From Specifications to Monitors

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Definition (Runtime Verification)

Runtime Verification is the discipline of computer science dedicated to the analysis of system executions, including checking them against formalized specifications.

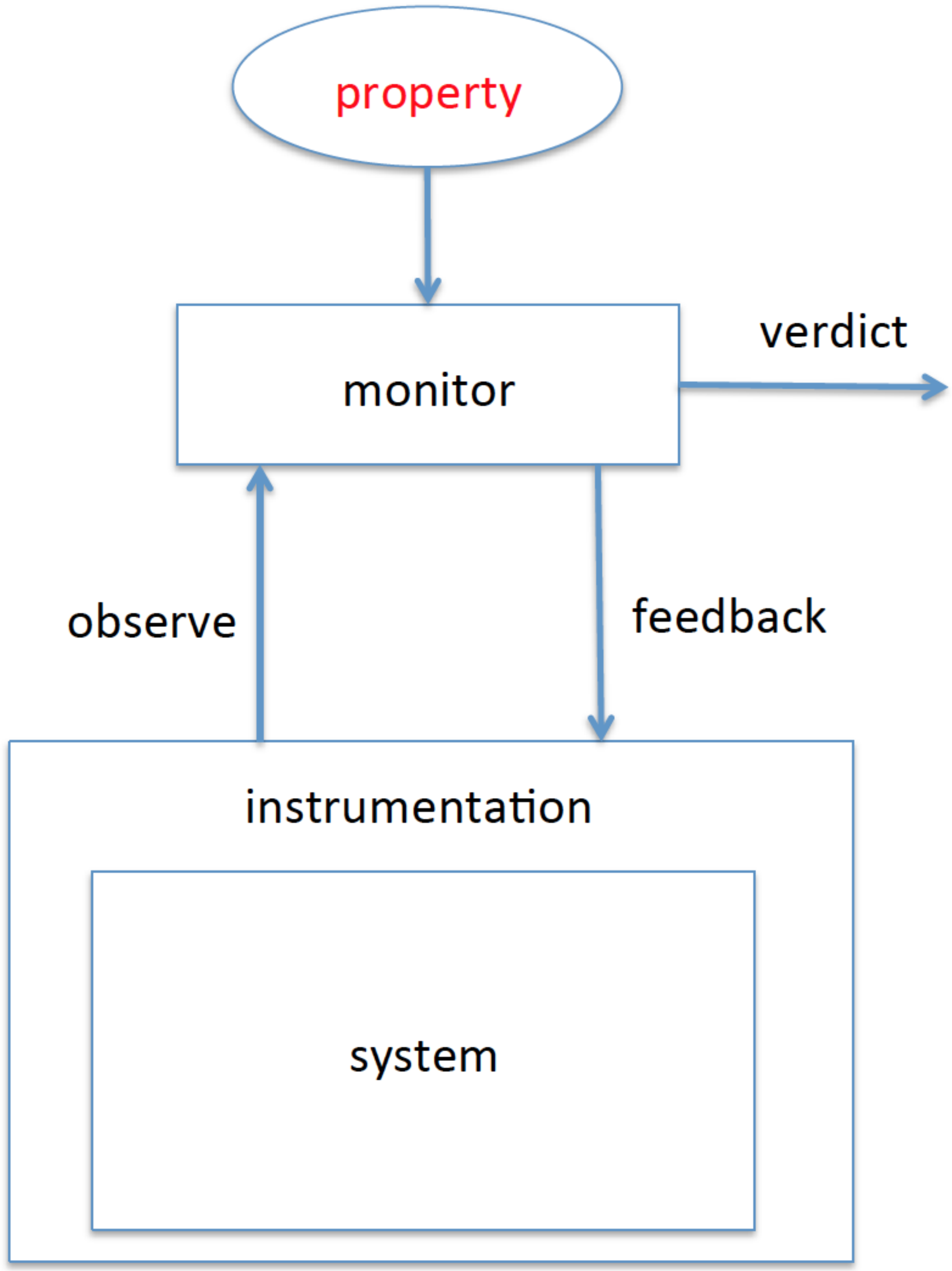
Alternative formulation: *"get as much out of your runs as possible"*:

- verification of execution traces, Boolean true or false
- collection of statistics, beyond the Boolean domain
- specification learning
- analysis with algorithms (no specs): data race and deadlock analysis
- trace visualization
- fault protection: changing behavior

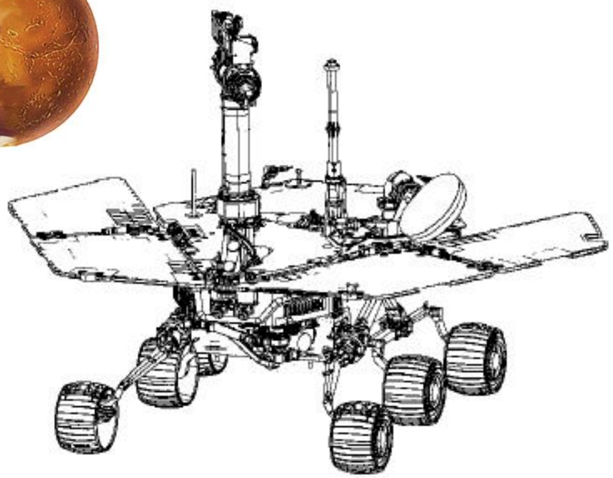
Runtime verification

$$M : \mathbb{E}^* \to D$$

$$M : \mathcal{P}(\mathbb{E}^*) \to D$$


property
monitor
verdict
observe
feedback
instrumentation
system

fault protection



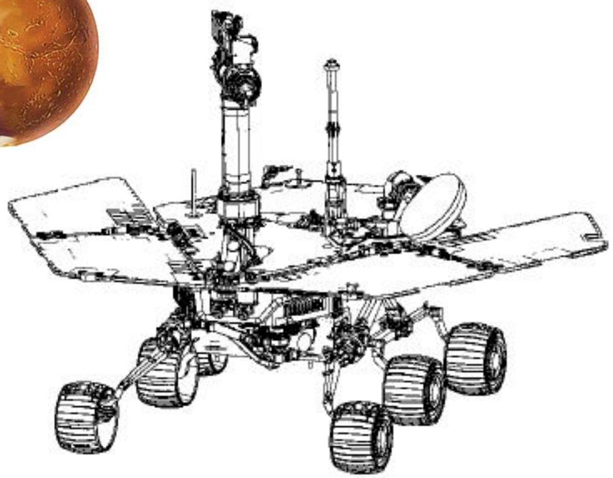
response

monitor

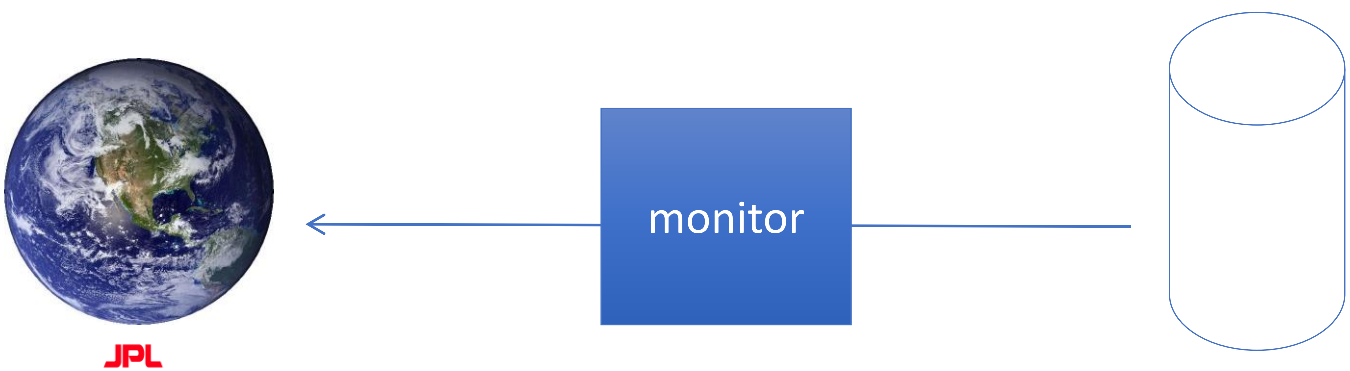
event
event
event

JPL

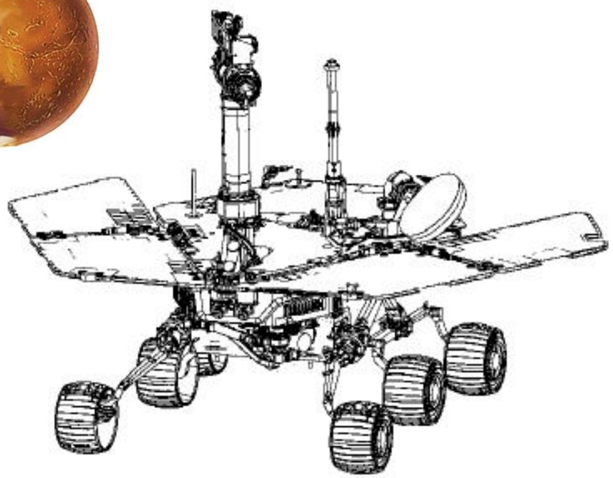
log file analysis



event
event
event



command sequence analysis

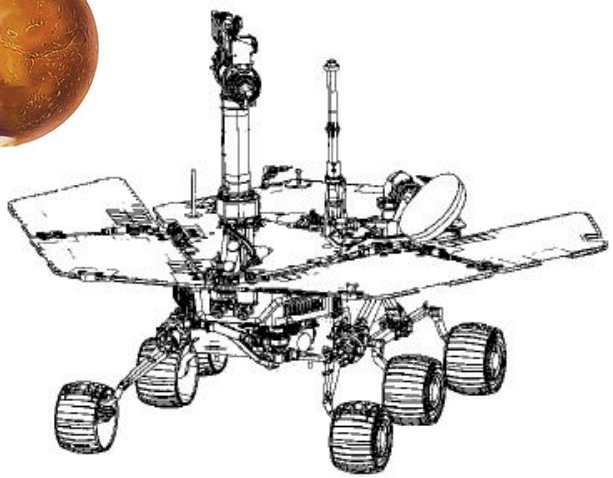


JPL

command
command
command

monitor

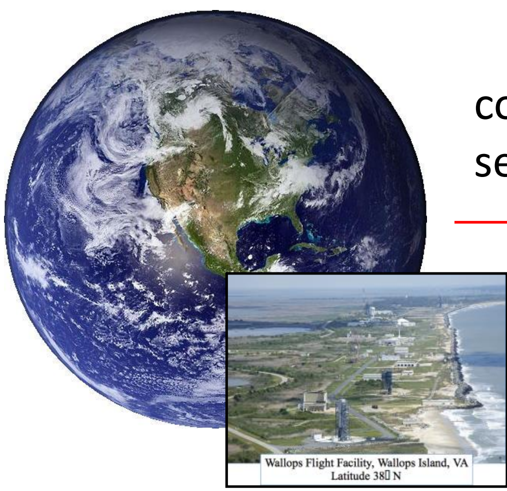
command sequence analysis



monitor

command
command
command

verified
command
sequence



command
sequence

In April 2011 TraceContract was selected by LADEE mission management for writing the flight rule checker!

