Alloy

Daniel Jackson
MIT Lab for Computer Science
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joint work with:
Ilya Shlyakhter, Manu Sridharan, Sarfraz Khurshid
Brian Lin, Jesse Pavel, Mana Taghdiri,
Mandana Vaziri, Hoeteck Wee

```
non  supporte

H:  42.5Hz     V:85.4Hz
```

didn’t you bring a hardcopy backup?
fool!

non supporte

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motivations

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- system implemented in software?
- infinitely many states?
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- SMV: automatic analysis
- Z: expression of structure

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Pittsburgh, home of SMV

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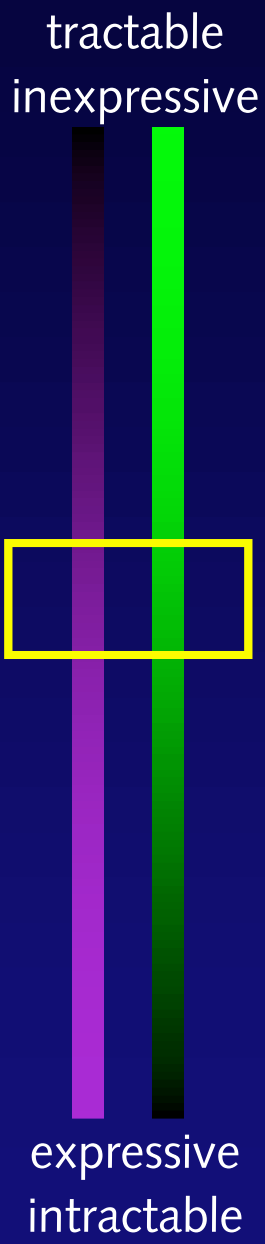
Oxford, home of Z

the challenge


tractable

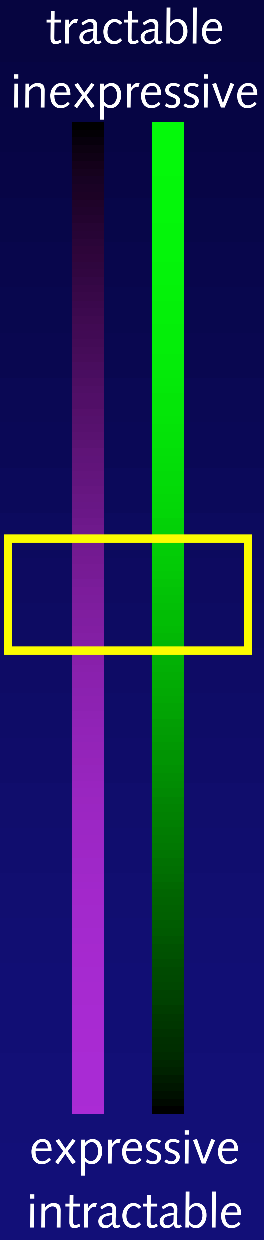
inexpressive

expressive

intractable

the challenge

language must support
- complex data structures
- declarative specification
    - partiality, separation of concerns



the challenge

language must support
- complex data structures
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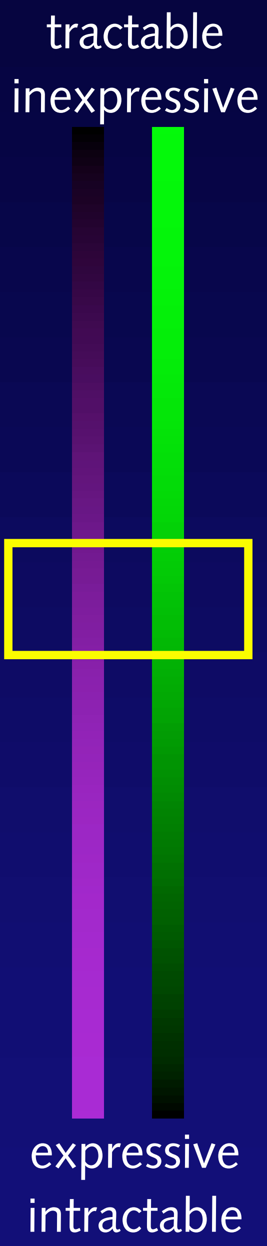
analysis must be
- fully automatic
- interactive performance
- easy to interpret output



key ideas: foundations

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- all data structures encoded as relations
- hierarchy with higher-arity relations

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exploit SAT technology
- analyzer is a compiler
- symmetry breaking, skolemization, sharing, etc
- pluggable backend

key ideas: pragmatics

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syntax

- ASCII based
- prefer existing conventions

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semantics

- relations only: no scalars, sets or tuples
  a represented as {a}
  (a,b) represented as {(a,b)}
- gives simpler syntax
- no complications from partial functions
  undefined, null, maybe, non-denoting terms

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visualization

- customizable, no built in notion of state, eg.

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sample applications

- Chord peer-to-peer lookup (Wee)
- Intentional Naming (Khurshid)
- Key management (Taghdiri)
- Microsoft COM (Sullivan)
- Classic distributed algorithms (Shlyakhter)
- Firewire leader election (Jackson)
- Red-black tree invariants (Vaziri)
- RM-ODP meta modelling (EPFL)
- Role-based access control (BBN)

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taught in courses at

- CMU, Waterloo, Wisconsin, Rochester, Kansas State, Irvine, Georgia Tech, Queen's, Michigan State, Imperial, Colorado State, Twente, WPI, MIT

outline of rest of talk

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elevator example

- translating a fragment
- expressing constraints
- trace-based analysis

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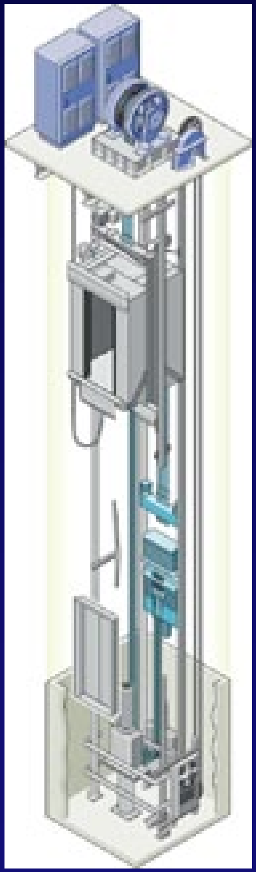
related work & conclusions

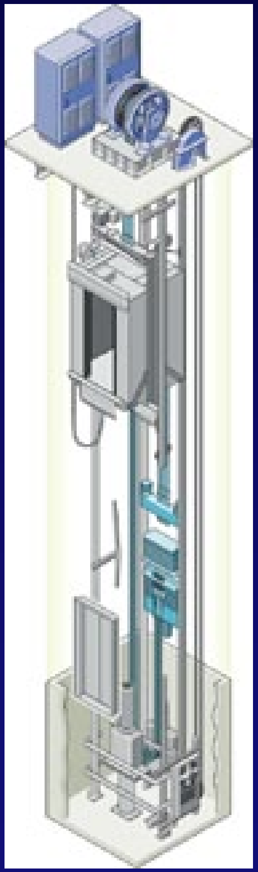
example: elevator policy



example: elevator policy

challenge

- specify a policy for scheduling elevators



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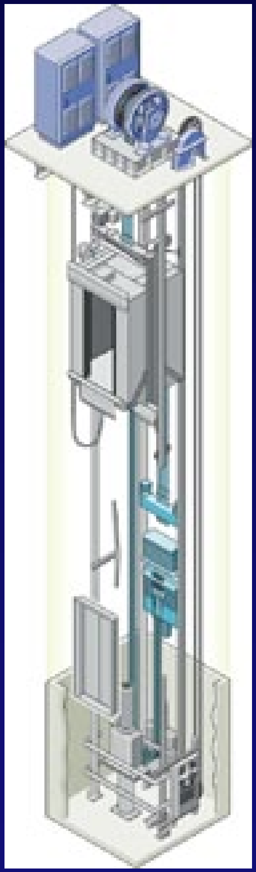
tight enough
- all requests eventually served
- don’t skip request from inside lift

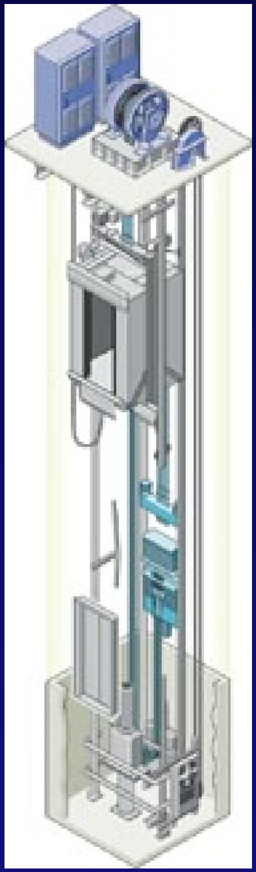


example: elevator policy

challenge
- specify a policy for scheduling elevators

tight enough
- all requests eventually served
- don’t skip request from inside lift

loose enough
- no fixed configuration of floors, lifts, buttons
- not one algorithm but a family



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deny request

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- if a lift denies a floor request
  some lift promises to take it later

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freedoms
- divide requests amongst lifts
- postpone decision until first skip or bounce
- unlike ‘closest serves’, can balance load

basic abstractions

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floor layout

- orderings above and below
- top and bottom floors

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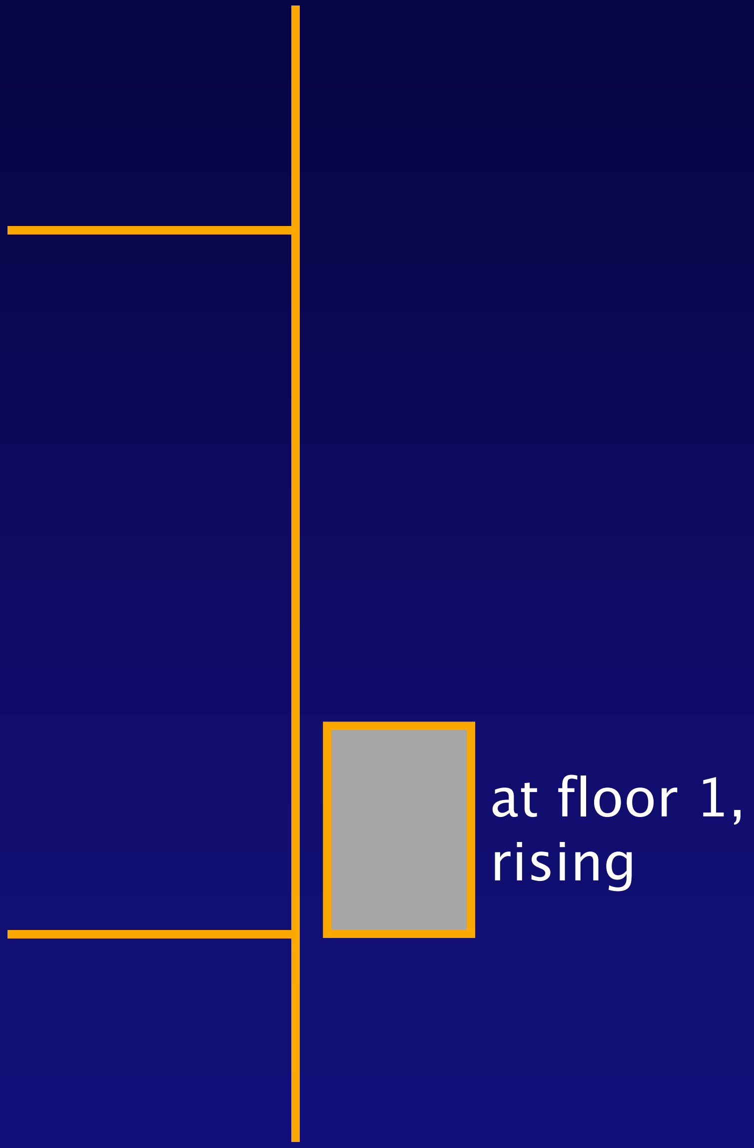

