Behavioral design with Alloy

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(original slides by Alcino Cunha)

Software *concepts*

THE ESSENCE OF SOFTWARE

WHY CONCEPTS MATTER FOR GREAT DESIGN

DANIEL JACKSON

Concepts

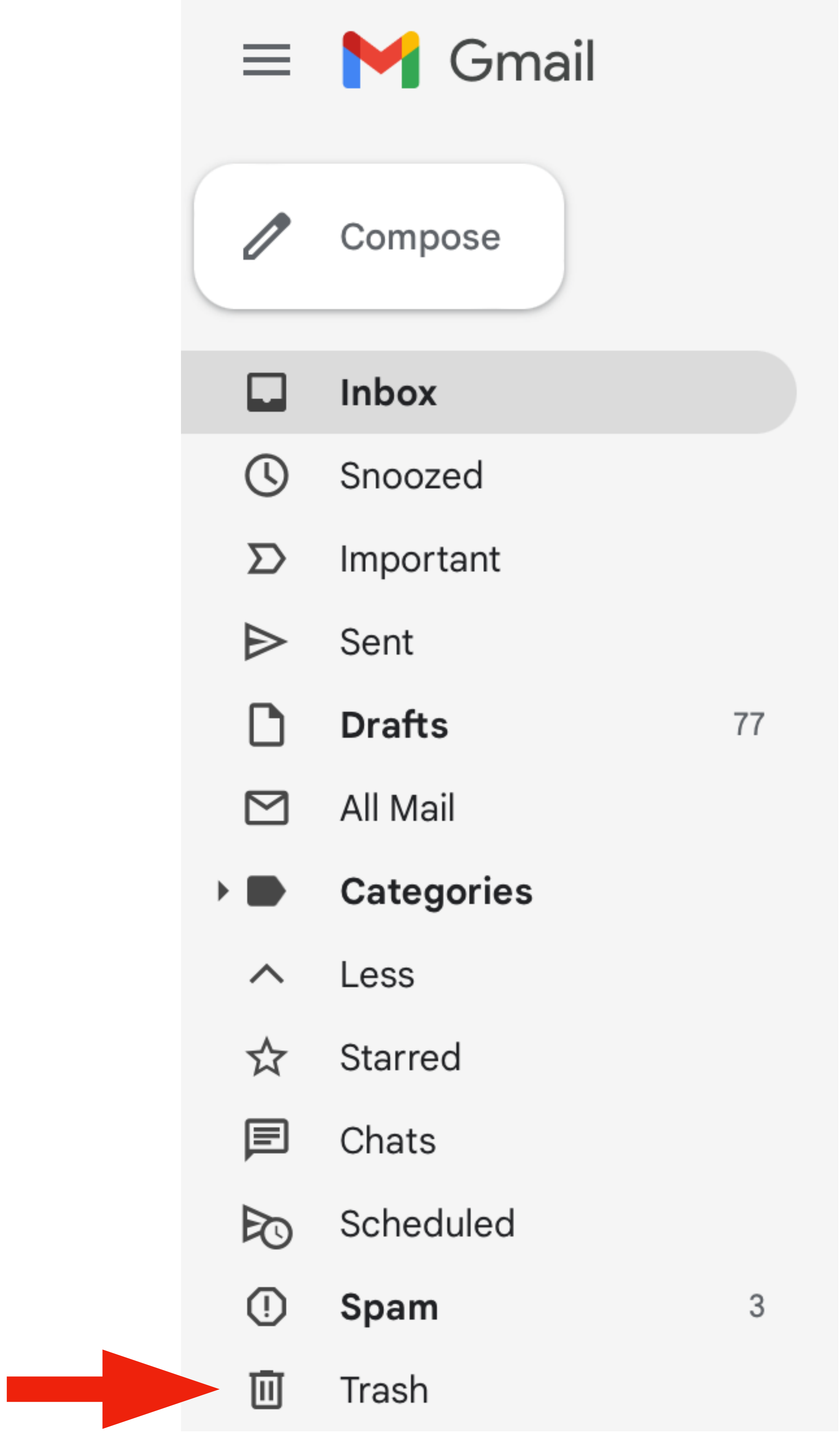
- Apps are made of recurring *concepts*
- Each *concept* is a self-contained unit of functionality with a clear purpose
- *Concepts* work together to provide the app overall functionality
- But can be understood independently of one another

Trash

Trash

Trash


Open
Empty Trash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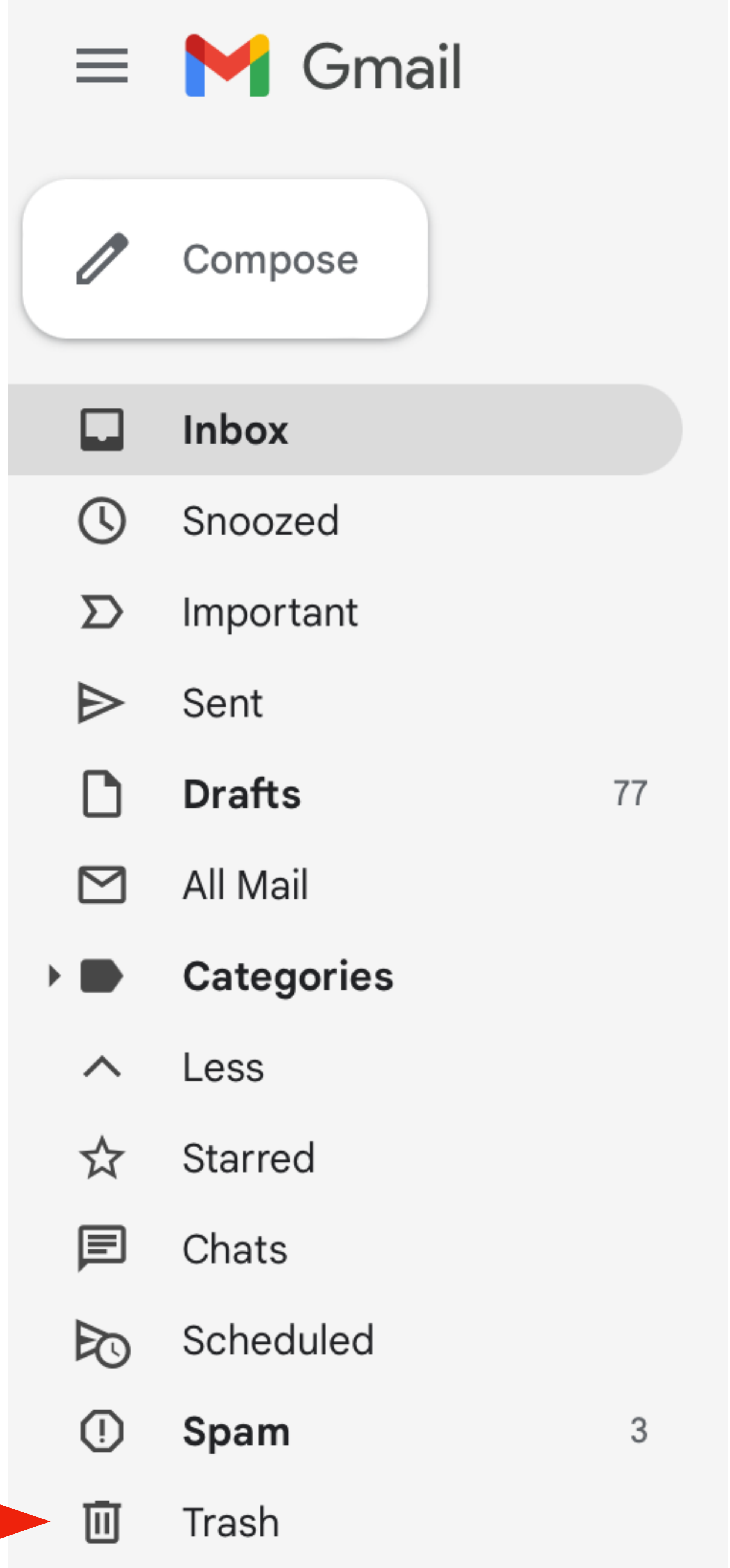
Trash

Trash


Open
Empty Trash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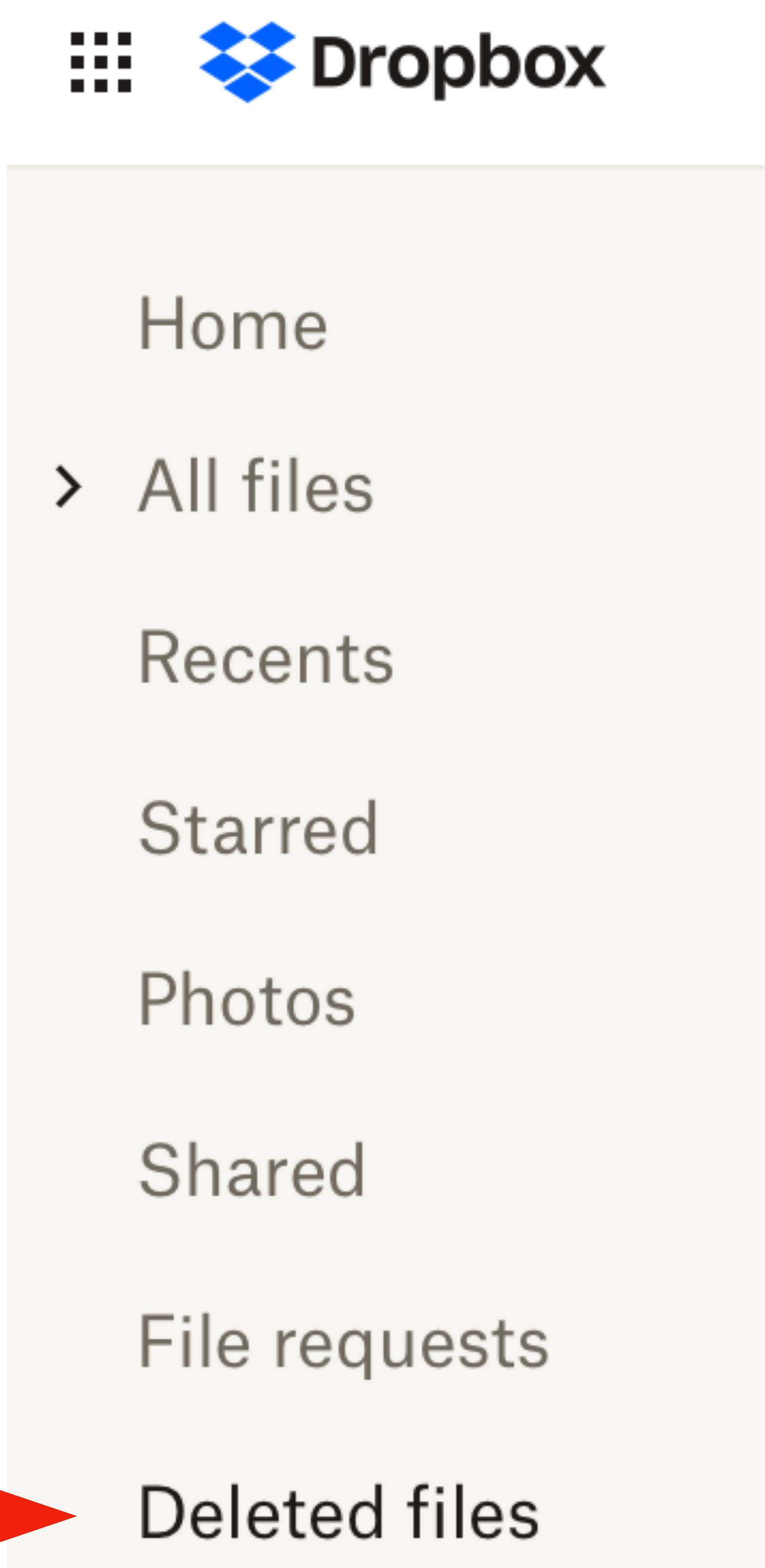
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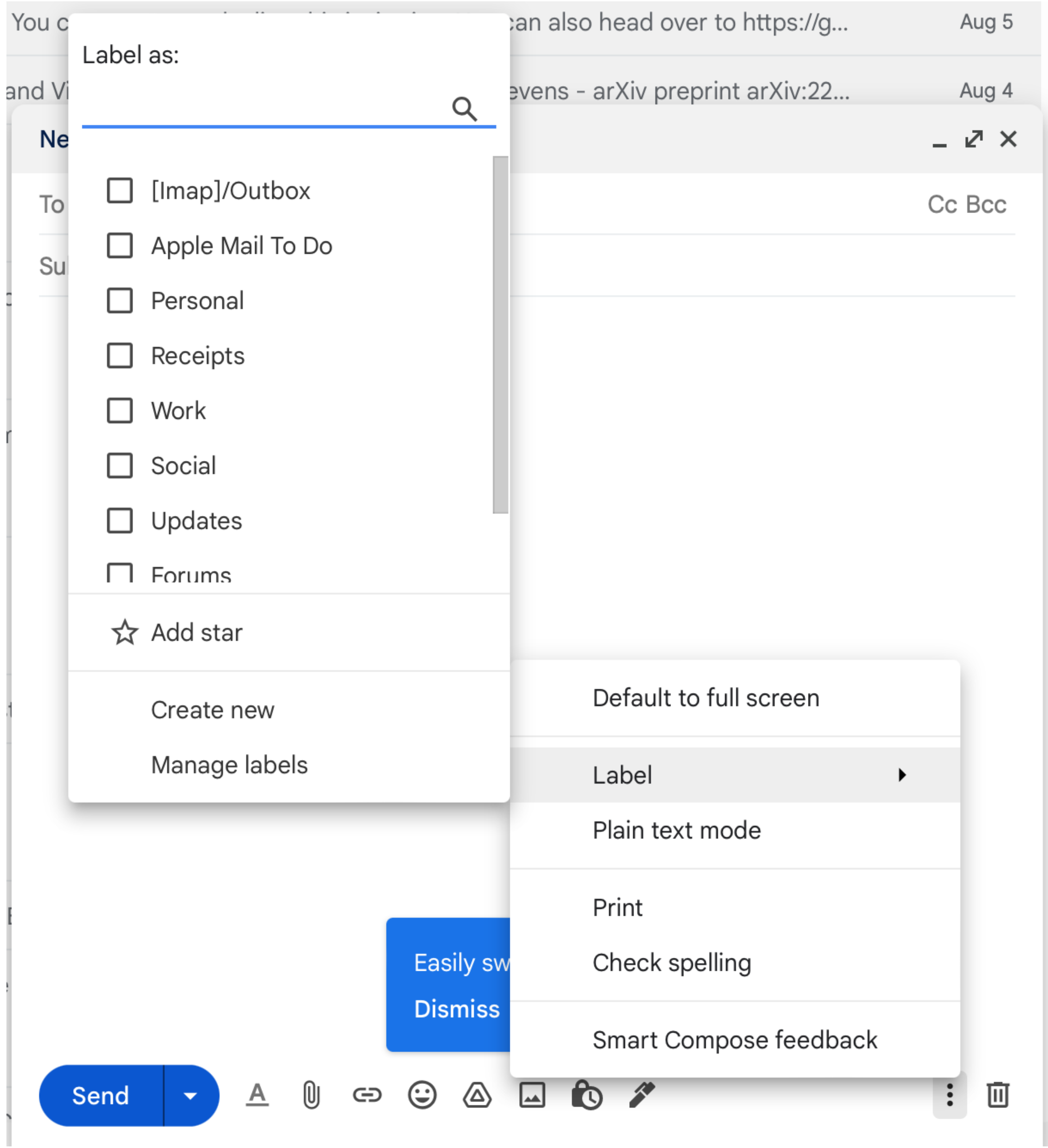
Label

Label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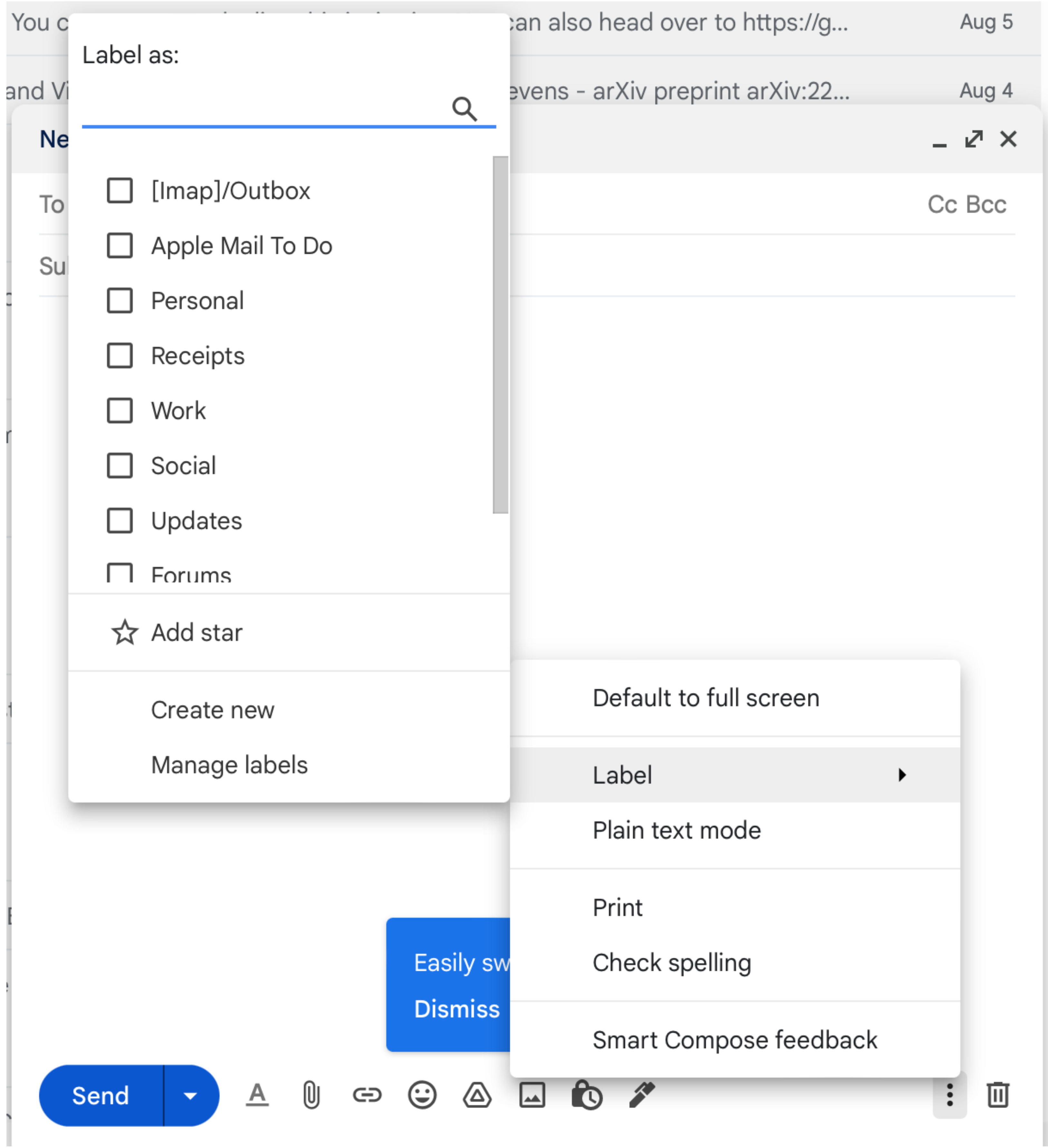

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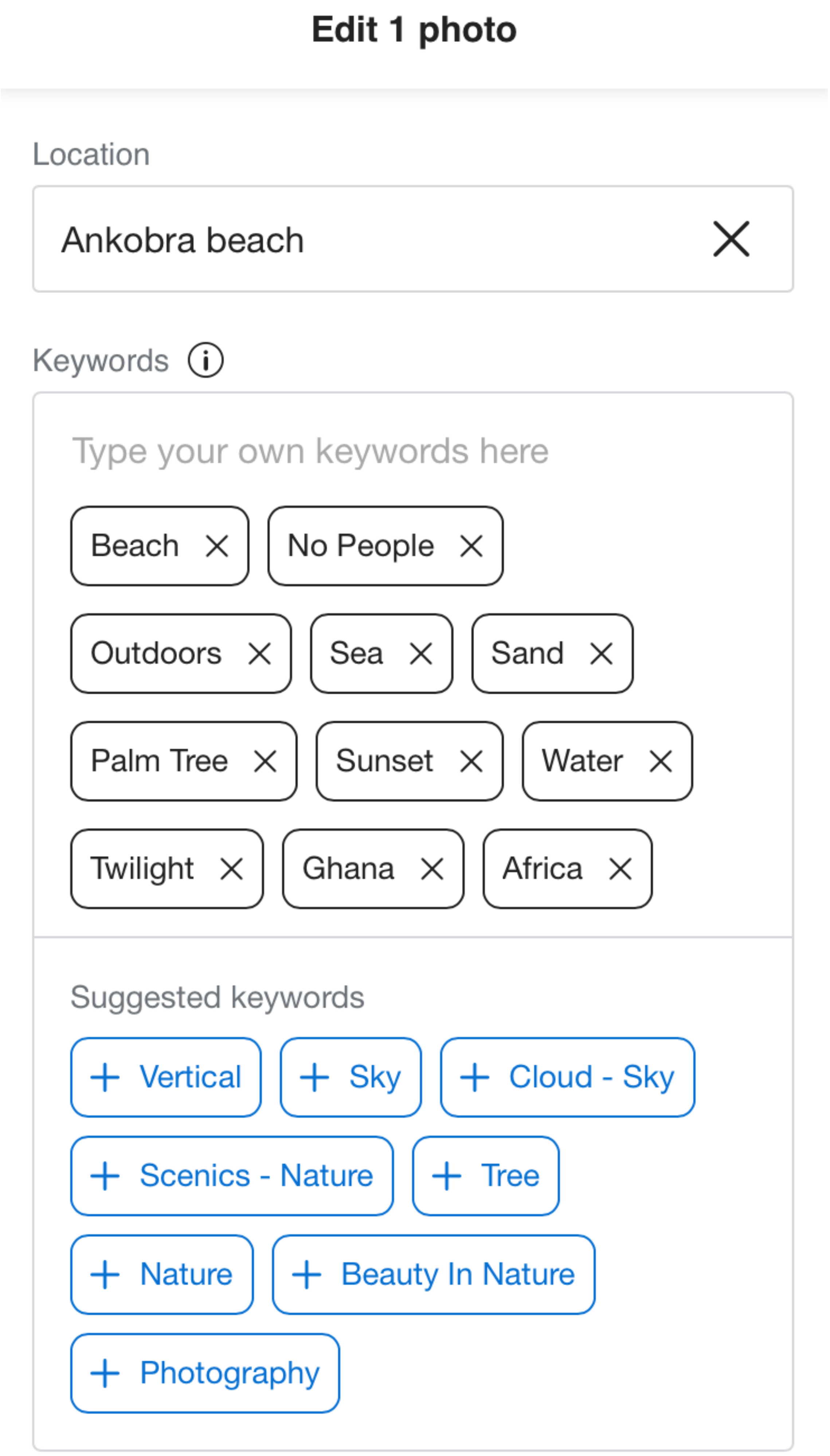