Classical dimensions to consider = E^3

- Efficiency

- Expressiveness

- Elegance

FAST

KEEP IT SIMPLE

DejaVu

With:

Doron Peled (Bar Ilan University, Israel)

Dogan Ulus (Verimag/Universite Grenoble-Alpes, France)

First-order past time temporal formulas

$$\forall f\,(close(f) \longrightarrow \mathbf{P}\,open(f))$$

$$\forall f\,(close(f) \longrightarrow \ominus(\neg close(f)\,\mathcal{S}\,open(f)))$$

The Logic

$$\varphi ::= true \mid p(t_1,\ldots,t_n) \mid \neg\varphi \mid \varphi_1 \vee \varphi_2 \mid \exists x \bullet \varphi \mid \ominus\varphi \mid \varphi_1\ \mathbf{S}\ \varphi_2$$

$$t ::= c \mid x$$

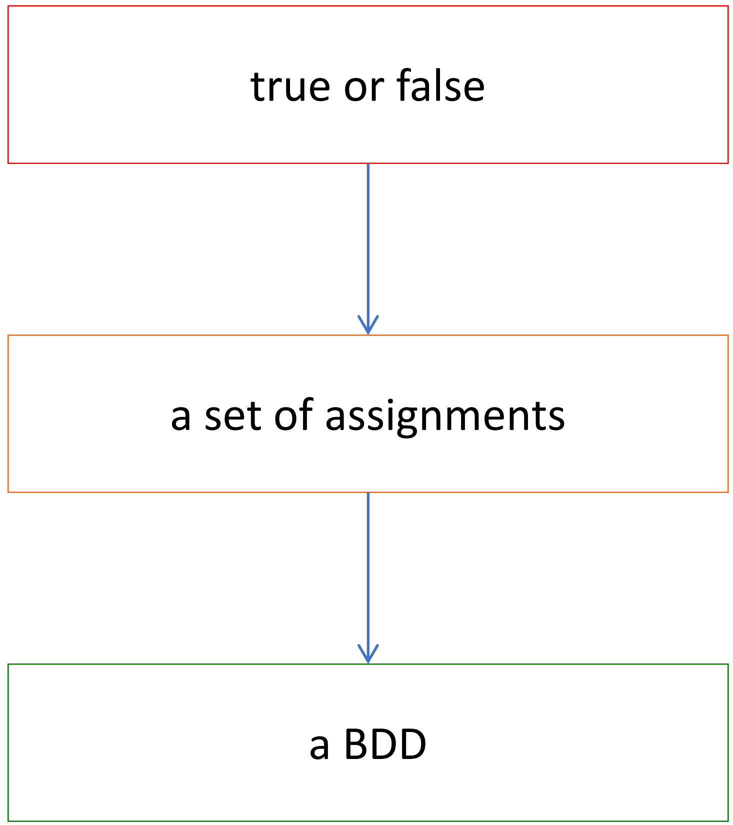
Derived Constructs

$$false = \neg true$$
$$\varphi_1 \wedge \varphi_2 = \neg(\neg\varphi_1 \vee \neg\varphi_2)$$
$$\varphi_1 \Rightarrow \varphi_2 = \neg\varphi_1 \vee \varphi_2$$
$$\forall x \bullet \varphi = \neg\exists x \bullet \neg\varphi$$
$$\mathbf{P}\ \varphi = true\ \mathbf{S}\ \varphi$$
$$\mathbf{H}\ \varphi = \neg\mathbf{P}\ \neg\varphi$$
$$[\varphi_1, \varphi_2) = (\neg\varphi_2)\ \mathbf{S}\ \varphi_1$$

Example

$$\begin{array}{l} \forall\, user \bullet \forall\, file \bullet \\ \quad access(user, file) \Rightarrow \\ \qquad [login(user), logout(user)) \\ \qquad\qquad \wedge \\ \qquad [open(file), close(file)) \end{array}$$

Result of verifying trace against a formula



Some definitions

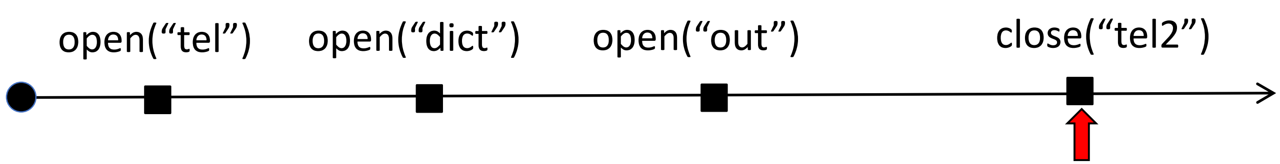
- **Domains** D_1, D_2, …, possibly infinite
- **Variables** V = {x,y,…} ranging over domains x : D_1, y : D_2, …
- **Assignments** [x -> “tel”, y -> “tel2”]
- **Predicates** open(“tel”), open(x), close(y), …
- **Ground predicates** open(“tel”)
- **A state** is a set of ground predicates: {open(“tel1”), open(“tel2”)}
- **A trace** is a finite sequence of states: $<s_1,s_2,\ldots,s_n>$

First Semantics: the "standard" definition

- $(\varepsilon, \sigma, i) \models true$.
- $(\varepsilon, \sigma, i) \models p(a)$ if $p(a) \in \sigma[i]$.
- $([v \mapsto a], \sigma, i) \models p(v)$ if $p(a) \in \sigma[i]$.
- $(\gamma, \sigma, i) \models (\varphi \wedge \psi)$ if $(\gamma|_{vars(\varphi)}, \sigma, i) \models \varphi$ and $(\gamma|_{vars(\psi)}, \sigma, i) \models \psi$.
- $(\gamma, \sigma, i) \models \neg\varphi$ if not $(\gamma, \sigma, i) \models \varphi$.
- $(\gamma, \sigma, i) \models (\varphi\, \mathcal{S}\, \psi)$ if for some $1 \leq j \leq i$, $(\gamma|_{vars(\psi)}, \sigma, j) \models \psi$ and for all $j < k \leq i$, $(\gamma|_{vars(\varphi)}, \sigma, k) \models \varphi$.
- $(\gamma, \sigma, i) \models \ominus\varphi$ if $i > 1$ and $(\gamma, \sigma, i-1) \models \varphi$.
- $(\gamma, \sigma, i) \models \exists x\, \varphi$ if there exists $a \in domain(x)$ such that[1] $(\gamma[x \mapsto a], \sigma, i) \models \varphi$.

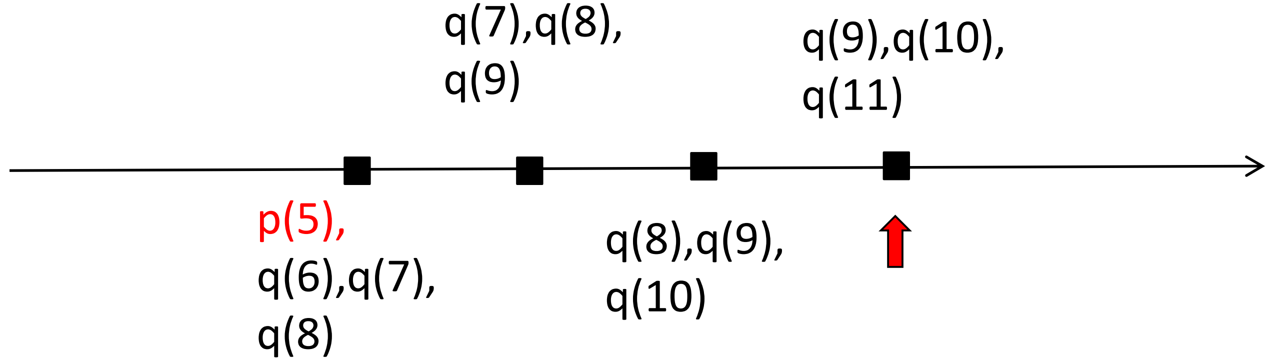
Example

$$\forall f\,(close(f) \longrightarrow \mathbf{P}\,open(f))$$



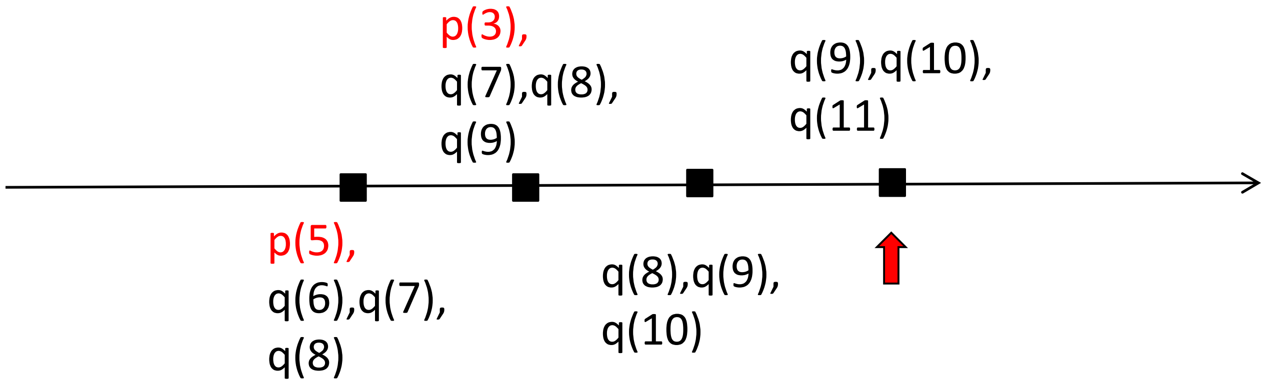
We need to save all past values of file names that were opened, and compare with the current one that is closed.

