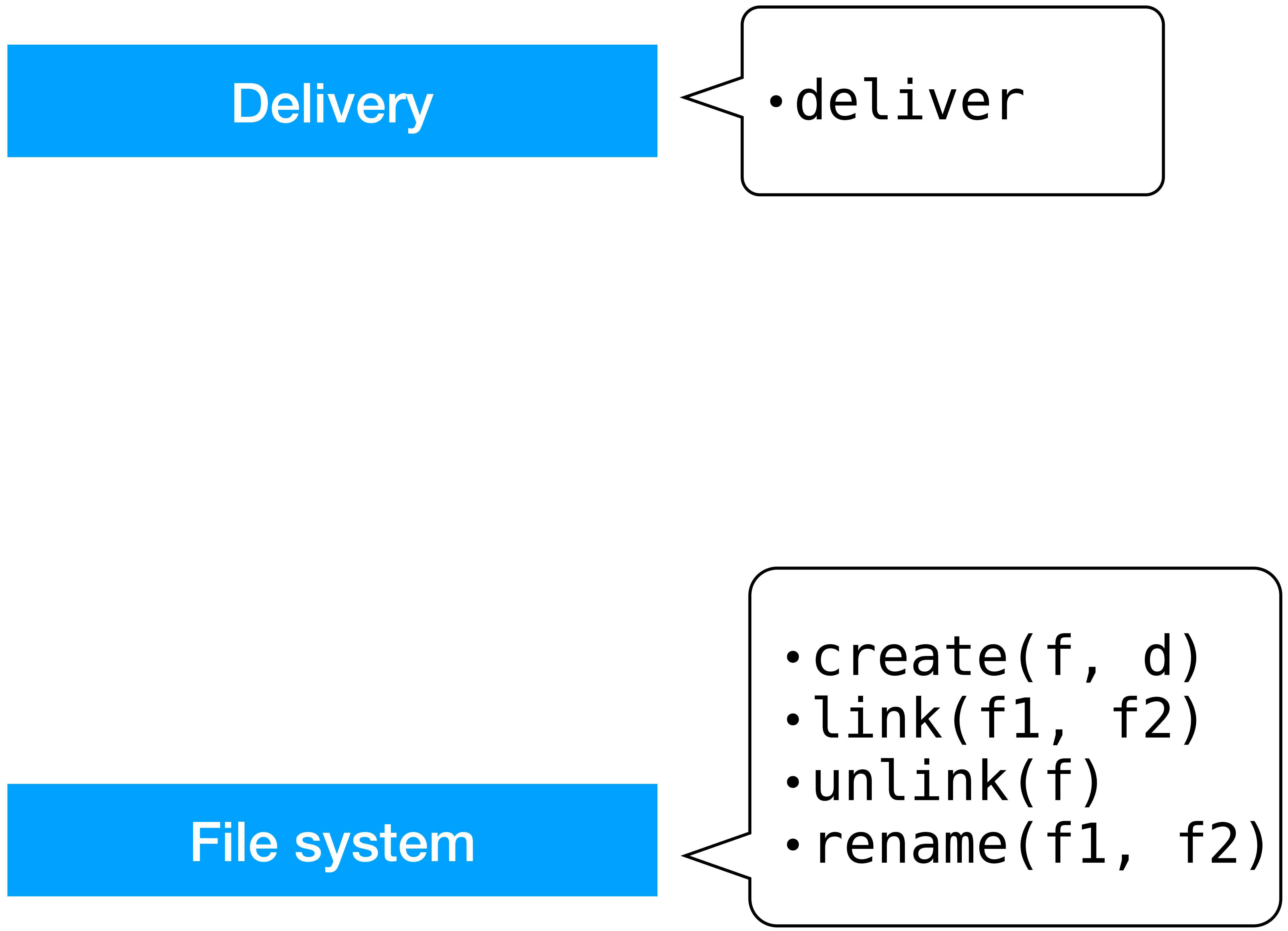


Layers enable mover reasoning

Layers **limit** what operations are available
$\Longrightarrow$ use **multiple layers** to make operations movers



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⟹ use **multiple layers** to make operations movers

Delivery

Restricted file system

File system

```
•create(/spool/$TID, d)
•link(/spool/$TID, /mbox/$t)
•unlink(/spool/$TID)
```