Edit 1 photo
Location
Ankobra beach
Keywords
Type your own keywords here
Beach
No People
Outdoors
Sea
Sand
Palm Tree
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Suggested keywords
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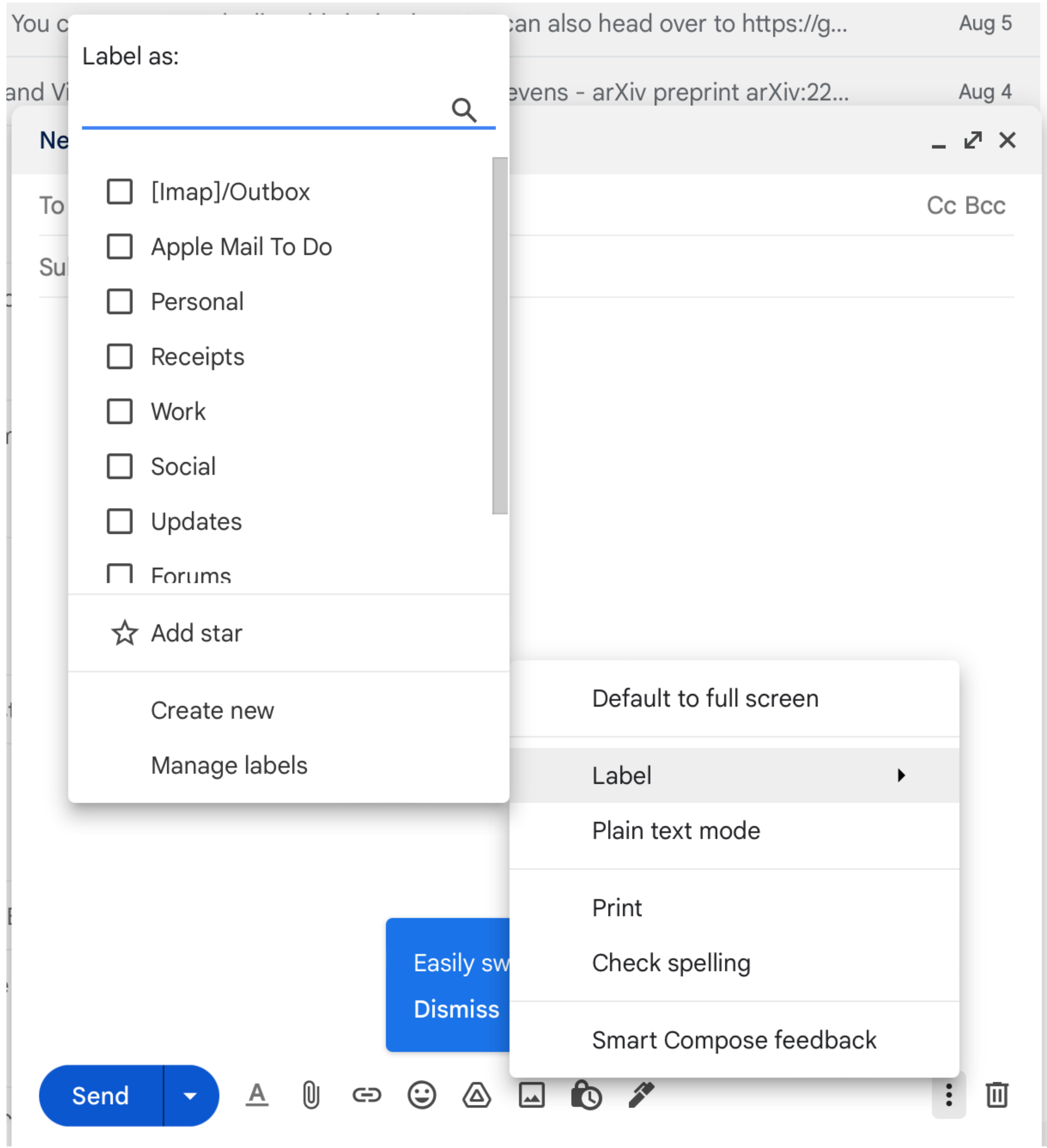
Cloud - Sky
Scenics - Nature
Tree
Nature
Beauty In Nature
Photography

Label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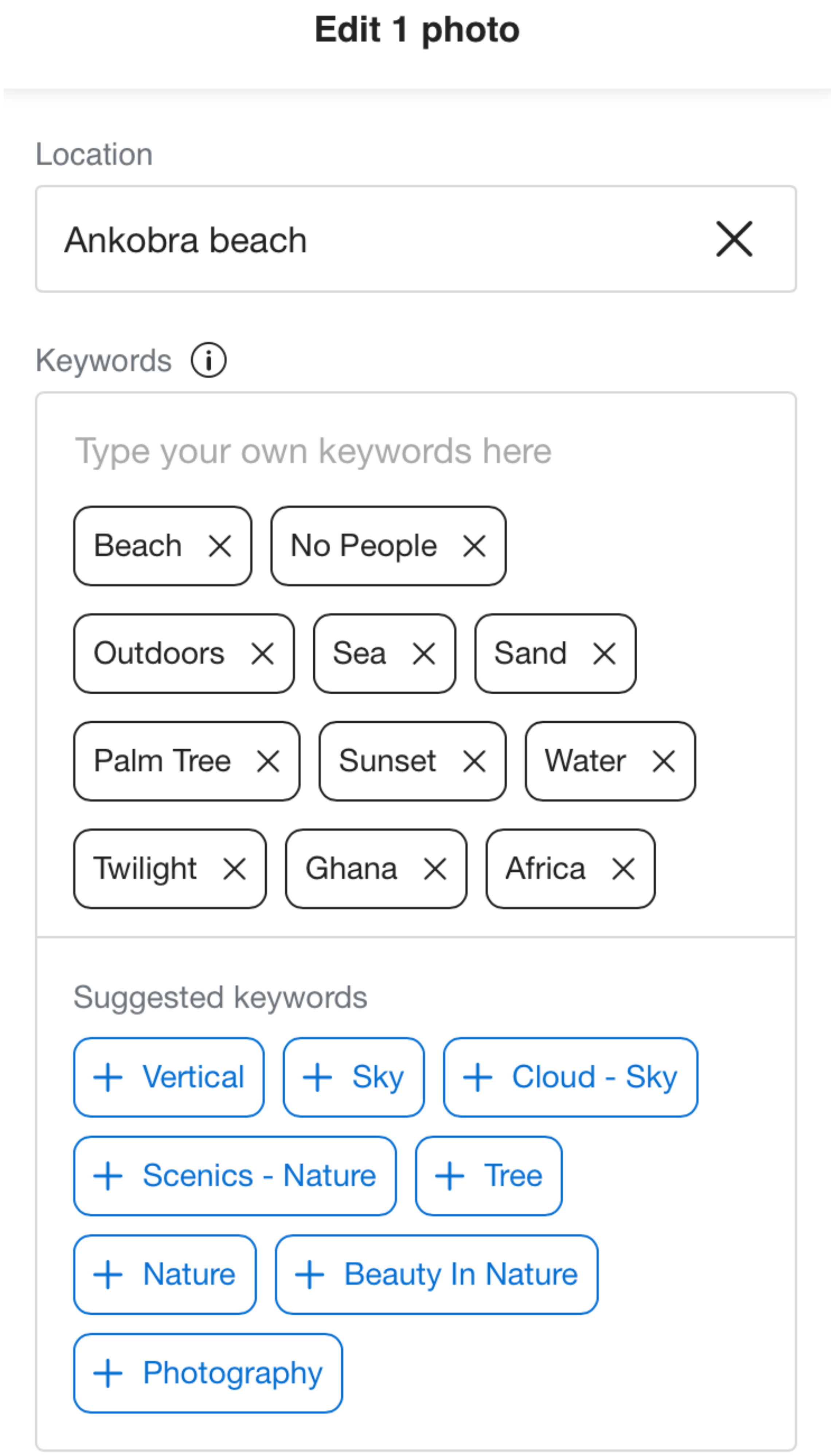
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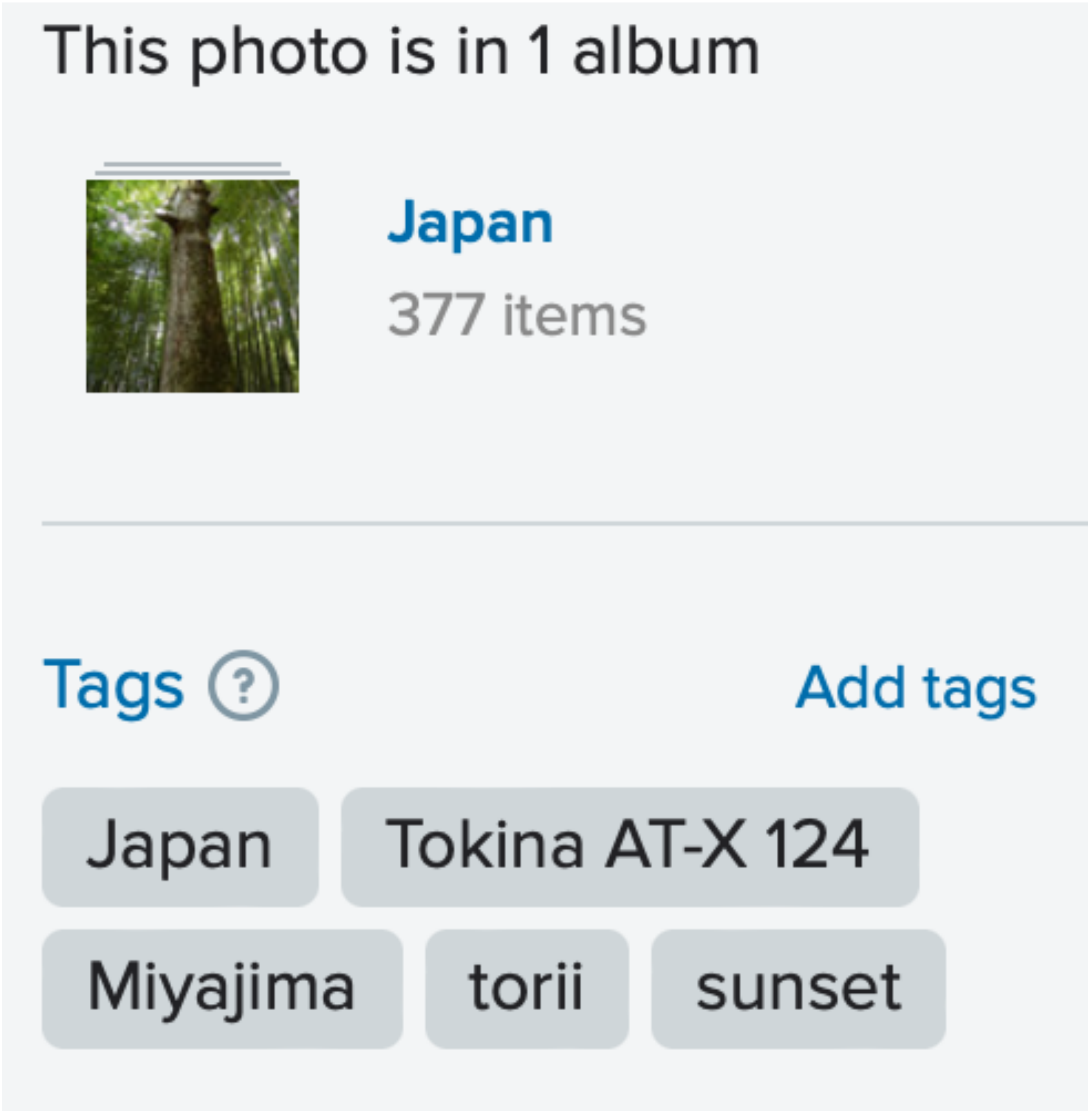
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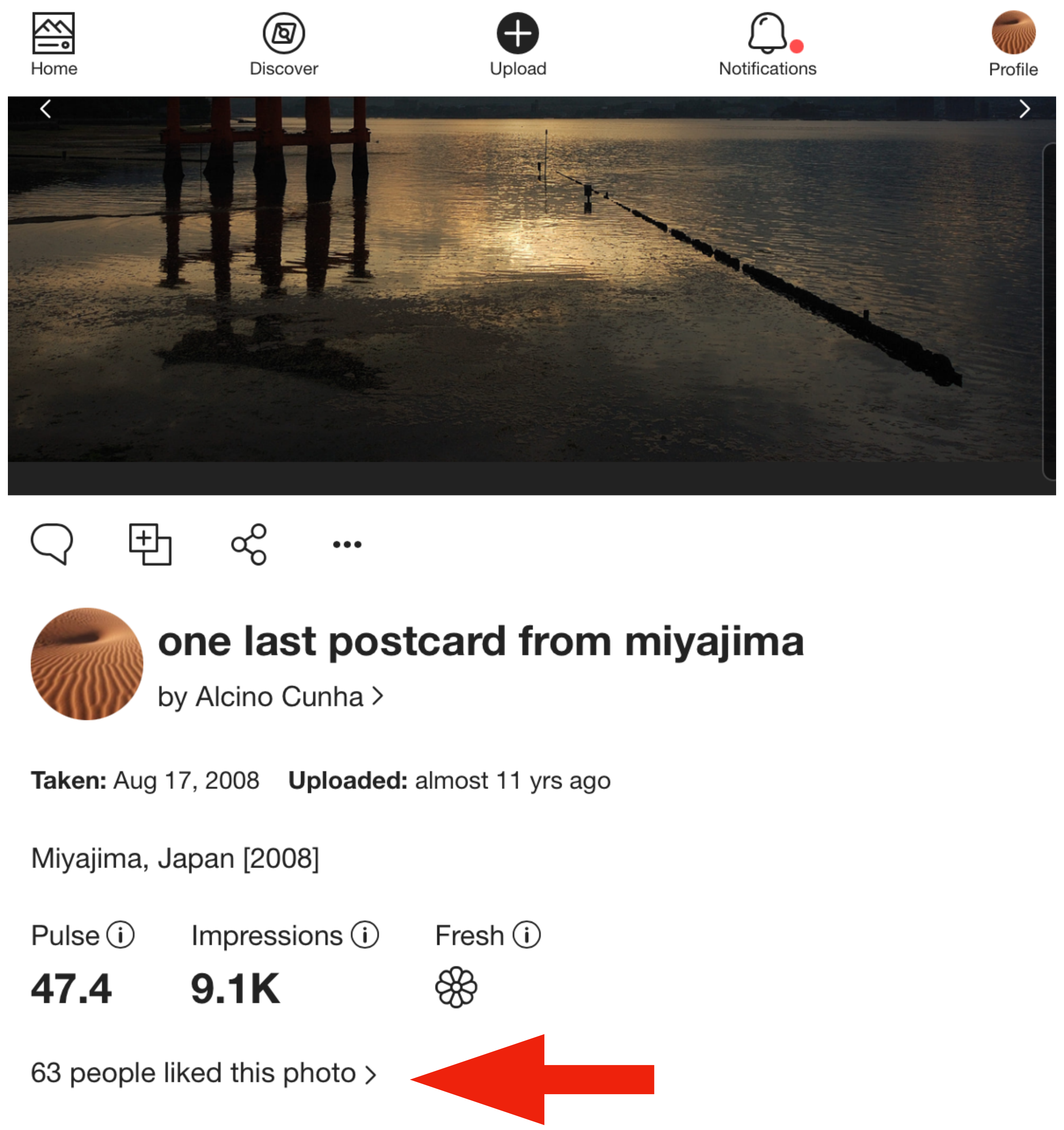
Like

Like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Upload
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one last postcard from miyajima
by Alcino Cunha
Taken: Aug 17, 2008 **Uploaded:** almost 11 yrs ago
Miyajima, Japan [2008]
Pulse
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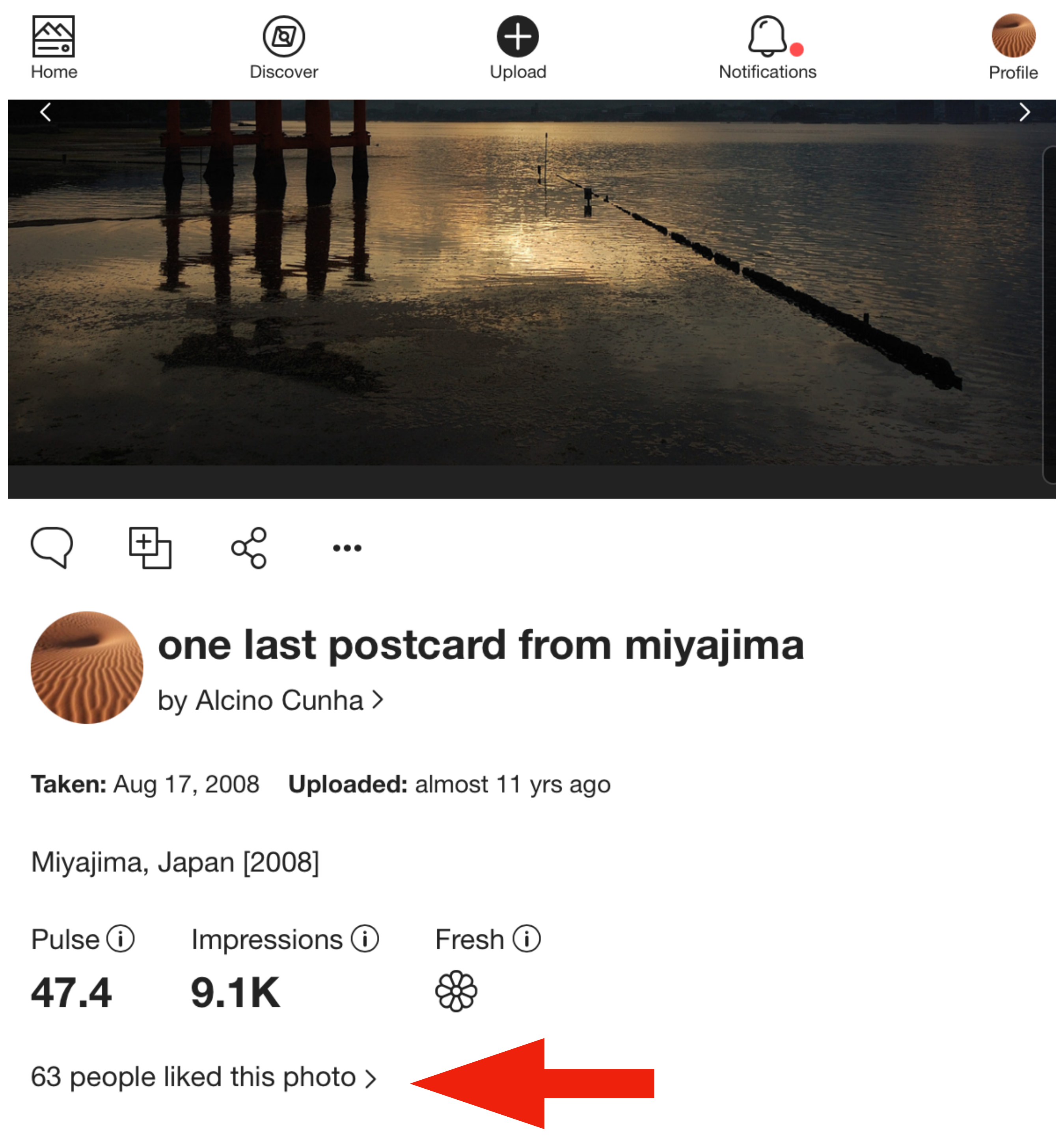
Impressions
9.1K
Fresh
63 people liked this photo

Like



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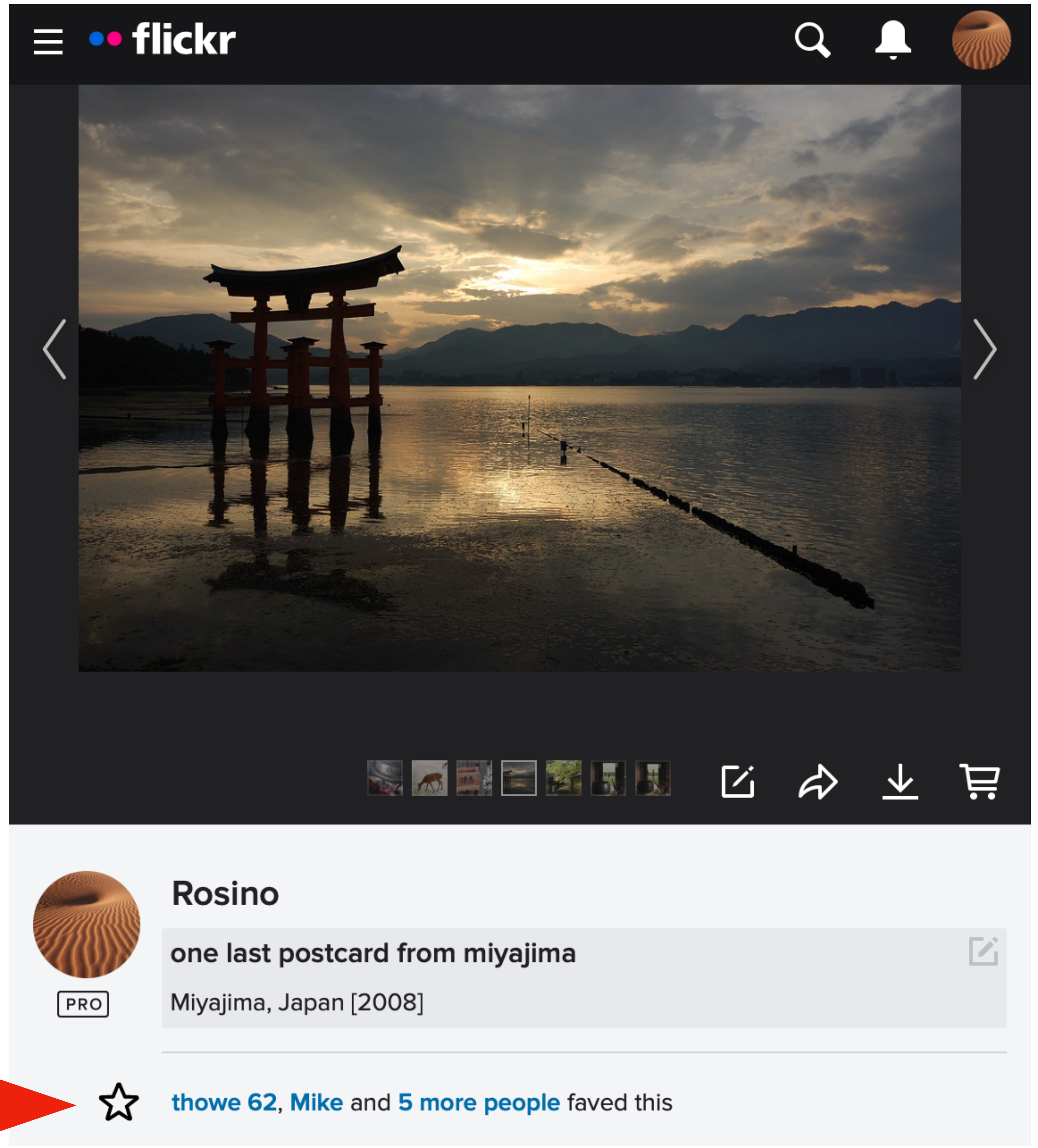