Lets look at a more complicated formula: $\exists x\ \exists y\ (q(y)\ \mathbf{S}\ p(x))$



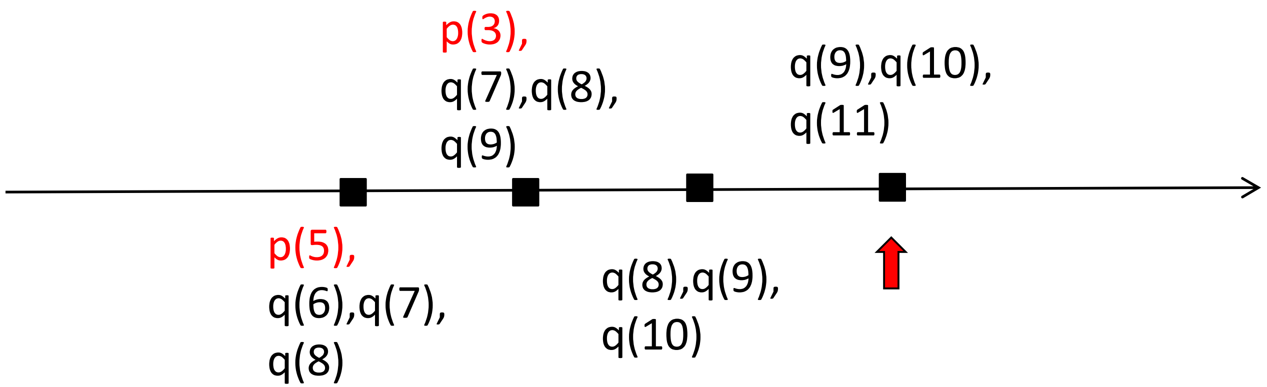
The answer is **F**: there is no common value of q(y) since q(5).

Lets look at a more complicated formula:
$\exists x \, \exists y \, (q(y) \; \mathbf{S} \; p(x))$



The answer is **T**: there is a common value of q(9) since p(3).

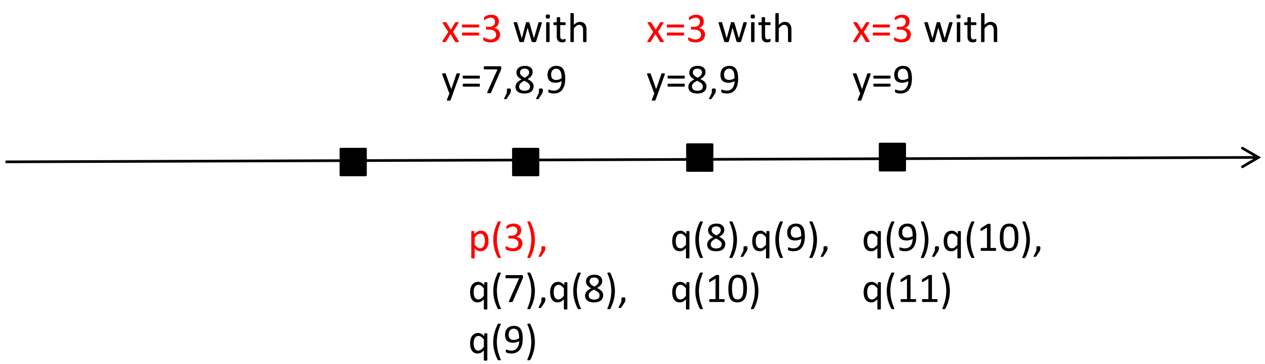
$\exists x\, \exists y\, (q(y)\ \mathbf{S}\ p(x))$
The "bookkeeping" is nontrivial:



The answer is **T**: there is a common value of q(9) since p(3).

Keep common subsets of values of y in q(y) since you see p(5).
Keep common subsets of values of y in q(y) since you see p(3).

∃x ∃y (q(y) **S** p(x))
The “bookkeeping” is nontrivial:



The answer is **T**: there is a common value of q(9) since p(3).
Keep common subsets of values of y in q(y) since you see p(3).
Do the same with x=5
In general we keep track of sets of tuples (assignments) of x and y values: e.g. {(3,7), (3,8), (3,9)}, at each point.
Standard semantics does not give a good intuition how to perform this bookkeeping!

Second semantics: Set semantics. Each (sub)formula on a prefix of an execution denotes a set of assignments that satisfy the formula.

- $I[\varphi,\sigma,0] = \emptyset$.
- $I[true,\sigma,i] = \{\varepsilon\}$.
- $I[p(a),\sigma,i] = \text{if } p(a) \in \sigma[i] \text{ then } \{\varepsilon\} \text{ else } \emptyset$.
- $I[p(v),\sigma,i] = \{[v \mapsto a] | p(a) \in \sigma[i]\}$.
- $I[(\varphi \wedge \psi),\sigma,i] = I[\varphi,\sigma,i] \bigcap I[\psi,\sigma,i]$.
- $I[\neg\varphi,\sigma,i] = \boxed{A_{vars(\varphi)} \setminus I[\varphi,\sigma,i]}$.
- $I[(\varphi\, \mathcal{S}\, \psi),\sigma,i] = I[\psi,\sigma,i] \bigcup (I[\varphi,\sigma,i] \bigcap I[(\varphi \mathcal{S} \psi),\sigma,i-1])$.
- $I[\ominus\varphi,\sigma,i] = I[\varphi,\sigma,i-1]$.
- $I[\exists x\, \varphi,\sigma,i] = hide(I[\varphi,\sigma,i],\{x\})$.

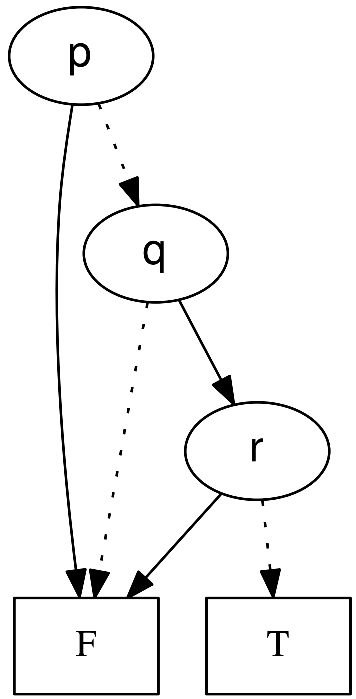
complement set = infinite set

$(\varphi \mathcal{S} \psi) = (\psi \vee (\varphi \wedge \ominus(\varphi \mathcal{S} \psi)))$

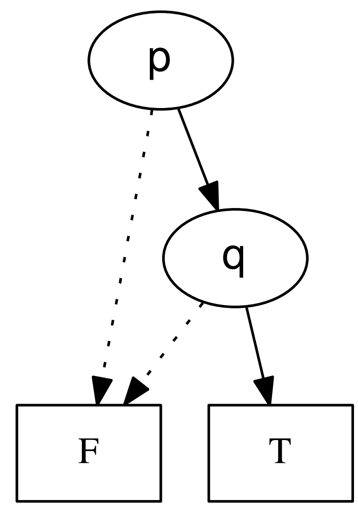
Theorem:

$$\gamma \in I[\varphi,\sigma,i] \text{ iff } (\gamma,\sigma,i) \models \varphi.$$

Third Semantics: representing sets of assignments as BDDs



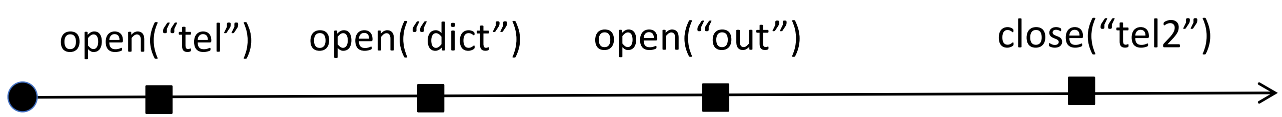
not(p) ∧ q ∧ **not**(r)



(p ∧ q ∧ r)
∨
(p ∧ q ∧ **not**(r))

We do not represent values directly. Instead we enumerate values in binary, and store sets of these binaries as BDDs.

$$\forall f\,(close(f) \longrightarrow \mathbf{P}\,open(f))$$



opened = {"tel", "dict","out"}

Value to bit string table

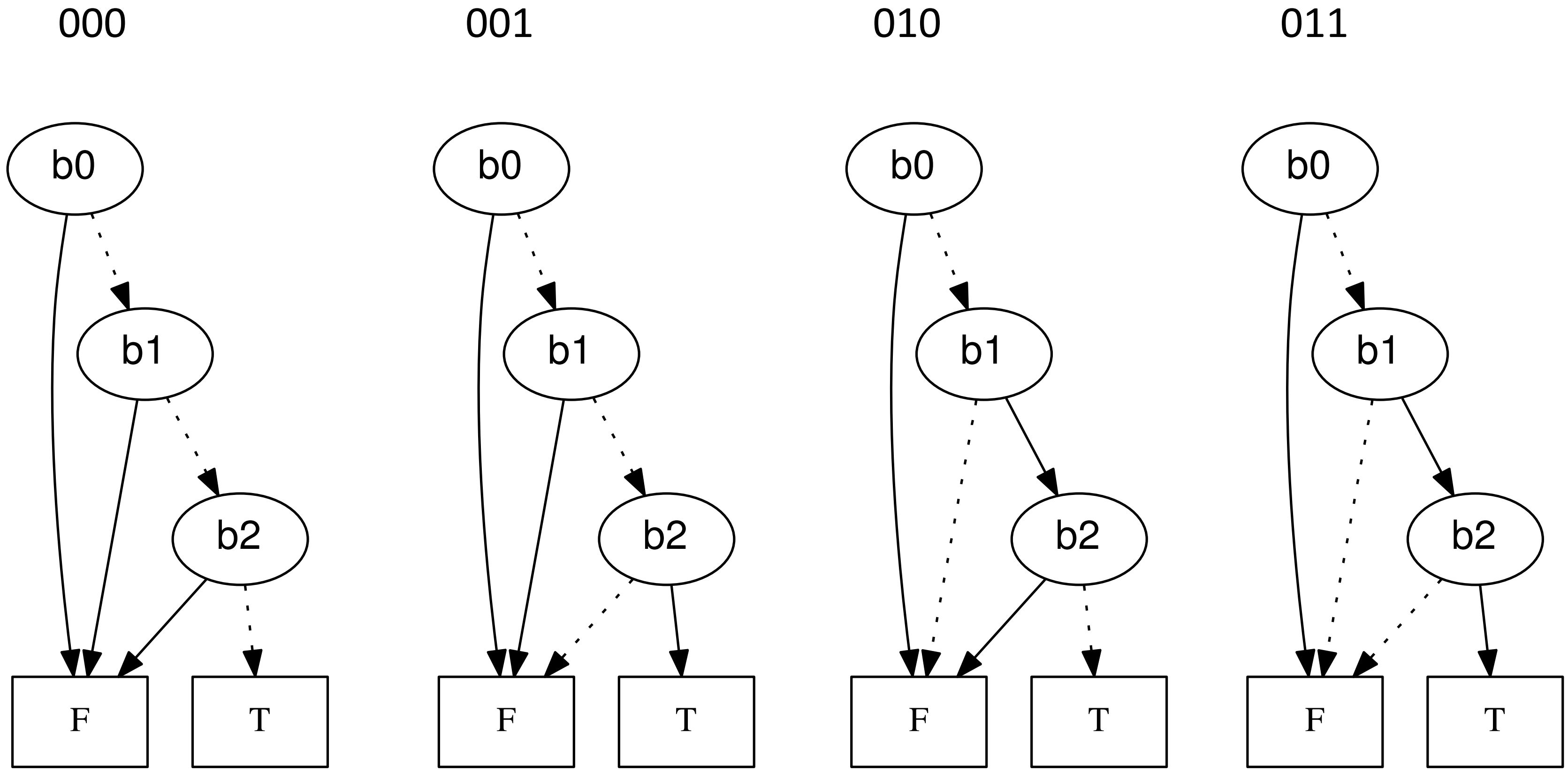
	$b_0b_1b_2$
"tel"	000
"dict"	001
"out"	010
"tel2"	011