mover proof ✓

restrict arguments to include `$TID`

Layers enable mover reasoning

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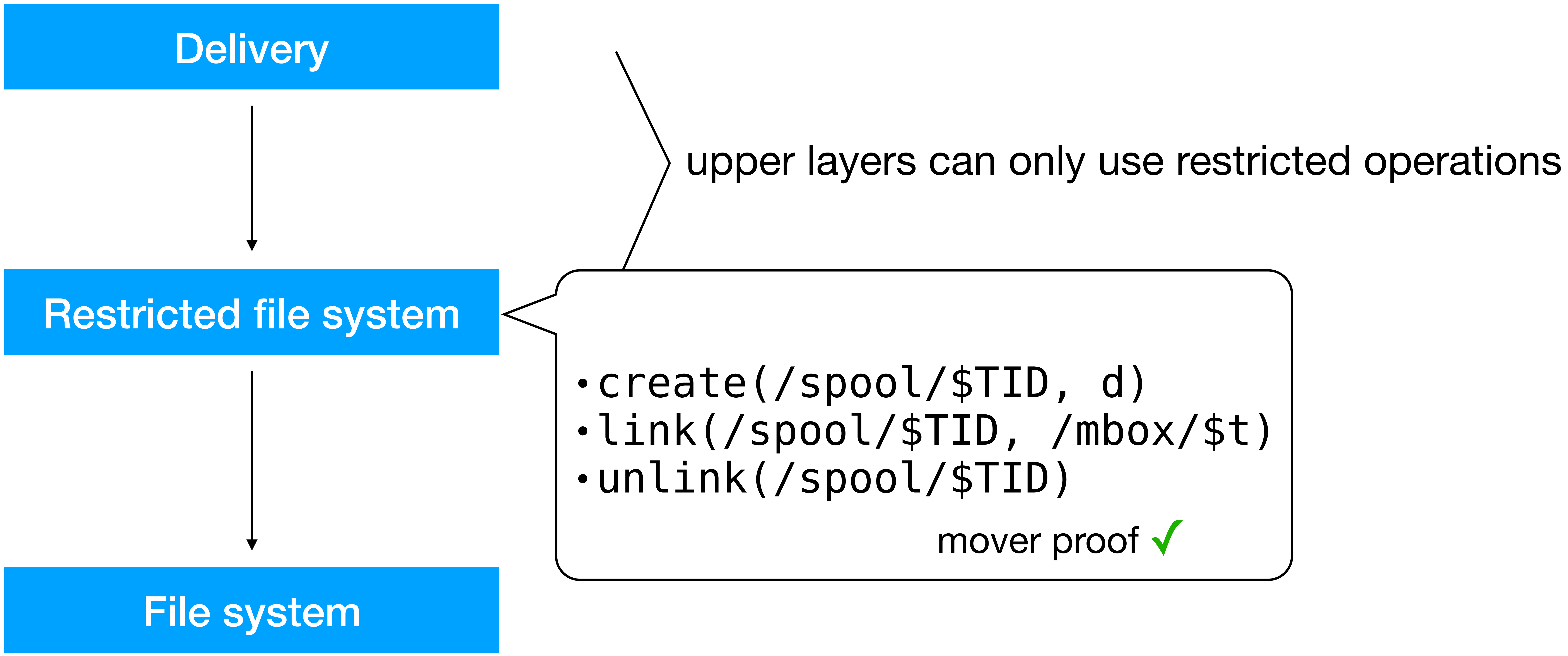
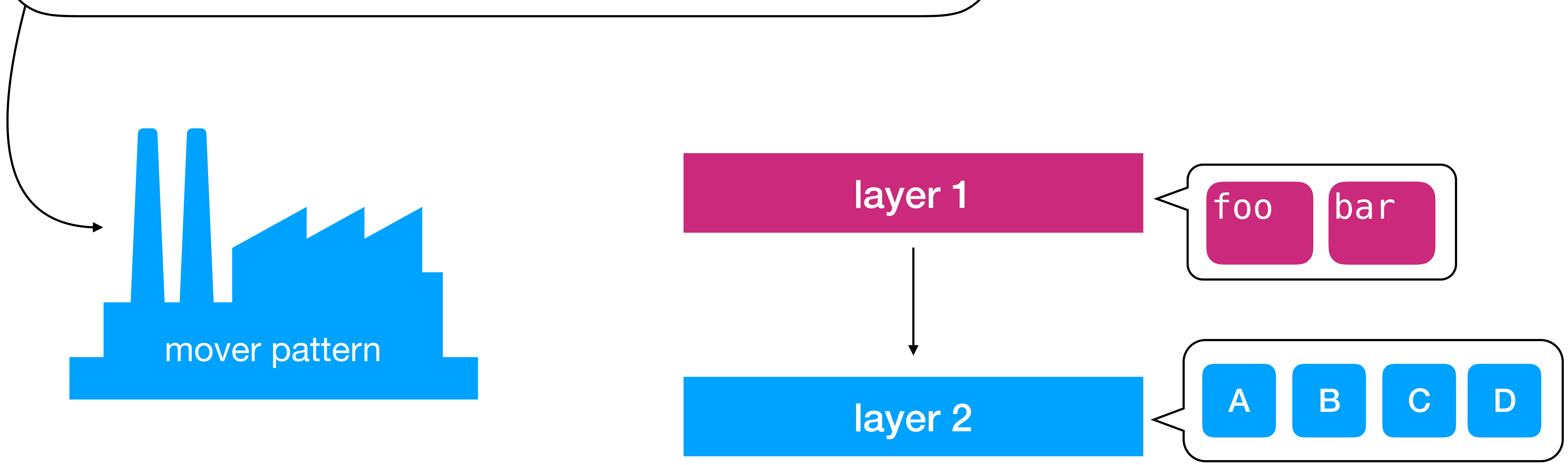


Movers are a layer proof *pattern*

Obligation for developer: movers for each implementation



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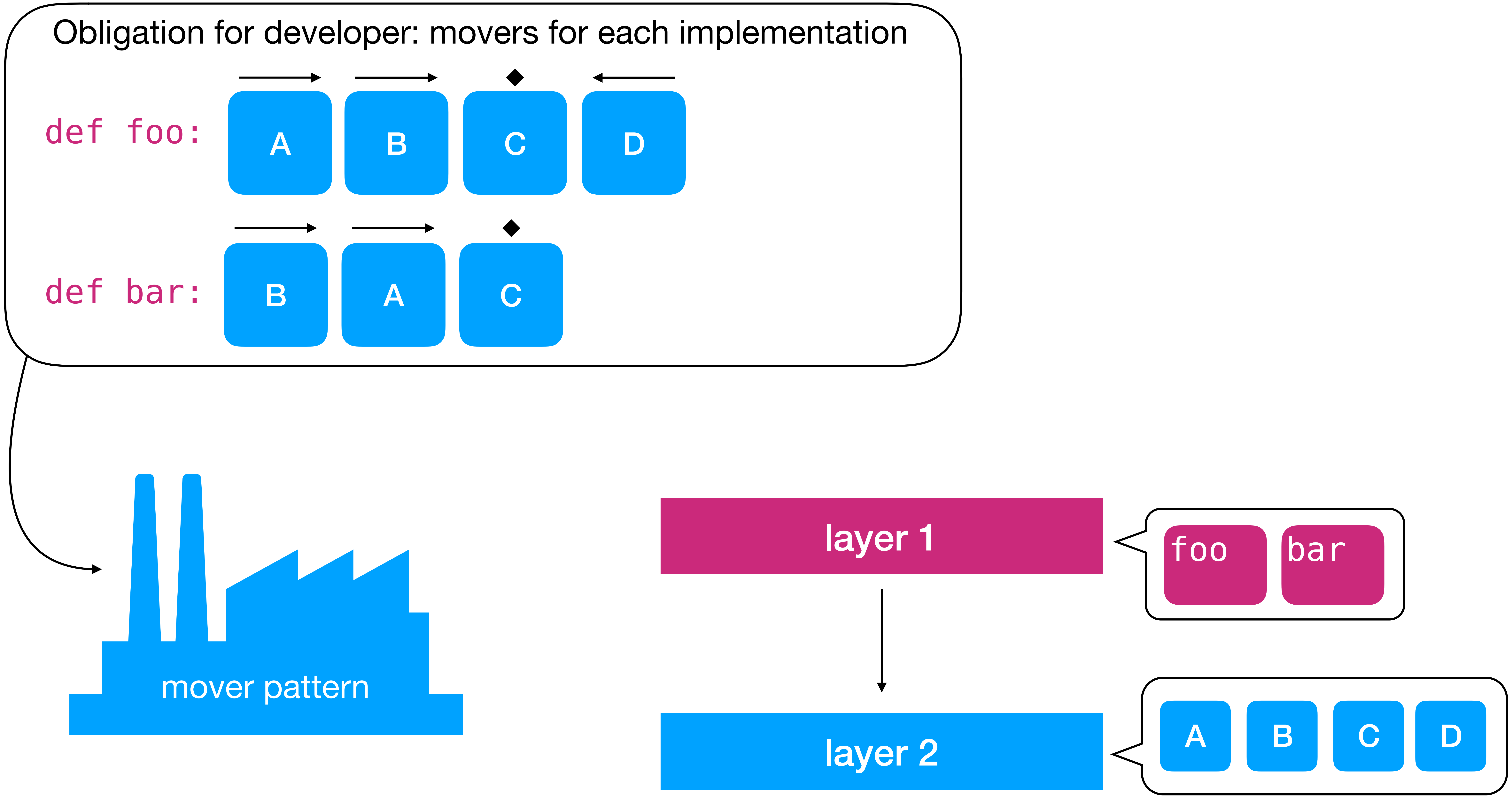

