App design with Alloy

Alcino Cunha

“I mean ‘design’ here in the same sense that the word is used in other design disciplines: **the shaping of some artifact to meet a human need.** […] For software, that means determining what the behavior of the software should be: what controls it will offer, and what responses it will provide in return.”

–Daniel Jackson

THE ESSENCE OF SOFTWARE

WHY CONCEPTS MATTER FOR GREAT DESIGN

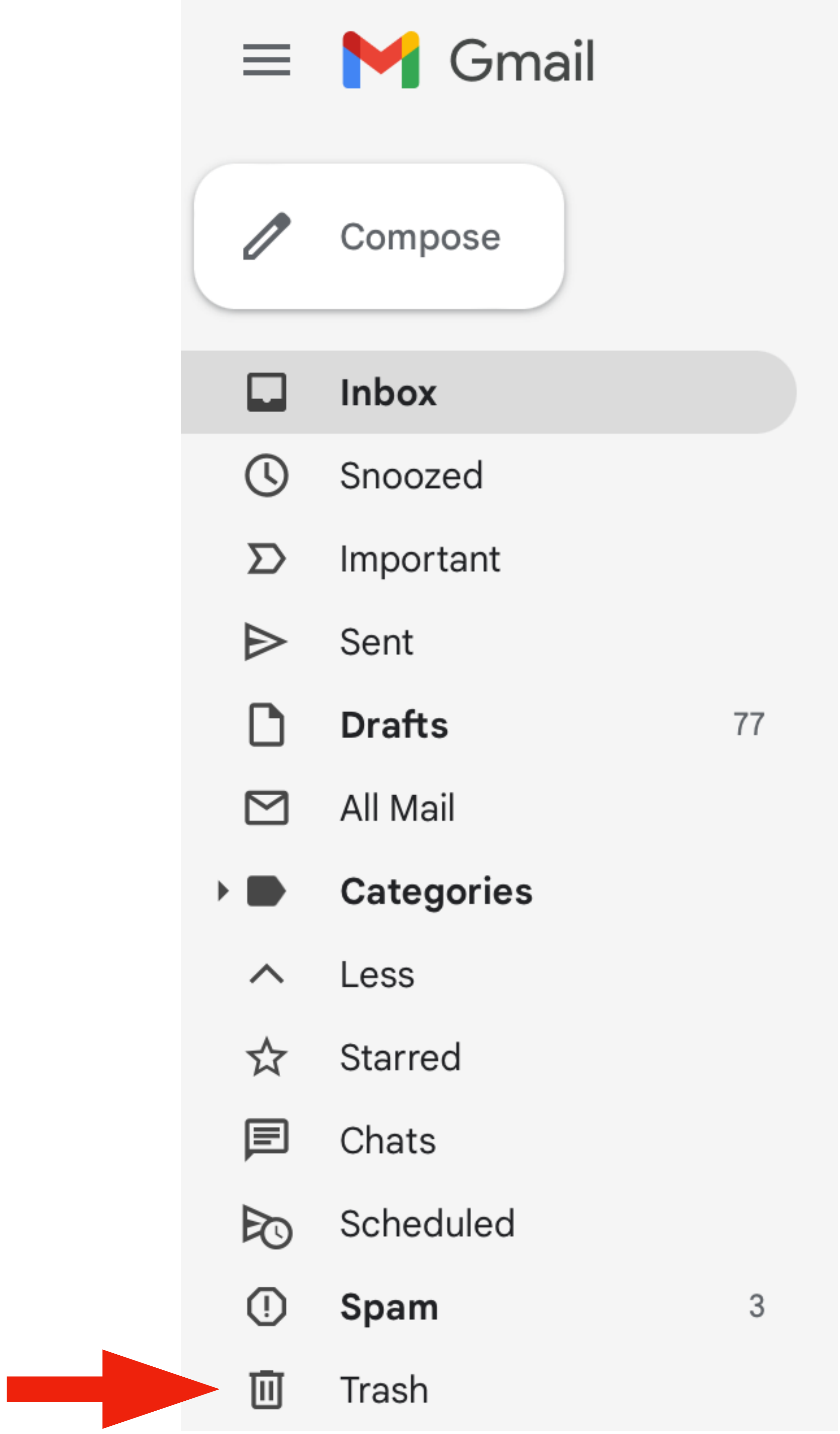
DANIEL JACKSON

Concepts

- Apps are made of *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


Open
Empty Trash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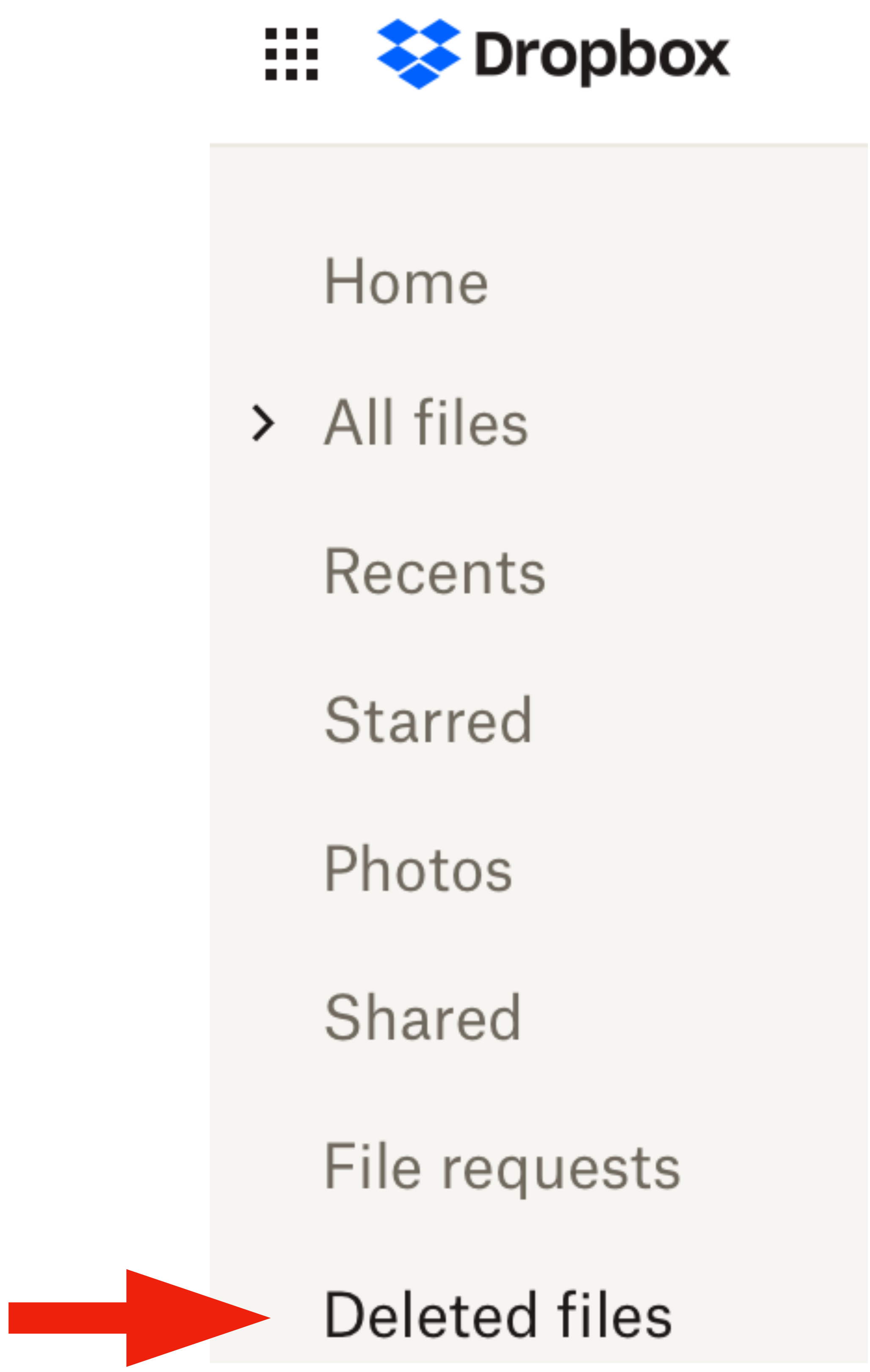
Trash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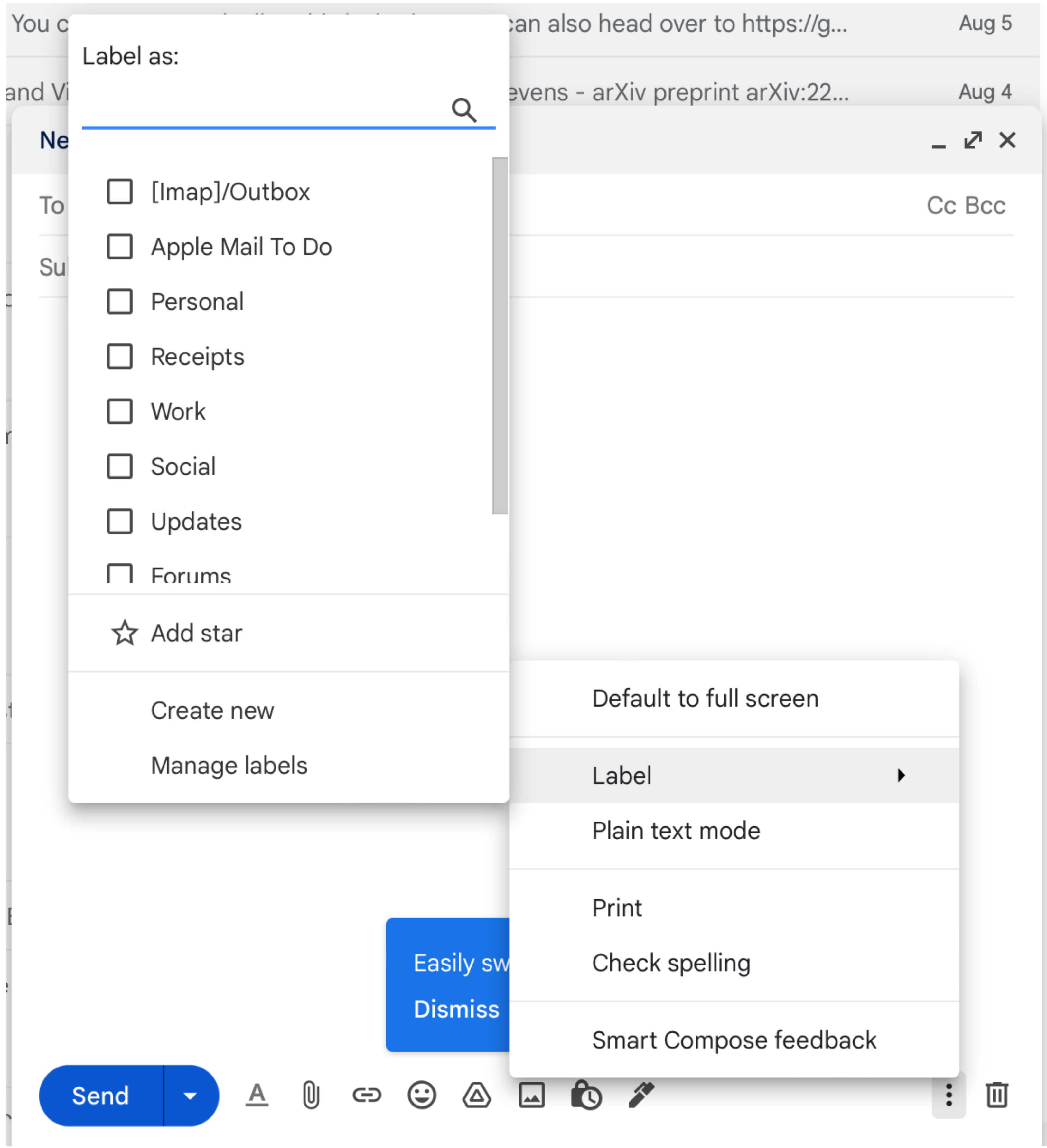
Label