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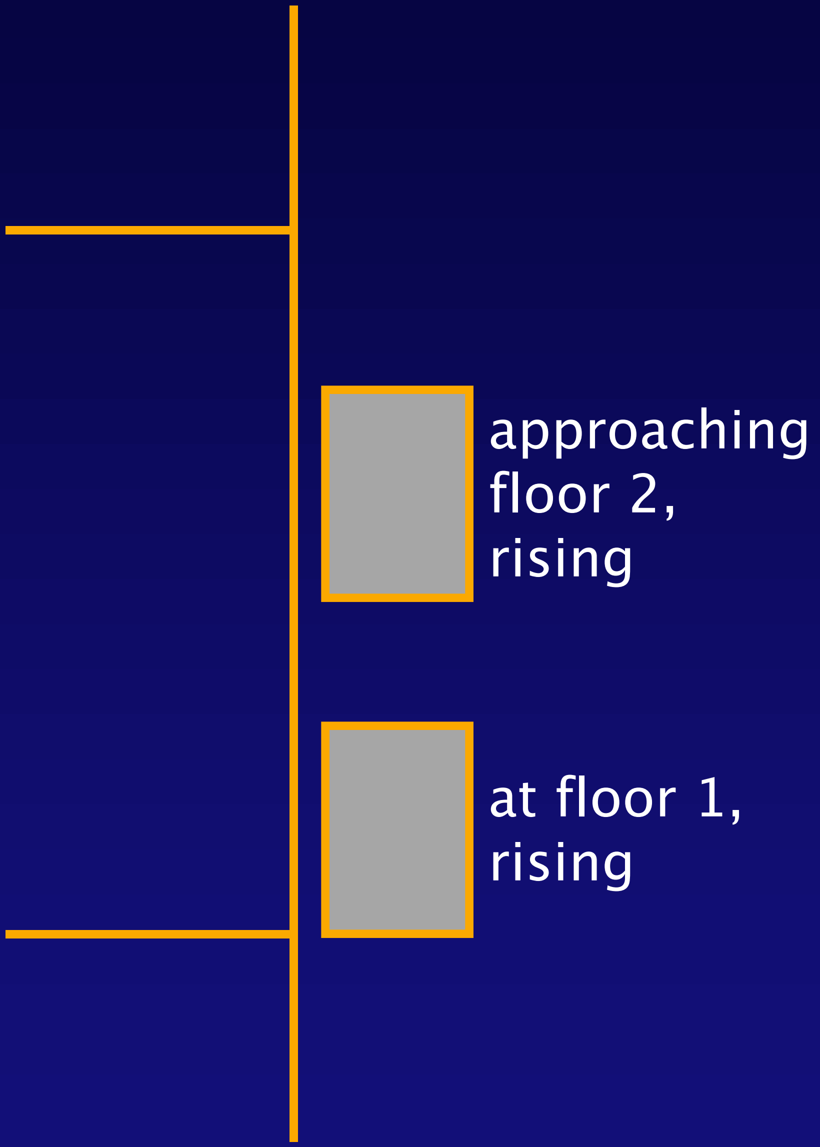

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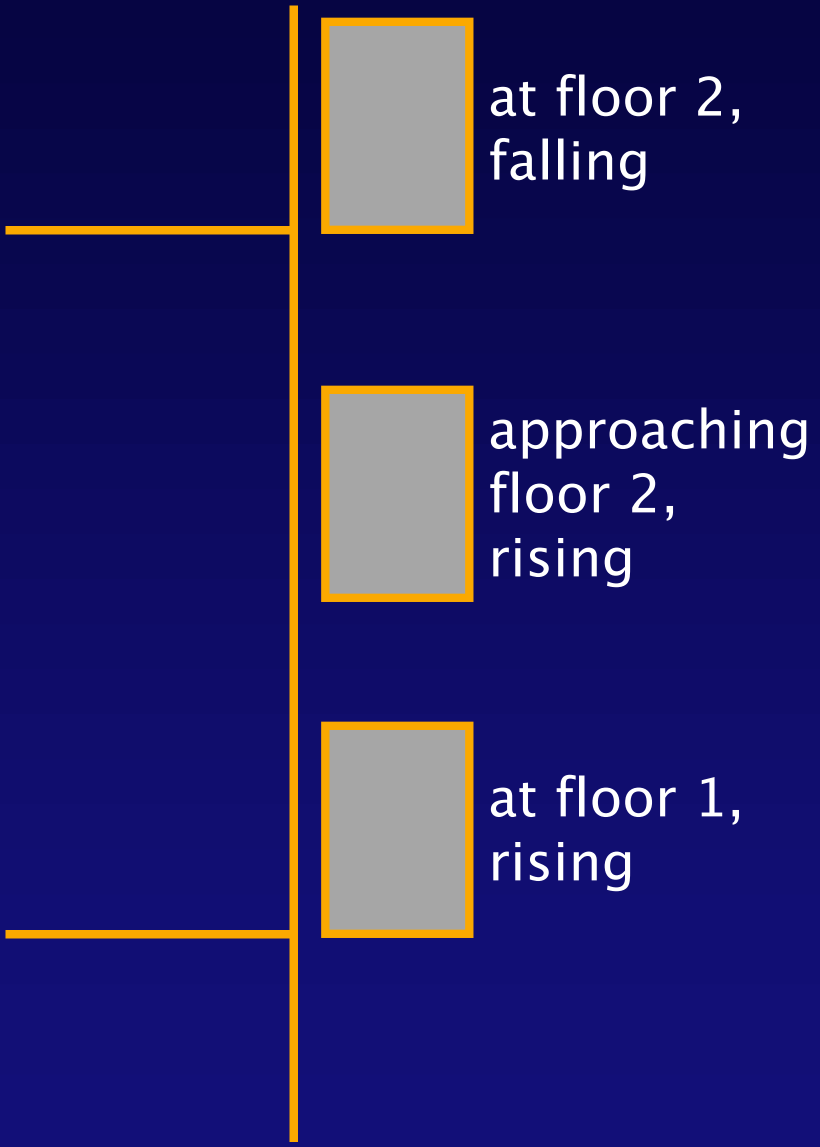

at floor 2,
falling

approaching
floor 2,
rising

at floor 1,
rising

language elements

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relations

  sig State {at: Lift ->? Floor}

  declares relation at with values like {(s0,p0,f0),(s1,p0,f1)}

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operators

+ & - .	union, intersection, difference, join
s.at	the lift/floor mapping for state s
p.(s.at), s.at[p]	the floor of lift p in state s