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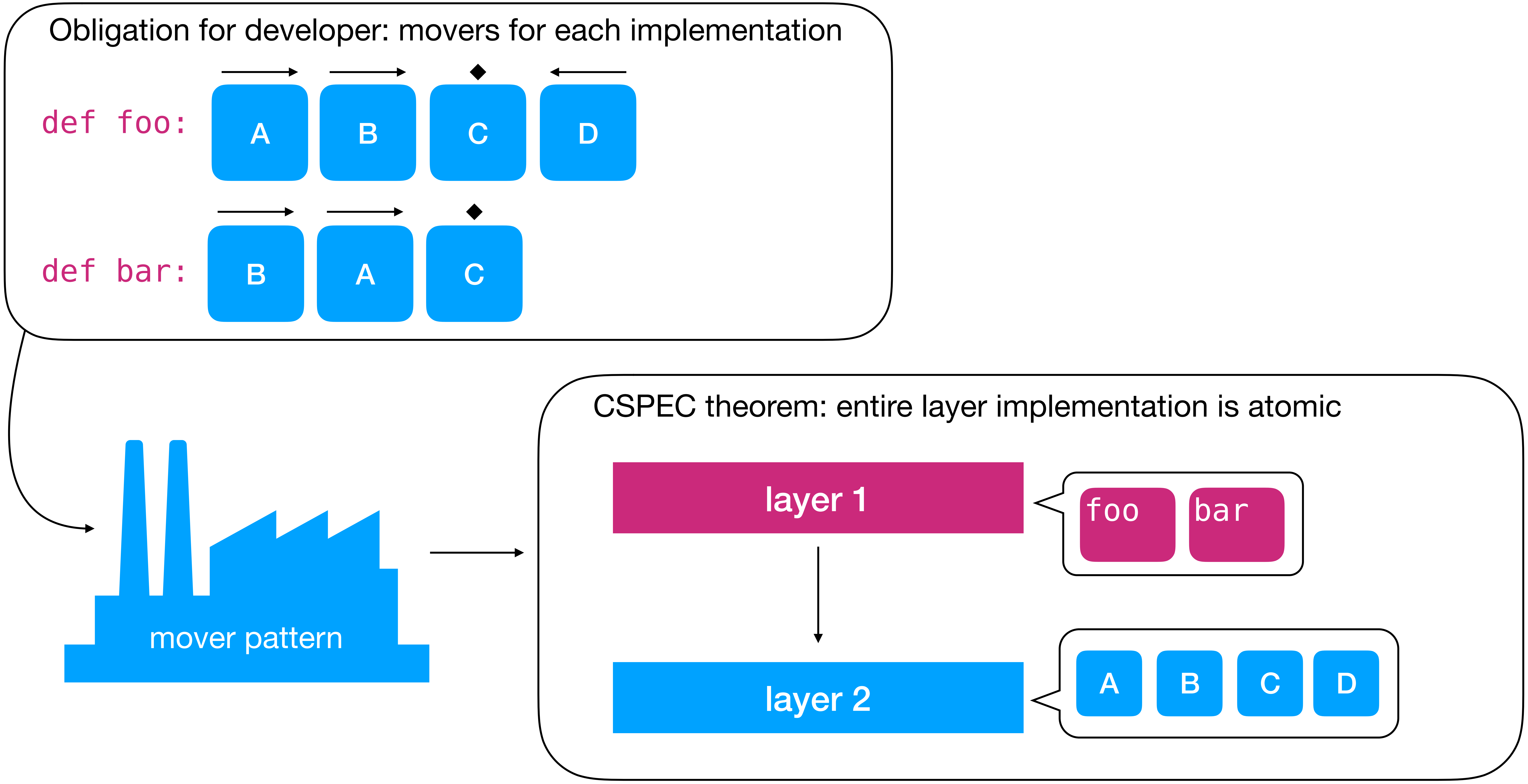
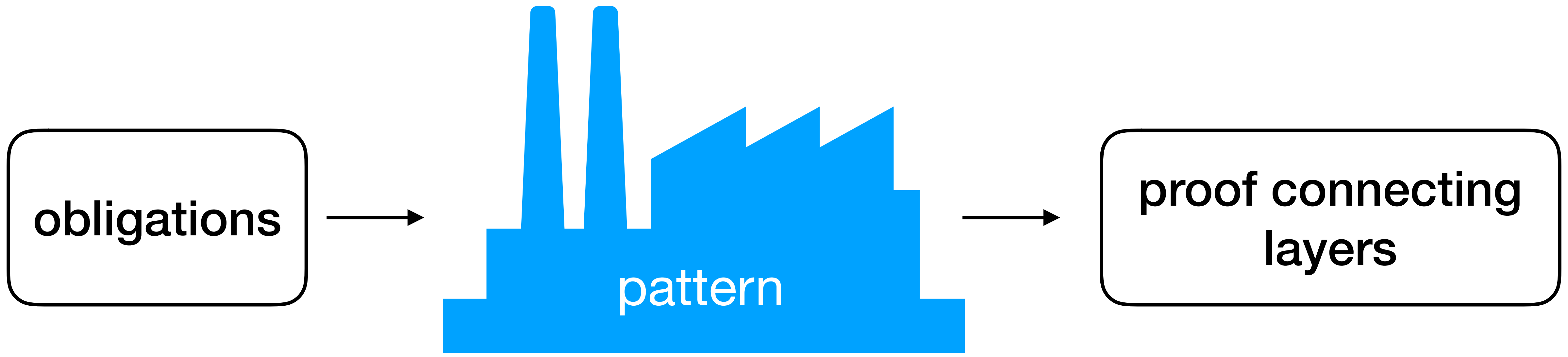