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Apple Mail To Do
Personal
Receipts
Work
Social
Updates
Forums
Add star
Create new
Manage labels
Default to full screen
Label
Plain text mode
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Check spelling
Smart Compose feedback
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Aug 4
Cc Bcc
Dismiss
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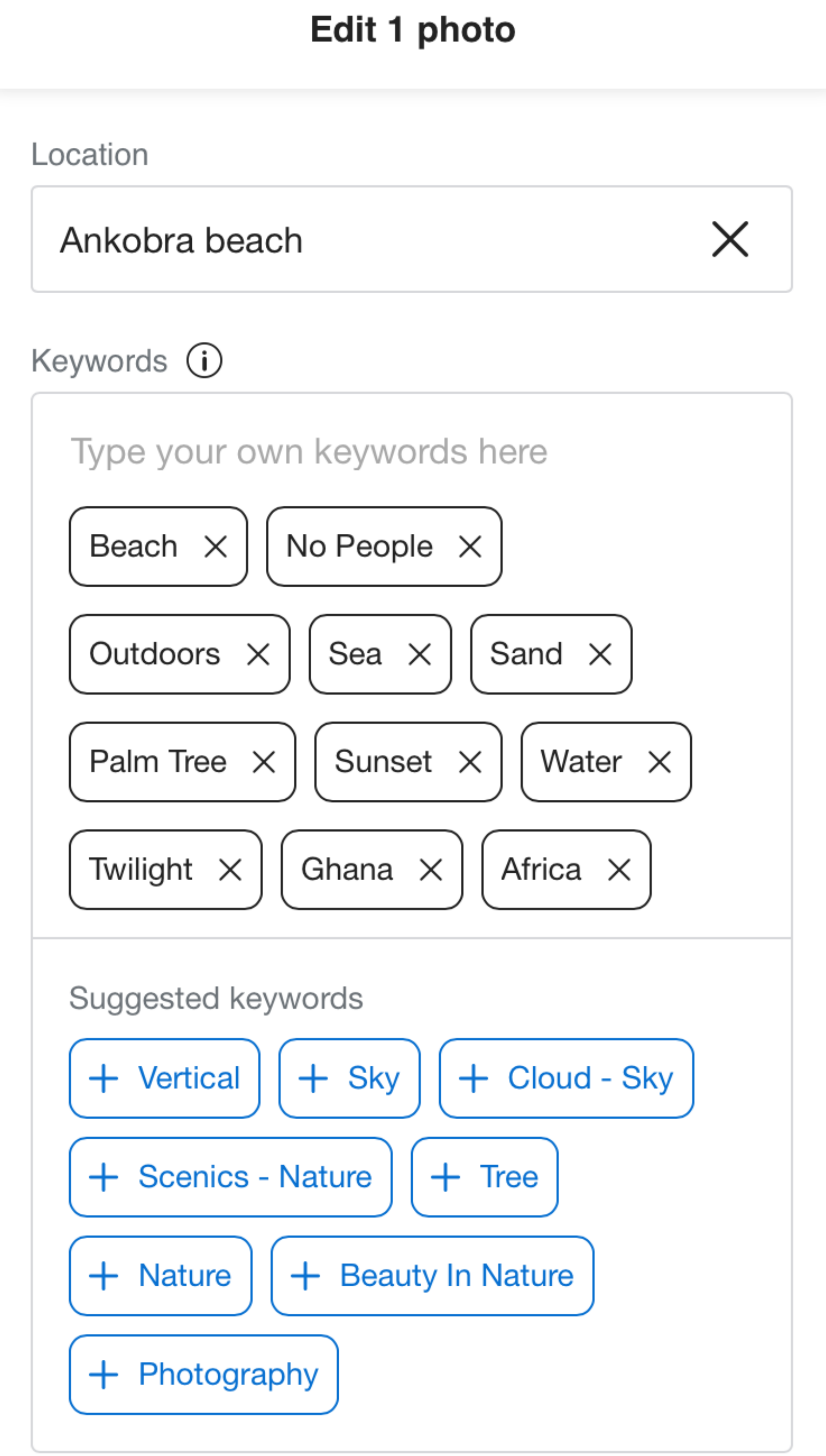

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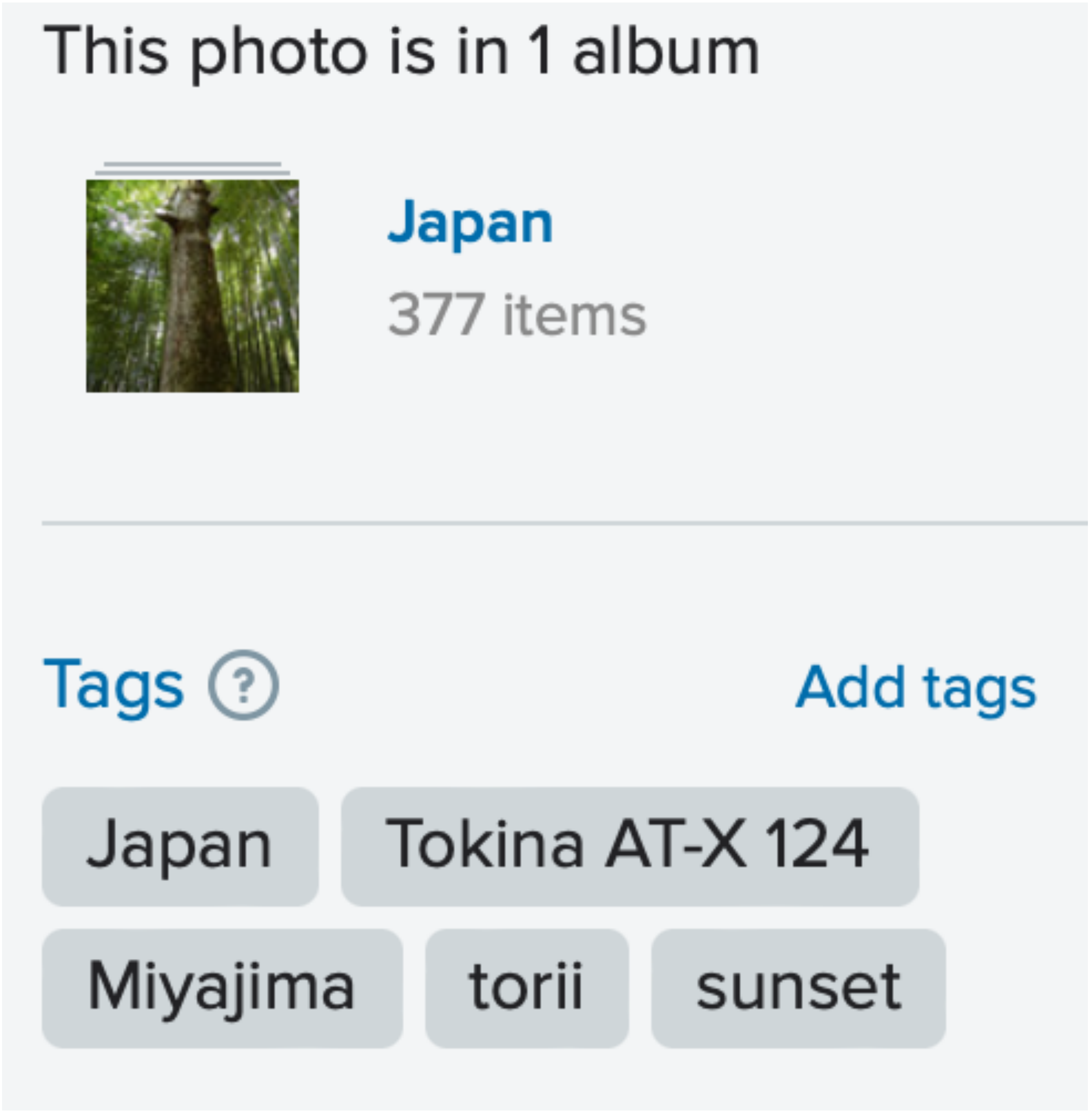