at = {(s0,p0,f0),(s1,p0,f1)} , s = {(s1)}, p = {(p0)}

s.at = {(p0,f1)}, s.at[p] = {(f1)}

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formulas

in	means subset
s.at[p] in f	if p is at a floor in state s, that floor is f

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-- above, below map each floor to at most one floor
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fact {all s: State, p: Lift | one s.(at+approaching)[p]}
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run show for 2 -- find instance with 2 states, lifts, floors
```

translation

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sig Floor {above, below: option Floor}
-- allocate boolean variables Floor[i] , above[i,j] , below[i,j]
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run show for 2 -- solve formula

an instance generated by the analyzer

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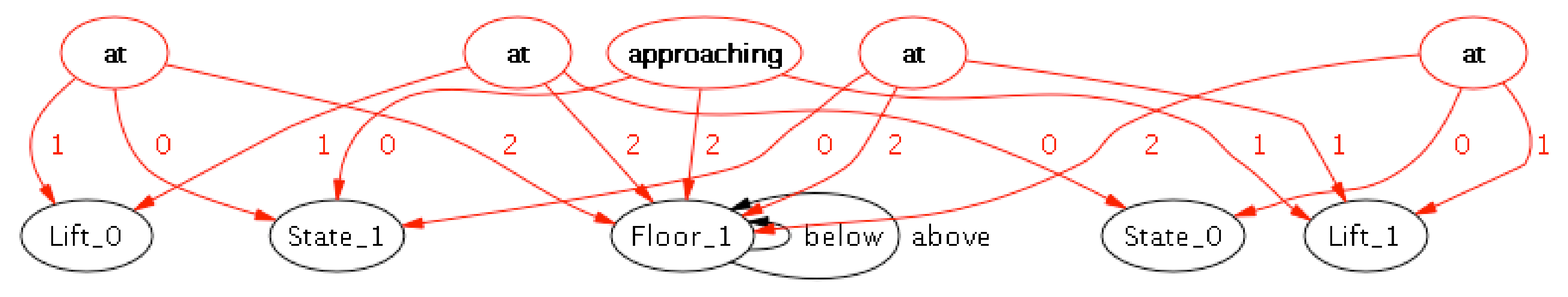

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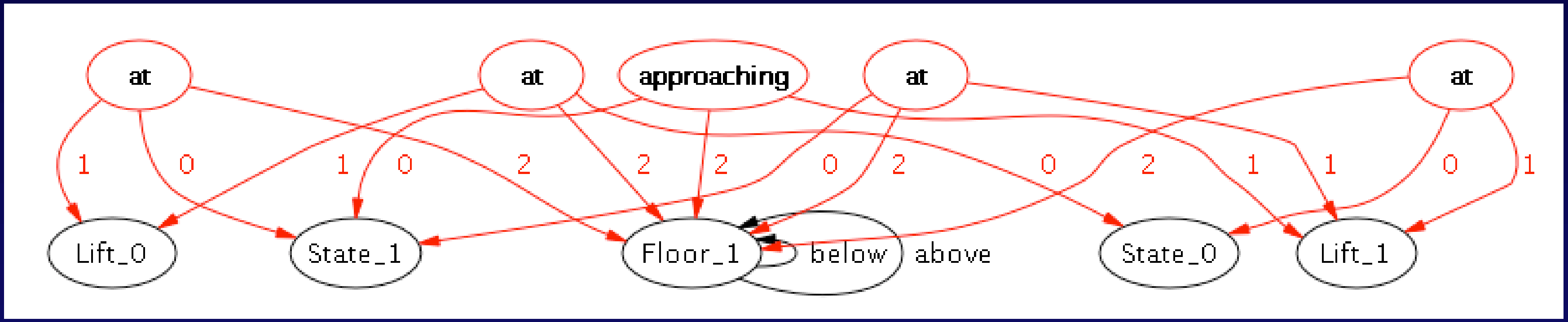
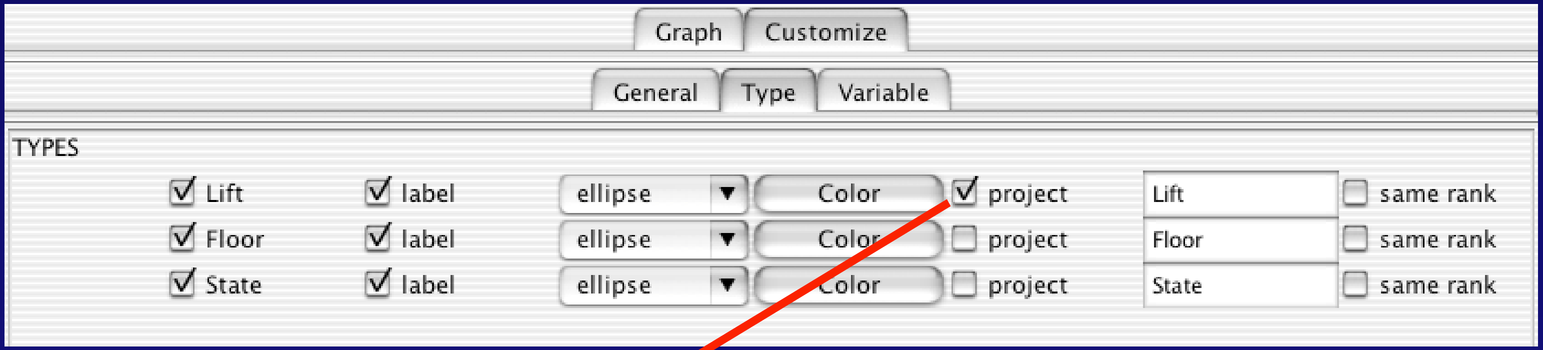


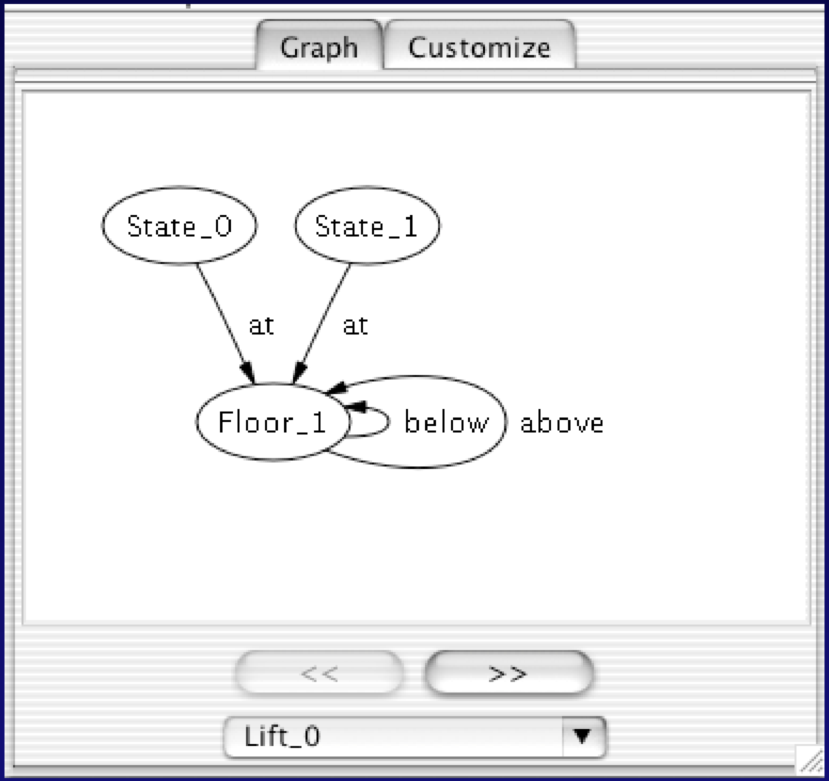


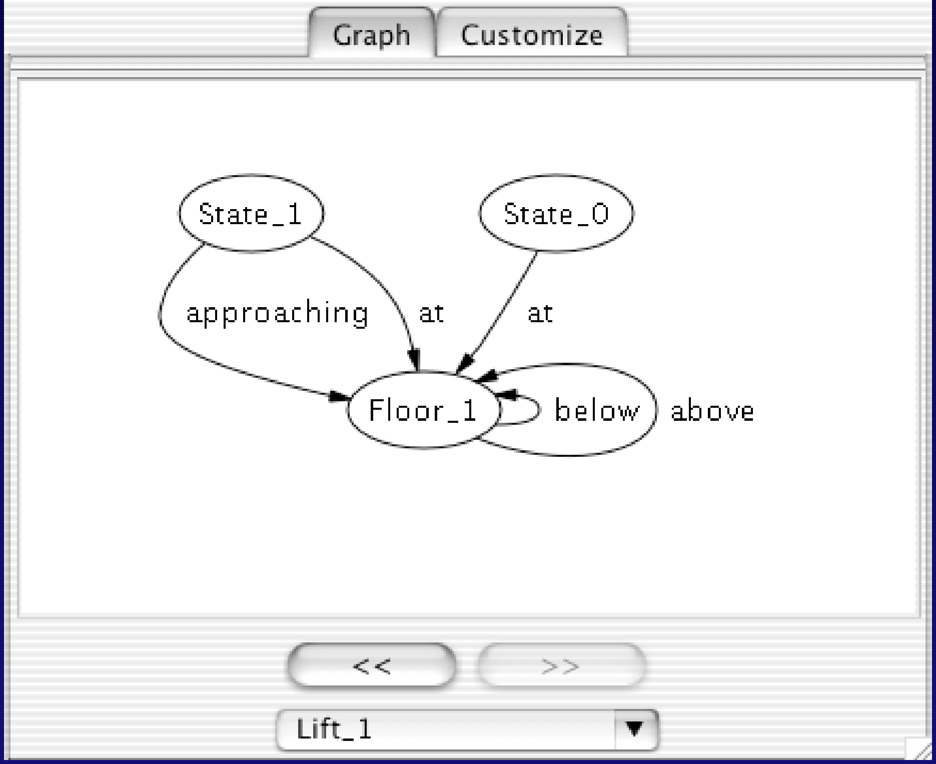
TYPES

☑ Lift	☑ label	ellipse	Color	☑ project	Lift	☐ same rank
☑ Floor	☑ label	ellipse	Color	☐ project	Floor	☐ same rank
☑ State	☑ label	ellipse	Color	☐ project	State	☐ same rank

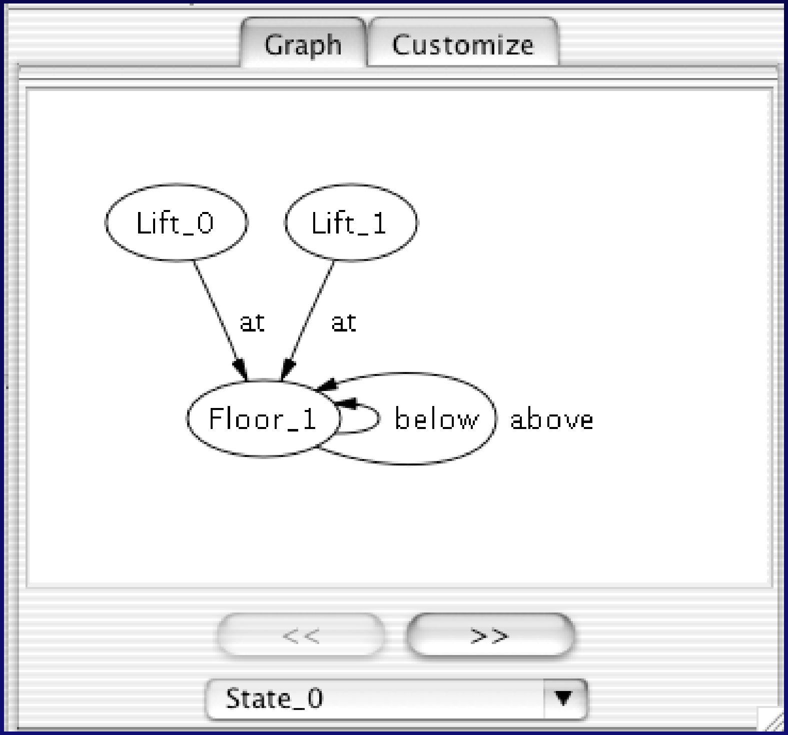
select projection for type

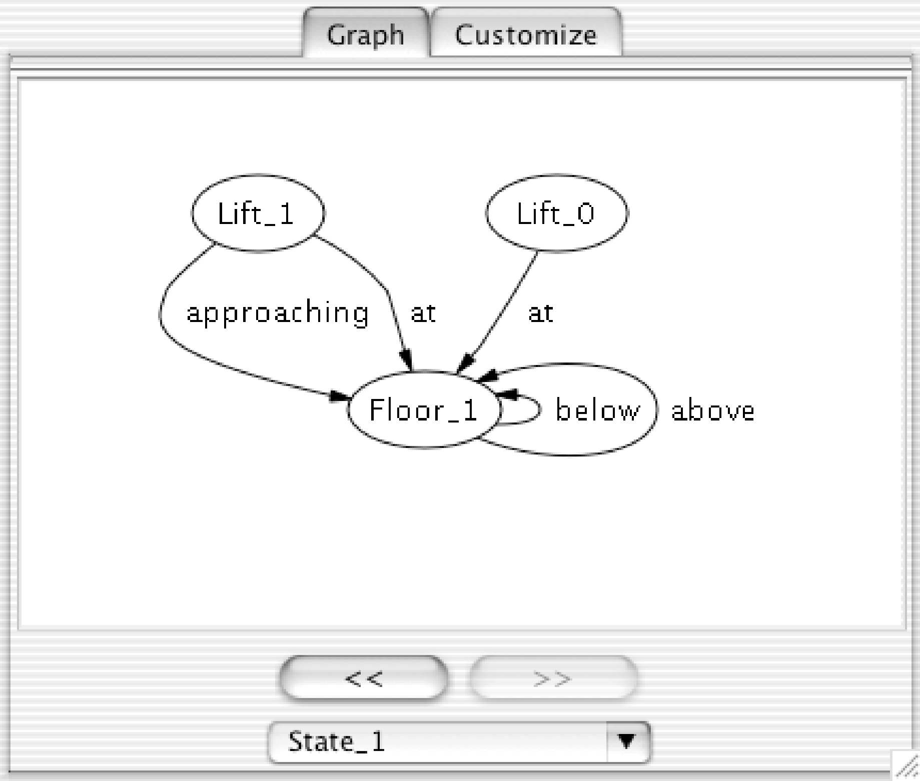
projection onto Lift





projection onto State

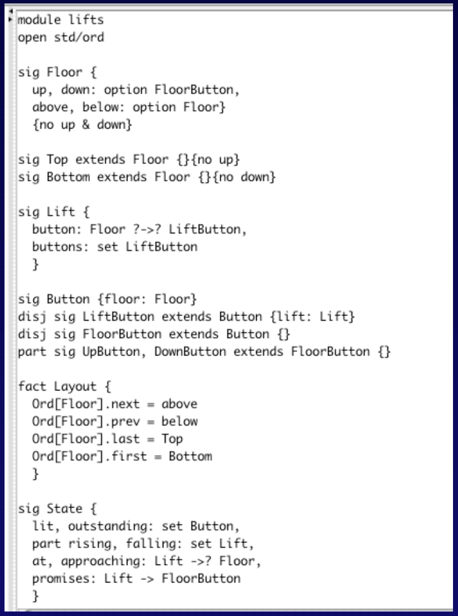




process

process

user
writes
model
and
selects
command



```
module lifts
open std/ord

sig Floor {
  up, down: option FloorButton,
  above, below: option Floor}
  {no up & down}

sig Top extends Floor {}{no up}
sig Bottom extends Floor {}{no down}

sig Lift {
  button: Floor ?->? LiftButton,
  buttons: set LiftButton
  }

sig Button {floor: Floor}
disj sig LiftButton extends Button {lift: Lift}
disj sig FloorButton extends Button {}
part sig UpButton, DownButton extends FloorButton {}

fact Layout {
  Ord[Floor].next = above
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sig State {
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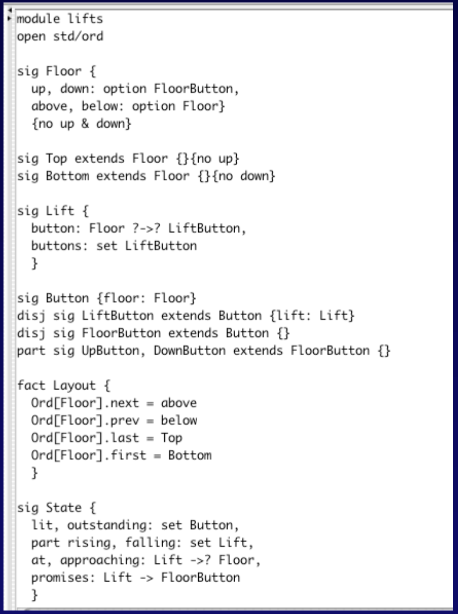

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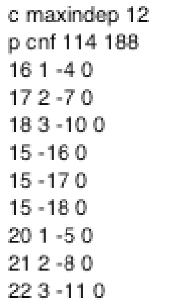
Alloy Analyzer
translates command
to boolean formula



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p cnf 114 188
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18 3 -10 0
15 -16 0
15 -17 0
15 -18 0
20 1 -5 0
21 2 -8 0
22 3 -11 0
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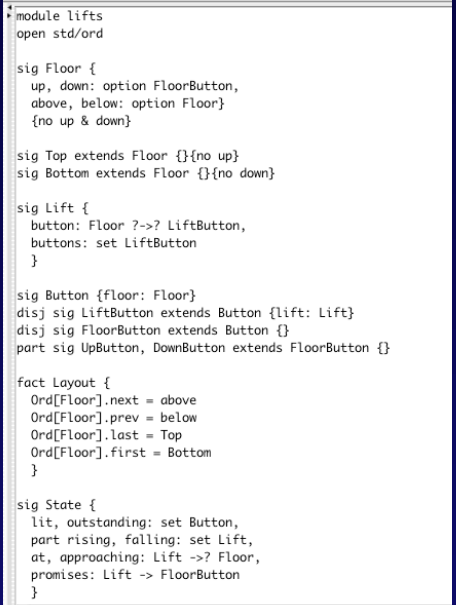

