Systematically exploring control programs (Lecture I)

Ratul Mahajan

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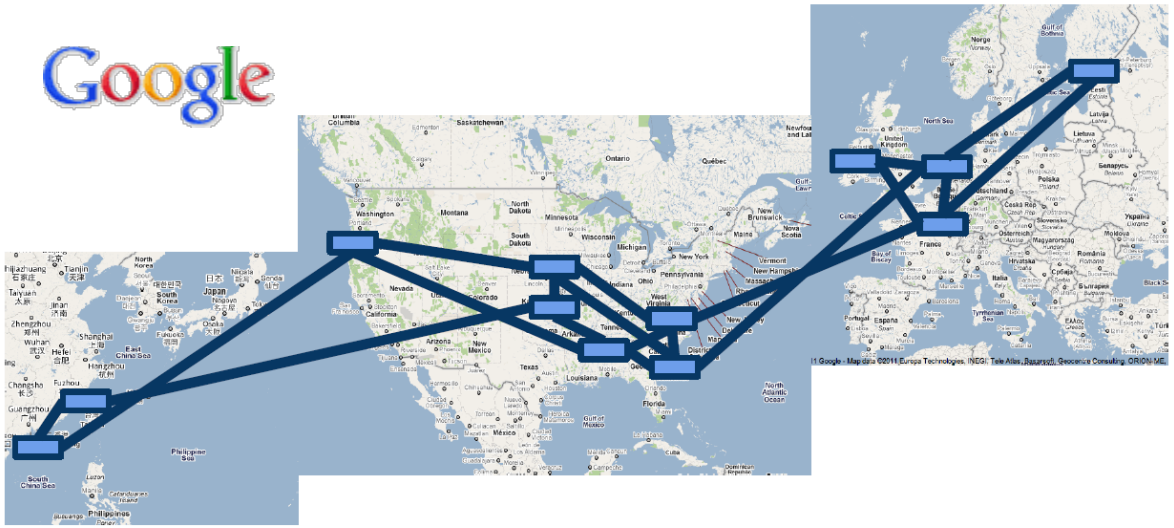
Joint work with Jason Croft,
Matt Caesar, and Madan Musuvathi

Control programs are everywhere

From the smallest of networks to the largest

Control programs are everywhere

From the smallest of networks to the largest



The nature of control programs

Collection of rules with triggers and actions

```
motionPorch.Detected:
  if (Now - tLastMotion < 1s
      && lightLevel < 20)
     porchLight.Set(On)
  tLastMotion = Now

@6:00:00 PM:
   porchLight.Set(On)

@6:00:00 AM:
   porchLight.Set(Off)
```

```
packetIn:
  entry = new Entry(inPkt.src,
                    inPkt.dst)
  if (!cache.Contains(entry)
     cache.Insert(entry, Now)

CleanupTimer:
  foreach entry in cache
    if (Now - cache[entry] < 5s)
       cache.Remove(entry)
```

Buggy control programs wreak havoc

One nice morning in the summer

Buggy control programs wreak havoc

"I had a rule that would turn on the heat, disarm the alarm, turn on some lights, etc. at 8am …..

I came home from vacation to find a warm, inviting, insecure, well lit house that had been that way for a week……

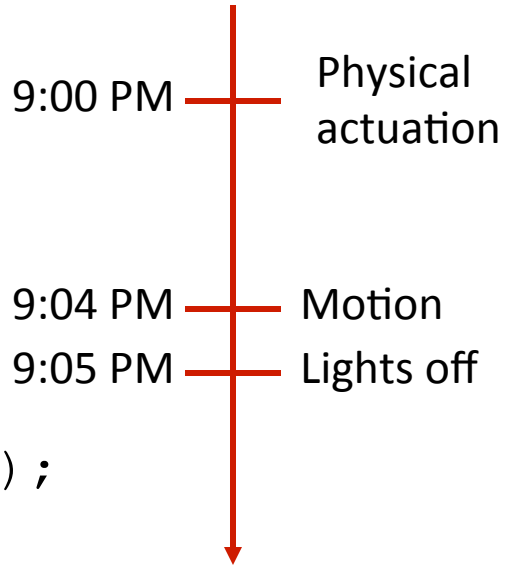
That's just one example, but the point is that it has taken me literally YEARS of these types of mistakes to iron out all the kinks."

Control programs are hard to reason about

```
motionPorch.Detected:
        if (Now - timeLastMotion < 1 secs
              && lightMeter.Level < 20)
               porchLight.Set(On);
        timeLastMotion = Now;

porchLight.StateChange:
        if (porchLight.State == On)
               timerPorchLight.Reset(5 mins);

timerPorchLight.Fired:
        if (Now.Hour > 6AM && Now.Hour < 6PM)
               porchLight.Set(Off);
```

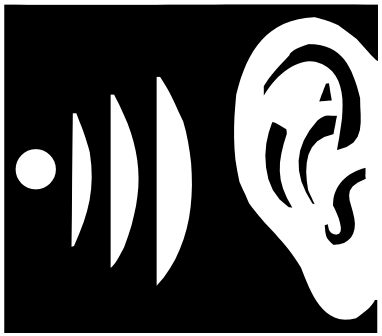


Large input space

Dependence on time

Rule interaction

Desirable properties for bug finders



Sound

Complete

Fast

Two bug finding methods

Testing

Model checking

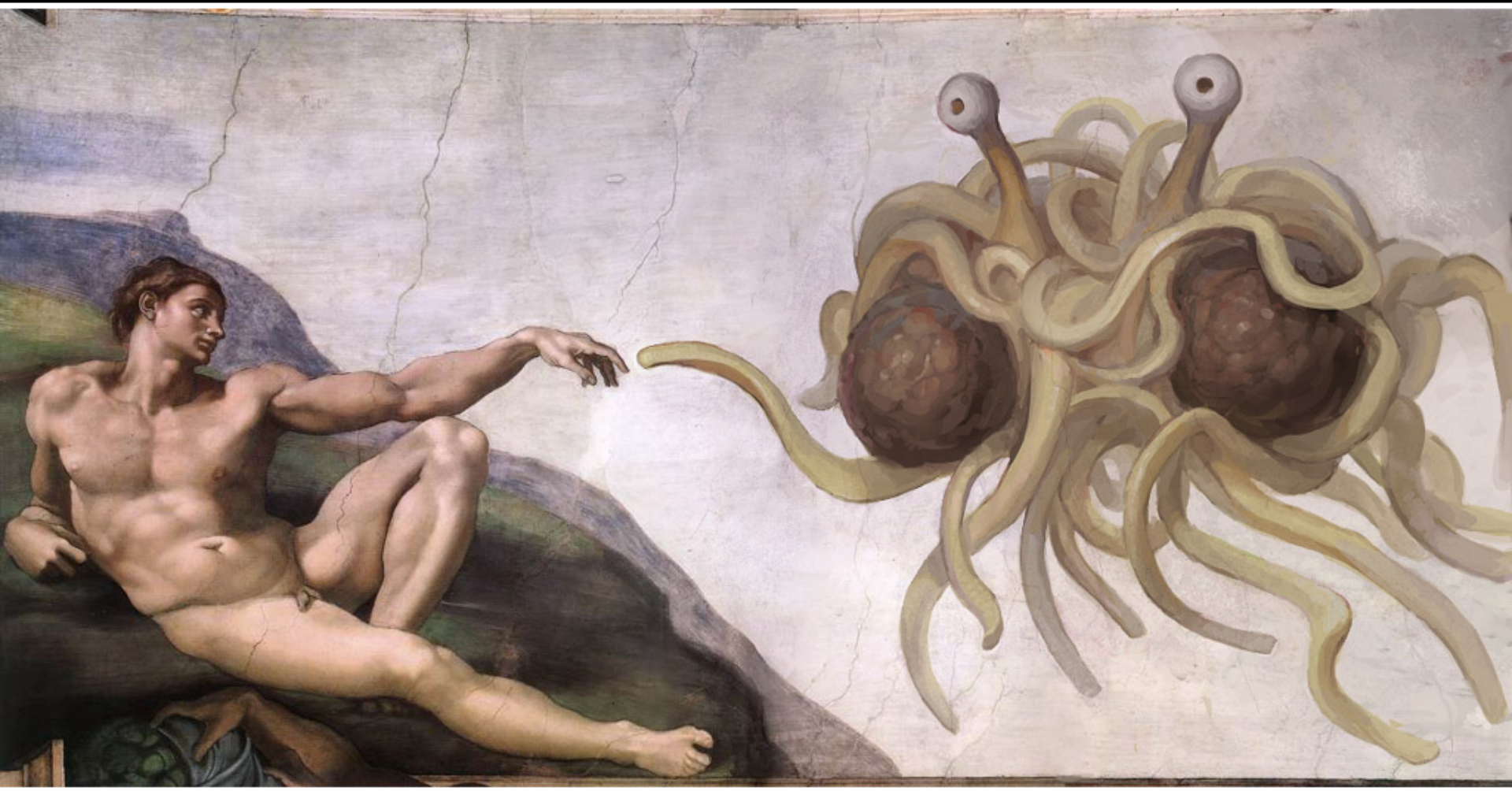
Two threads in model checking

Check models

Check code

Model checking code

FSM is the most popular abstraction



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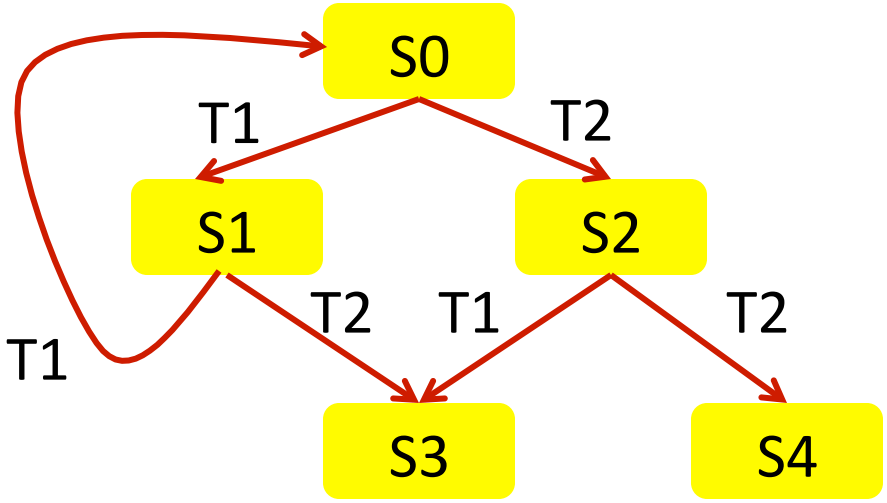
Model checking code

FSM is the most popular abstraction

– Decide what are “states” and “transitions”



Example

motionPorch:

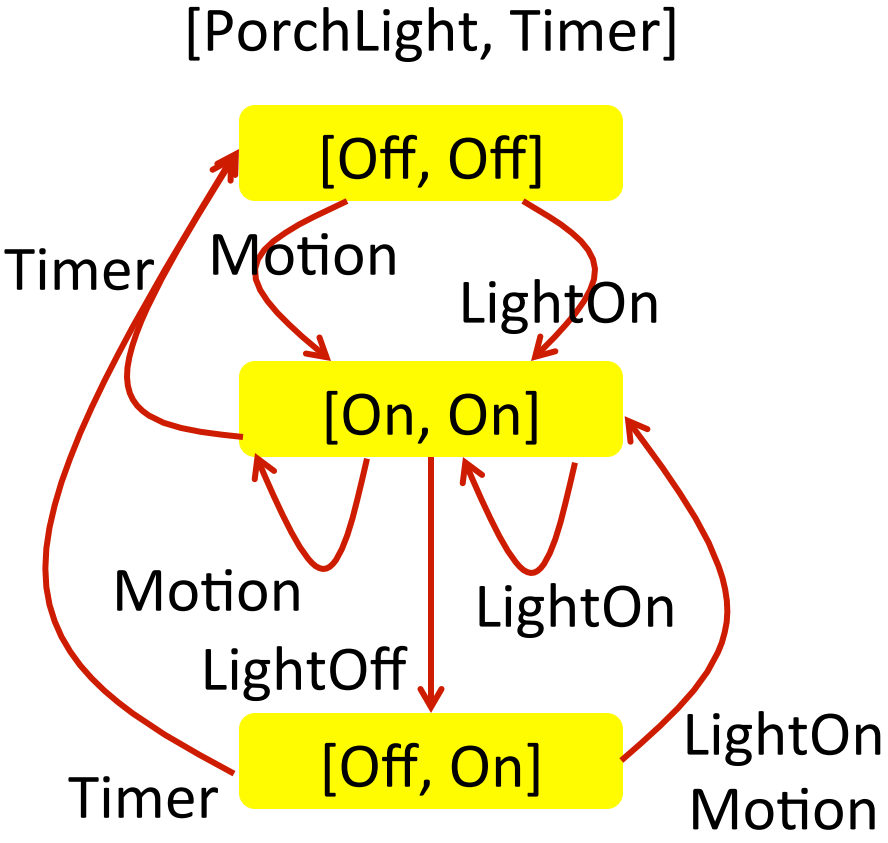
```
porchLight.Set(On)
timer.Start(5 mins)
```

porchLight.On:

```
timer.Start(5 mins)
```

timer.Fired:

