Verification of Implementations of Distributed Systems under Churn

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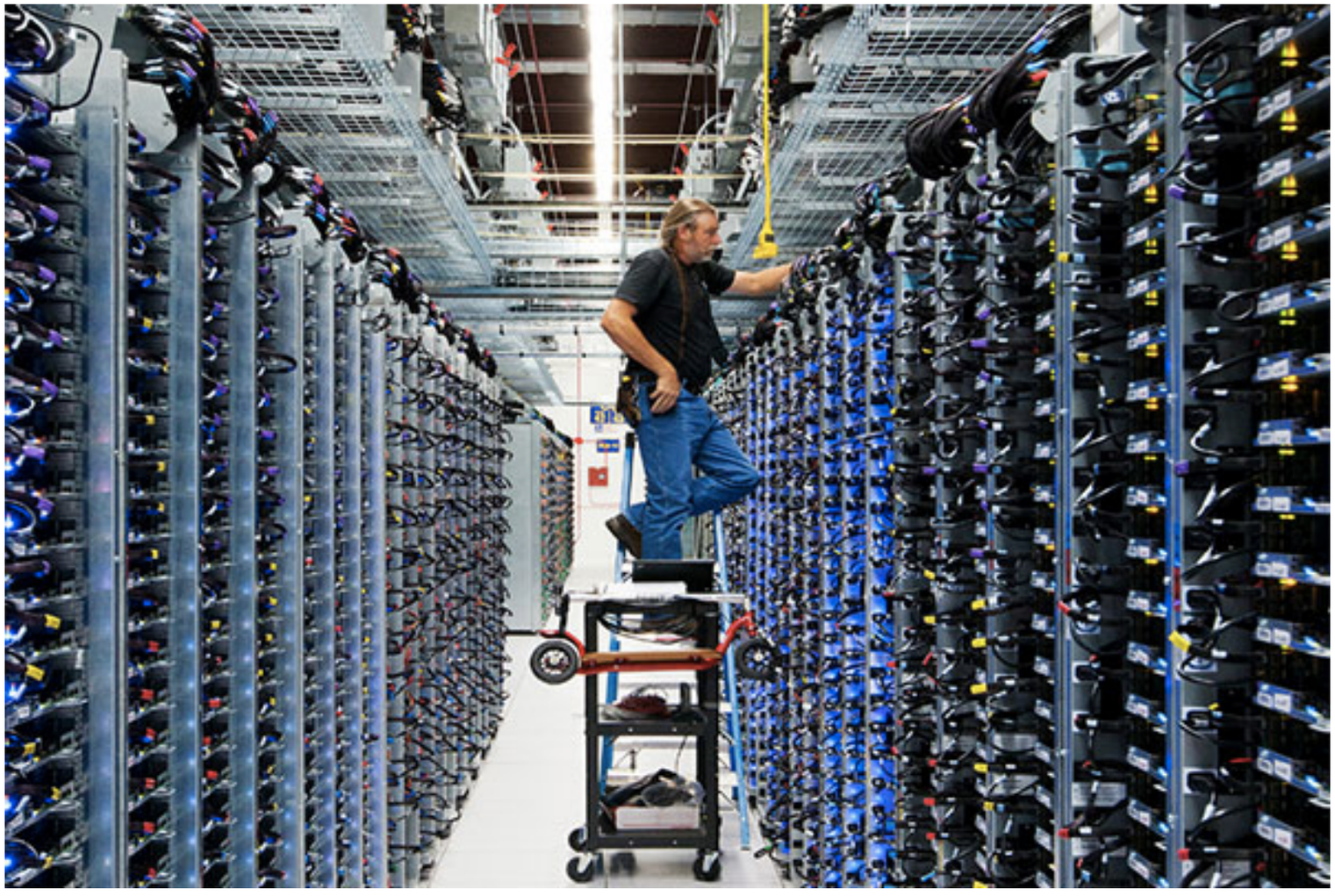
We should verify implementations of distributed systems...



...and we have!

Framework	*Prover*	*Verified system*
Verdi	Coq	Raft consensus
IronFleet	Dafny	Paxos consensus
EventML	NuPRL	Paxos consensus
Chapar	Coq	Key-value stores

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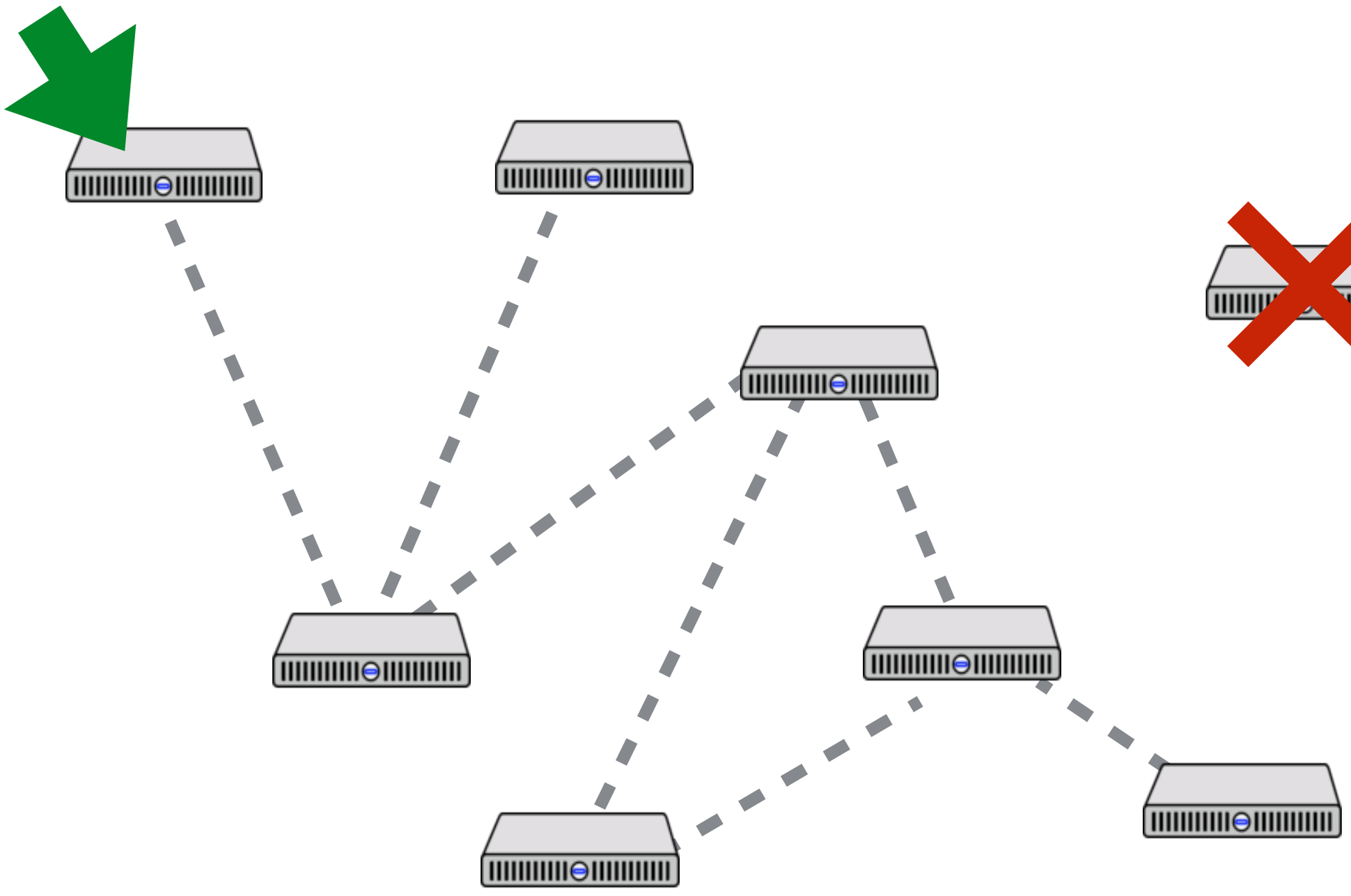
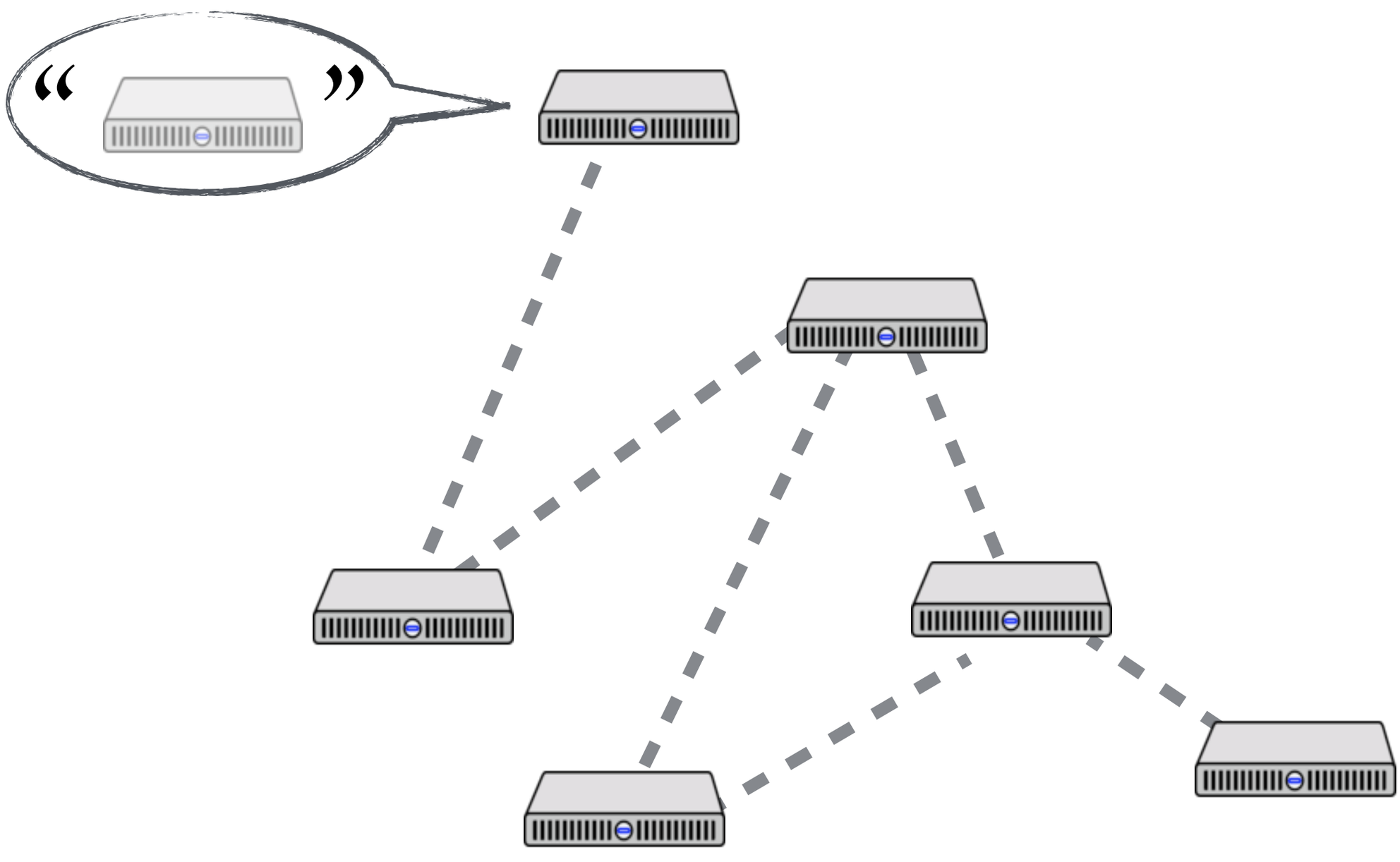
Assumption: each node has a list of all nodes in the system

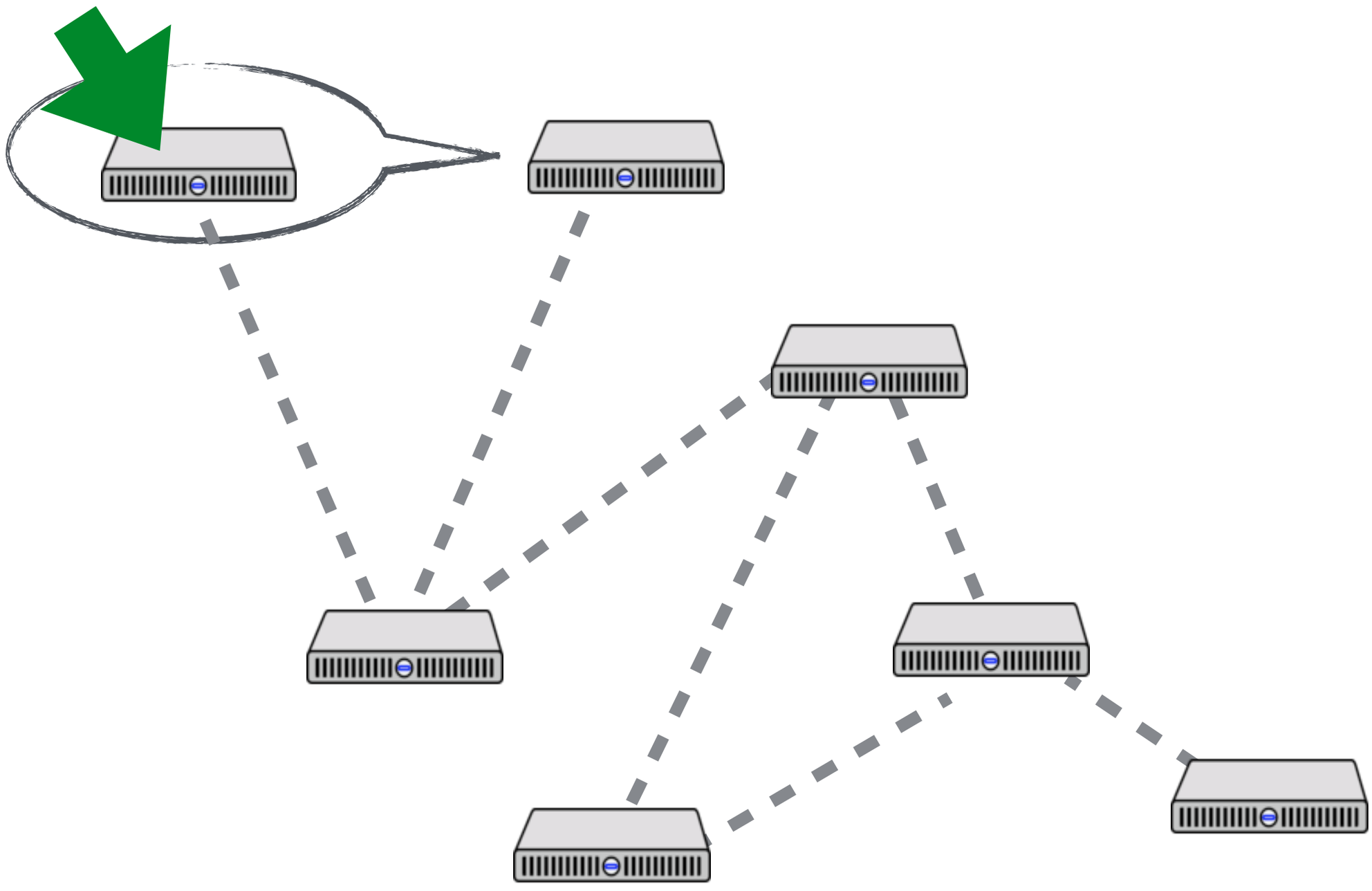
Churn = nodes joining & leaving a system at run time



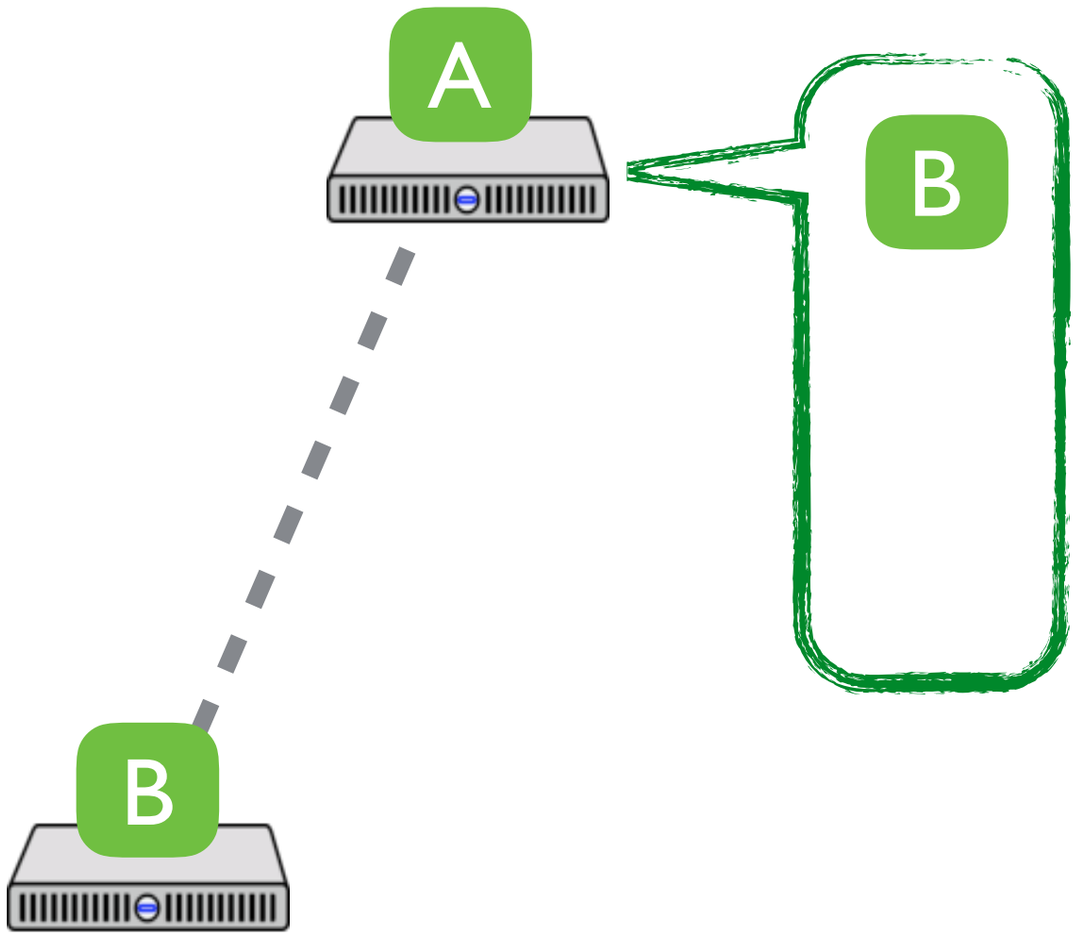
Existing frameworks don't distinguish between knowing *an* address



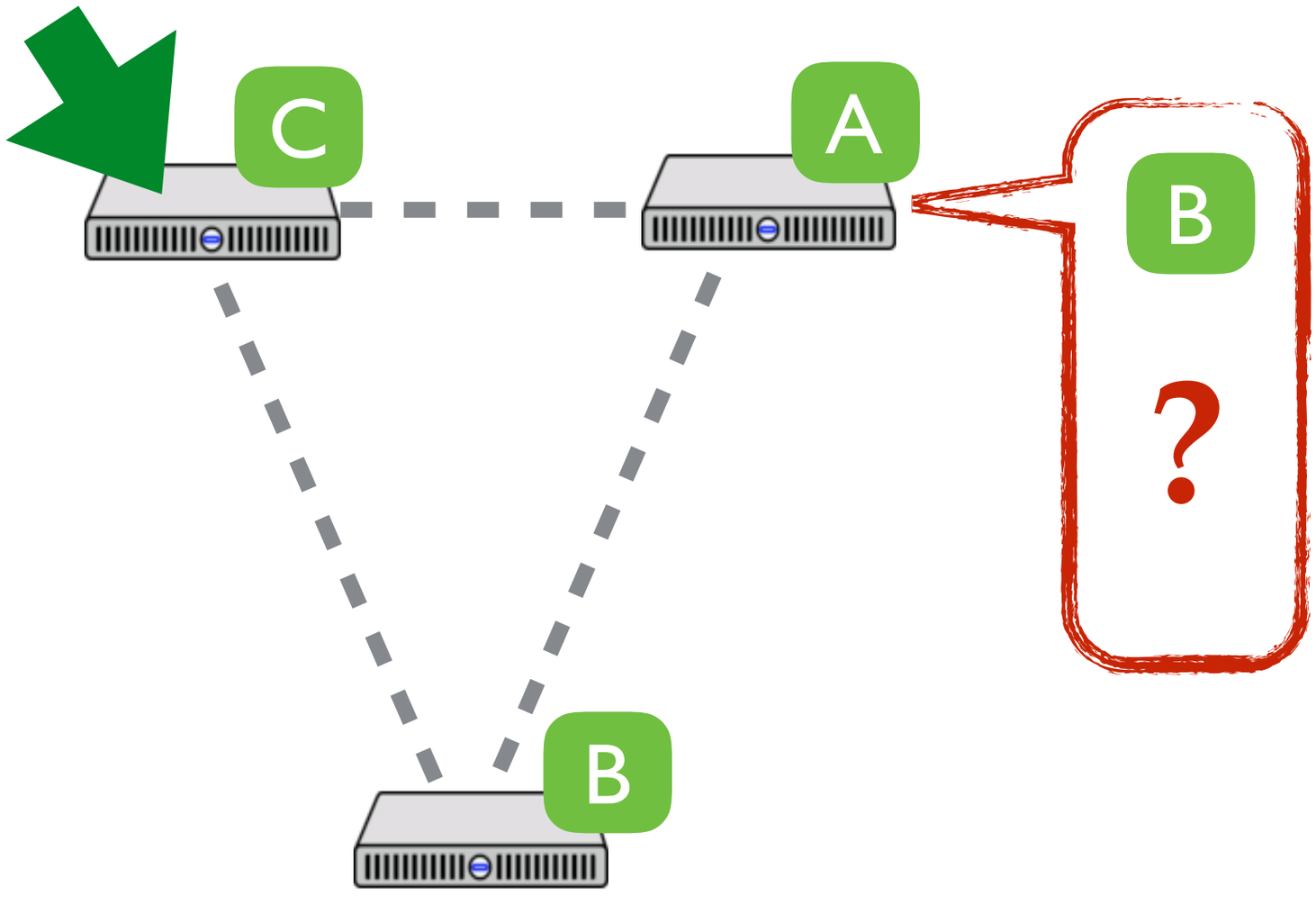
and knowing *a node*'s address.



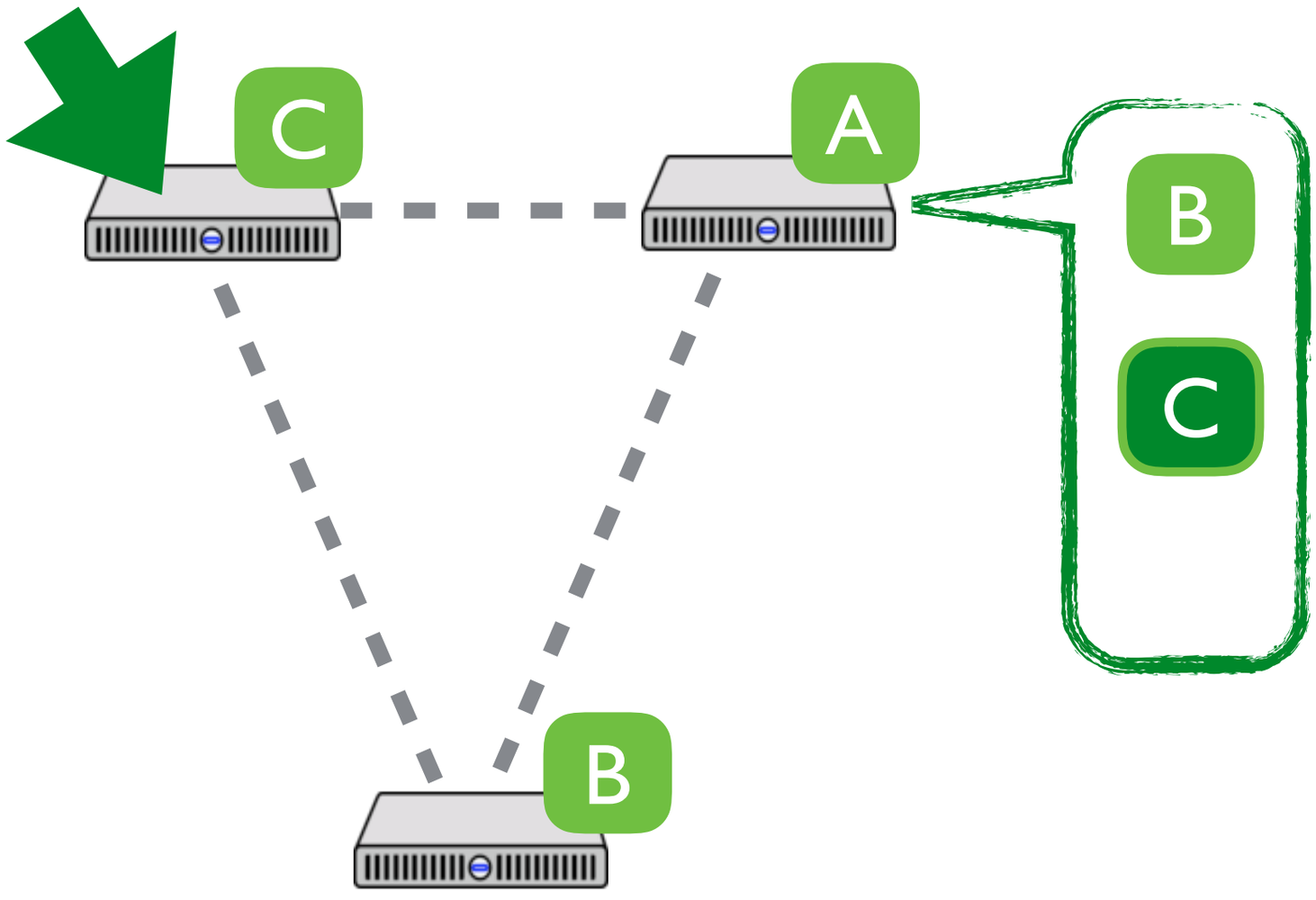
Under churn, systems depend on a "routing table"



But it can't be correct all of the time!