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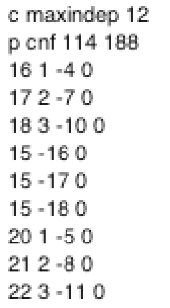

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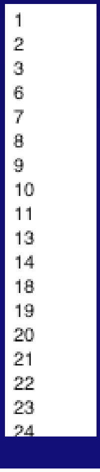
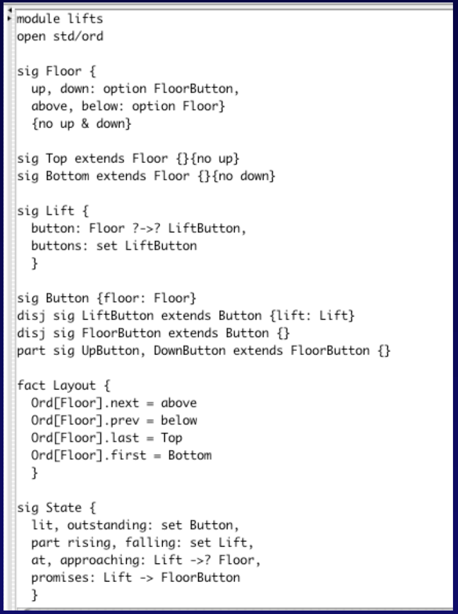
SAT solver
finds boolean
solution



```
1
2
3
6
7
8
9
10
11
13
14
18
19
20
21
22
23
24
```

process

user writes model and selects command



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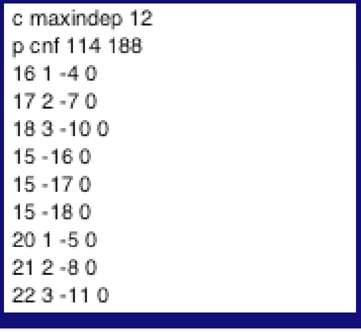
disj sig LiftButton extends Button {lift: Lift}
disj sig FloorButton extends Button {}
part sig UpButton, DownButton extends FloorButton {}

fact Layout {
  Ord[Floor].next = above
  Ord[Floor].prev = below
  Ord[Floor].last = Top
  Ord[Floor].first = Bottom
  }

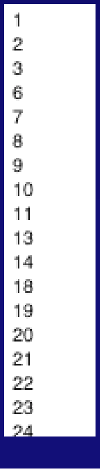
sig State {
  lit, outstanding: set Button,
  part rising, falling: set Lift,
  at, approaching: Lift ->? Floor,
  promises: Lift -> FloorButton
  }
```

Alloy Analyzer translates command to boolean formula

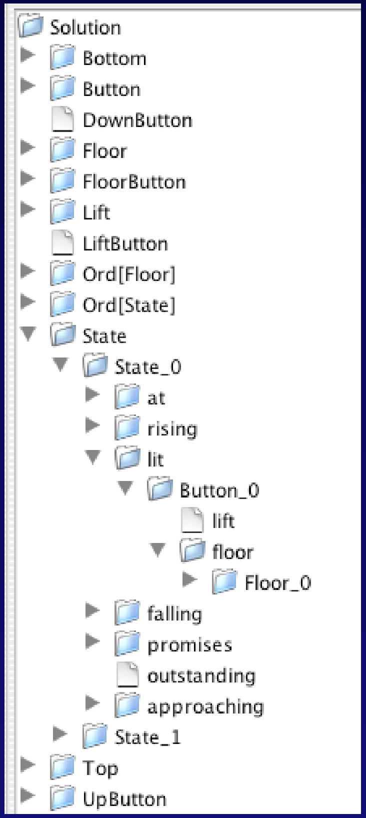


```
c maxindep 12
p cnf 114 188
16 1 -4 0
17 2 -7 0
18 3 -10 0
15 -16 0
15 -17 0
15 -18 0
20 1 -5 0
21 2 -8 0
22 3 -11 0
```

SAT solver finds boolean solution



```
1
2
3
6
7
8
9
10
11
13
14
18
19
20
21
22
23
24
```

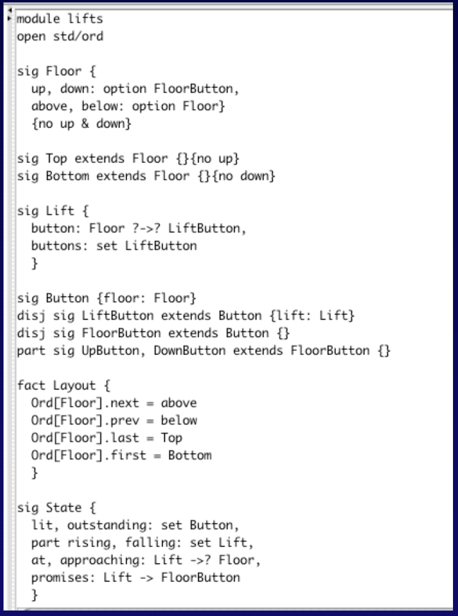


```
Solution
▶ Bottom
▶ Button
  DownButton
▶ Floor
▶ FloorButton
▶ Lift
  LiftButton
▶ Ord[Floor]
▶ Ord[State]
▼ State
    ▼ State_0
        ▶ at
        ▶ rising
        ▼ lit
            ▼ Button_0
                lift
                ▼ floor
                    ▶ Floor_0
        ▶ falling
        ▶ promises
          outstanding
        ▶ approaching
    ▶ State_1
▶ Top
▶ UpButton
```

Alloy Analyzer translates boolean solution to relational

process

user writes model and selects command



```
module lifts
open std/ord

sig Floor {
  up, down: option FloorButton,
  above, below: option Floor}
  {no up & down}

sig Top extends Floor {}{no up}
sig Bottom extends Floor {}{no down}

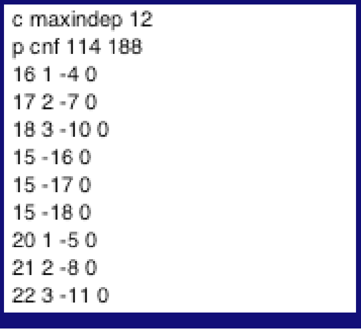
sig Lift {
  button: Floor ?->? LiftButton,
  buttons: set LiftButton
  }

sig Button {floor: Floor}
disj sig LiftButton extends Button {lift: Lift}
disj sig FloorButton extends Button {}
part sig UpButton, DownButton extends FloorButton {}

fact Layout {
  Ord[Floor].next = above
  Ord[Floor].prev = below
  Ord[Floor].last = Top
  Ord[Floor].first = Bottom
  }

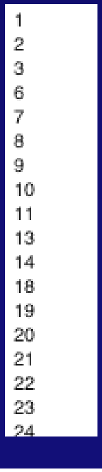
sig State {
  lit, outstanding: set Button,
  part rising, falling: set Lift,
  at, approaching: Lift ->? Floor,
  promises: Lift -> FloorButton
  }
```

Alloy Analyzer translates command to boolean formula



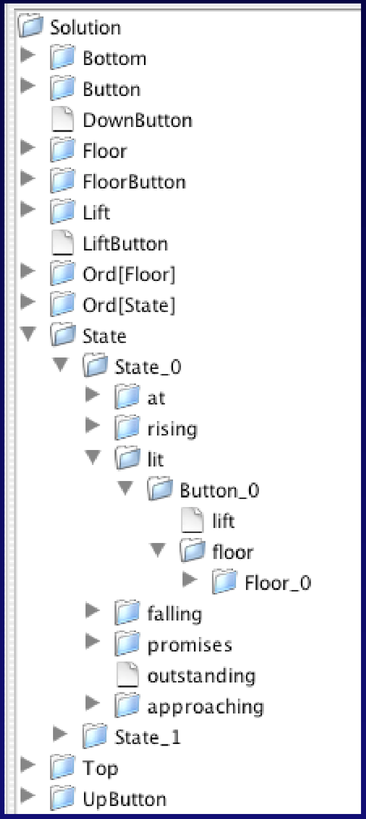
```
c maxindep 12
p cnf 114 188
16 1 -4 0
17 2 -7 0
18 3 -10 0
15 -16 0
15 -17 0
15 -18 0
20 1 -5 0
21 2 -8 0
22 3 -11 0
```

SAT solver finds boolean solution



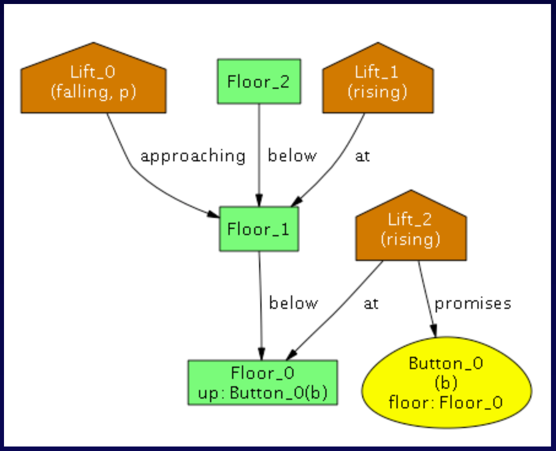
```
1
2
3
6
7
8
9
10
11
13
14
18
19
20
21
22
23
24
```

Alloy Analyzer translates boolean solution to relational



```
Solution
▶ Bottom
▶ Button
  DownButton
▶ Floor
▶ FloorButton
▶ Lift
  LiftButton
▶ Ord[Floor]
▶ Ord[State]
▼ State
  ▼ State_0
    ▶ at
    ▶ rising
    ▼ lit
      ▼ Button_0
          lift
        ▼ floor
          ▶ Floor_0
    ▶ falling
    ▶ promises
      outstanding
    ▶ approaching
  ▶ State_1
▶ Top
▶ UpButton
```

Alloy Analyzer creates custom visualization



constraints

constraints

lift physics & hardware

- can’t be at and approaching a floor
- can’t jump from floor to floor
- can’t change direction between floors

constraints

lift physics & hardware

- can’t be at and approaching a floor
- can’t jump from floor to floor
- can’t change direction between floors

policy

- can’t skip a request from inside the lift
- buttons reset when requests serviced

constraints

lift physics & hardware

- can’t be at and approaching a floor
- can’t jump from floor to floor
- can’t change direction between floors

policy

- can’t skip a request from inside the lift
- buttons reset when requests serviced

analyses

- generate samples of states, steps, traces
- show policy implies desired properties (eg, no starvation)

static environmental constraints

static environmental constraints

sig Bottom extends Floor {}

static environmental constraints

```
sig Bottom extends Floor {}

sig State {
    part rising, falling: set Lift
    at, approaching: Lift ->? Floor
    }
```

static environmental constraints

```
sig Bottom extends Floor {}

sig State {
   part rising, falling: set Lift
   at, approaching: Lift ->? Floor
   }

fun LiftPosition (s: State) {
   all p: Lift {
      -- lift is not at and approaching same floor
      no s.at[p] & s.approaching[p]
      -- can't be approaching the bottom floor when rising
      p in s.rising => s.approaching[p] != Bottom
      ...}
   }
```

static environmental constraints

```
sig Bottom extends Floor {}

sig State {
    part rising, falling: set Lift
    at, approaching: Lift ->? Floor
    }

fun LiftPosition (s: State) {
    all p: Lift {
       -- lift is not at and approaching same floor
       no s.at[p] & s.approaching[p]
       -- can't be approaching the bottom floor when rising
       p in s.rising => s.approaching[p] != Bottom
       ...}
    }
```

function: an ‘invocable’ constraint

dynamic environmental constraints

dynamic environmental constraints

```
fun LiftMotion (s, s': State) {
   all p: Lift {
      -- if at a floor after, was at or approaching that floor before
      s'.at[p] in s.(at + approaching)[p]
      …}
   }
```

dynamic environmental constraints

```
fun LiftMotion (s, s': State) {
   all p: Lift {
      -- if at a floor after, was at or approaching that floor before
      s'.at[p] in s.(at + approaching)[p]
      …}
   }
```

terse relational operators

`s'.at[p] in s.(at + approaching)[p]`

`all f: Floor | f = s’.at[p] => f = s.at[p] or f = s.approaching[p]`

dynamic environmental constraints

s pre, s' post:
just a convention