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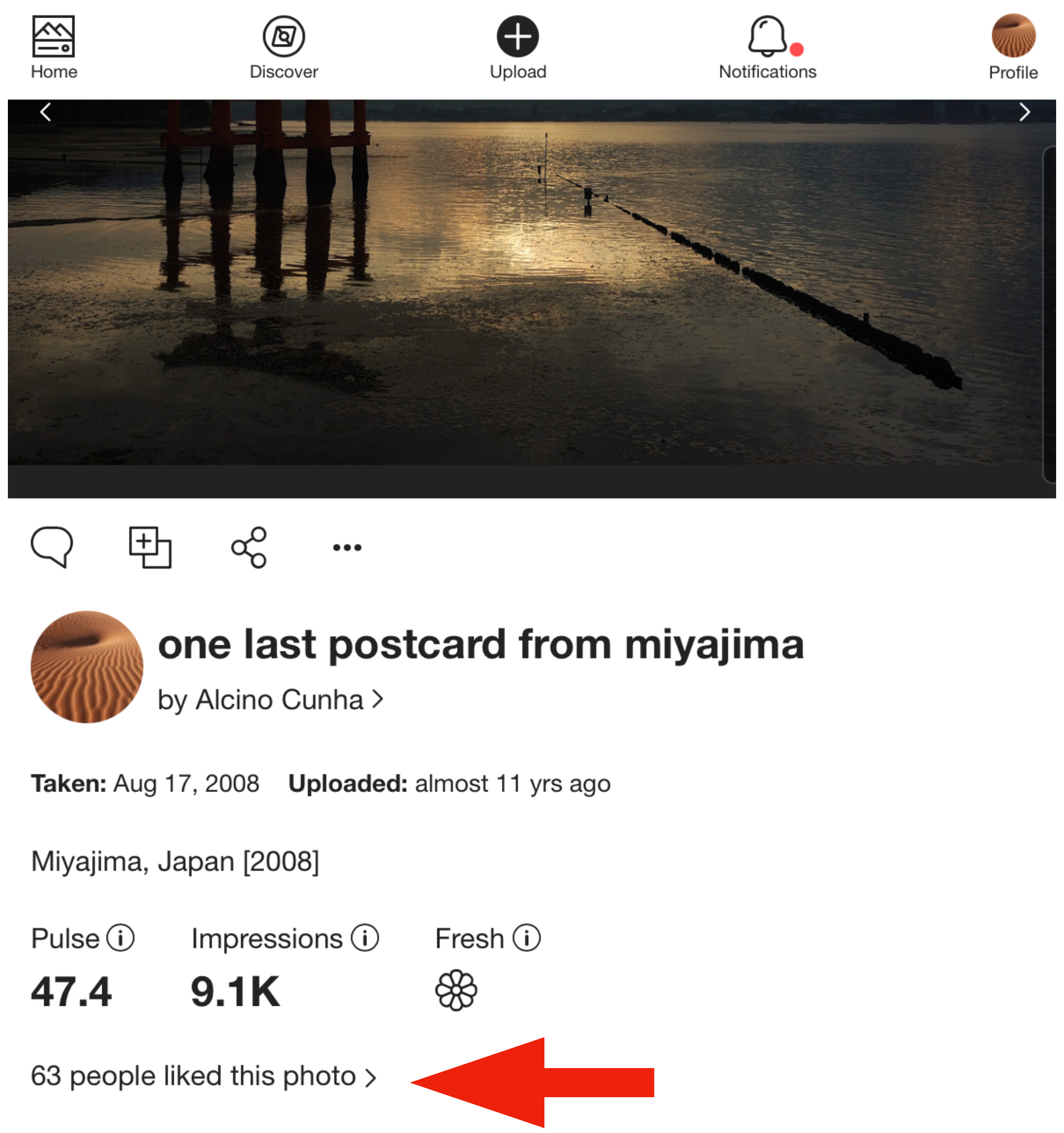
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by Alcino Cunha >
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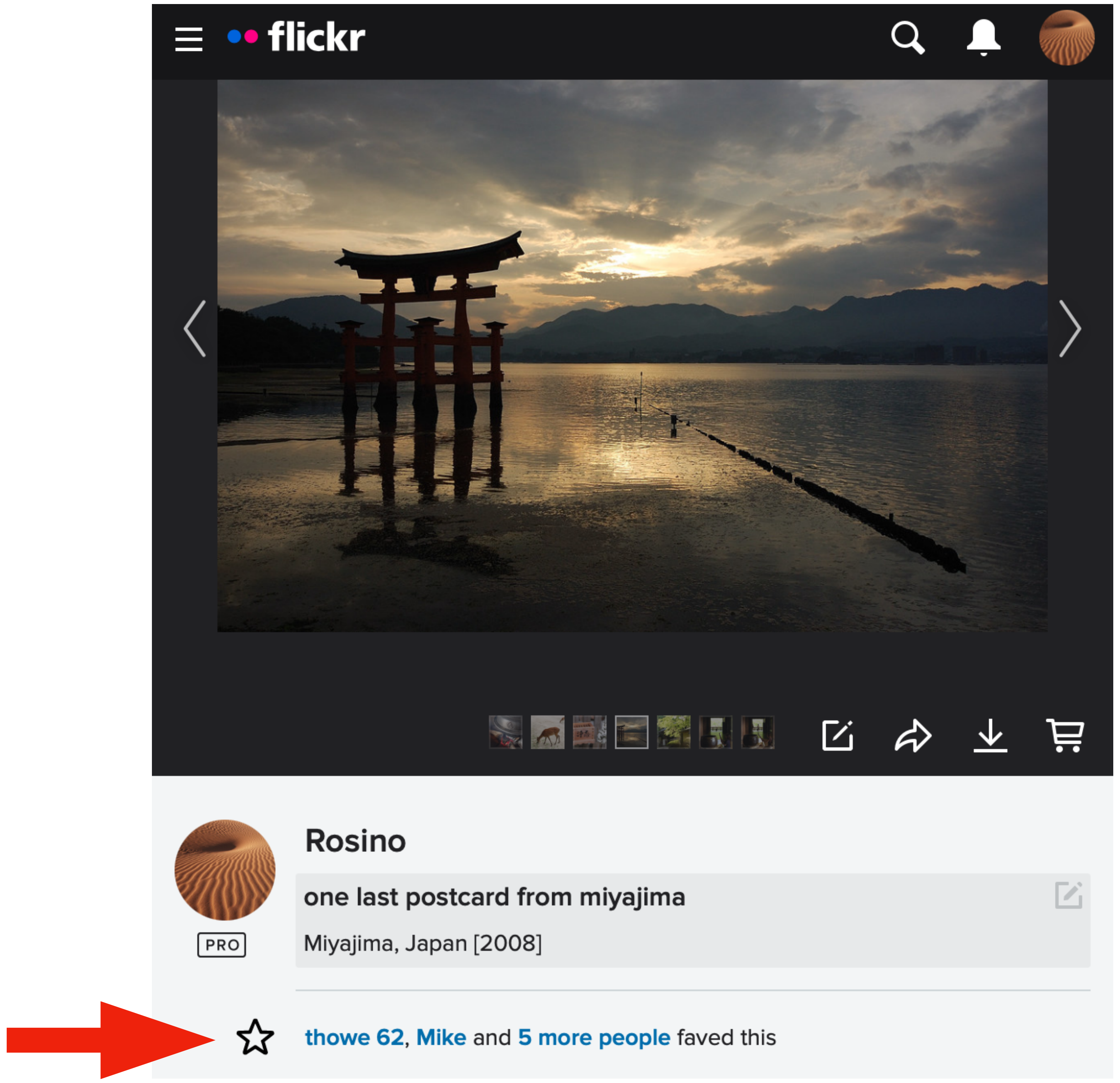
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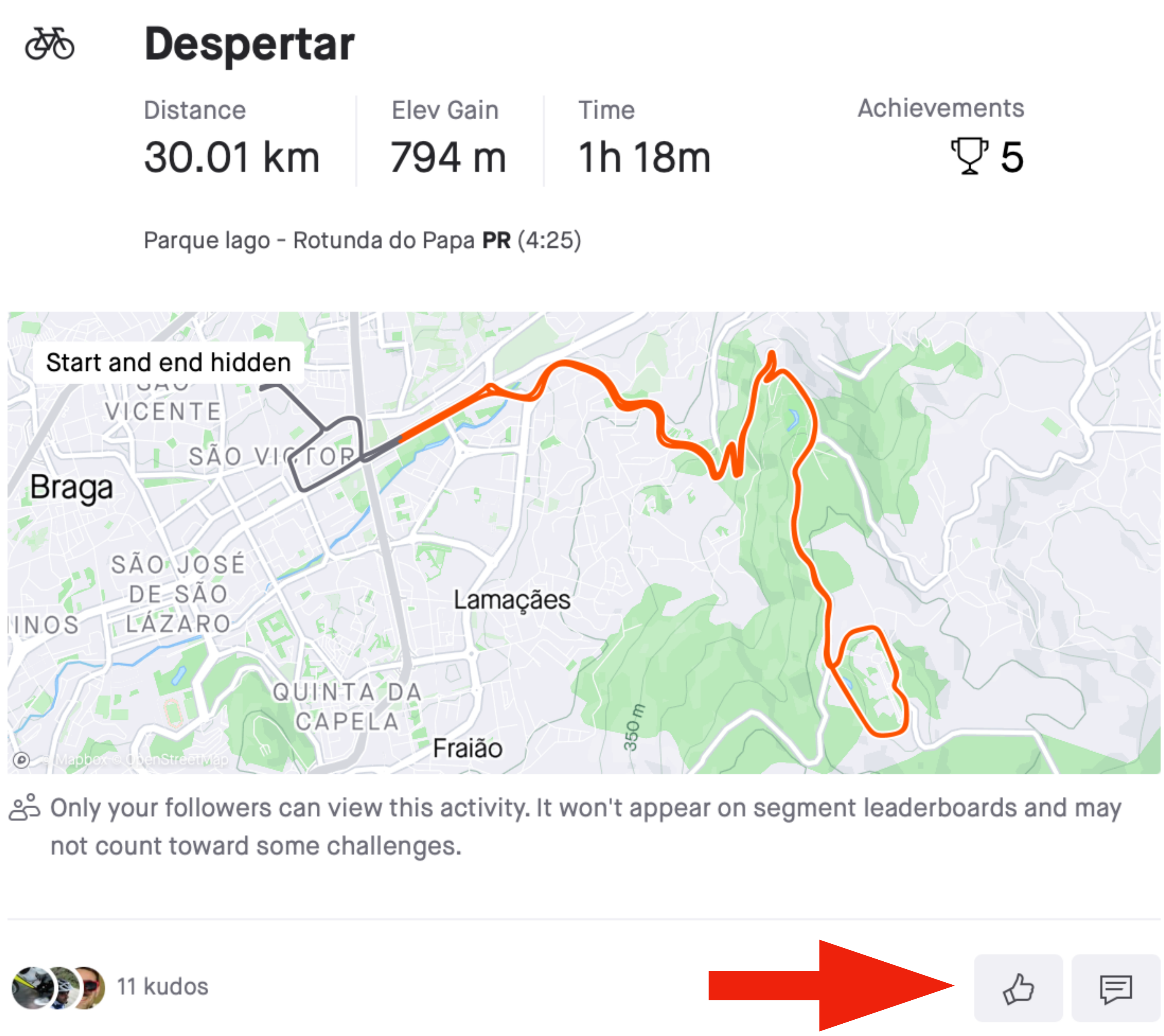
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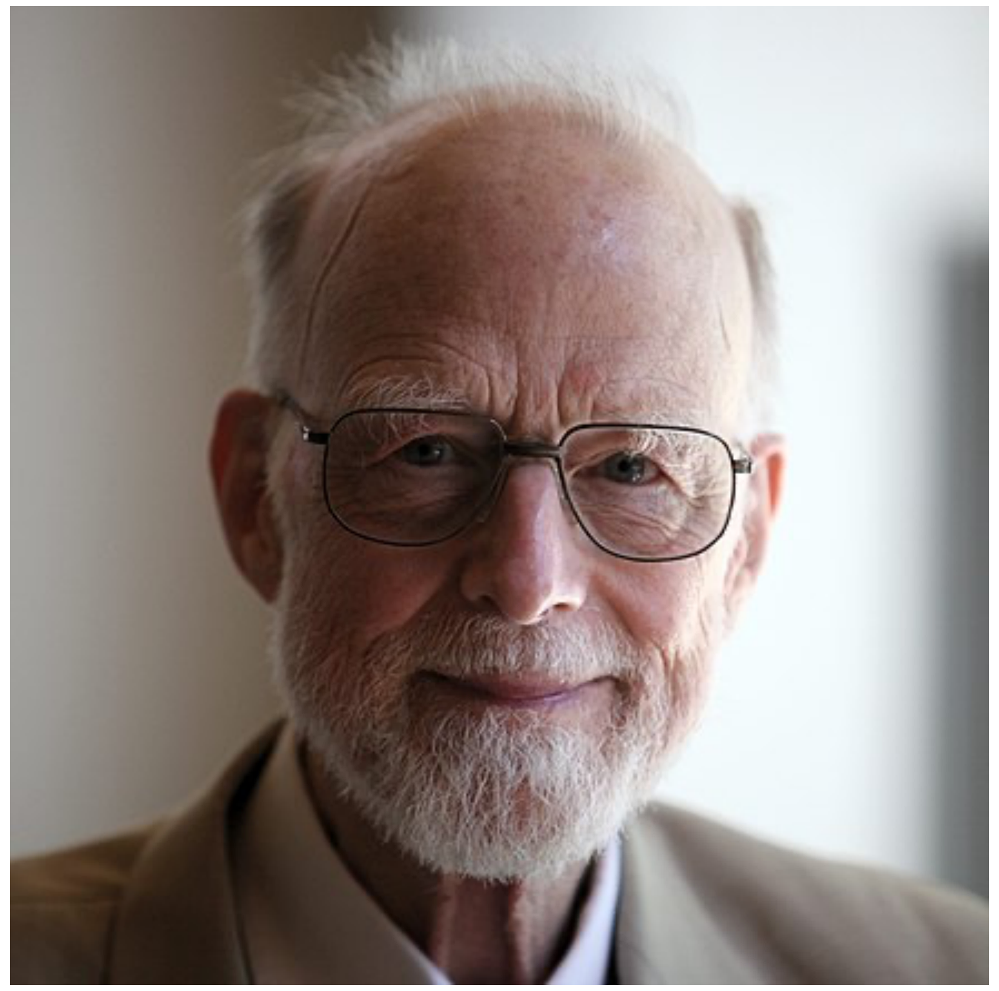
Braga
Lamaçães
Fraião
Only your followers can view this activity. It won't appear on segment leaderboards and may not count toward some challenges.
11 kudos

Concept design

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

“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

App design

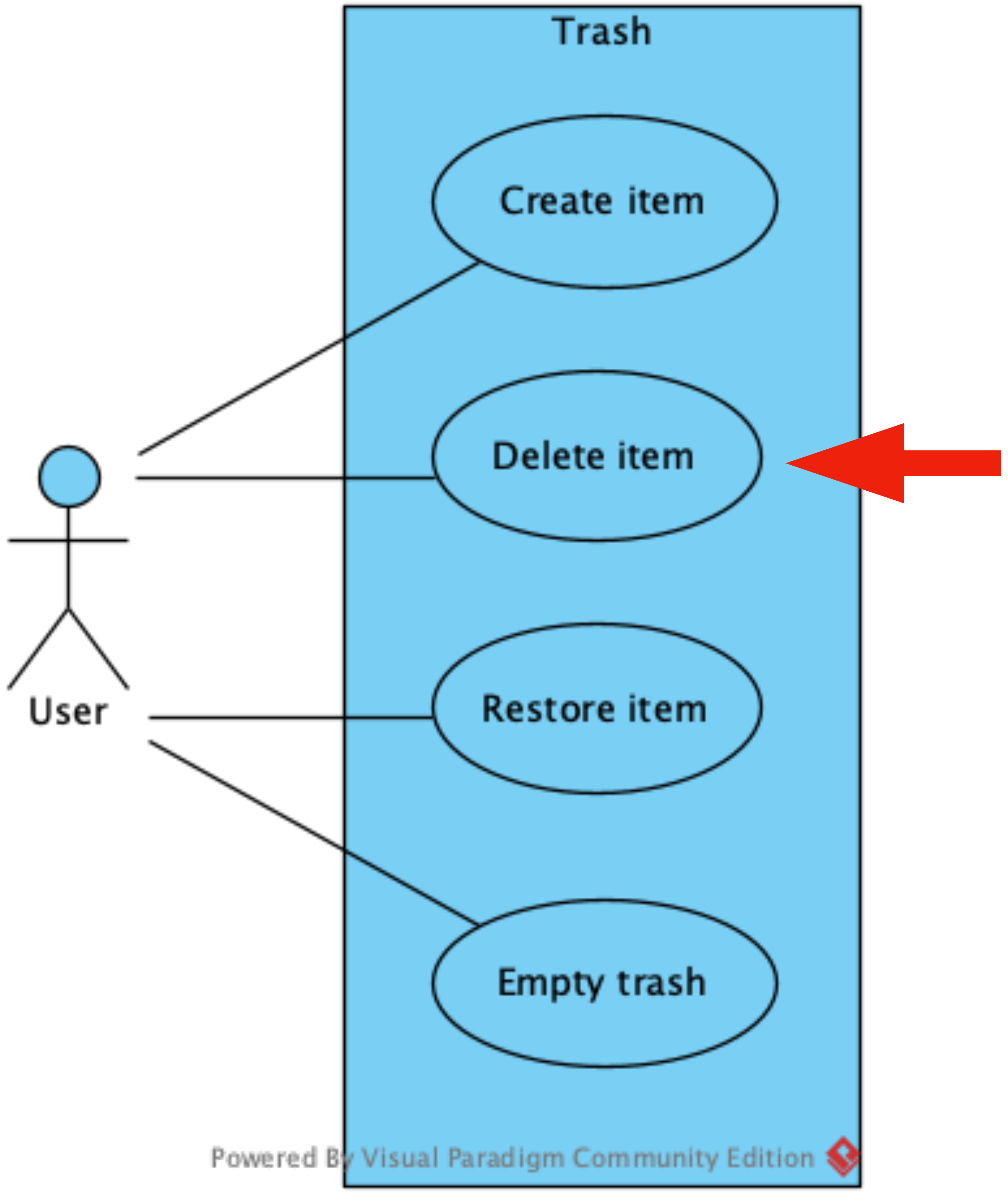
- Identify the core concepts
- Compose them, maybe providing new functionality
- The focus is on exploration