{000, 001, 010}

$\lambda(b_0b_1b_2).$

$\in$ $\boxed{(!b_0 \wedge !b_1 \wedge !b_2) \vee (!b_0 \wedge !b_1 \wedge b_2) \vee (!b_0 \wedge b_1 \wedge !b_2)}$

We keep values in a *hash* to check reoccurrence



Value to bit string table

	$b_0b_1b_2$
"tel" →	000
"dict" →	001
"out" →	010
"tel2" →	011

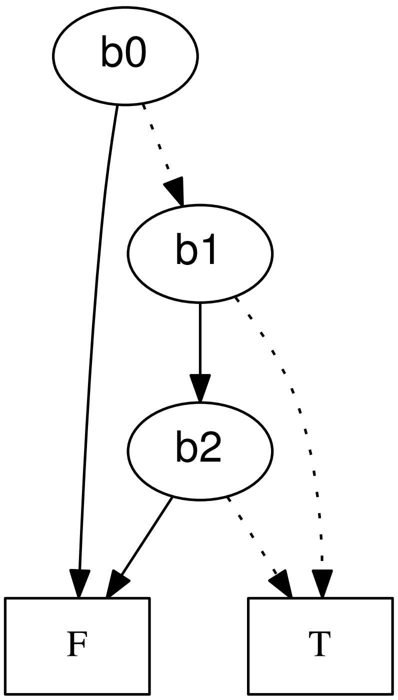
Characteristic function for our bit vector set representing the accumulated set of values **P** open(f)

{“tel”, “dict”,”out”}

{000, 001, 010}

{000} **union** {001} **union** {010}

BDD(000) **or** BDD(001) **or** BDD(010)



But **not** BDD(011) (for “tel2”)

numerations ≥ 100 are
for values not seen so far.

$\lambda(b_0 b_1 b_2)$.

$$\boxed{\begin{array}{l} (!b_0 \wedge !b_1 \wedge !b_2) \vee \\ (!b_0 \wedge !b_1 \wedge b_2) \vee \\ (!b_0 \wedge b_1 \wedge !b_2) \end{array}}$$

Characteristic function for our bit vector set

We account for values not seen so far.

As long as we use n bits and there will be less than 2^n values, then the higher enumerations represent values not seen so far.

In particular, the value 11…111 represents "all values not yet seen".

We can negate, obtaining the BDD for ¬**P** open(**f**)
This is easy: replace F by T at leaf level.

We can start with a rather large value of n, hoping that the BDD will be compact.

We may also add a bit "on the fly", when more than 2^n values occur.

Representing a set of assignments using enumerations

{
[x -> "a" , y -> 42] ,

[x -> "b" , y -> 52]
}

$x_0x_1x_2y_0y_1y_2$

0 0 0 0 0 0

or

0 0 1 0 0 1

forall x . **forall** y .
send(x,y) -> **P** recv(x,y)

recv("a",42)
recv("b",52)
...

x ➔ ("a" → 000 ; "b" → 001)

y ➔ (42 → 000 ; 52 → 001)

Representing a set of assignments

{
  [x -> “a” , y -> 42] ,

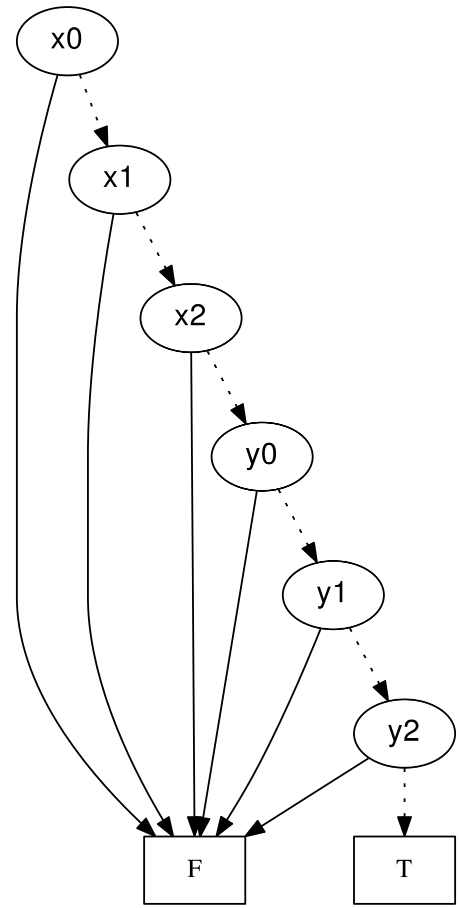
  [x -> “b” , y -> 52]
}

$x_0x_1x_2y_0y_1y_2$

0 0 0 0 0 0 →

or

0 0 1 0 0 1



x ➔ (“a” → 000 ; “b” → 001)

y ➔ (42 → 000 ; 52 → 001)

Representing a set of assignments

{
[x -> "a" , y -> 42] ,

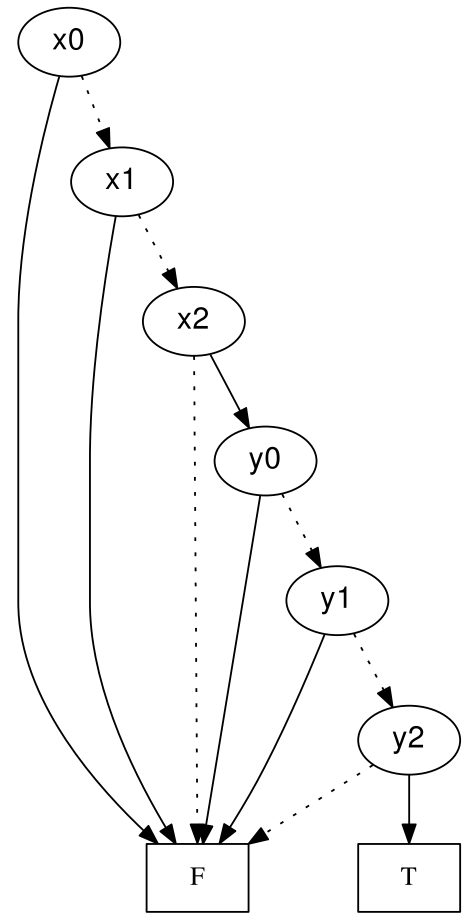
[x -> "b" , y -> 52]
}

$x_0x_1x_2y_0y_1y_2$

0 0 0 0 0 0

or

0 0 1 0 0 1 →



x → ["a" → 000, "b" → 001]

y → [42 → 000, 52 → 001]

Representing a set of assignments

{
[x -> "a" , y -> 42] ,

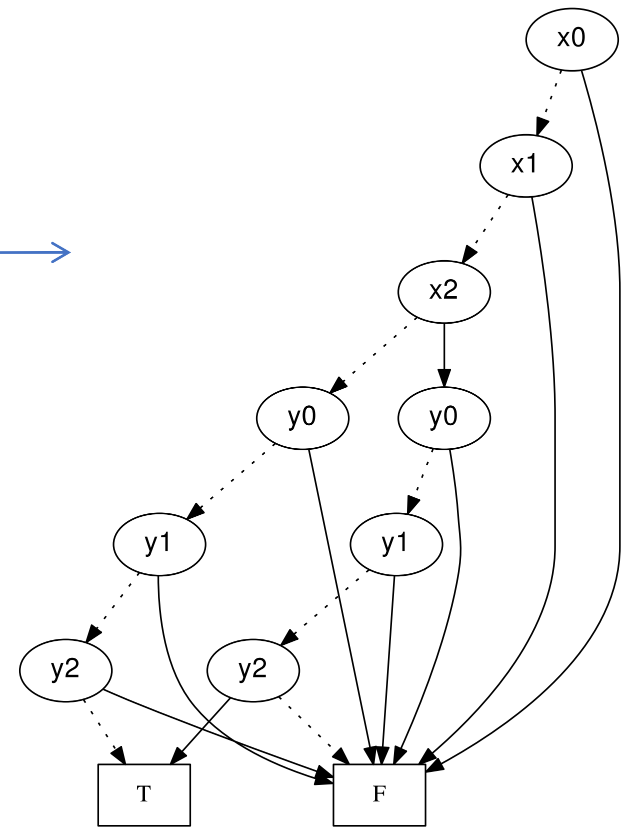
[x -> "b" , y -> 52]
}

$x_0x_1x_2y_0y_1y_2$

0 0 0 0 0 0

or

0 0 1 0 0 1



x ➔ ["a" → 000, "b" → 001]

y ➔ [42 → 000, 52 → 001]

Looking back at the set semantics: since every assignment is a BDD

- $I[\varphi, \sigma, 0] = \emptyset$.
- $I[true, \sigma, i] = \{\varepsilon\}$.
- $I[p(a), \sigma, i] = \text{ if } p(a) \in \sigma[i] \text{ then } \{\varepsilon\} \text{ else } \emptyset$.
- $I[p(v), \sigma, i] = \{[v \mapsto a] | p(a) \in \sigma[i]\}$.
- $I[(\varphi \wedge \psi), \sigma, i] = I[\varphi, \sigma, i] \bigcap I[\psi, \sigma, i]$.
- $I[\neg\varphi, \sigma, i] = A_{vars(\varphi)} \setminus I[\varphi, \sigma, i]$.
- $I[(\varphi \, \mathcal{S} \, \psi), \sigma, i] = I[\psi, \sigma, i] \bigcup (I[\varphi, \sigma, i] \bigcap I[(\varphi \mathcal{S} \psi), \sigma, i-1])$.
- $I[\ominus\varphi, \sigma, i] = I[\varphi, \sigma, i-1]$.
- $I[\exists x \, \varphi, \sigma, i] = hide(I[\varphi, \sigma, i], \{x\})$.