It can only be correct given enough time without churn: *punctuated safety*



Our contributions

1. First-class support for churn in Verdi
2. An approach to verifying punctuated safety
3. Ongoing case studies
   - Tree-aggregation protocol
   - Chord distributed hash table

Today

- The tree-aggregation protocol
- Churn in Verdi
- Proving punctuated safety

An example: counting nodes

These Pis live in Zach's office.

We need them for experiments.

They're subject to churn...

but they can count themselves!

Tree-aggregation: the idea

Combine distributed data into a single global measurement

Why not just ping every computer involved?

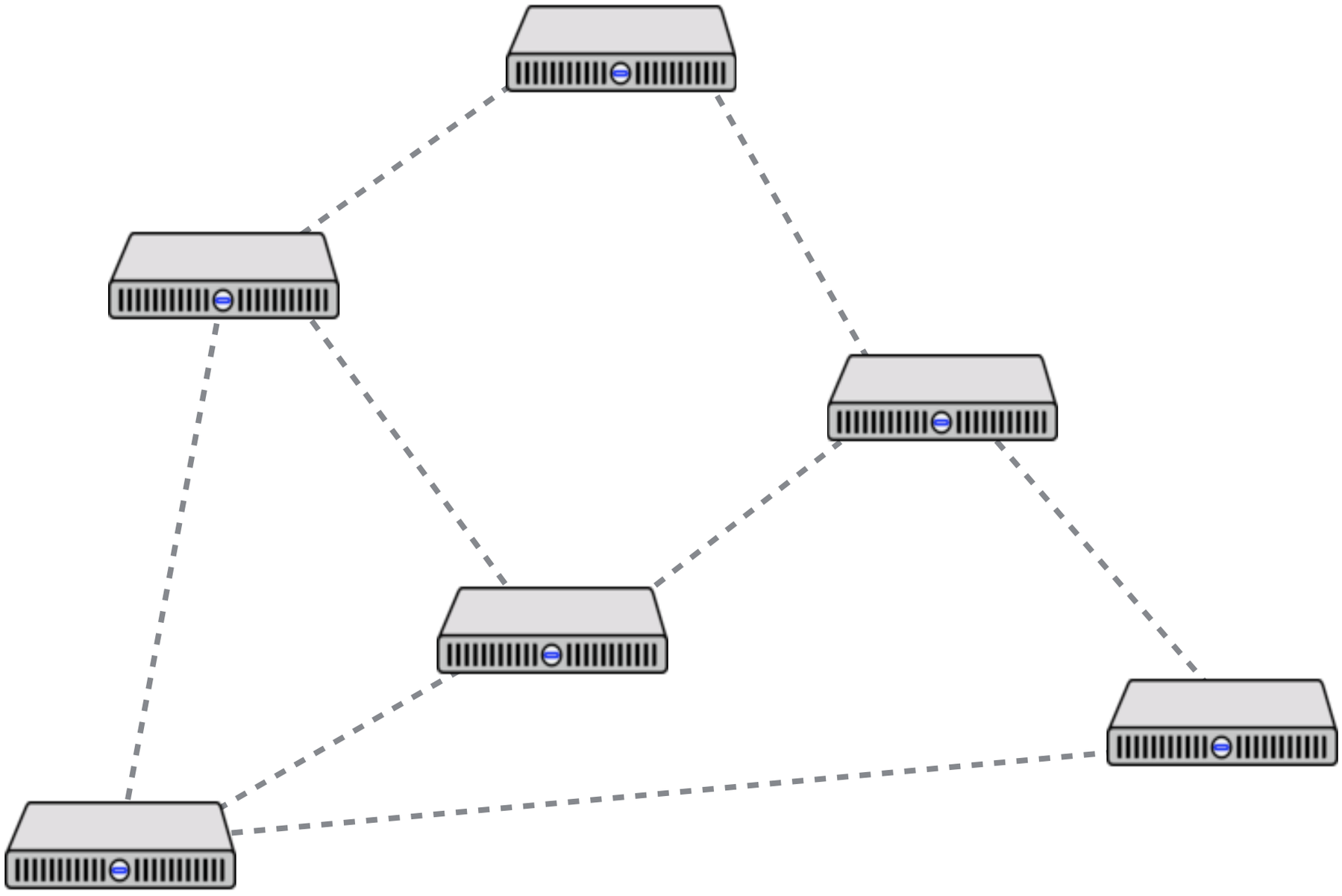
- No fixed list of nodes under churn
- The network may not be fully connected
- Can't handle large networks efficiently

Tree-aggregation: 2 protocols

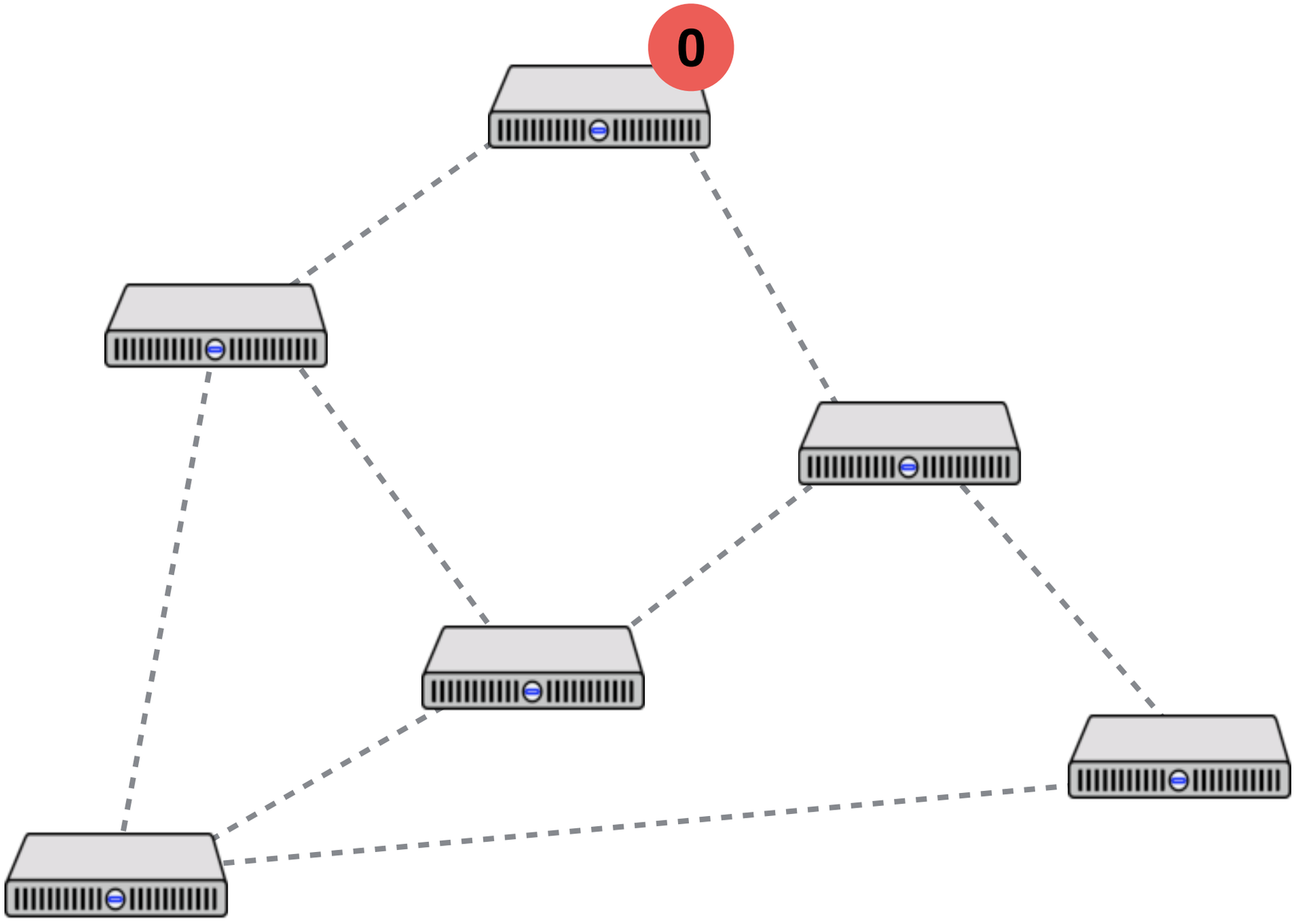
1. Tree building: constructing a tree in the network
2. Data aggregation: moving data towards the root of the tree

Counting Pis is a very simple example. The protocol can aggregate more interesting data.

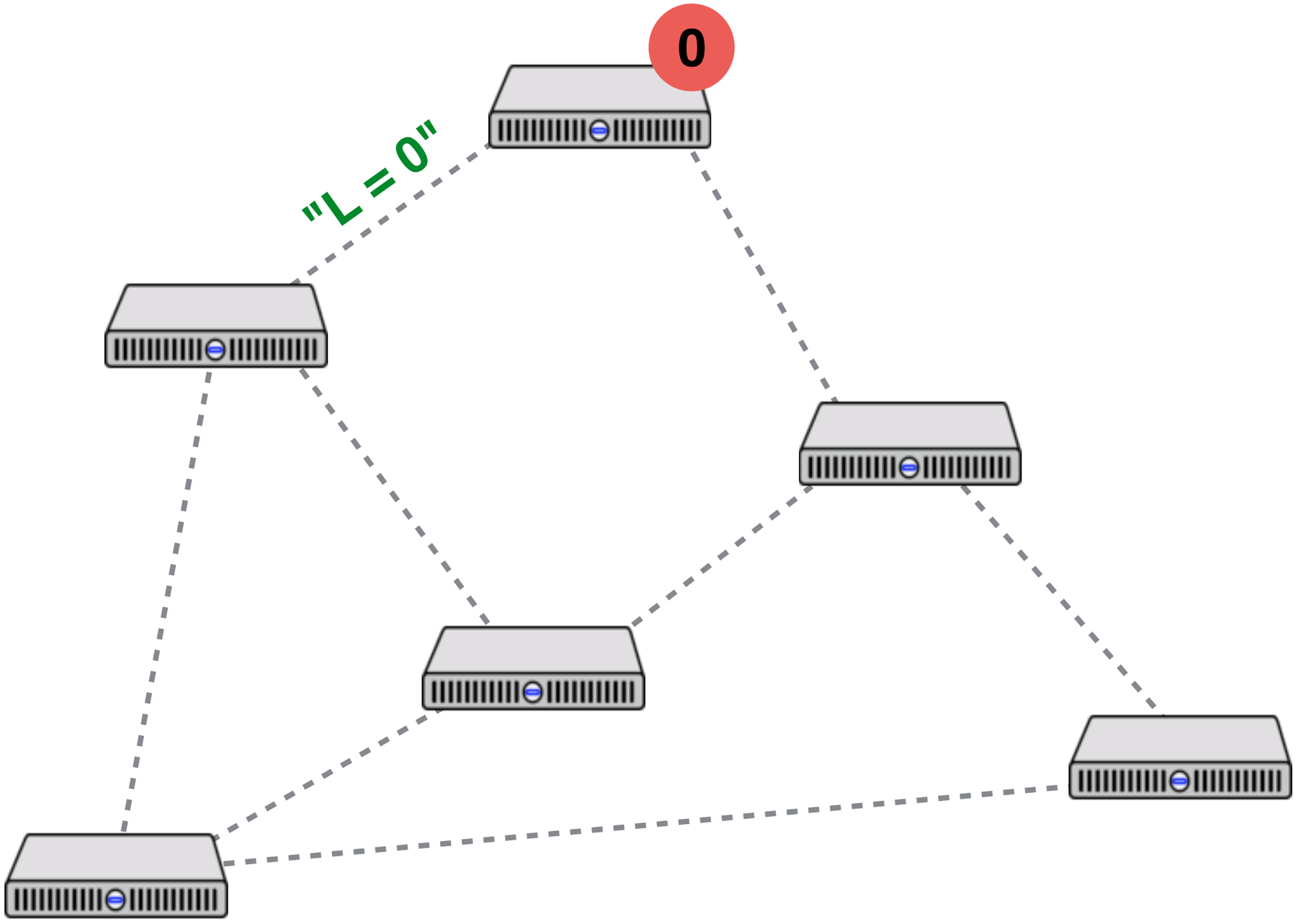
A network of nodes



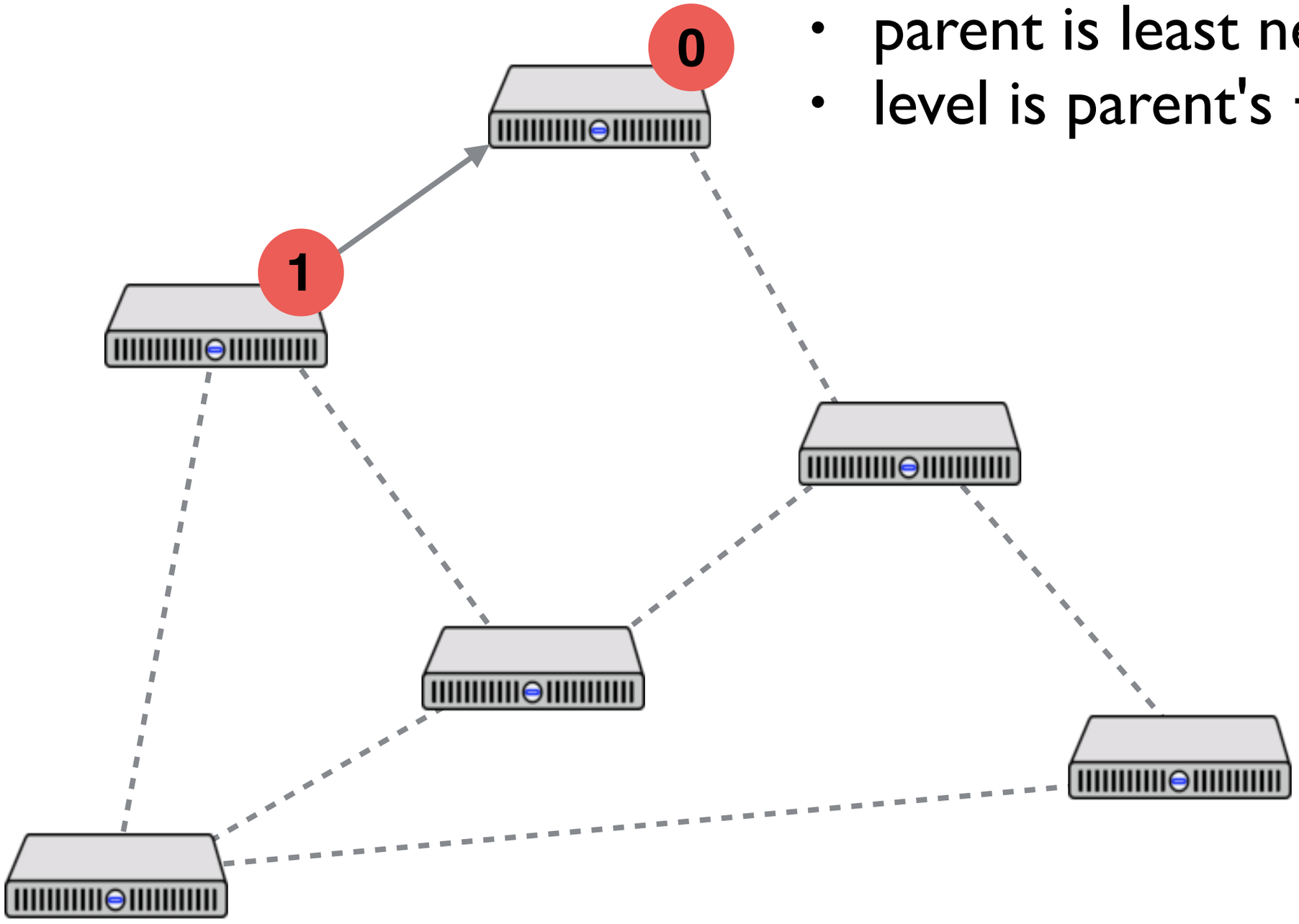
Tree building: a root



Tree building: broadcasting levels

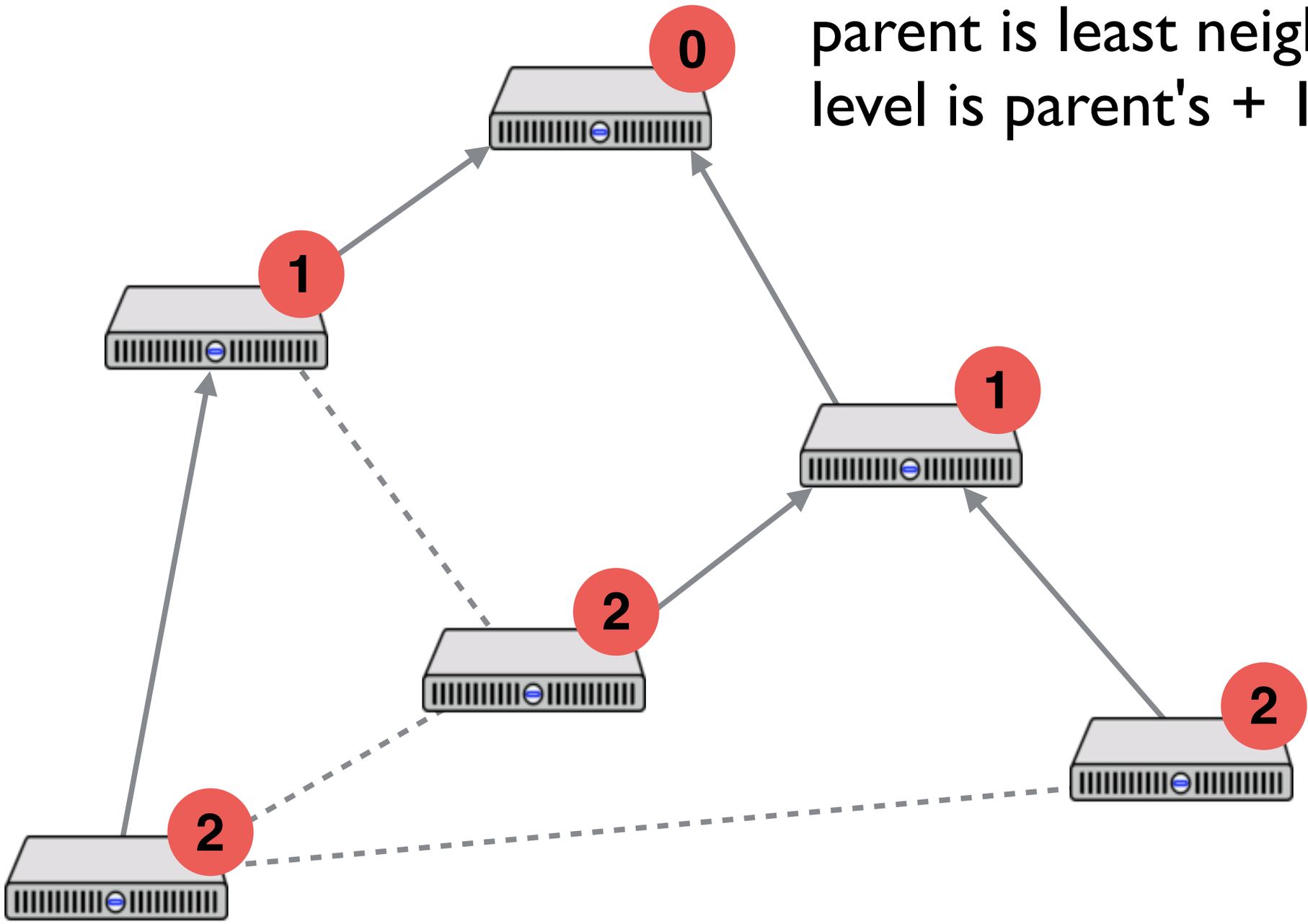


Tree building: broadcasting levels



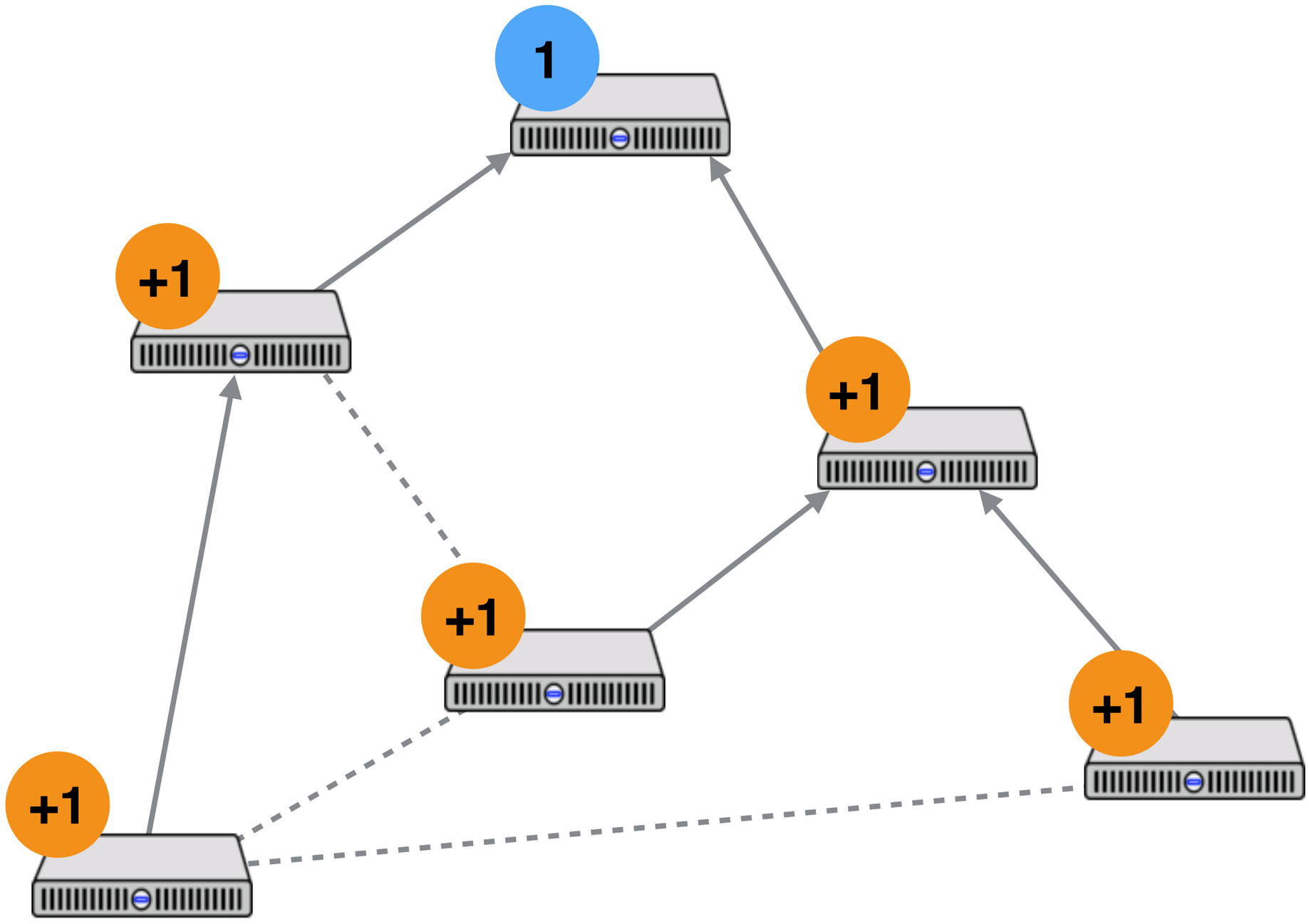
- parent is least neighbor
- level is parent's + 1