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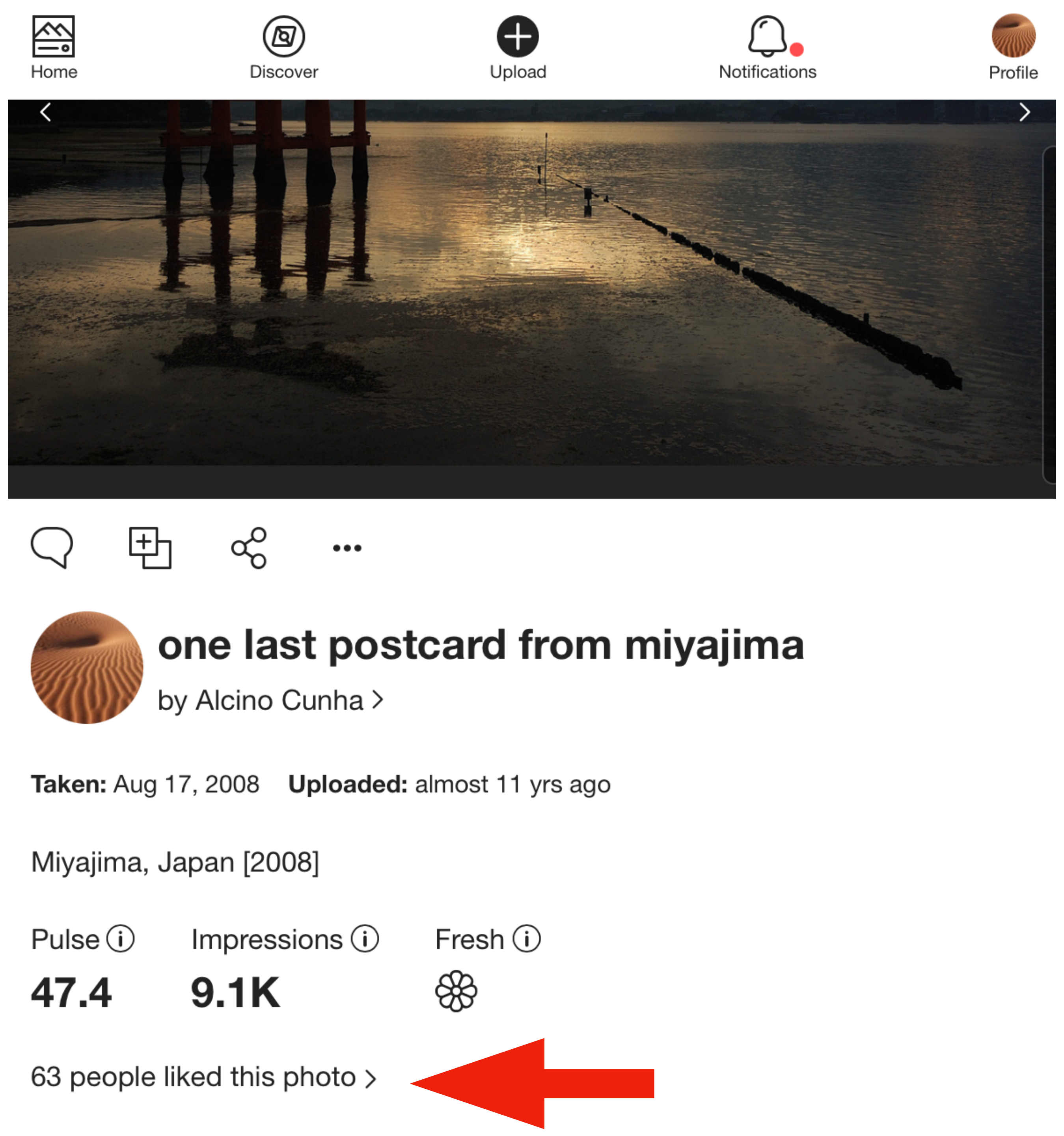
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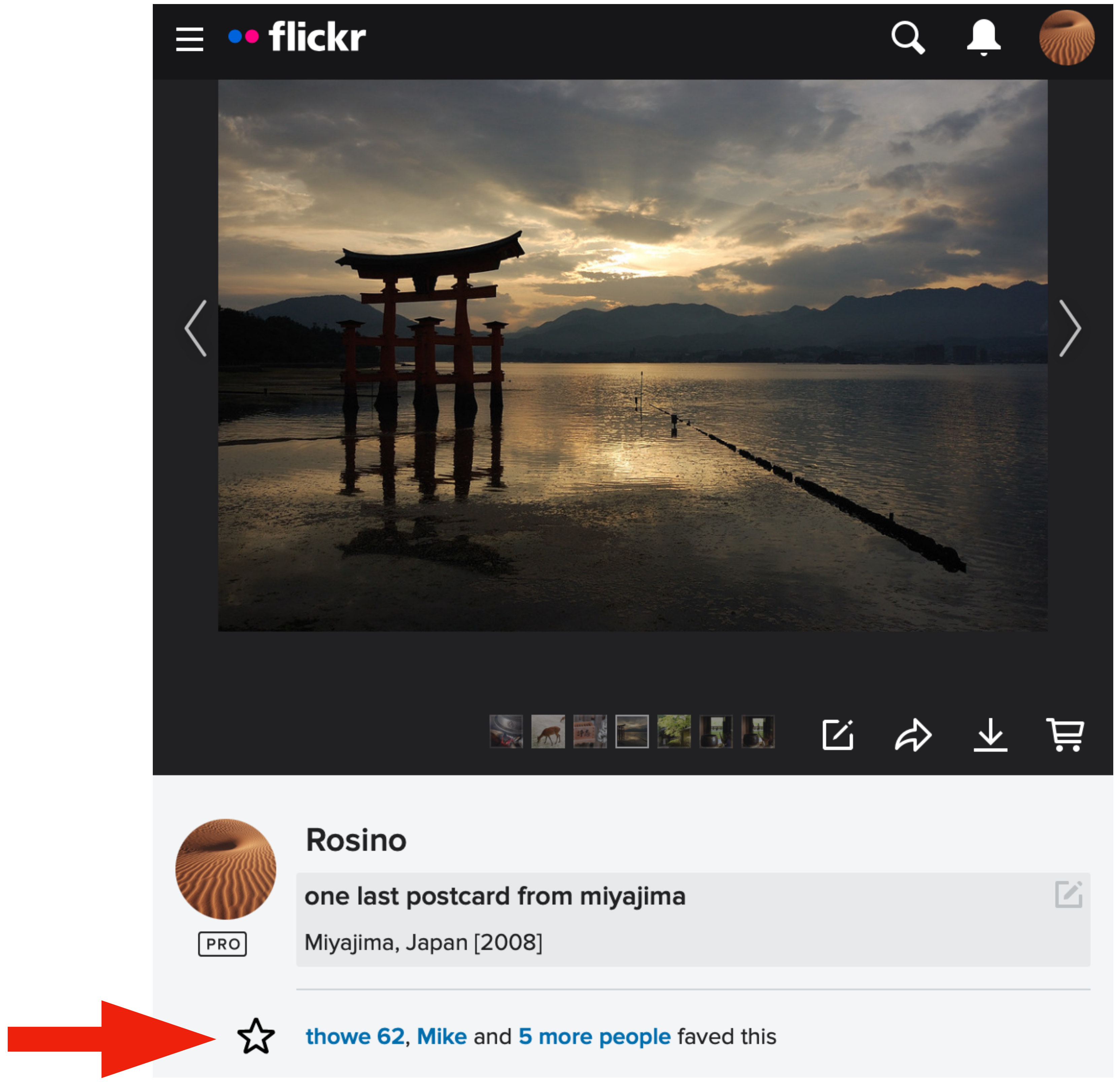
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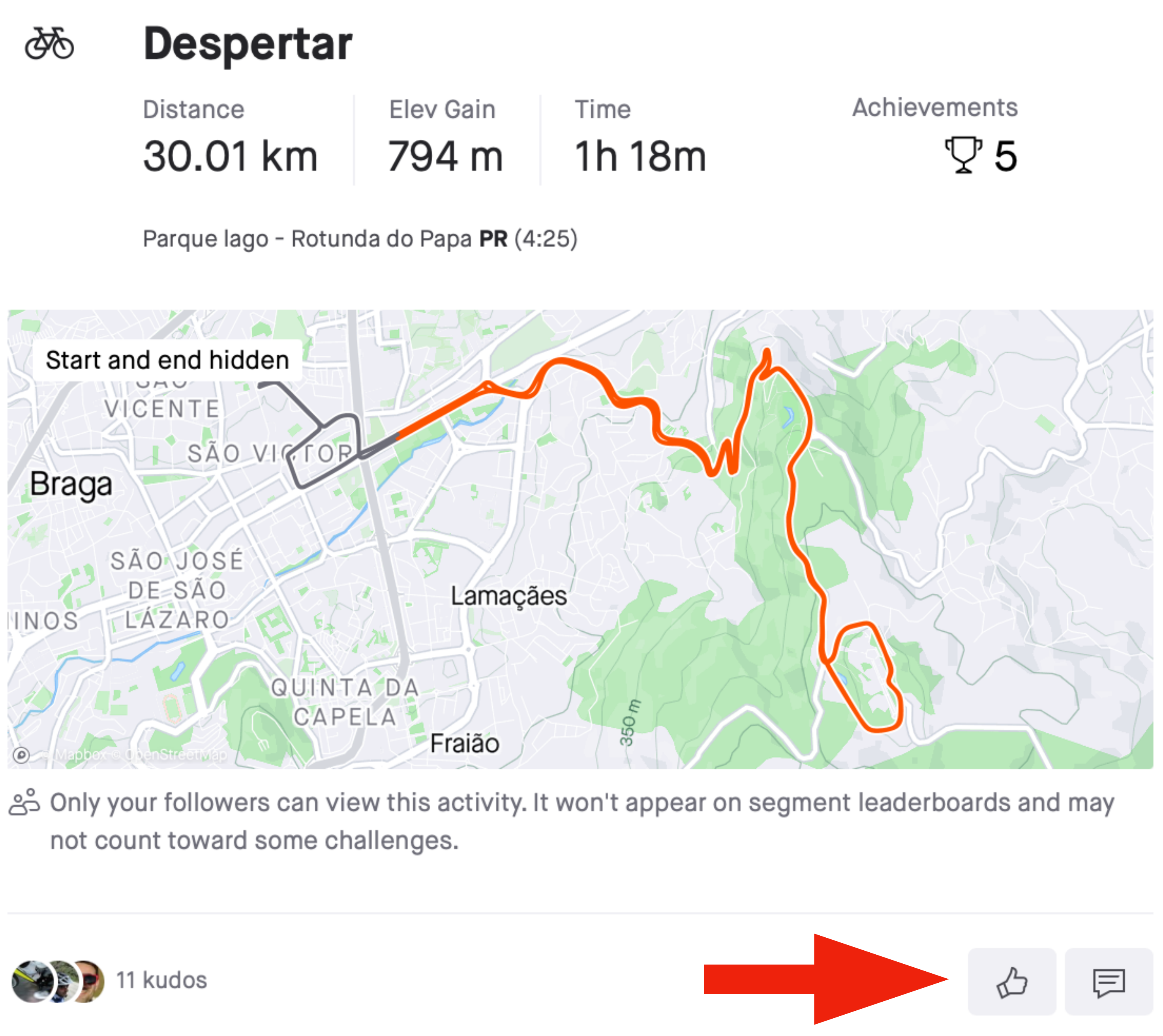
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Braga
Lamaçães
Fraião
Only your followers can view this activity. It won't appear on segment leaderboards and may not count toward some challenges.
11 kudos

Concept design

- Identify a clear purpose
- Choose the appropriate *state* and *actions* to fulfill that purpose
- The focus is on ensuring correctness and reusability

App design

- Identify the core *concepts*
- Compose them, maybe providing new functionality
- The focus is on exploration

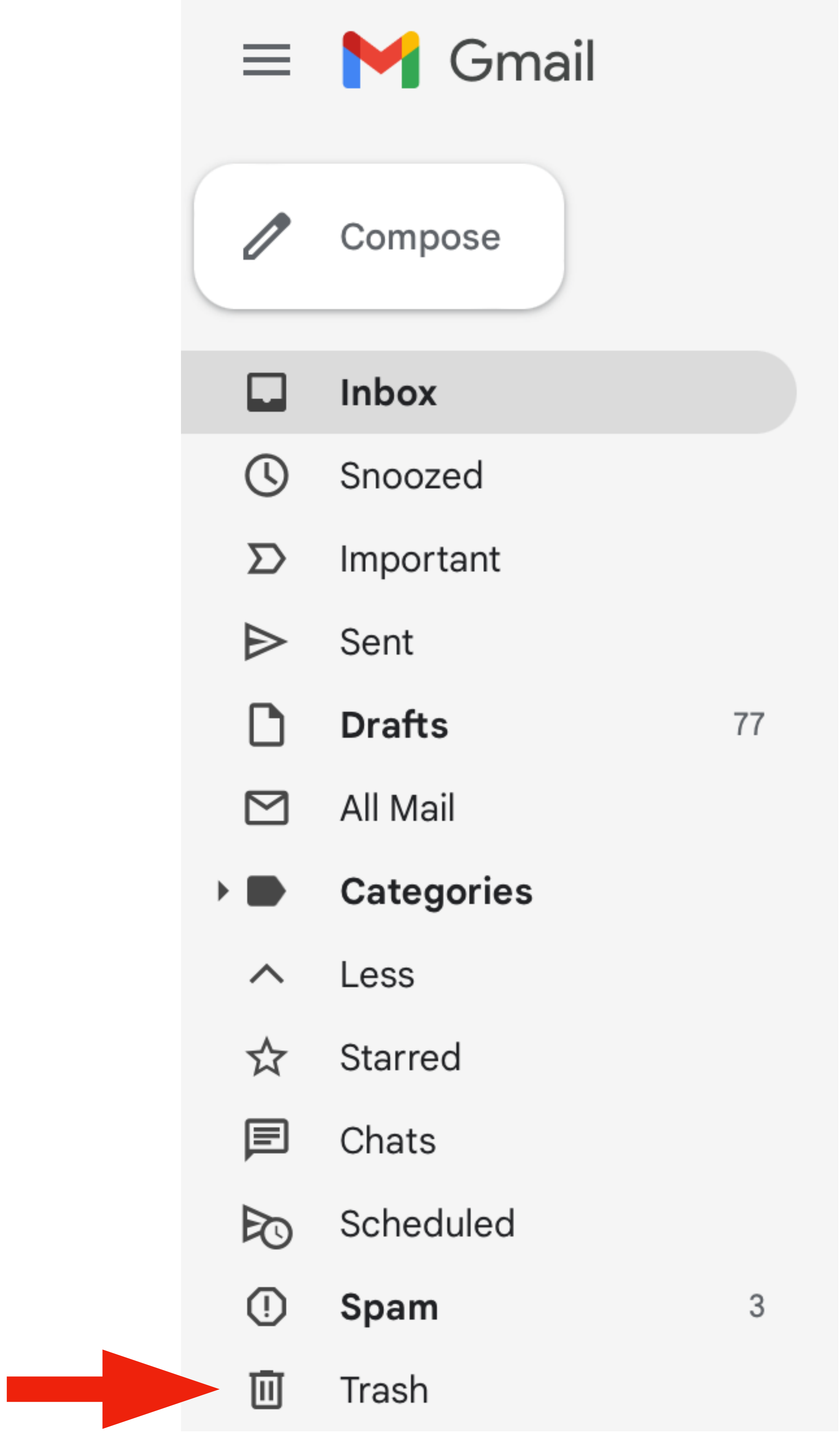
Modeling *concepts*

Trash

Trash

Trash


Open
Empty Trash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Trash

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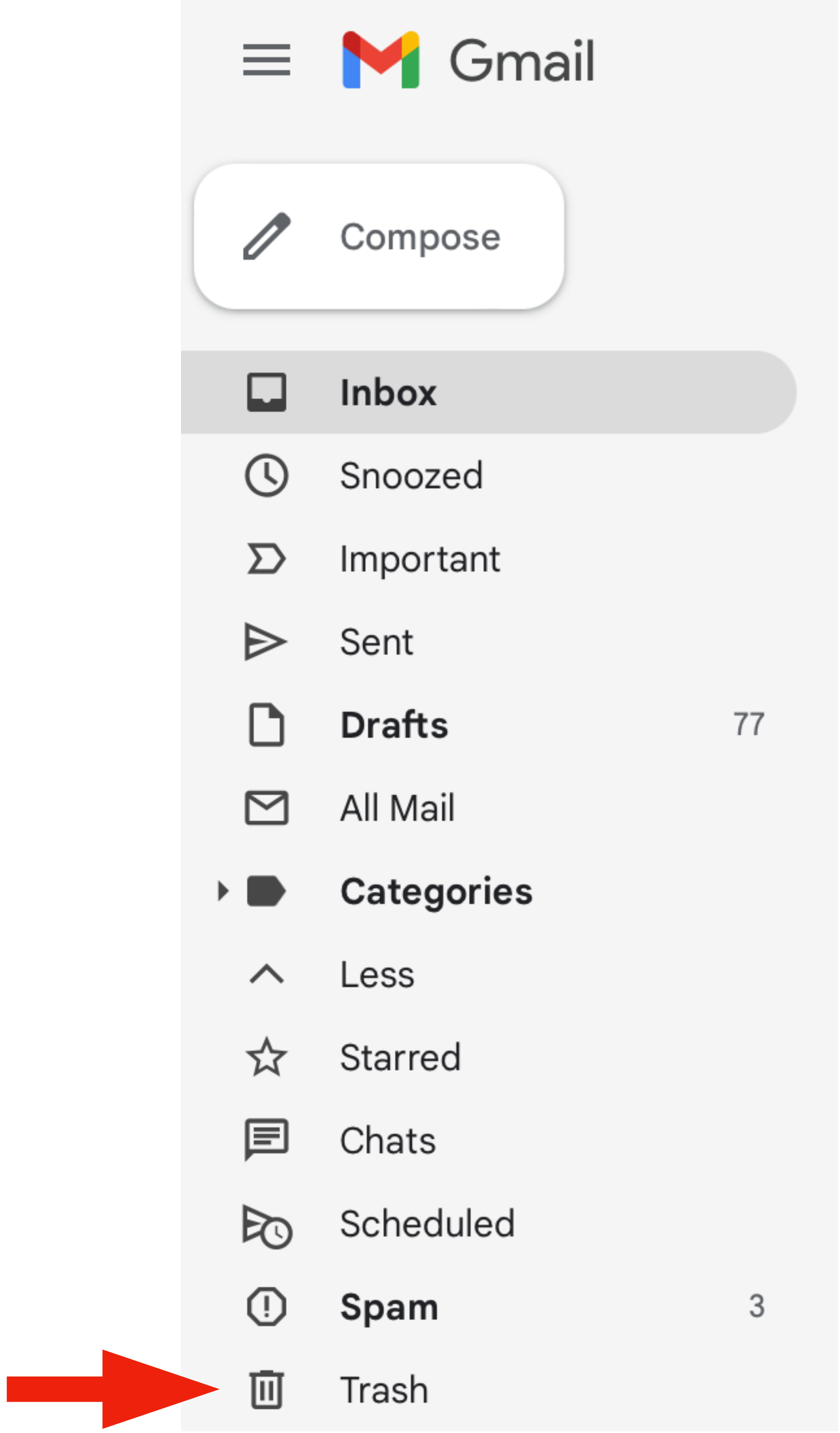
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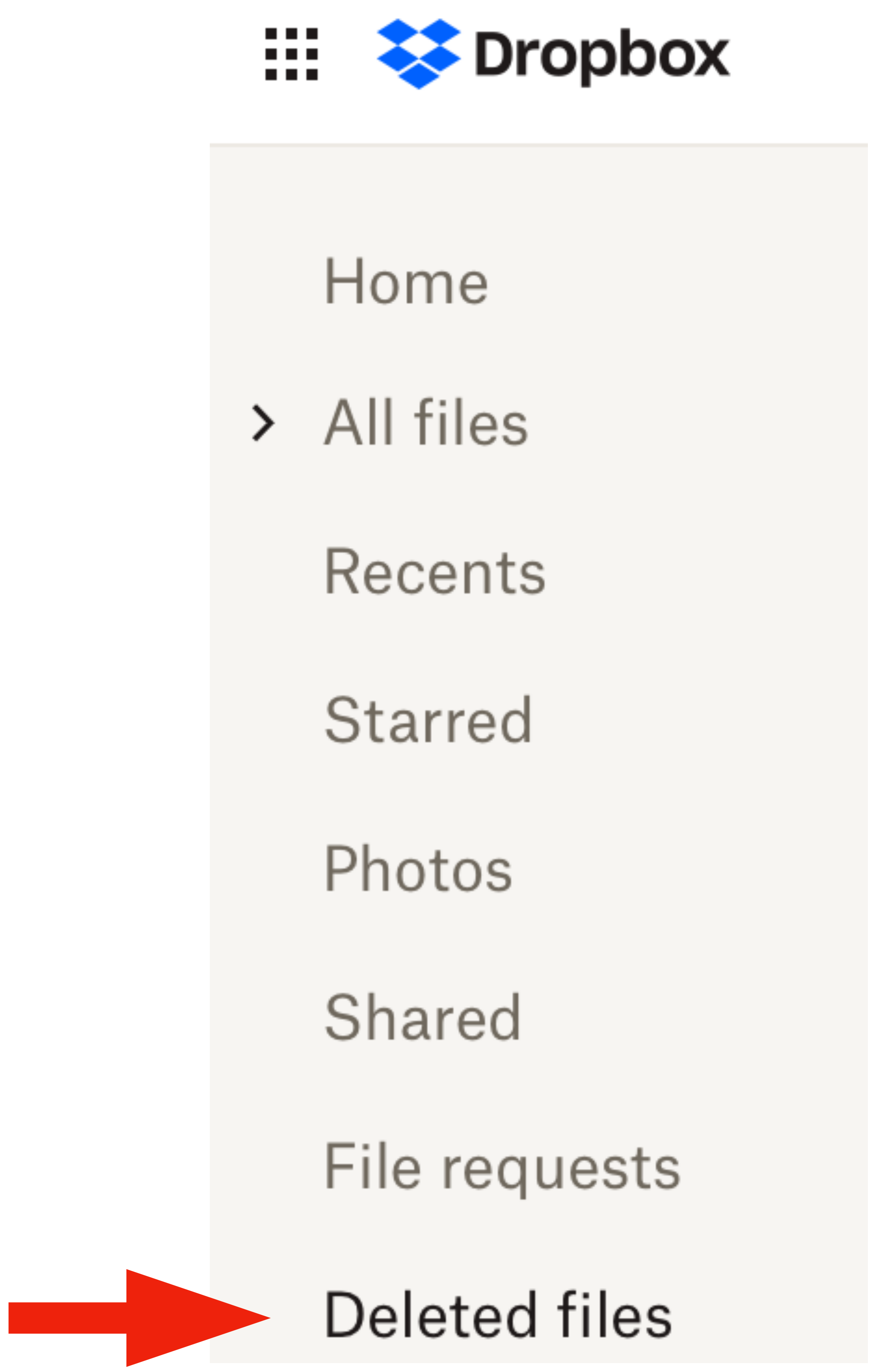
Trash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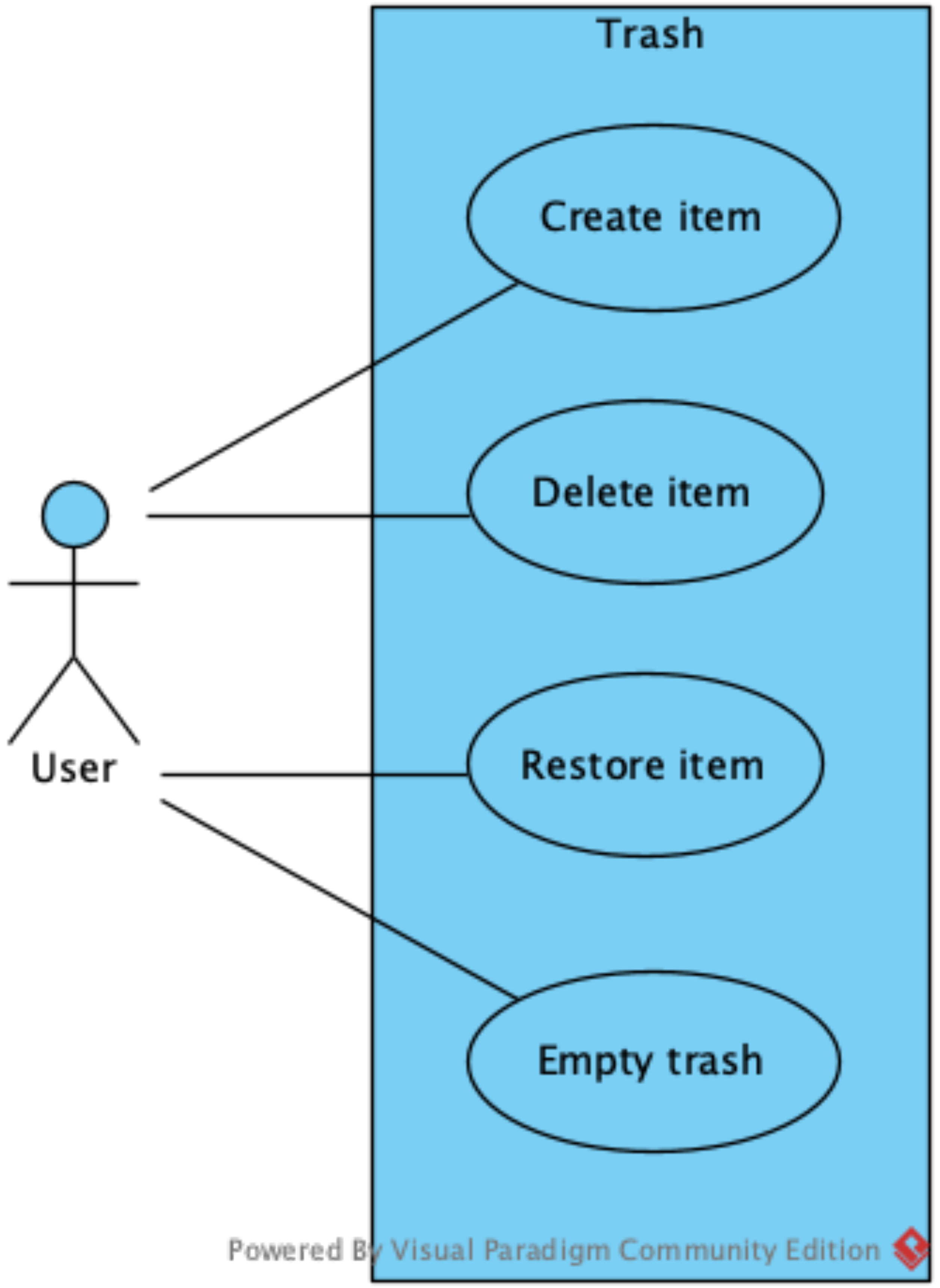
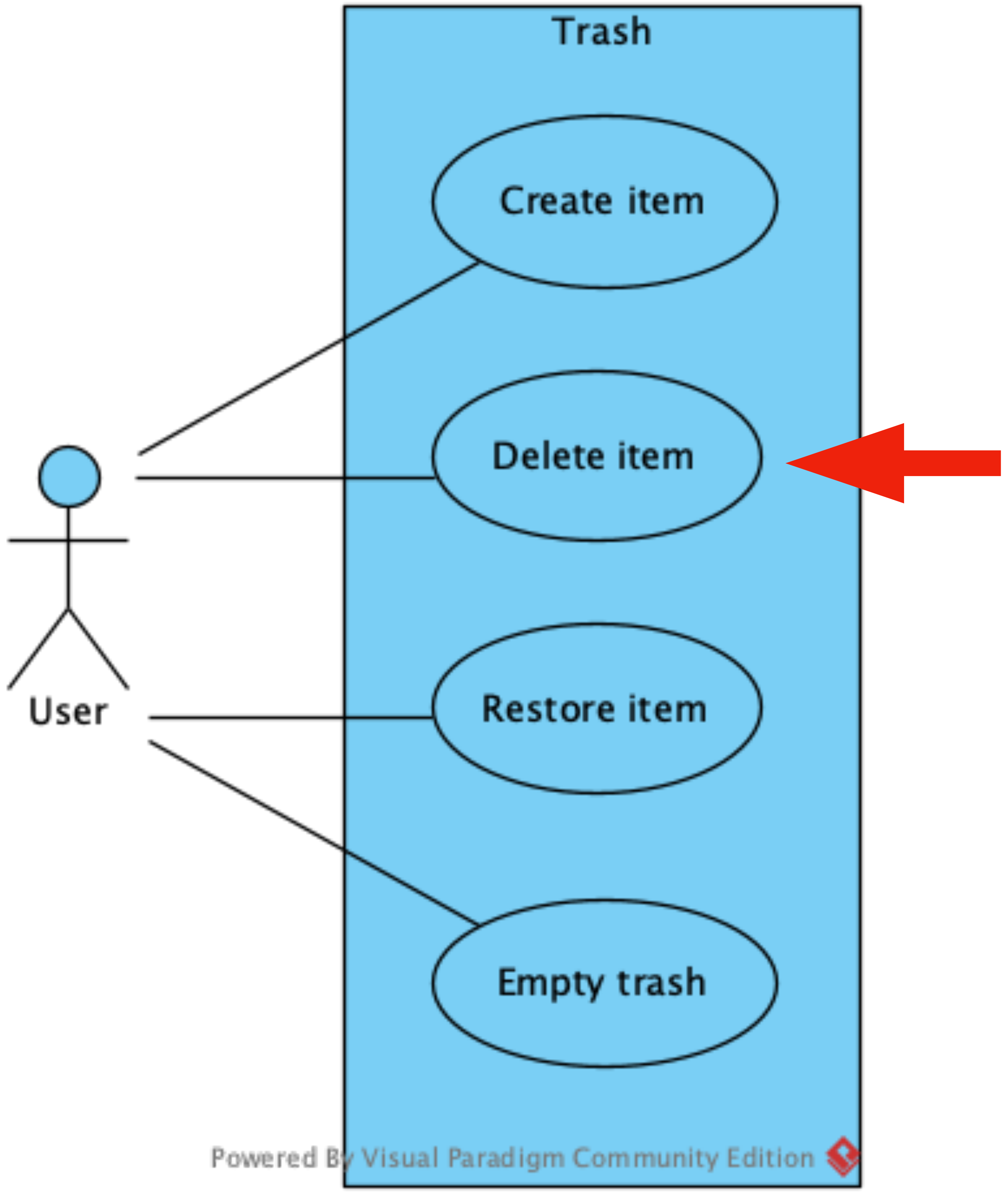
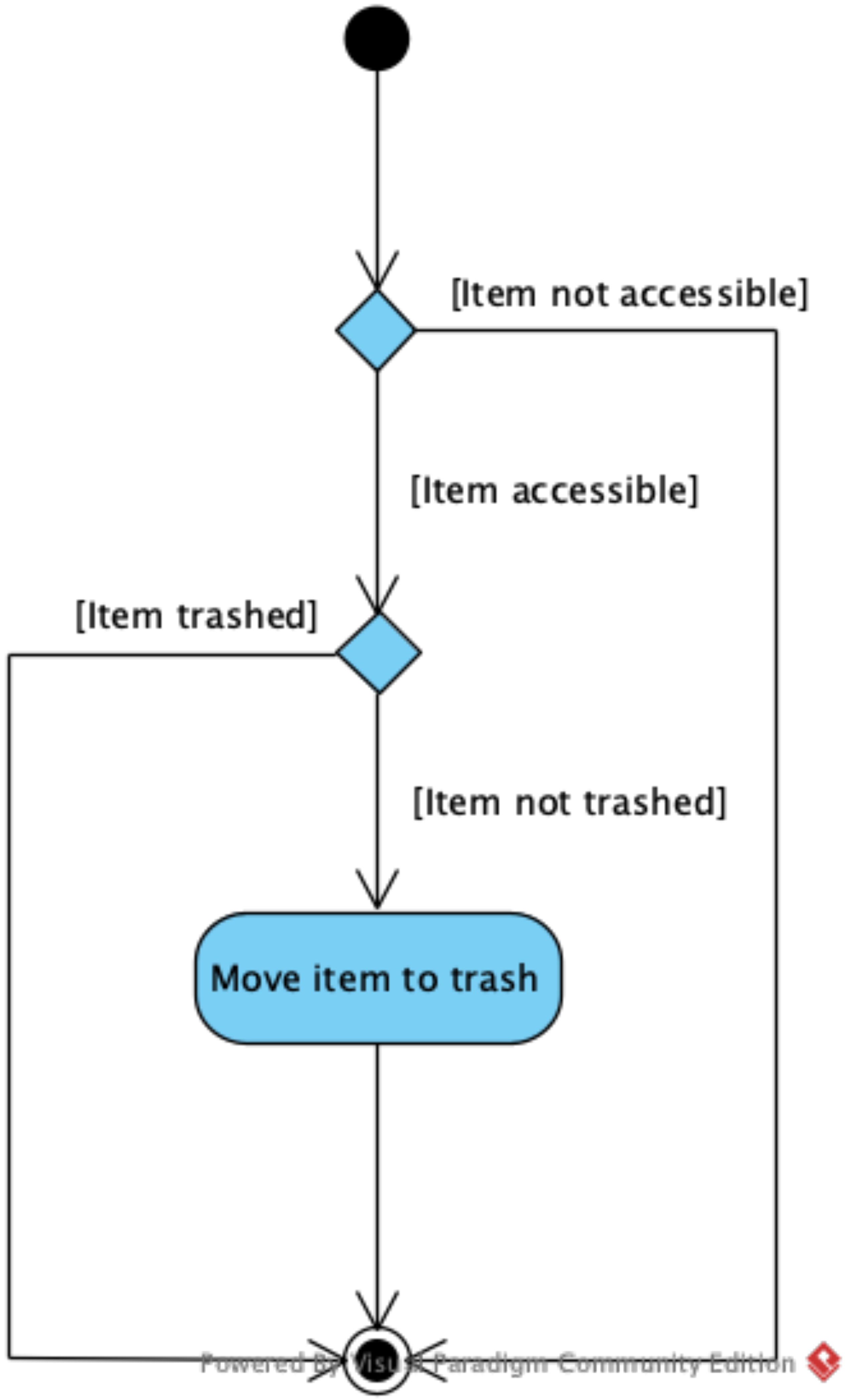
Trash modeling *à la* UML

