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Formal Methods in Software Engineering

Case Study: Hotel Lock System

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Acknowledgments

These notes are based on an Alloy example in the following book:

[Jack06] Daniel Jackson. *Software abstractions – Logic, Language, and Analysis*. The MIT press, 2006.

The Problem

- We will model in Alloy the disposable **card key system** used in most hotels for locking and unlocking guest rooms
- The system uses **recordable locks**, which prevent previous guests from entering a room once its has been re-assigned
- We will **model** both **static and dynamic aspects** of the system

Problem Description [Jack06]

“ [...] the hotel issues a new key to the next occupant, which recodes the lock, so that previous keys will no longer work. The lock is a simple, stand-alone unit [...] with a memory holding the current key combination. A hardware device [...] generates a sequence of pseudorandom numbers. The lock is opened either by the current key combination, or by its successor; if a key with the successor is inserted, the successor is made to be the current combination, so that the old combination will no longer be accepted.”

Problem Description [Jack06]

“This scheme requires no communication between the front desk and the door lock. By synchronizing the front desk and the door locks initially, and by using the same pseudorandom generator, the front desk can keep its records of the current combinations in step with the doors themselves.”

Signatures and Fields

Signatures: **Time**, **Key**, **Room**, **Guest**, **FrontDesk**

- **Key** refers to the key combination stored in the magnetic strip of the card
- **FrontDesk** stores at any time a mapping
 - between each room and its most recent key combination (if any), and
 - between each room and its current guest

Signatures and Fields

- **Room** refers to the room lock
- Each room (lock) has
 - an associated set of keys, and
 - exactly one current key at a time
- Each key belongs to at most one room
- Each guest has zero or more keys at any time

Signatures and Fields

```
module hotel  
open util/ordering [Time] as TO  
open util/ordering [Key] as KO
```

```
}
```


Signatures and Fields

```
module hotel
open util/ordering [Time] as TO
open util/ordering [Key] as KO

sig Key {}
sig Time {}

sig Room {
  keys: set Key,
  currentKey: Key one -> Time
}

sig Guest {
  keys: Key -> Time
}

one sig FrontDesk {
  lastKey: (Room -> !one Key) -> Time,
  occupant: Room -> Guest -> Time
}
```

Room Constraint

- Each key belongs to at most one room

```
fact {  
    all k: Key | !one keys.k  
}
```

New Key Generation

Given a key `k` and a set `ks` of keys, the function `nextKey` returns the smallest key (in the key ordering) in `ks` that follows `k`.

```
fun nextKey [k: Key, ks: set Key]: set Key
{
  KO/min [KO/nexsts[k] & ks]
}
```

Initial State

```
module examples/hotel  
open util/ordering [Time] as TO  
open util/ordering [Key] as KO
```

```
sig Key {}  
sig Time {}
```

```
sig Room {  
  keys: set Key,  
  currentKey: Key one -> Time  
}
```

) *No constraints*

```
sig Guest {  
  keys: Key -> Time  
}
```

) *No guests have keys*

*the record of each room's key
at the front desk is
synchronized with the current
combination of the lock itself*

```
one sig FrontDesk {  
  lastKey: (Room -> one Key) -> Time,  
  occupant: Room -> Guest -> Time  
}
```

) *No rooms are occupied*

Hotel Operations: Initial State

```
pred init [t: Time] {  
  -- no guests have keys  
  no Guest.keys.t  
  
  -- the roster at the front desk shows  
  -- no room as occupied  
  no FrontDesk.occupant.t  
  
  -- the record of each room's key at the  
  -- front desk is synchronized with the  
  -- current combination of the lock itself  
  all r: Room |  
    r.(FrontDesk.lastKey.t) = r.currentKey.t  
}
```

Hotel Operations: Guest Entry

pred entry [g: Guest, r: Room, k: Key,
t, t': Time]

- Preconditions:
 - The key used to open the lock is one of the keys the guest is holding
- Pre and Post Conditions:
 - The key on the card
 - either matches the lock's current key, and the lock remains unchanged (not a new guest), or
 - matches its successor, and the lock is advanced (new guest)
- Frame conditions:
 - no changes to the state of other rooms, or to the set of keys held by guests, or to the records at the front desk