```
fun LiftMotion (s, s': State) {
   all p: Lift {
      -- if at a floor after, was at or approaching that floor before
      s'.at[p] in s.(at + approaching)[p]
      ...}
   }
```

terse relational operators

```
s'.at[p] in s.(at + approaching)[p]
all f: Floor | f = s’.at[p] => f = s.at[p] or f = s.approaching[p]
```

policy: defining denial

policy: defining denial

```
fun nextFloor (s: State, p: Lift): Floor -> Floor {
    result = if p in s.rising then above else below
    }
```

policy: defining denial

```
fun nextFloor (s: State, p: Lift): Floor -> Floor {
   result = if p in s.rising then above else below
   }

fun Towards (s: State, p: Lift, f: Floor) {
   -- p is going towards serving floor f
   let next = nextFloor(s,p) |
     f in s.at[p].^next + s.approaching[p].*next
   }
```

policy: defining denial

```
fun nextFloor (s: State, p: Lift): Floor -> Floor {
   result = if p in s.rising then above else below
   }

fun Towards (s: State, p: Lift, f: Floor) {
   -- p is going towards serving floor f
   let next = nextFloor(s,p) |
     f in s.at[p].^next + s.approaching[p].*next
   }

fun Denies (s, s': State, p: Lift, b: Button) {
   -- p was going to serve b, but is no longer
   let f = b.floor |
     Towards (s,p,f) and not Towards (s',p,f) and !Serves (s,s',p,b)
   }
```

policy: defining denial

```
fun nextFloor (s: State, p: Lift): Floor -> Floor {
    result = if p in s.rising then above else below
    }

fun Towards (s: State, p: Lift, f: Floor) {
    -- p is going towards serving floor f
    let next = nextFloor(s,p) |
      f in s.at[p].^next + s.approaching[p].*next
    }

fun Denies (s, s': State, p: Lift, b: Button) {
    -- p was going to serve b, but is no longer
    let f = b.floor |
      Towards (s,p,f) and not Towards (s',p,f) and !Serves (s,s',p,b)
    }
```

transitive closure

policy

policy

```
sig State {
    lit: set Button,
    promises: Lift -> Button, …
    }
```

policy

```
sig State {
   lit: set Button,
   promises: Lift -> Button, ...
   }

fun Policy (s, s': State) {
   -- a lift can't deny a promise or a request from inside the lift
   no p: Lift, b: s.promises[p] + p.buttons & s.lit | Denies (s,s',p,b)
   -- if a lift denies a request some lift serves it or promises to
   all b: s.lit & FloorButton - s.promises[Lift], p: Lift |
     Denies (s,s',p,b) =>
        (some q: Lift | Serves(s,s',q,b)) or b in s'.promises[Lift]
...}
```

policy

```
sig State {
    lit: set Button,
    promises: Lift -> Button, ...
    }

fun Policy (s, s': State) {
    -- a lift can't deny a promise or a request from inside the lift
    no p: Lift, b: s.promises[p] + p.buttons & s.lit | Denies (s,s',p,b)
    -- if a lift denies a request some lift serves it or promises to
    all b: s.lit & FloorButton – s.promises[Lift], p: Lift |
       Denies (s,s',p,b) =>
          (some q: Lift | Serves(s,s',q,b)) or b in s'.promises[Lift]
...}
```

non-deterministic

putting things together

putting things together

```
fun Trans (s, s': State) {
   -- the before and after positions and the motion are legal
   LiftPosition (s) and LiftPosition (s') and LiftMotion (s,s')
   -- the policy is satisfied
   Policy (s,s’)
   -- the buttons are reset appropriately
   some press: set Button | ButtonUpdate (s,s',press)
   }
```

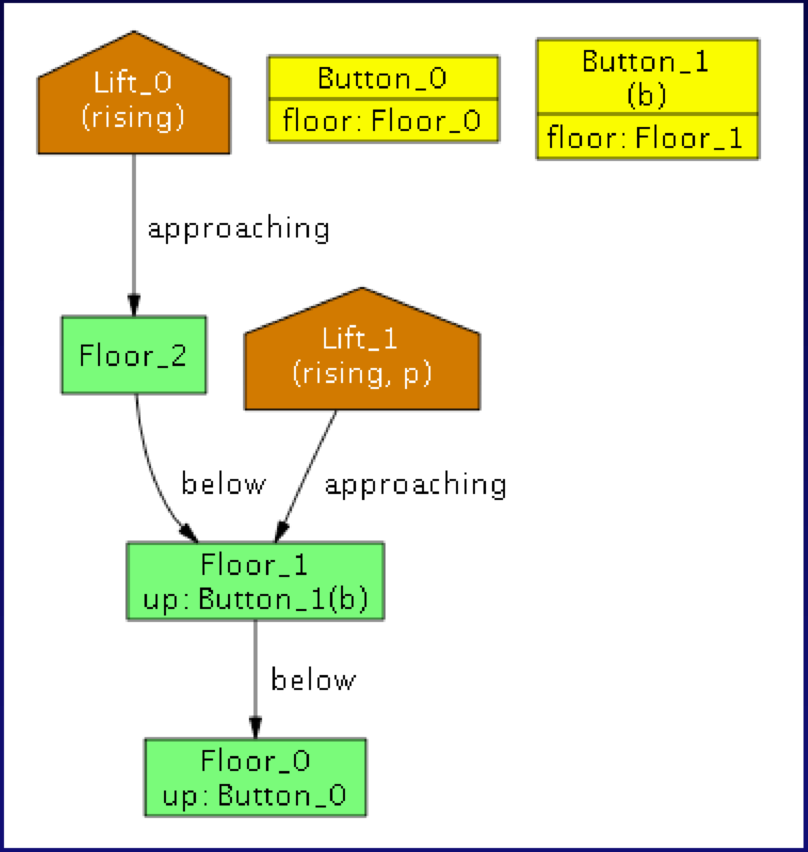
animating denial

animating denial

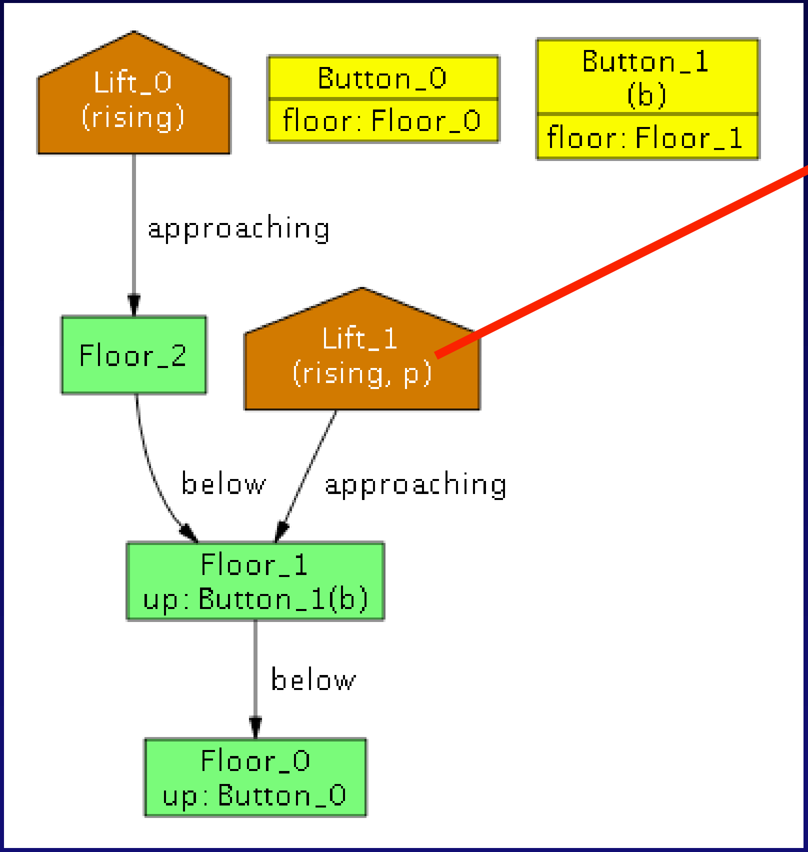
```
fun ShowPolicy (s, s': State) {
    Trans (s, s')
    some b: s.lit & FloorButton, p: Lift | Denies (s,s',p,b)
    no s.promises & some s’.promises
    }
run ShowPolicy for 2 but 3 Floor
```

sample denial

sample denial

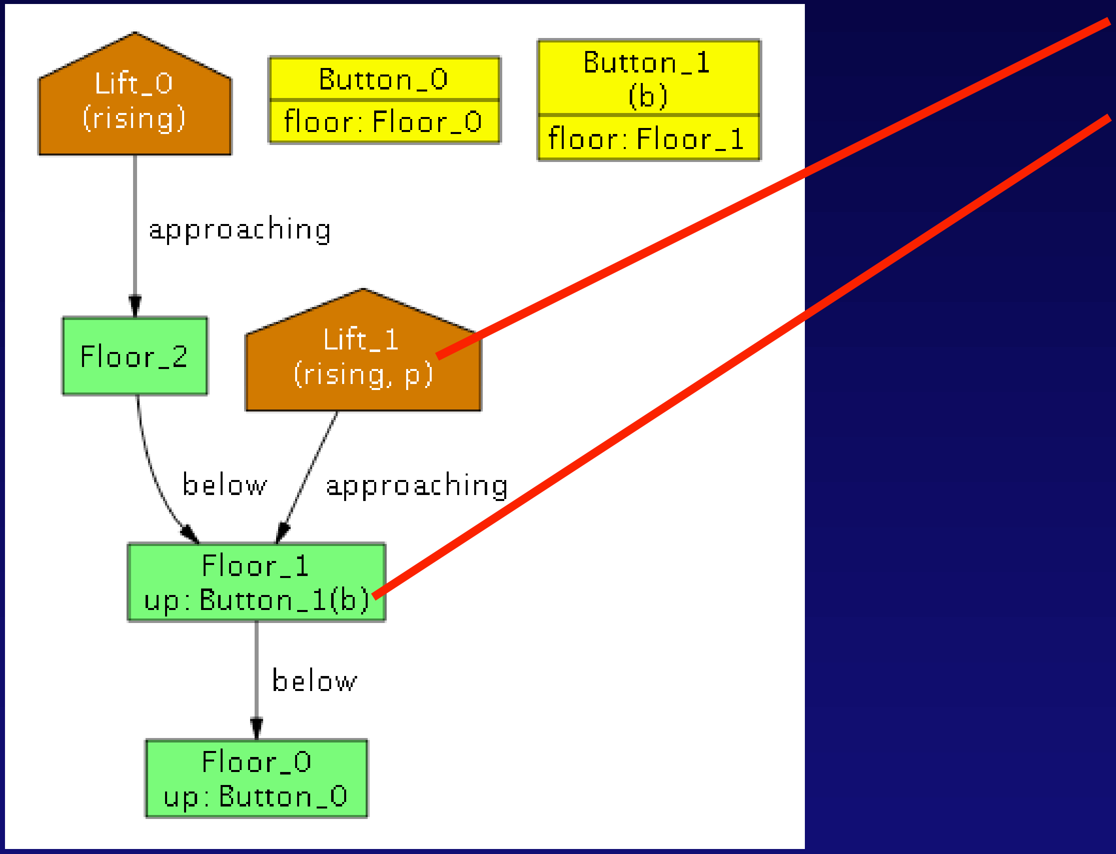


sample denial



the denying lift

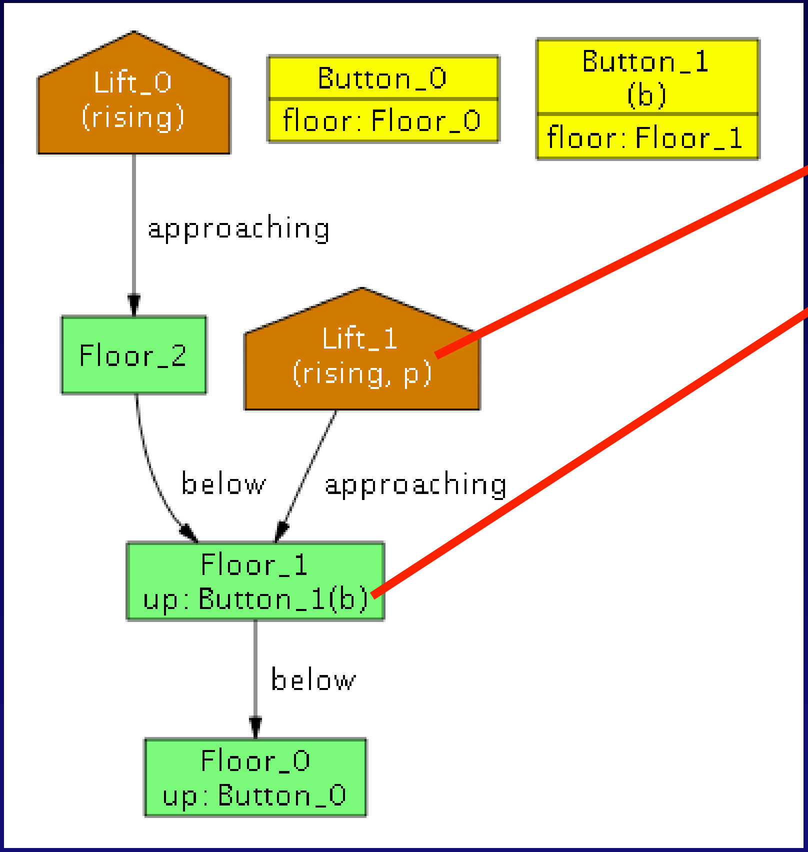
sample denial



the denying lift

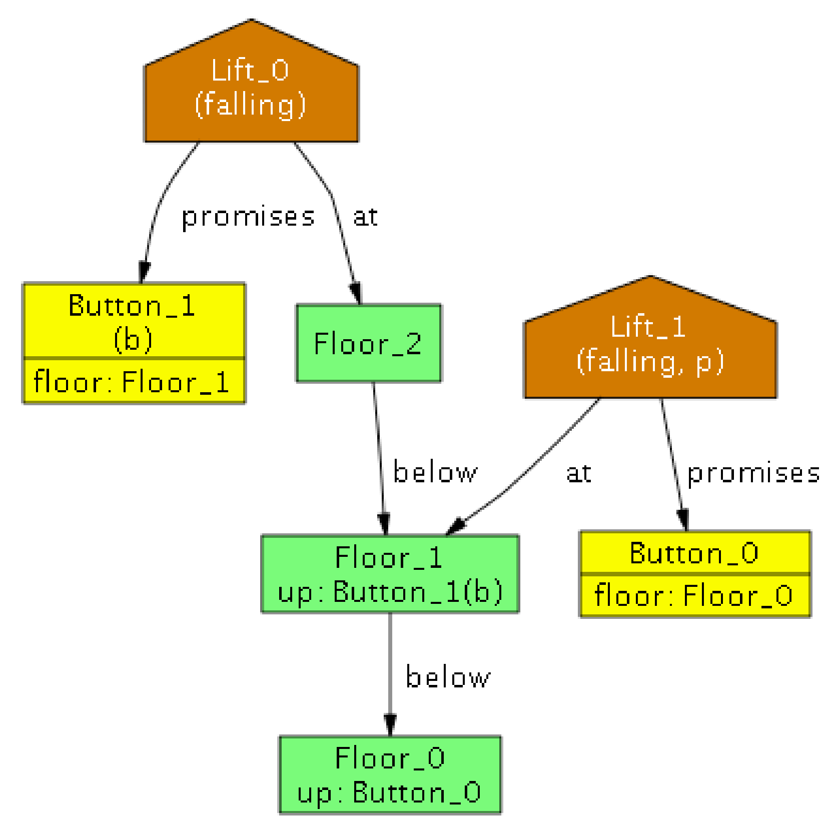
the denied button

sample denial

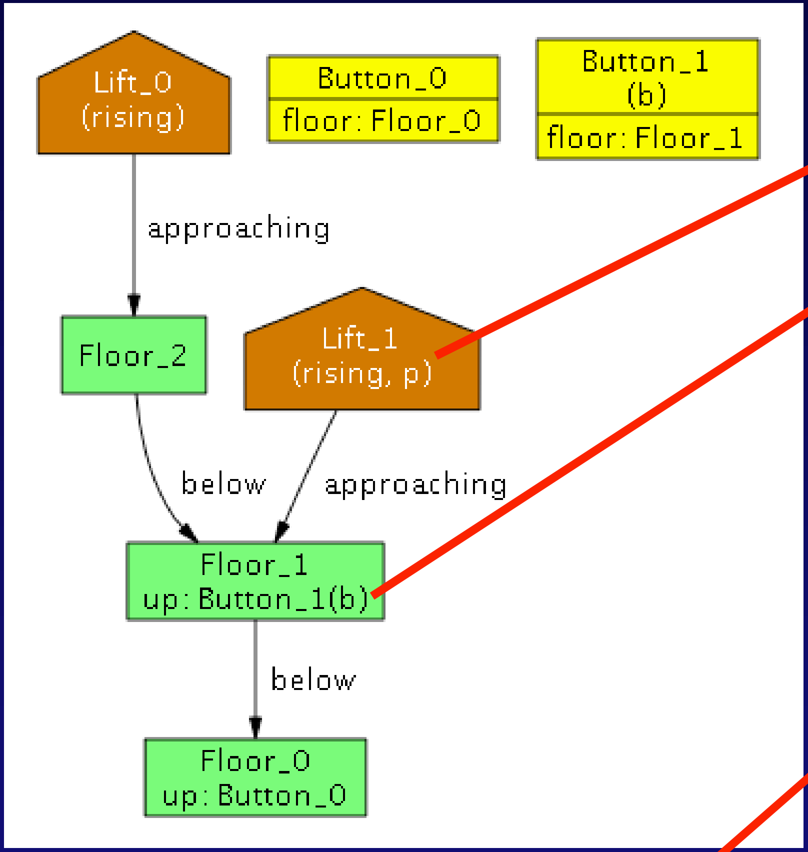


the denying lift

the denied button

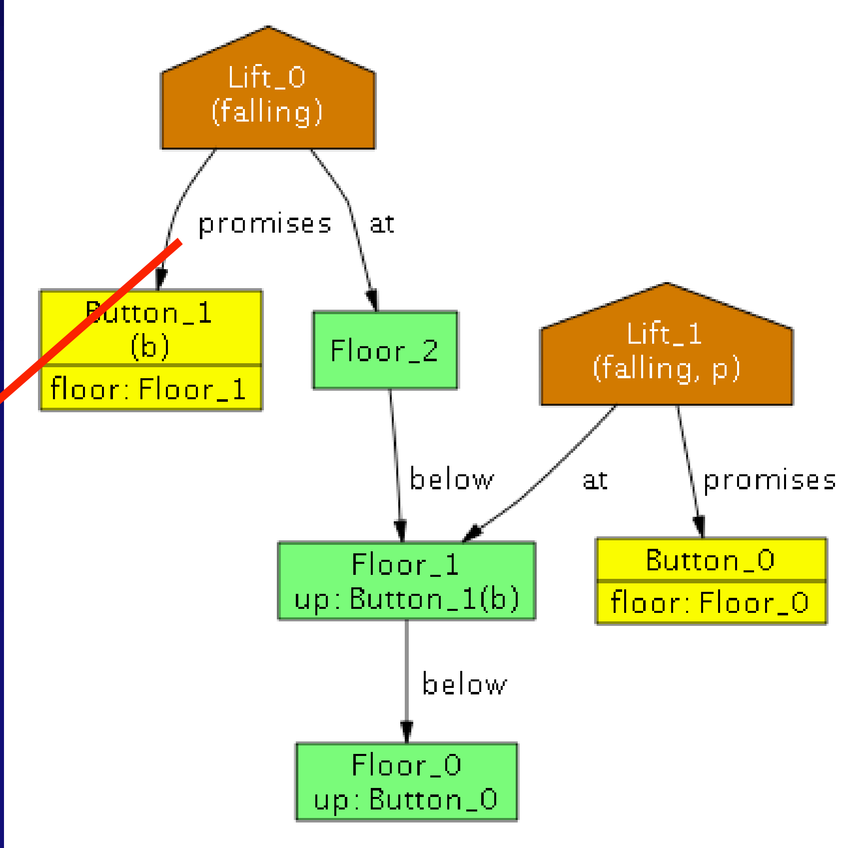


sample denial



the denying lift

the denied button



another lift promises

traces: checking starvation

traces: checking starvation