CSPEC provides other patterns to support mover reasoning

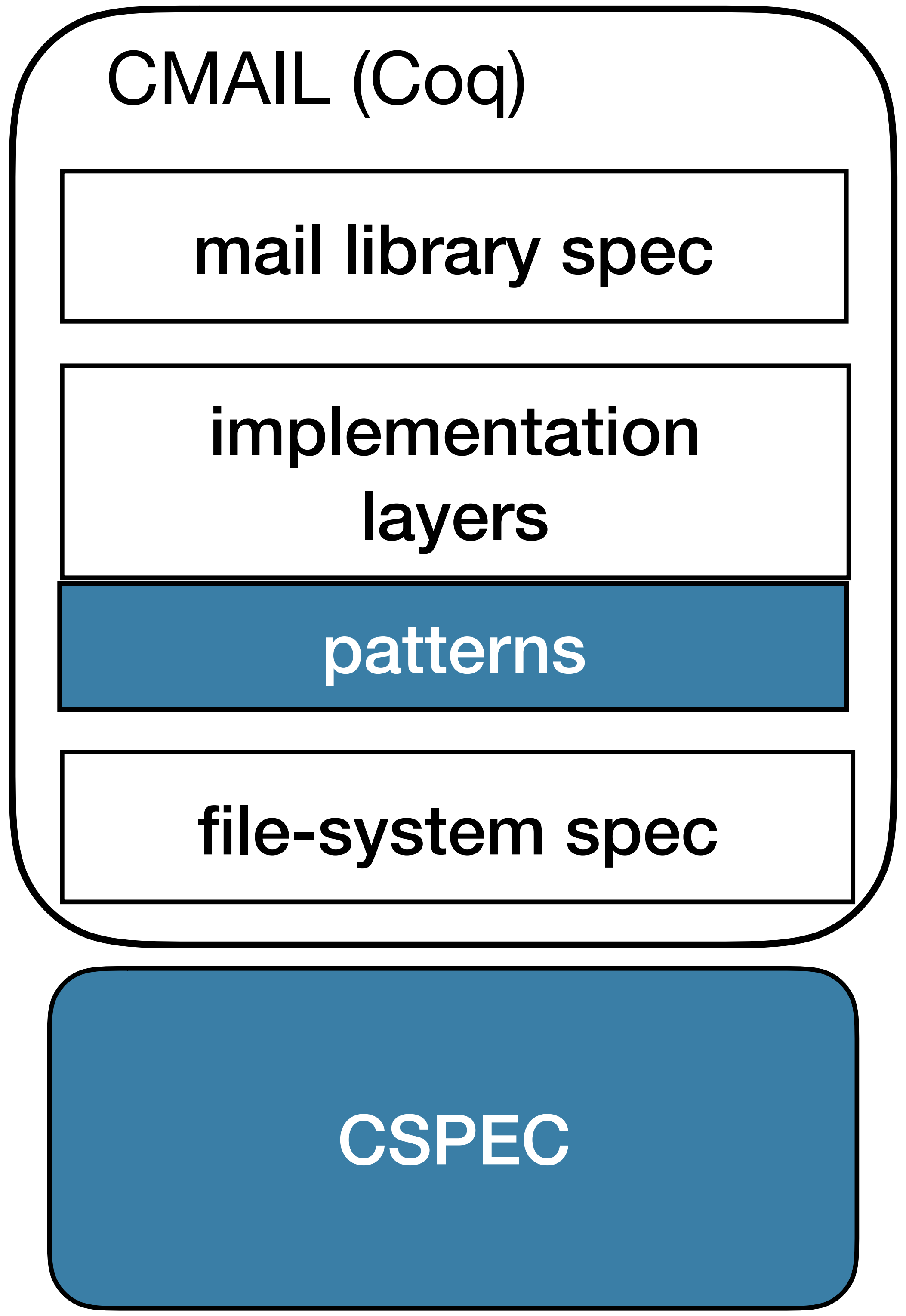
(see paper for details)

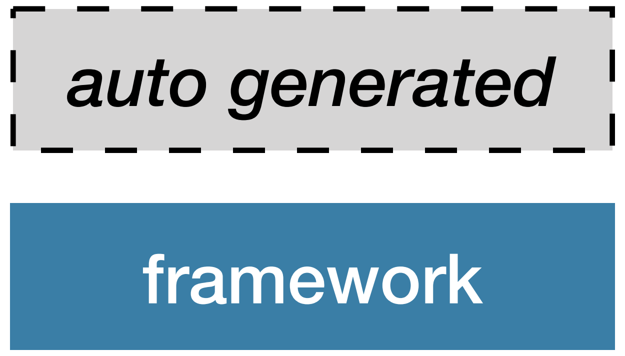
- Abstraction / forward simulation
  - Invariants
  - Error state
- Protocols
- Retry loops
- Partitioning