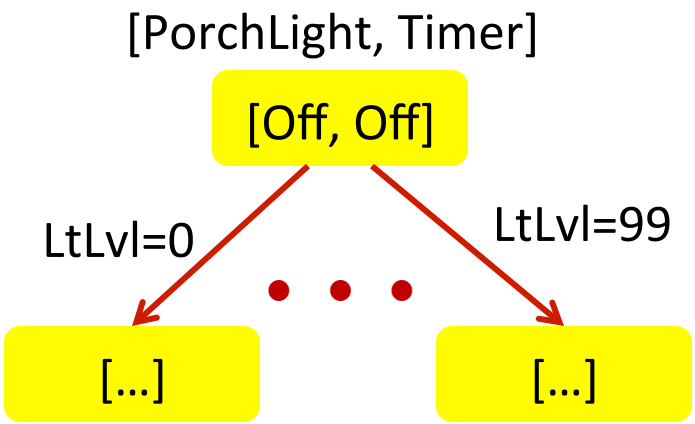
```
porchLight.Set(Off)
```

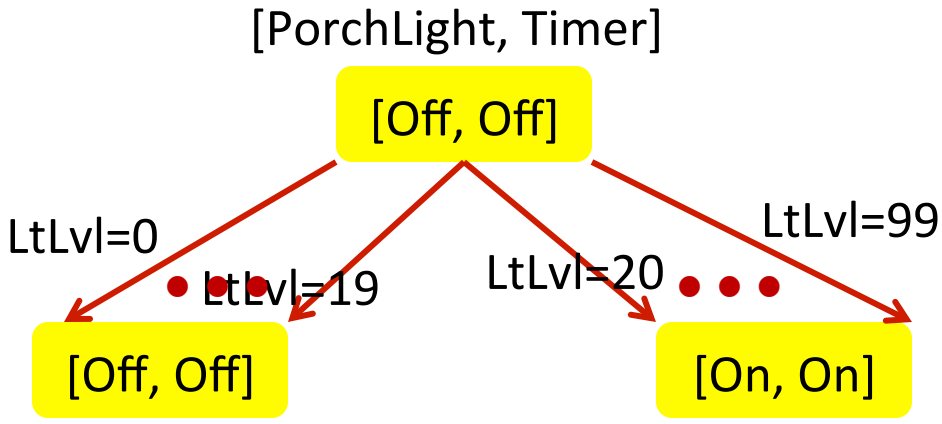


Exploring input space

```
motionPorch:
   if (lightLevel < 20)
     porchLight.Set(On)
     timer.Start(10 mins)
porchLight.On:
   timer.Start(5 mins)
timer.Fired:
   porchLight.Set(Off)
```

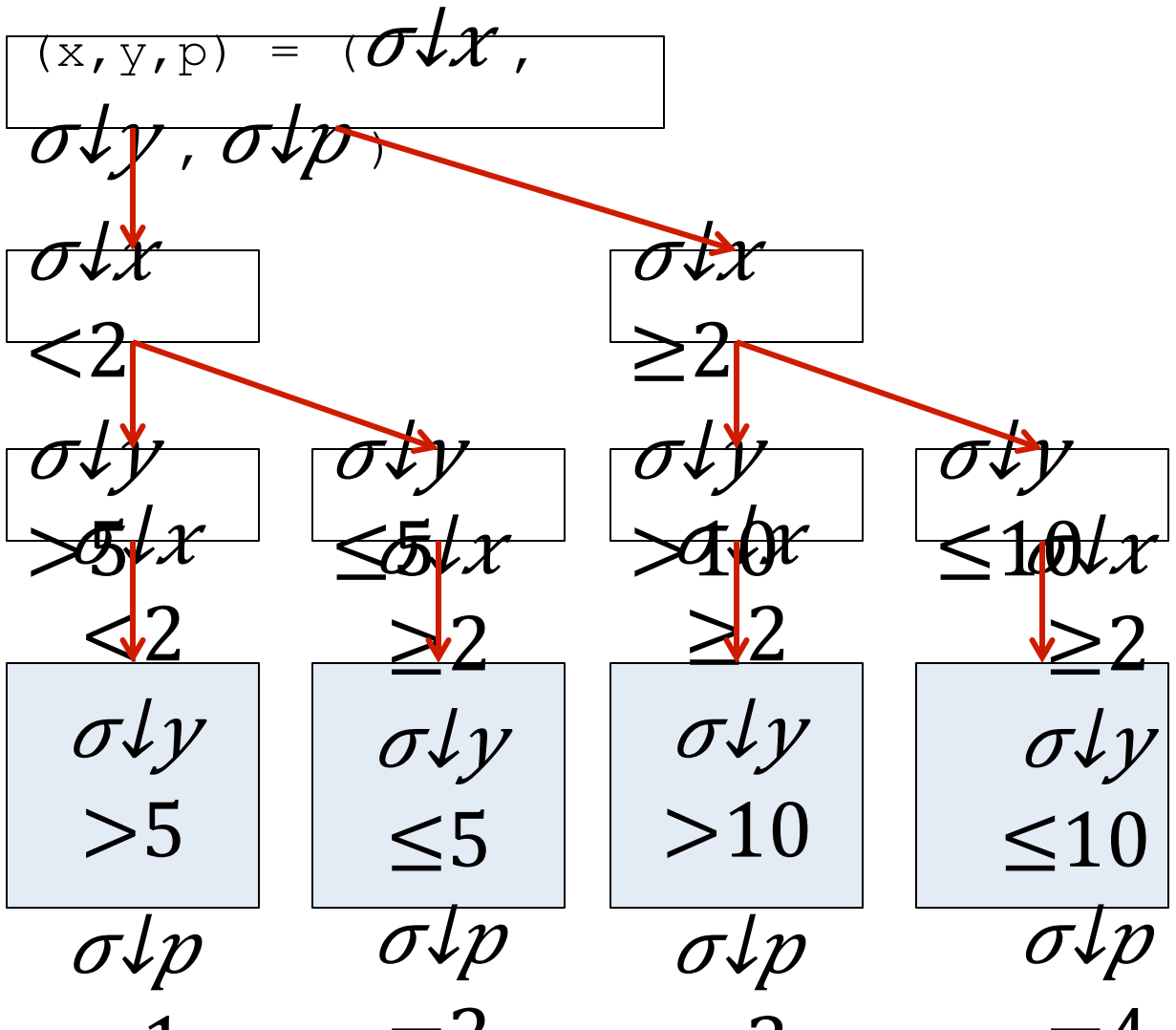
To explore comprehensively, must consider all possible values of input parameters





Symbolic execution

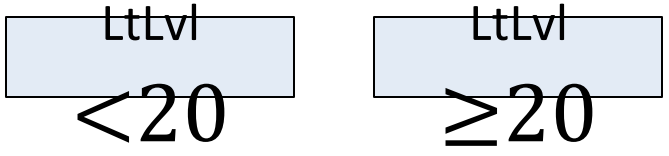
```
if (x < 2)
   if (y > 5)
      p = 1;
   else
      p = 2;
else
 if (y > 10)
      p = 3;
   else
      p = 4;
```



Finding equivalent inputs using symbolic execution

1. Symbolically execute each trigger
2. Find input ranges that lead to same *state*

```
motionPorch:
  if (lightMeter.level < 20)
    porchLight.Set(On)
    timer.Start(5 mins)

porchLight.On:
  timer.Start(5 mins)

timer.Fired:
  porchLight.Set(Off)
```

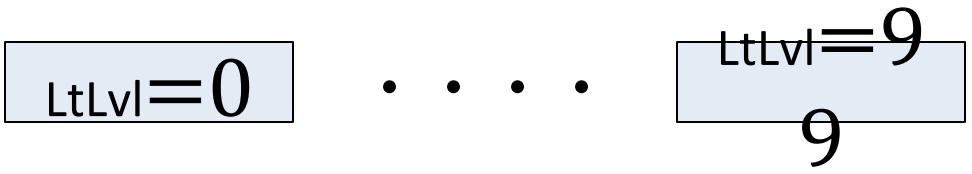


Finding equivalent inputs using symbolic execution

1. Symbolically execute each trigger
2. Find input ranges that lead to same *state*

motionPorch:

```
x = lightMeter.Level
```



porchLight.On:

```
timer.Start(5 mins)
```

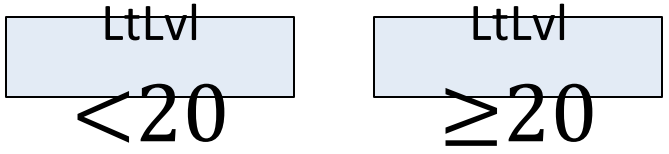
timer.Fired:

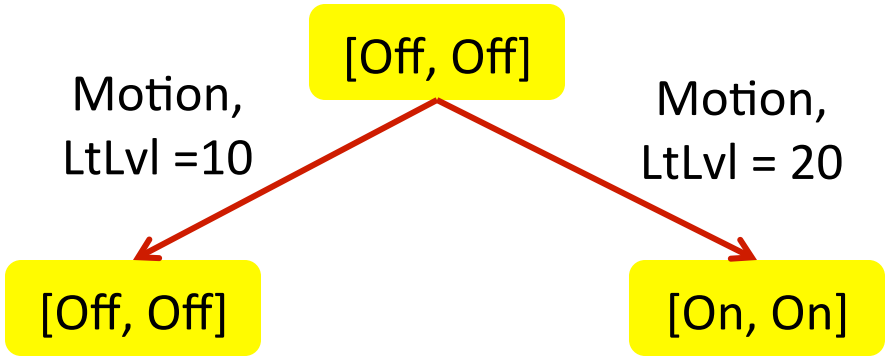
```
porchLight.Set(Off)
```

Efficiently exploring the input space

Pick random values in equivalent classes

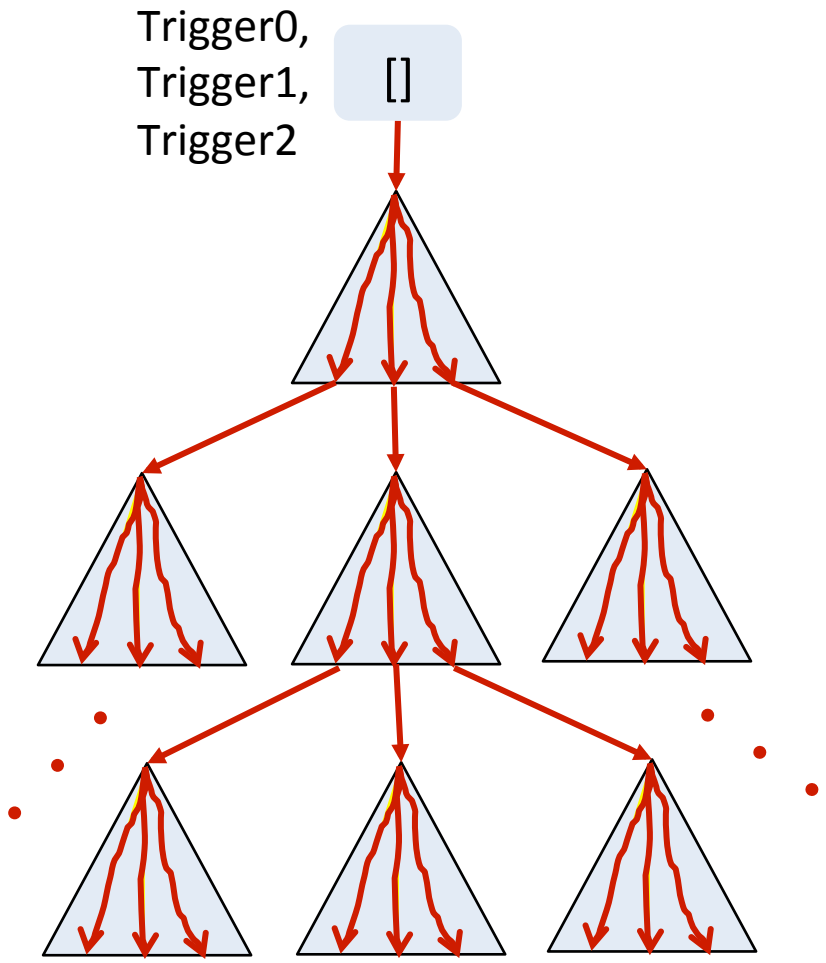
```
motionPorch:
  if (lightMeter.level < 20)
    porchLight.Set(On)
    timer.Start(5 mins)

porchLight.On:
  timer.Start(5 mins)

timer.Fired:
  porchLight.Set(Off)
```