Trash modeling *à la* UML



Trash modeling *à la* UML





Trash modeling *à la* Jackson

```
concept trash [Item]
purpose
  to allow undoing of deletions
state
  accessible, trashed : set Item
actions
  create (x : Item)
    when x not in accessible or trashed
    add x to accessible
  delete (x : Item)
    when x in accessible but not trashed
    move x from accessible to trashed
  restore (x : Item)
    when x in trashed
    move x from trashed to accessible
  empty ()
    when some item in trashed
    remove every item from trashed
operational principle
  after delete(x), can restore(x) and then x in accessible
  after delete(x), can empty() and then x not in accessible or trashed
```

Concept modeling *à la* Jackson

- Name
  - Optionally parametrized by types that can be specialized when composing
- Purpose
  - A clear reason why you might want it
- State + Actions
  - A description of the concept behavior using a *transition system*
- Operational principle
  - Properties that show how the purpose is fulfilled by the actions

Transition systems

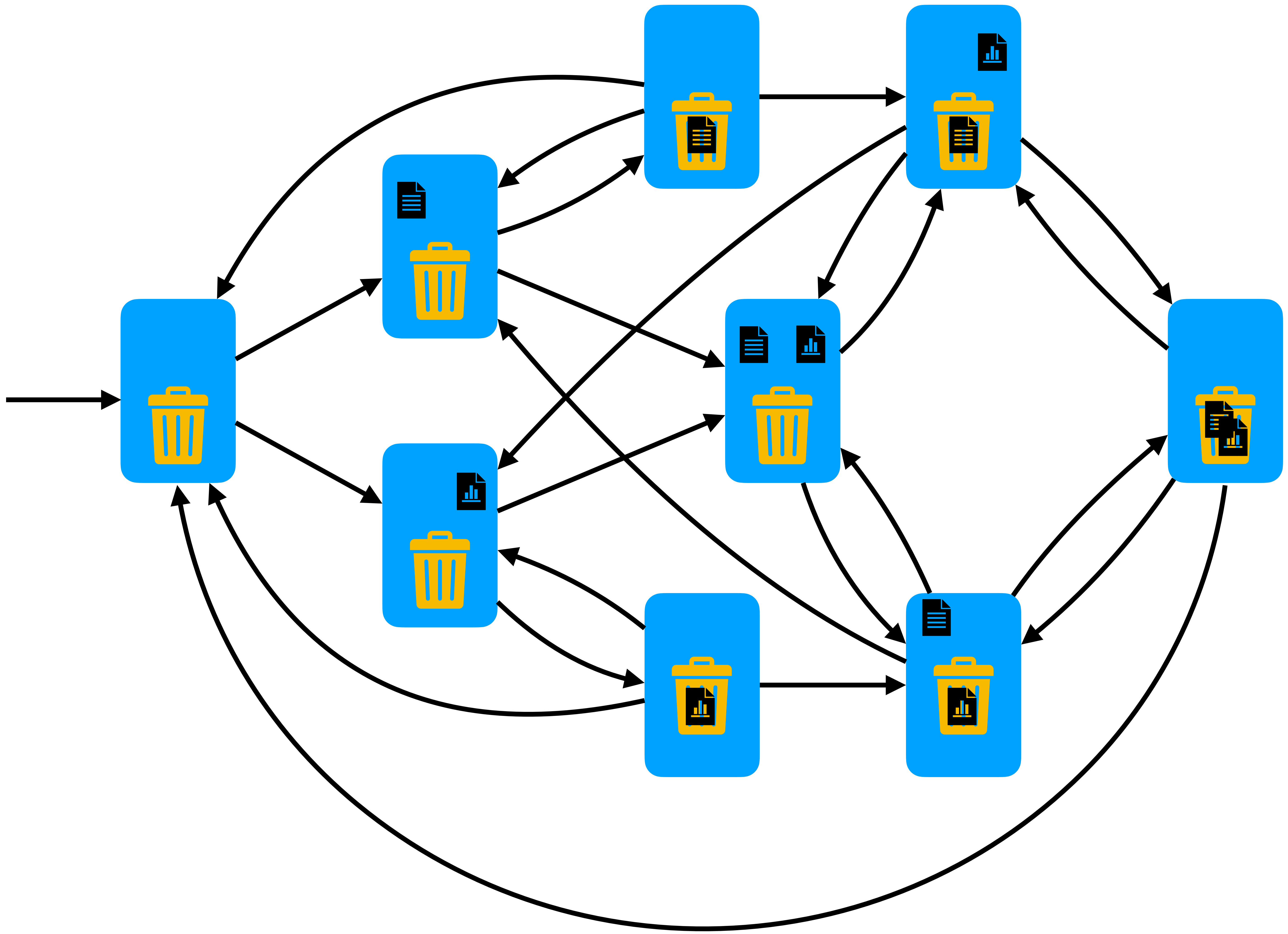
Transition systems

- A popular model to describe the behavior of a system
- A *model* is often a synonym for a transition system
- There are many variants and related formalisms
  - Labeled transition systems
  - Kripke structures
  - Finite state machines
  - Hybrid and timed automata
  - ...

States, transitions, and traces

- States
  - A *state* is a possible valuation to the structures of the system
  - *Initial* states describe how the system starts
- Transitions
  - A *transition* is a possible evolution between states
  - Transitions originate from actions of the system or the environment
- Traces
  - A *trace* is a sequence of states, describing a possible execution
  - A valid trace in a transition system is a path starting in an initial state

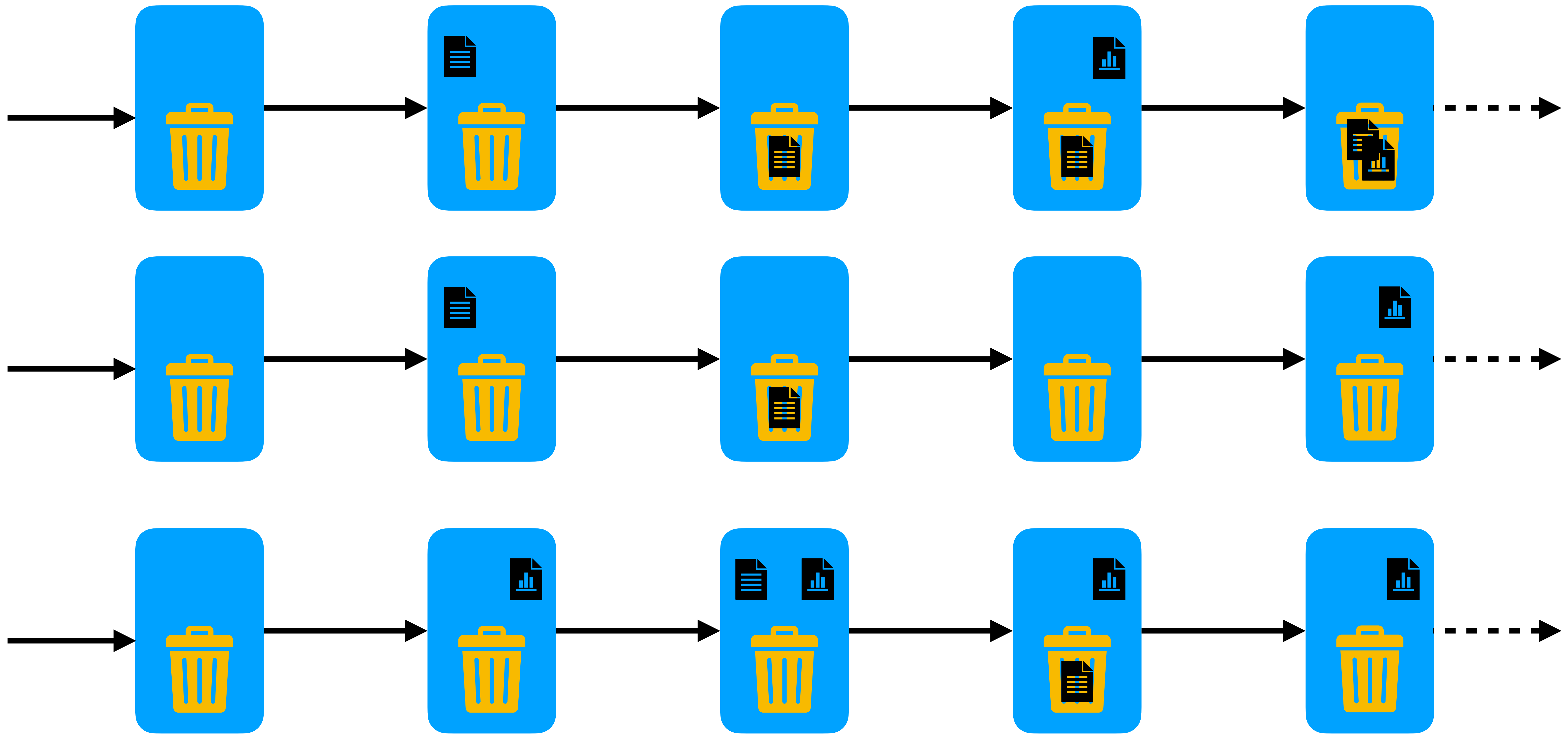
Trash transition system



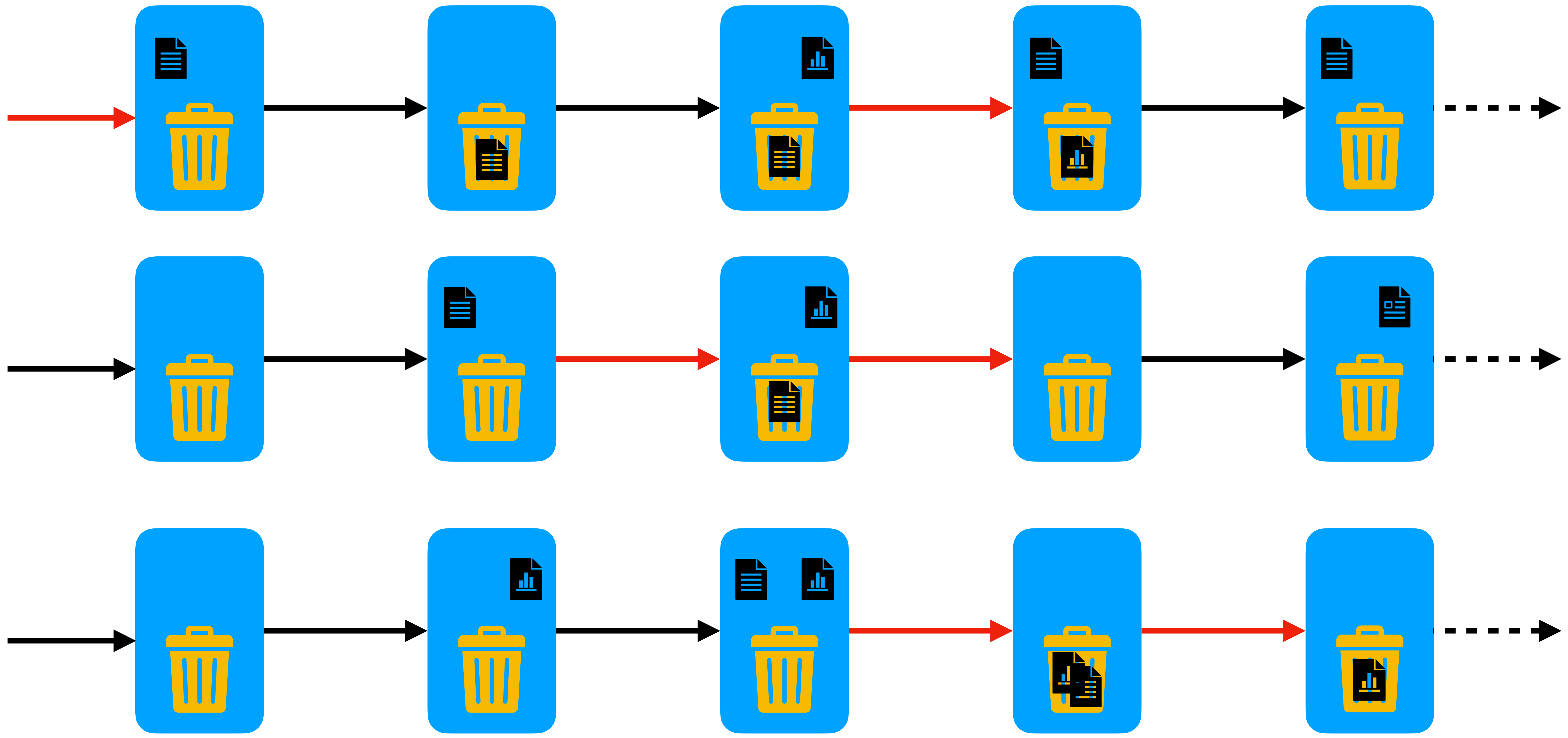
Declarative modeling

- It is possible to describe a transition system by specifying instead which are its valid traces
- This requires specifying a property whose validity is established in a trace and not just in a single state
- The specification of properties about traces requires some sort of *temporal logic*

Valid trash traces



Invalid trash traces



Specifying transition systems

Mutability

- In Alloy 6 mutable signatures and fields can be declared with keyword **`var`**
- Warnings are thrown when:
  - Static field inside mutable signature
  - Static signature extending or subset of a mutable signature

Trash states

```
sig Item {}
var sig Accessible in Item {}
var sig Trashed in Item {}
```

Instances

- When mutable structures are declared, instances become **infinite** *traces*
- Analysis commands only return traces that can be represented finitely
  - Traces that loop back at some point
- Static signatures and fields are known as the *configuration* and have the same value in all states
- If there are mutable top-level signatures, **`univ`** (and **`iden`**) are also mutable

Temporal logic

- Alloy 6 also supports linear *temporal logic*
- Temporal logic adds *temporal operators* to relational logic
- Allow “quantifying” the validity of a formula over different states of a trace
- A formula without temporal operators refers to the *first* state
- Alloy 6 has both *future* and *past* temporal operators
- Also has the *prime* operator to retrieve the value of a term in the next state