```
fun Trace () {
   -- a state is related to its successor by the transition relation
   all s: State – Ord[State].last |
     let s' = Ord[State].next[s] | Trans (s,s')
   }
```

traces: checking starvation

```
fun Trace () {
   -- a state is related to its successor by the transition relation
   all s: State - Ord[State].last |
      let s' = Ord[State].next[s] | Trans (s,s')
   }

assert EventuallyServed {
   -- if the states form a trace
   Trace () =>
   -- then a button lit in the start state is eventually reset
      all b: (Ord[State].first).lit | some s': State | b !in s'.lit
   }
```

traces: checking starvation

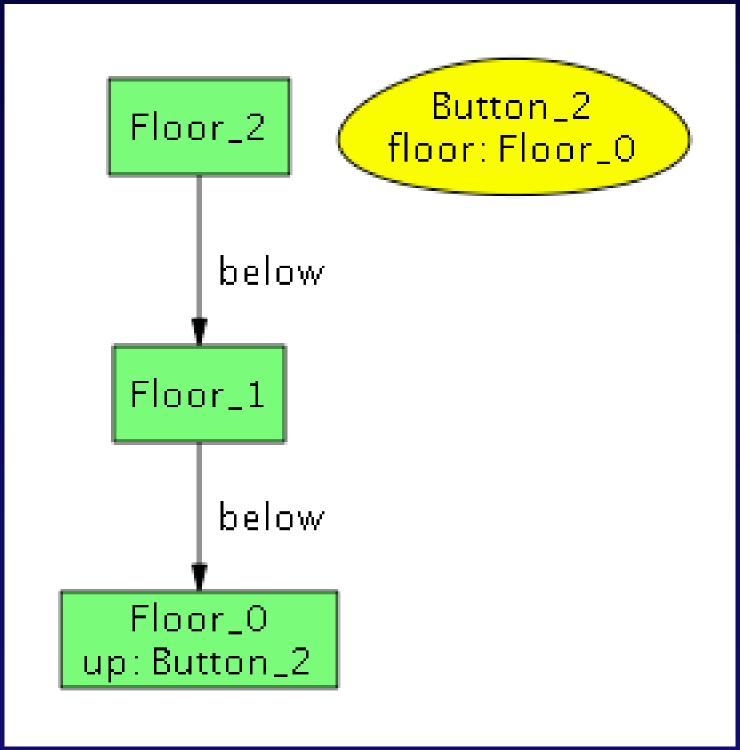
```
fun Trace () {
   -- a state is related to its successor by the transition relation
   all s: State - Ord[State].last |
     let s' = Ord[State].next[s] | Trans (s,s')
   }

assert EventuallyServed {
   -- if the states form a trace
   Trace () =>
   -- then a button lit in the start state is eventually reset
     all b: (Ord[State].first).lit | some s': State | b !in s'.lit
   }