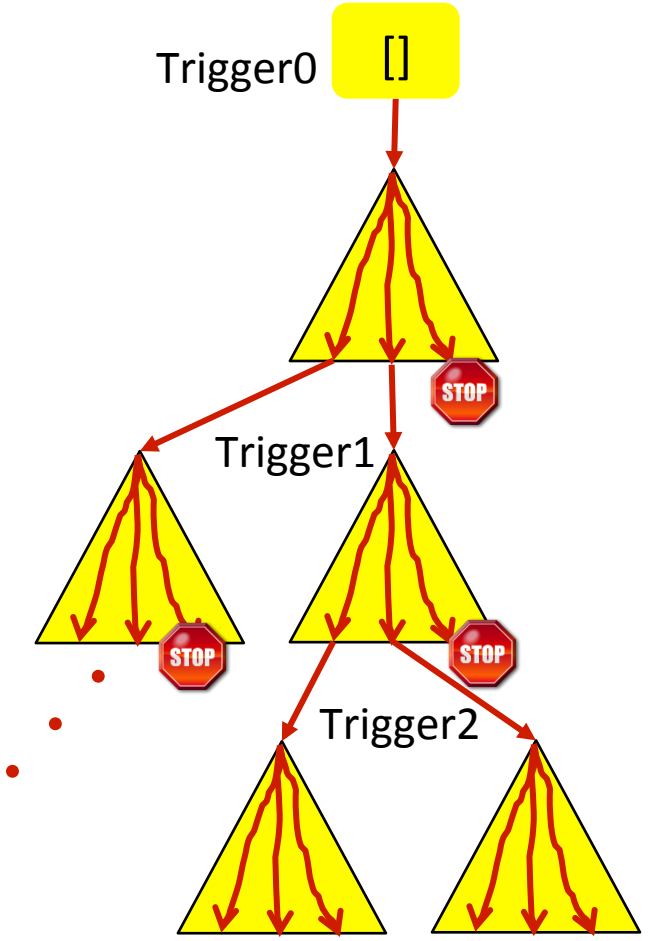


Use symbolic execution alone?

Symbolic, path-based

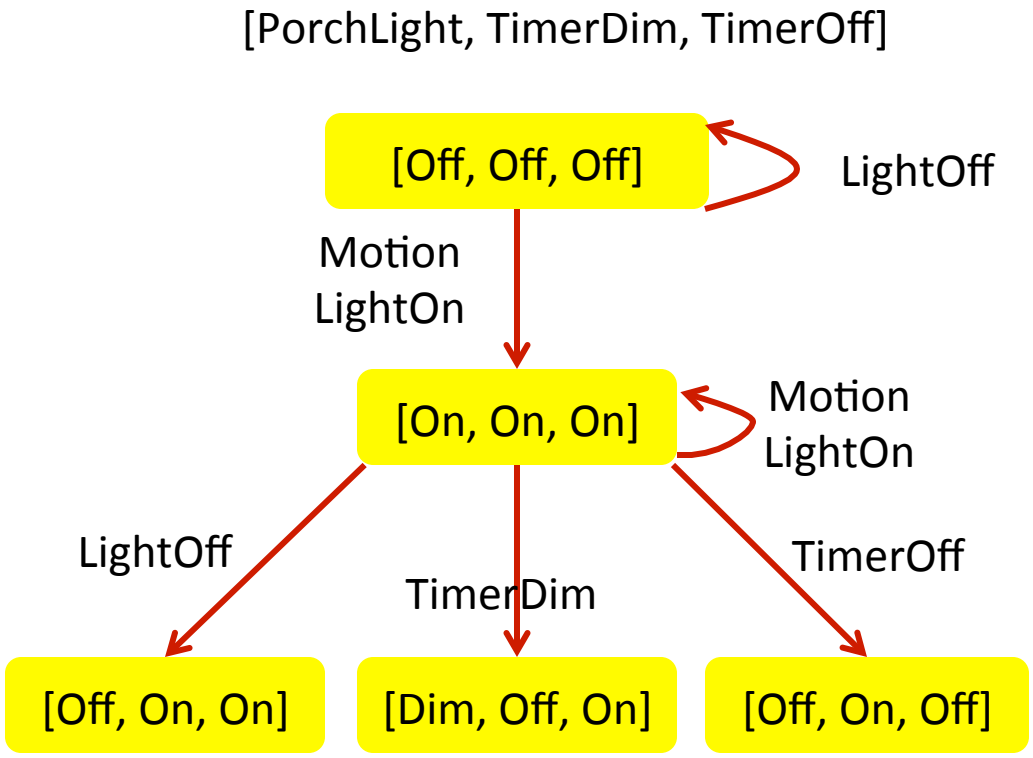


Concrete, state-based



Exploring temporal behavior: soundness

```
motionPorch:
   porchLight.Set(On)
   timerDim.Start(5 mins)
   timerOff.Start(10 mins)
porchLight.On:
   timerDim.Start(5 mins)
   timerOff.Start(10 mins)
timerDim.Fired:
   porchLight.Set(Dim)
timerOff.Fired:
   porchLight.Set(Off)
   if timerDim.On()
      Abort();
```

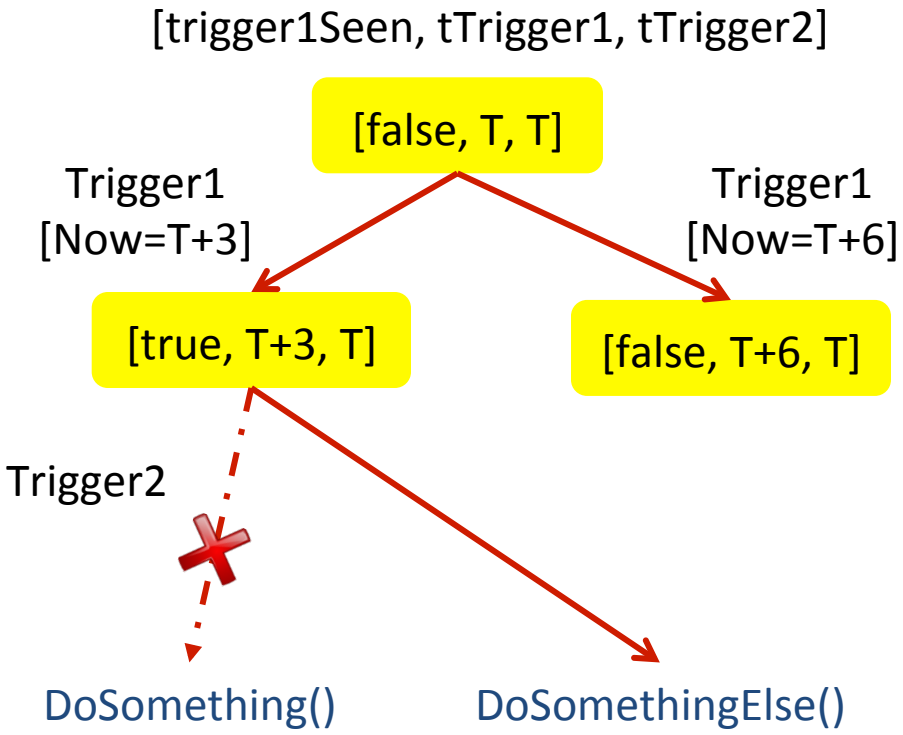


Exploring temporal behavior: completeness

```
motionPorch:
  if (Now - tLastMotion < 60)
    porchLight.Set(On)
    timer.Start(600)
  tLastMotion = Now

porchLight.On:
  timer.Start(600)

timer.Fired:
  porchLight.Set(Off)
```

To explore comprehensively, must fire all possible events at all possible times

```
Trigger0:
  tTrigger1 = Now
  tTrigger2 = Now
  trigger1Seen = false
Trigger1:
  if (Now - tTrigger1 < 5)
    trigger1Seen = true
  tTrigger1 = Now
Trigger2:
  if (trigger1Seen)
     if (Now - tTrigger2 < 2)
        DoSomething()
     else
        DoSomethingElse()
```



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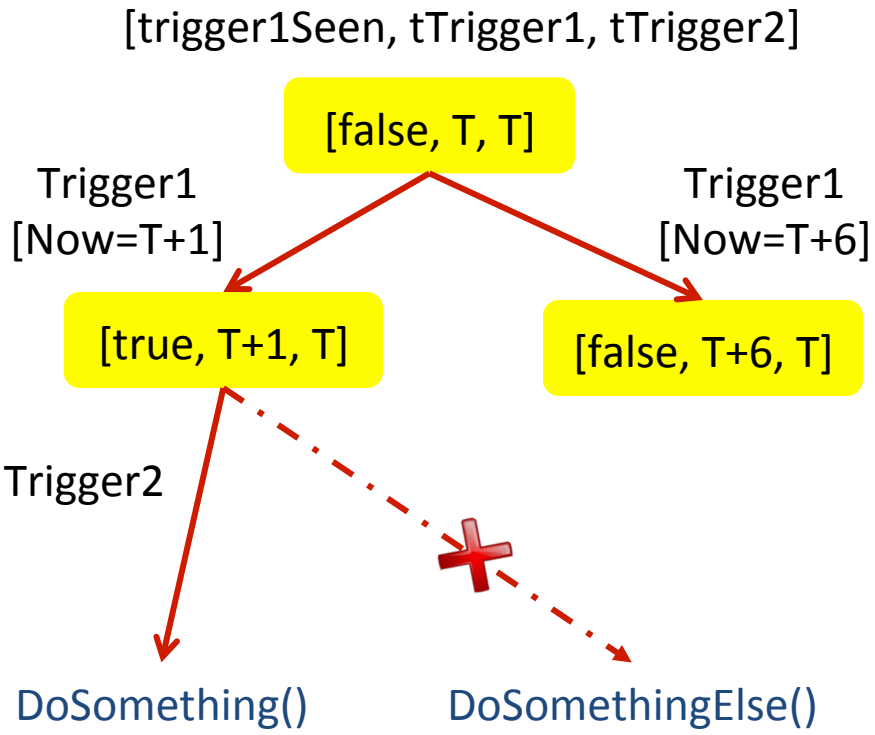

The tyranny of “all possible times”

Timed automata

FSM (states, transitions) + the following:

- Finite number of real-values clocks (VCs)
- All VCs progress at the same rate, except that one or more VCs may reset on a transition
- VC constraints gate transitions

```
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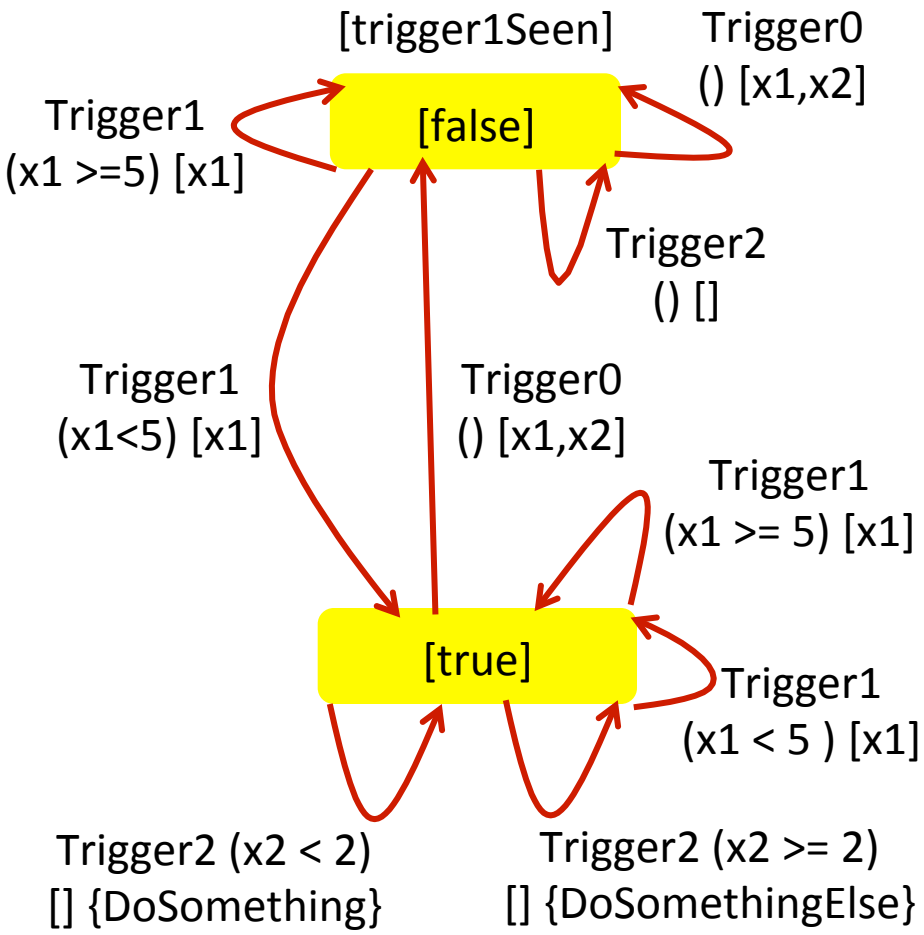


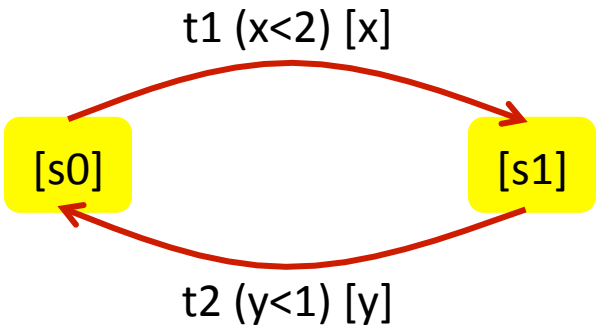
Properties of timed automata

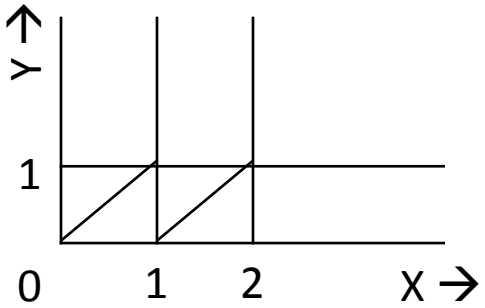
If VC constraints are such that:

- No arithmetic operation involving two VCs
- No multiplication operation involving a VC
- No irrational constants in constraints

$x < 2$ ✔ $x < y + 2$ ✔ ~~$x + y < z$~~ ~~$2x < 3$~~ ~~$x < \sqrt{2}$~~

Time can be partitioned into equivalence regions





28 regions

- Corner points (6)
- Line segments (14)
- Spaces (8)

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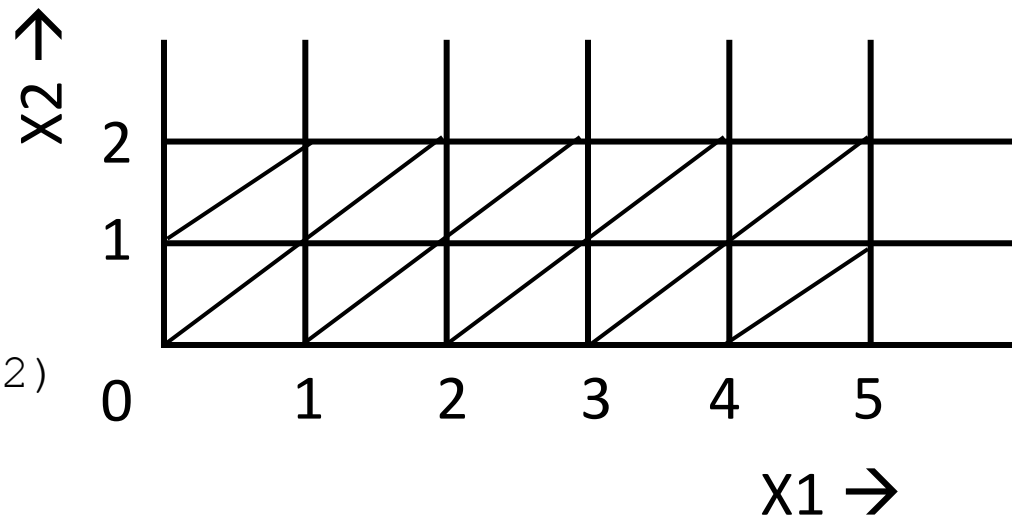
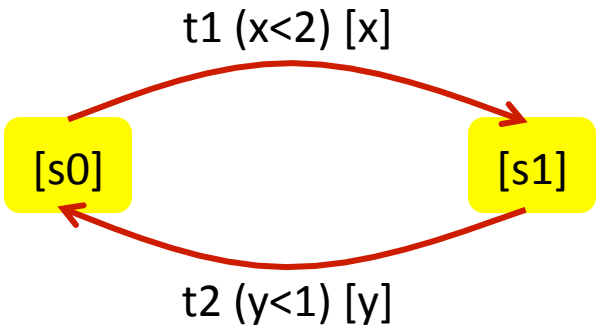
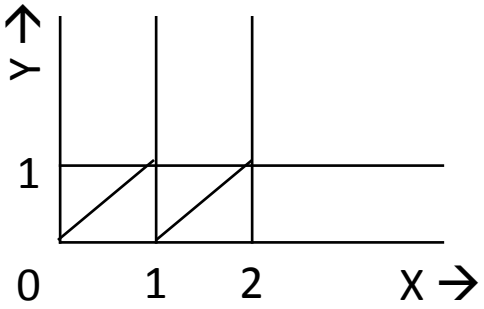
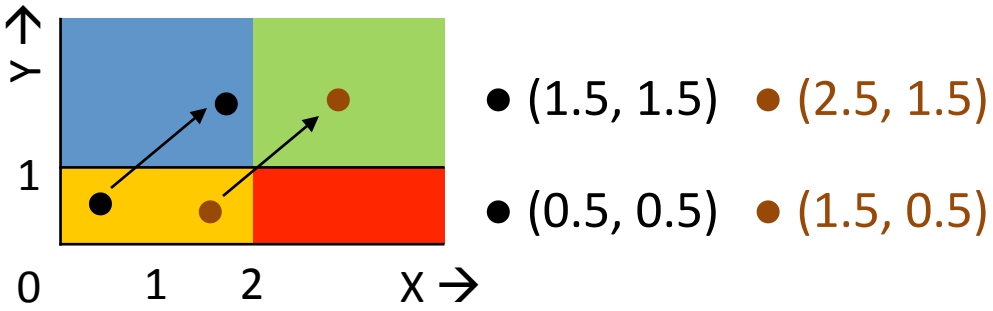
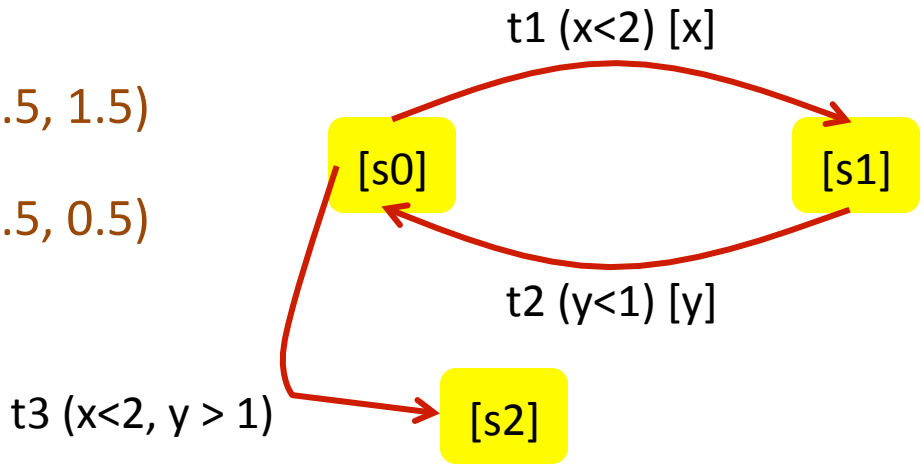


Why regions are fine-grained









Region construction

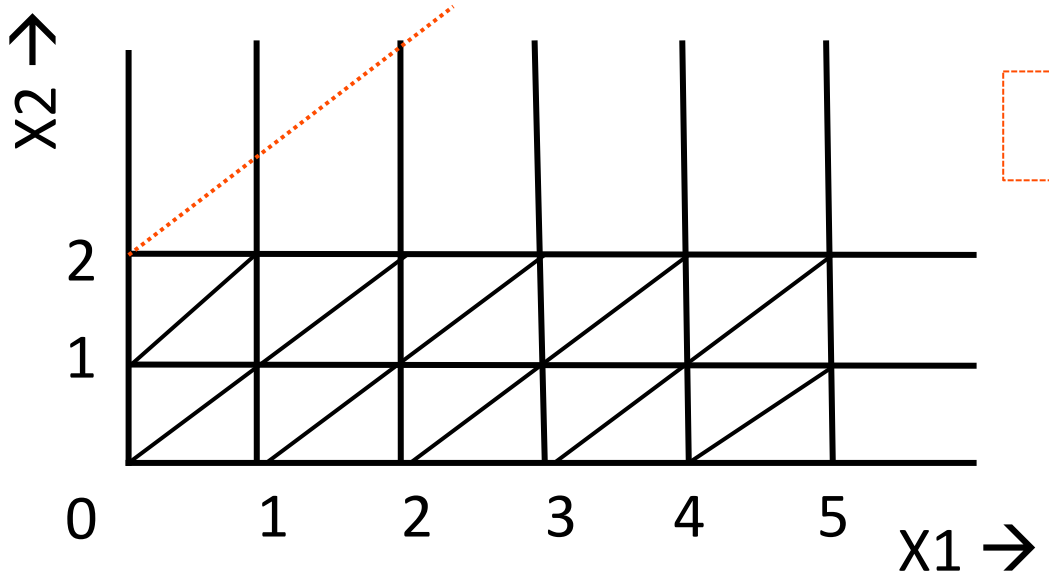
If integer constants and simple constraints (e.g., $x < c$)

Straight lines