Hotel Operations: Guest Entry

```
pred entry[ g:Guest, r:Room, k:Key, t,t':Time ]
{
  -- the key used to open the lock is one of
  -- the keys the guest is holding
  k in g.keys.t
  -- pre and post conditions
  let ck = r.currentKey |
    -- not a new guest
    (k = ck.t and ck.t' = ck.t) or
    -- new guest
    (k = nextKey[ck.t, r.keys] and ck.t' = k)
  -- frame conditions
  noFrontDeskChange[t, t']
  noRoomChangeExcept[r, t, t']
  noGuestChangeExcept[none, t, t']
}
```

Frame conditions

```
pred noFrontDeskChange [t,t': Time]
{
  FrontDesk.lastKey.t = FrontDesk.lastKey.t'
  FrontDesk.occupant.t = FrontDesk.occupant.t'
}

pred noRoomChangeExcept [rs: set Room, t,t': Time]
{
  all r: Room - rs |
    r.currentKey.t = r.currentKey.t'
}

pred noGuestChangeExcept [gs: set Guest, t,t': Time]
{
  all g: Guest - gs | g.keys.t = g.keys.t'
}
```


Hotel Operations: Check-out

pred checkout [g: Guest, t,t': Time]

- Preconditions:
 - the guest occupies one or more rooms
- Postconditions:
 - the guest's rooms become available
- Frame conditions:
 - Nothing changes but the occupant relation

Hotel Operations: Check-out

```
one sig FrontDesk {
  lastKey: (Room -> !one Key) -> Time,
  occupant: Room -> Guest -> Time
}

pred checkout [ g: Guest, t,t': Time ]
{
  let occ = FrontDesk.occupant | {
    -- the guest occupies one or more rooms
    some (occ.t).g
    -- the guest's rooms become available
    occ.t' = occ.t - (Room -> g)
  }
  -- frame condition
  FrontDesk.lastKey.t = FrontDesk.lastKey.t'
  noRoomChangeExcept[none, t, t']
  noGuestChangeExcept[none, t, t']
}
```

Hotel Operations: Check-in

pred checkin [g: Guest, r: Room, k: Key
t, t': Time]

- Preconditions:
 - the room is available
 - the input key is the successor of the last key in the sequence associated to the room
- Postconditions:
 - the guest holds the input key and becomes the new occupant of the room
 - the input key becomes the room's current key
- Frame conditions:
 - Nothing changes but the occupant relation and the guest's relations

Hotel Operations: Check-in

```
pred checkin [ g: Guest, r: Room, k: Key, t,t': Time ] {
  -- the guest holds the input key
  g.keys.t' = g.keys.t + k
  let occ = FrontDesk.occupant | {
    -- the room has no current occupant
    no r.occ.t
    -- the guest becomes the new occupant of the room
    occ.t' = occ.t + r->g
  }
  let lk = FrontDesk.lastKey | {
    -- the input key becomes the room's current key
    lk.t' = lk.t ++ r->k
    -- the input key is the successor of the last key in
    -- the sequence associated to the room
    k = nextKey[r.lk.t, r.keys]
  }
  noRoomChangeExcept[none, t, t']
  noGuestChangeExcept[g, t, t']
}
```

Trace generation

- The first time step satisfies the initialization conditions
- Any pair of consecutive time steps are related by
 - an entry operation, or
 - a check-in operation, or
 - a check-out operation

Trace generation

```
pred trans[t,t': Time] {
  some g: Guest, r: Room, k: Key |
    entry[g, r, k, t, t'] or
    checkin[g, r, k, t, t'] or
    checkout[g, t, t']
}
fact Traces {
  init[T0/first]
  all t: Time - T0/last |
  let t' = T0/next[t] |
    trans[t, t']
}
```

Analysis

- Let's check if unauthorized entries are possible:
 - If a guest g enters room r at time t , and the front desk records show r as occupied at that time, then g must be a recorded occupant of r .