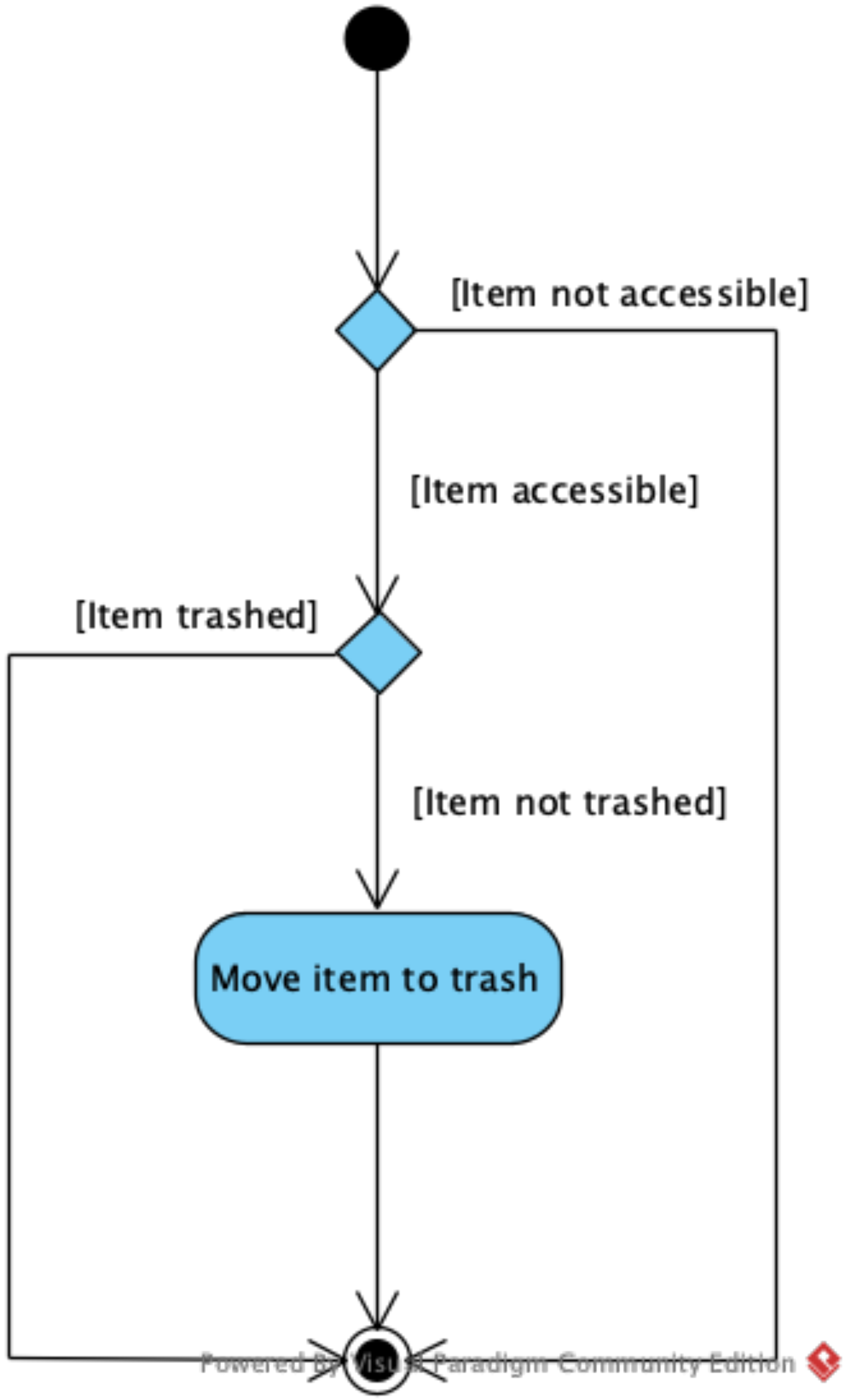
"[…] For software, that means determining what the behavior of the software should be: what controls it will offer, and what responses it will provide in return. **These questions have no right or wrong answers, only better or worse ones.**"

–Daniel Jackson

Modeling concepts

Trash modeling *a la* UML

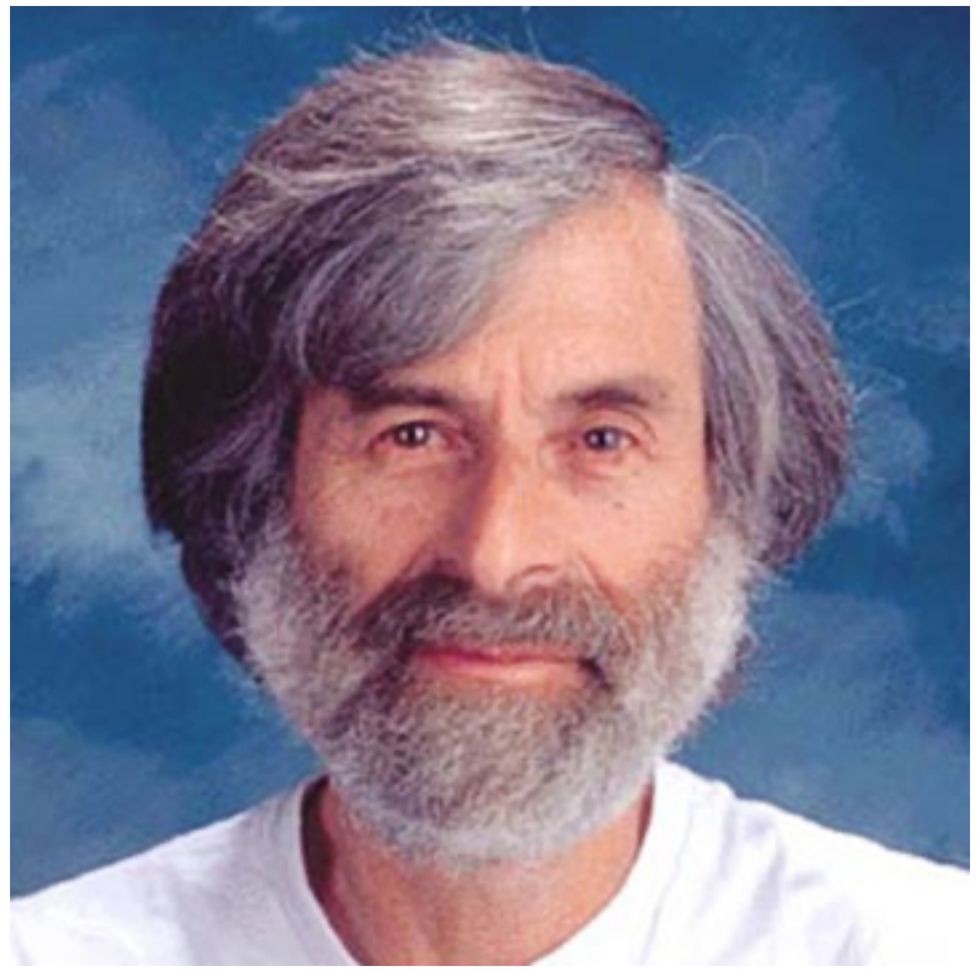




Trash “modeling” with code

```
class Trash<Item> {

  private HashSet<Item> accessible;
  private HashSet<Item> trashed;

  void delete(Item i) throws Exception {
    if (!accessible.contains(i)) {
      throw new Exception("Item not accessible");
    }
    if (trashed.contains(i)) {
      throw new Exception("Item already trashed");
    }
    trashed.add(i);
    accessible.remove(i);
  }

  ...
}
```

“If you’re not writing a program, don’t use a programming language.”



–Leslie Lamport

Trash modeling *a 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 *a 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
  - Archetypical scenarios that show how the concept is fulfilled by the actions

Transition systems

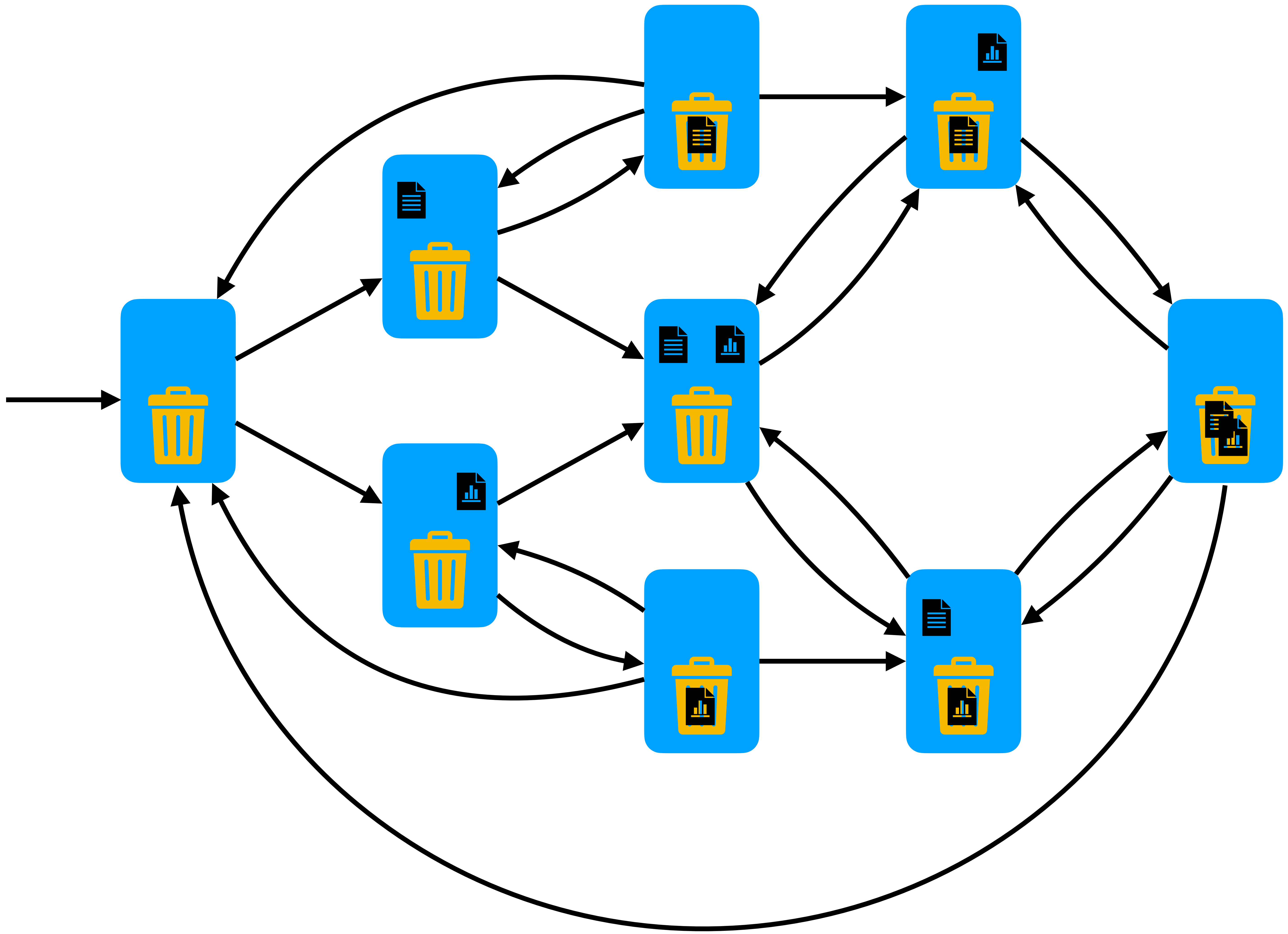
Transition systems

- A popular model to describe the behavior of a system
- In some areas a *model* is 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
  - ...

Transition system = States + Transitions

- 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 valid path (a sequence of states) in the transition system, starting in an initial state