Using CSPEC to verify CMAIL

Coq





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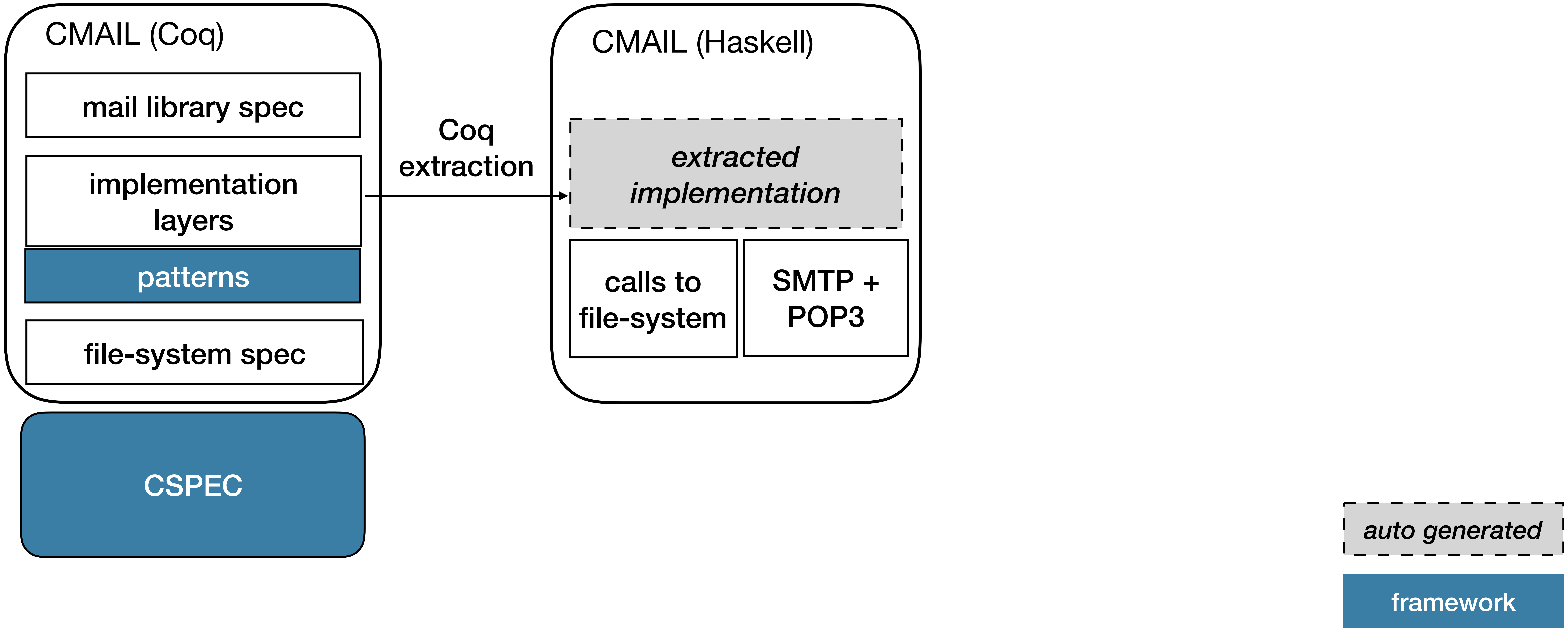
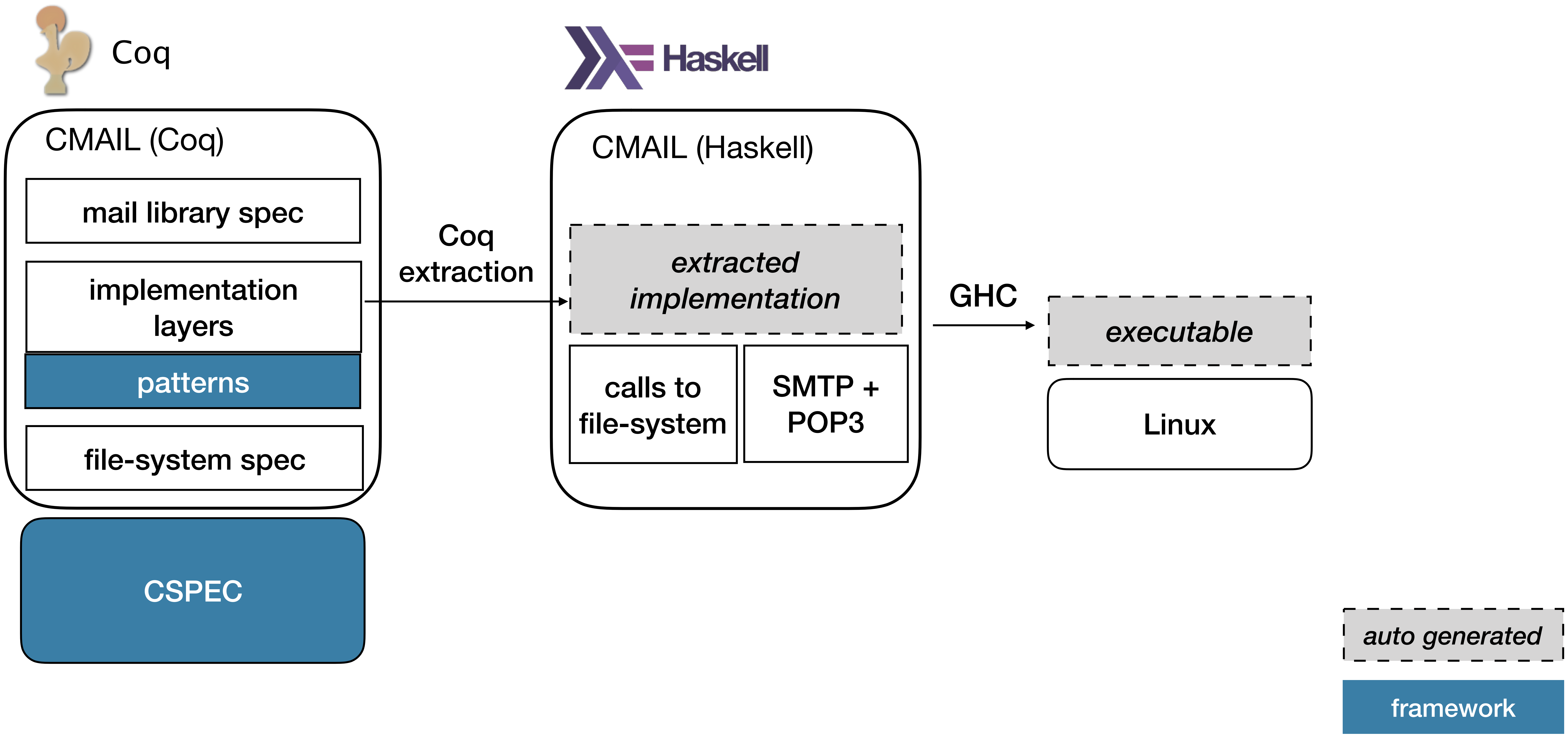
Coq