We can replace the set operations with BDD operations:
Union $\cup$ by disjunction $\vee$, Intersection $\cap$ by conjunction $\wedge$, hide is existential quantification over all bits of variable.

Algorithm

var pre : SubFormula –m-> BDD
var now : SubFormula –m-> BDD

1) Initially, for each subformula φ, $\mathsf{now}(\varphi) = \mathrm{BDD}(0)$.
2) Observe a new state (as set of ground predicates) s as input.
3) Let $\mathsf{pre} := \mathsf{now}$.
4) Make the following updates for each subformula. If φ is a subformula of ψ then $\mathsf{now}(\varphi)$ is updated before $\mathsf{now}(\psi)$.
   - $\mathsf{now}(\mathit{true}) = \mathrm{BDD}(1)$
   - $\mathsf{now}(p(a)) = \text{if } p(a) \in s \text{ then } \mathrm{BDD}(1) \text{ else } \mathrm{BDD}(0)$
   - $\mathsf{now}(p(x)) = \text{if } \exists a\, p(a) \in s \text{ then } \mathbf{build}(x, a) \text{ else } \mathrm{BDD}(0)$
   - $\mathsf{now}((\varphi \wedge \psi)) = \mathbf{and}(\mathsf{now}(\varphi), \mathsf{now}(\psi))$
   - $\mathsf{now}(\neg\varphi) = \mathbf{not}(\mathsf{now}(\varphi))$
   - $\mathsf{now}((\varphi \mathcal{S} \psi)) = \mathbf{or}(\mathsf{now}(\psi), \mathbf{and}(\mathsf{now}(\varphi), \mathsf{pre}((\varphi \mathcal{S} \psi))))$
   - $\mathsf{now}(\ominus \varphi) = \mathsf{pre}(\varphi)$
   - $\mathsf{now}(\exists x\, \varphi) = \mathbf{exists}(\langle x_0, \ldots, x_{k-1} \rangle, \mathsf{now}(\varphi))$
5) Goto step 2.

$$(\varphi \mathcal{S} \psi) = (\psi \vee (\varphi \wedge \ominus \varphi \mathcal{S} \psi))$$

Limiting quantification

- Limiting quantification to seen values:

$$\exists x \, \neg P \, g(x)$$

$$\exists x \, (seen(x) \wedge \neg P \, g(x))$$

- Finite domains:

$$smaller(y, 3) = \neg(y_0 \wedge y_1)$$

$$\exists x \, (smaller(x, m) \wedge \varphi)$$

$$\forall x \, (smaller(x, m) \rightarrow \varphi)$$

Implementation: DejaVu

http://javabdd.sourceforge.net

SOURCEFORGE.NET®

JavaBDD

Last published: October 29, 2007 4:33:11 AM PST |Doc for 2.0 — SourceForge.net Project Page | Hosted by SourceForge

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- What is it?

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- Build Instructions
- Installing
- Performance
- Links

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- JavaBDD for Linux
- JavaBDD for Mac OS X
- JavaBDD Source code

Project Documentation
- **About**
- Project Info
- Project Reports
- Development Process

Legend
- External Link
- Opens in a new window

built by maven

JavaBDD

JavaBDD is a Java library for manipulating BDDs (Binary Decision Diagrams). Binary decision diagrams are widely used in model checking, formal verification, optimizing circuit diagrams, etc. For an excellent overview of the BDD data structure, see this set of lecture notes by Henrik Reif Andersen.

The JavaBDD API is based on that of the popular BuDDy package, a BDD package written in C by J?rn Lind-Nielsen. However, JavaBDD's API is designed to be object-oriented. The ugly C function interface and reference counting schemes have been hidden underneath a uniform, object-oriented interface.

JavaBDD includes a 100% Java implementation. It can also interface with the JDD library, or with three popular BDD libraries written in C via a JNI interface: BuDDy, CUDD, and CAL. JavaBDD provides a uniform interface to all of these libraries, so you can easily switch between them without having to make changes to your application.

JavaBDD is designed for high performance applications, so it also exposes many of the lower level options of the BDD library, like cache sizes and advanced variable reordering.

Architecture

Scala

```
prop secure :
  forall (user) forall (file)
    access(user,file) ->
     [login(user),logout(user))
        &
     [open(file),close(file))
```

Scala parser combinators

JavaBDD

```
class Formula_secure extends Formula {
  val var_user :: var_file :: Nil = declareVariables("user", "file")

  override def evaluate(): Boolean = {
    now(10) = build("close")(V("file"))
    now(9) = build("open")(V("file"))
    now(8) = now(9).or(now(10).not().and(pre(8)))
    now(7) = build("logout")(V("user"))
    now(6) = build("login")(V("user"))
    now(5) = now(6).or(now(7).not().and(pre(5)))
    now(4) = now(5).and(now(8))
    now(3) = build("access")(V("user"),V("file"))
    now(2) = now(3).not().or(now(4))
    now(1) = now(2).forAll(var_file)
    now(0) = now(1).forAll(var_user)

    tmp = now
    now = pre
    pre = tmp
    !tmp(0).isZero
  }

  pre = Array.fill(11)(False)
  now = Array.fill(11)(False)
}
```

```
login,John
open,tel
access,John,tel
close,tel
access,John,tel
logout,John
```

Apache commons CSV (Comma Separated Value format) parser

```
*** Property secure violated on event number 5:
    access(John,tel)
```

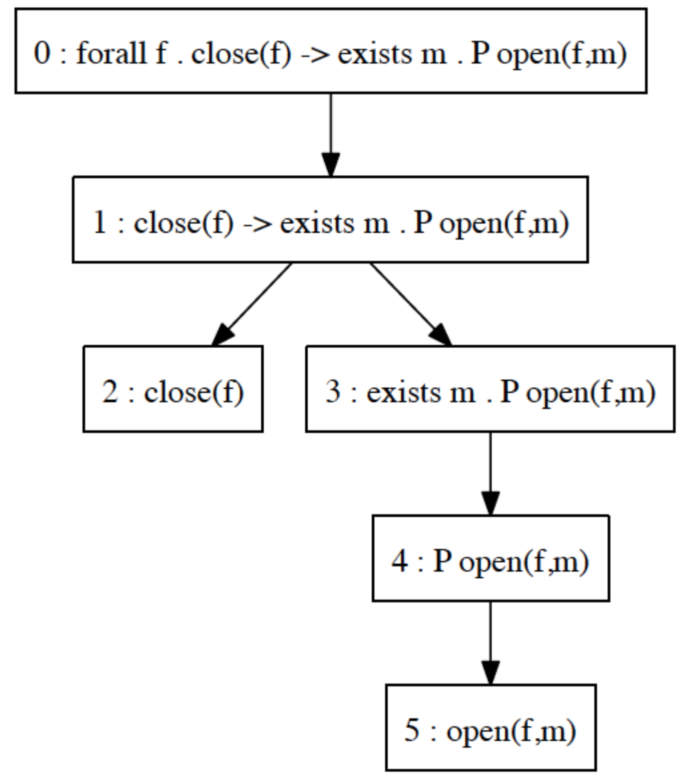
```
dejavu <specFile> <logFile> [<bitsPerVariable>]
```

Grammar:

```
<spec> ::= <prop> ... <prop>
<prop> ::= 'prop' <id> ':' <form>
<form> ::= 'true' | 'false'
  | <id> [ '(' <param> ',' ... ',' <param> `)' ]
  | <form> <binop> <form>
  | '[' <form> ',' <form> ')'
  | <unop>  <form>
  | ('exists' | 'forall') <id> '.' <form>
  | '(' <form> ')'
<binop> ::= '->' | '|' | '&' | 'S'
<unop>  ::= '!' |  '@' | 'P' | 'H'
<param> ::= <id> | <string> | <integer>
```

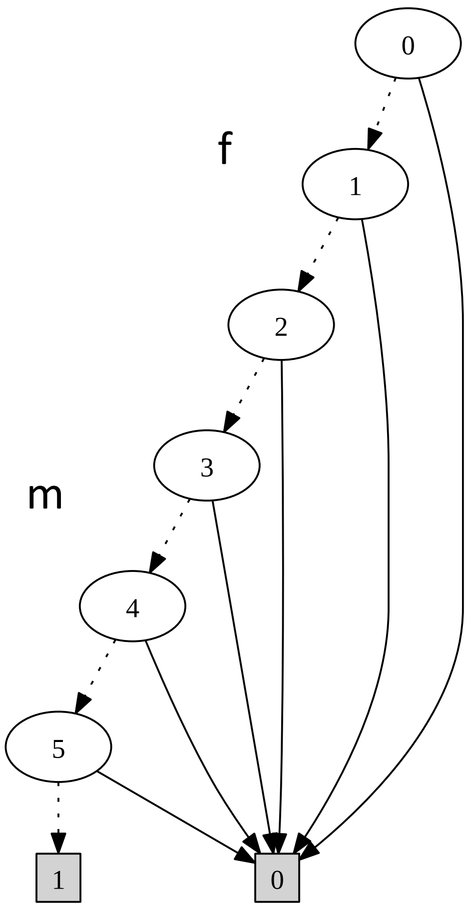
prop p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)