Tree building: broadcasting levels

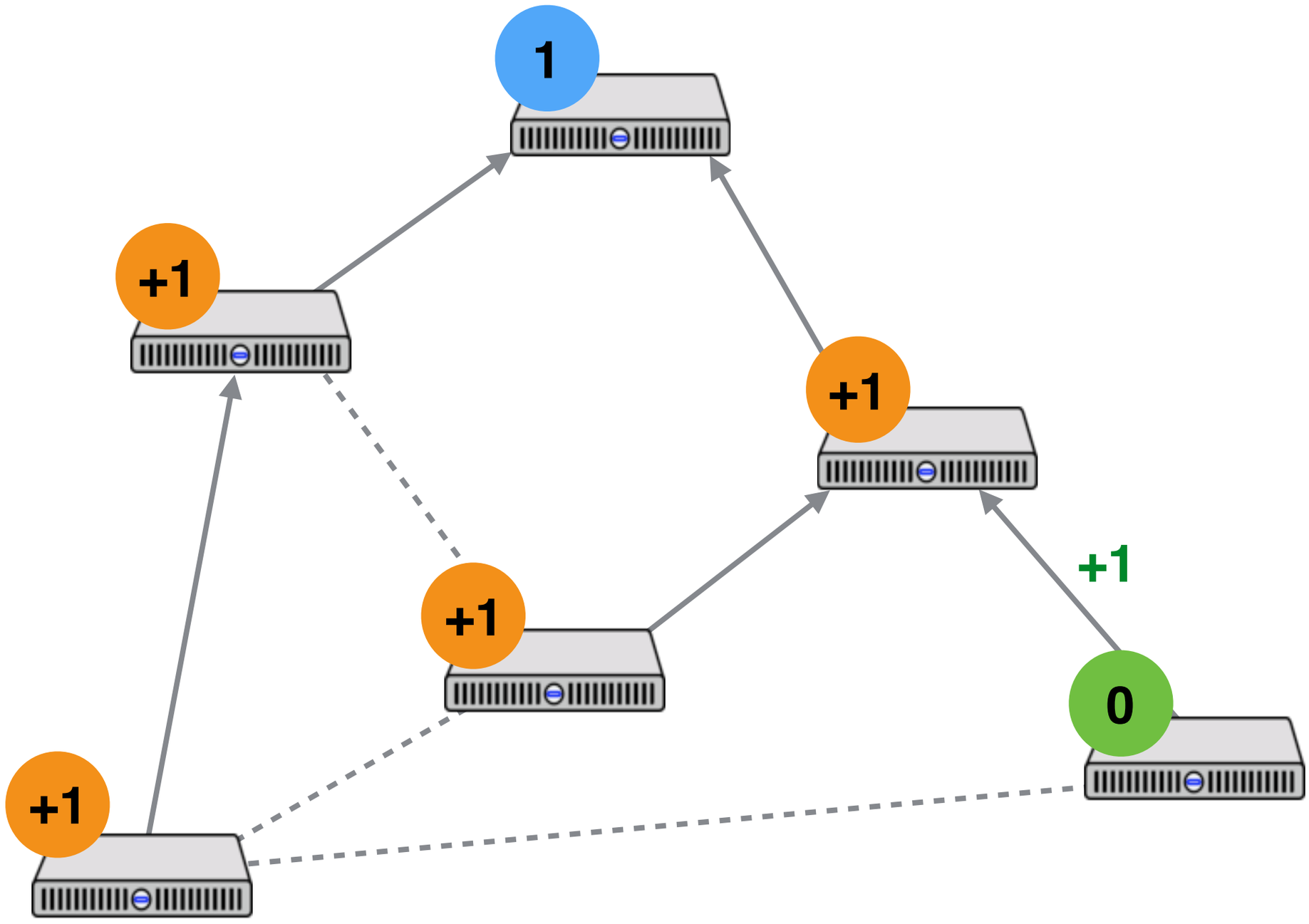


parent is least neighbor
level is parent's + 1

Aggregation: pending counts



Aggregation: send pending to parent



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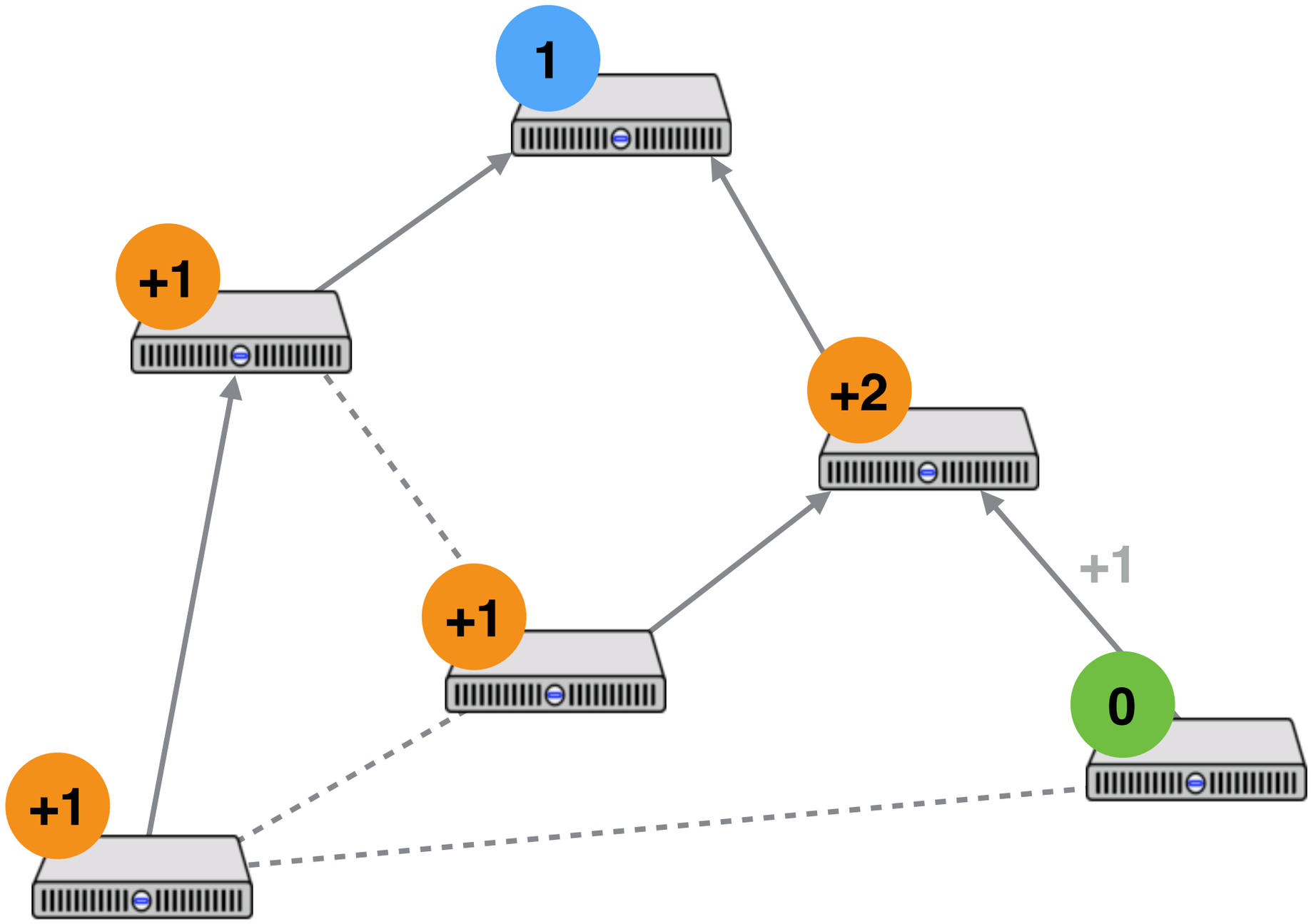
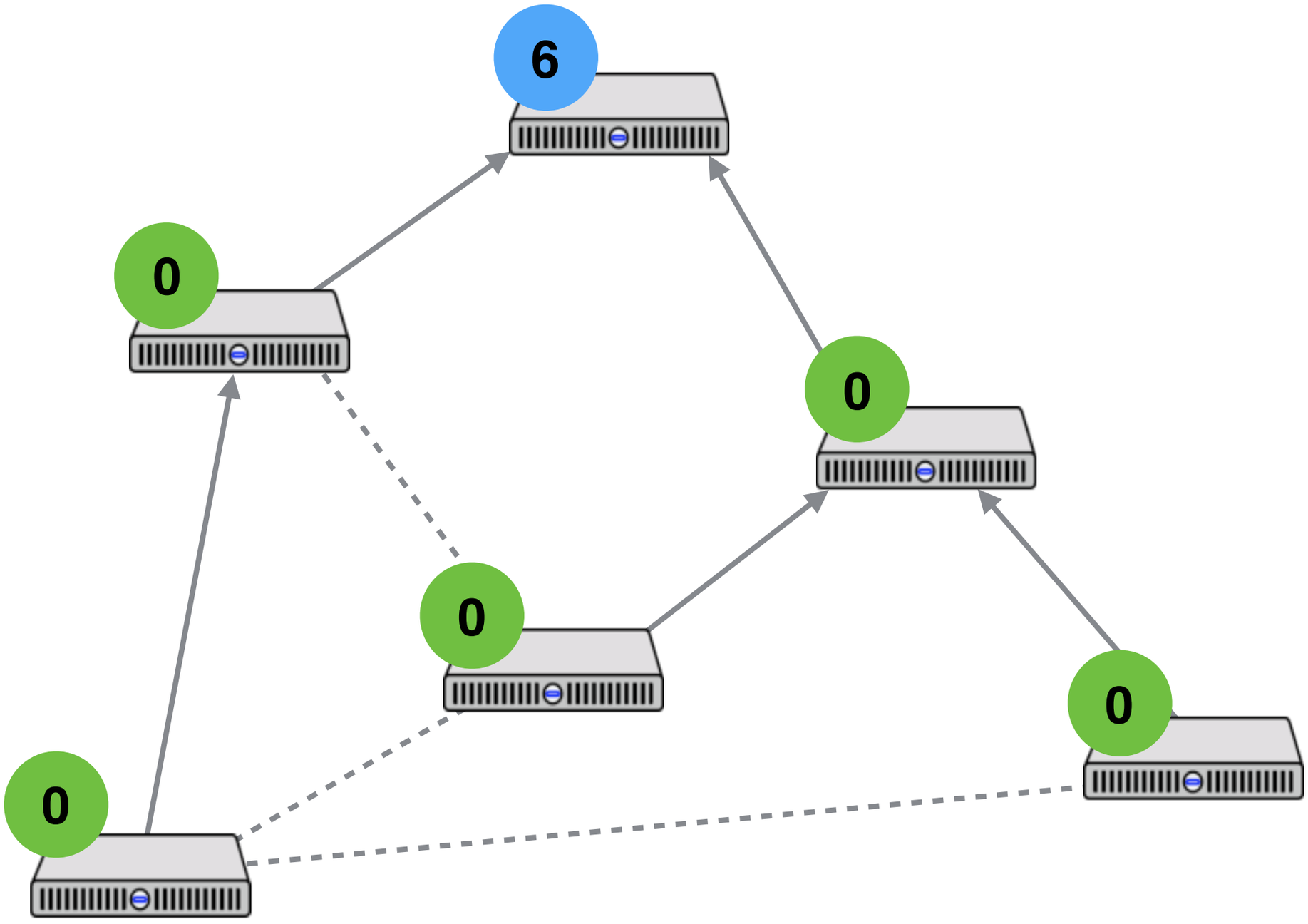
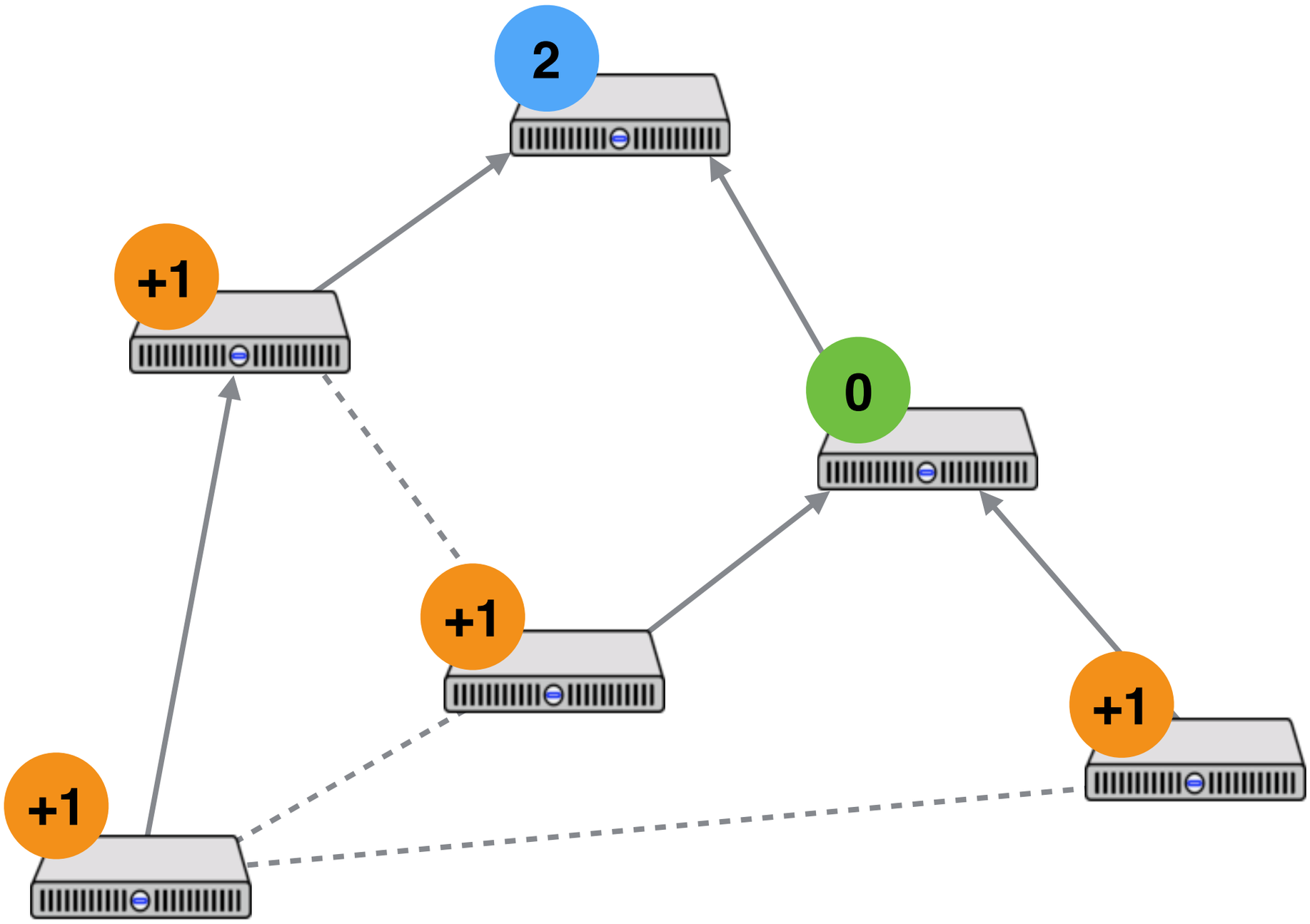


The root gets the total count



Handling churn: failures



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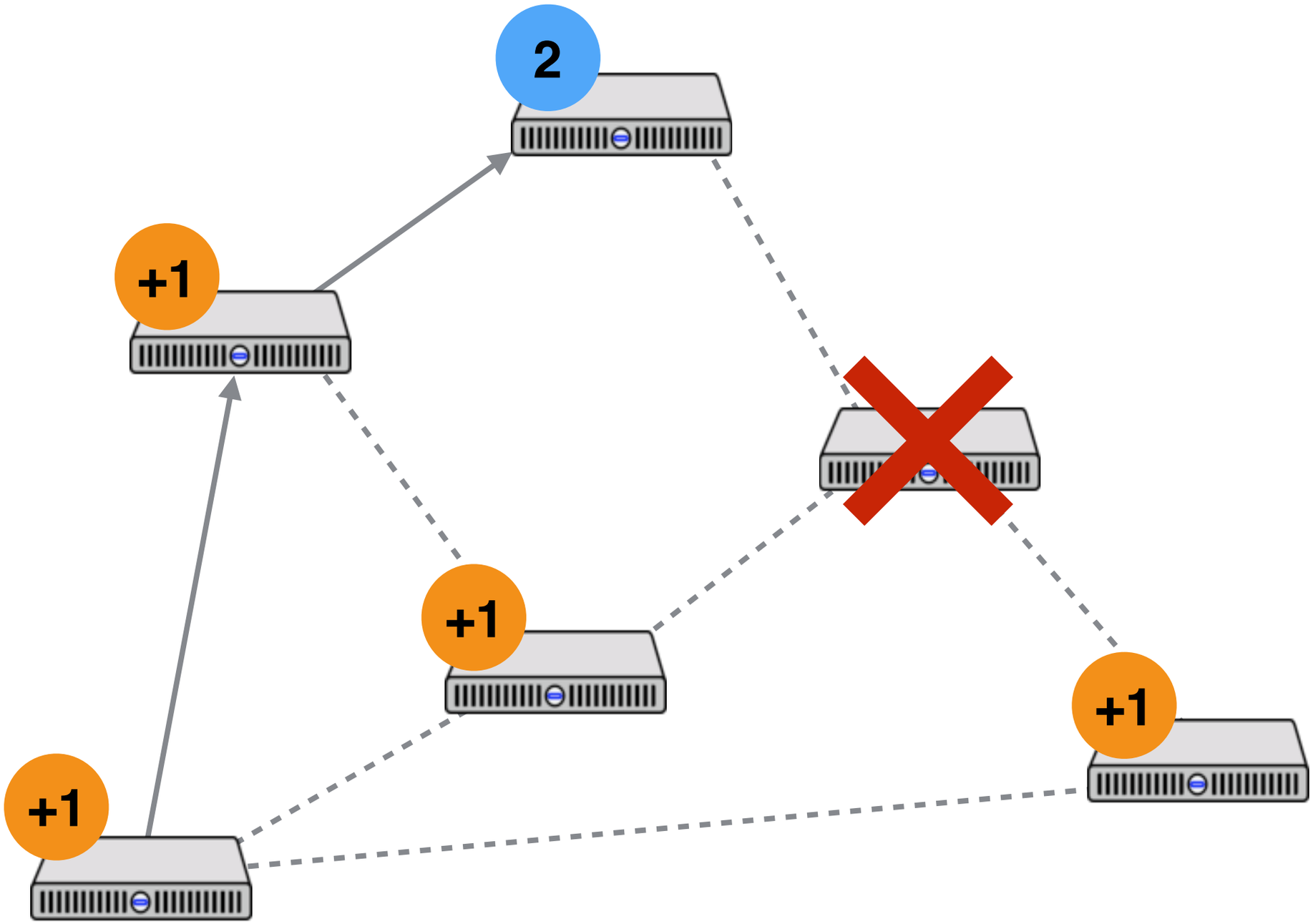

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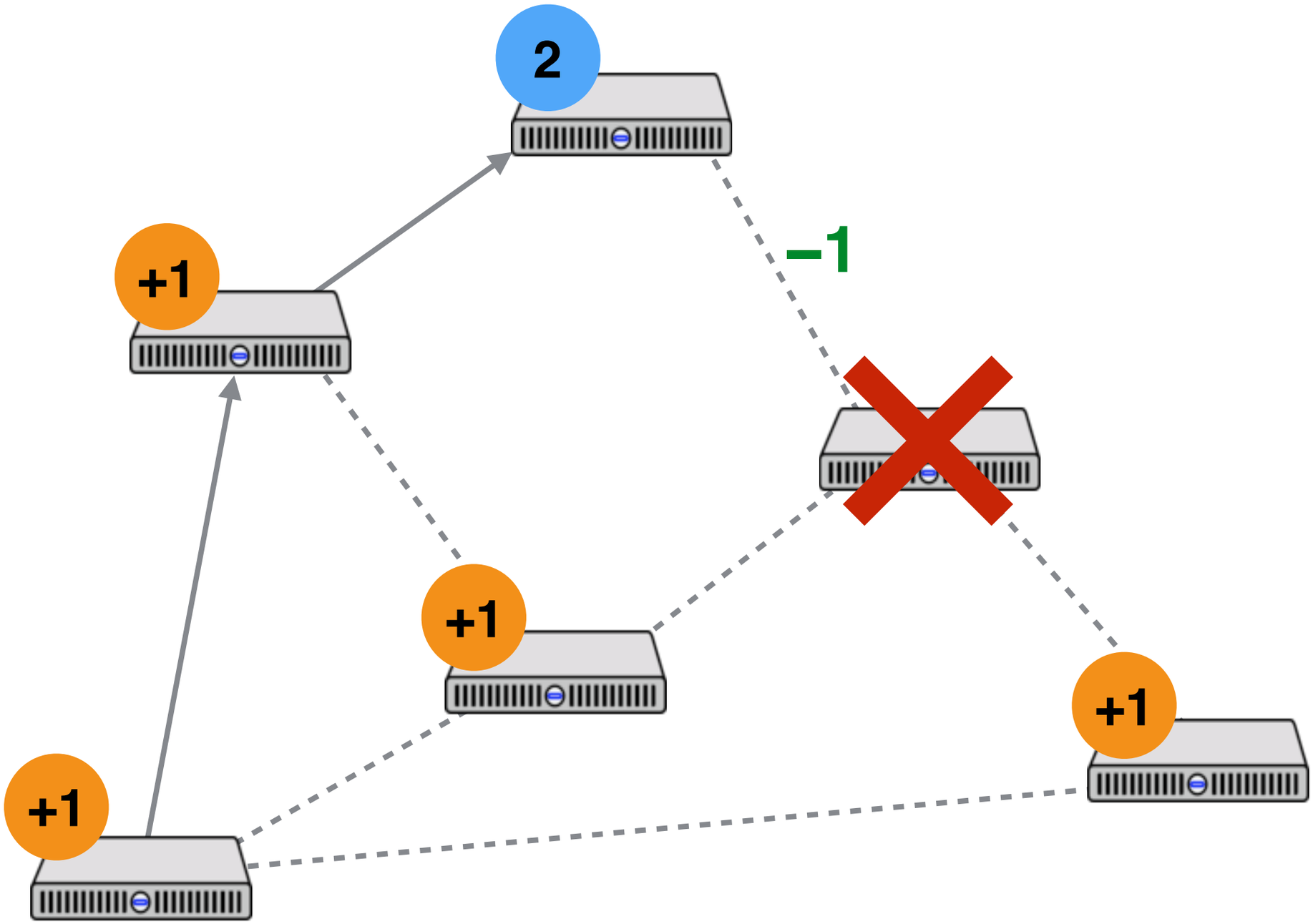

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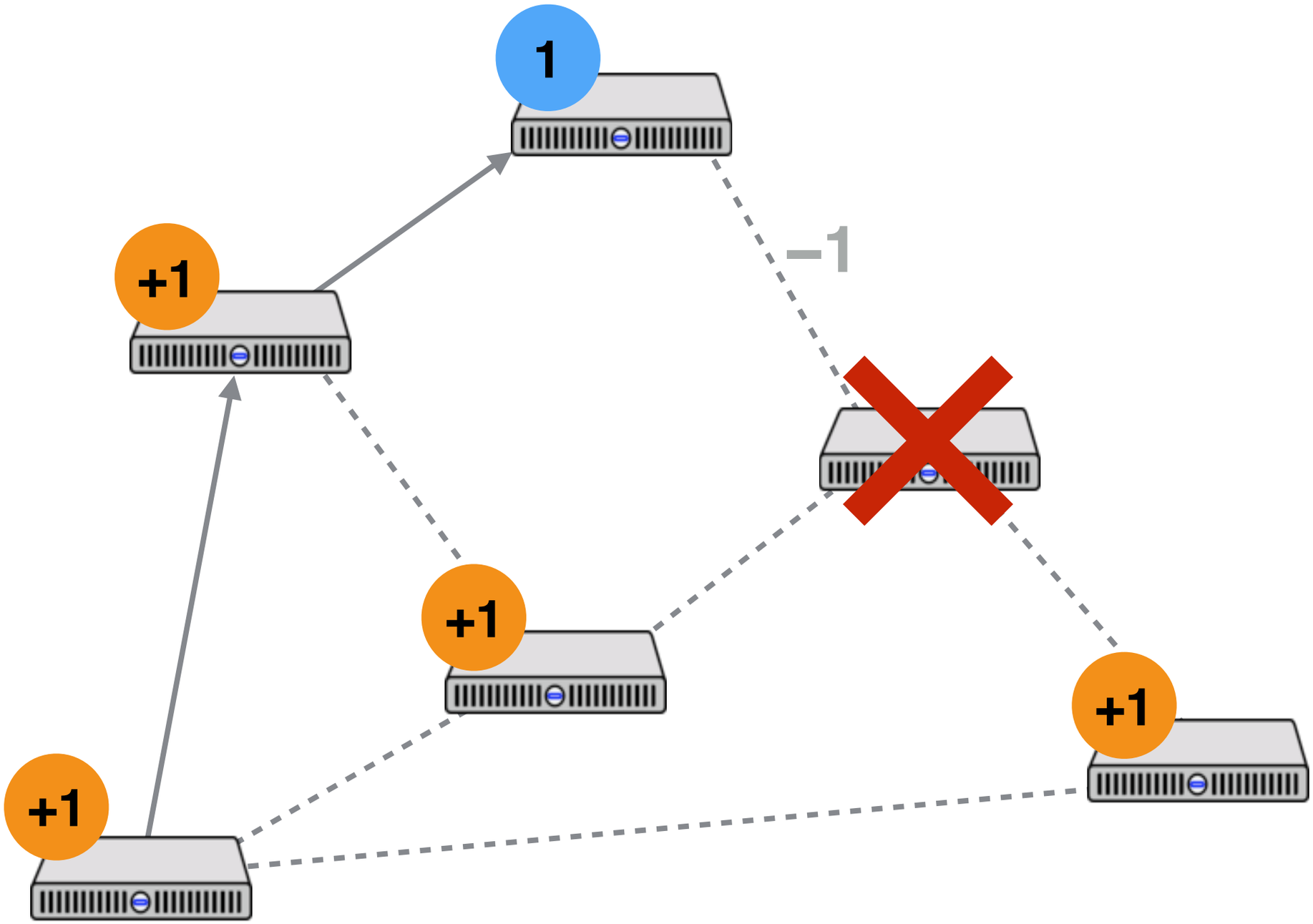