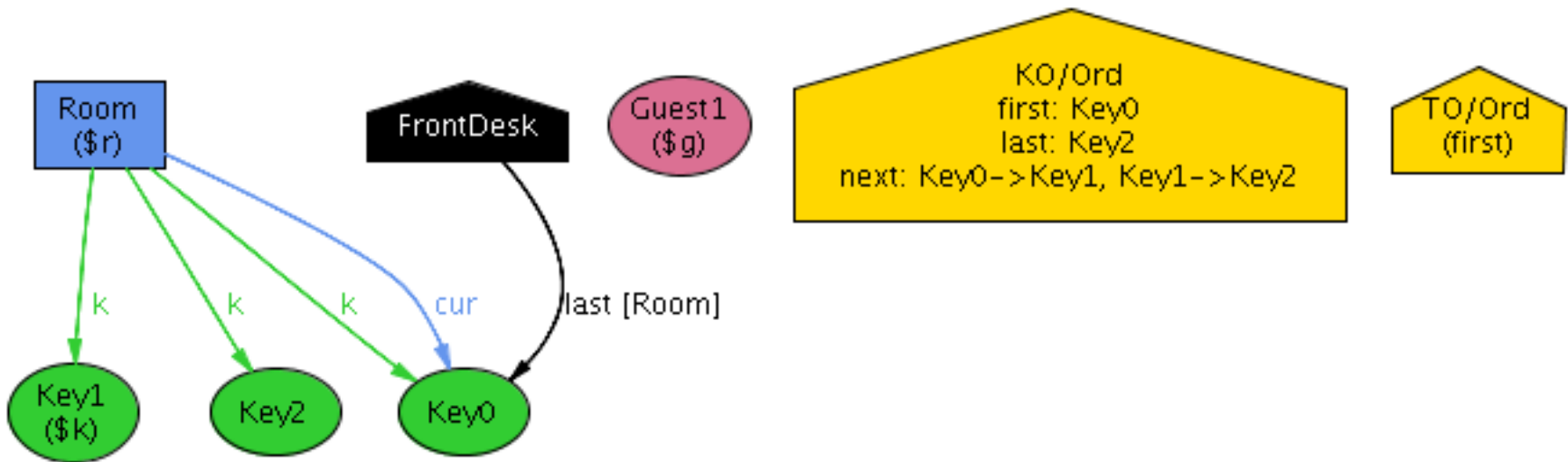
```
assert noBadEntry {  
  all t: Time, r: Room, g: Guest, k: Key |  
  let t' = TO/next [t],  
      o = r.FrontDesk.occupant.t |  
  (entry[g, r, k, t, t'] and some o)  
  implies g in o  
}
```

Analysis

check noBadEntry for 3
but 2 Room, 2 Guest, 5 Time

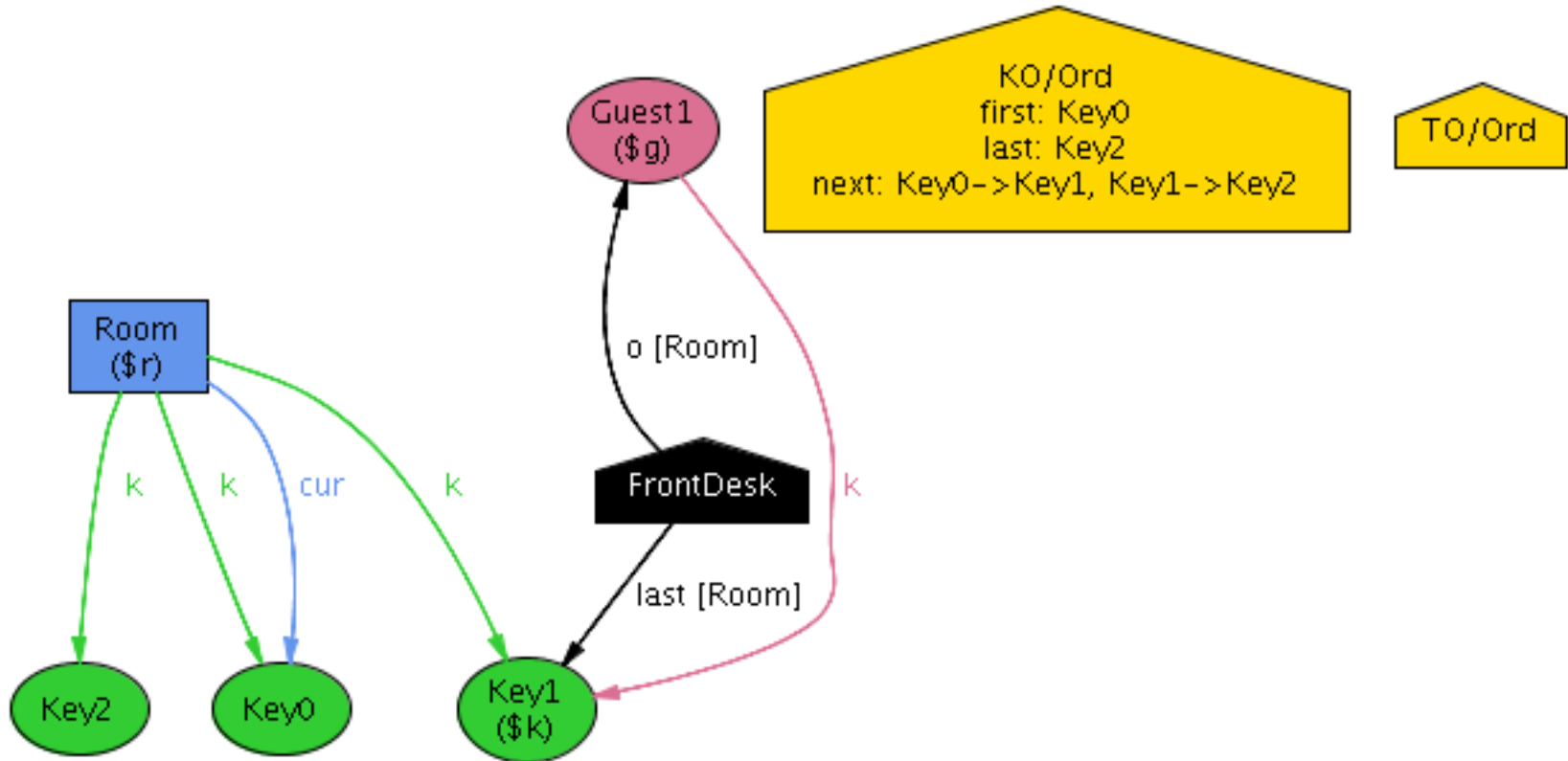
- It is enough to check for problem already with just 2 guests and 2 rooms
- Time's scope must be at least 5 because at least 4 time steps are needed to execute each operation once.
- There is a counter-example (file hotel1.als)