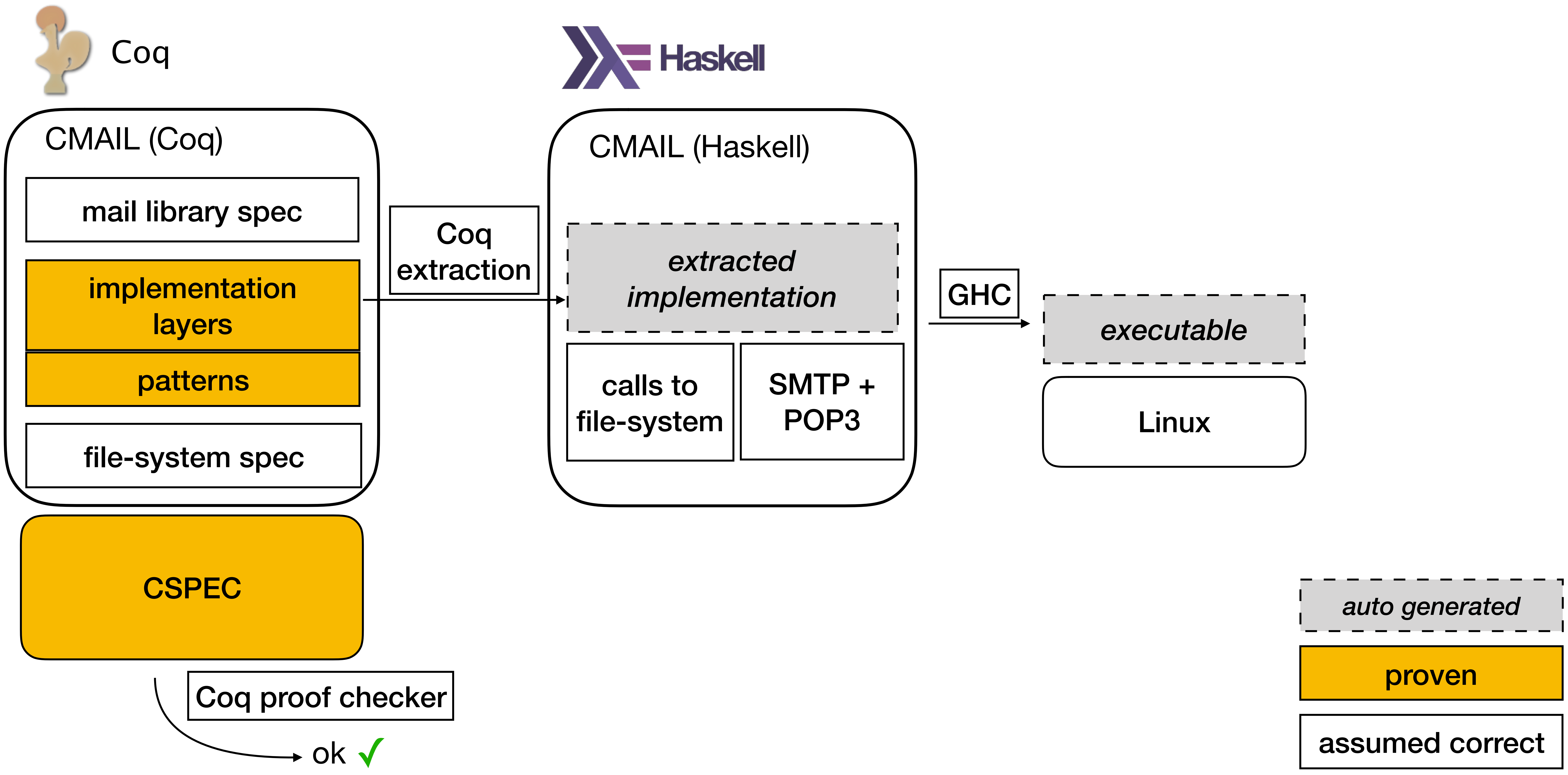
Haskell



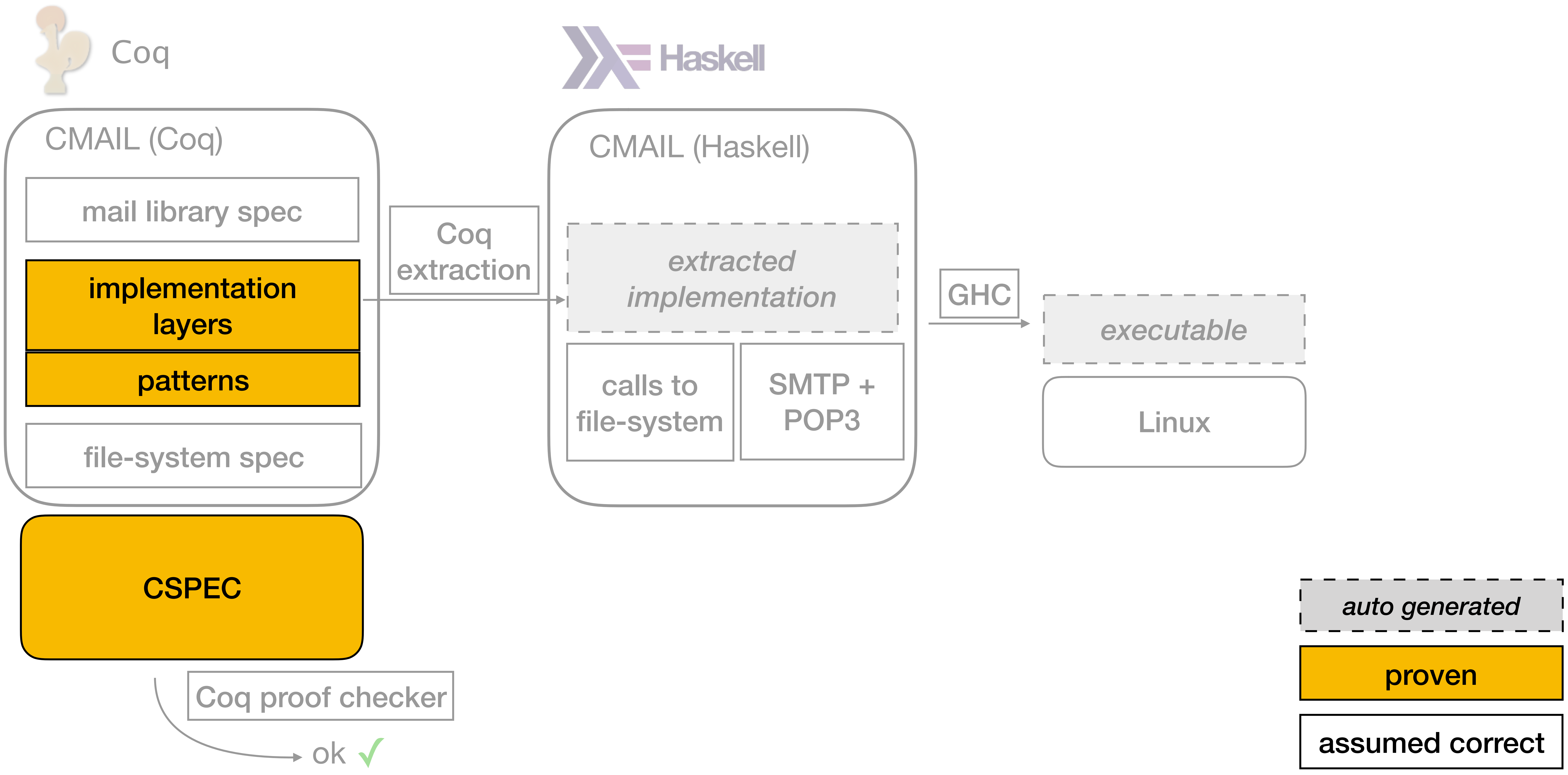