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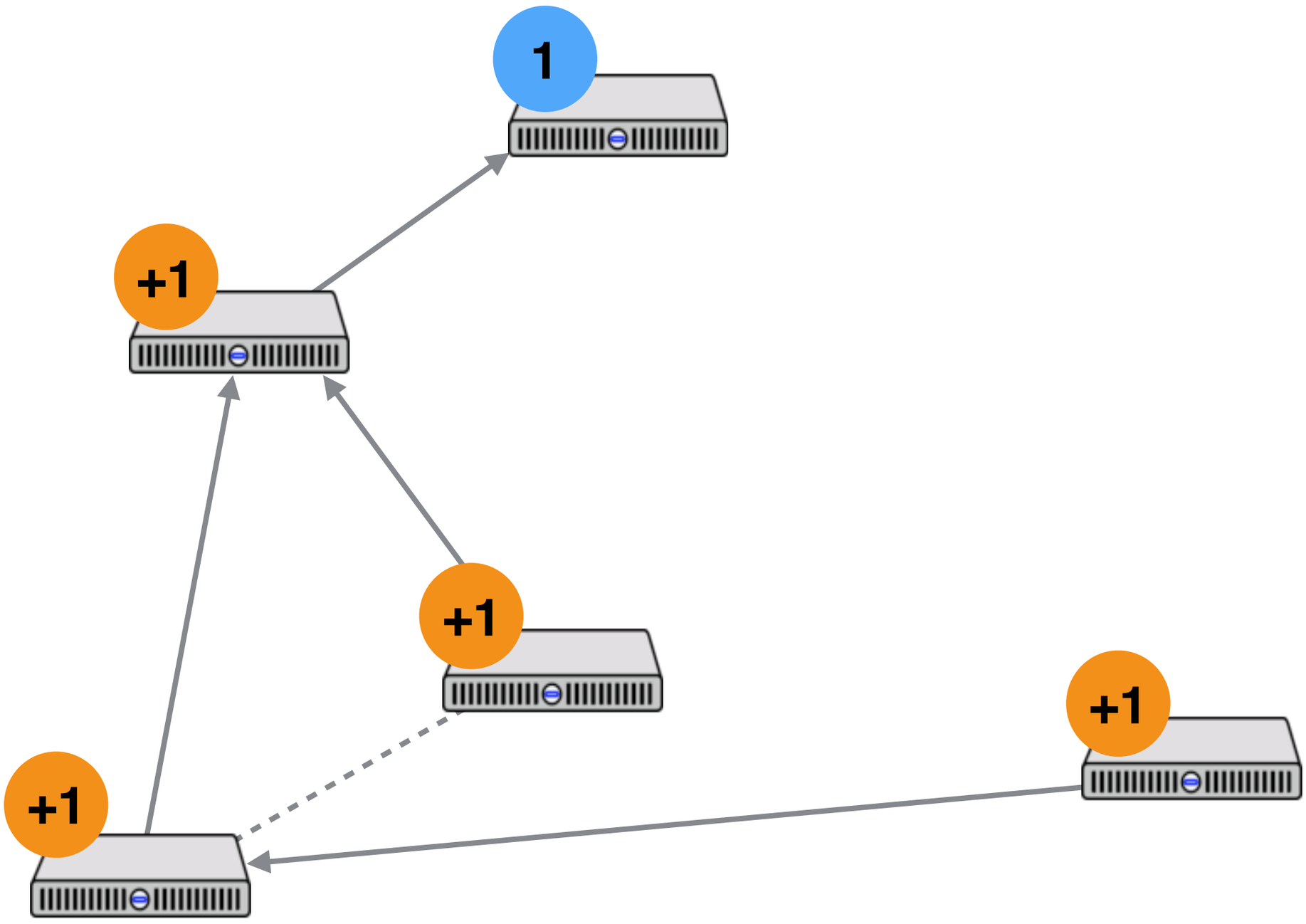
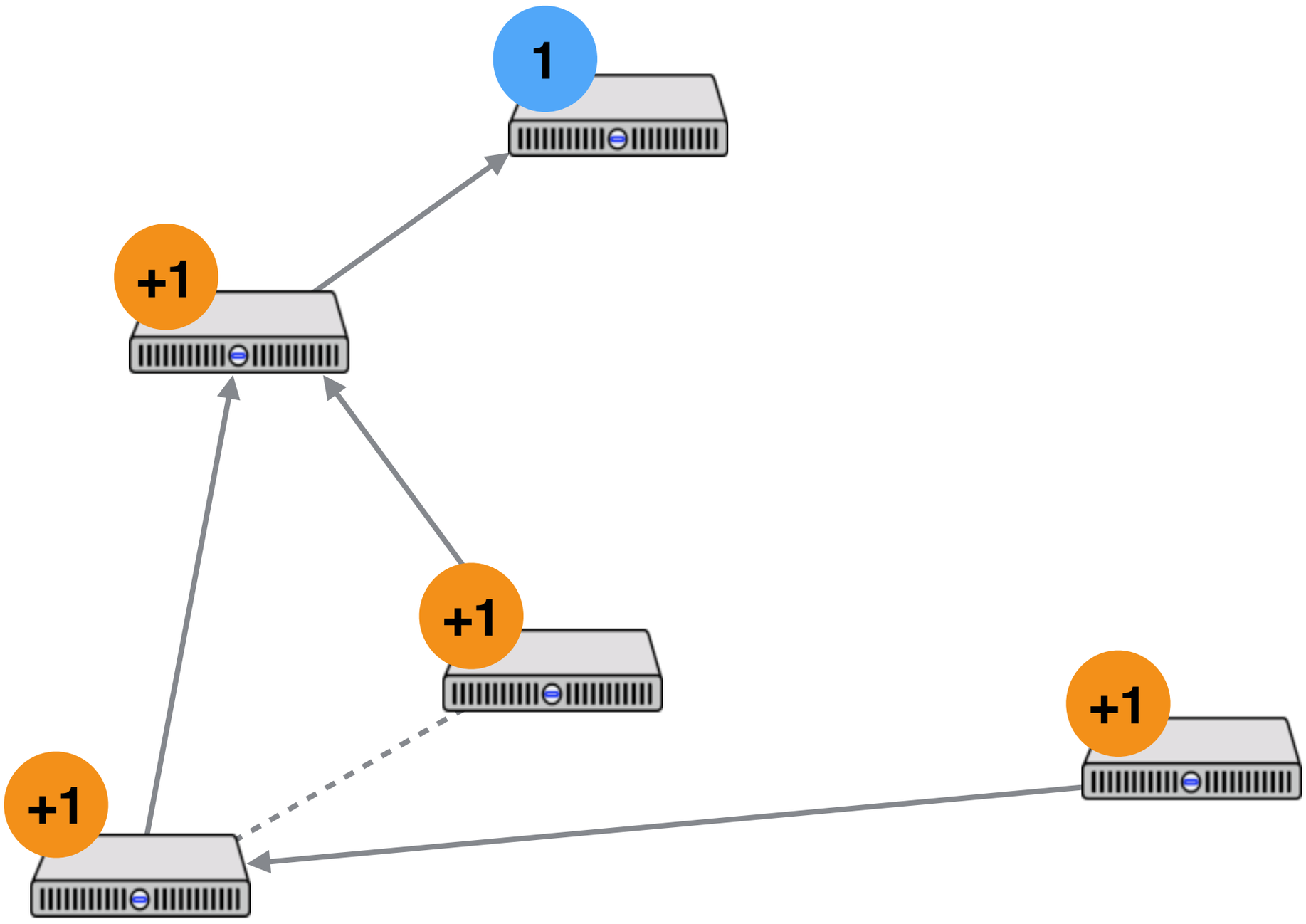


Handling churn: joins



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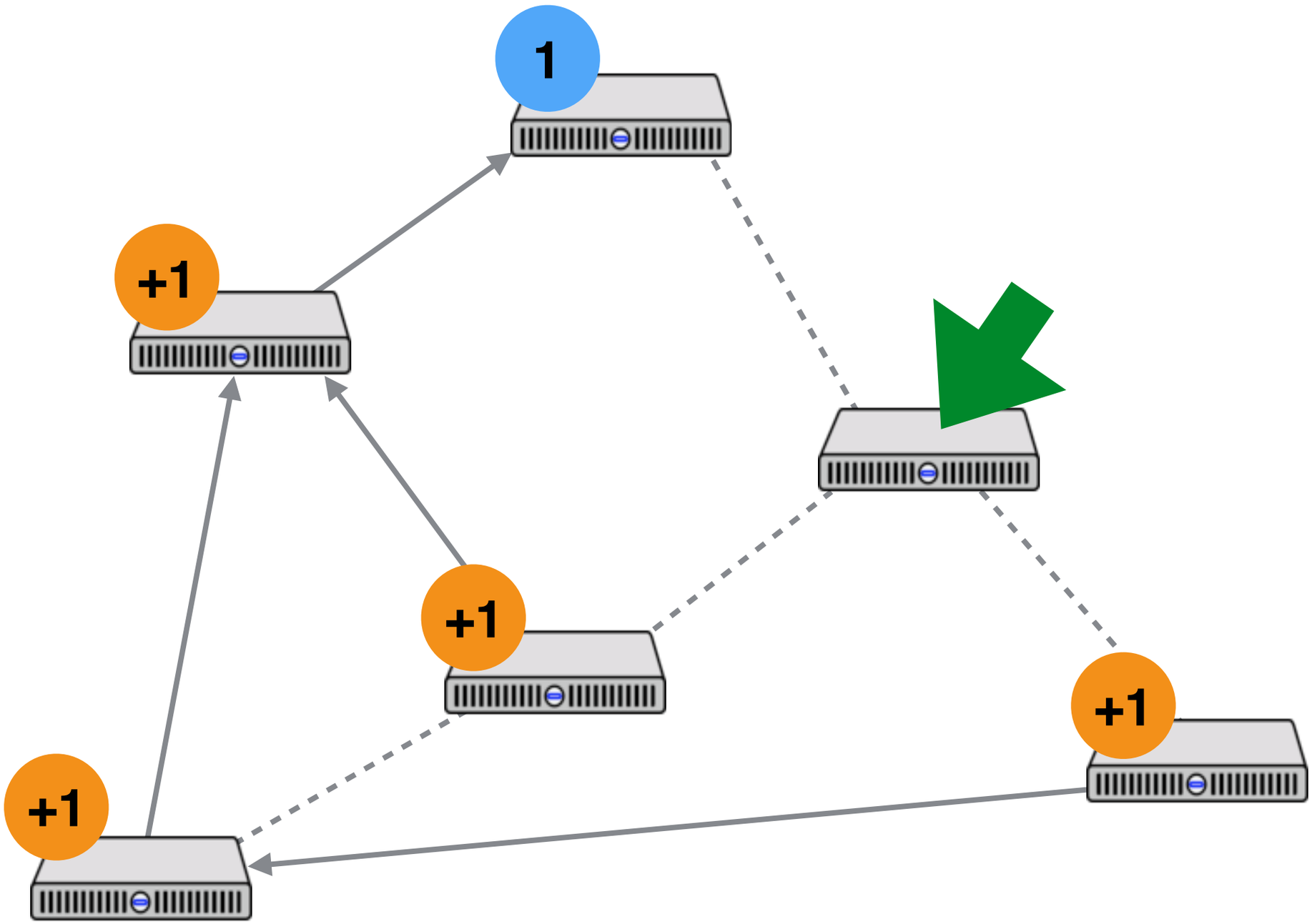

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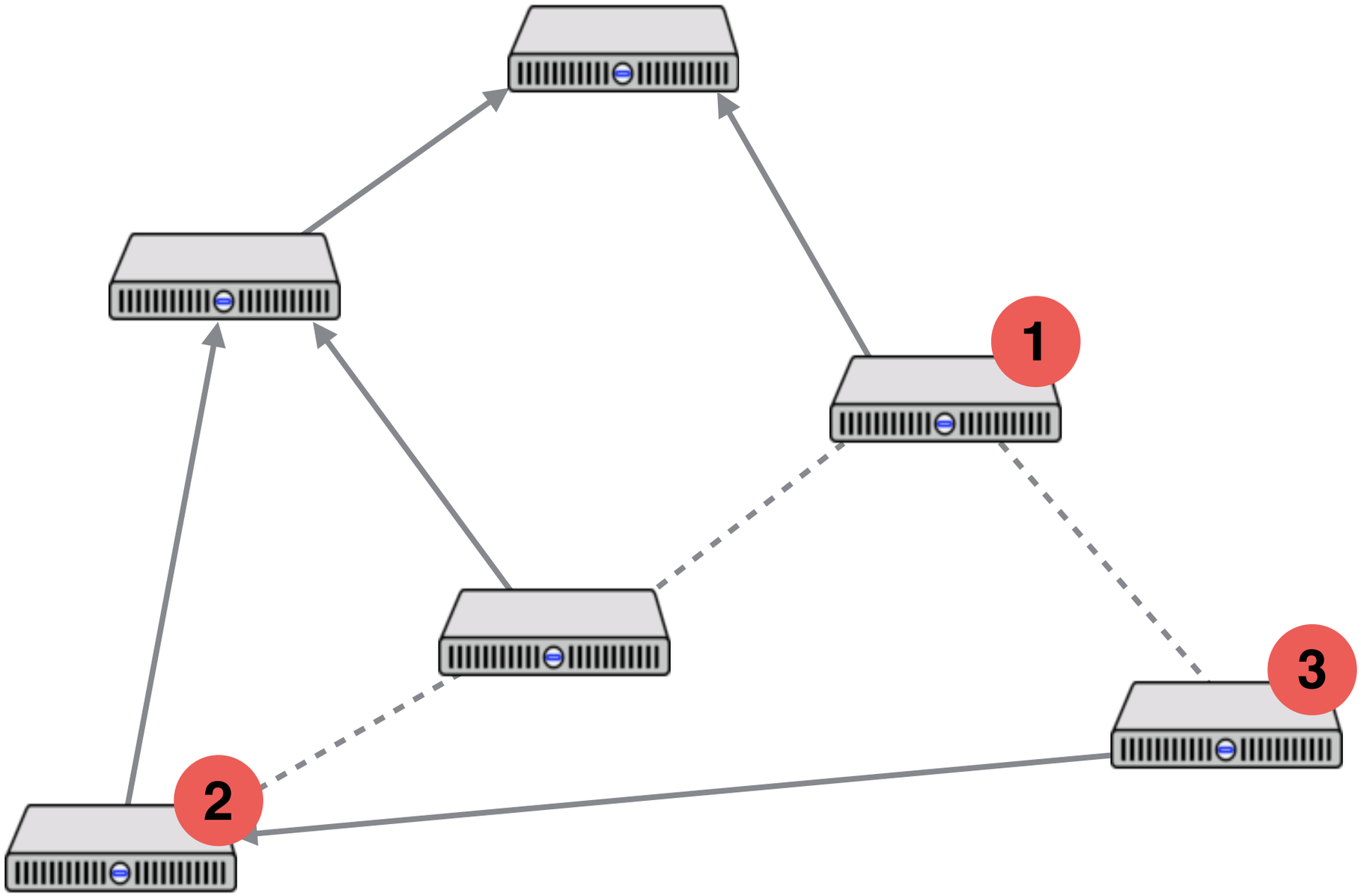

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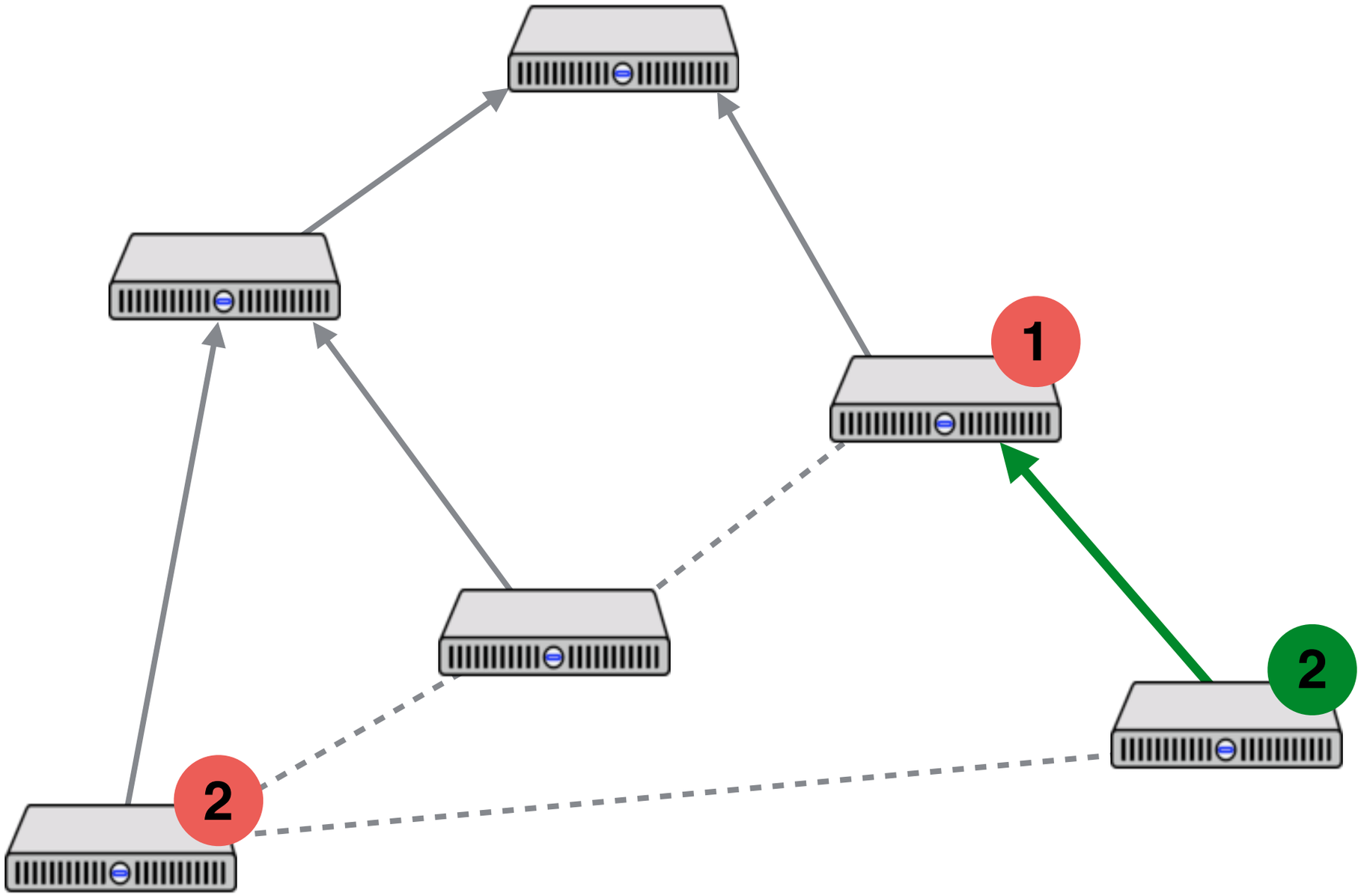
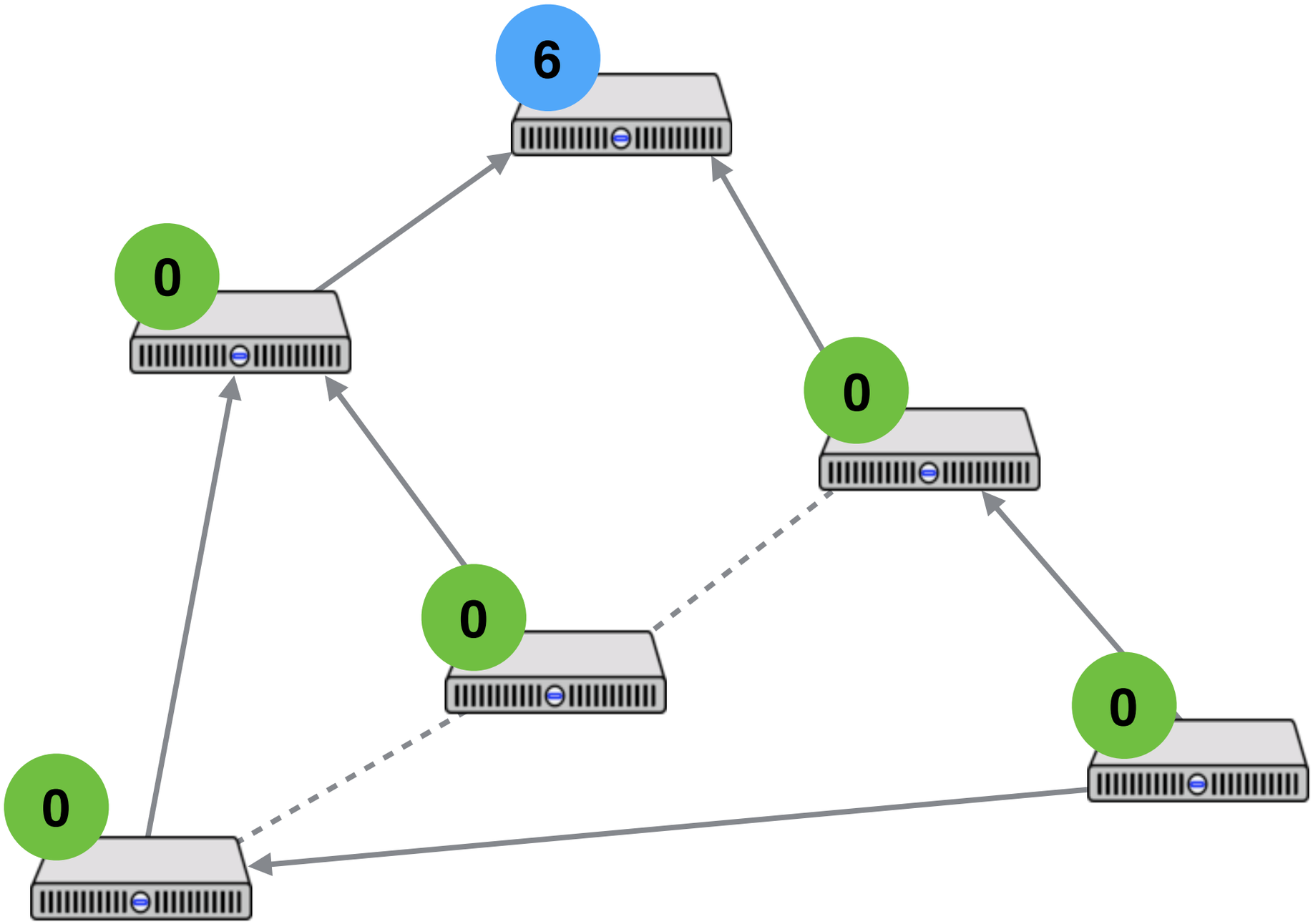


We can't finish counting during churn



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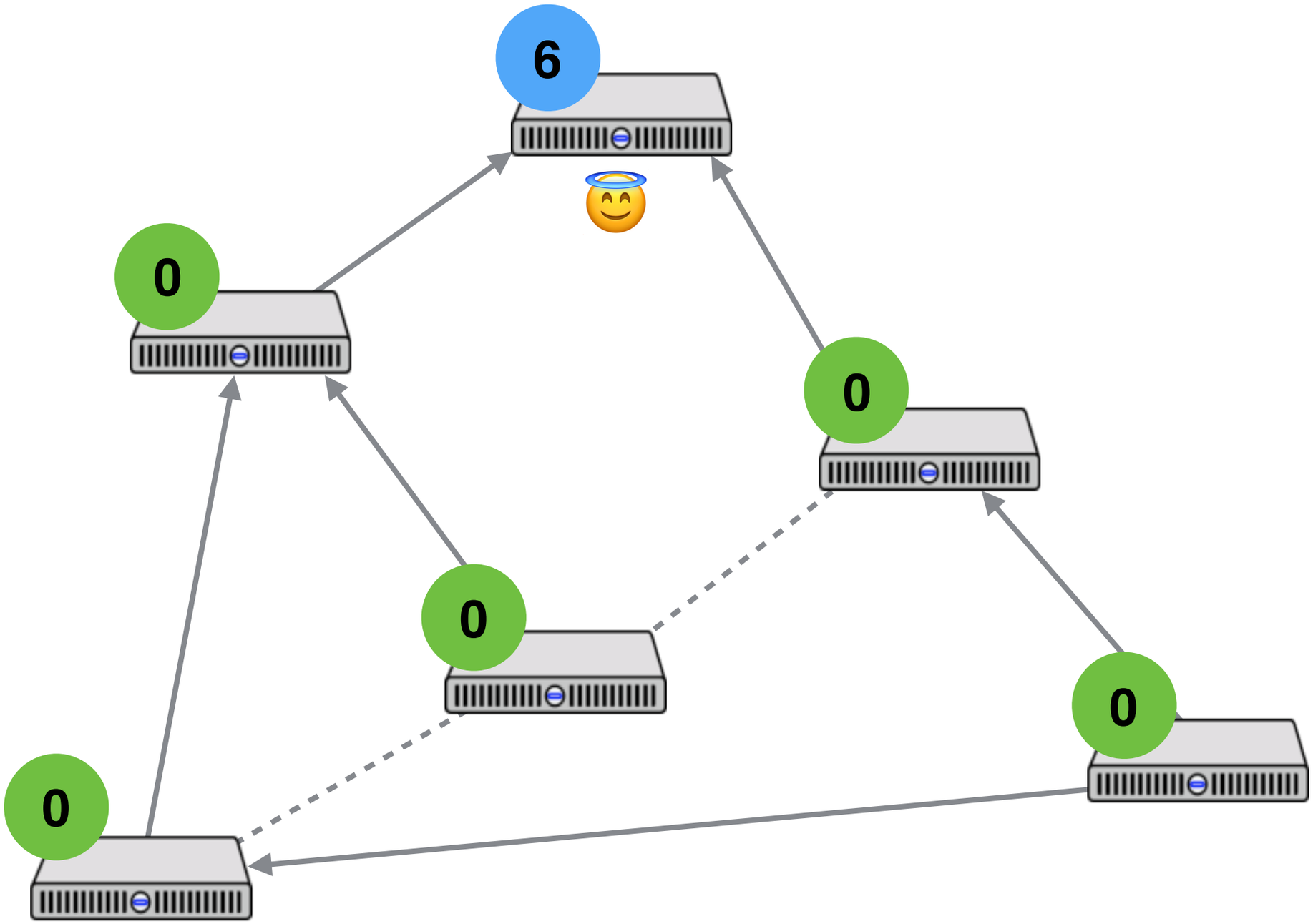