T0: Initial State



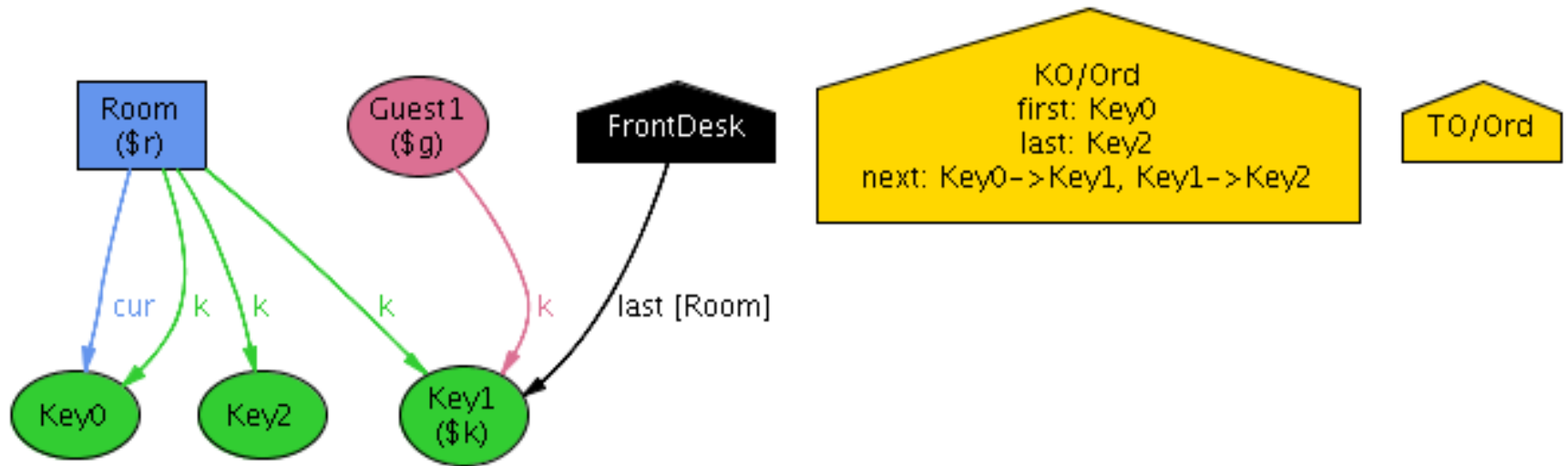
Initially, the current key of **Room** is **Key0**, which is also reflected in the front desk's record