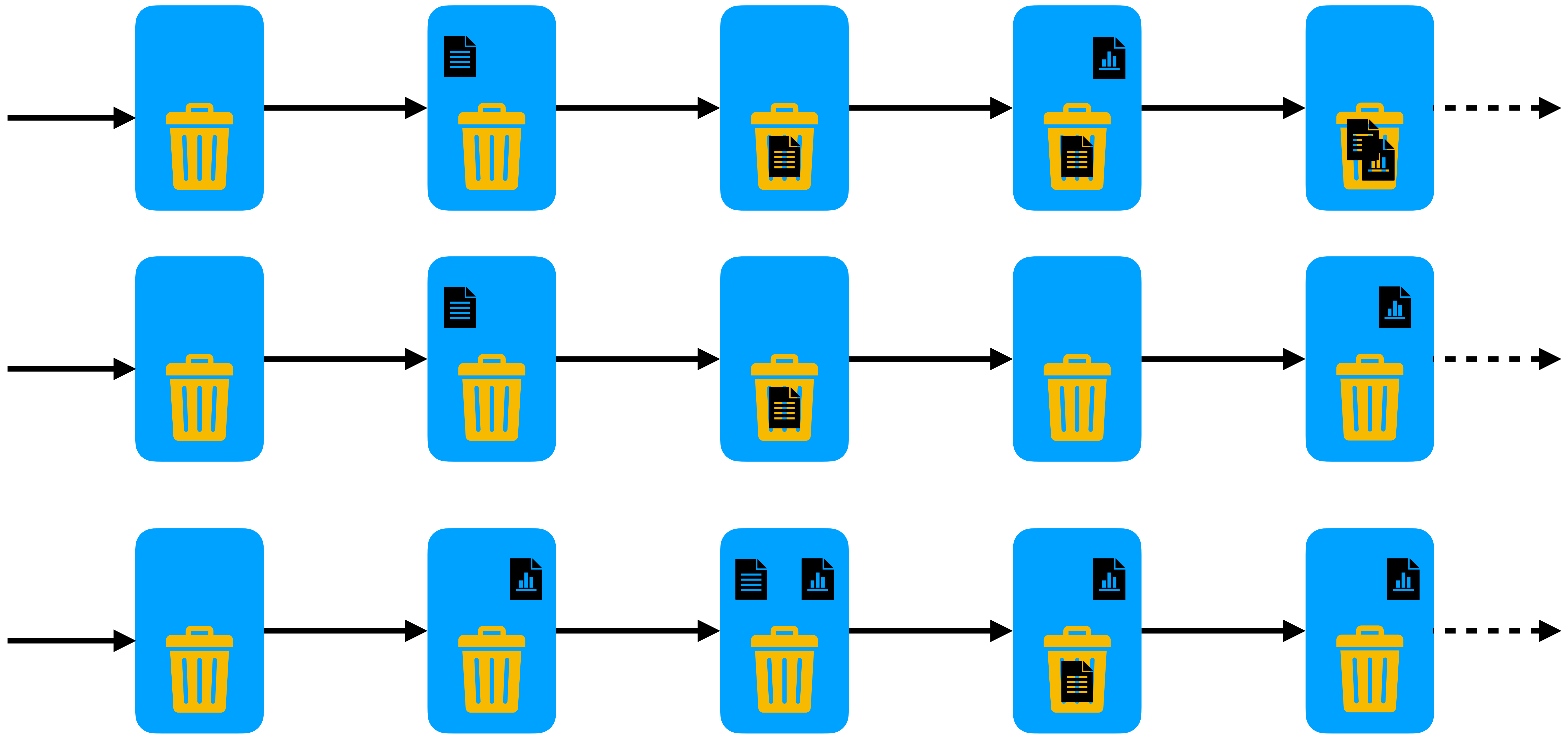
Trash transition system



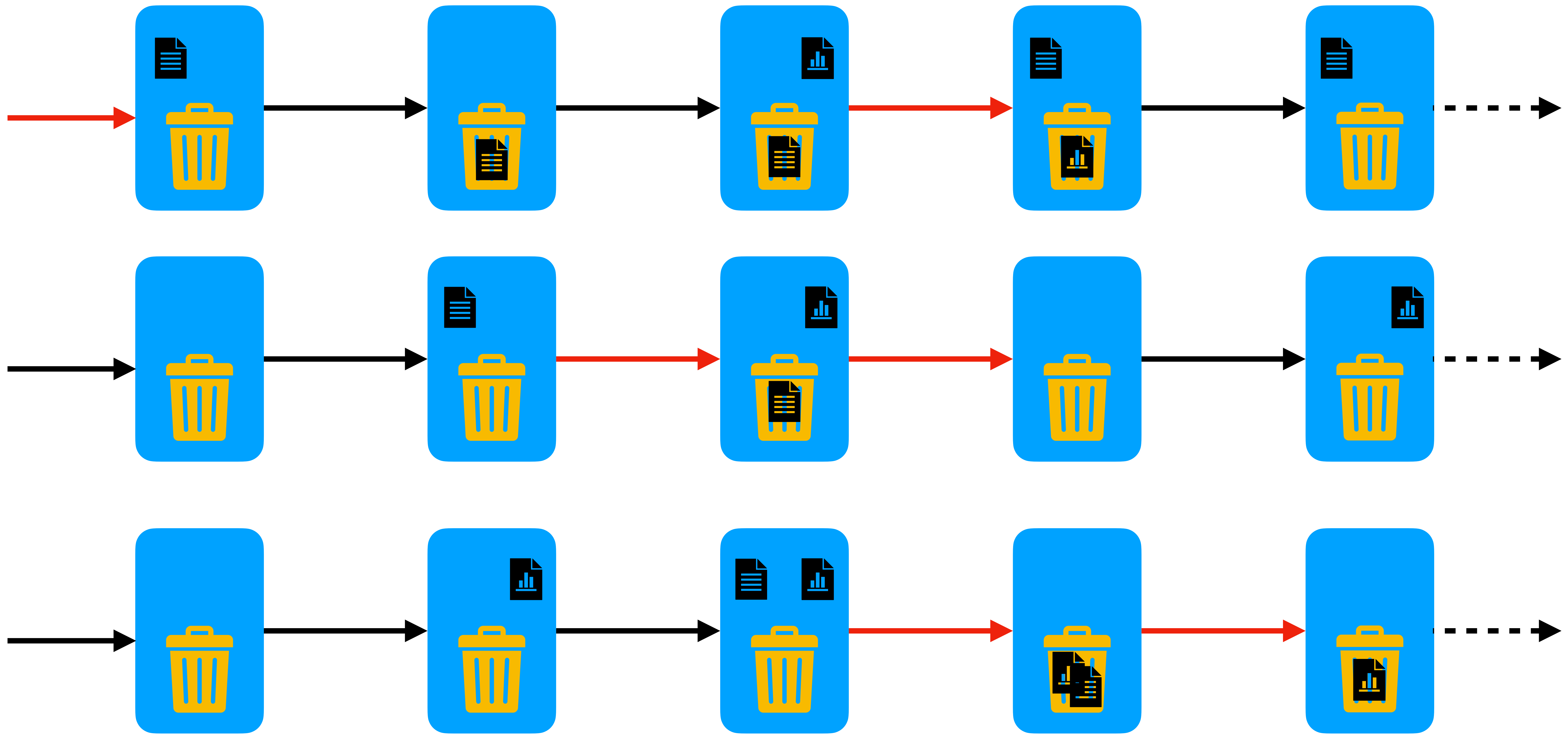
Declarative modeling

- It is possible to describe a transition system by specifying which traces are valid
- The specification talks about a sequence of states and not just about a single state
- And thus requires some sort of *temporal logic*

Valid trash traces



Invalid trash traces



Transition systems in Alloy

Mutability

- In Alloy 6 mutable signatures and fields can be declared with keyword **`var`**
  - Previously only possible with the Electrum extension
  - It was possible to describe behavior in Alloy 5 by explicitly modeling the concept of state
  - But it was confusing and error prone
- Mixing mutable and static structures
  - Static field inside mutable signature yields a warning
  - Same for static signature extending or inside mutable one

Trash states

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

Instances

- When mutable structures are declared, instances are **infinite** *traces*
- Analysis commands only return traces that can be represented finitely
  - Instances are traces that loop back at some point
- Static signatures and fields 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
- They allow us to “quantify” the validity of a formula over the different states of a trace
- A formula without temporal operators is only required to hold in the initial states
- Alloy 6 has both future and past temporal operators

Always, historically, and prime

`always` ϕ	ϕ will always be true
`historically` ϕ	ϕ was always true
R`'`	The value of R in the next state

Trash behavior

```
fact Behavior {
  // Initial state
  no Accessible
  no Trashed
  // Transitions
  always {
    // At most one item is created or deleted
    lone (Accessible - Accessible') + (Accessible' - Accessible)
    // All deleted items go to the trash
    Accessible - Accessible' = Trashed' - Trashed
    // If no item was deleted or created an empty must have occurred
    Accessible' = Accessible implies no Trashed'
    // ...
  }
}
```

Trash behavior

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

Anatomy of an action

- The specification of an action is a conjunction of three kinds of formulas
  - *Guards*, that specify when it can occur
  - *Effects*, that specify what changes when it occurs
  - *Frame conditions*, special effects that specify what does not change when it occurs
- Guards usually have no temporal operators
  - But can use past temporal operators to recall something about the past
- Effects and frame conditions use the prime operator to specify the relation between the present and the next value of mutable signatures and fields
  - If nothing is specified about a mutable signature or field it can change freely

Create item

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

Delete item

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

Restore item

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

Empty trash

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

Validation

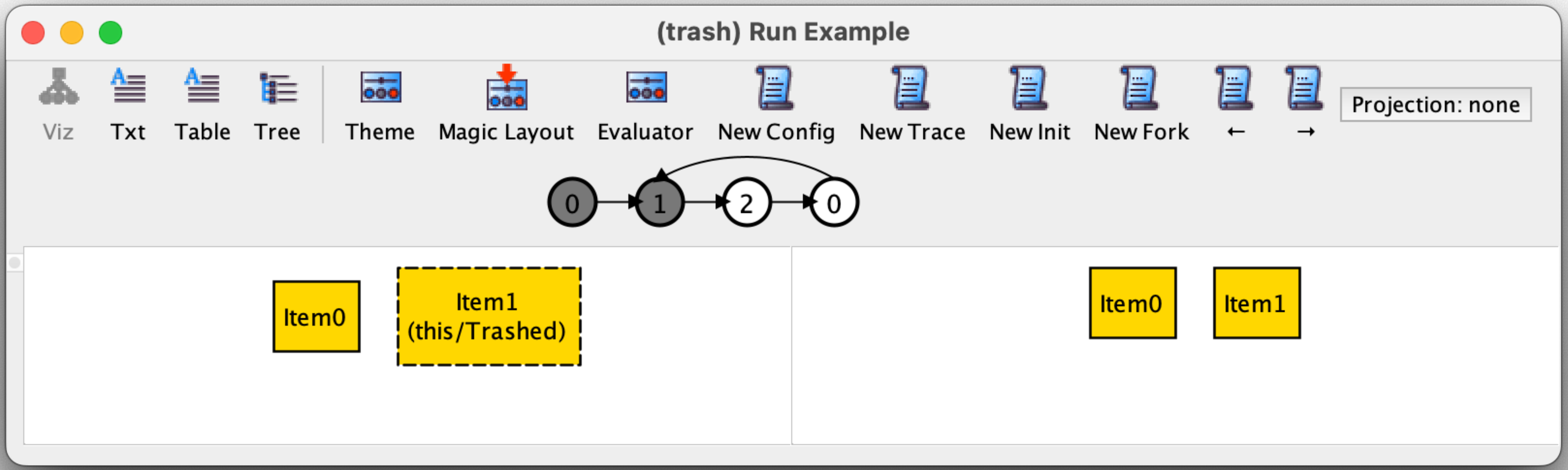
Validation

- 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 above
  - 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



Simulation

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

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

$\phi \; ; \; \psi$

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
```

Some trash scenarios

```
Executing "Run Scenario1 expect 1"
   Solver=sat4j Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=OFF Mode=batch
   2..8 steps. 17099 vars. 378 primary vars. 28707 clauses. 355ms.
   Instance found. Predicate is consistent, as expected. 76ms.

Executing "Run Scenario2 expect 0"
   Solver=sat4j Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=20 Mode=batch
   2..10 steps. 51735 vars. 998 primary vars. 86980 clauses. 496ms.
   No instance found. Predicate may be inconsistent, as expected. 20ms.

Executing "Run Scenario3 for 1 Item expect 1"
   Solver=sat4j Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=OFF Mode=batch
   2..10 steps. 74773 vars. 1322 primary vars. 121547 clauses. 199ms.
   No instance found. Predicate may be inconsistent, contrary to expectation. 7ms.