$$\forall x: \{x = c \mid c = 0, 1, \ldots c \downarrow x\}$$

Diagonals lines

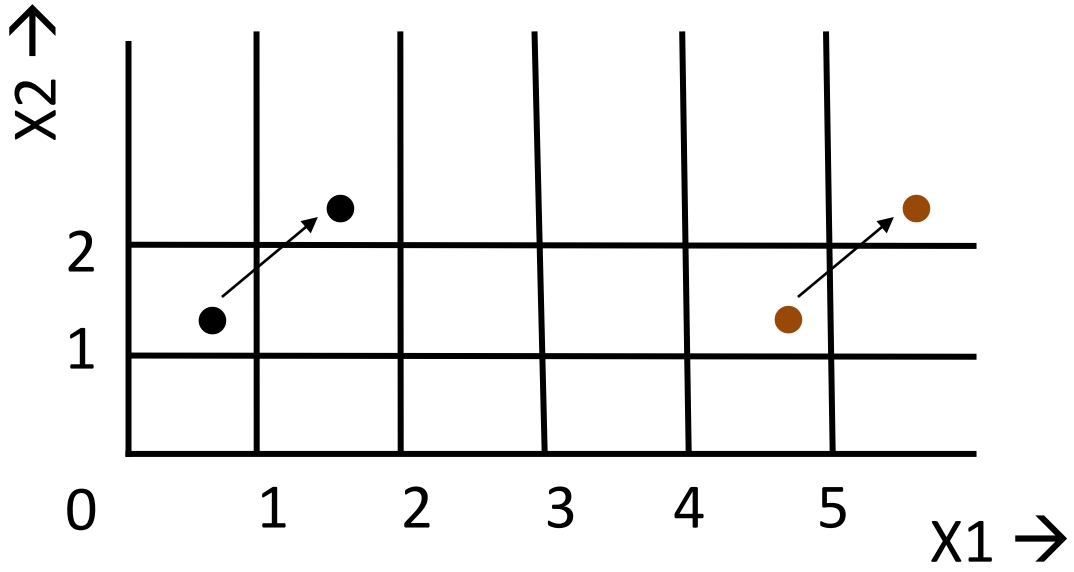
$$\forall x, y: \{\text{fract}(x) = \text{fract}(y) / x < c \downarrow x, y < c \downarrow y\}$$



x2 < x1 + 2

Why this construction works

1. X1 < 5
2. X2 < 2
3. X1 < 5 && X2 > 2



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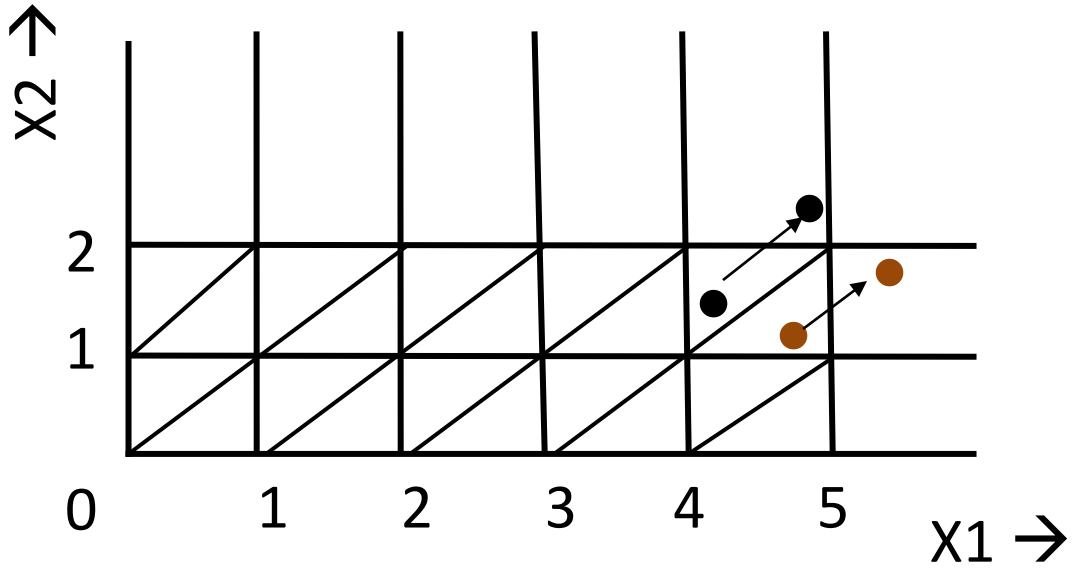
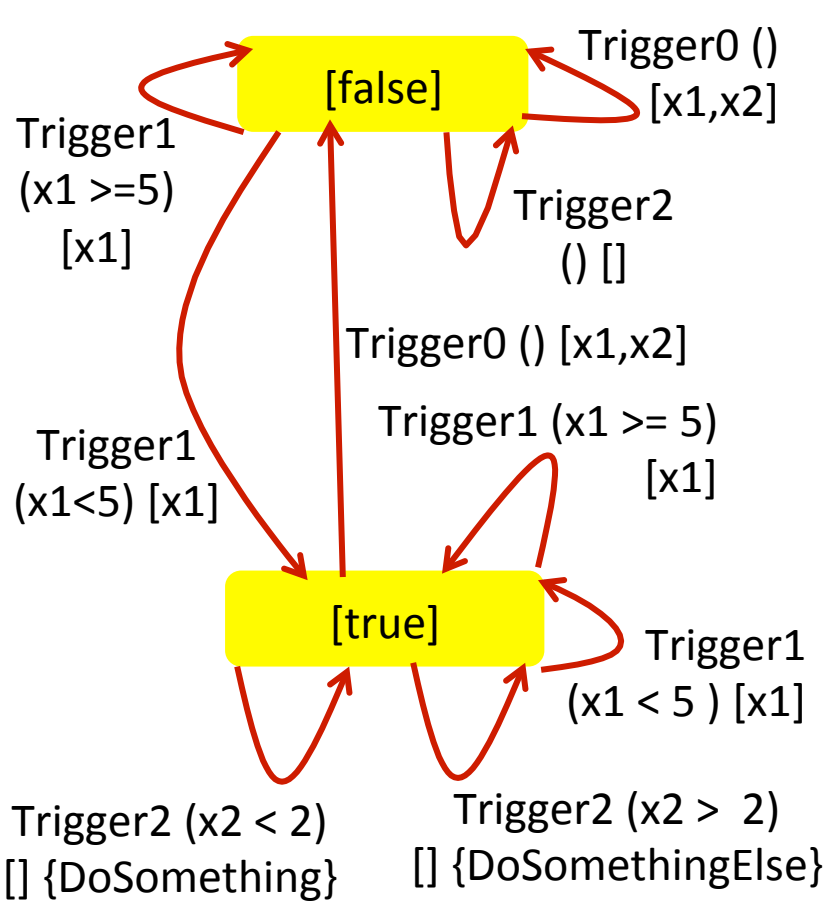
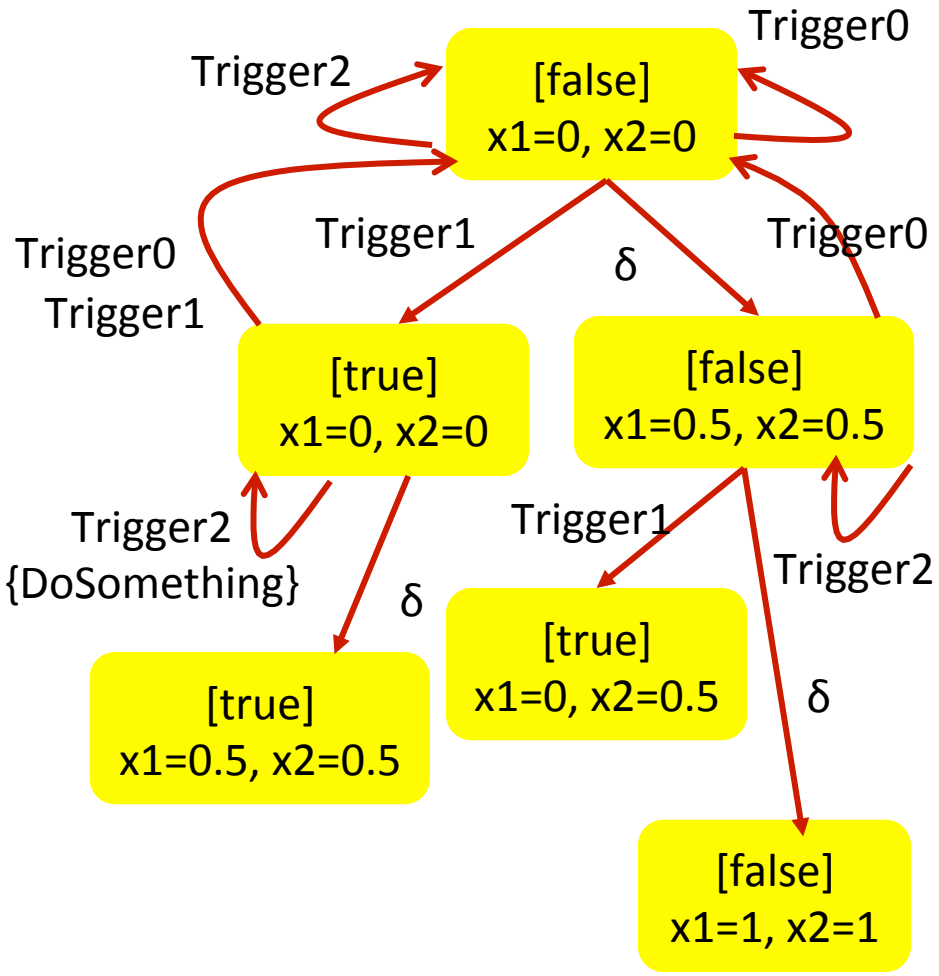


Exploring a TA





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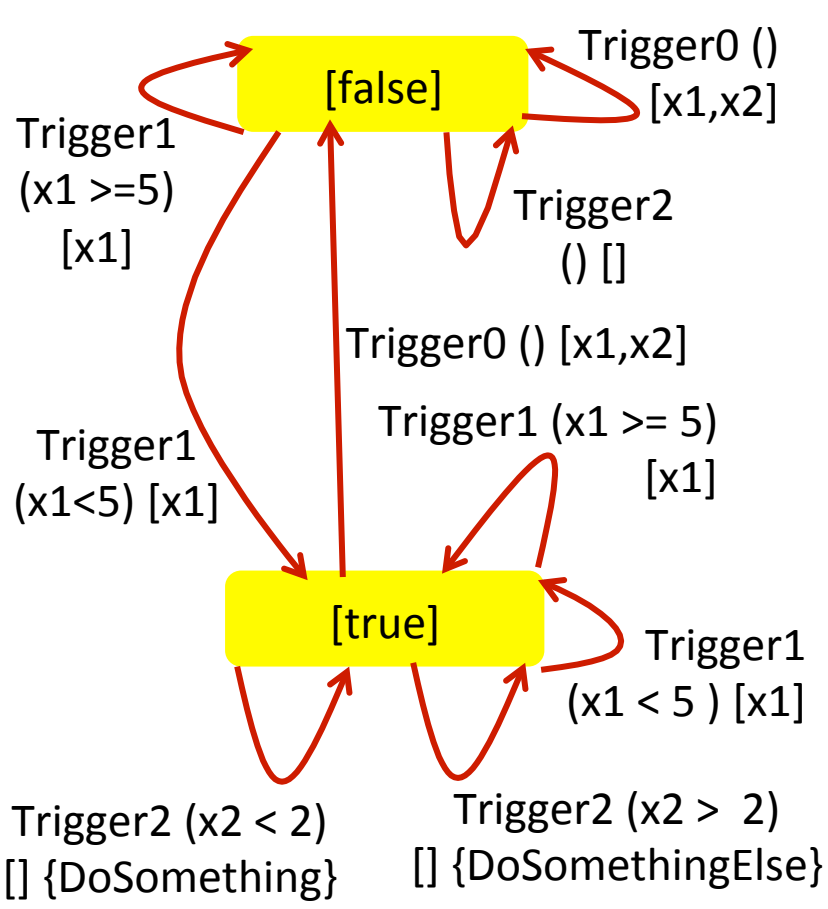

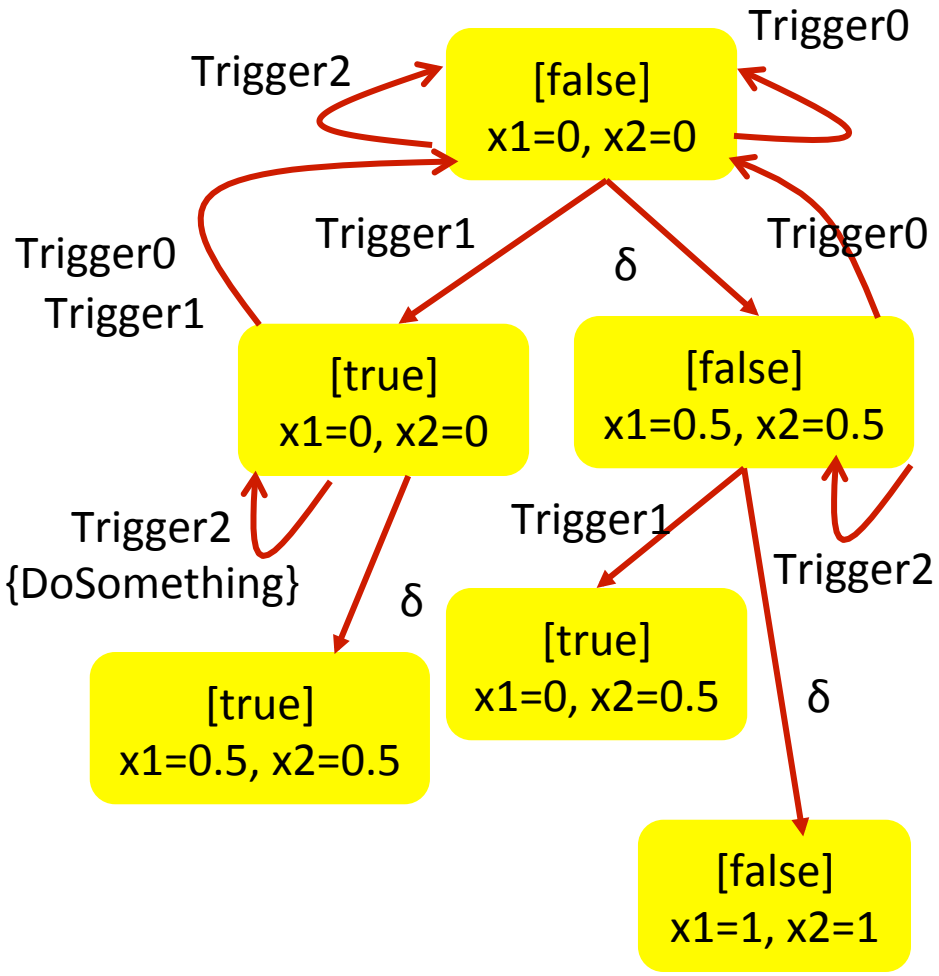

Systematically exploring control programs (Lecture II)

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Microsoft Research

Joint work with Jason Croft,
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Recap: The nature of control programs

Collection of rules with triggers and actions

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motionPorch.Detected:
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  tLastMotion = Now

@6:00:00 PM:
   porchLight.Set(On)

@6:00:00 AM:
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```