T1: Checkin Operation



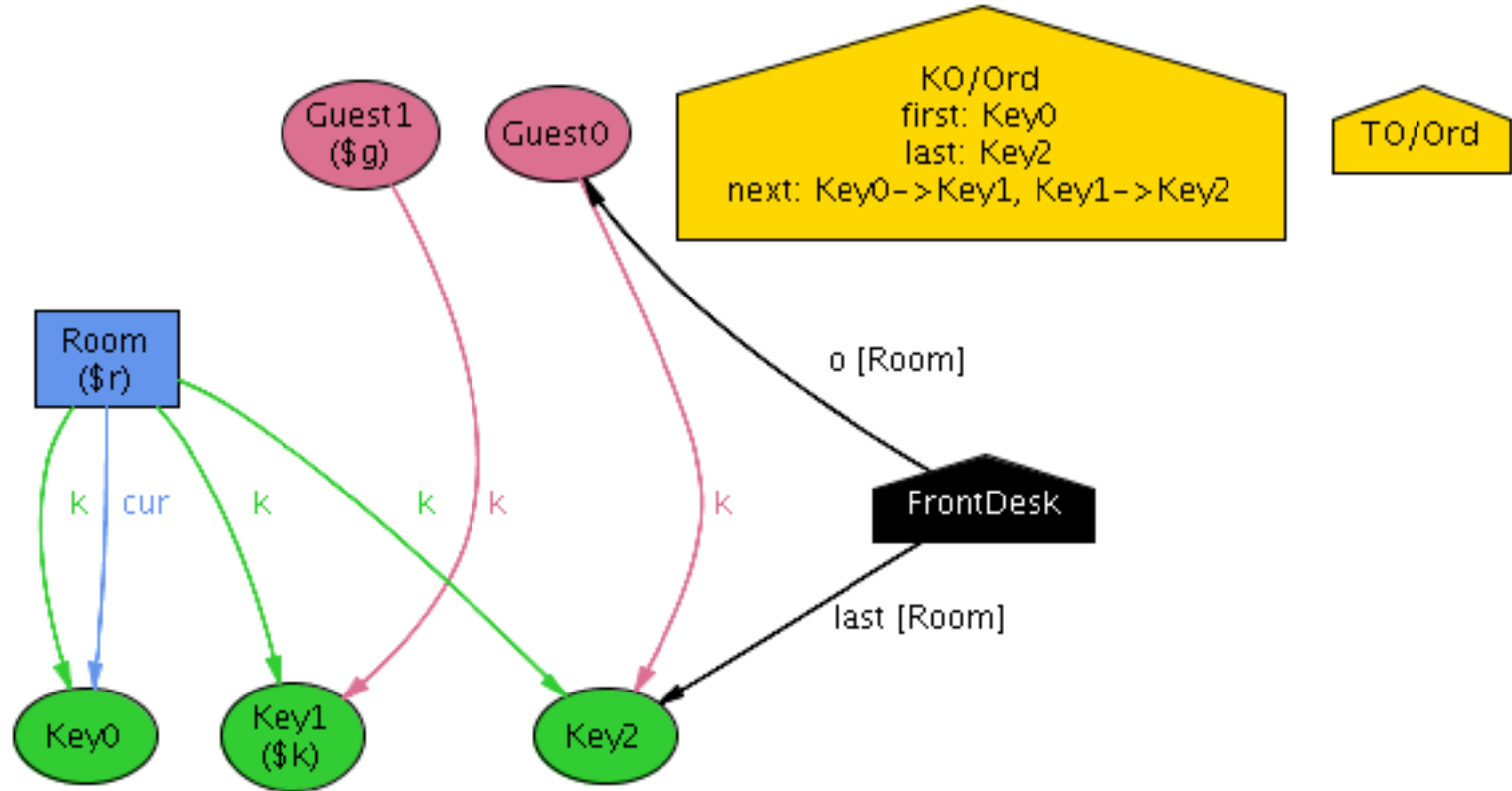
Guest1 checks in to **Room** and receives key **Key1**; the occupancy roster at the front desk is updated accordingly; **Key1** is recorded as the last key assigned to **Room**