3 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: No instance found. Scenario3 may be inconsistent, contrary to expectation.
```

Inconsistency

- This scenario is not possible because it cannot be extended to an infinite trace
- Once the trash is empty no other action is possible and we stated that at every state some action must occur
- At least a *stuttering* action should be possible at that point

Stuttering

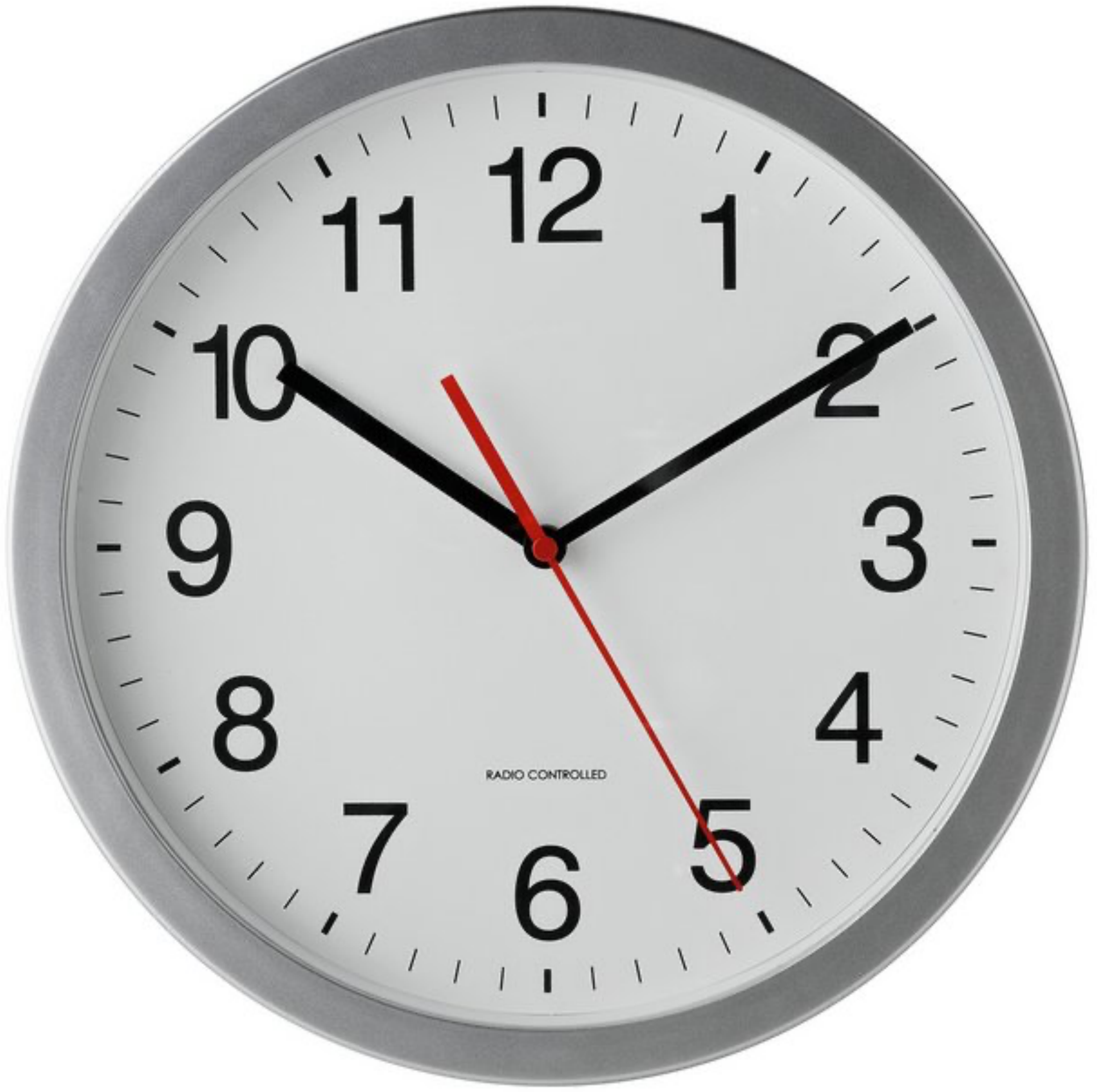
A clock specification

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



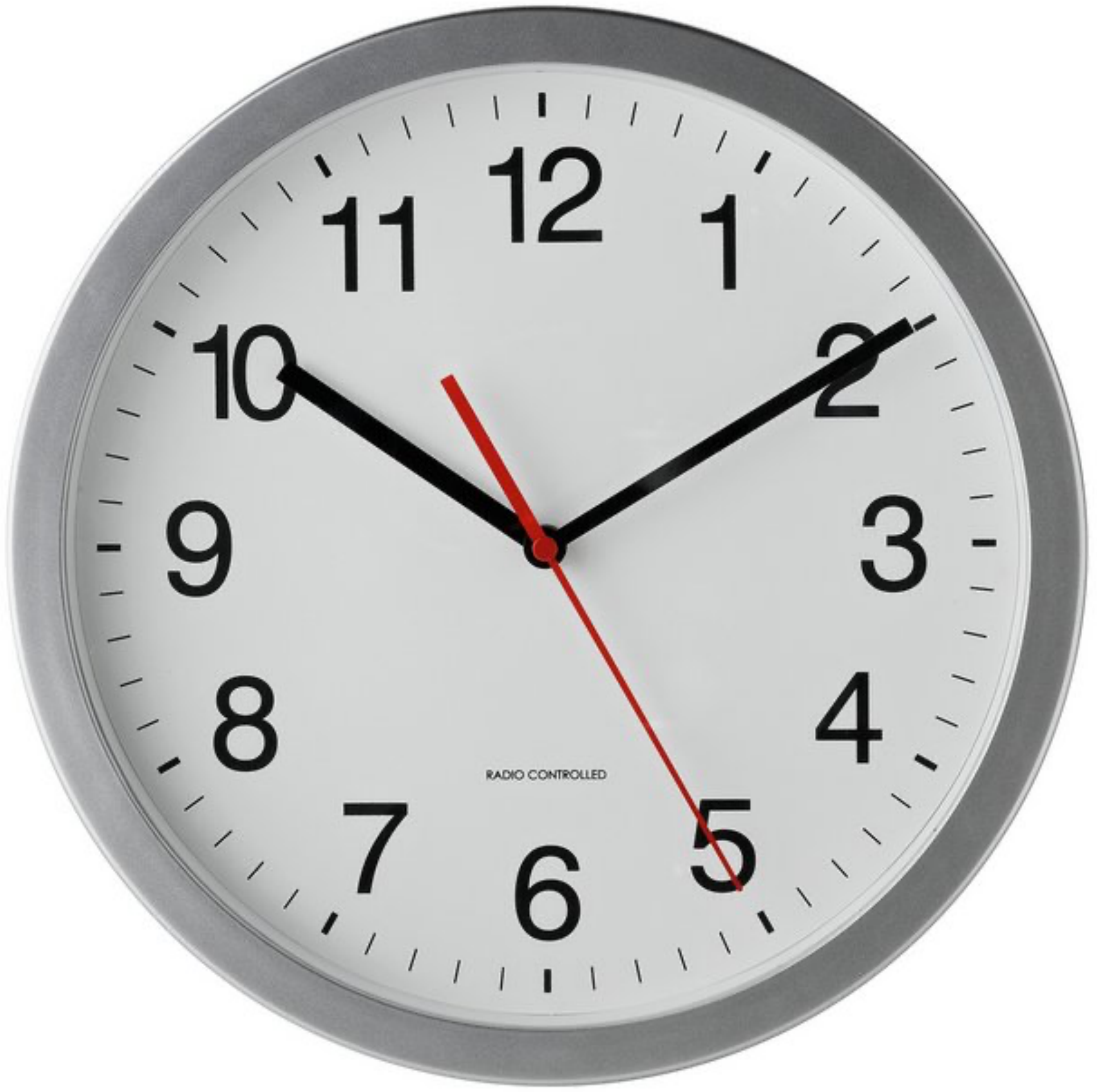
A clock specification

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

A 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

- It is good practice to allow the system to stutter in every state
- Stuttering can represent events by the environment or by other components of the system (not yet modeled)
- Stuttering will enable the composition of concepts when specifying apps

Stuttering

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

Fixing the trash behavior

```
fact Behavior {
  // Initial state
  no Accessible
  no Trashed
  // 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

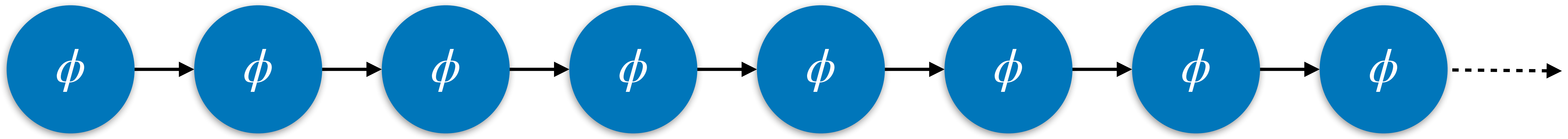
- As usual, **`check`** commands can be used to verify assertions
- The default verification mechanism is bounded model checking
  - The default maximum number of transitions is 10
  - This can be changed by setting a scope for **`steps`**
- Alloy 6 also supports unbounded model checking
  - Activated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

Future temporal operators

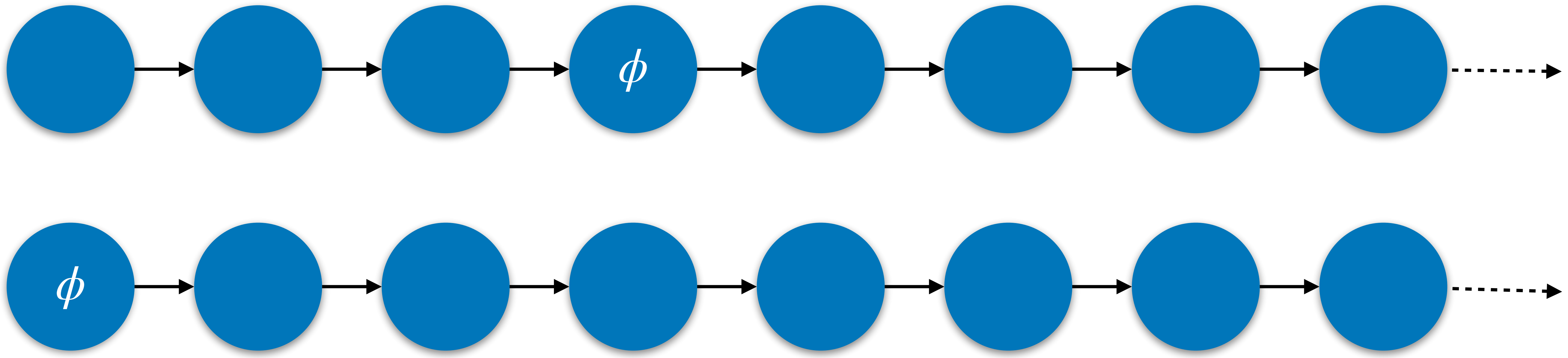
`always` ϕ	ϕ will always be true
`eventually` ϕ	ϕ will eventually be true
`after` ϕ	ϕ will be true in the next state
ψ `until` ϕ	ϕ will eventually be true and ψ is true until then
ϕ `releases` ψ	ψ can only stop being true after ϕ