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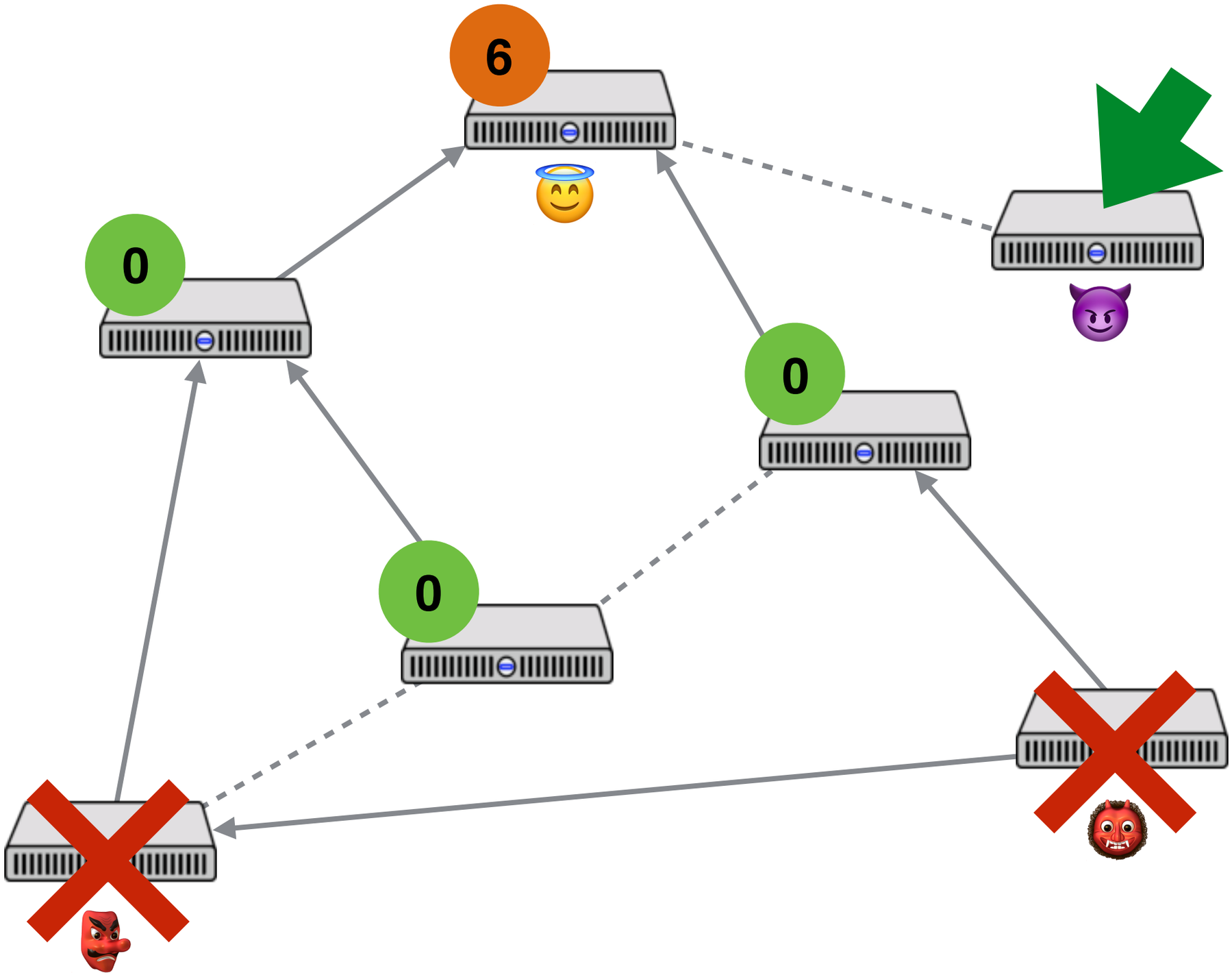

Correctness (punctuated safety): Beginning from a state reachable under churn, *given enough time without churn*, the count at the root node becomes and remains correct

Roadmap

- The tree-aggregation protocol
- Churn in Verdi
- Proving punctuated safety

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Verdi workflow

1. Write your system as *event handlers*
2. Verify it using our *network semantics*
3. Run it with the corresponding *shim*

Handlers change local state and send messages.

```
Definition result :=
  state * list (addr * msg).
```

new state

what to send

where to send it

Existing event: delivery

```
Definition result :=
  state * list (addr * msg).

Definition recv  handler
  (dst : addr)
  (st  : state)
  (src : addr)
  (m   : msg)
  : result := ...
```

New event: node start-up

```
Definition result :=
  state * list (addr * msg).

Definition init  handler
           _
(h       : addr)
(knowns : list addr)
: result := ...
```

Semantics: fixed networks

```
Record net :=
  {| failed_nodes : list addr;
     packets : addr -> addr -> list msg;
     state : addr -> state |}.

Inductive step : net -> net -> Prop :=
| Step_deliver :   ...
| Step_fail :   ...
```

Semantics: fixed networks

probably Fin *n*

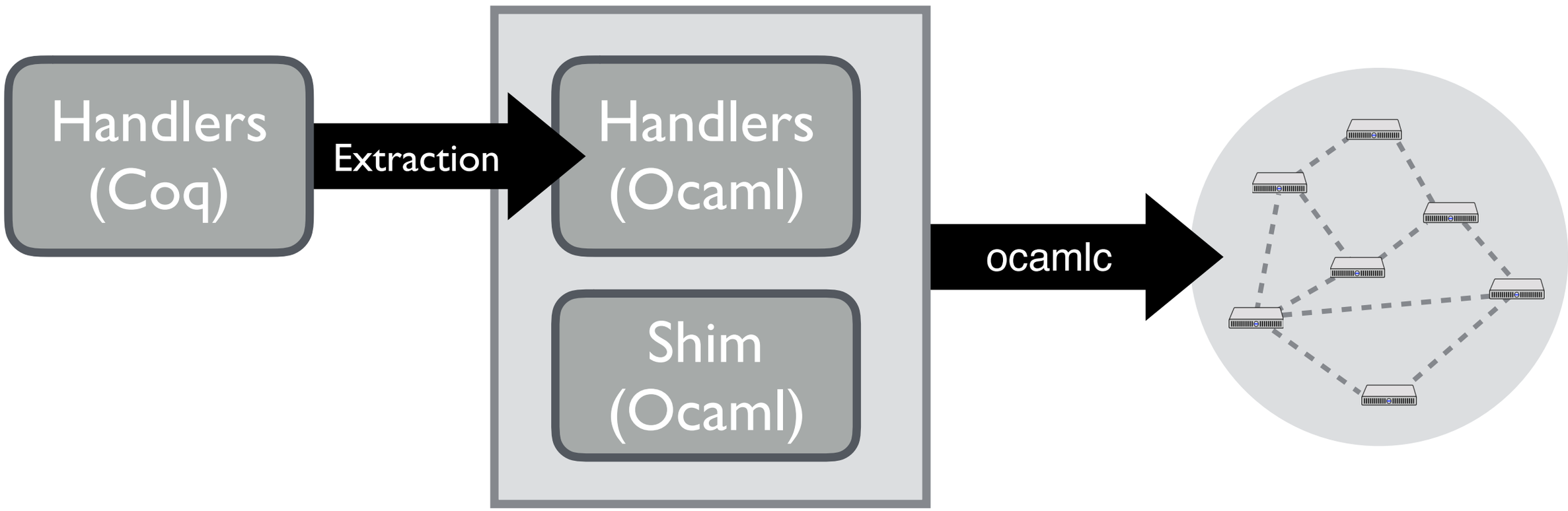
```
Record net :=
  {| failed_nodes : list addr;
     packets : addr -> addr -> list msg;
     state : addr -> state |}.

Inductive step : net -> net -> Prop :=
| Step_deliver :   ...
| Step_fail :   ...
```

Semantics with churn

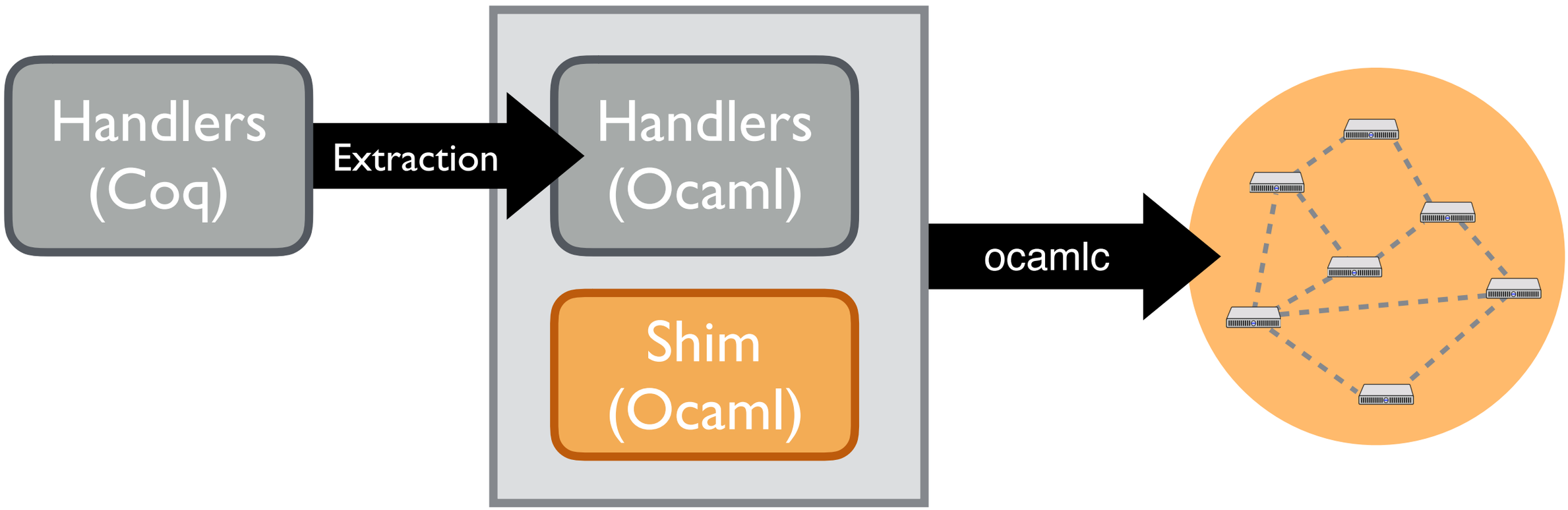
```
Record net :=
  {| failed_nodes : list addr;
     nodes : list addr;
     packets : addr -> addr -> list msg;
     state : addr -> option state |}.

Inductive step : net -> net -> Prop :=
| Step_deliver :   ...
| Step_fail :   ...
| Step_init :   ...
```

Now we can start verifying some properties of tree-aggregation!

The shim lets us run a system



We trust that the semantics describe the behavior of the shim and the network



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Churn forces safety violations

- Routing information can't be right all the time, and this typically violates top-level guarantees
- In the case of tree aggregation, any churn invalidates a correct total count

Detour: safety and liveness properties

Safety: nothing bad ever happens

Liveness: something good eventually happens

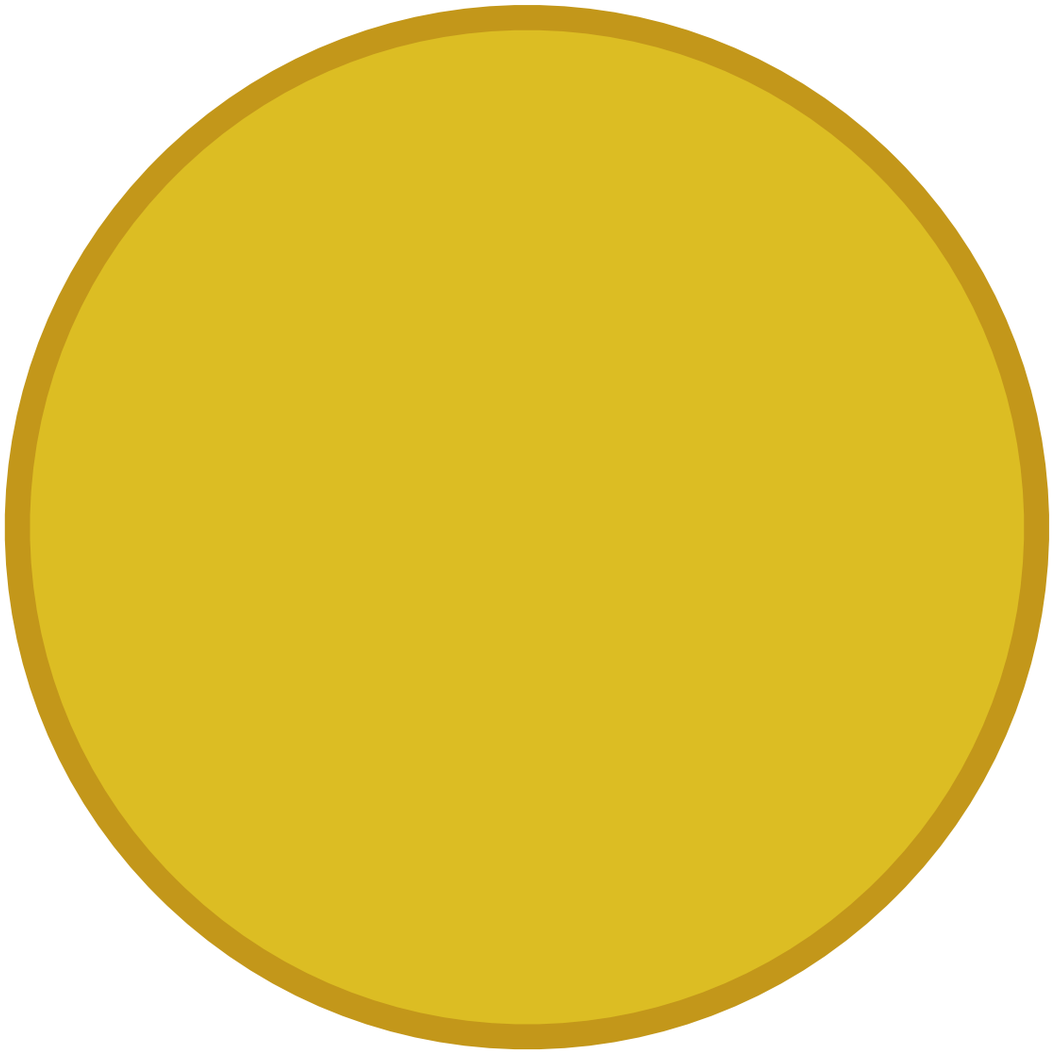
Safety and liveness properties

Define execution = infinite sequence of system states, ordered by step relation.

Then a safety property can be proved by examining only finite prefixes of an execution.

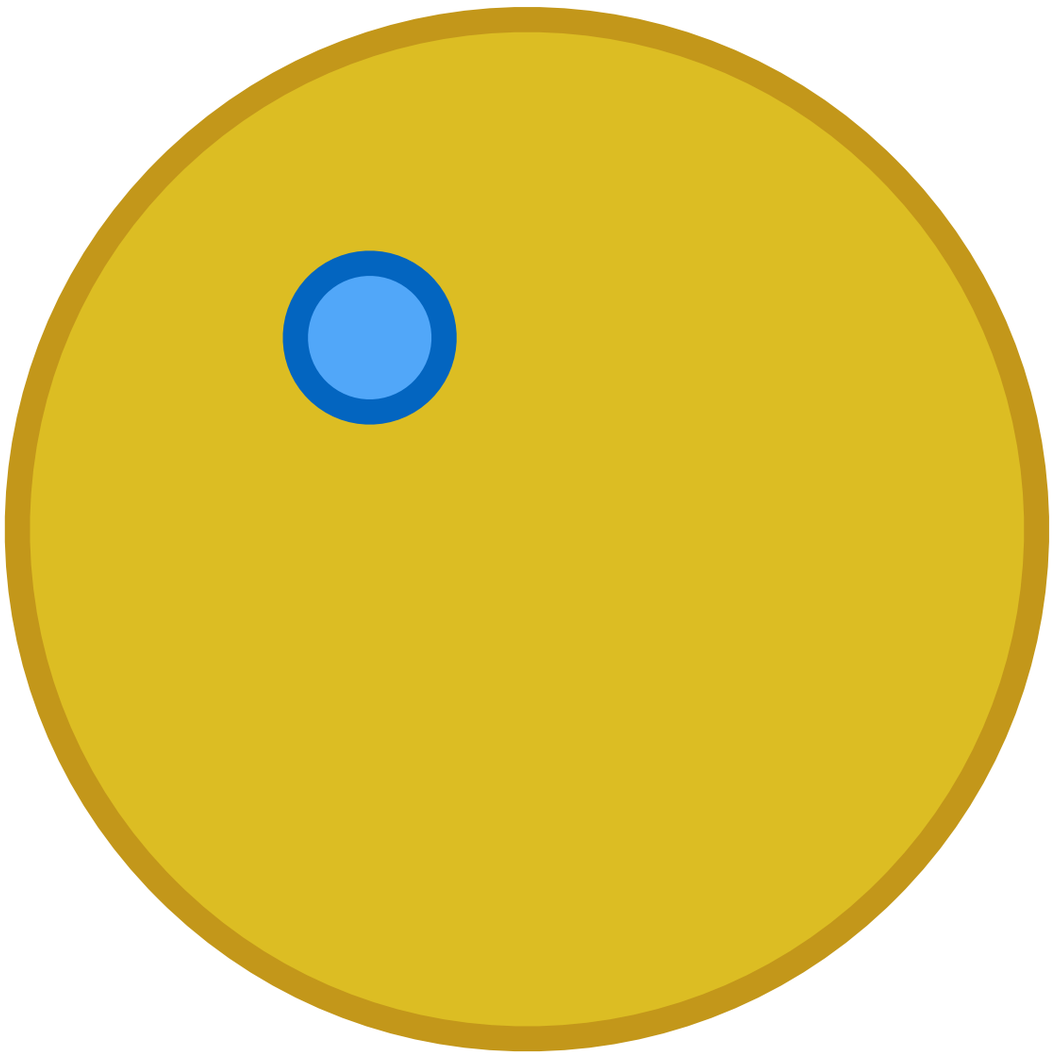
A liveness property cannot be disproved by examining finite prefixes of an execution.

We can prove safety properties with inductive invariants



A predicate P on states is an inductive invariant when

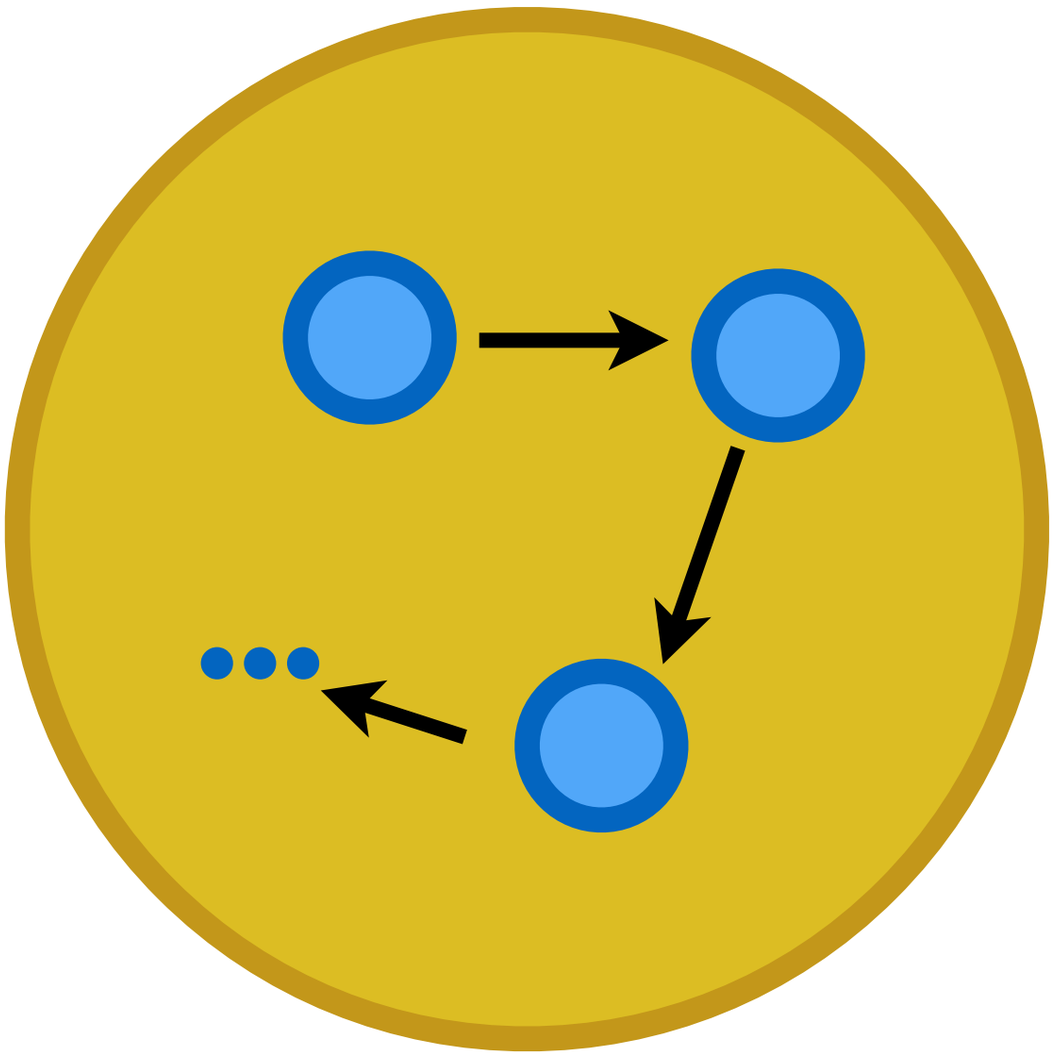
Inductive invariants



A predicate P on states is an inductive invariant when

- P holds for the initial state

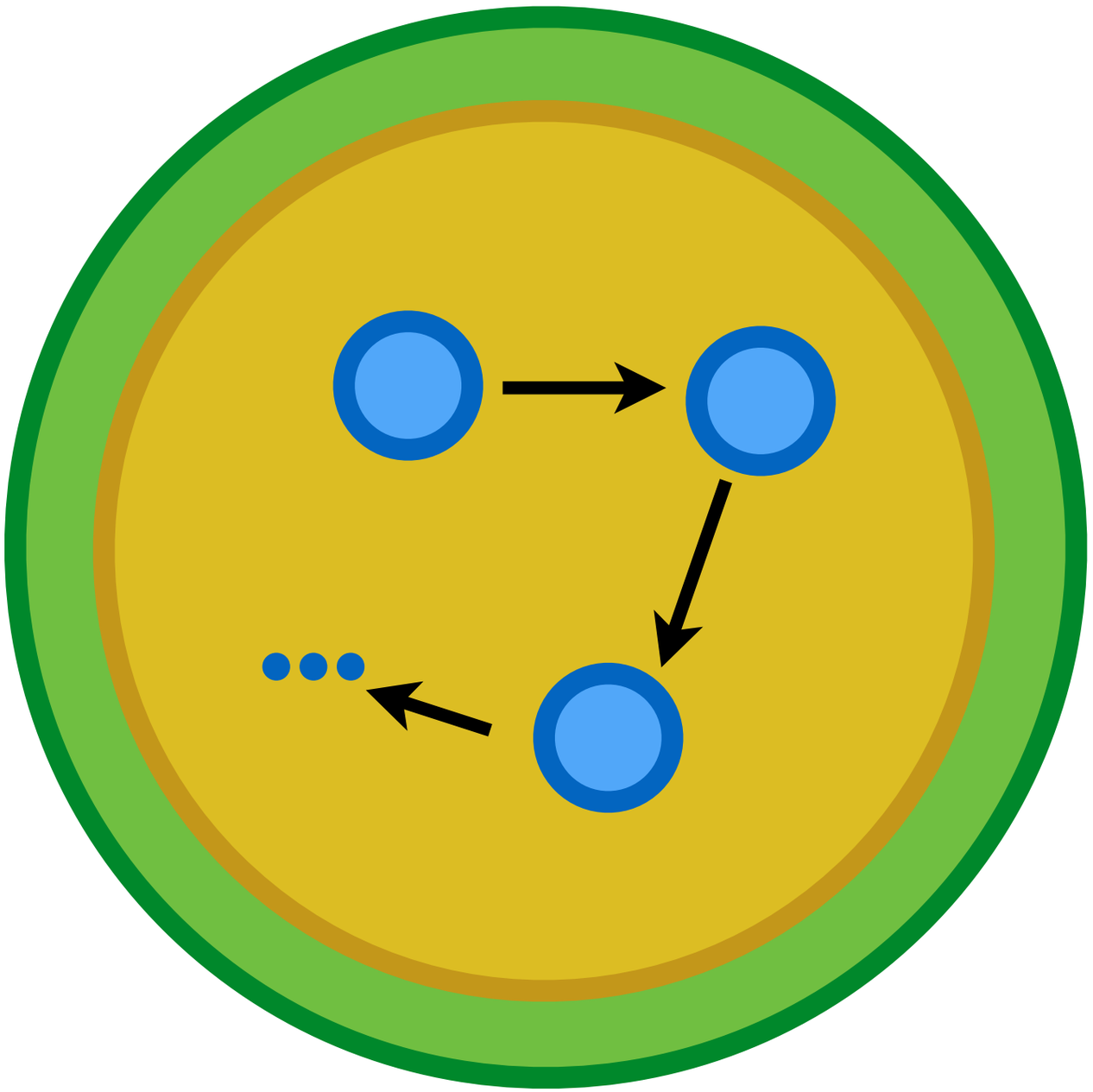
Inductive invariants



A predicate P on states is an inductive invariant when

- P holds for the initial state
- P is preserved by the step

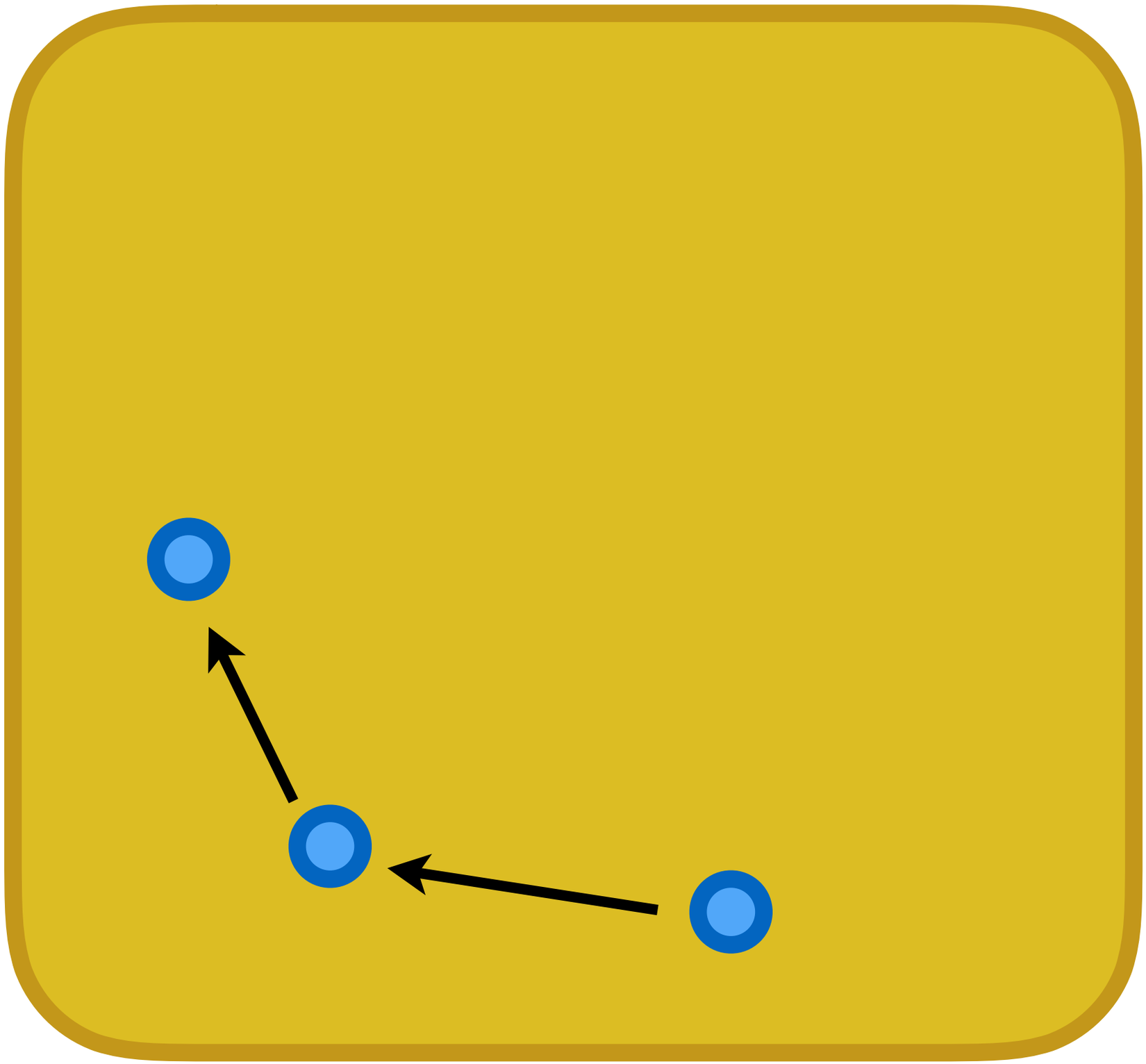
Inductive invariants



If P implies our safety property, we've shown safety for all reachable states without needing to describe infinite executions in our Coq code!