T2: Checkout Operation



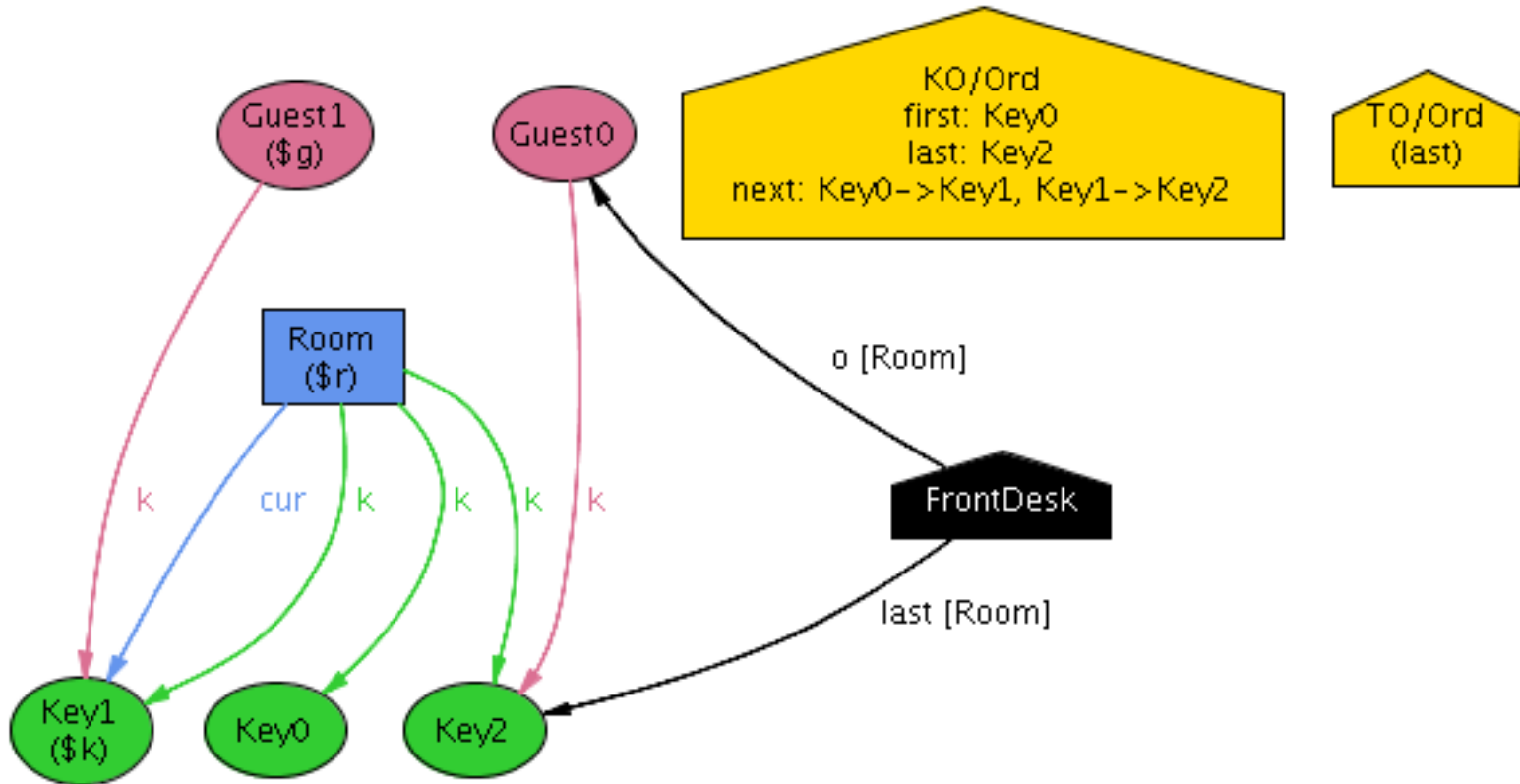
Guest1 checks out, and the occupancy roster is cleared

T3: Checkin Operation



Guest0 checks in to **Room** and receives key **Key2**; the occupancy roster at the front desk is updated accordingly; **Key2** is recorder as the last key assigned to **Room**

T4: Enter Operation



Guest1 presents Key1 to the lock of Room, and is admitted

Necessary Restriction

- There is no intervening operations between a guest's check-in and room entry.

```
fact noIntervening {
  all t: Time - TO/last |
  let t' = TO/next [t], t'' = TO/next [t'] |
  all g: Guest, r: Room, k: Key |
  checkin[g, r, k, t, t'] implies
  (
    entry[g, r, k, t', t''] or
    no t''
  )
}
```

Analysis

- We check once again:
 - check noBadEntry for 3
 - but 2 Room, 2 Guest, 5 Time
 - No counter-example (file hotel2.als)
- For greater confidence, we increase the scope:
 - check noBadEntry for 5
 - but 3 Room, 3 Guest, 9 Time
 - No counter-examples