Future operators

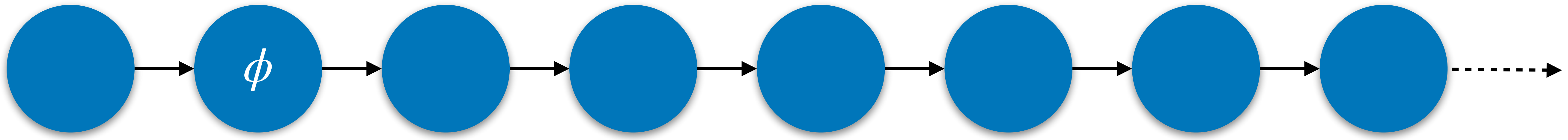
always ϕ



eventually ϕ

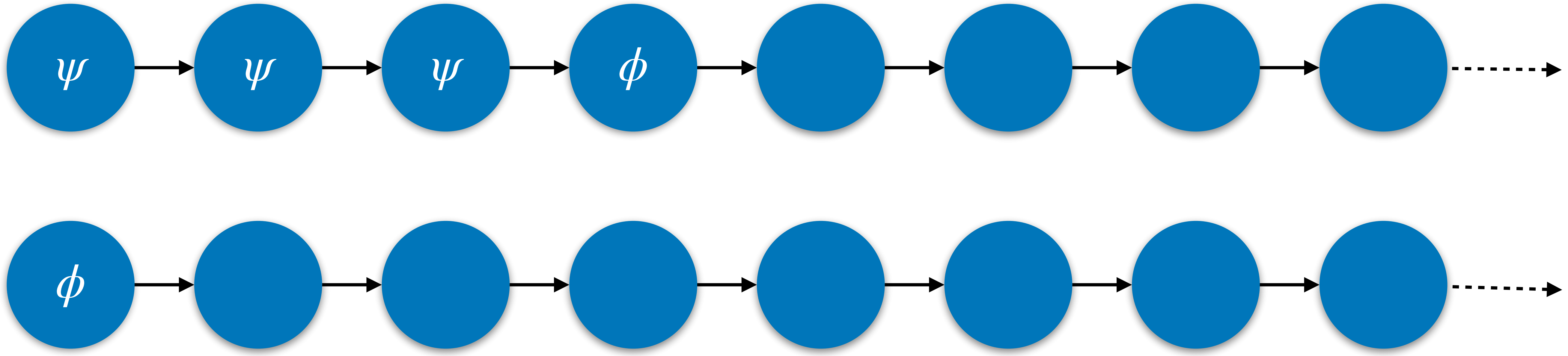


after ϕ

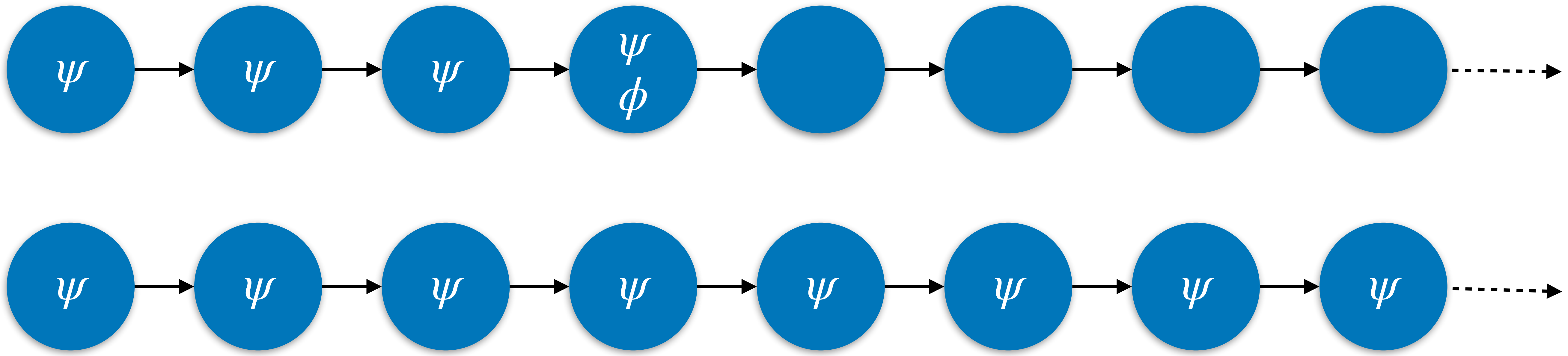


Future operators

ψ **until** ϕ

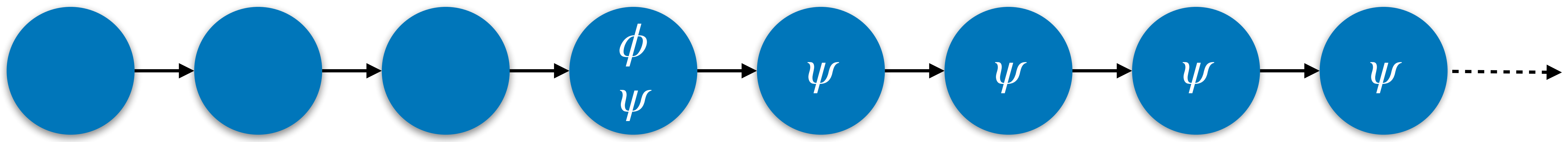


ϕ **releases** ψ

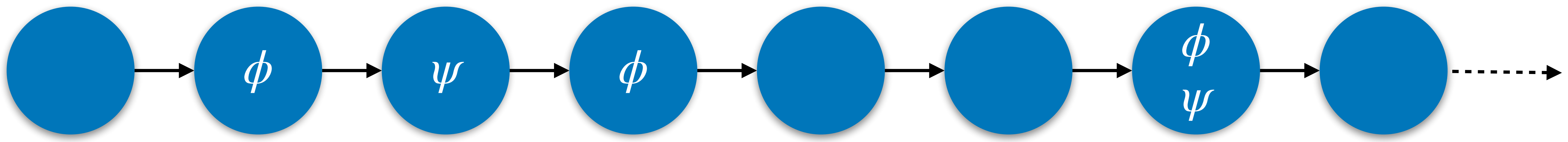


Mixing operators

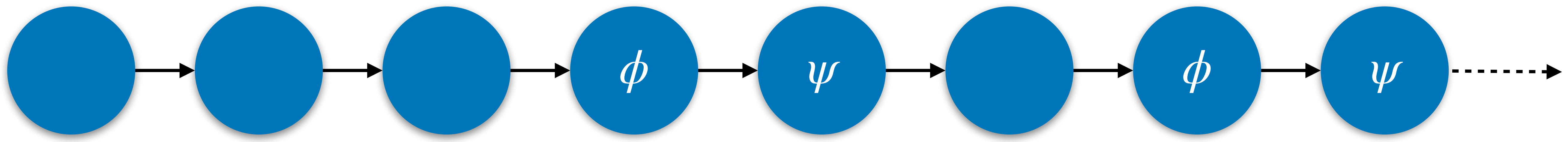
`always (`ϕ` implies always `ψ`)`



`always (`ϕ` implies eventually `ψ`)`

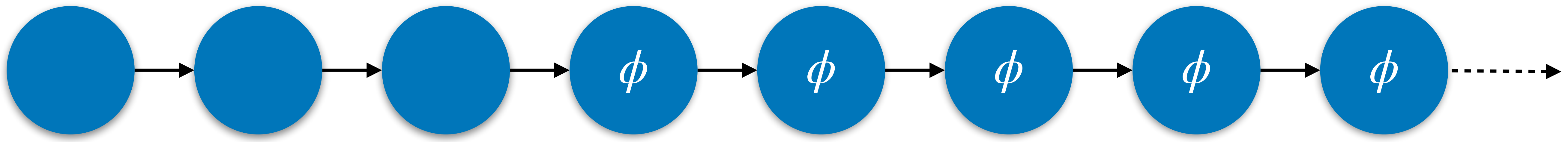


`always (`ϕ` implies after `ψ`)`

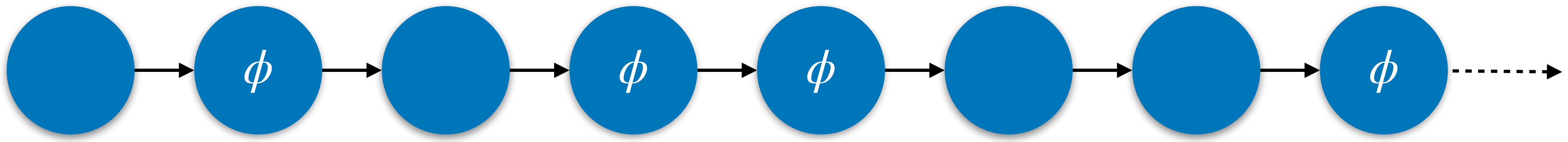


Mixing operators

`eventually (always` ϕ`)`



`always (eventually` ϕ`)`

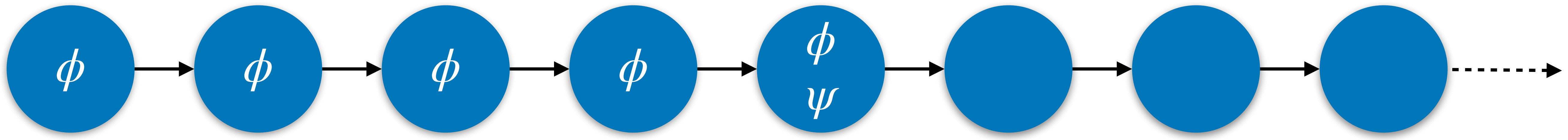


Past temporal operators

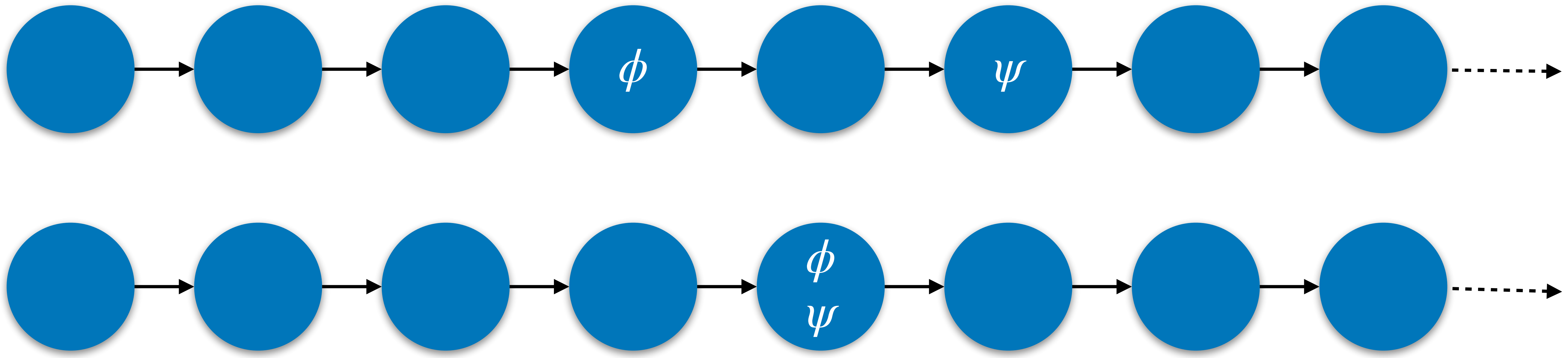
`historically` ϕ	ϕ was always true
`once` ϕ	ϕ was once true
`before` ϕ	ϕ was true in previous state
ψ **`since`** ϕ	ϕ was once true and ψ was true since then
ϕ **`triggered`** ψ	ψ was always true back to the point where ϕ was true

Past operators

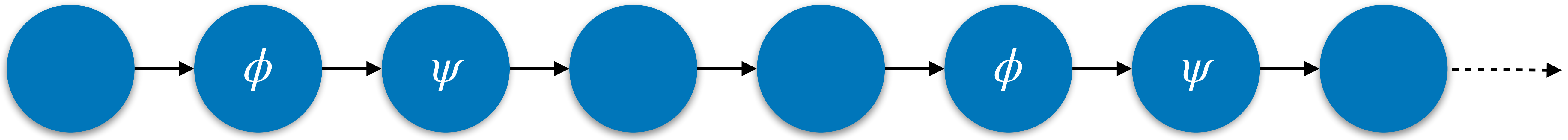
`always (`ψ` implies historically `ϕ`)`



`always (`ψ` implies once `ϕ`)`

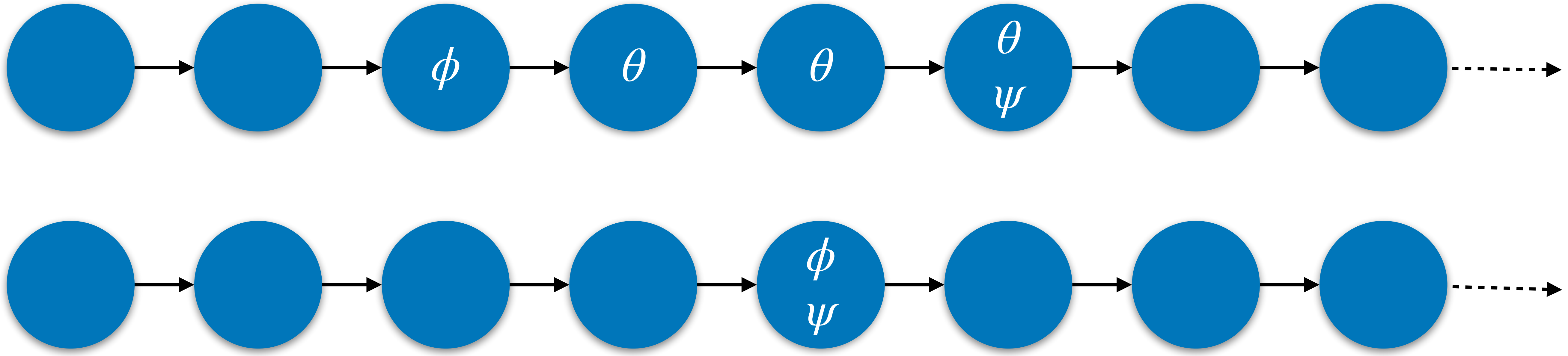


`always (`ψ` implies before `ϕ`)`

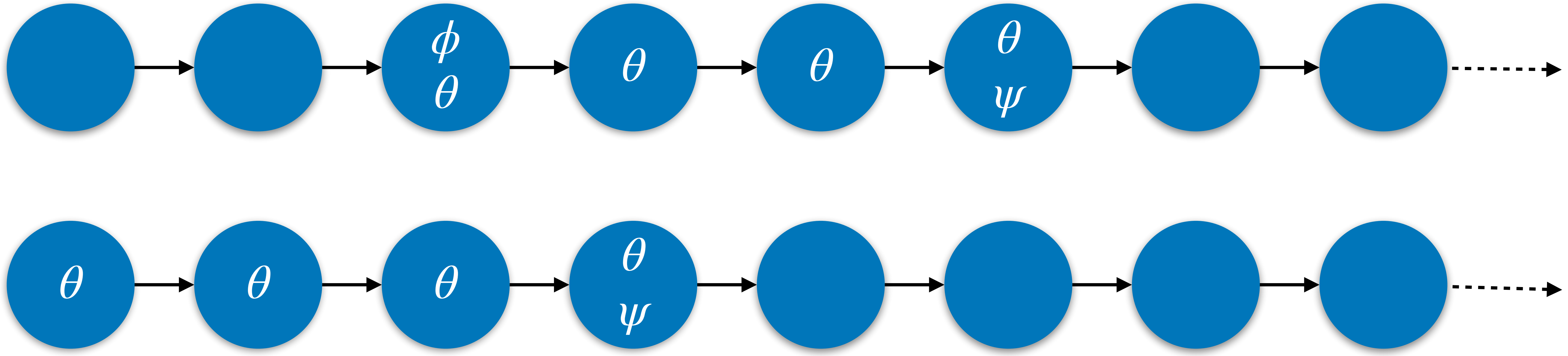


Past operators

always (ψ implies θ since ϕ)



always (ψ implies ϕ triggered θ)



Safety vs Liveness

- *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, and any continuation leads to a counter-example
  - The archetypal safety property is **`always`** ϕ
- *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 happened
  - Harder to specify, since they require fairness assumptions that prevent the system from stuttering forever
  - The archetypal liveness property is **`eventually`** ϕ
- In this course we will focus only on safety properties

Some operational principles

```
assert Properties {
  // No item can simultaneously be accessible and trashed
  always no Accessible & Trashed
  // A restore is only possible after a delete
  all x : Item | always (restore[x] implies once delete[x])
  // If all items are in the trash and the trash is emptied no more items will exist
  always (Item in Trashed and empty implies always no Accessible)
  // After deleting an item only leaves the trash after an empty or a restore
  all x : Item | always (delete[x] implies after ((empty or restore[x]) releases x in Trashed))
  // A restore undos a delete
  all x : Item | always ((delete[x];restore[x]) implies Accessible'' = Accessible and Trashed'' = Trashed)
}

check Properties
```

```
Executing "Check Properties"
   Solver=minisat(jni) Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=20 Mode=batch
   1..10 steps. 79912 vars. 560 primary vars. 189949 clauses. 3388ms.
   No counterexample found. Assertion may be valid. 2295ms.
```

The main operational principle

```
assert OperationalPrinciple {
  all x : Item | always {
    // after delete(x), can restore(x) and then x in accessible
    delete[x] implies after (x in Trashed and (restore[x] implies after x in Accessible))
    // after delete(x), can empty() and then x not in accessible or trashed
    delete[x] implies after (some Trashed and (empty implies after x not in Trashed+Accessible))
  }
}

check OperationalPrinciple for 4 Item, 20 steps
```

```
Executing "Check OperationalPrinciple for 20 steps, 4 Item"
   Solver=minisat(jni) Steps=1..20 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=20 Mode=batch
   1..20 steps. 60638 vars. 2260 primary vars. 102411 clauses. 463ms.
   No counterexample found. Assertion may be valid. 7ms.
```

Another concept

The label

```
concept label [Item]
purpose
  organize items into overlapping categories
state
  labels : Item -> set Label
actions
  affix (i : Item, l : Label)
    add l to the labels of i
  detach (i : Item, l : Label)
    remove l from the labels of l
  find (l : Label) : set Item
    return the items labelled with l
  clear (i : Item)
    remove item i and all its labels
operational principle
  after affix(i,l) and no detach(i,l), i in find(l)
  if no affix(i,l), or detach(i,l), i not in find(l)
```

The label in Alloy

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

fun find [l : Label] : set Item { labels.l }

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

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

Affix label

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

Detach label

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

Clear item

```
pred clear [i : Item] {
  // 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