Using CSPEC to verify CMAIL



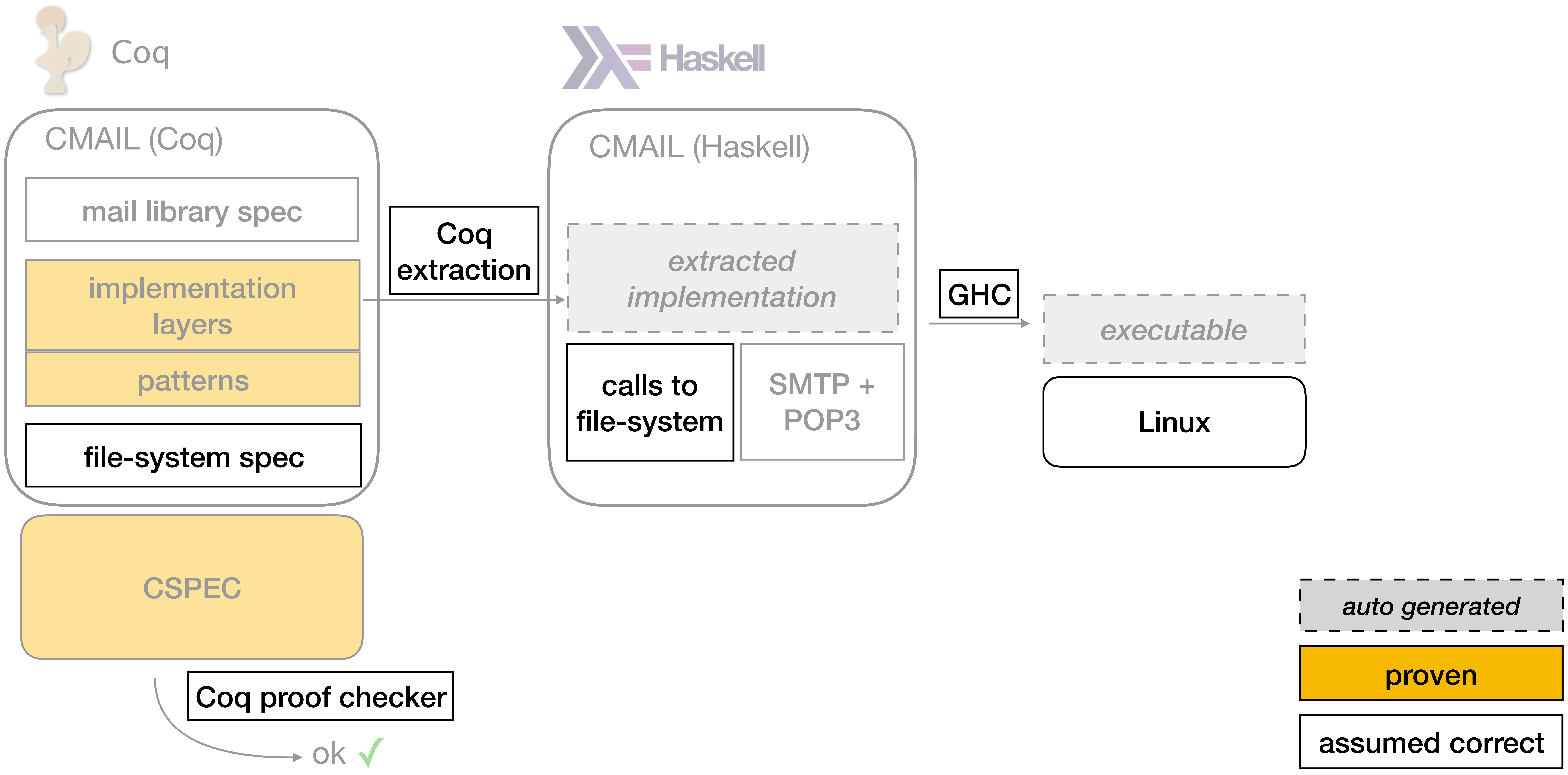
What is proven vs. assumed correct?