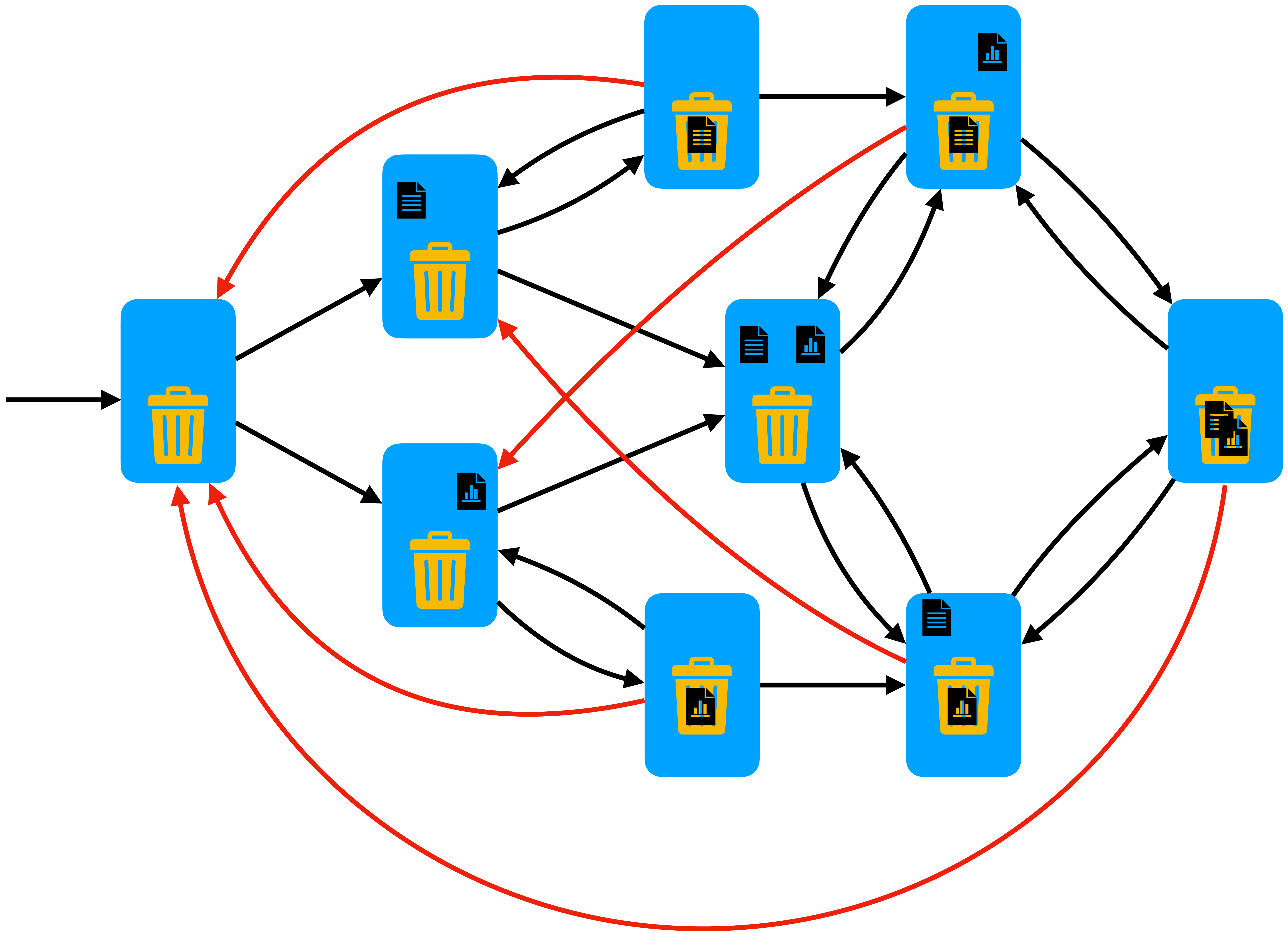
Always, eventually, and prime

`always` ϕ	ϕ is true in all future states
`eventually` ϕ	ϕ is true in some future state
R`'`	The value of R in the next state

Actions

- A set of transitions can be specified declaratively with an *action*
- An action is a formula without temporal operators, referring to primed and unprimed variables
  - A condition without primed variables is a *guard* that specifies when is the action enabled
  - A condition with a primed variable is an *effect* that specifies what are the possible values for that variable after the action occurs
  - If a variable does not change, a *frame condition* should be included stating that the next value of the variable remains the same
- By combining actions with the **always** temporal operator we can specify a system behavior
- Actions were first introduced by Leslie Lamport in the *Temporal Logic of Actions*

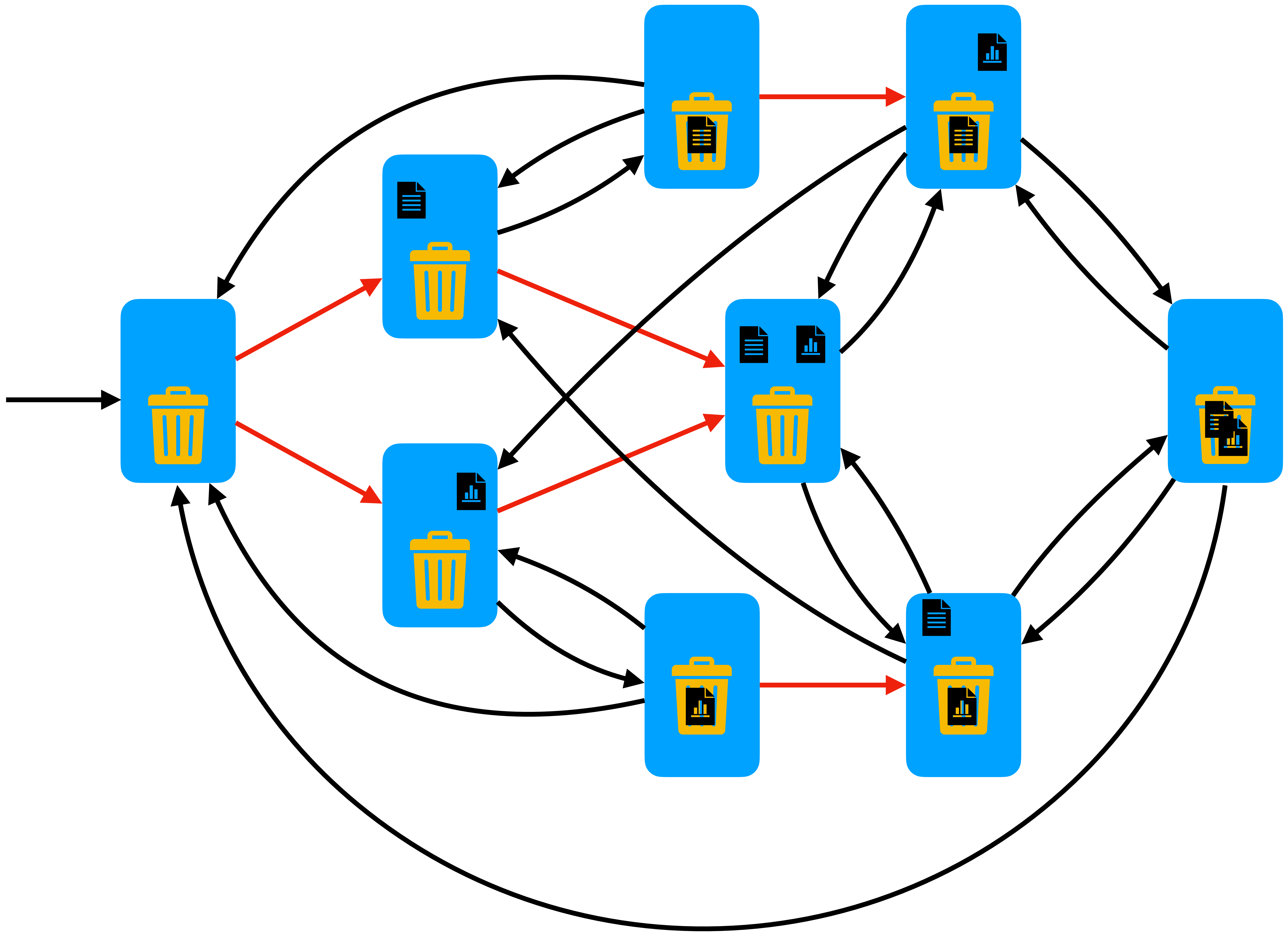
Empty trash



Empty trash

```
pred empty {
  // guard
  some Trashed
  // effect
  no Trashed'
  // frame condition
  Accessible' = Accessible
}
```

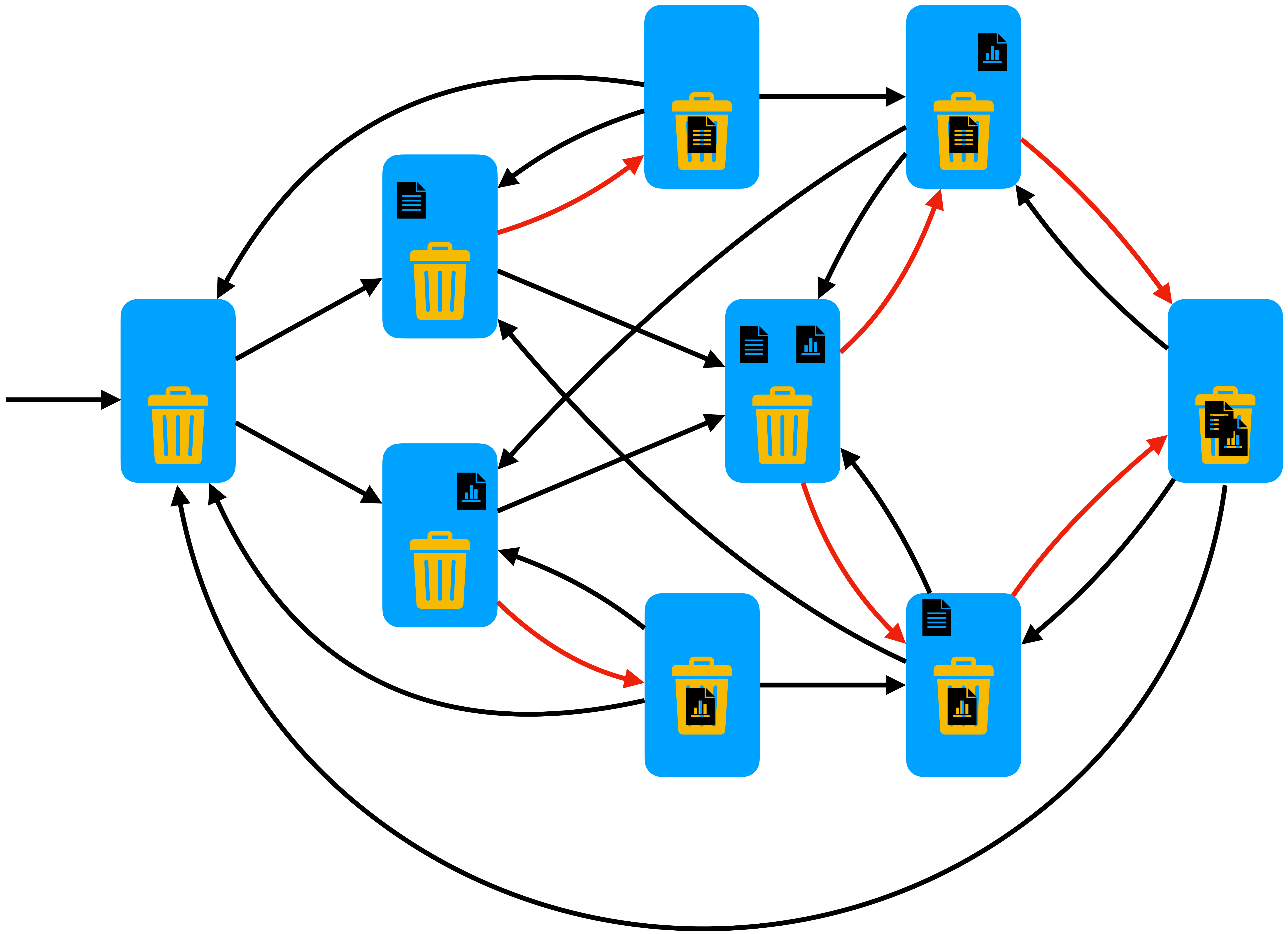
Create item



Create item

```
pred create[i : Item] {
  // guard
  i not in Accessible + Trashed
  // effect
  Accessible' = Accessible + i
  // frame condition
  Trashed' = Trashed
}
```

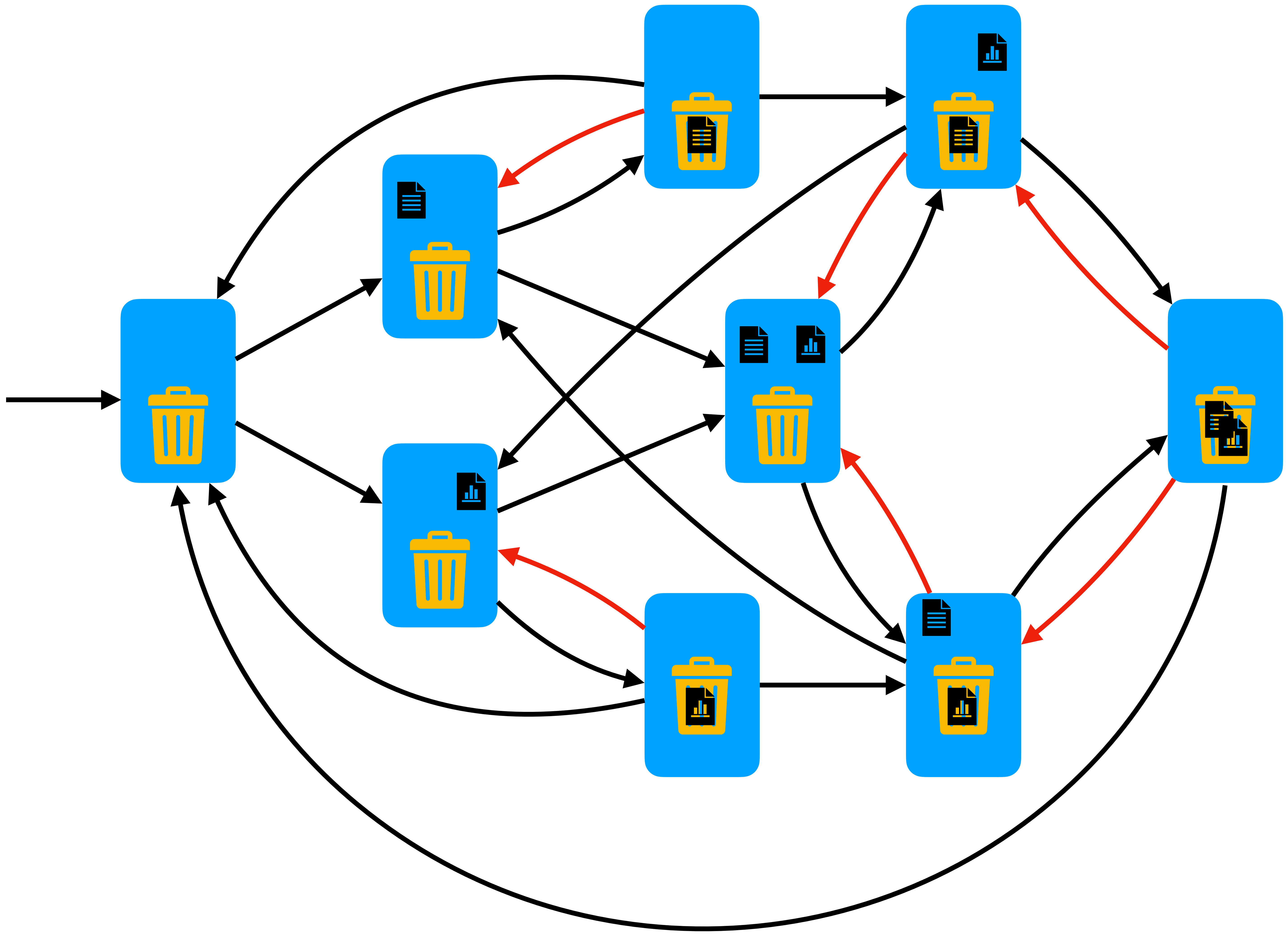
Delete item



Delete item

```
pred delete[i : Item] {
  // guard
  i in Accessible
  // effects
  Accessible' = Accessible - i
  Trashed' = Trashed + i
}
```

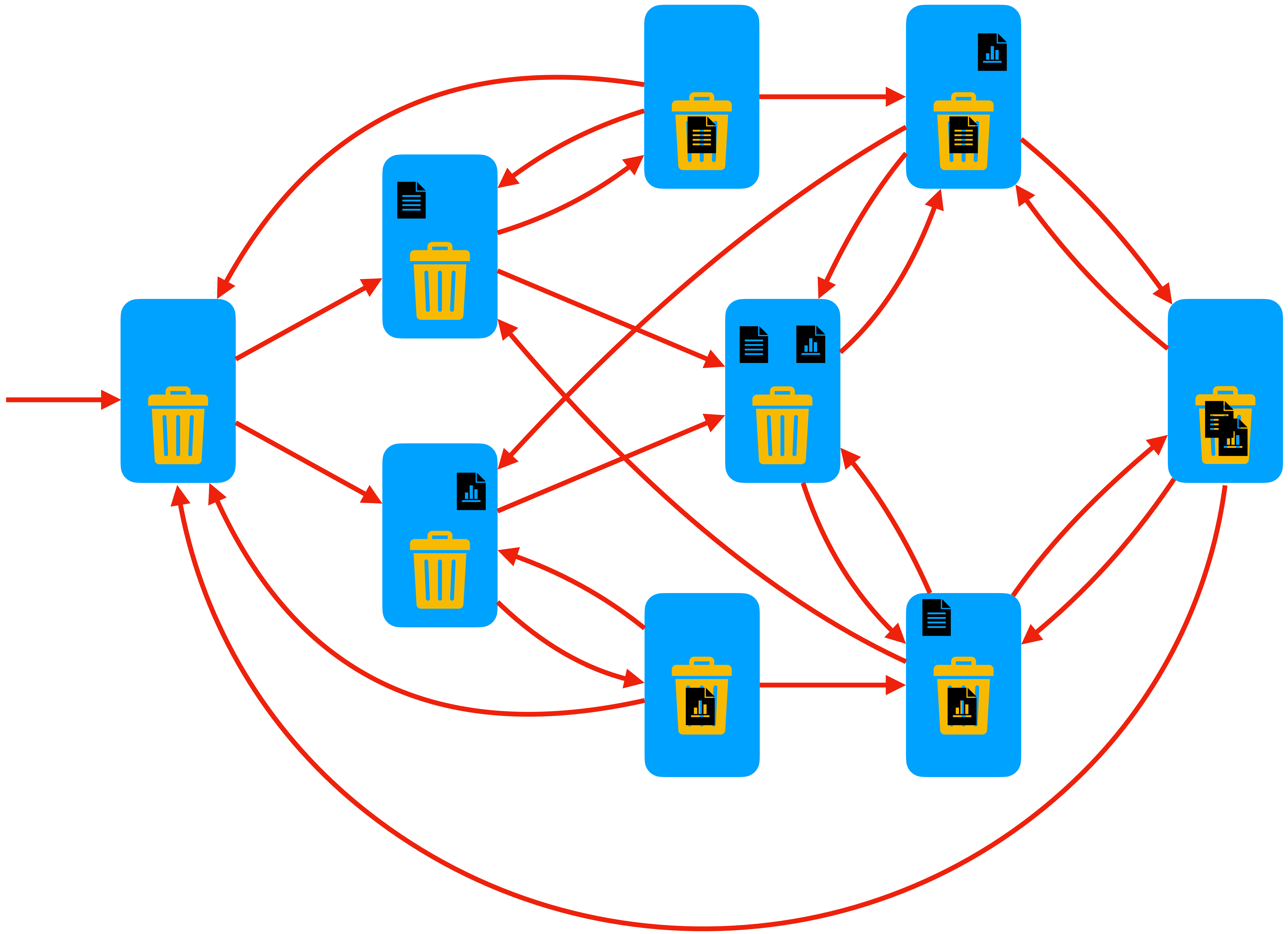
Restore item



Restore item

```
pred restore[i : Item] {
  // guard
  i in Trashed
  // effects
  Accessible' = Accessible + i
  Trashed' = Trashed - i
}
```

Trash behavior



Trash behavior

```
fact Behavior {
  // initial state
  no Accessible
  no Trashed
  // possible transitions
  always {
    (some i : Item | create[i] or delete[i] or restore[i])
    or
    empty
  }
}
```

Validation

Run commands

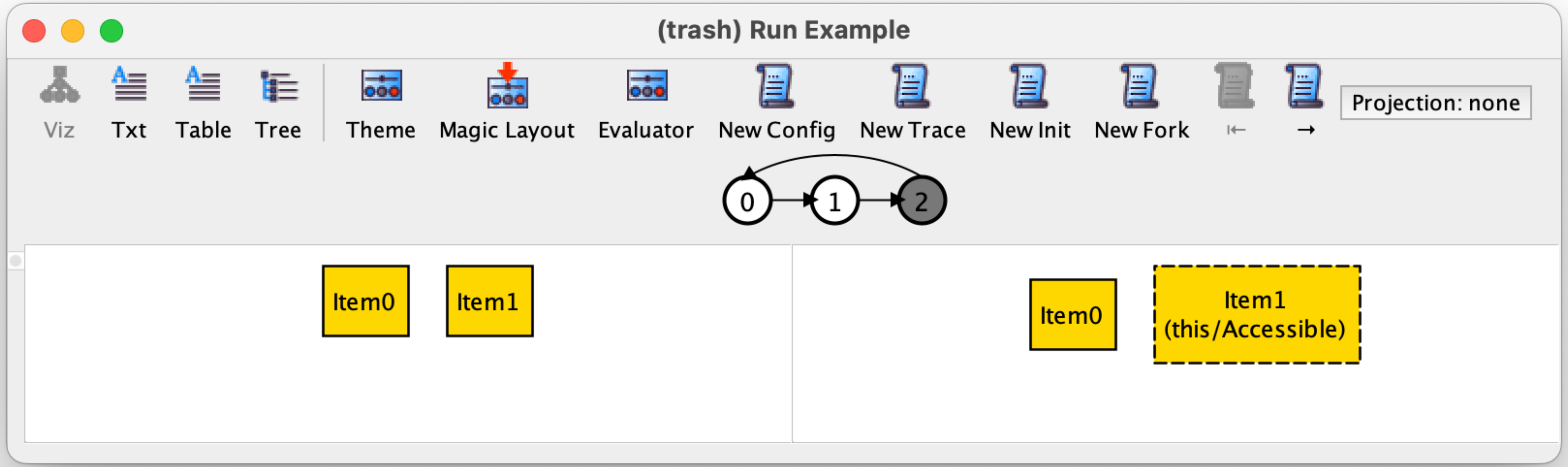
- As usual, **`run`** commands can be used to validate the model
- The scope of a mutable signature defines the maximum number of different atoms in the full trace, not a maximum per state