```
packetIn:
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                    inPkt.dst)
  if (!cache.Contains(entry)
     cache.Insert(entry, Now)

CleanupTimer:
  foreach entry in cache
    if (Now - cache[entry] < 5s)
       cache.Remove(entry)
```

Recap: Timed automata

FSM (states, transitions) + the following:

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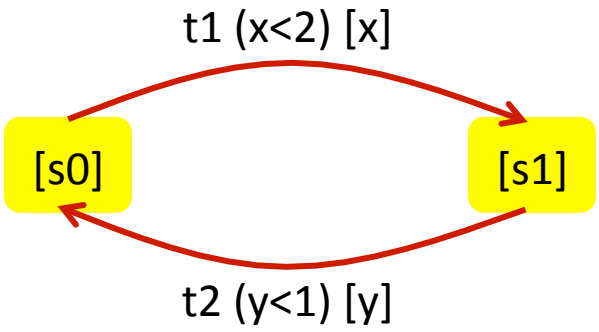
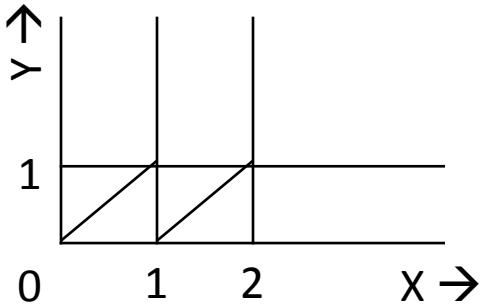
Time can be partitioned into equivalence regions





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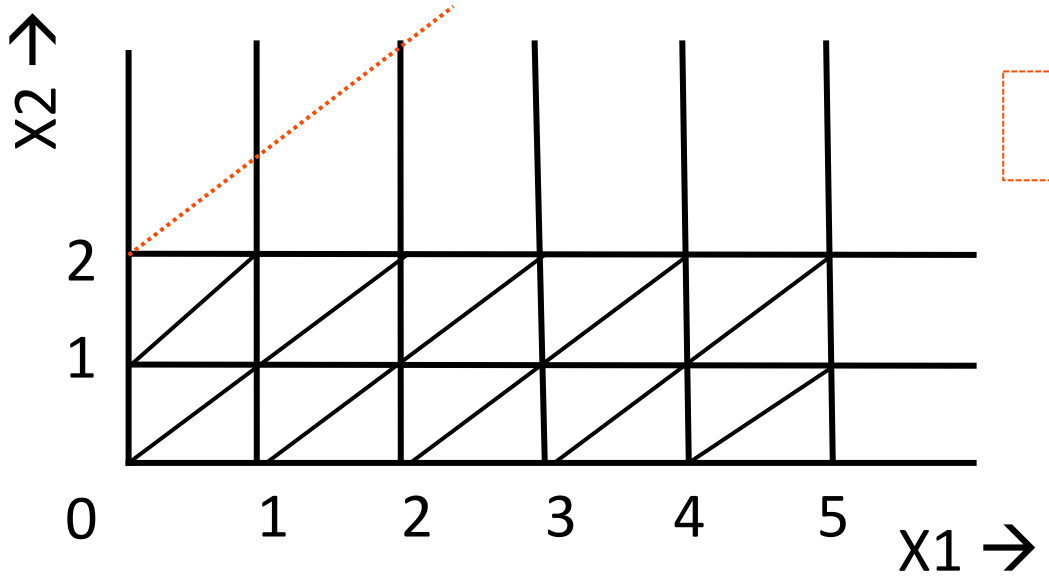

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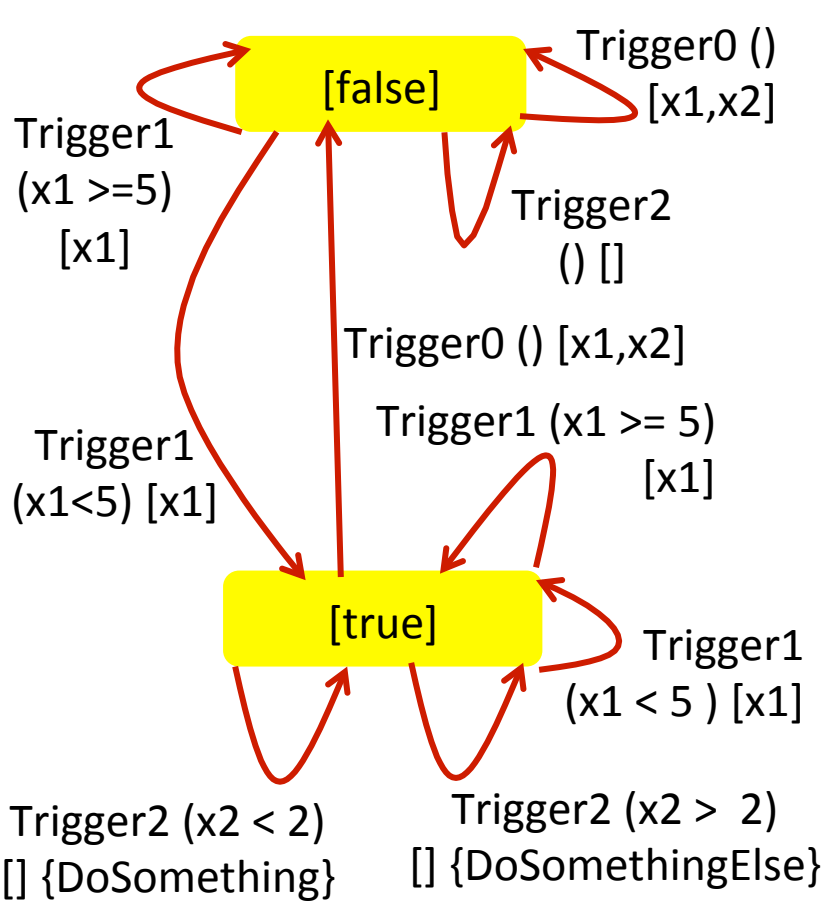
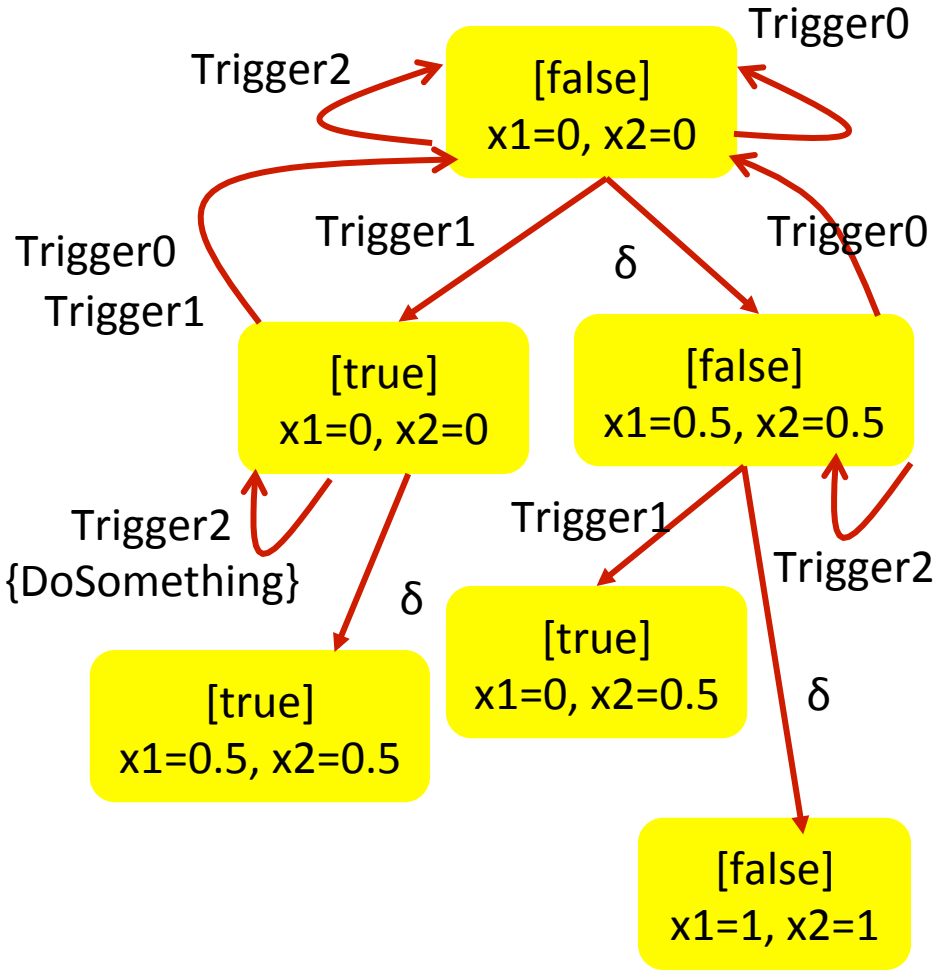
Recap: Exploring a TA





Exploring control programs with TAs

1. Mapping time-related activity to VCs
2. Model devices
3. Construct time regions
4. Compute equivalent classes for inputs
5. Explore states

Mapping to VCs (1/4): Delay measurers

```
Trigger1:
   ...
   tLast = Now
   ...

Trigger2:
   ...
   if (Now - tLast < 60)
   ...
```

```
Trigger1:
   ...
   VC_tLast = 0
   ...

Trigger2:
   ...
   if (VC_tLast < 60)
   ...
```

Mapping to VCs (2/4): Periodic timers

```
timer1.Period = 600
timer1.Event += Timer1Fired
...

Timer1Fired:
   ...
```

```
VC_timer1 = 0

...

VC_timer1 == 600:
   ...
   VC_timer1 = 0
```

Mapping to VCs (2/4): Delayed actions

```
Trigger1:
   ...
   timer1.Start(600)
   ...

timer1.Fired:
   ...
```

```
Trigger1:
   ...
   VC_timer1 = 0
   ...

VC_timer1 == 600:
   ...
```

Mapping to VCs (4/4): Sleep calls

```
Trigger:
  ...
  Sleep(10)
  ...
```

```
Trigger:
  ...   // pre-sleep actions
  VC_sleeper = 0

VC_sleeper == 10:
  ...  // post-sleep actions
```

Reducing the number of VCs: Combining periodic timers

```
timer1.Period = 600
timer1.Event += Timer1Fired
timer2.Period = 800
timer2.Event += Timer2Fired
...

Timer1Fired:
   ...

Timer2Fired:
   ...
```

```
VC_timer = 0



...

VC_timer == 600:
   ...