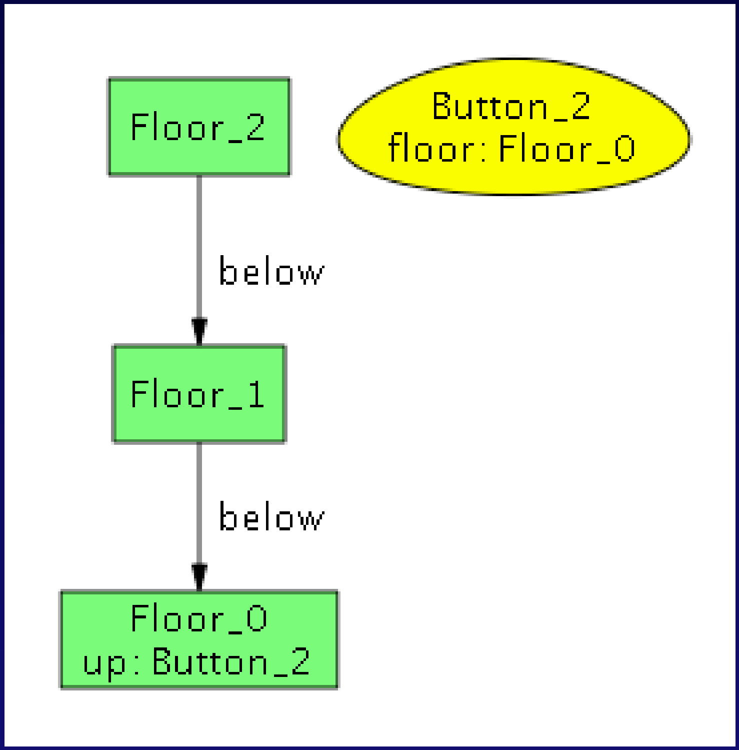
check EventuallyServed for 3 Lift, 3 Button, 3 Floor, 8 State
```

counterexample!

counterexample!



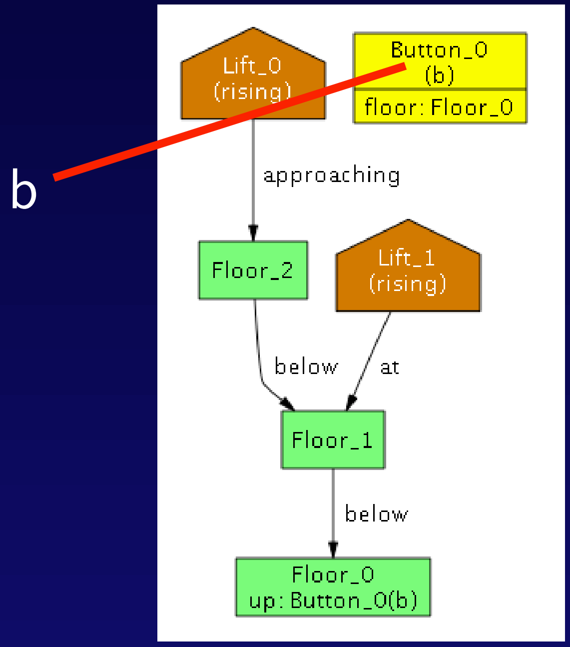
counterexample!



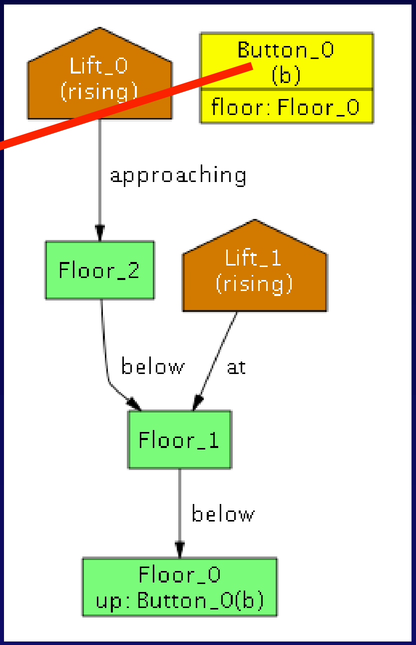
```
assert EventuallyServed {
   Trace () and some Lift =>
     all b: (Ord[State].first).lit | some s': State | b !in s'.lit
   }
```

another...

another…

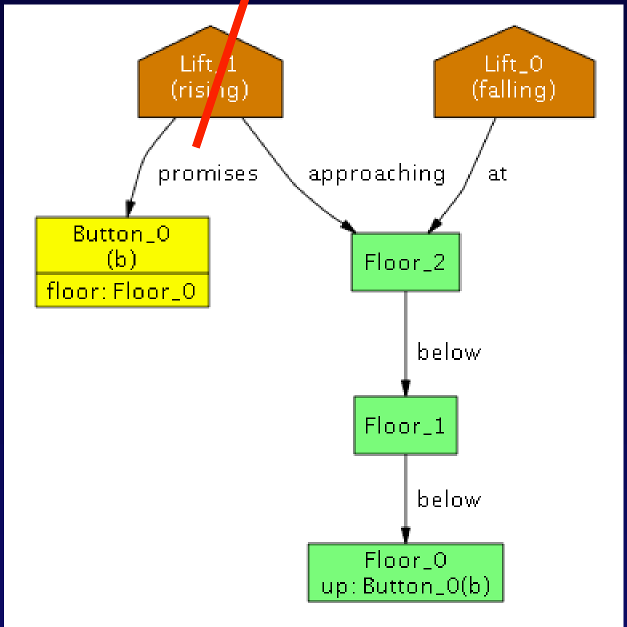

b
Lift_0
(rising)
Button_0
(b)
floor: Floor_0
approaching
Floor_2
Lift_1
(rising)
below
at
Floor_1
below
Floor_0
up: Button_0(b)

another…

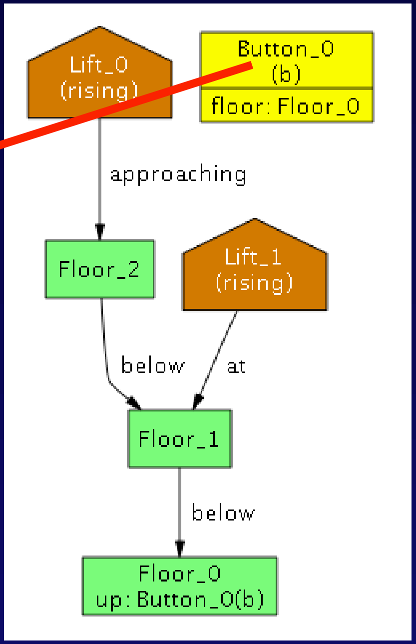


b

Lift_1 promises

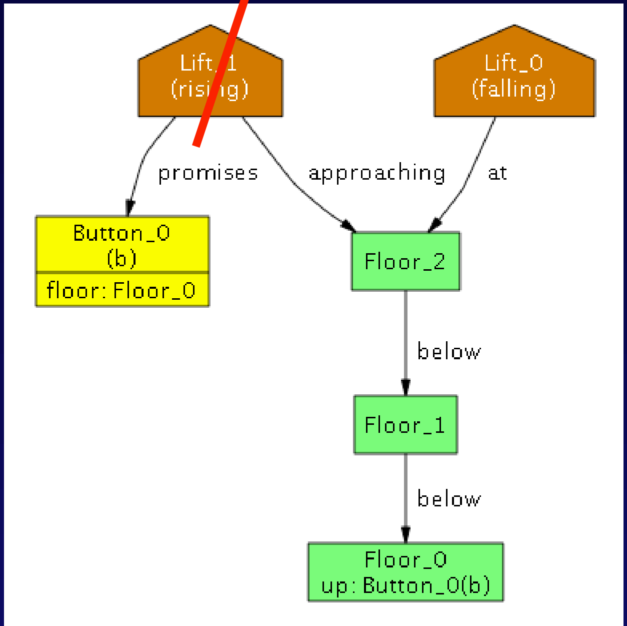


another…

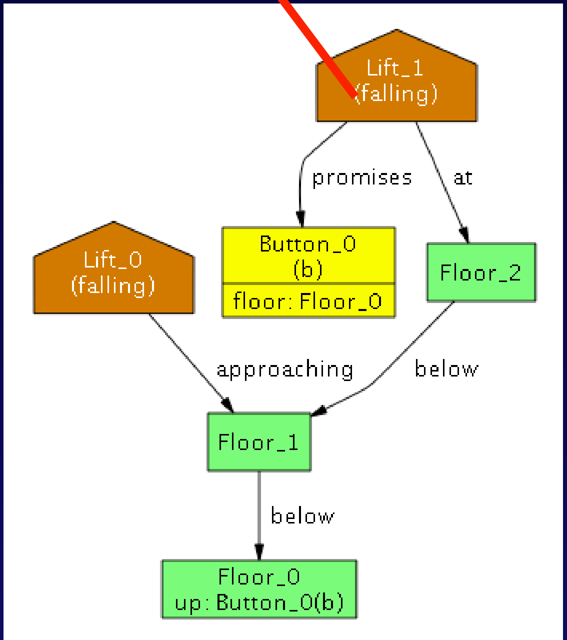


b

Lift_1 promises

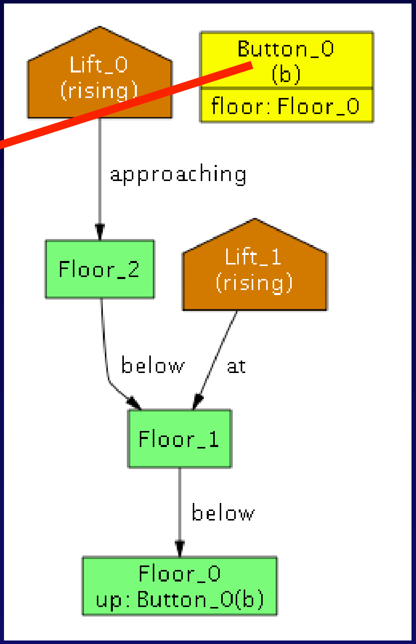


Lift_1 turns

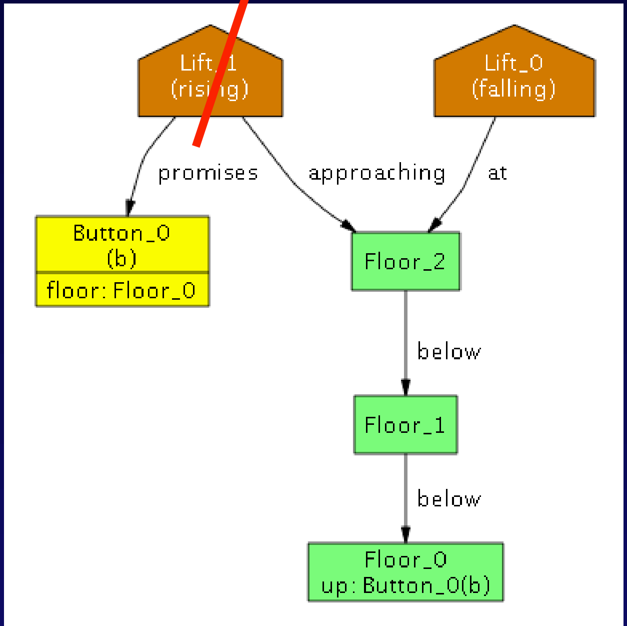


another…

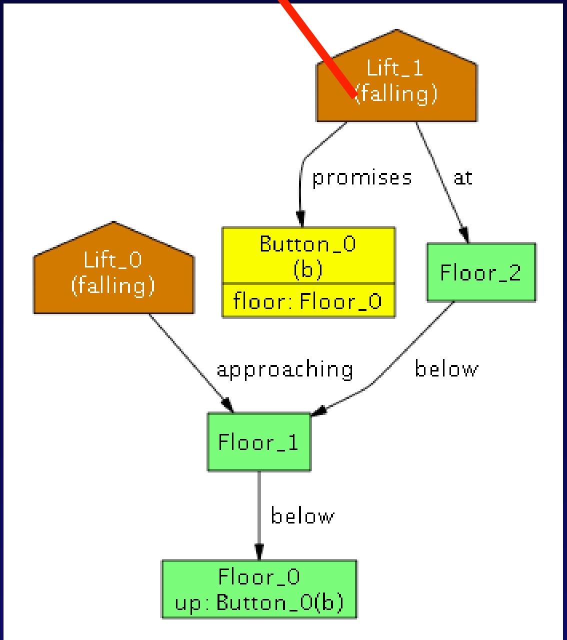
b



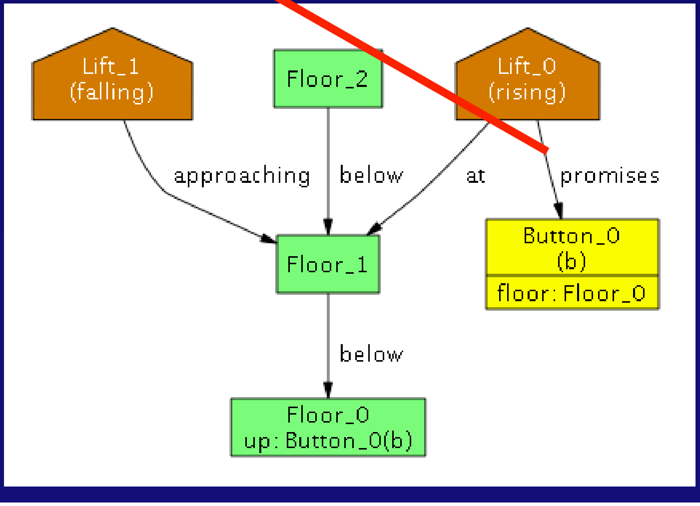
Lift_1 promises



Lift_1 turns

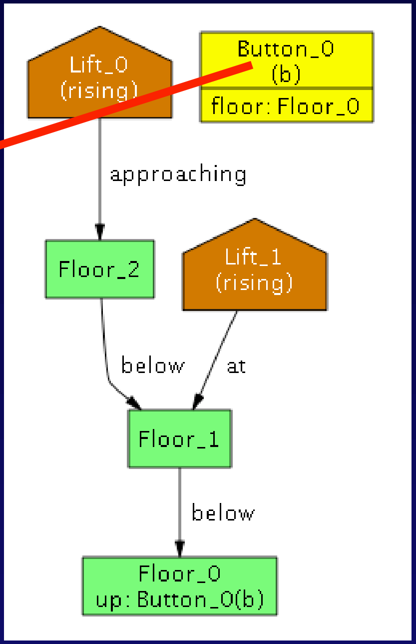


promise passes from Lift_1 to Lift_0 !

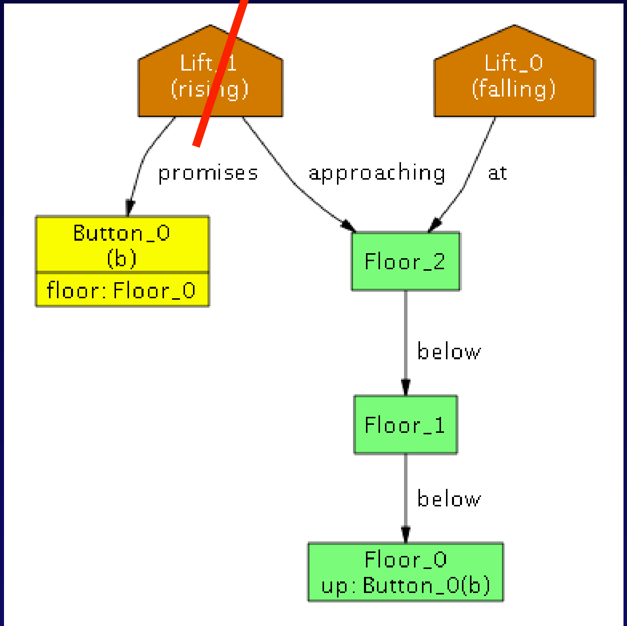


another…

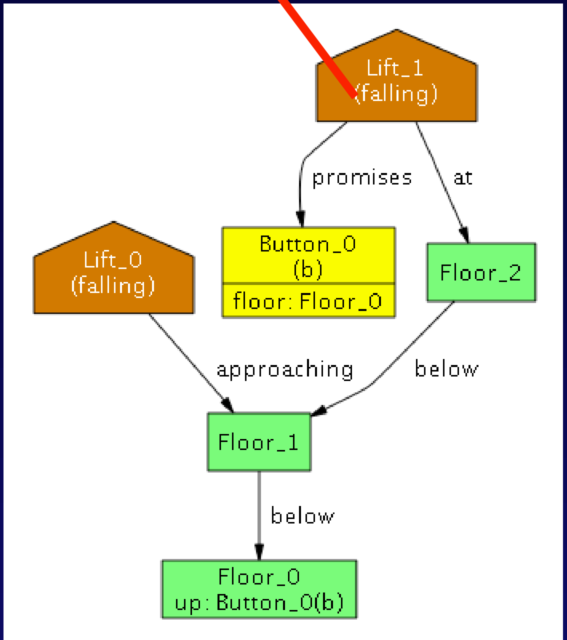
b



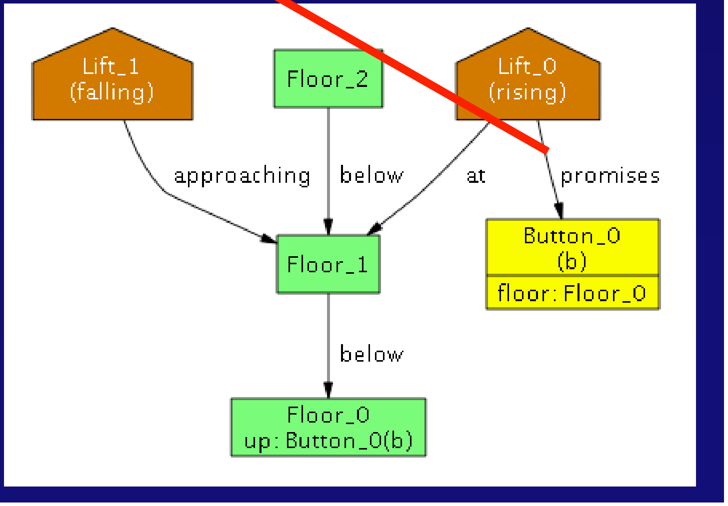
Lift_1 promises



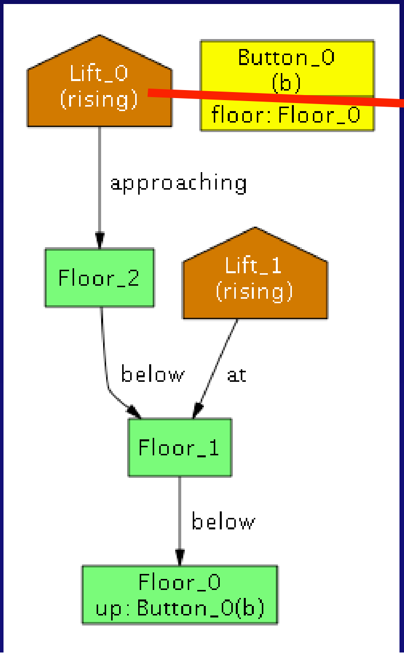
Lift_1 turns



promise passes from Lift_1 to Lift_0 !



Lift_0 drops promise



what you've seen

what you've seen

simple logic, complex system

- relations for all structuring
  - buttons to lifts, components to states, states to successors
- declarative style
  - separation of concerns by conjunction
- relational operators
  - succinct, idioms easy to grasp
  - students did lift problem as homework after 3 lectures

what you've seen

simple logic, complex system

- relations for all structuring
  - buttons to lifts, components to states, states to successors
- declarative style
  - separation of concerns by conjunction
- relational operators
  - succinct, idioms easy to grasp
  - students did lift problem as homework after 3 lectures

one analysis -- model finding

- for simulation and consequence checking
- (for checking refactoring)

when is a trace long enough?

when is a trace long enough?

for safety properties, check all traces

- but how long? ie, what is scope of State?

when is a trace long enough?

for safety properties, check all traces

- but how long? ie, what is scope of State?

idea: bound the diameter

- if all states reached in path ≤ k
- enough to consider only traces ≤ k

when is a trace long enough?

for safety properties, check all traces
- but how long? ie, what is scope of State?

idea: bound the diameter
- if all states reached in path ≤ k
- enough to consider only traces ≤ k

strategy
- ask for loopless trace of length k+1
  if none, then k is a bound
- tighter bounds possible: eg, no shortcuts

when is a trace long enough?

for safety properties, check all traces

- but how long? ie, what is scope of State?

idea: bound the diameter

- if all states reached in path ≤ k
- enough to consider only traces ≤ k

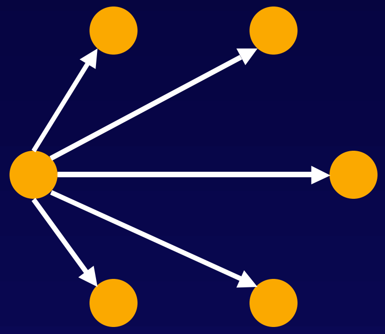
strategy

- ask for loopless trace of length k+1
  if none, then k is a bound
- tighter bounds possible: eg, no shortcuts

like bounded model checking

- but can express conditions directly

when is a trace long enough?



diameter = 1
max loopless = 1

for safety properties, check all traces
- but how long? ie, what is scope of State?

idea: bound the diameter
- if all states reached in path ≤ k
- enough to consider only traces ≤ k

strategy
- ask for loopless trace of length k+1
  if none, then k is a bound
- tighter bounds possible: eg, no shortcuts

like bounded model checking
- but can express conditions directly

when is a trace long enough?

for safety properties, check all traces

- but how long? ie, what is scope of State?

idea: bound the diameter

- if all states reached in path ≤ k
- enough to consider only traces ≤ k

strategy

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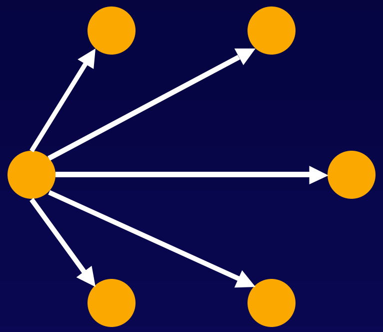
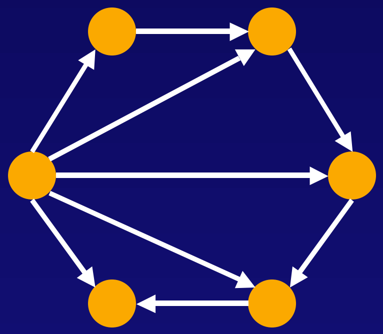


diameter = 1
max loopless = 1



diameter = 1
max loopless = 5

applications to code

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Alloy Annotation Language

- mutation, nulls, dynamic dispatch

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- can test one operation of an abstract type
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example: red-black trees