Trace visualization

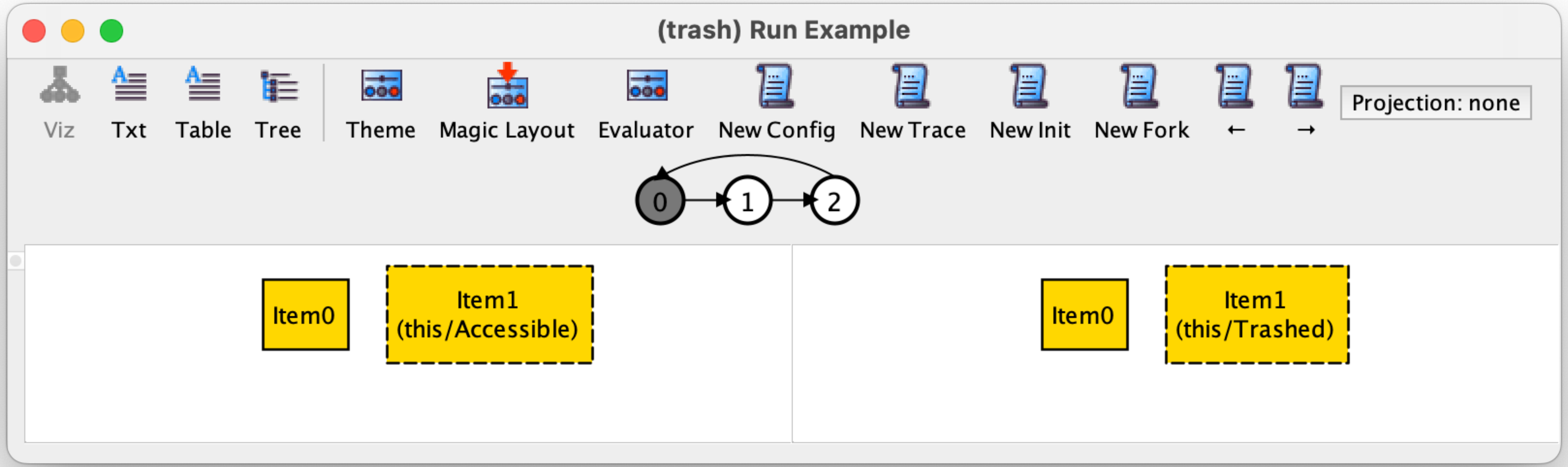
- The visualizer depicts two consecutive states of the trace side-by-side
    - By default mutable structures are depicted with dashed lines
- A representation of the infinite trace is shown on top
    - Different states have different numbers
    - The loop back is explicitly depicted
    - Clicking on a state focus on that (and the succeeding) state
    - It is possible to move forwards and backwards in the trace with → and ←

Trace visualization

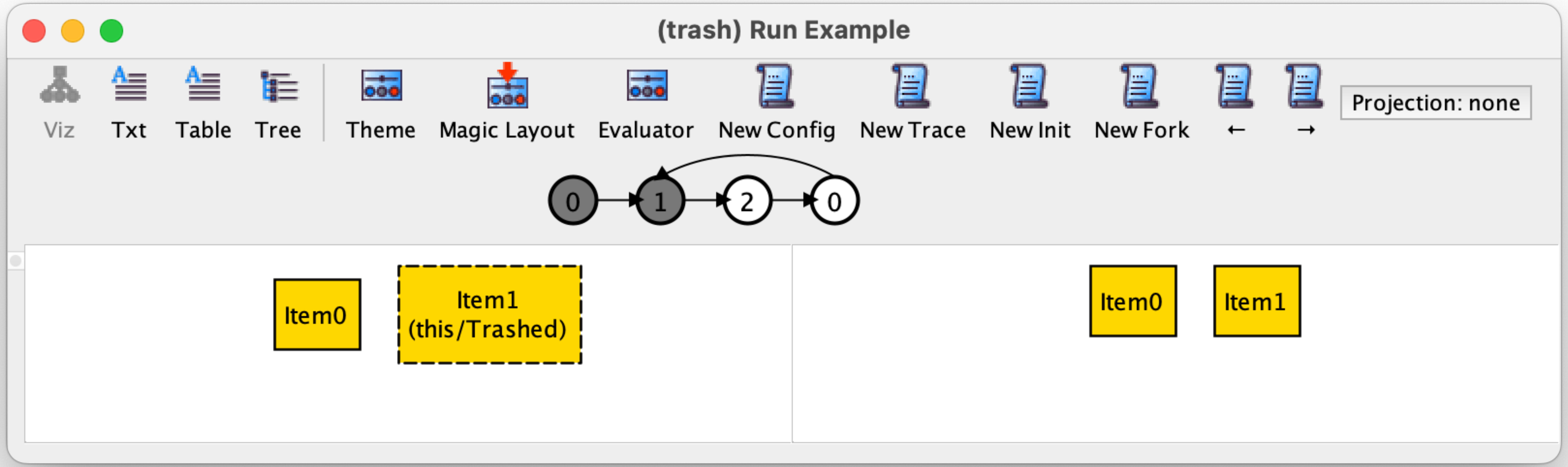
Trace visualization



Trace visualization



Trace visualization



Simulation

- It possible to perform “simulation” with the *New* instance buttons
  - *New config*, returns a trace with a different configuration (a different value for the immutable structures)
  - *New trace*, returns any different trace with the same configuration
  - *New init*, returns a trace with the same configuration, but a different initial state
  - *New fork*, returns a trace with the same prefix, but a different next state (at the focused transition)

Simulation

DEMO

Specifying scenarios

- A formula can be given in a **`run`** command to look for specific scenarios
- Keyword **`expect`** can be used to distinguish positive and negative scenarios

Semi-colon

$\phi \;\; \mathtt{;} \;\; \psi$

ψ is valid after ϕ

Some trash scenarios

```
run Scenario1 {
  some i : Item {
    create[i]; delete[i]; restore[i]; delete[i]; empty
  }
} expect 1

run Scenario2 {
  some disj i,j : Item {
    create[i]; delete[j]
  }
} expect 0

run Scenario3 {
  some i : Item {
    create[i]; delete[i]; empty
  }
} for 1 Item expect 1
```

Stuttering

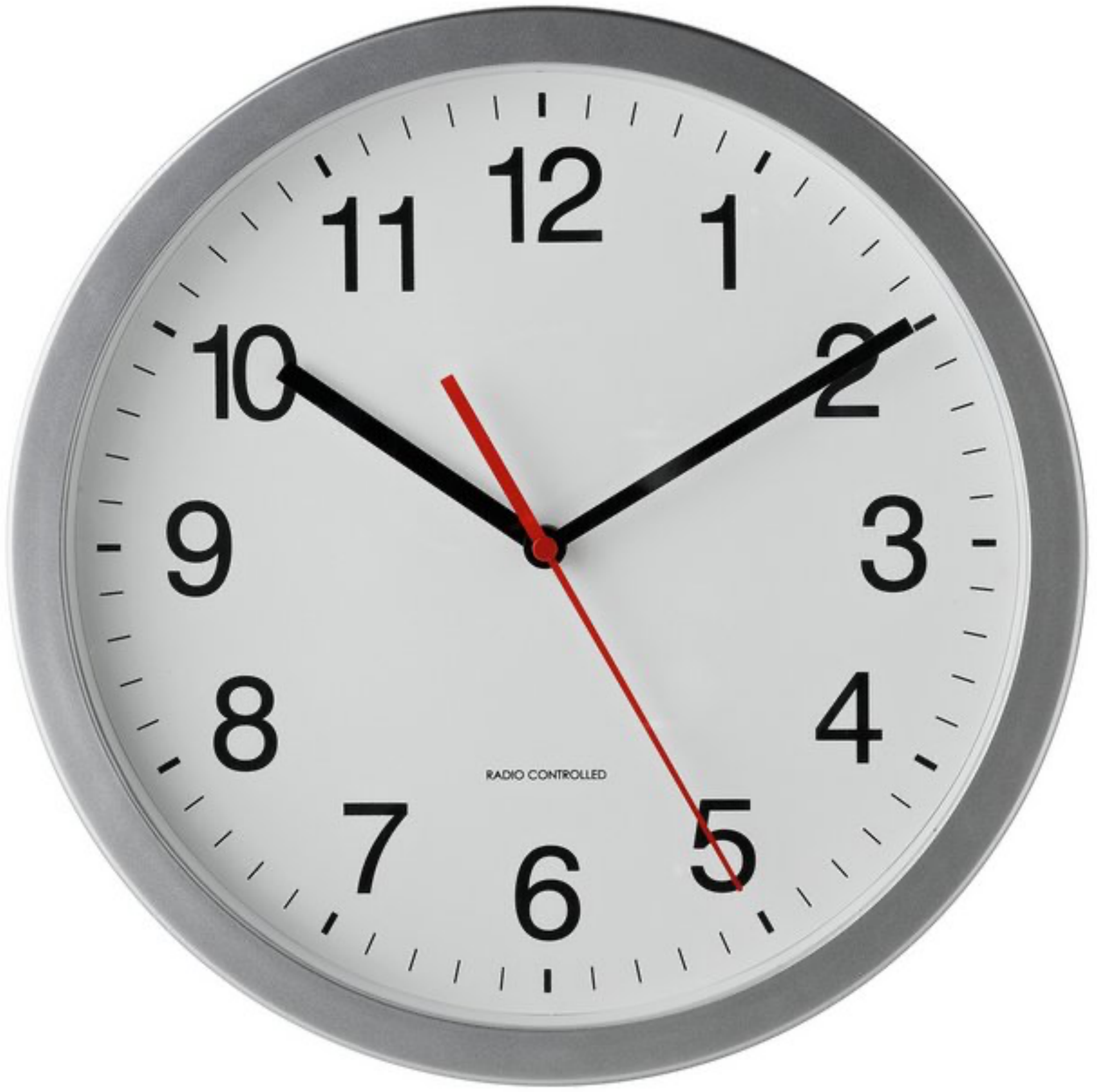
A clock specification

```
pred clock_spec {
  h = 12 and m = 0
  always {
    m'=(m+1)%60 and
    m=59 implies h'=(h%12)+1 else h'=h
 }
}
```

Ceci n'est pas une montre?!

```
check clock_spec
```

```
Executing "Check clock_spec"
   Solver=sat4j Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=20 Mode=batch
   1..2 steps. 55 vars. 12 primary vars. 59 clauses. 3ms.
   Counterexample found. Assertion is invalid. 3ms.
```



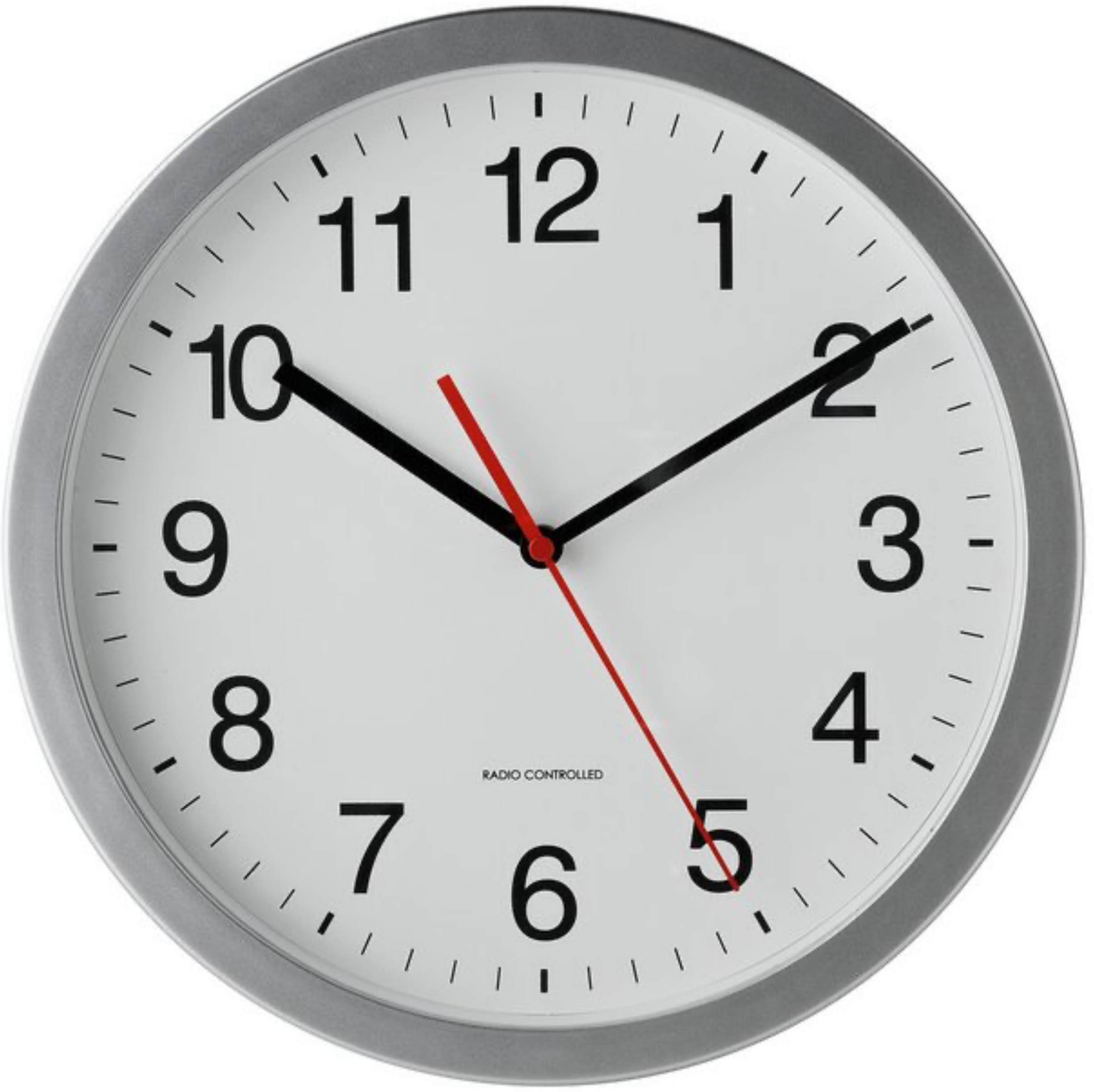
A clock specification

```
pred clock_spec {
  h = 12 and m = 0
  always {
    m’=(m+1)%60 and
    m=59 implies h’=(h%12)+1 else h’=h
    or
    m’=m and h’=h
  }
}
```

Another clock

```
check clock_spec
```

```
Executing "Check clock_spec"
   Solver=sat4j Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=20 Mode=batch
   1..10 steps. 151901 vars. 1875 primary vars. 413006 clauses. 1042ms.
   No counterexample found. Assertion may be valid. 298ms.
```



Stuttering

- *Stuttering* can represent events by the environment or by other components of the system (not yet modeled)
- Stuttering enables *refinement*
    - adding detail or new components to a system
    - namely, it enables concepts to be composed to build apps
- In terminating systems, stuttering enables traces to be infinite

Trash stuttering

```
pred stutter {
  Accessible' = Accessible
  Trashed' = Trashed
}
```

Trash behavior

```
fact Behavior {
  // initial state
  no Accessible
  no Trashed
  // possible transitions
  always {
    (some i : Item | create[i] or delete[i] or restore[i])
    or
    empty
    or
    stutter
  }
}
```

Verification

Model checking

- *Model checking* is the process of automatically verifying if a temporal logic specification holds in a finite transition system model of a system
  - If the specification is false a counter-example is returned
  - A finite transition system may have infinite non-looping traces
  - But every invalid specification can be falsified with a looping trace
- *Complete* or *unbounded* model checking explores all traces of the transition system
- *Bounded* model checking explores all traces up to a given maximum number of transitions before looping back

Verification

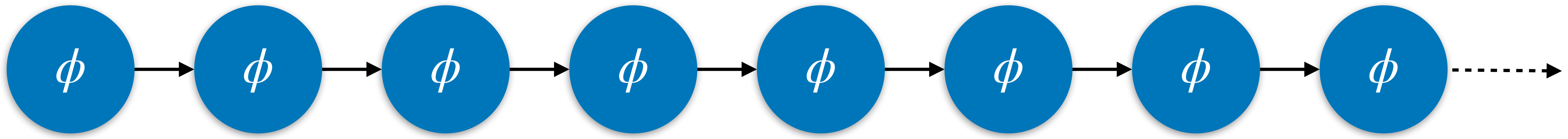
- **`check`** commands can be used to verify temporal assertions
- The default verification mechanism is bounded model checking
  - The default maximum number of transitions is 10
  - This can be changed by setting a scope for **`steps`**
- Alloy 6 also supports unbounded model checking
  - Activated by the special scope `1..` **`steps`**
  - Requires model checkers nuXmv or NuSMV to be installed

Future temporal operators

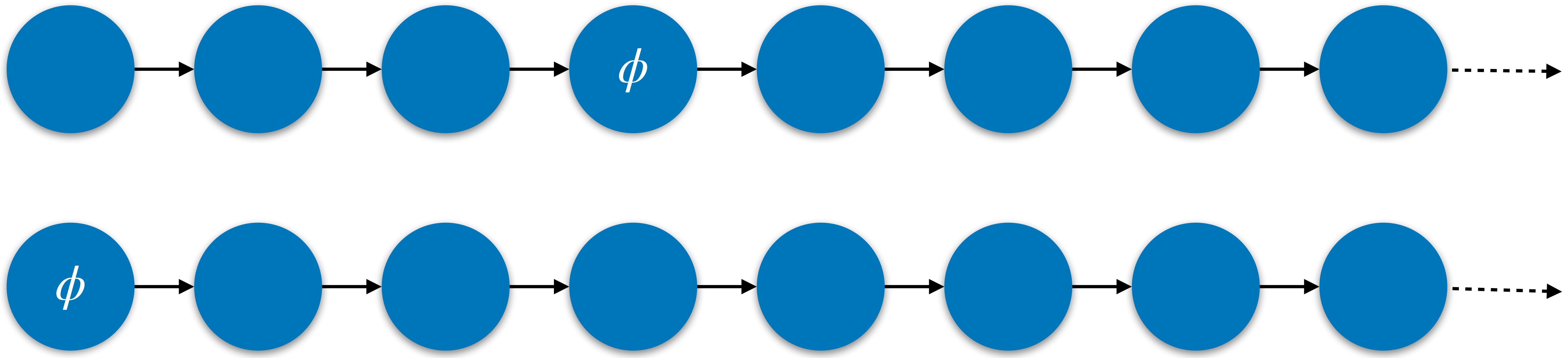
`always` ϕ	ϕ will always be true
`eventually` ϕ	ϕ will eventually be true
`after` ϕ	ϕ will be true in the next state
ψ **`until`** ϕ	ϕ will eventually be true and ψ is true until then
ϕ **`releases`** ψ	ψ can only stop being true after ϕ

Future operators

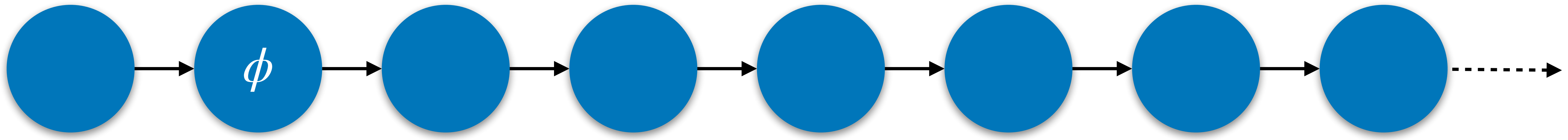
always ϕ



eventually ϕ

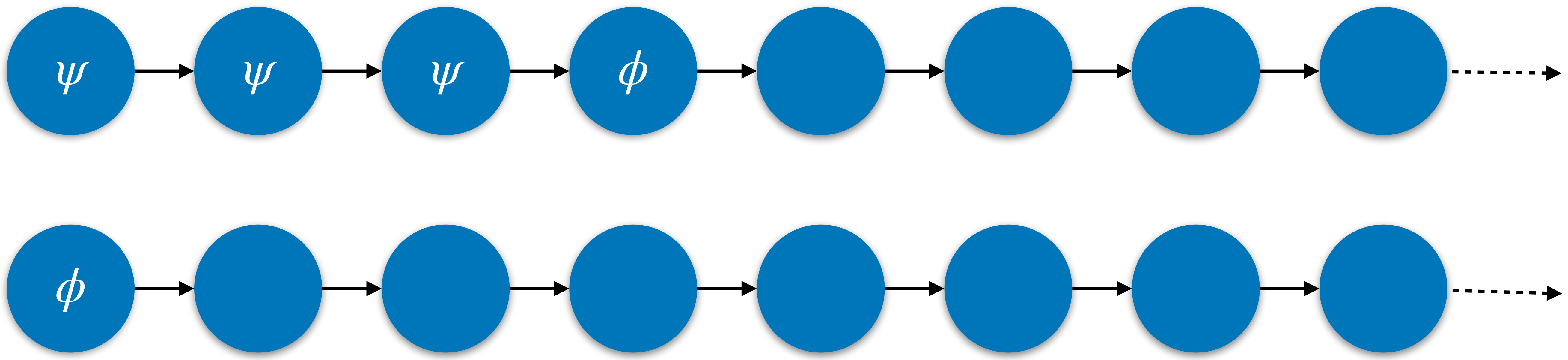


after ϕ

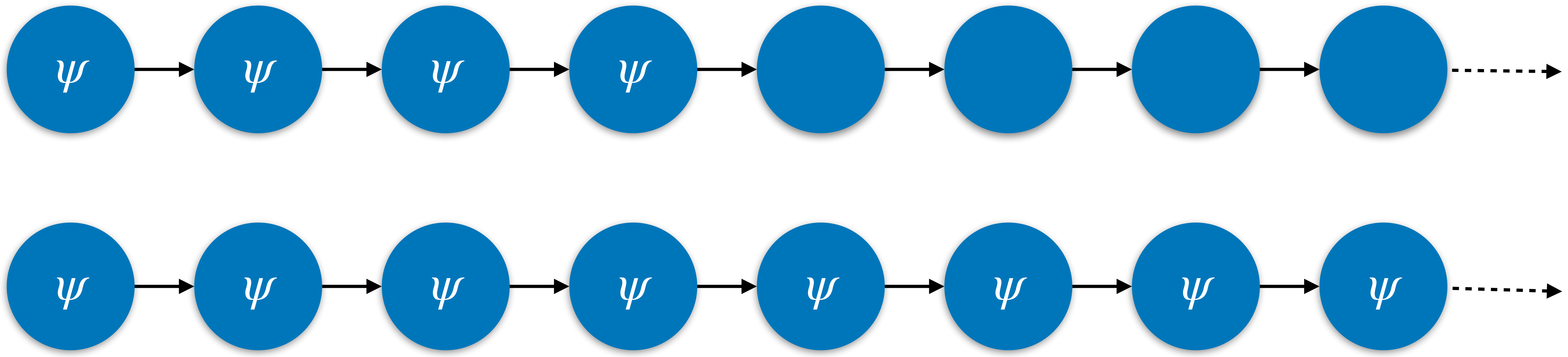


Future operators

ψ **until** ϕ

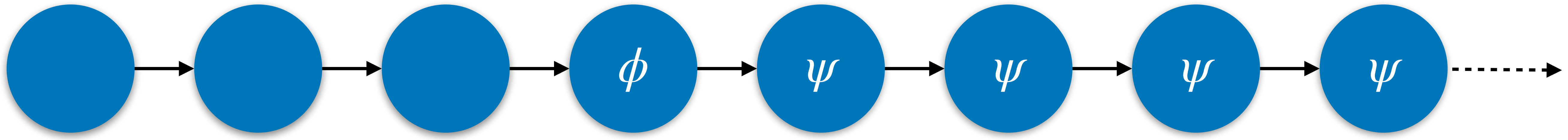


ϕ **releases** ψ

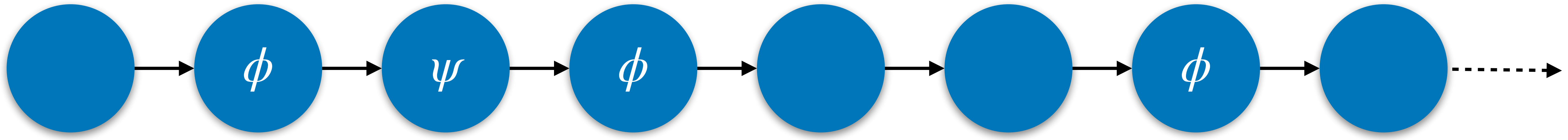


Mixing operators

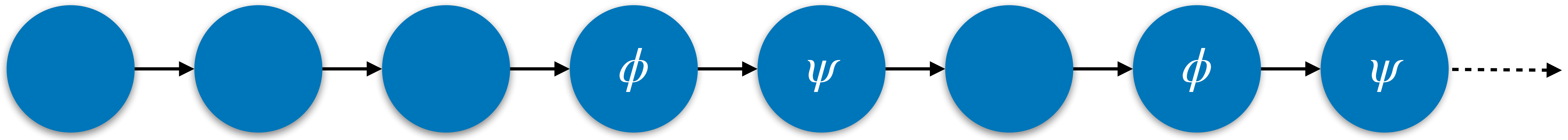
always (ϕ implies always ψ)



always (ϕ implies eventually ψ)