..but "the root node eventually has a correct count" isn't a safety property!

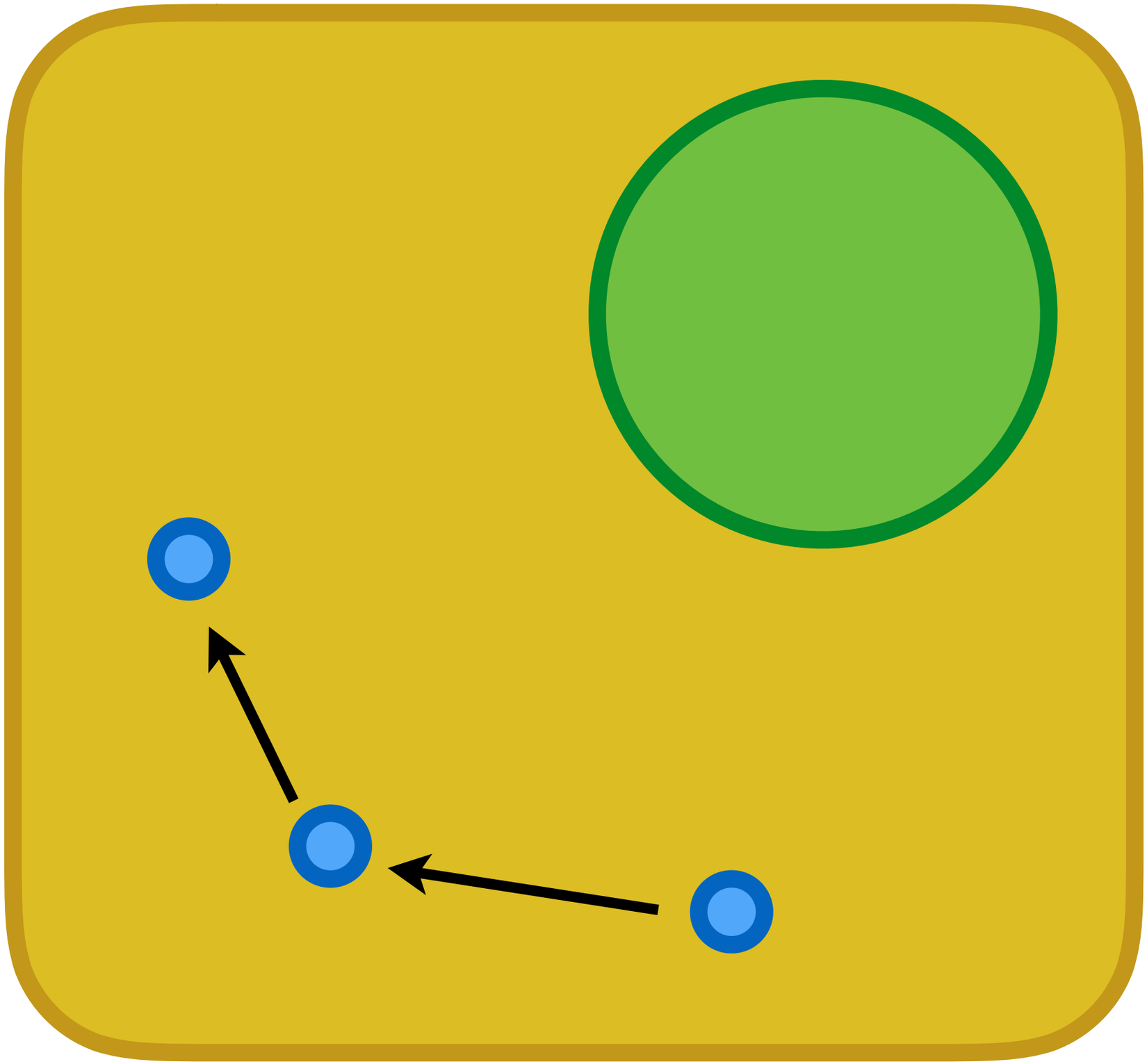
Punctuated safety properties



Reachable

under churn

Punctuated safety properties



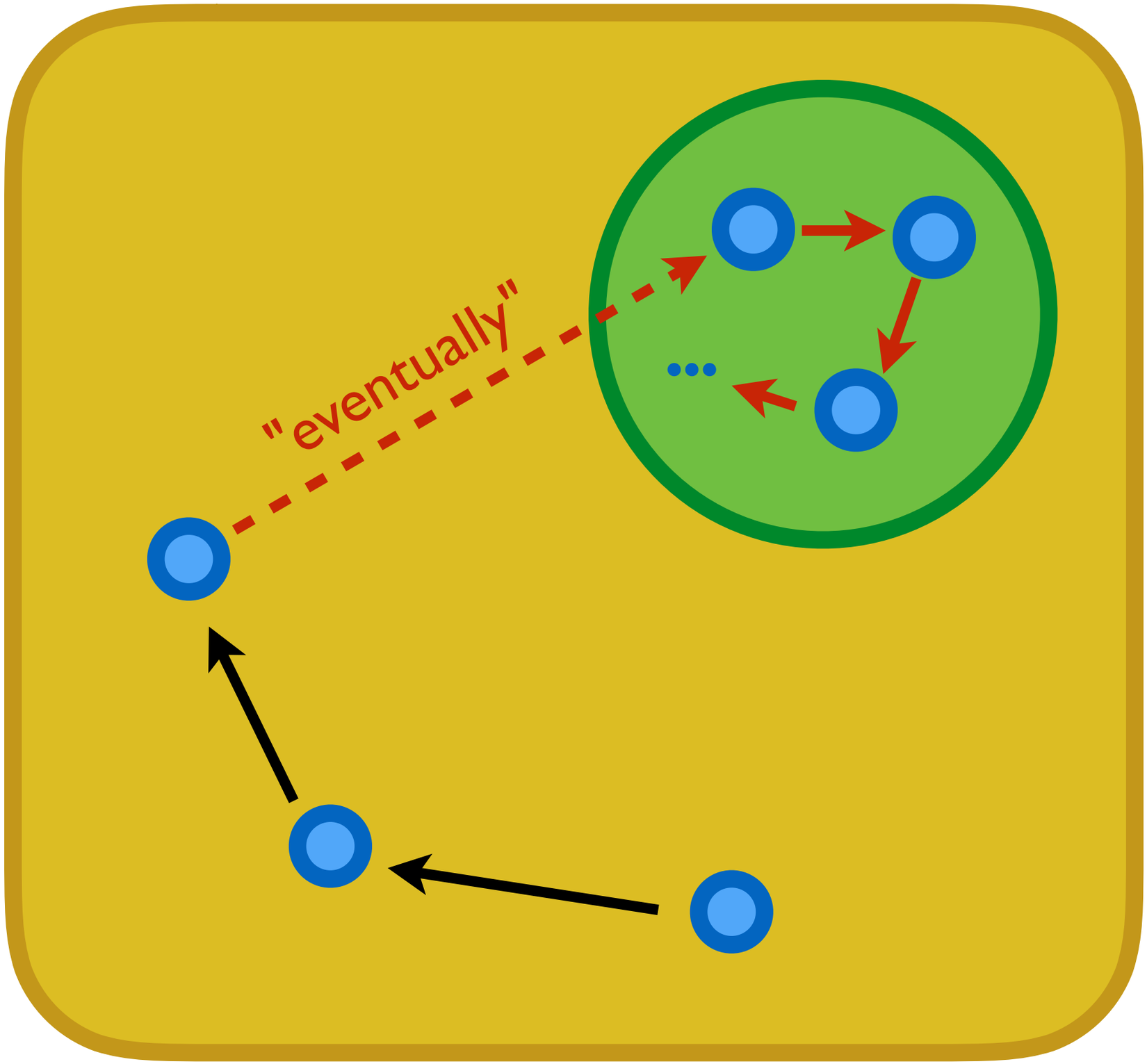
Reachable

under churn

Safety

after churn stops

Punctuated safety properties



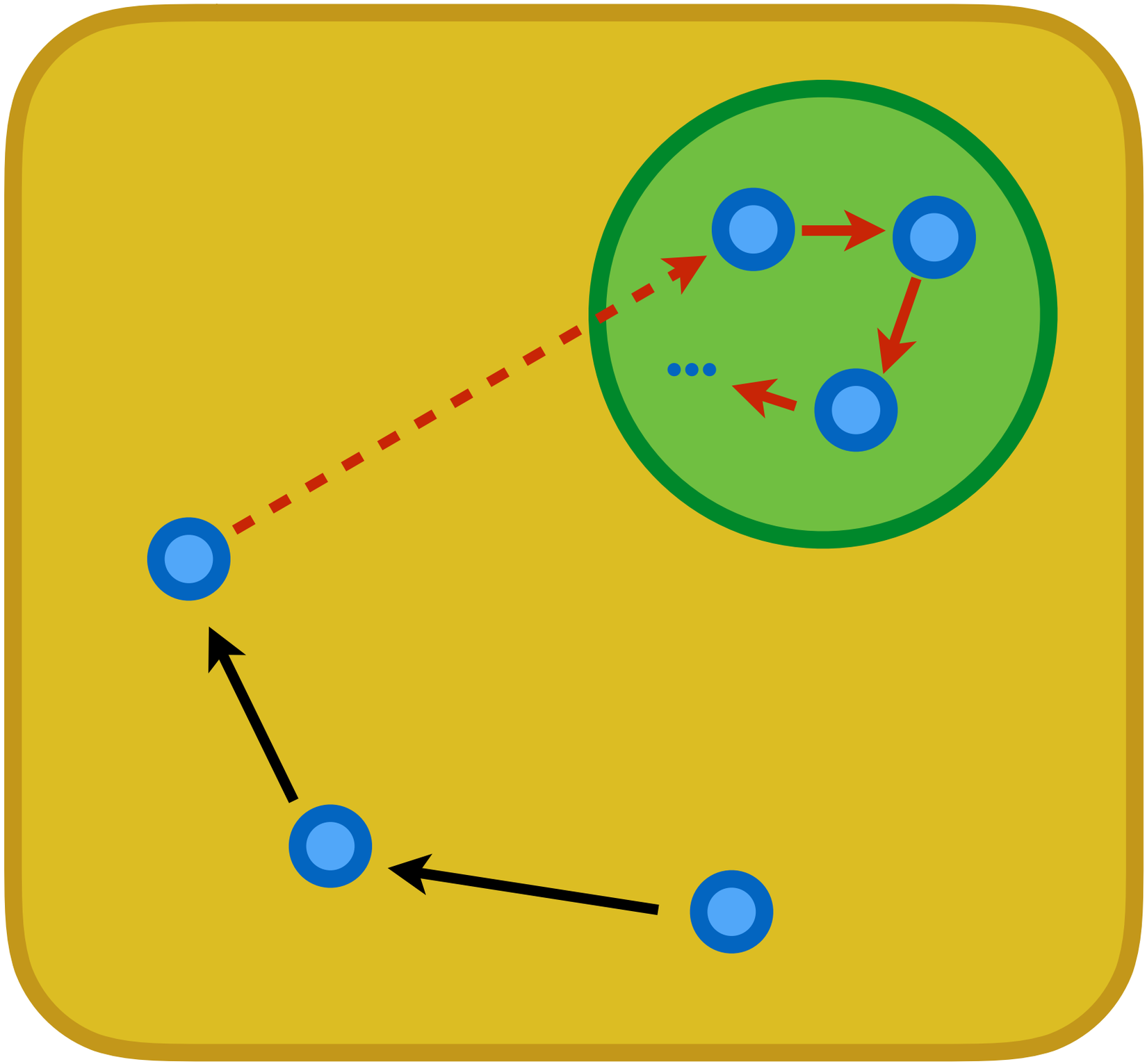
Reachable

under churn (→)

Safety

after churn stops (→)

Punctuated safety properties



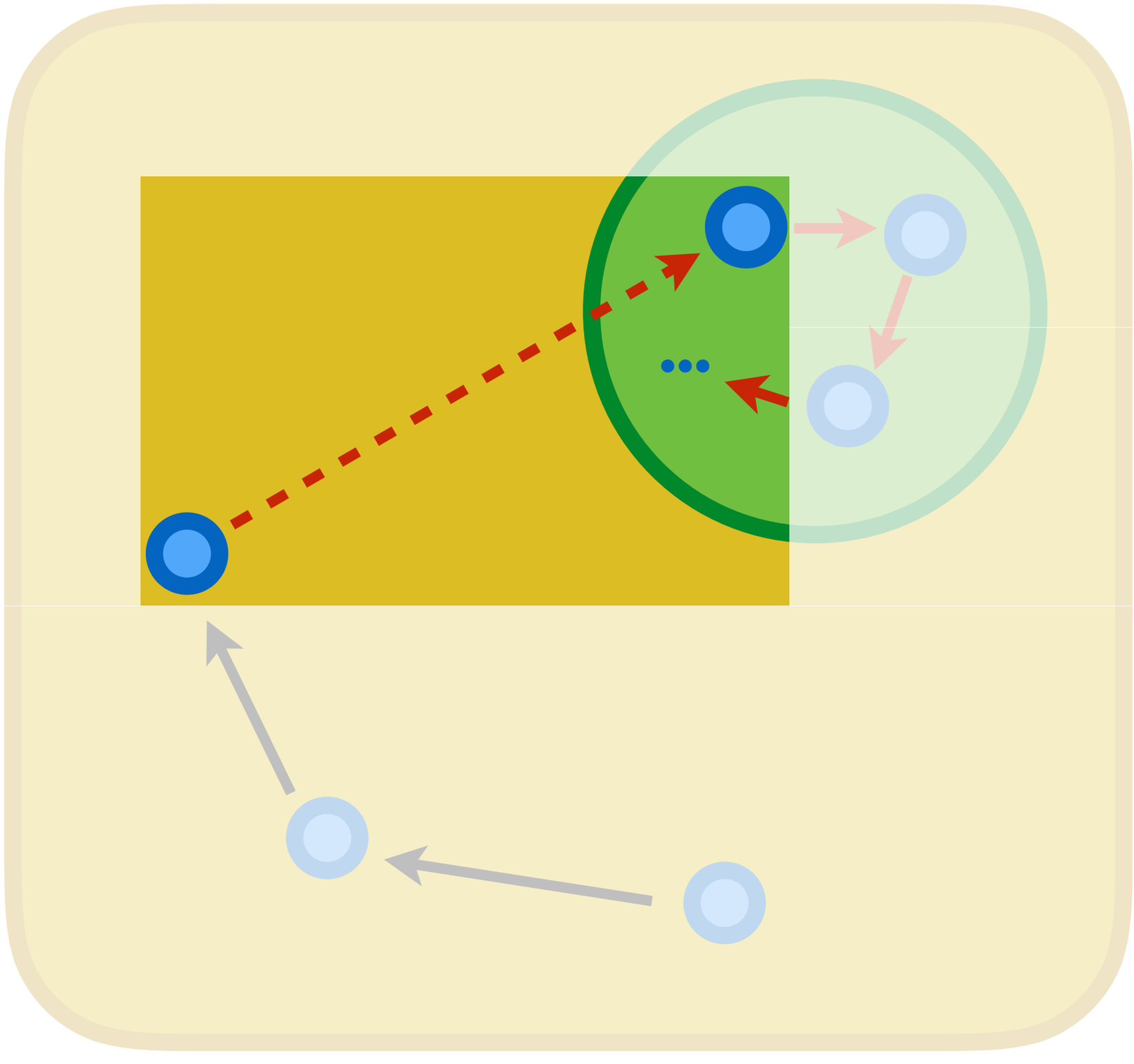
Reachable

under churn (→)

Safety

after churn stops (→)

We don't know how to prove this yet



Reachable

under churn (→)

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after churn stops (→)

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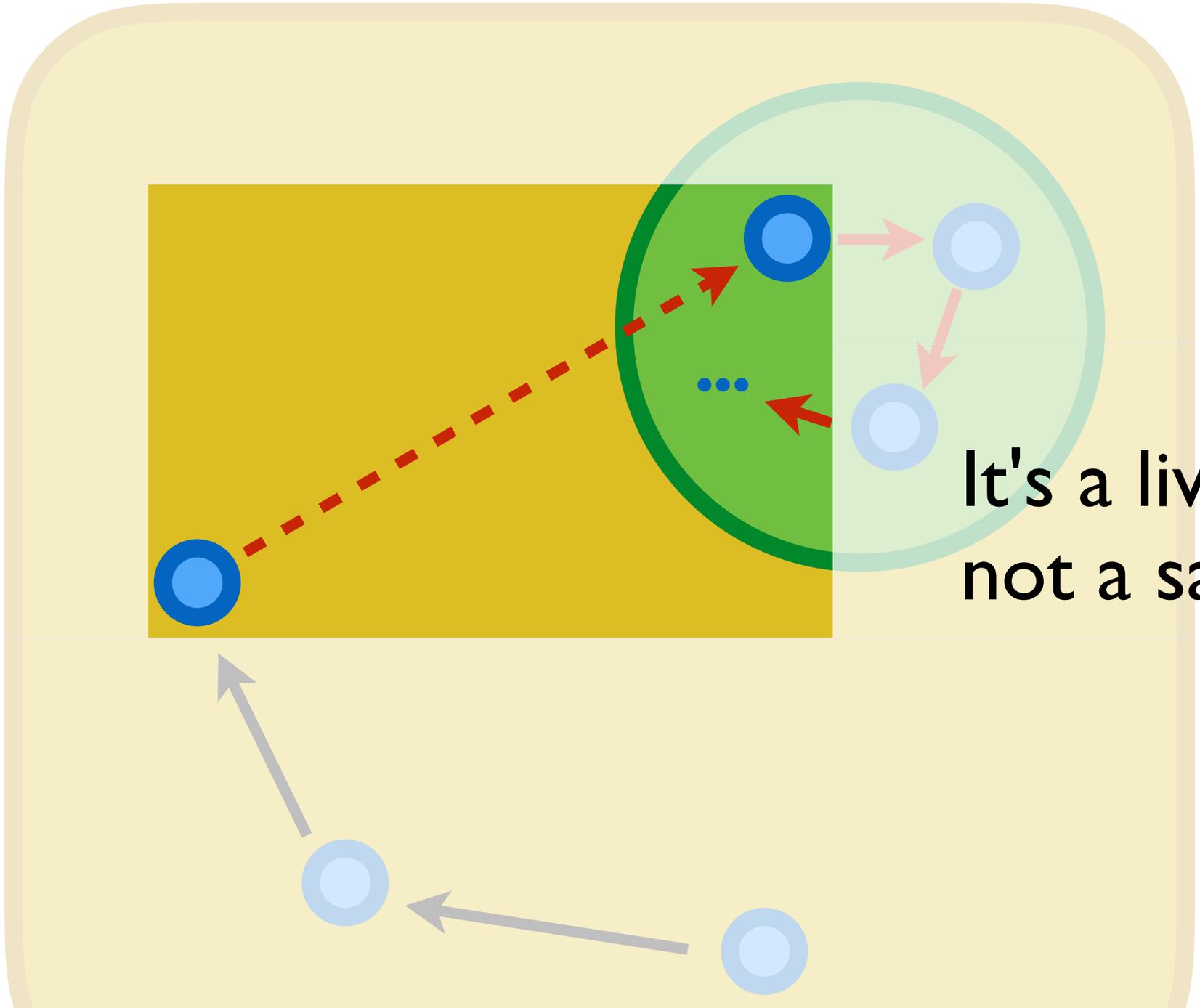


Reachable

under churn (→)

Safety

after churn stops (→)

It's a liveness argument,
not a safety argument

We need a way to talk about infinite executions: liveness can't be proved with only finite traces.

Representing infinite executions in Coq

```
(* Infinite stream of terms in T *)
CoInductive infseq (T : Type) :=
  Cons : T -> infseq -> infseq.

(* Stream of system states connected by step *)
CoInductive execution
: infseq (net * label) -> Prop :=
  Cons_exec : forall n n',
    step n n' ->
    execution (Cons n' s) ->
    lb_execution (Cons n (Cons n' s)).
```

Reasoning about executions: linear temporal logic (LTL)

Next P

Always P

Eventually P

...and much, much more!