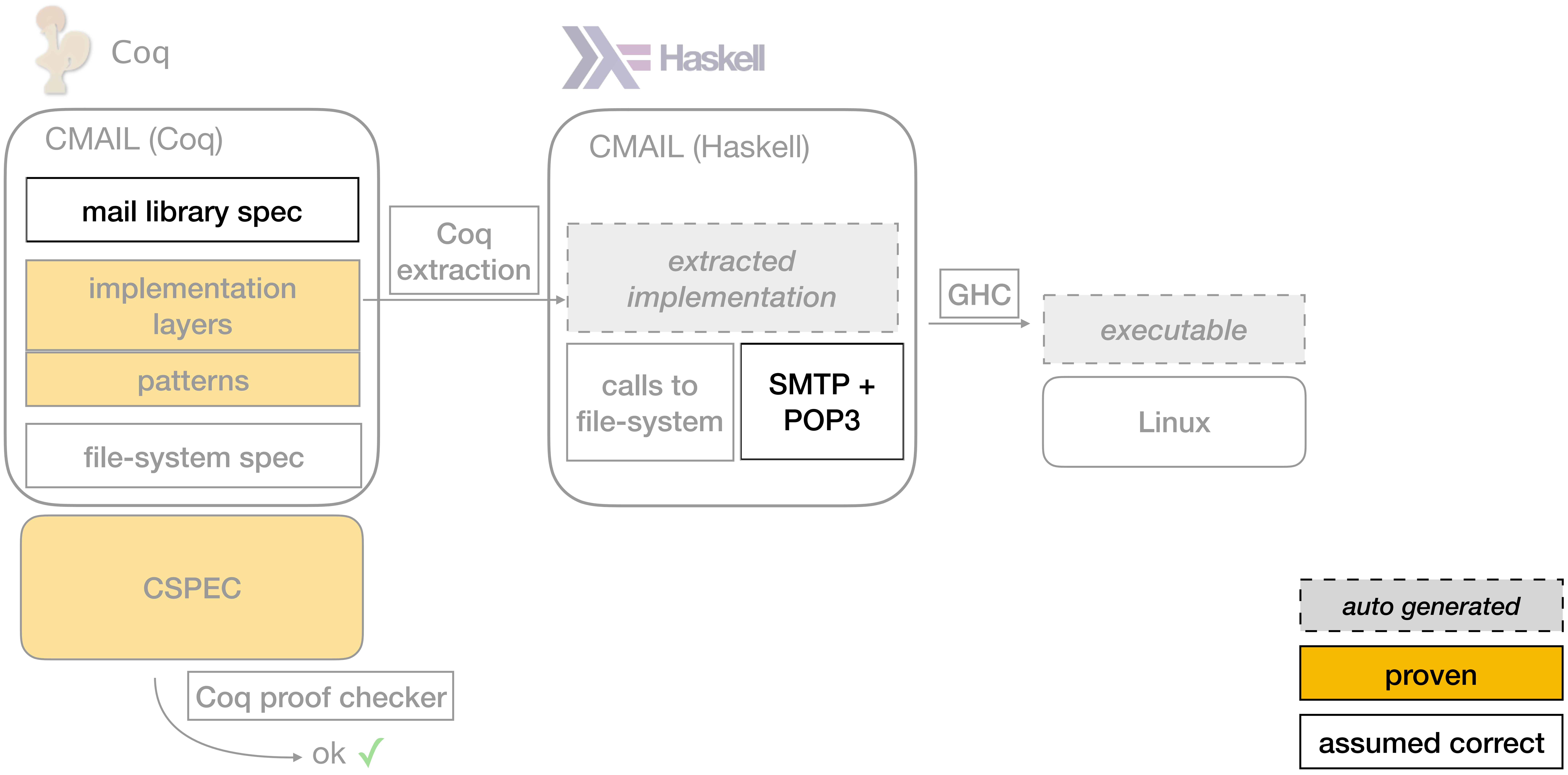
Concurrency inside CMAIL is proven



Trust that the tools and OS are correct



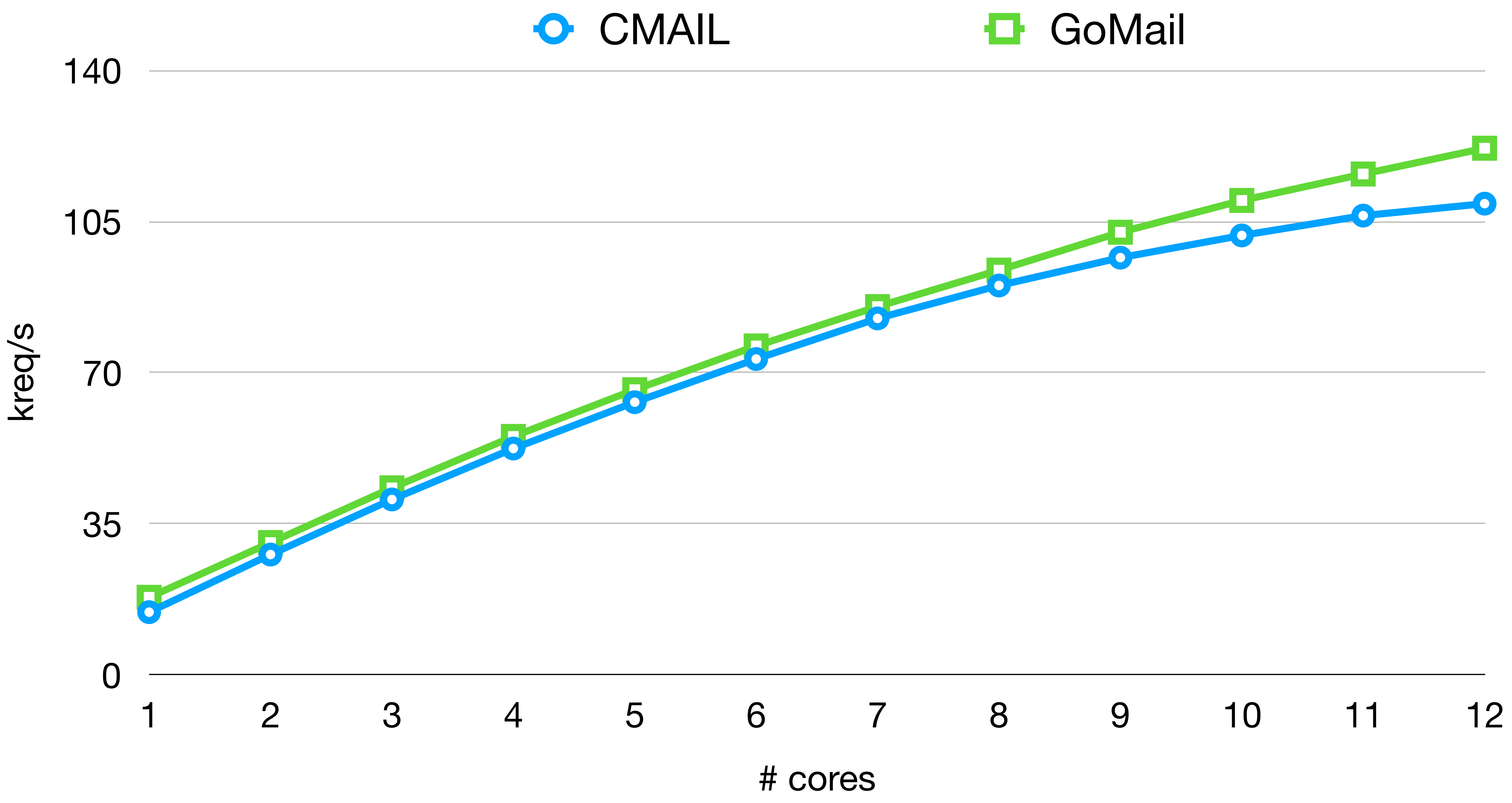
Mail server-specific assumptions



Evaluation

- Can CMAIL exploit file-system concurrency for speedup?
- How much effort was verifying CMAIL?
- What is the benefit of CSPEC's machine-checked proofs?

CMAIL achieves speedup with multiple cores



CMAIL was work but doable

		proof:code ratio
concurrent	CMAIL	**11.5x**
	CertiKOS	13.8x
	IronFleet	7.7x
sequential	IronClad	4.8x
	CompCert	4.6x

Took two authors 6 months

Machine-checked proofs give confidence in framework changes

Three anecdotes of changes to CSPEC:

Machine-checked proofs ensure soundness of entire system

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- Implemented **partitioning pattern** to support multiple users

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Three anecdotes of changes to CSPEC:

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- Improved **mover pattern** for a CMAIL left mover proof

Machine-checked proofs ensure soundness of entire system

Machine-checked proofs give confidence in framework changes

Three anecdotes of changes to CSPEC:

- Implemented **partitioning pattern** to support multiple users
- Improved **mover pattern** for a CMAIL left mover proof
- Implemented **error-state pattern** for the x86-TSO lock proof

Machine-checked proofs ensure soundness of entire system

CSPEC is a framework for verifying concurrency in systems software

- Layers and patterns (esp. movers) make proofs manageable
- Machine-checked framework supports adding new patterns
- Evaluated by verifying mail server and x86-TSO lock

  github.com/mit-pdos/cspec

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poster #1