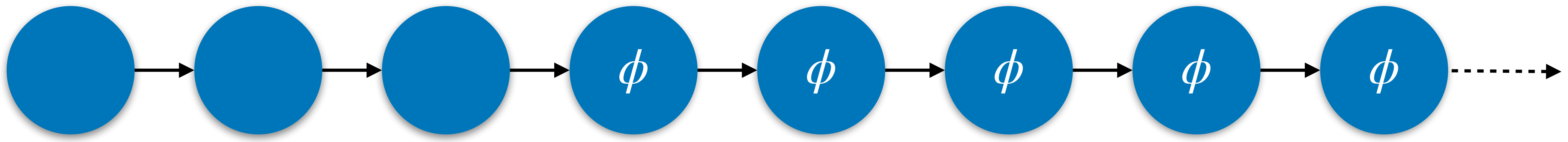


always (ϕ implies after ψ)

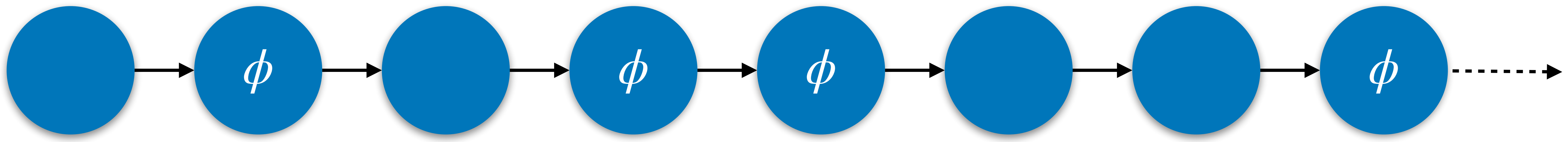


Mixing operators

`eventually (always` ϕ`)`



`always (eventually` ϕ`)`

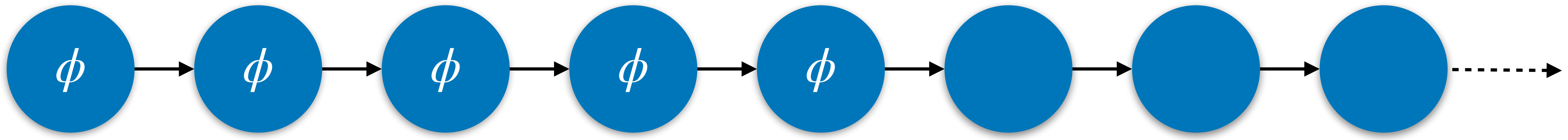


Past temporal operators

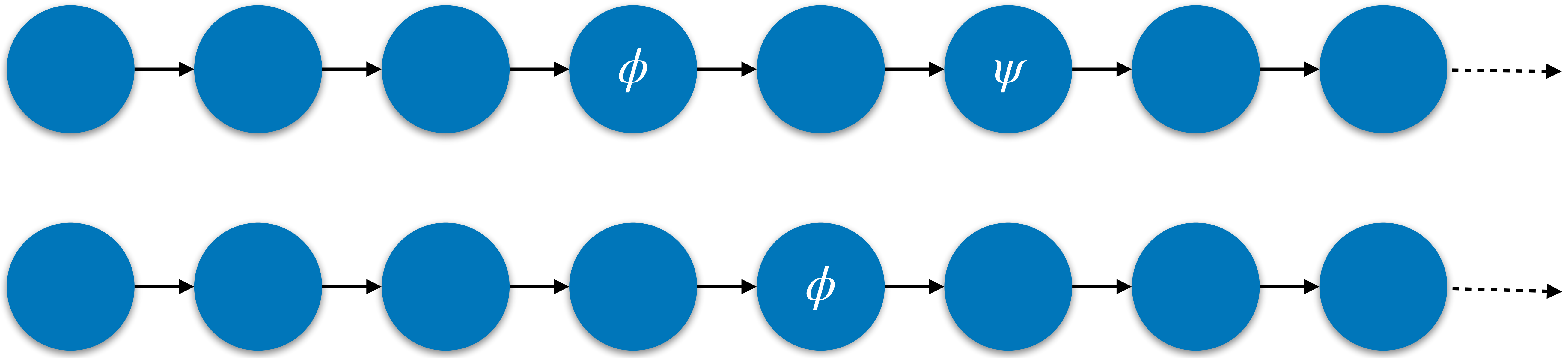
`historically` ϕ	ϕ was always true
`once` ϕ	ϕ was once true
`before` ϕ	ϕ was true in previous state
ψ **`since`** ϕ	ϕ was once true and ψ was true since then
ϕ **`triggered`** ψ	ψ was always true back to the point where ϕ was true

Past operators

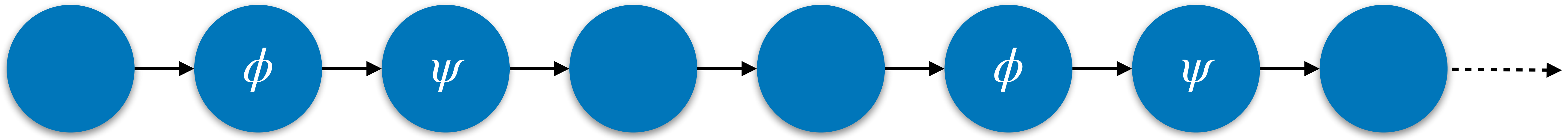
always (ψ implies historically ϕ)



always (ψ implies once ϕ)

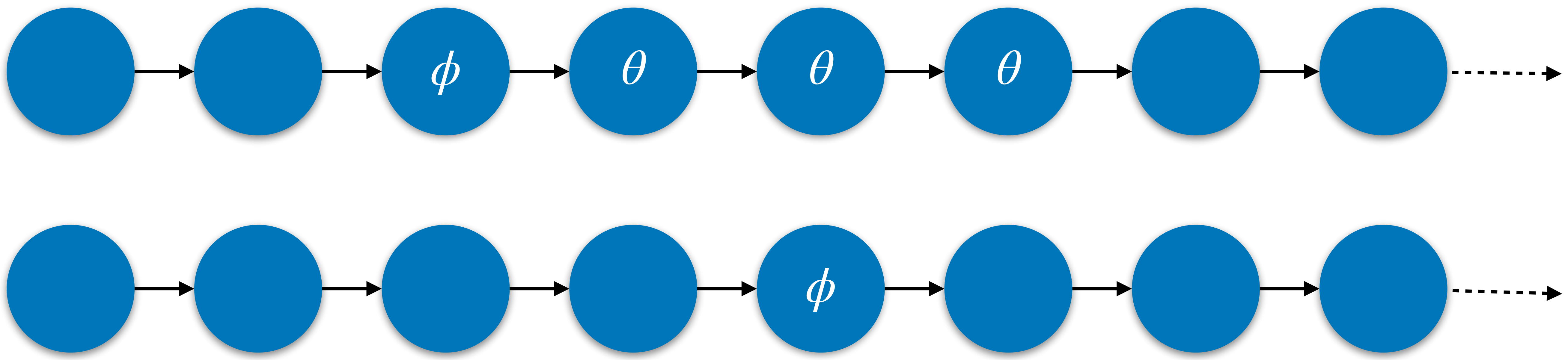


always (ψ implies before ϕ)

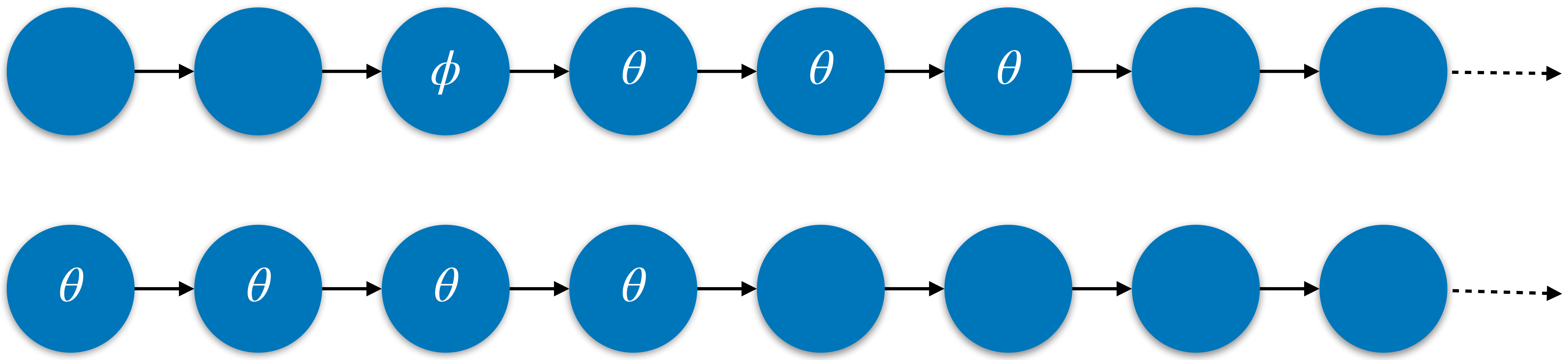


Past operators

always (ψ **implies** θ **since** ϕ)



always (ψ **implies** ϕ **triggered** θ)



Safety properties

- *Safety* properties prevent some undesired behaviors from happening
    - Easier to model check, since it suffices to search for a finite sequence of steps that leads to a bad state
    - It is irrelevant what happens afterwards, any continuation leads to a counter-example
    - The archetypal safety property is an *invariant* specified as **`always`** ϕ

Liveness properties

- *Liveness* properties force some desired behaviors to happen
  - Harder to model check, since it is necessary to search for a complete infinite trace where the desired behavior never happens
  - Harder to specify, since they require fairness assumptions that prevent the system from stuttering forever
  - The archetypal liveness property is **`eventually`** ϕ

Some operational principles

```
check invariant {
    // No item can simultaneously be accessible and trashed
    always no Accessible & Trashed
}
check restore_after_delete {
    // A restore is only possible after a delete
    all x : Item | always (restore[x] implies once delete[x])
}
check accessible_after_delete {
    // A deleted item only becomes accessible again after being restored or created
    all x : Item | always {
        delete[x] implies after {
            (restore[x] or create[x]) releases x not in Accessible
        }
    }
}
```

The key operational principles

```
pred can_restore[x : Item] { x in Trashed }
check delete_restore {
    // After delete(x), can restore(x) and then x in accessible
    all x : Item | always {
        delete[x] implies after can_restore[x]
        (delete[x]; restore[x]) implies x in Accessible''
    }
} for 4 Item, 20 steps

pred can_empty { some Trashed }
check delete_empty {
    // After delete(x), can empty() and then x not in accessible or trashed
    all x : Item | always {
        delete[x] implies after can_empty
        delete[x] and after empty implies x not in (Trashed+Accessible)''
    }
} for 4 Item, 20 steps
```

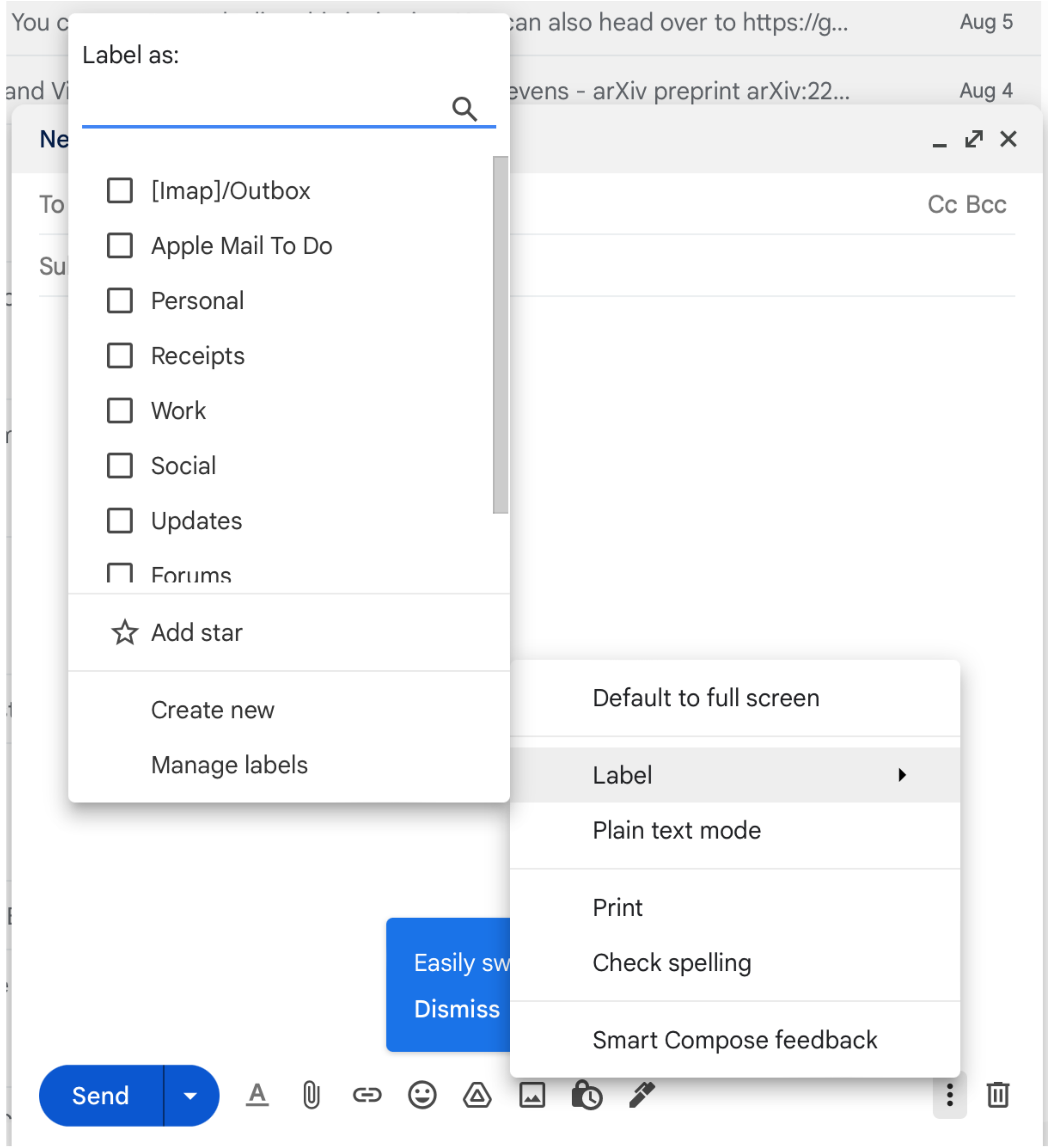
Verification

```
8 commands were executed. The results are:
   #1: Instance found. Scenario1 is consistent, as expected.
   #2: No instance found. Scenario2 may be inconsistent, as expected.
   #3: Instance found. Scenario3 is consistent, as expected.
   #4: No counterexample found. invariant may be valid.
   #5: No counterexample found. restore_after_delete may be valid.
   #6: No counterexample found. accessible_after_delete may be valid.
   #7: No counterexample found. delete_restore may be valid.
   #8: No counterexample found. delete_empty may be valid.
```

Another *concept*

Label

Label



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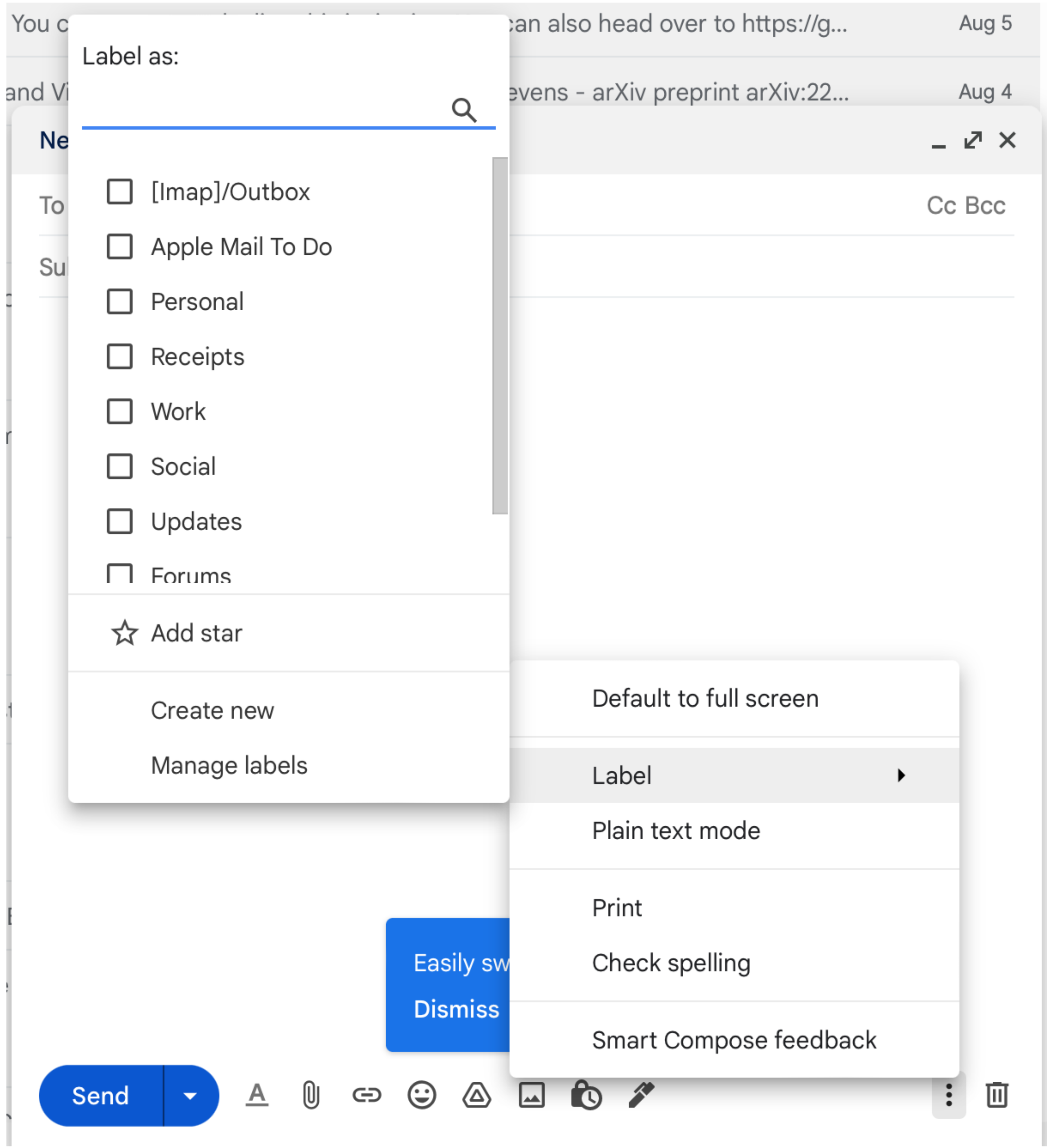
Label


Label as:
[Imap]/Outbox
Apple Mail To Do
Personal
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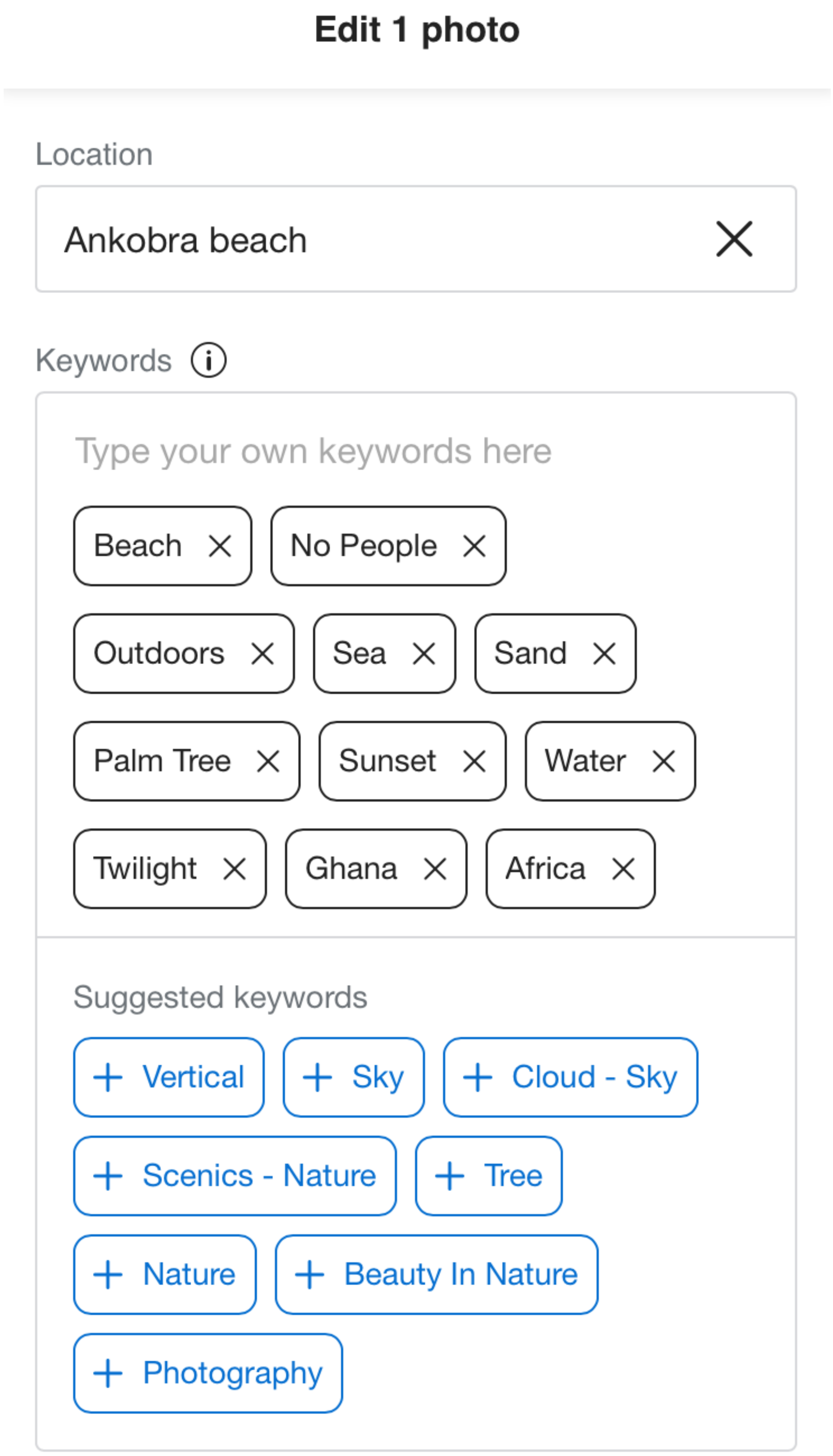
Edit 1 photo
Location
Ankobra beach
Keywords
Type your own keywords here
Beach
No People
Outdoors
Sea
Sand
Palm Tree
Sunset
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Twilight
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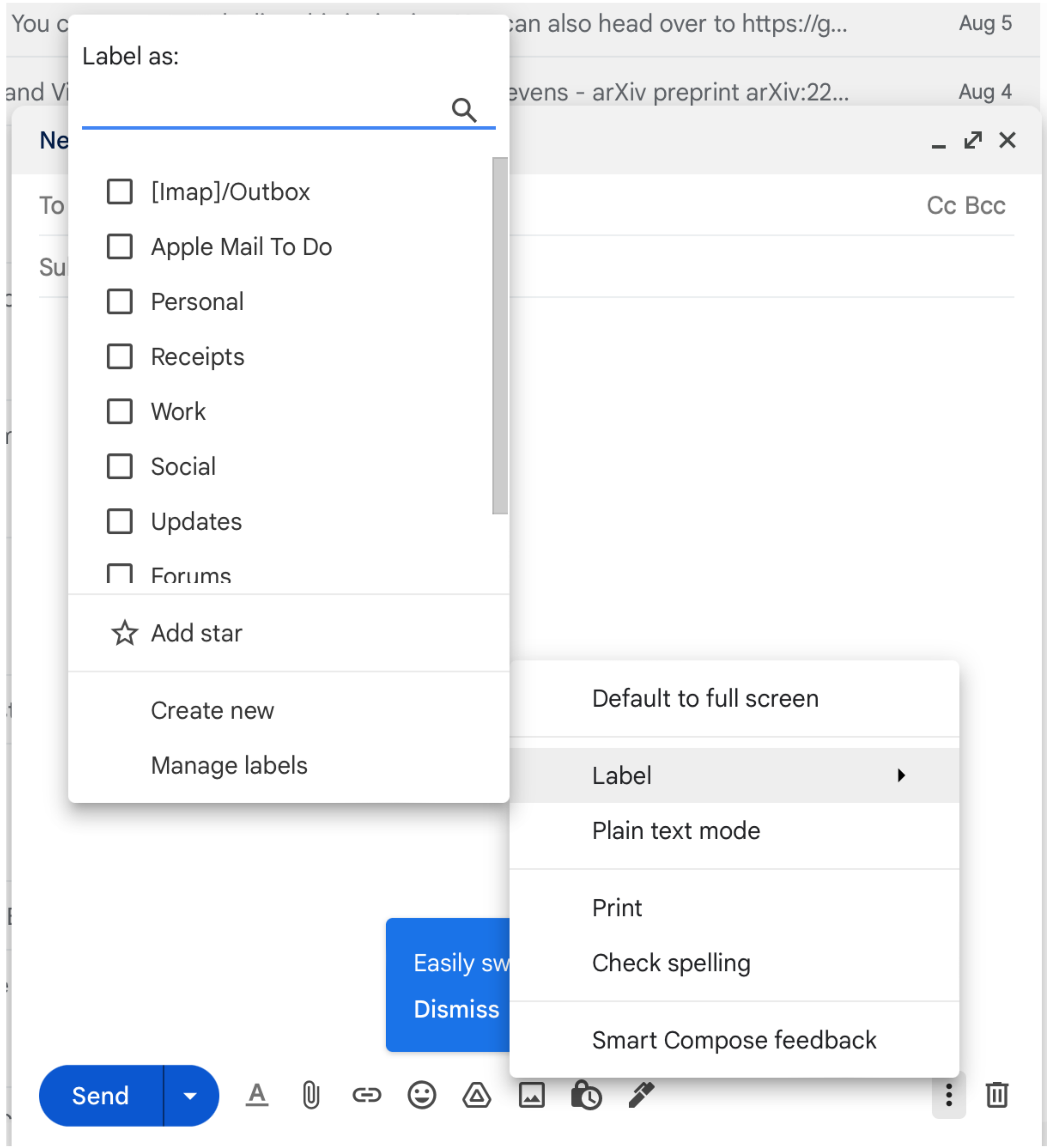
Africa
Suggested keywords
Vertical
Sky
Cloud - Sky
Scenics - Nature
Tree
Nature
Beauty In Nature
Photography