LTL in Coq

```
Inductive eventually P : infseq T -> Prop :=
 | E0 : forall s,
     P s -> eventually P s
 | E_next : forall x s,
     eventually P s ->
     eventually P (Cons x s).

CoInductive always P : infseq T -> Prop :=
 | Always : forall s,
     P s ->
     always P (tl s) ->
     always P s.
```

InfSeqExt: LTL in Coq

- Extensions to a library by Deng & Monin for doing LTL over infinite (coinductive) streams of events

- Coq source code is on GitHub at `DistributedComponents/InfSeqExt`

We still can't prove correctness

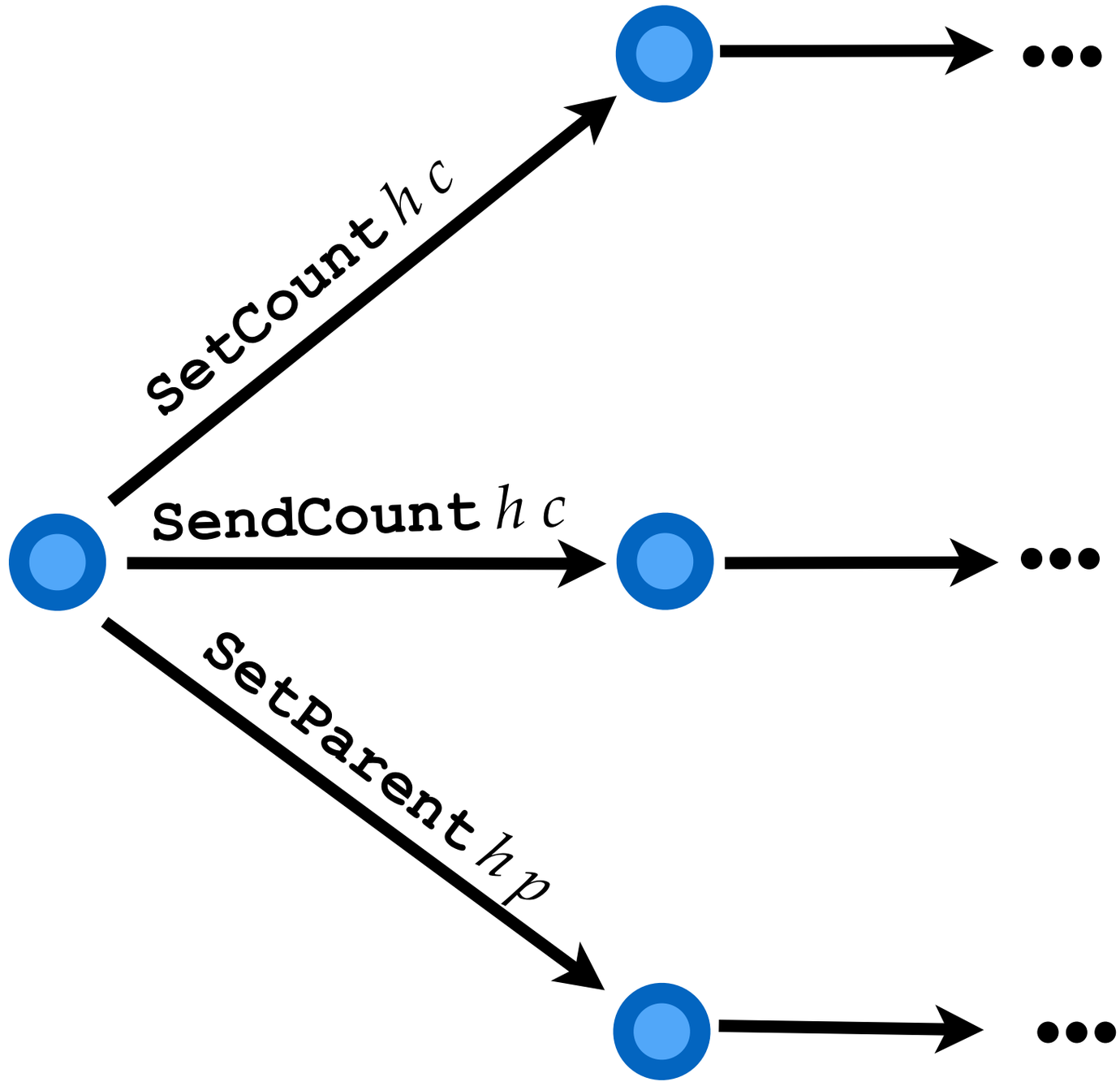
What if messages from one node are indefinitely delayed while messages from another are still delivered?

Intuitively such an execution is "unfair" to the first node.

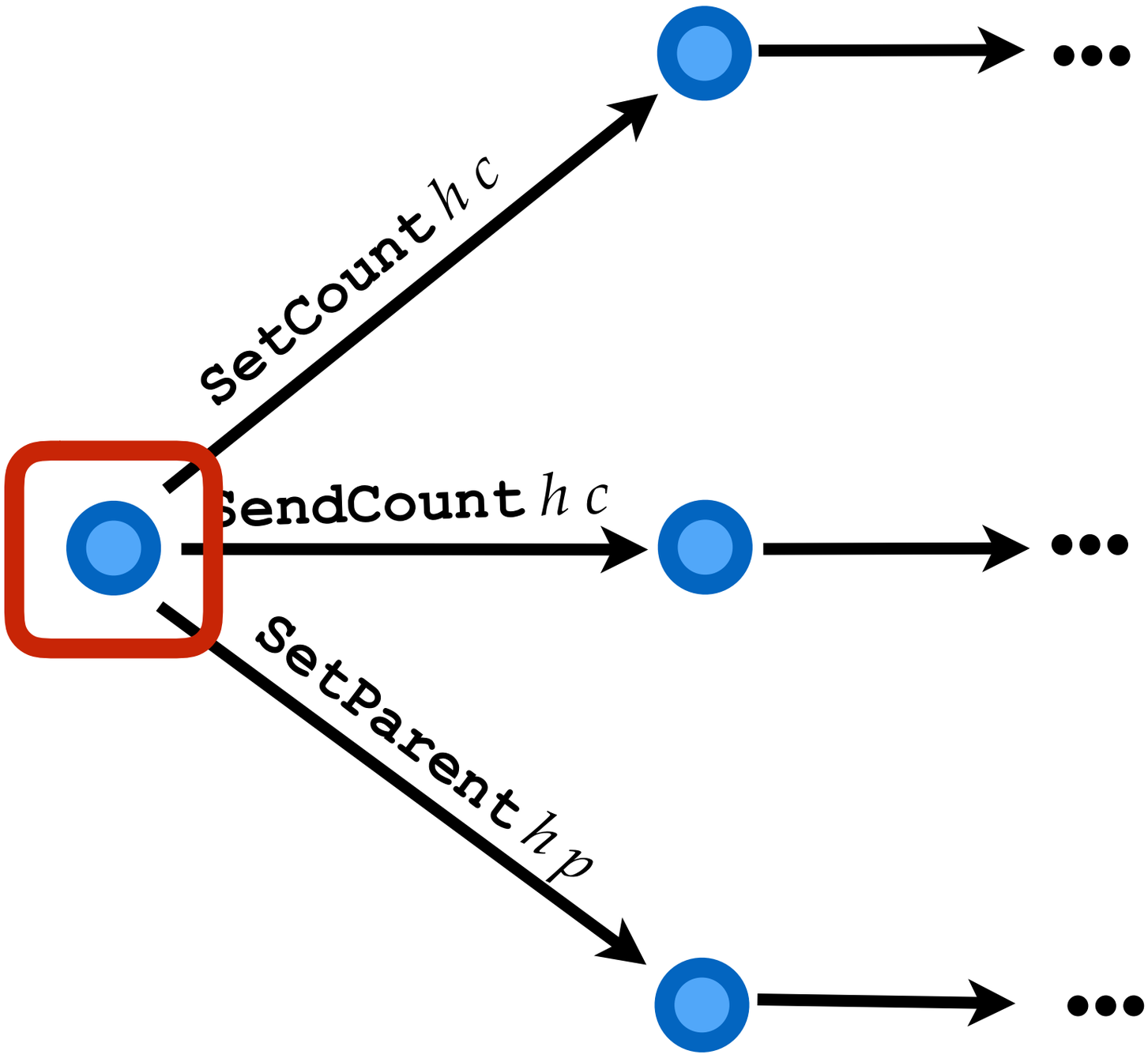
We have to assume a *fairness hypothesis*.

Weak fairness: If an action is *eventually always* enabled, then it is *always eventually* taken.

Labels: turning steps into actions

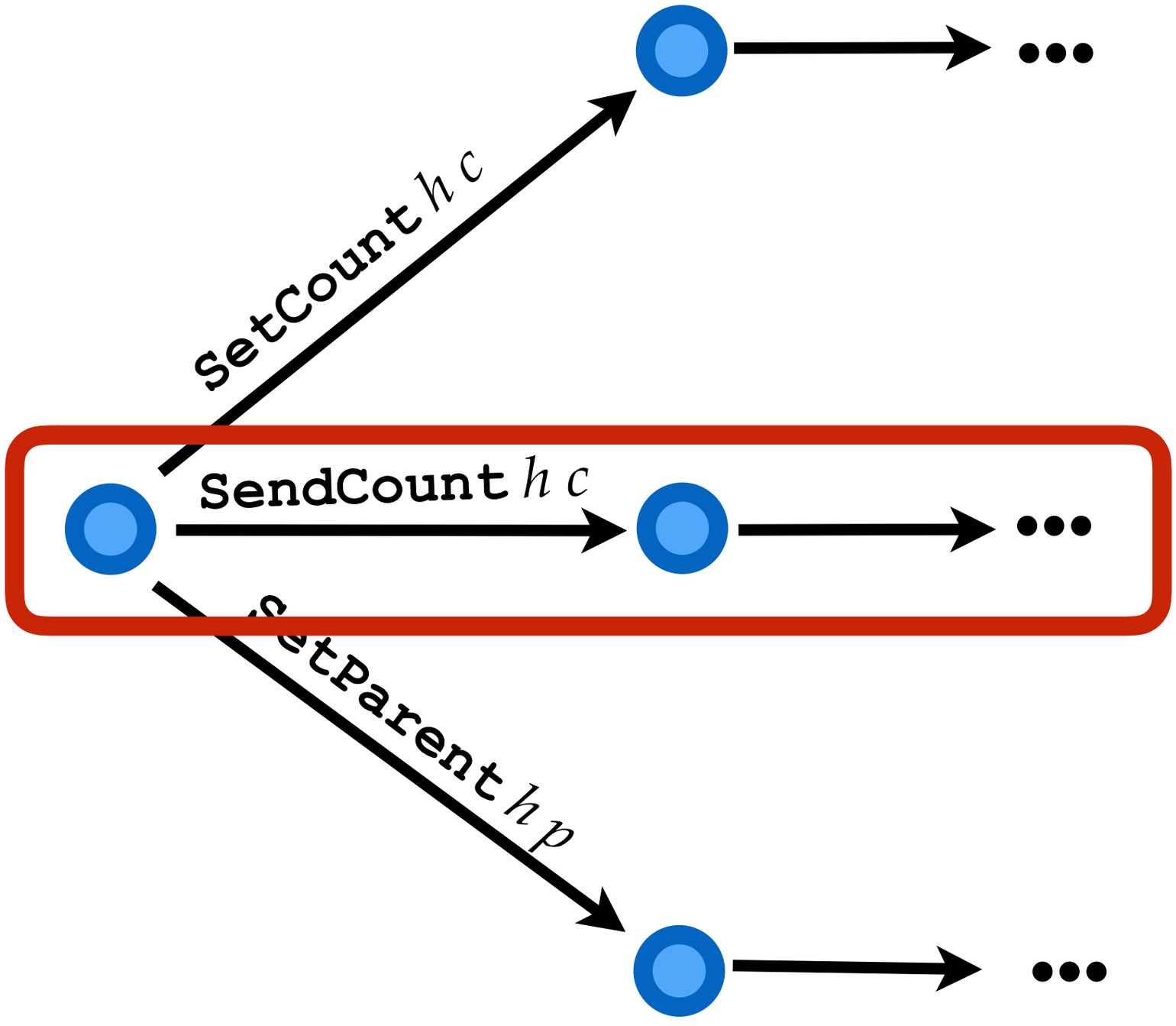


`SetCount` $h\ c$ is enabled at this state



`SetCount` $h\ c$ is not taken in this execution,

but **`SendCount`** $h\ c$ is taken.



Note: fairness has to be implemented and assumed

The shim could fail to handle messages fairly and prevent liveness

The network could delay packets and schedule delivery events unfairly

We can now state correctness for tree aggregation!

```
∀ ex r,
  reachable_under_churn (hd ex) ->
  execution churn_free_step ex ->
  connected (hd ex) ->
  weakly_fair ex ->
  eventually (always
    (λ ex' =>
      correct_sum_at_root (hd ex')))
    ex
```

Roadmap

- The tree-aggregation protocol
- Churn in Verdi
- Proving punctuated safety

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Thanks!

We're on GitHub:

- uwplse/verdi
- DistributedComponents/verdi-aggregation
- DistributedComponents/InfSeqExt

Acknowledgements

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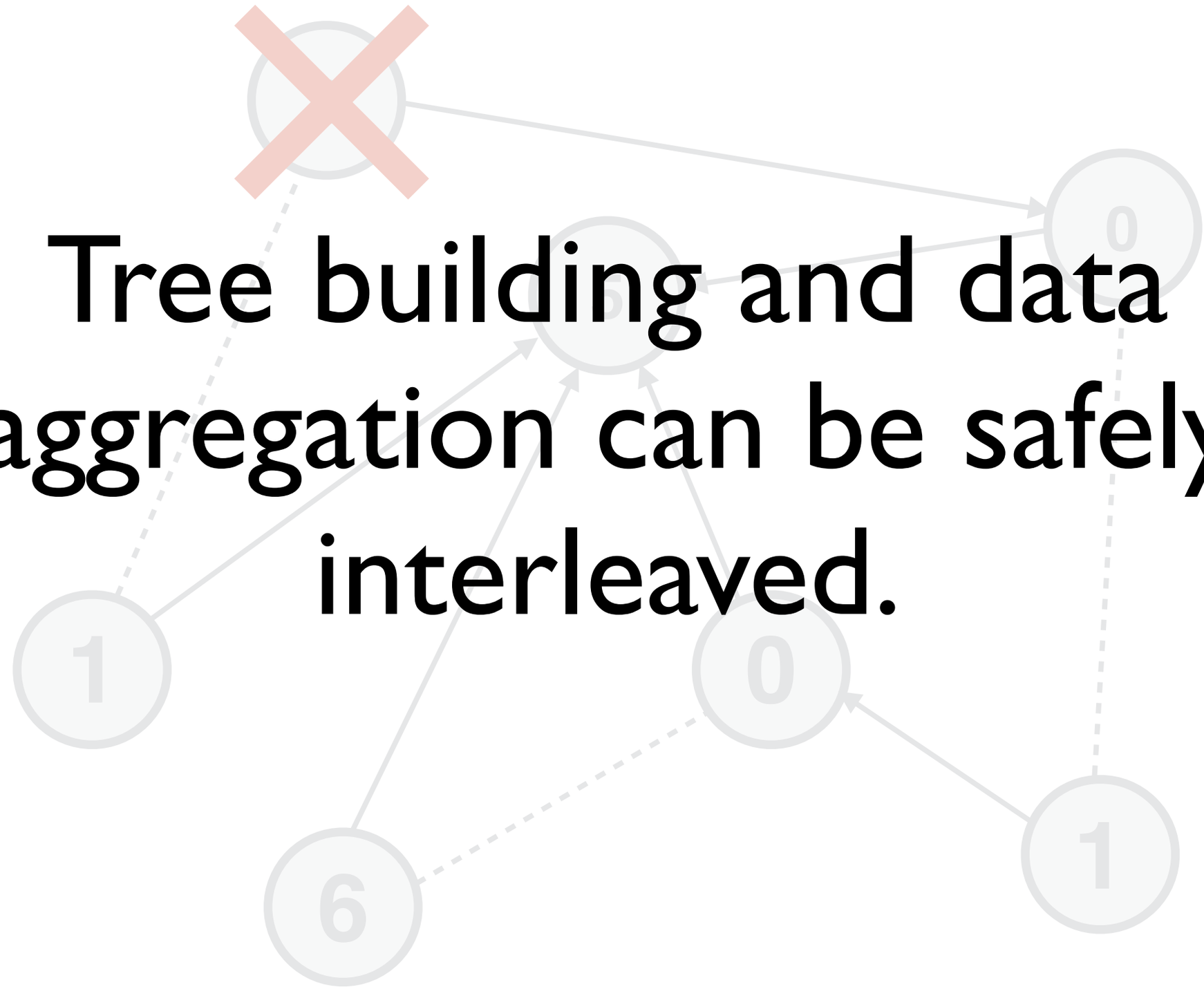
Punctuated safety properties

- Churn happens, and the system arrives at some state *st* reachable under churn
- Churn stops
- In a sequence of churn-free steps starting at *st*, we eventually reach the punctuated safety property.

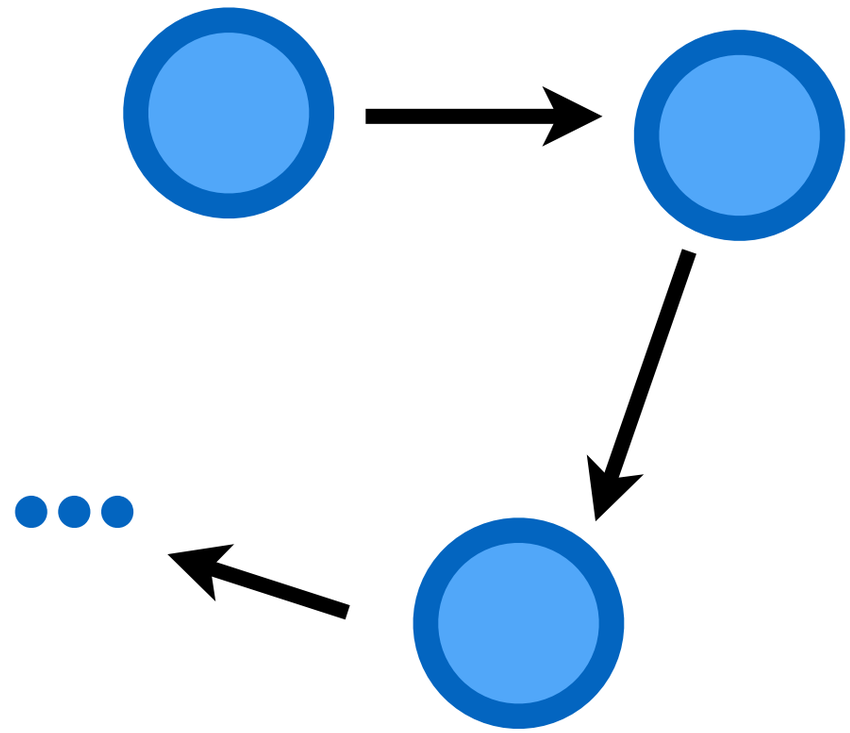
If a node fails, subtract its contribution.



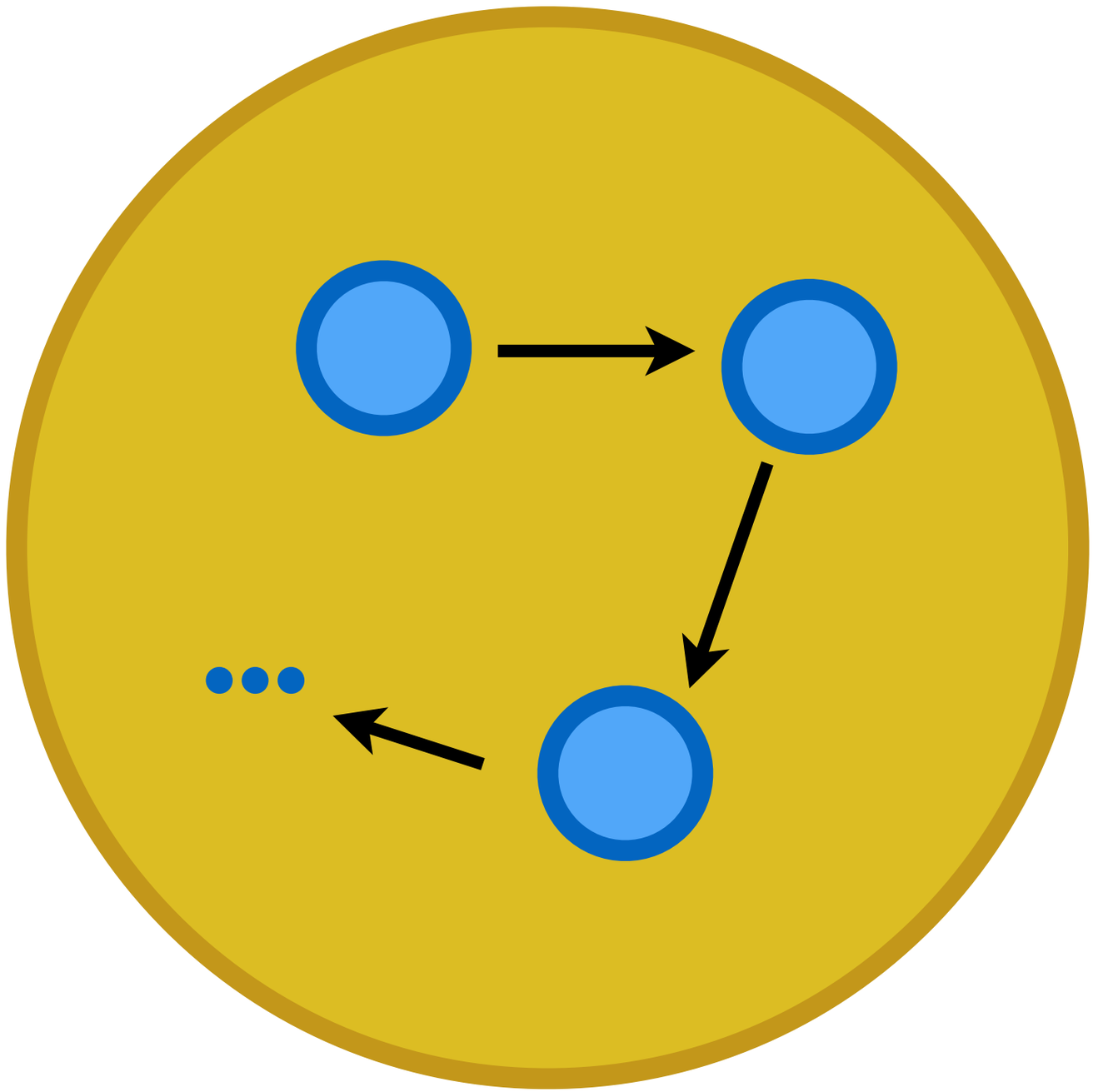
Tree building and data aggregation can be safely interleaved.