```
all x,y: Leaf | #(x.~*children & Black) = #(y.~*children & Black)
```

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- › not fully declarative
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see UML metamodel in Alloy on sdg.lcs.mit.edu/alloy

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- but in software, essence is incremental modelling
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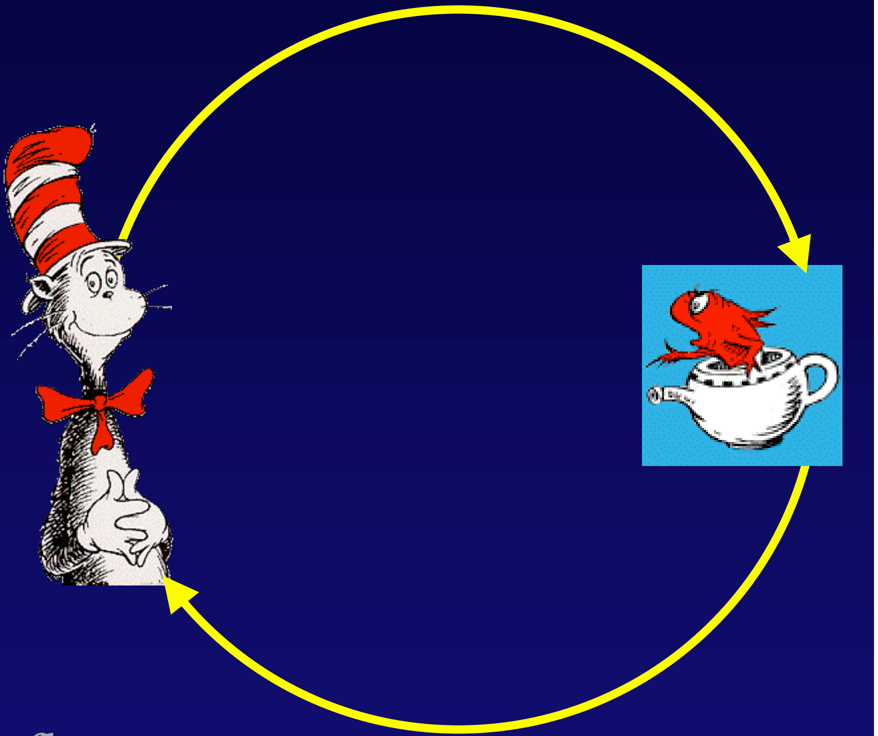

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shape analyses (eg, PEGs, TVLA)

- automatic and complete for whole program
- but for modular analysis, not complete
  eg, assume arguments to procedure aren't aliased

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  from 30 bits (1995) to 1000 bits (2002)
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- tool downloads
- papers