Label



Label as:
[Imap]/Outbox
Apple Mail To Do
Personal
Receipts
Work
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Updates
Forums
Add star
Create new
Manage labels
can also head over to https://g...
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Aug 4
Cc Bcc
Default to full screen
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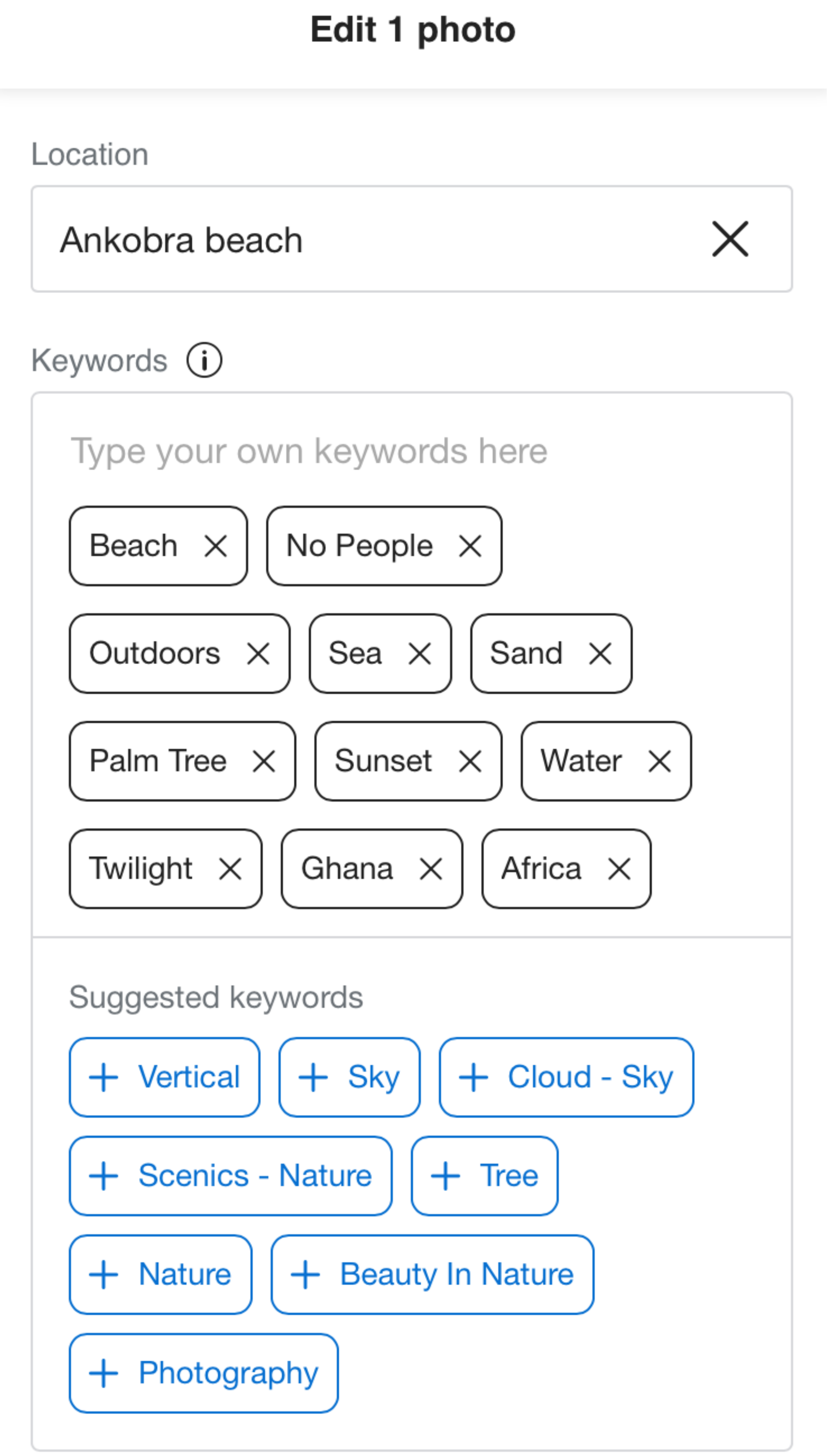

Edit 1 photo
Location
Ankobra beach
Keywords
Type your own keywords here
Beach
No People
Outdoors
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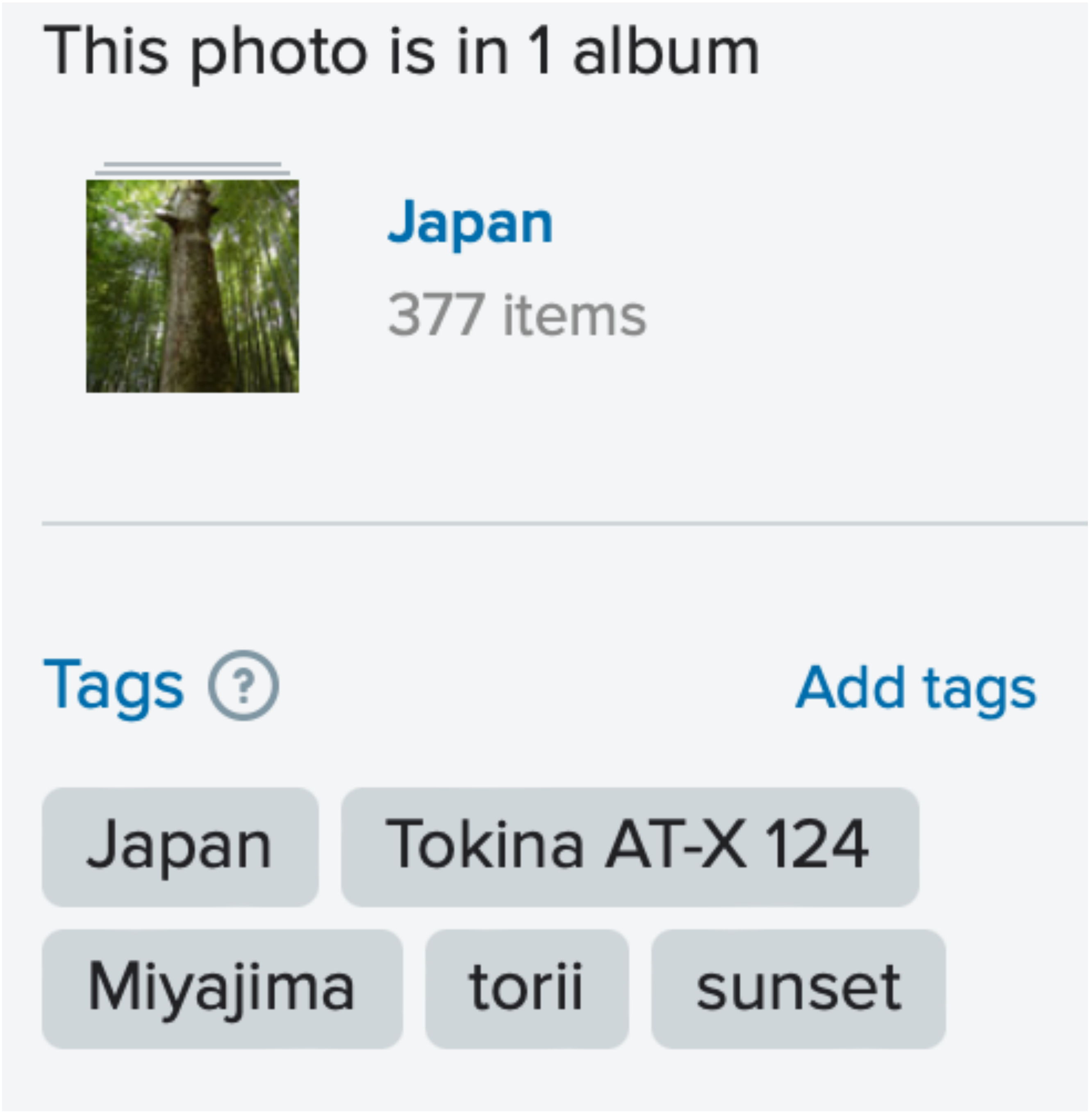
Sand
Palm Tree
Sunset
Water
Twilight
Ghana
Africa
Suggested keywords
Vertical
Sky
Cloud - Sky
Scenics - Nature
Tree
Nature
Beauty In Nature
Photography



This photo is in 1 album
Japan
377 items
Tags
Add tags
Japan
Tokina AT-X 124
Miyajima
torii
sunset

Label modeling *à la* Jackson

```
concept label [Item]
purpose
  organize items into overlapping categories
state
  labels : Item -> set Label
actions
  affix (i : Item, l : Label)
    when l not in the labels of i
    add l to the labels of i
  detach (i : Item, l : Label)
    when l in the labels of i
    remove l from the labels of l
  clear (i : Item)
    when i has some labels
    remove all labels of i
operational principle
  after affix(i,l), while no detach(i,l) and no clear(i), i is in the labels of l
```

The label in Alloy

```
sig Item {
  var labels : set Label
}
sig Label {}

fact Behavior {
  no labels
  always {
    (some i : Item, l : Label | affix[i,l] or detach[i,l])
    or
    (some i : Item | clear[i])
    or
    stutter
  }
}
```

Affix label with *point-wise* effect

```
pred affix[i : Item, l : Label] {
  // guard
  l not in i.labels
  // effect
  i.labels' = i.labels + l
  // frame condition
  all j : Item - i | j.labels' = j.labels
}
```

Affix label with *point-free* effect

```
pred affix[i : Item, l : Label] {
  // guard
  l not in i.labels
  // effect
  labels' = labels + i->l
}
```

Detach label

```
pred detach[i : Item, l : Label] {
  // guard
  l in i.labels
  // effect
  labels' = labels - i->l
}
```

Clear item

```
pred clear[i : Item] {
  // guard
  some i.labels
  // effect
  labels' = labels - i->Label
}
```

Label scenarios

```
run Scenario1 {
  some i : Item, disj l,m : Label {
    affix[i,l]; affix[i,m]; clear[i]
  }
} expect 1

run Scenario2 {
  some i : Item, l : Label {
    affix[i,l]; affix[i,l]
  }
} expect 0
```

Label operational principle

```
check affix_find {
    // after affix(i,l), while no detach(i,l) and no clear(i), i is in the labels of l
    all i : Item, l : Label | always {
        affix[i,l] implies after ((detach[i,l] or clear[i]) releases l in i.labels)
    }
}
```

App design

Modularizing concepts

- To enable reuse and instantiation each concept should be in a parametrized module
- The module can still be used on its own, as Alloy implicitly declares parameter signatures
- Since a parameter signature cannot be extended with new fields, some tricks might be necessary to declare them

Trash

```
module Trash[Item]

sig Item {}
var sig Accessible in Item {}
var sig Trashed in Item {}

...
```

Label

```
module Label[Item]

sig Item {
  var labels : set Label
}
sig Aux in Item {
  var labels : set Label
}
fact { Aux = Item }
sig Label {}

...
```

Specifying apps

- Import the required concepts, instantiating parameter signatures as needed
- Compose the concepts
  - Enforce interleaving, by requiring at most one concept not to stutter
  - Synchronize actions as needed
- Validate, validate, validate
- Check some expected properties

A filesystem app

- Composed of trash and label
- Many options to explore
  - When to allow affixing labels?
  - When to delete labels?
  - Whether to use special labels?

Free composition

```
open Trash[File] as trash
open Label[File] as label

sig File {}

fact Interleave {
  always {
    trash/stutter or
    label/stutter
  }
}

run Example {}
```

Filesystem v1

- Allow labelling only when accessible
- Clear labels when file is deleted

Filesystem v1

```
fact Synchronization {
  // allow affixing only if file is accessible
  all f : File, l : Label | always (affix[f,l] implies f in Accessible)

  // clear all labels after file is deleted
  all f : File | always (delete[f] and some f.labels implies after clear[f])
}
```

Filesystem v1

```
run Scenario1 {
  some f : File, l : Label {
    create[f]; affix[f,l]; delete[f]
  }
} expect 1

run Scenario2 {
  some f : File, l : Label {
    create[f]; delete[f]; affix[f,l]
  }
} expect 0
```

Filesystem v1

DEMO

Filesystem v2

- Allow labelling when accessible or trashed
- Clear labels when trash is emptied

Filesystem v2

```
fact Synchronization {
  // allow labelling when accessible or trashed
  all f : File, l : Label | always (affix[f,l] implies f in Accessible+Trashed)

  // clear labels when trash is emptied
  always {
    empty implies after {
     (some f : File-Accessible | clear[f]) until no (File-Accessible).labels
    }
  }
}
```

Filesystem v2

```
run Scenario1 {
  some f : File, l : Label {
    create[f]; affix[f,l]; delete[f]
  }
} expect 1

run Scenario2 {
  some f : File, l : Label {
    create[f]; delete[f]; affix[f,l]
  }
} expect 1
```

Filesystem v2

```
run Scenario3 {
    some f : File, l : Label {
        create[f]; delete[f]; empty; affix[f,l]
    }
} expect 0

run Scenario4 {
    some disj f1,f2 : File, l : Label {
        create[f1]; create[f2]; delete[f1]; affix[f2,l]; delete[f2]; affix[f1,l]; empty
    }
} expect 1

run Scenario5 {
    some disj f1,f2 : File, l : Label {
        create[f1]; delete[f1]; affix[f1,l]; empty; create[f2]
    }
} expect 0
```

Filesystem v2

DEMO

Filesystem v3

- Allow labelling when accessible or trashed
- Clear labels when trash is emptied
- Affix special label Trashed when file is deleted
- Detach special label Trashed when file is restored

Filesystem v3

```
one sig Dirty extends Label {}

fact Synchronization {
  // allow labelling when accessible or trashed
  all f : File, l : Label | always (affix[f,l] implies f in Accessible+Trashed)

  // clear labels when trash is emptied
  always {
    empty implies after ((some f : File-Accessible | clear[f]) until no (File-Accessible).labels)
  }

  // affix label Trashed after delete
  all f : File | always (delete[f] and Dirty not in f.labels implies after affix[f,Dirty])

  // detach label Trashed after restore
  all f : File | always (restore[f] and Dirty in f.labels implies after detach[f,Dirty])
}
```

Filesystem v3

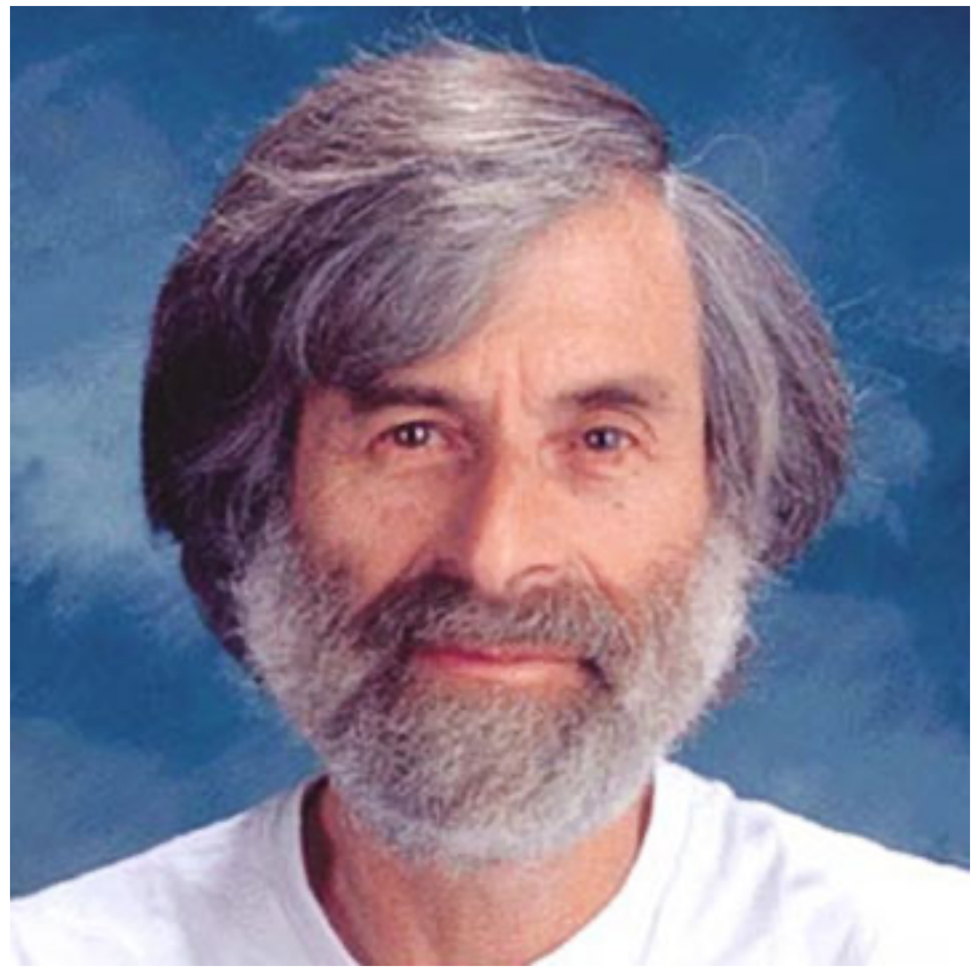
DEMO

Epilogue

"Software is built on abstractions. Pick the right ones, and programming will flow naturally from design [...] **Pick the wrong ones, and programming will be a series of nasty surprises.**"

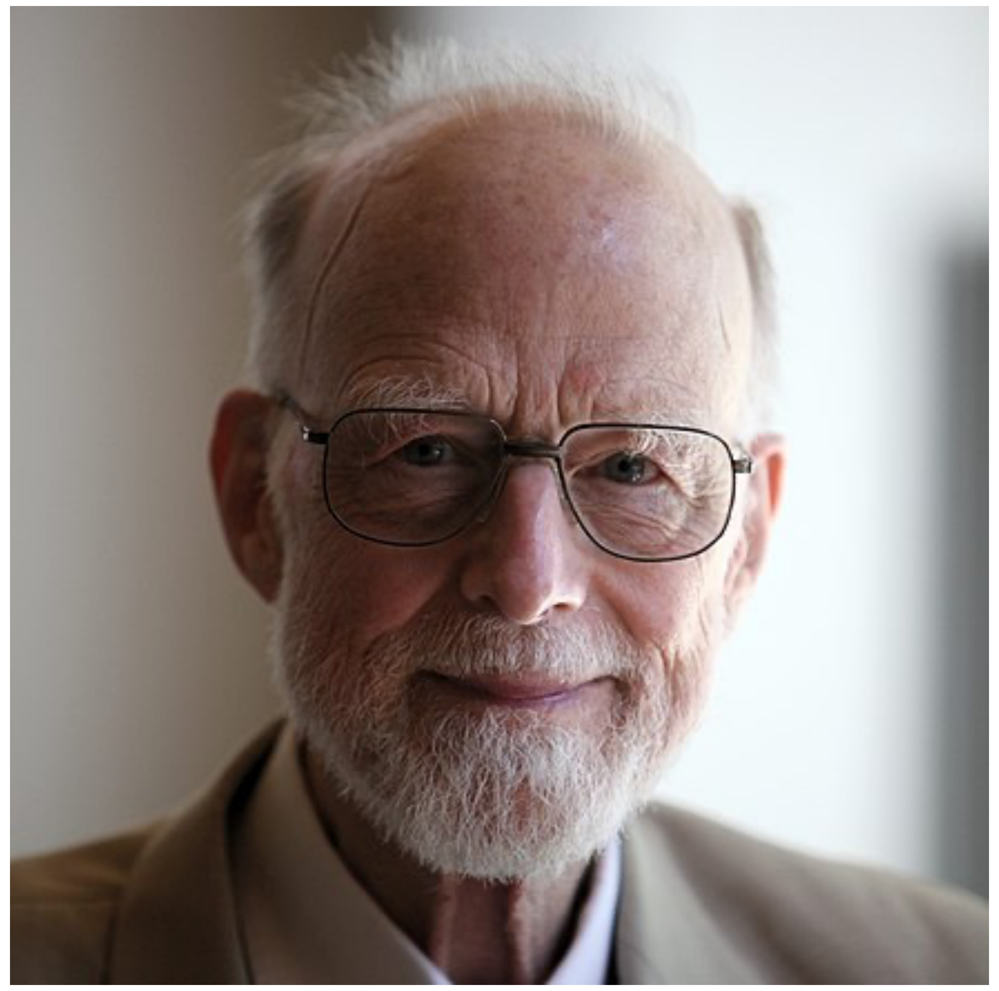
–Daniel Jackson

“A specification is an *abstraction*. [...] But I don’t know how to teach you about abstraction. A good engineer knows how to abstract the essence of a system and suppress the unimportant details when specifying and designing it. **The art of abstraction is learned only through experience.**”



–Leslie Lamport

“There are two ways of constructing a software design: One way is to make it so simple that there are obviously no deficiencies, and the other way is to make it so complicated that there are no obvious deficiencies. **The first method is far more difficult.**”



–Tony Hoare

Epigram 31

“Simplicity does not precede complexity, but follows it.”

–Alan Perlis

always eventually some Alloy