VC_timer == 800:
   ...
   VC_timer = 0
```

Reducing the number of VCs: Combining sleep calls

```
Trigger:
  Act1()
  Sleep(5)
  Act2()
  Sleep(10)
  Act3()
```

```
Trigger:
  Act1()
  VC_sleeper = 0
  sleep_counter = 1;

VC_sleeper == 5:
  Act2()

VC_sleeper == 15:
  Act3()
```

Modeling devices

Model a device using one of more key value pairs

- Motion sensor: Single key with binary value
- Dimmer: Single key with values in range [0..99]
- Thermostat: Multiple keys

Keys can be notifying or non-notifying

- Triggers are used for notifying keys

Queries for values are treated as program inputs

Limitations of device modeling

Values can change arbitrarily

Key value pairs of a device are independent

Different devices are independent

Constructing time regions

1. Extract VC constraints using symbolic execution

2. Construct time regions using the constraints

```
Trigger0:
  tTrigger1 = Now
  tTrigger2 = Now
  trigger1Seen = false
Trigger1:
  if (Now - tTrigger1 < 5)
    trigger1Seen = true
  tTrigger1 = Now
Trigger2:
  if (trigger1Seen)
     if (Now - tTrigger2 < 2)
        DoSomething()
     else
        DoSomethingElse()
```

Exploration using TA

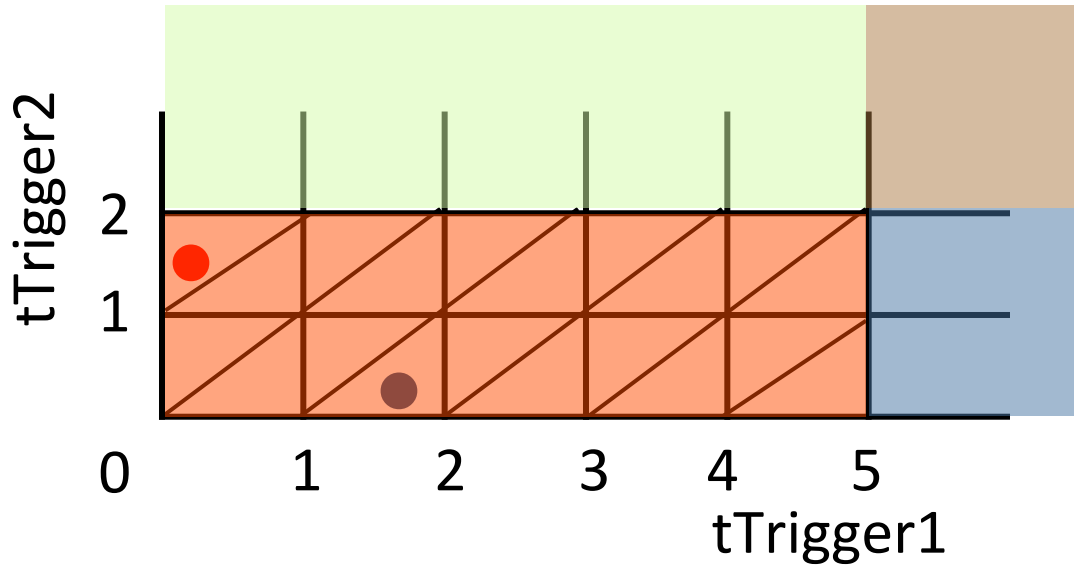
Region state = Variables values + VC region + ready timers

1. exploredStates = {}
2. unexploredStates = {$S\downarrow initial$}
3. **While** (unexploredStates $\neq \phi$)
4. $S\downarrow i$ = PickNext(UnexploredStates)
5. **foreach** event in Events, $S\downarrow i$.$ReadyTimers$
6. **foreach** input in Inputs
7. $S\downarrow o$ = Compute($S\downarrow i$, event, input)
8. if ($S\downarrow o \notin$ exploredStates) unexploredStates.Add($S\downarrow o$)
9. **if** ($S\downarrow i$.$ReadyTimers = \phi$)
10. $S\downarrow o$ = AdvanceRegion($S\downarrow i$) //also marks ReadyTimers

Optimization: Predicting successor states

Observation: Multiple region states can have identical response to a trigger

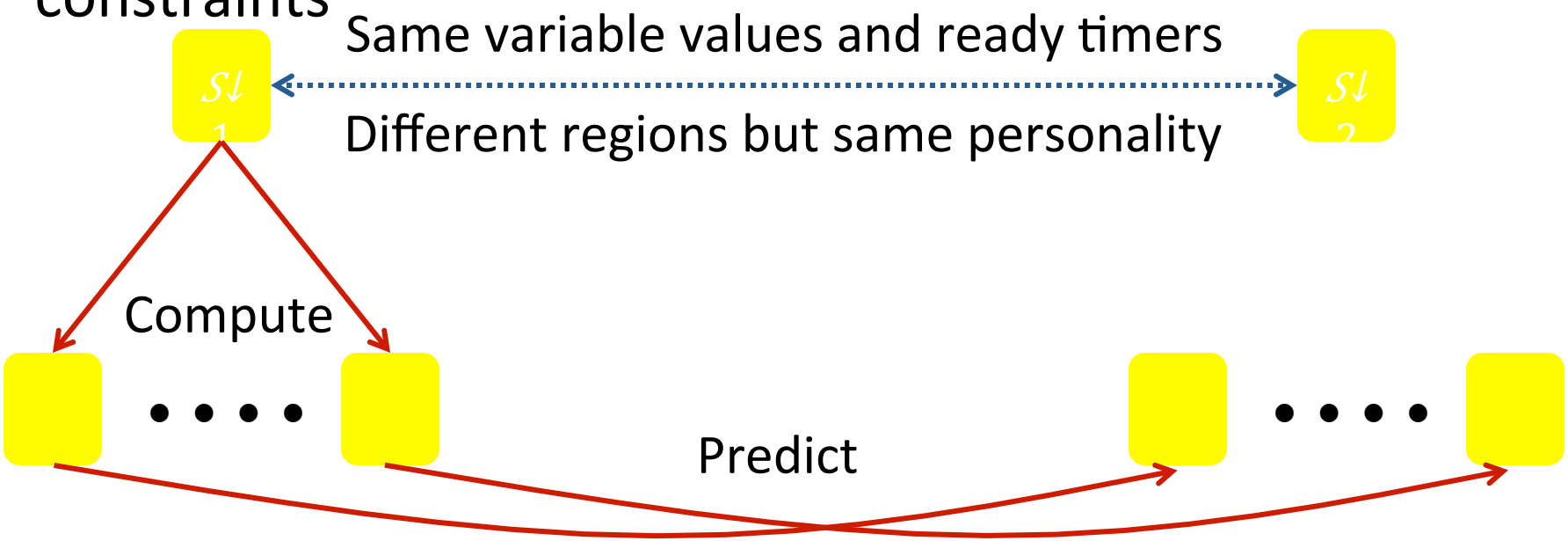
```
Trigger1:
  if (x1 < 5)
    trigger1Seen = true
  x1= 0
Trigger2:
  if (trigger1Seen)
     if (x2 < 2)
        DoSomething()
     else
        DoSomethingElse()
```



Optimization: Predicting successor states

Observation: Multiple region states can have identical response to a trigger

Clock personality: region's evaluation of clock constraints

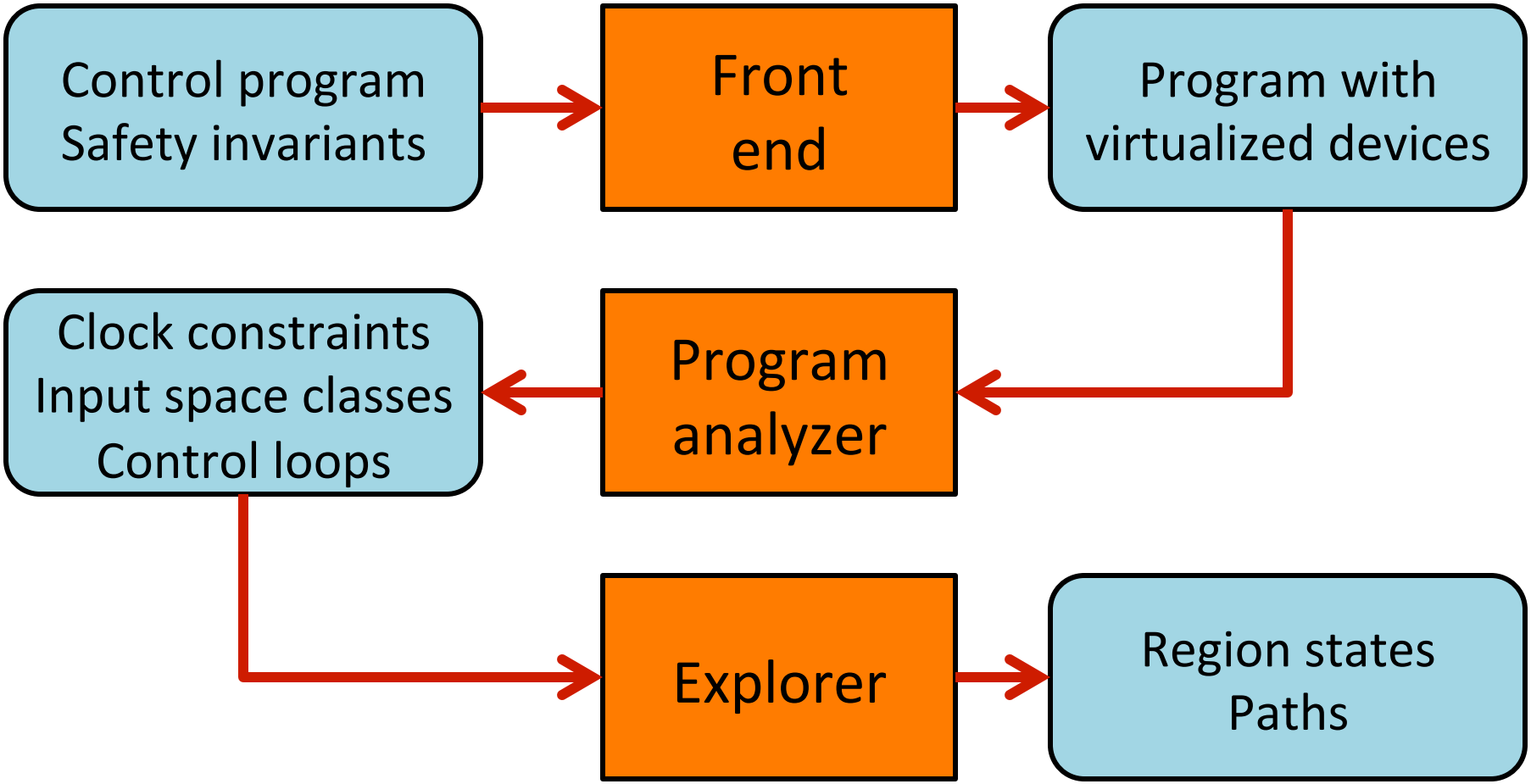


Optimization: Independent control loops