Infinite executions

Safety properties

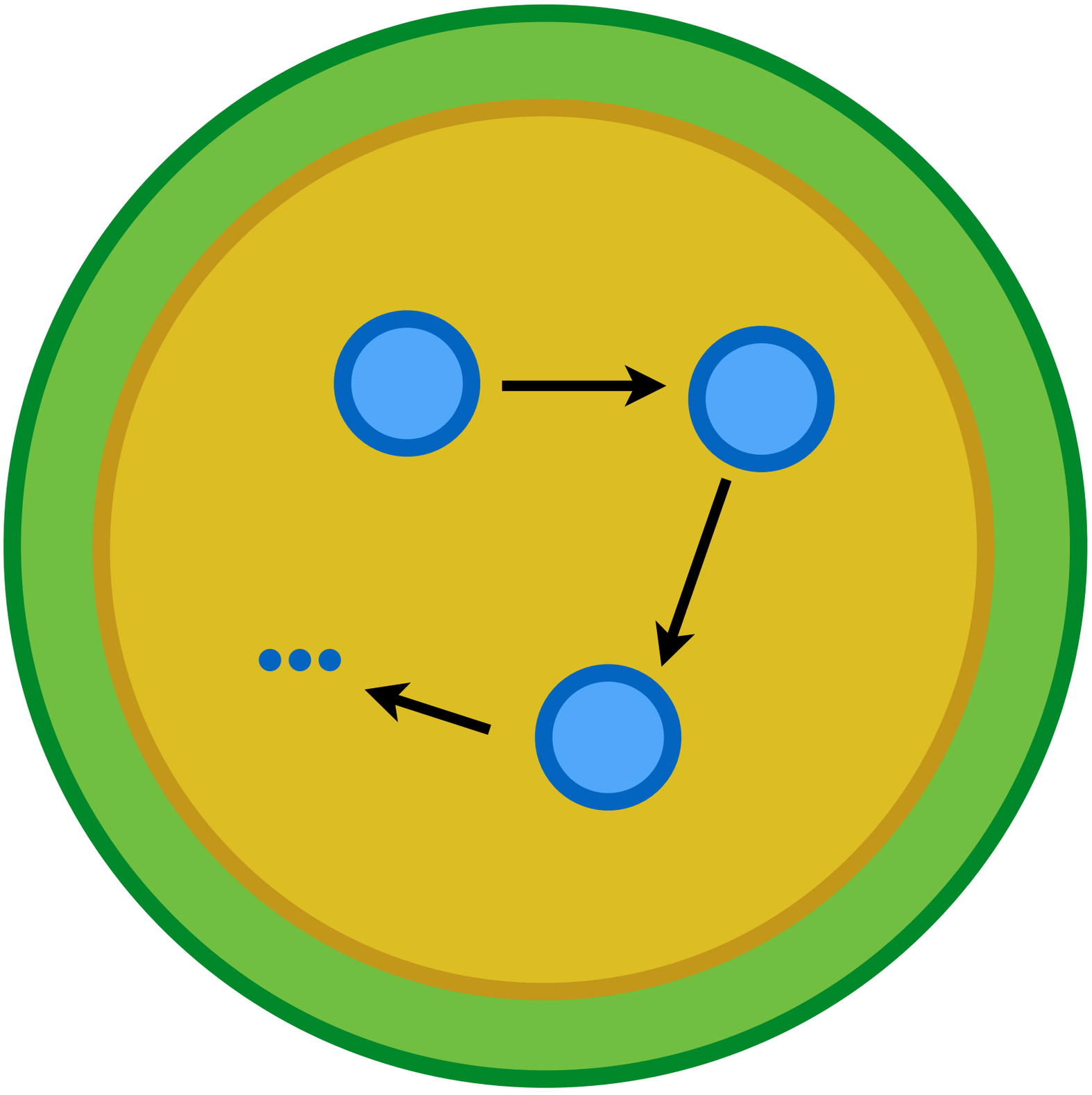


Safety properties



Reachable

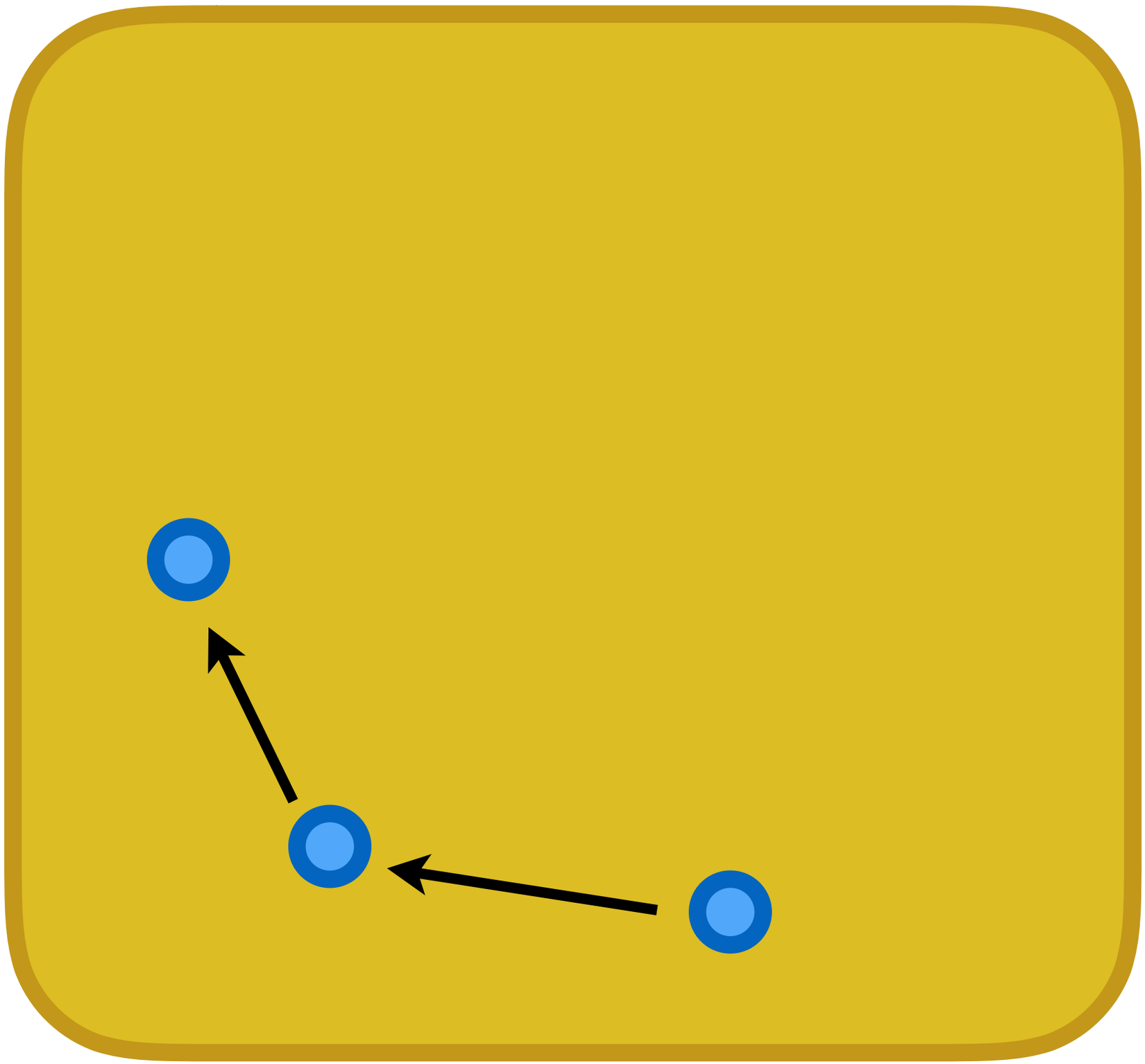
Safety properties



Reachable

Safety

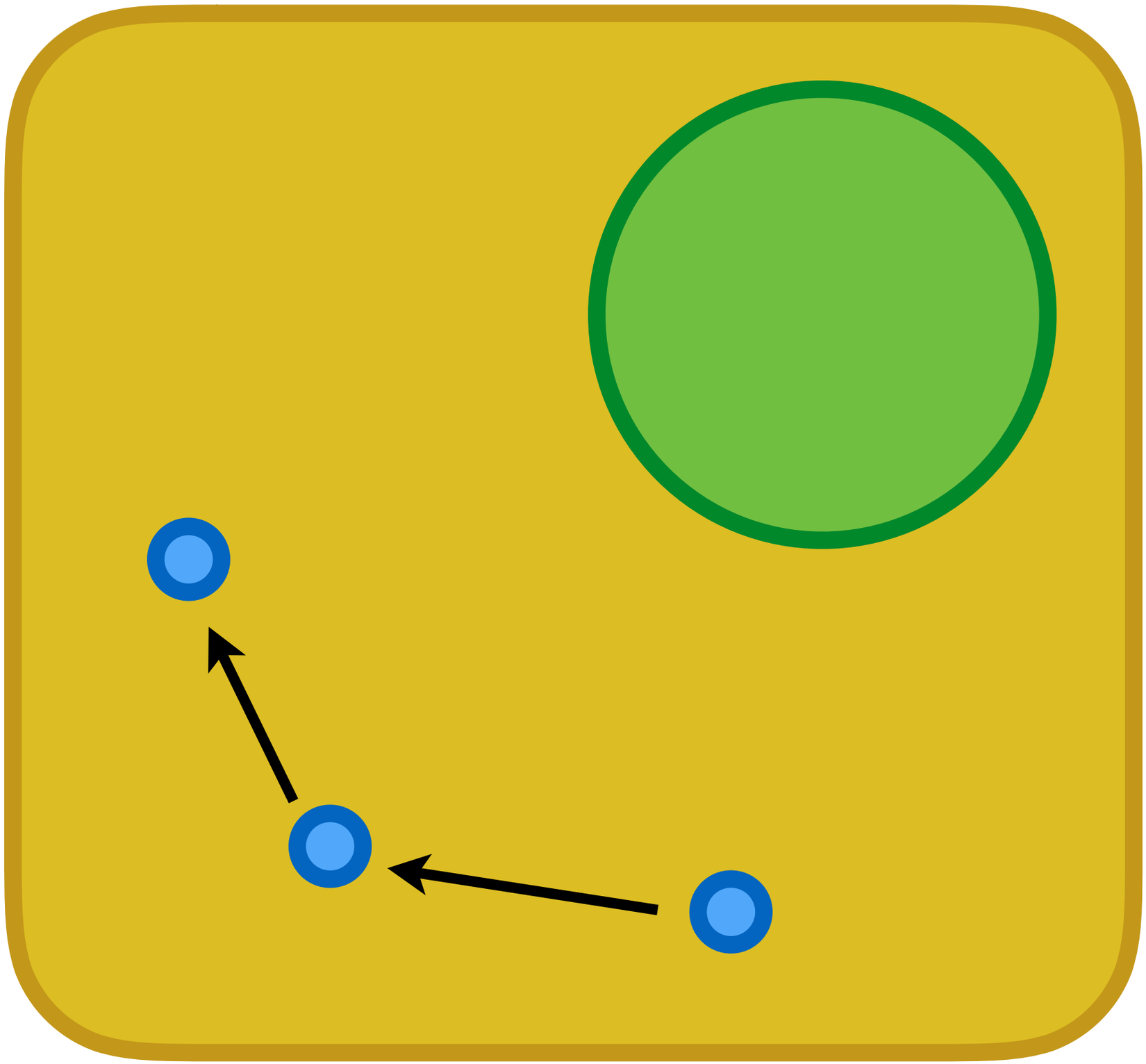
Punctuated safety properties



Reachable

under churn

Punctuated safety properties

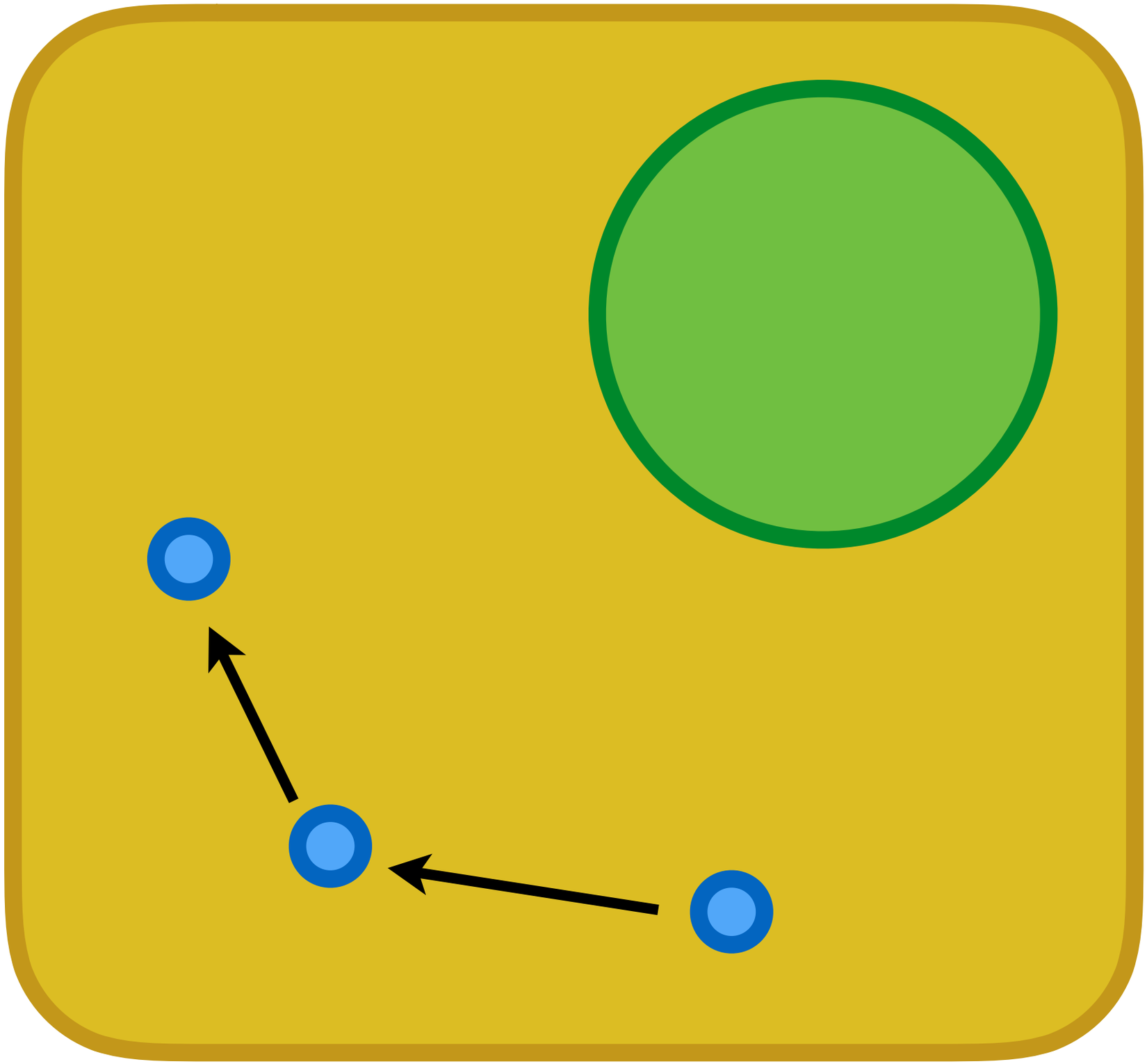


Reachable

under churn

Safety

Punctuated safety properties



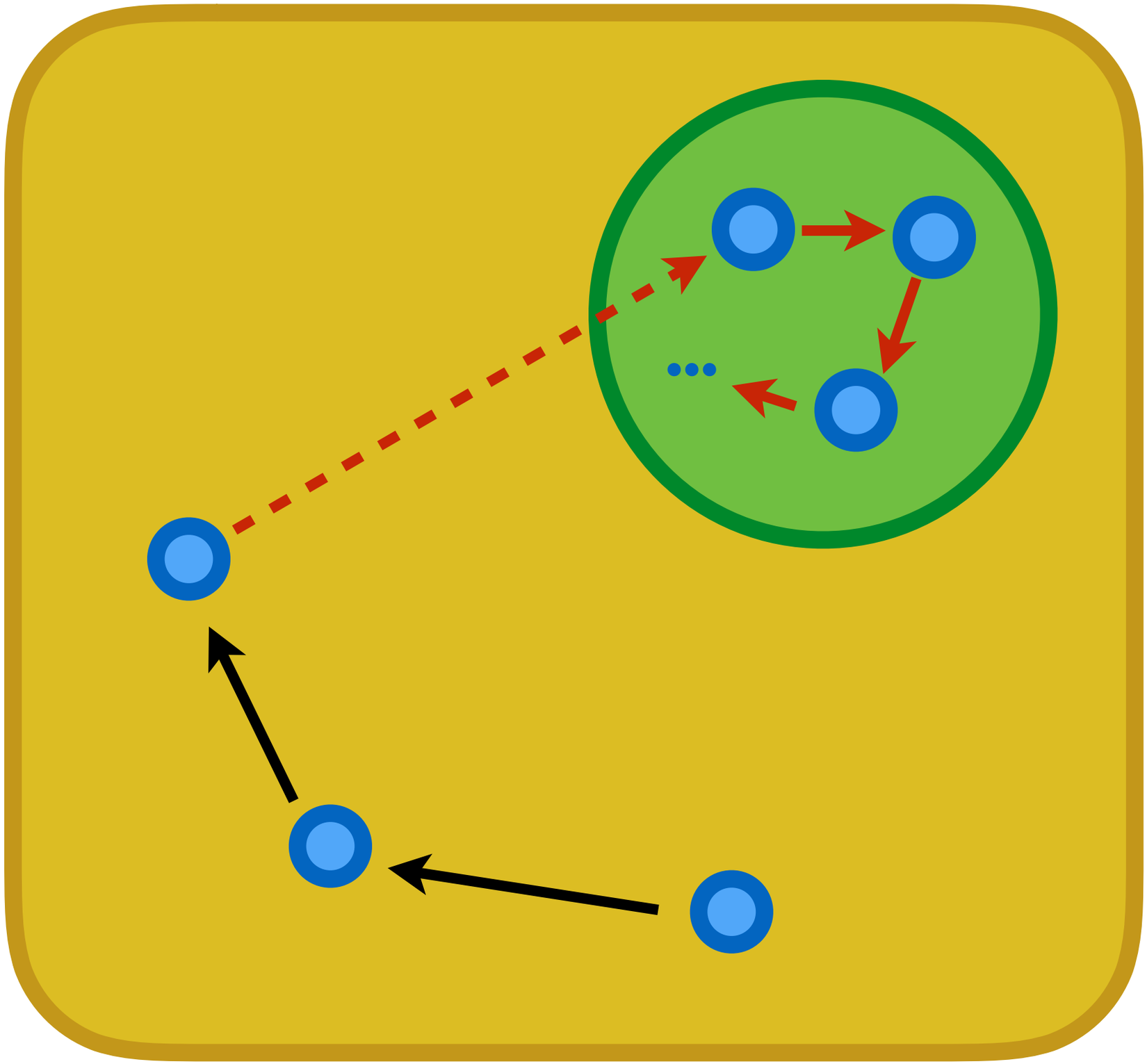
Reachable

under churn

Safety

after churn stops

Punctuated safety properties



Reachable

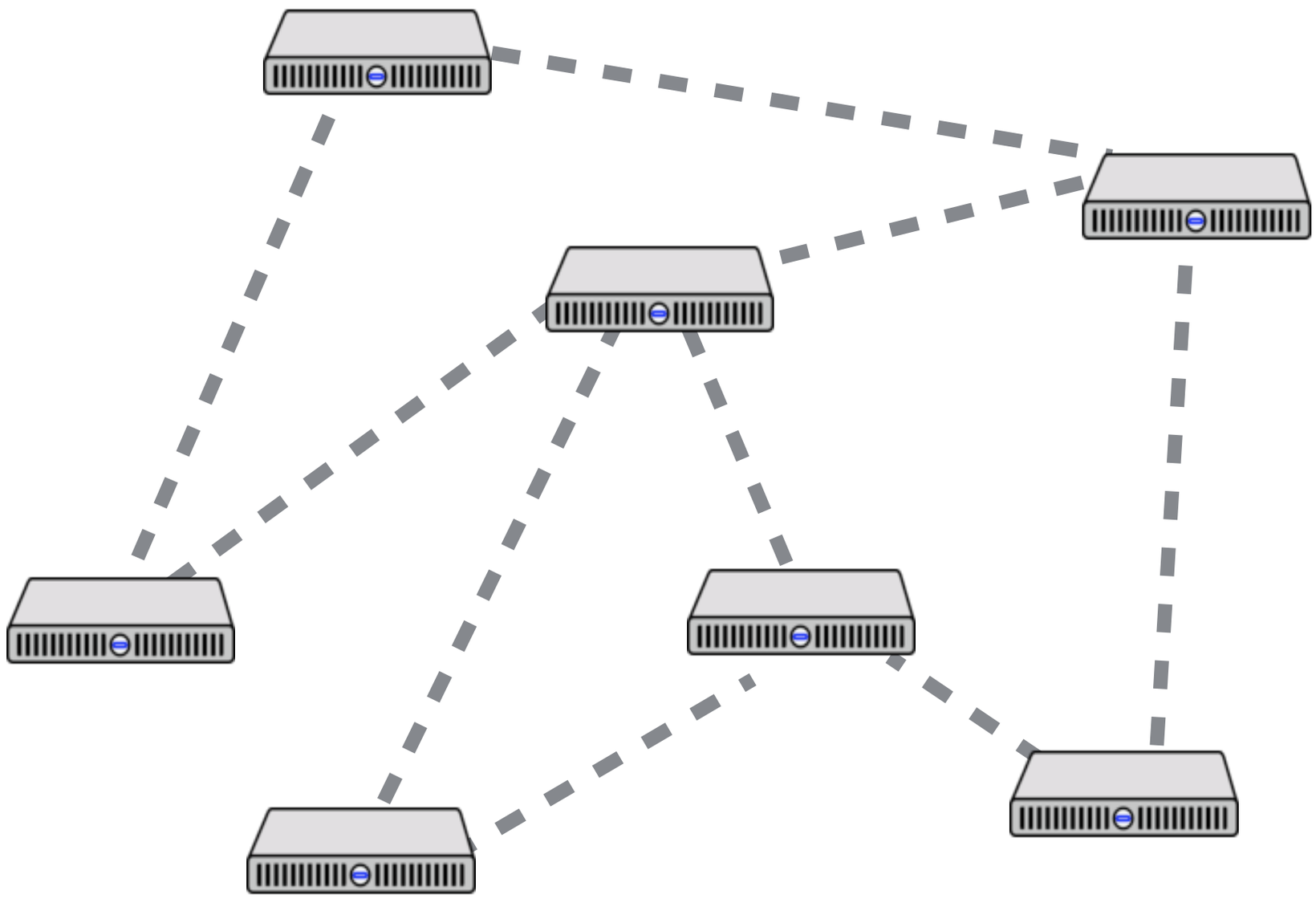
under churn (→)

Safety

after churn stops (→)

We extend Verdi with support for proving punctuated safety under churn

These frameworks do account for crashes.



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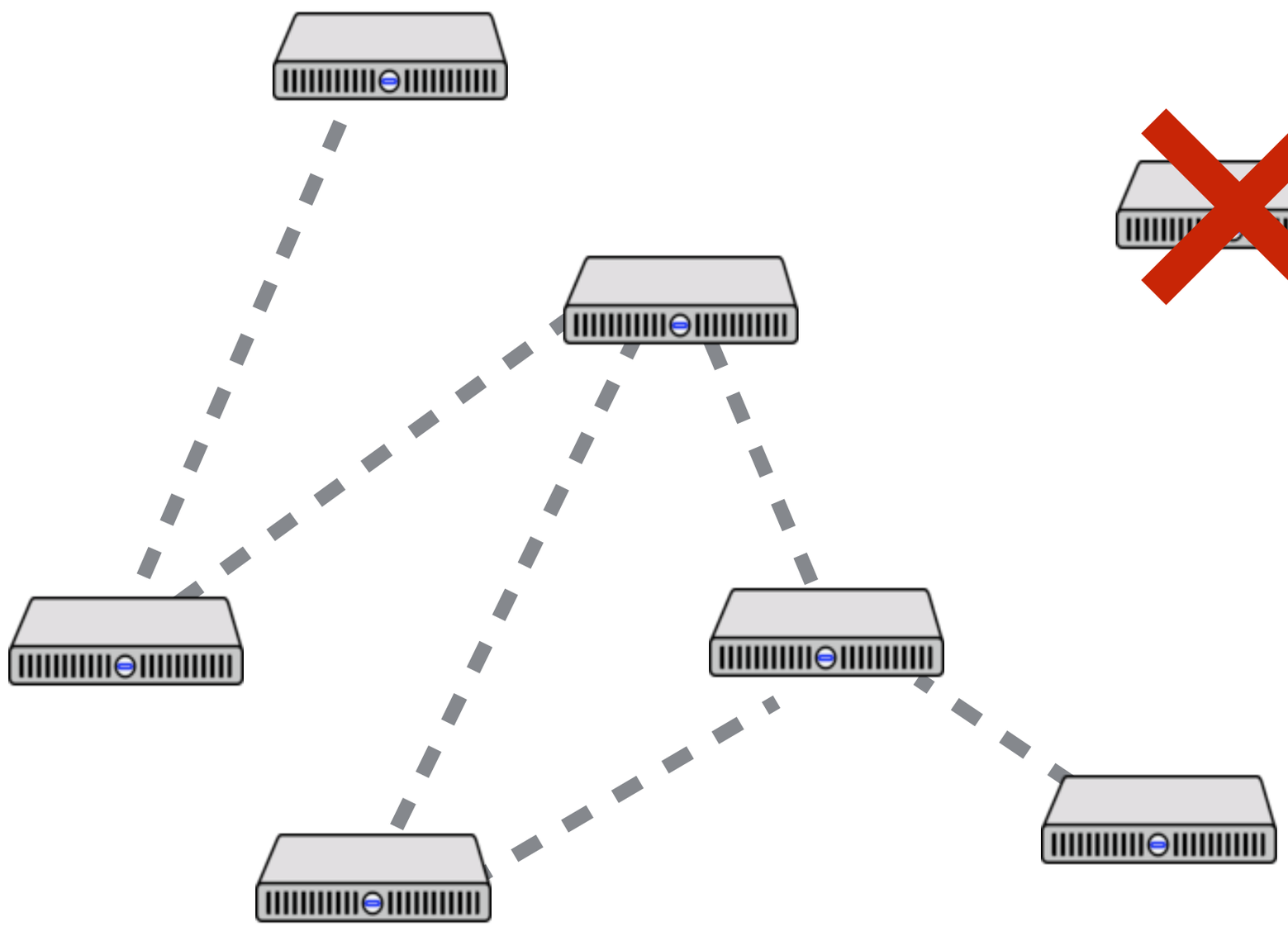
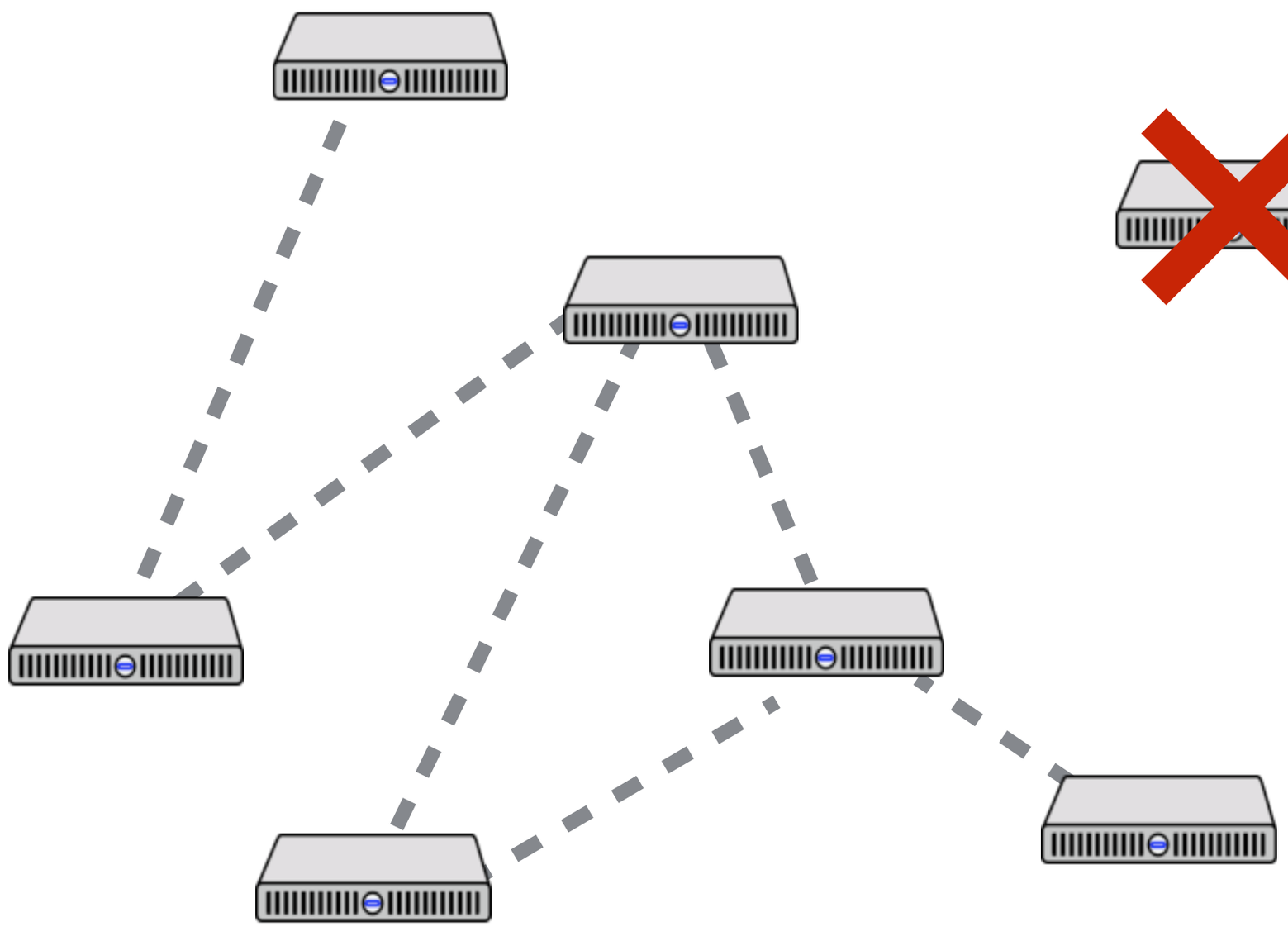


But what about new nodes?



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