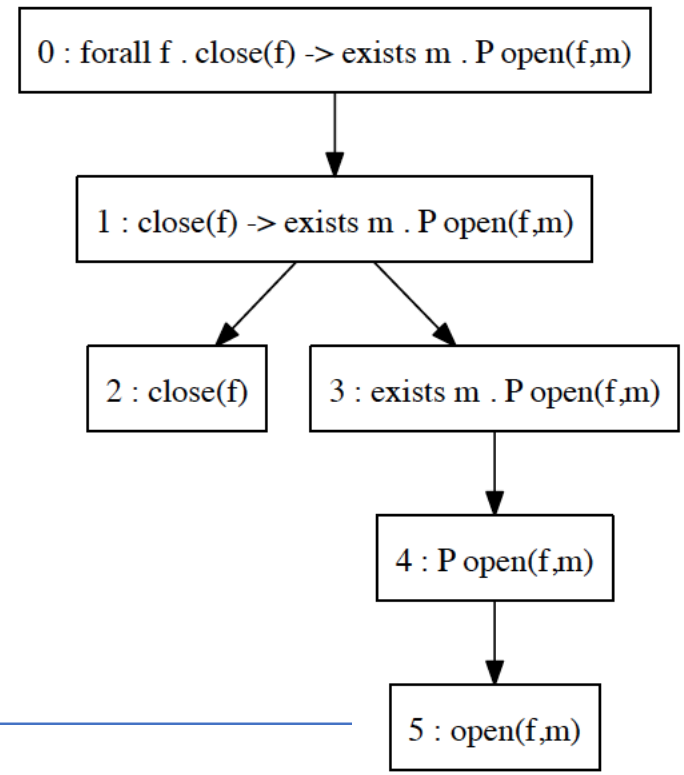
```
class Formula_p extends Formula {
  var pre: Array[BDD] = Array.fill(6)(False)
  var now: Array[BDD] = Array.fill(6)(False)
  var tmp: Array[BDD] = null
  val var_f :: var_m :: Nil =
    declareVariables("f", "m")

  override def evaluate(): Boolean = {
    now(5) = build("open")(V("f"),V("m"))
    now(4) = now(5).or(pre(4))
    now(3) = now(4).exist(var_m)
    now(2) = build("close")(V("f"))
    now(1) = now(2).not().or(now(3))
    now(0) = now(1).forAll(var_f)
    tmp = now; now = pre; pre = tmp
    !tmp(0).isZero
  }
}
```



```
open,input,read
open,output,write
close,out
```

$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)





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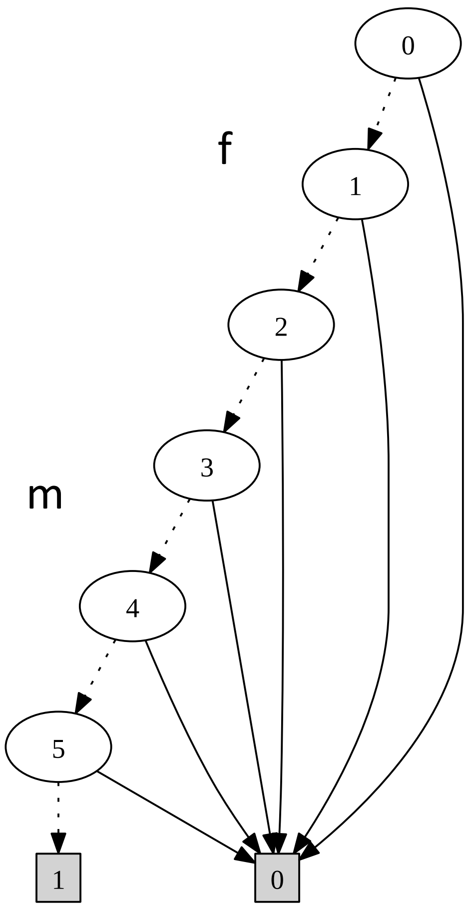

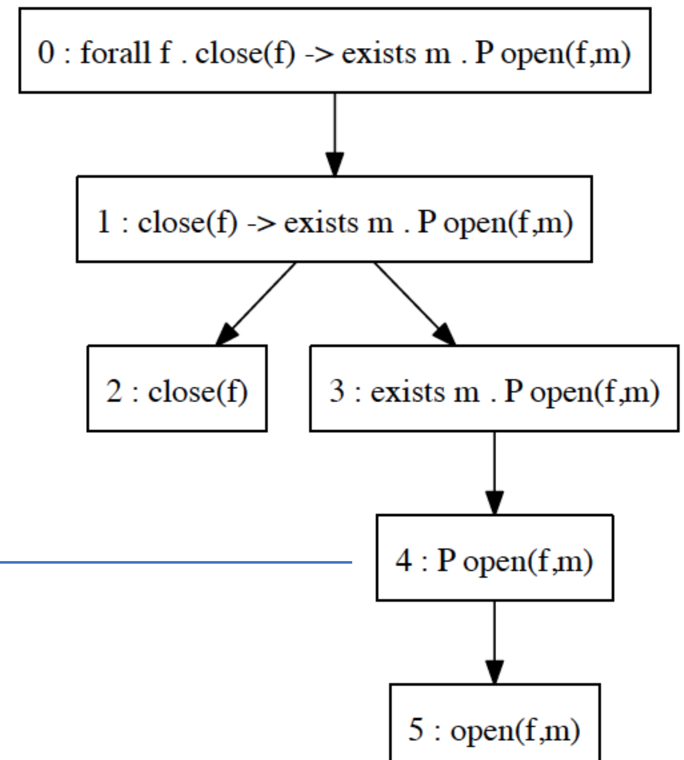

```
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```

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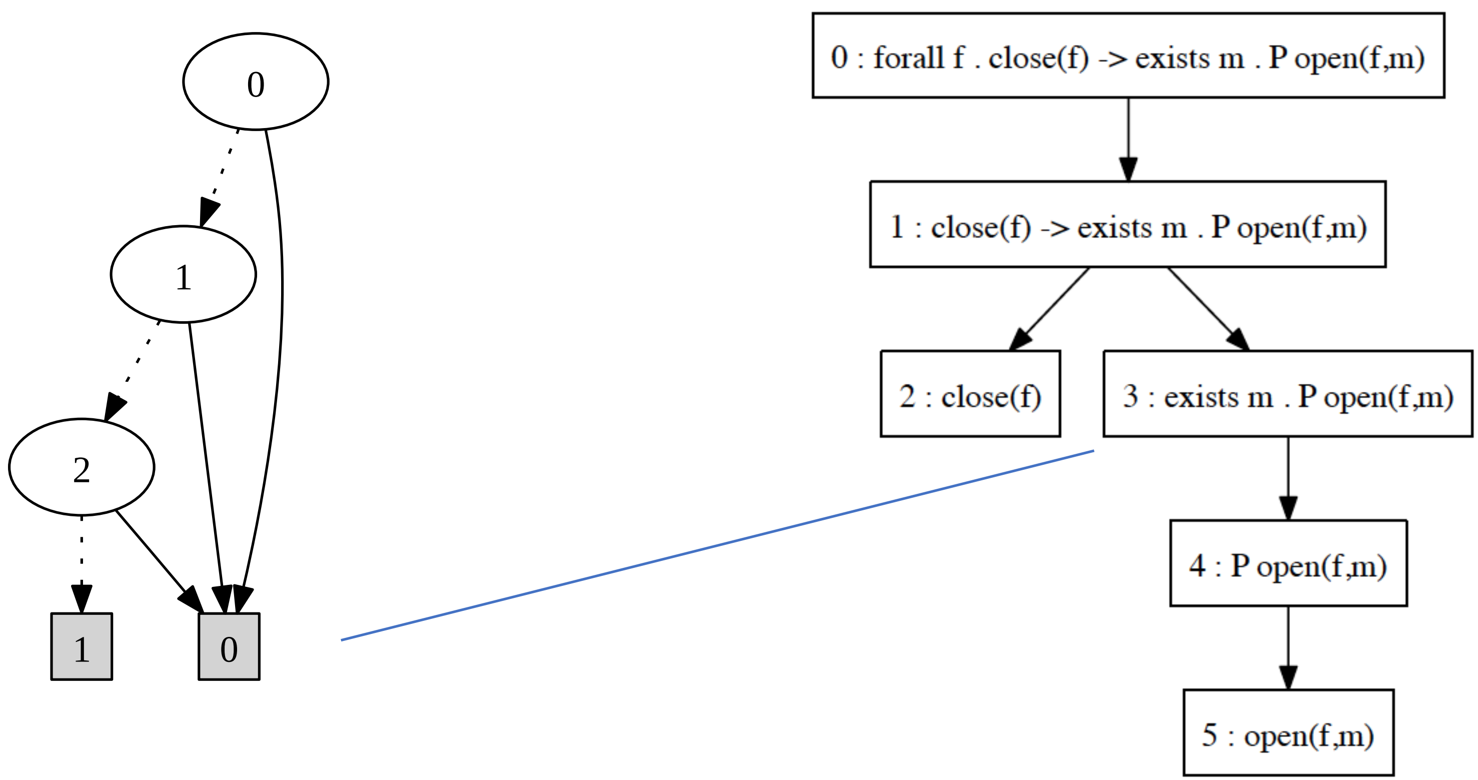

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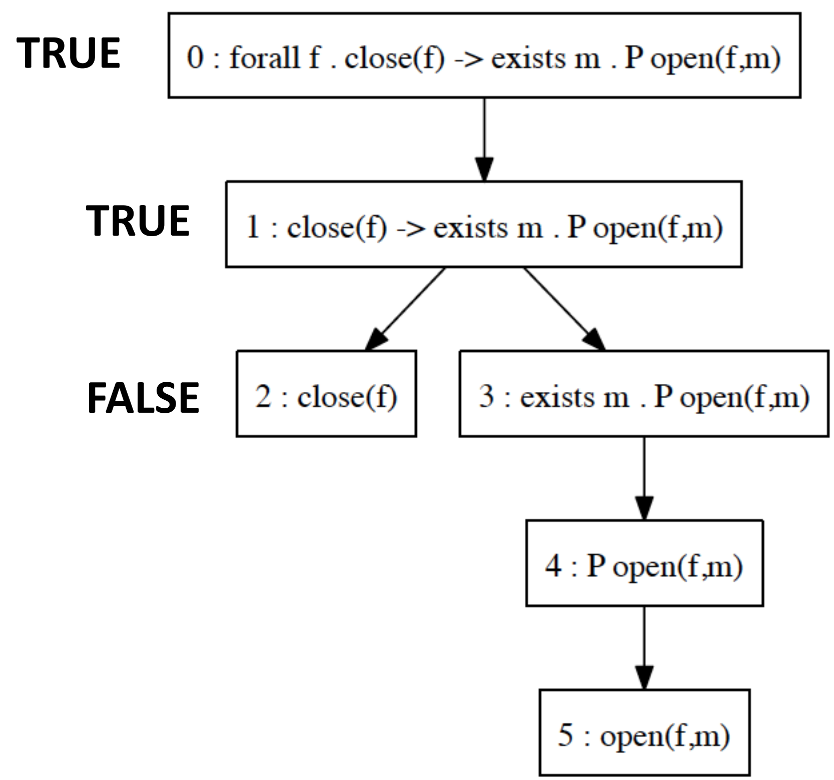