```
assert OperationalPrinciple {
    all i : Item, l : Label {
        // after affix(i,l) and no detach(i,l), i in find(l)
        always (affix[i,l] implies after ((detach[i,l] or clear[i]) releases i in find[l]))
        // if no affix(i,l), or detach(i,l), i not in find(l)
        all i : Item, l : Label | affix[i,l] releases i not in find[l]
        always ((clear[i] or detach[i,l]) implies after (affix[i,l] releases i not in find[l]))
    }
}

check OperationalPrinciple
```

Concept composition

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 trick 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 Label {
    var items : set Item
}
fun labels : Item -> set Label {
    ~items
}
...
```

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

- 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 {}
```

Simulation

DEMO

Filesystem v1

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

Filesystem v1

```
pred labelled [f : File] {
   some l : Label | f in find[l]
}

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 labelled[f] 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 v2

- Allow labelling when accessible or trashed
- Clear labels when file is permanently deleted

Filesystem v2

```
pred labelled [f : File] {
  some l : Label | f in find[l]
}

pred exists [f : File] {
  f in Accessible+Trashed
}

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

  // Clear all labels after file is permanently deleted
  all f : File | always {
    delete[f] f in Trashed and empty and labelled[f] implies after clear[f]
  }
}
```

Filesystem v2

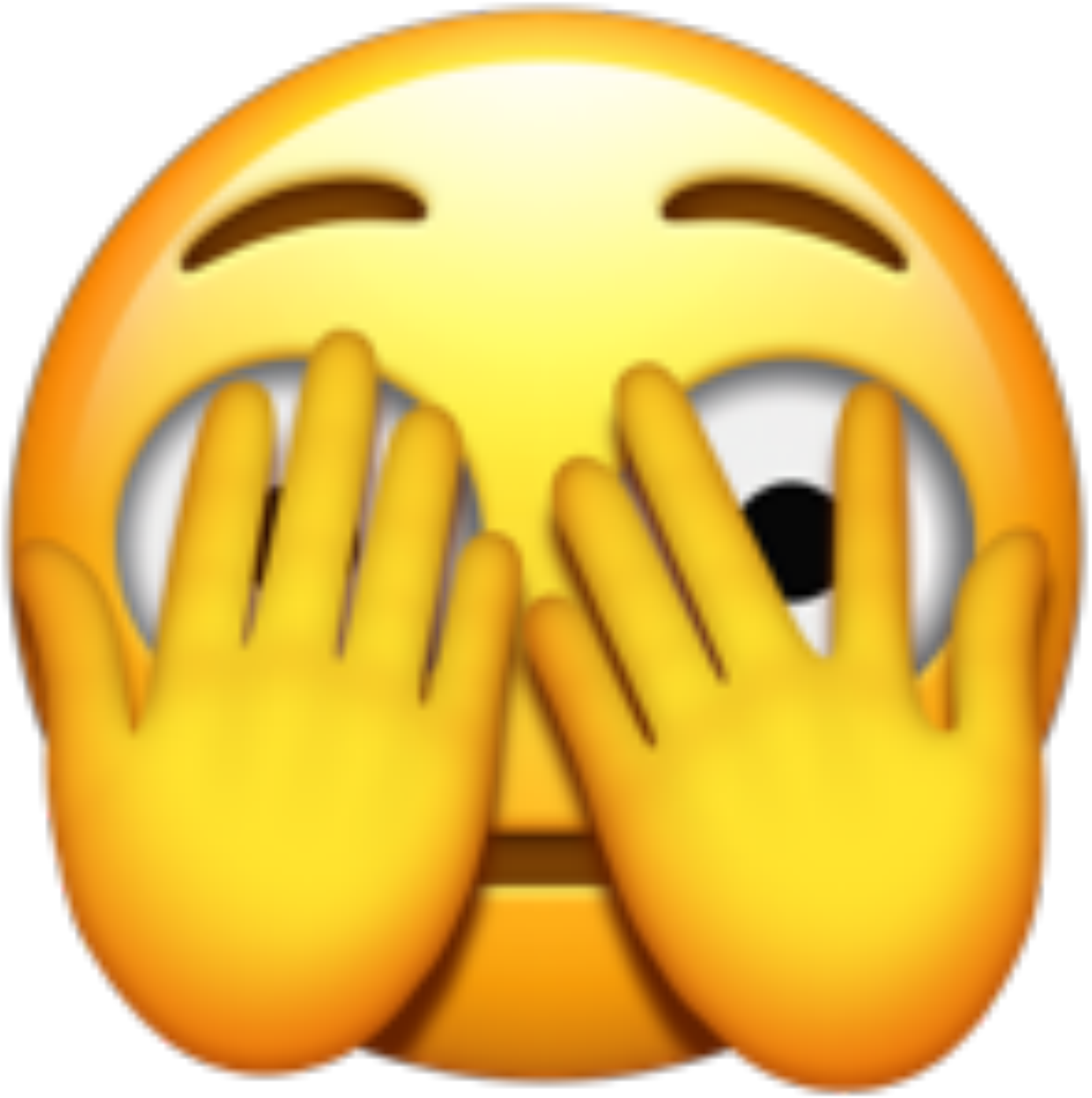
```
run Scenario1 {
  some f : File, l : Label | create[f]; affix[f,l]; delete[f]
} expect 1

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

run Sc
  some
} expe
```

```
Executing "Run Scenario4 expect 1"
   Solver=minisat(jni) Steps=1..10 Bitwidth=4 MaxSeq=4 SkolemDepth=1 Symmetry=OFF Mode=batch
   2..10 steps. 72419 vars. 1791 primary vars. 158243 clauses. 453ms.
   No instance found. Predicate may be inconsistent, contrary to expectation. 16ms.
```

```
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

```
pred labelled [f : File] {
  some l : Label | f in find[l]
}

pred exists [f : File] {
  f in Accessible+Trashed
}

fact Synchronization {
  // Allow affixing only if file is exists
  all f : File, l : Label | always (affix[f,l] implies exists[f])

  // Clear all labels after file is permanently deleted
  all f : File | always {
    f in Trashed and empty and labelled[f] implies after clear[f]
      ((some t : File | not exists[t] and labelled[t] and clear[t]) until clear[f])
  }
}
```



Filesystem v3

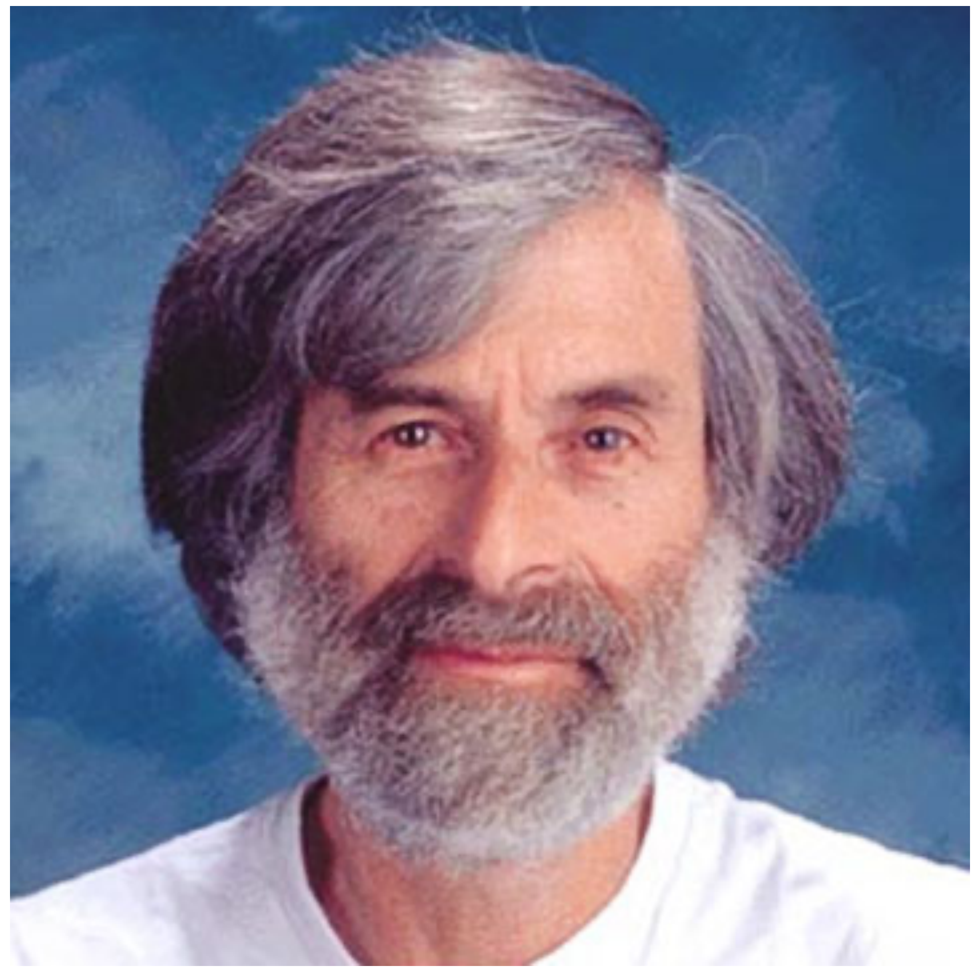
- Allow labelling when accessible or trashed
- Clear labels when file is permanently deleted
- Affix special label Trashed when file is deleted
- Detach special label Trashed when file is restored

Filesystem v3

```
one sig Trashed extends Label {}

fact Synchronization {
  // Allow affixing only if file is exists
  all f : File, l : Label | always (affix[f,l] implies exists[f])

  // Clear all labels after file is permanently deleted
  all f : File | always {
    f in Trashed and empty and labelled[f] implies after
      ((some t : File | not exists[t] and labelled[t] and clear[t]) until clear[f])
  }

  // Affix label Trashed when deleting
  all f : File | always (delete[f] and f not in find[Trashed] implies after affix[f,Trashed])

  // Detach label Trashed when restoring
  all f : File | always (restore[f] and f in find[Trashed] implies after detach[f,Trashed])
}
```

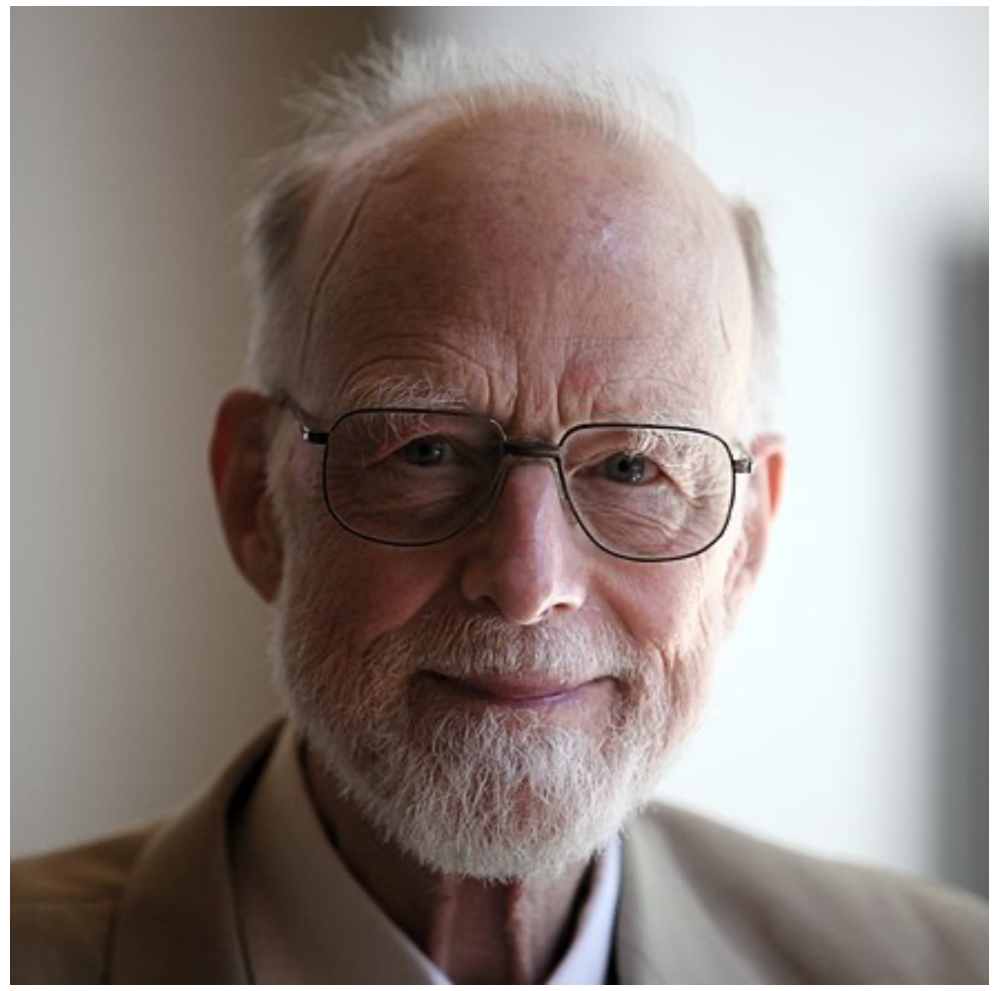
Epilogue

“A specification is an *abstraction*. It describes some aspects of the system and ignores others. [...] 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