Observation: Control programs tend to have multiple, independent control loops

1. Determine independent sets of variables
2. Explore independent sets independently

DeLorean


Control program
Safety invariants
Front end
Program with virtualized devices
Clock constraints
Input space classes
Control loops
Program analyzer
Explorer
Region states
Paths

Demo

Evaluation on ten real home automation rograms

	type	#rules	#devs	SLoC	#VCs	GCD (s)
P1	OmniPro	6	3	59	2	7200
P2	Elk	3	3	75	2	1800
P3	MiCasaVerde	6	29	143	2	300
P4	Elk	13	20	193	5	5
P5	ActiveHome	35	6	216	14	5
P6	mControl	10	19	221	4	5
P7	OmniIIe	15	27	277	6	60
P8	HomeSeer	21	28	393	10	2
P9	ISY	25	51	462	6	60
P10	ISY	90	39	867	6	10

Example bugs

P9-1: Lights turned on even in the absence of motion

- Bug in conditional clause: used OR instead of AND

P9-2: Lights turned off between sunset and 2AM

- Interaction between rules that turned lights on and off

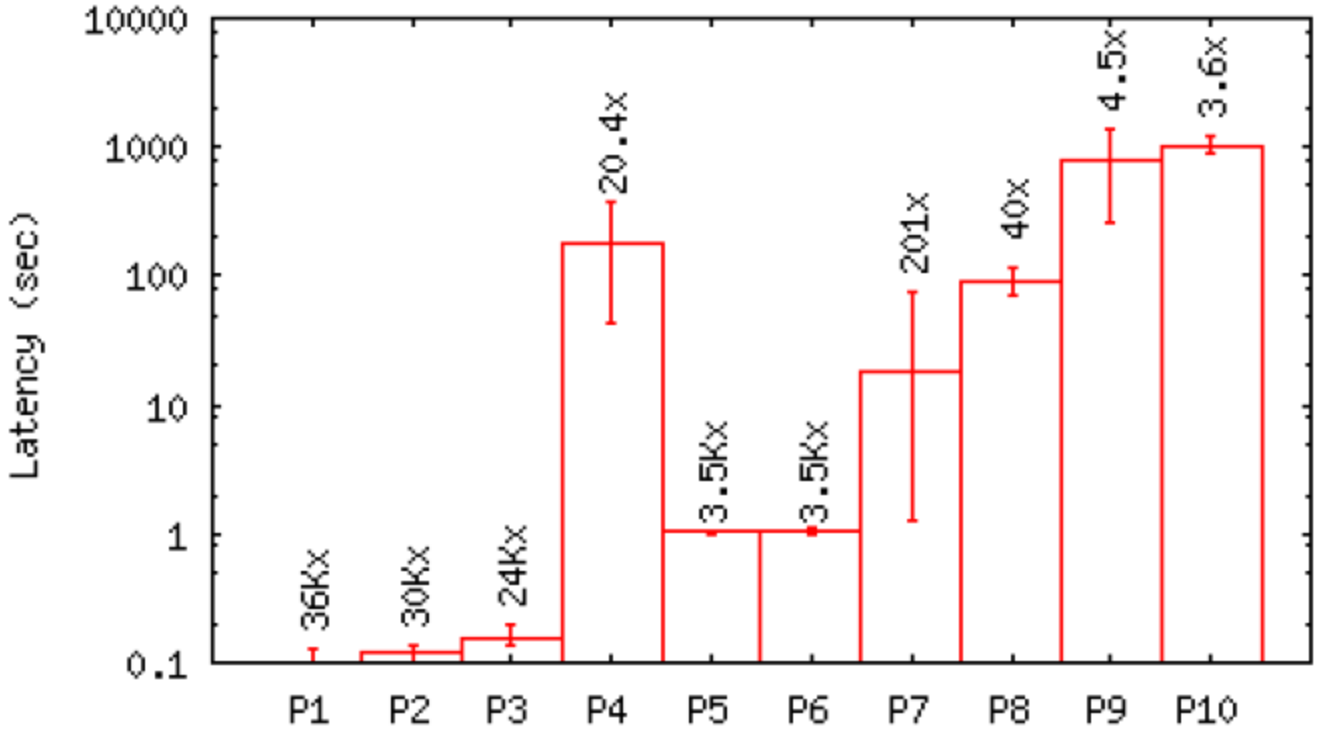
P10-1: Dimmer wouldn't turn on despite motion

- No rule to cover a small time window

P10-2: One device in a group behaved differently

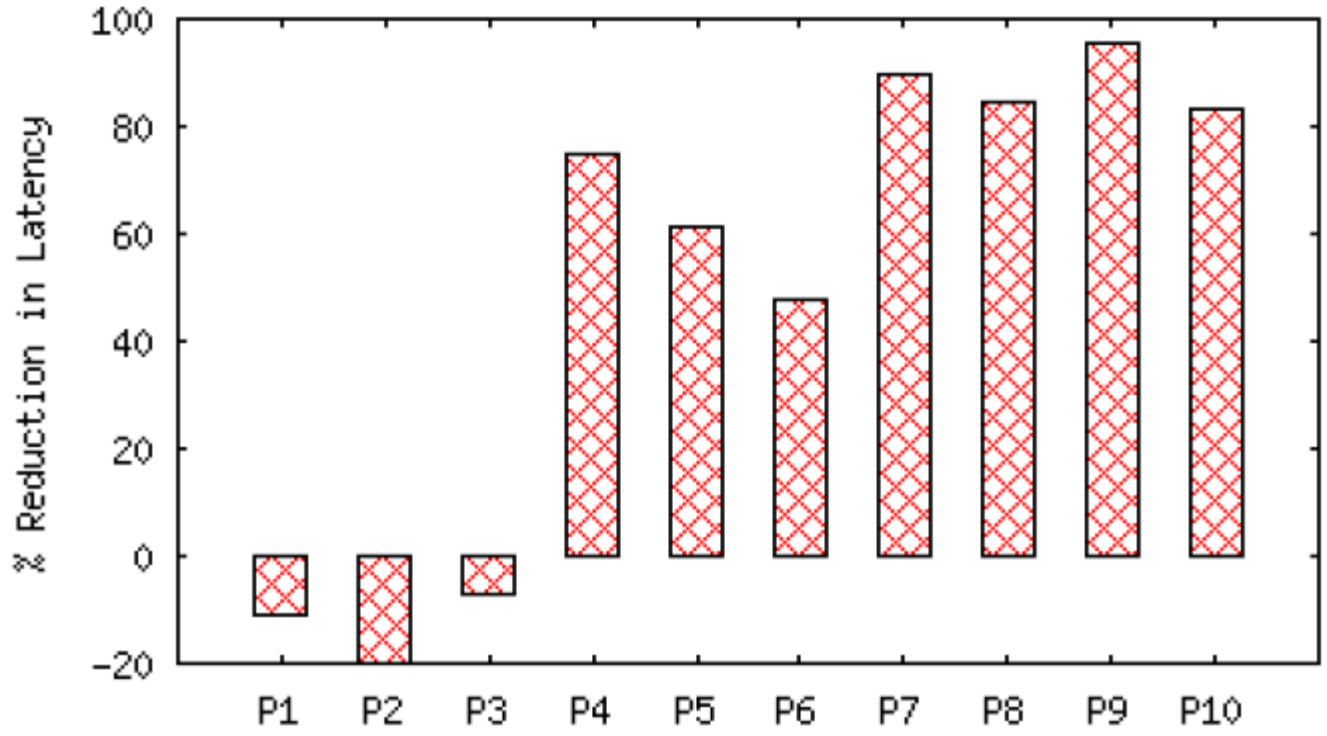
- Missing reference to the device in one of the rules

Performance of exploration



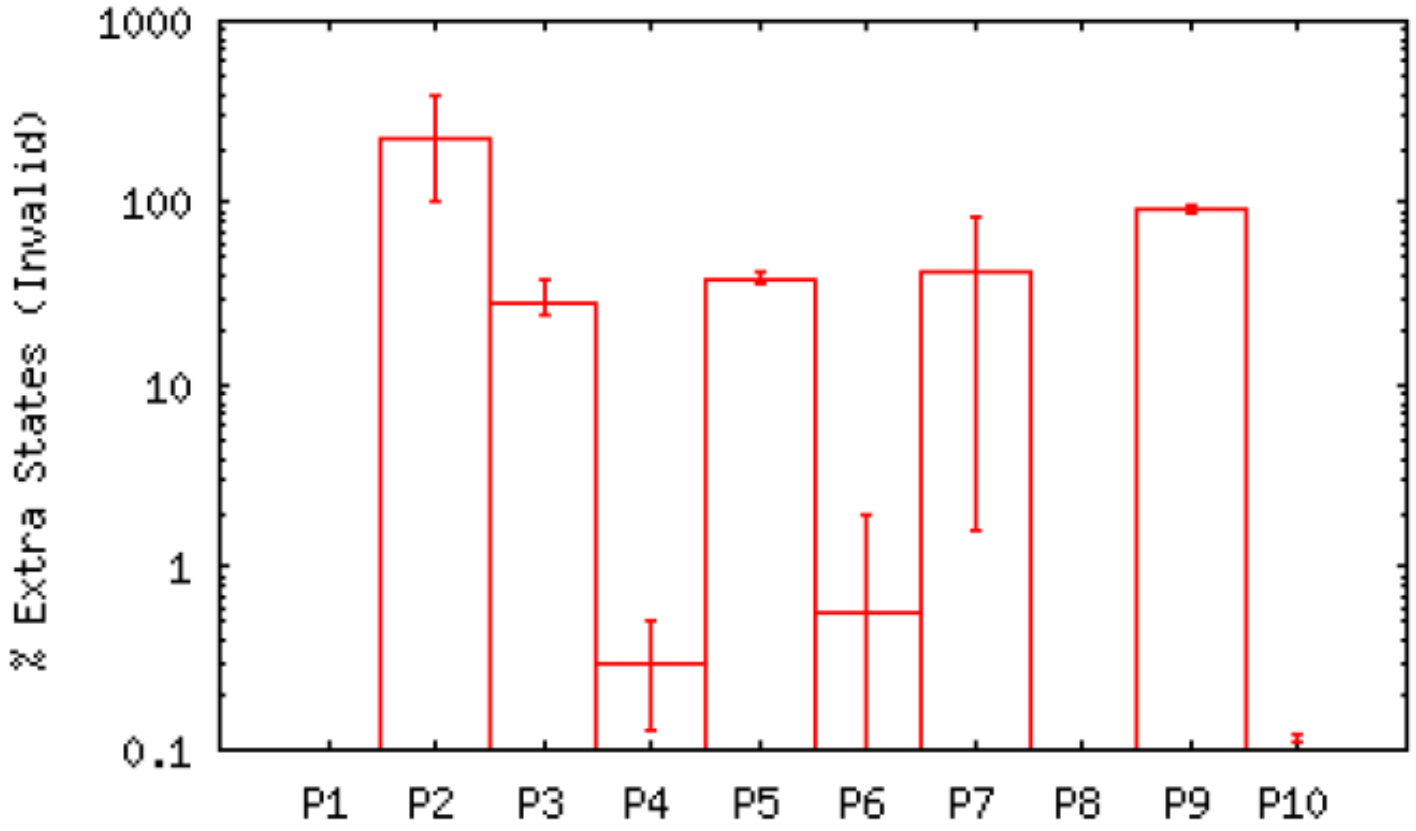
Time to “fast forward” the home by one hour

Benefit of successor prediction



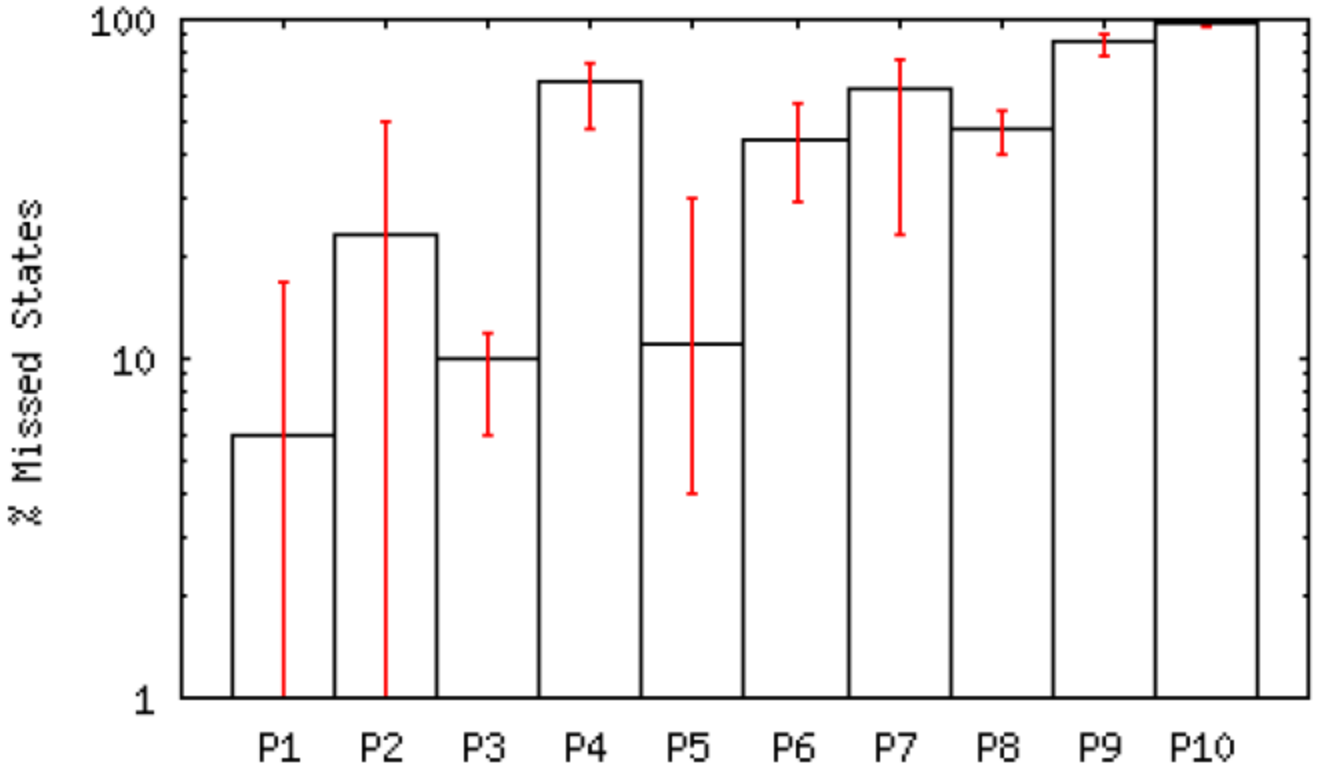
Successor prediction yields significant advantage

Comparison with untimed model checking



Untimed model checking reaches many invalid states

Comparison with randomized testing



Random testing misses many valid states

Exploring OpenFlow programs

	#devs	SLoC	#VCs	GCD
MAC-Learning Switch (PySwitch)	2 hosts, 2 sw, 1 ctrl	128	>= 6	1
Web Server Load Balancer	3 hosts, 1 sw, 1 ctrl	1307	>= 4	1
Energy-Efficient Traffic Engineering	3 hosts, 3 sw, 1 ctrl	342	>= 8	2

Additional challenges in OF programs

```
packetIn:
   timer = new Timer(5s)
   Insert(timer, inPkt.src, inPkt.dst)
```

Dynamically created VCs

Variable number of VCs along different paths

Open problems

Handling communicating control programs

Exploring all possible topologies

Summary

Control programs are tricky to debug

- Interaction between rules
- Large space of inputs
- Intimate dependence on time

These challenges cab be tacked using

- Systematic exploration (model checking)
- Symbolic execution to find equivalent input classes
- Timed automata based exploration (equivalent times)