```
open,input,read
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close,out
```

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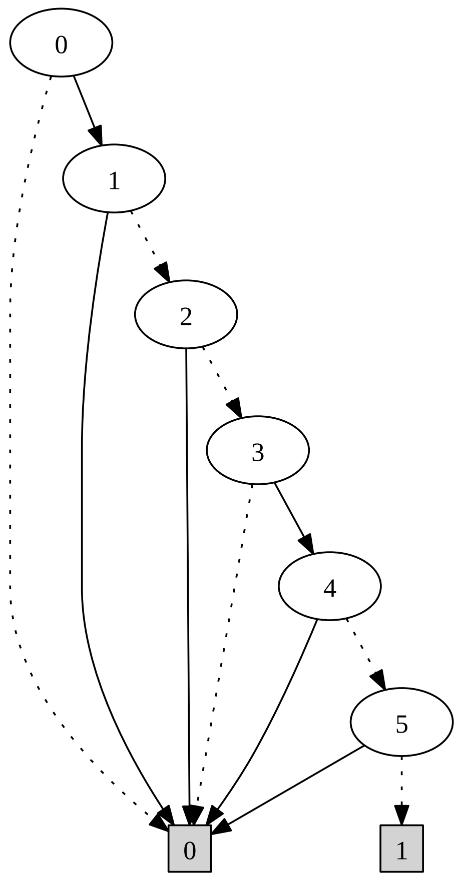

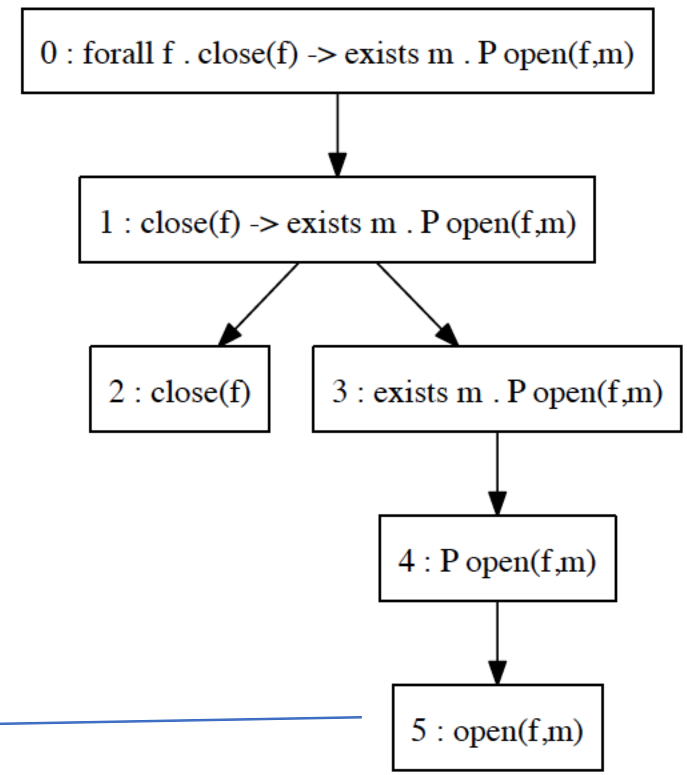

```
open,input,read
open,output,write
close,out
```

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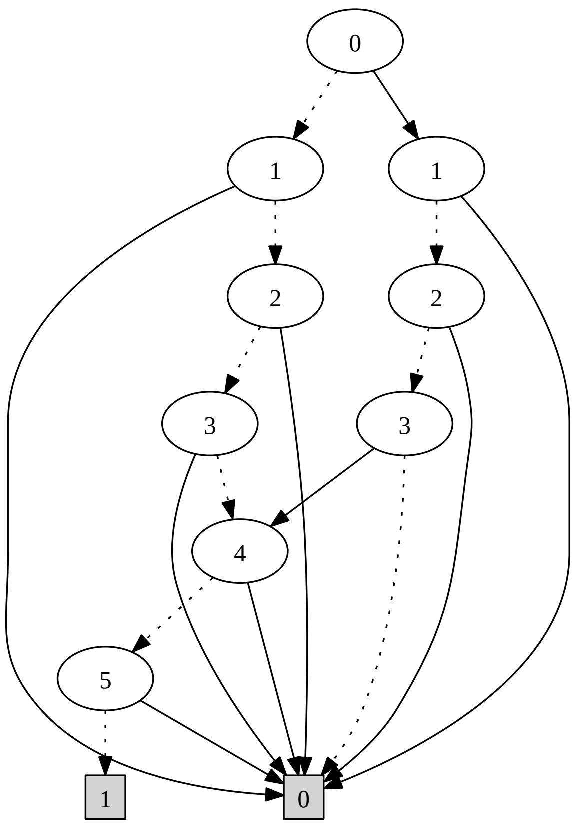
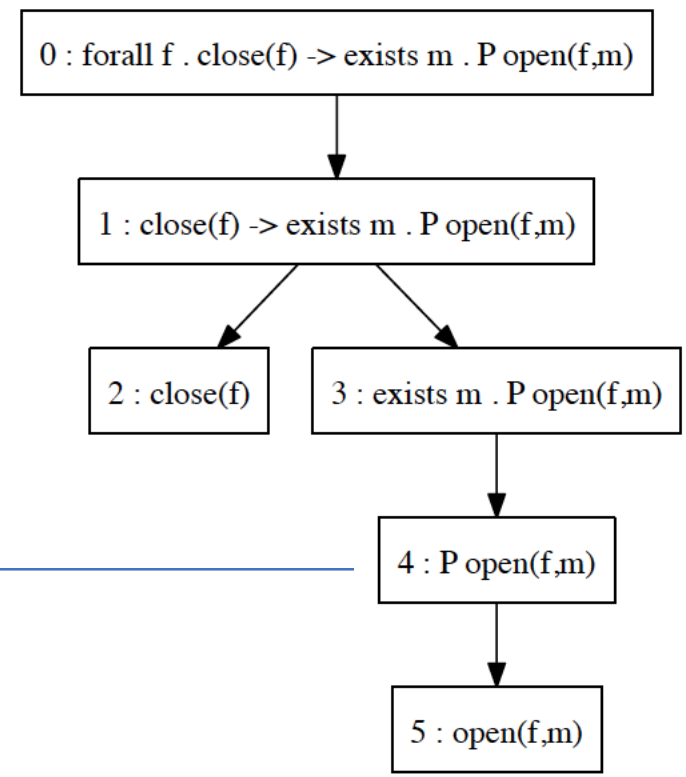
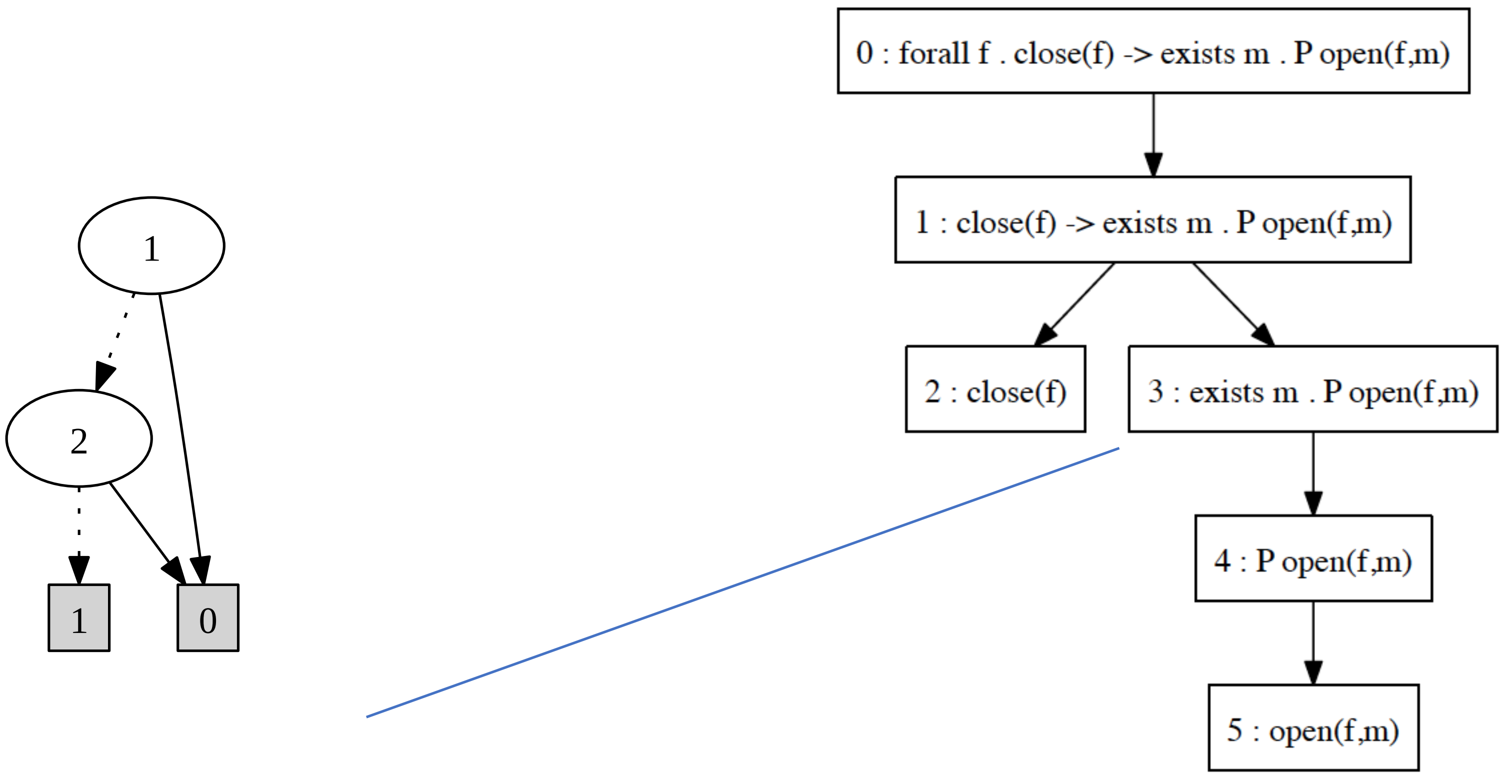




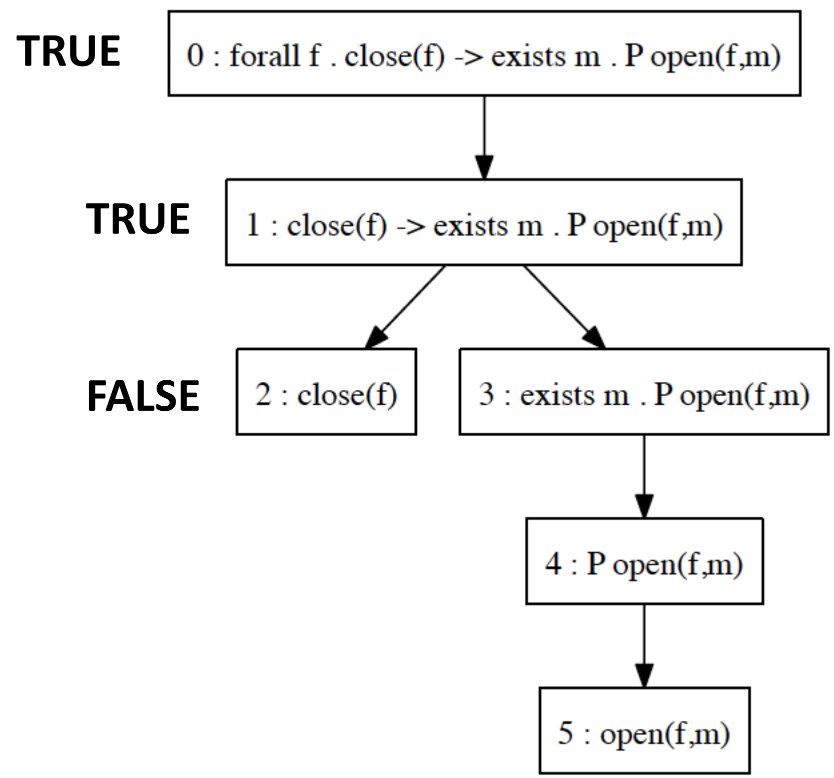
```
open,input,read
open,output,write
close,out
```

$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)



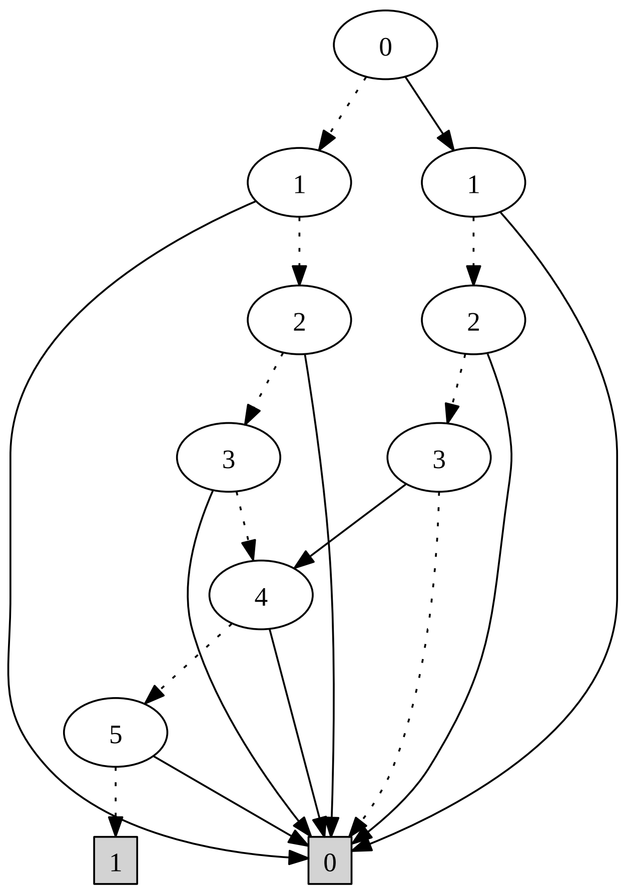
```
open,input,read
open,output,write
close,out
```

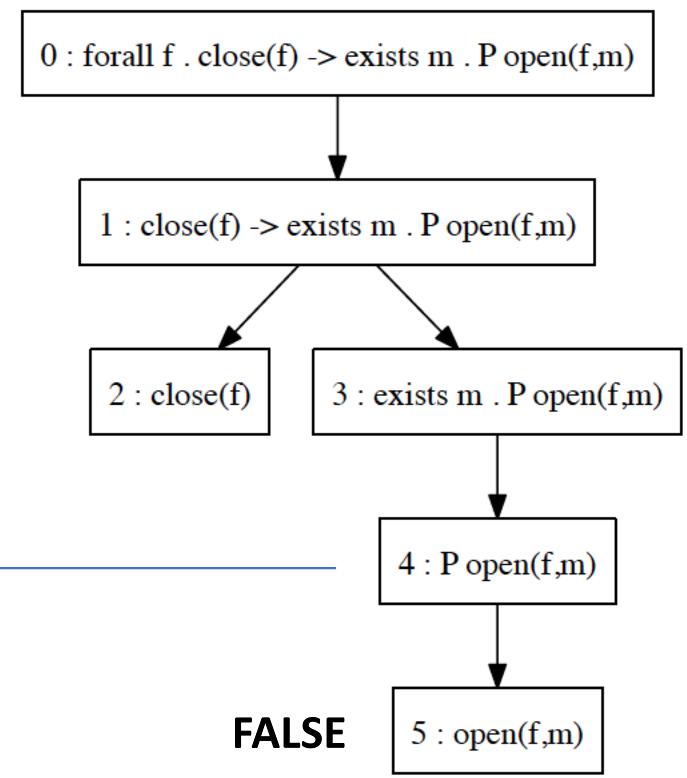
$$\models \textbf{prop}\ p\text{: } \textbf{forall}\ f\ .\ close(f) \rightarrow \textbf{exists}\ m\ .\ \textbf{P}\ open(f,m)$$



```
open,input,read
open,output,write
close,out
```

$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)

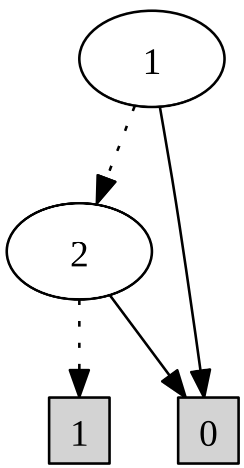


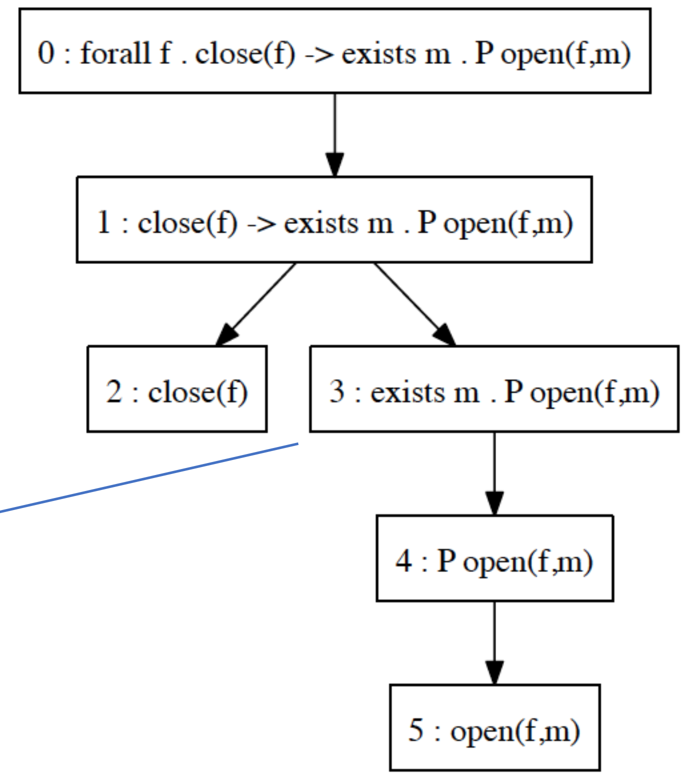


FALSE

```
open,input,read
open,output,write
close,out
```

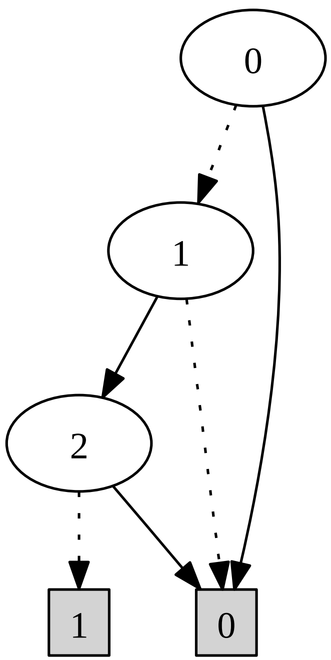
$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)

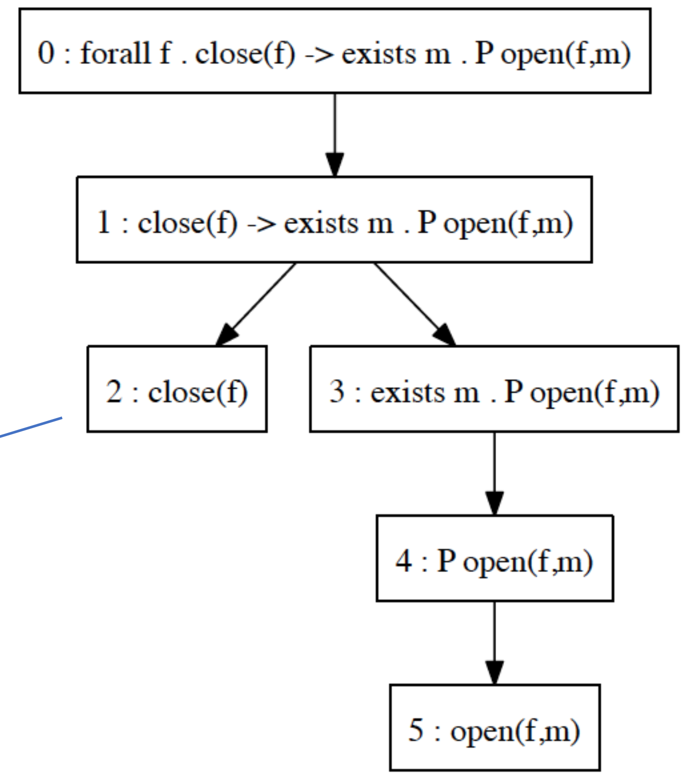




```
open,input,read
open,output,write
close,out
```

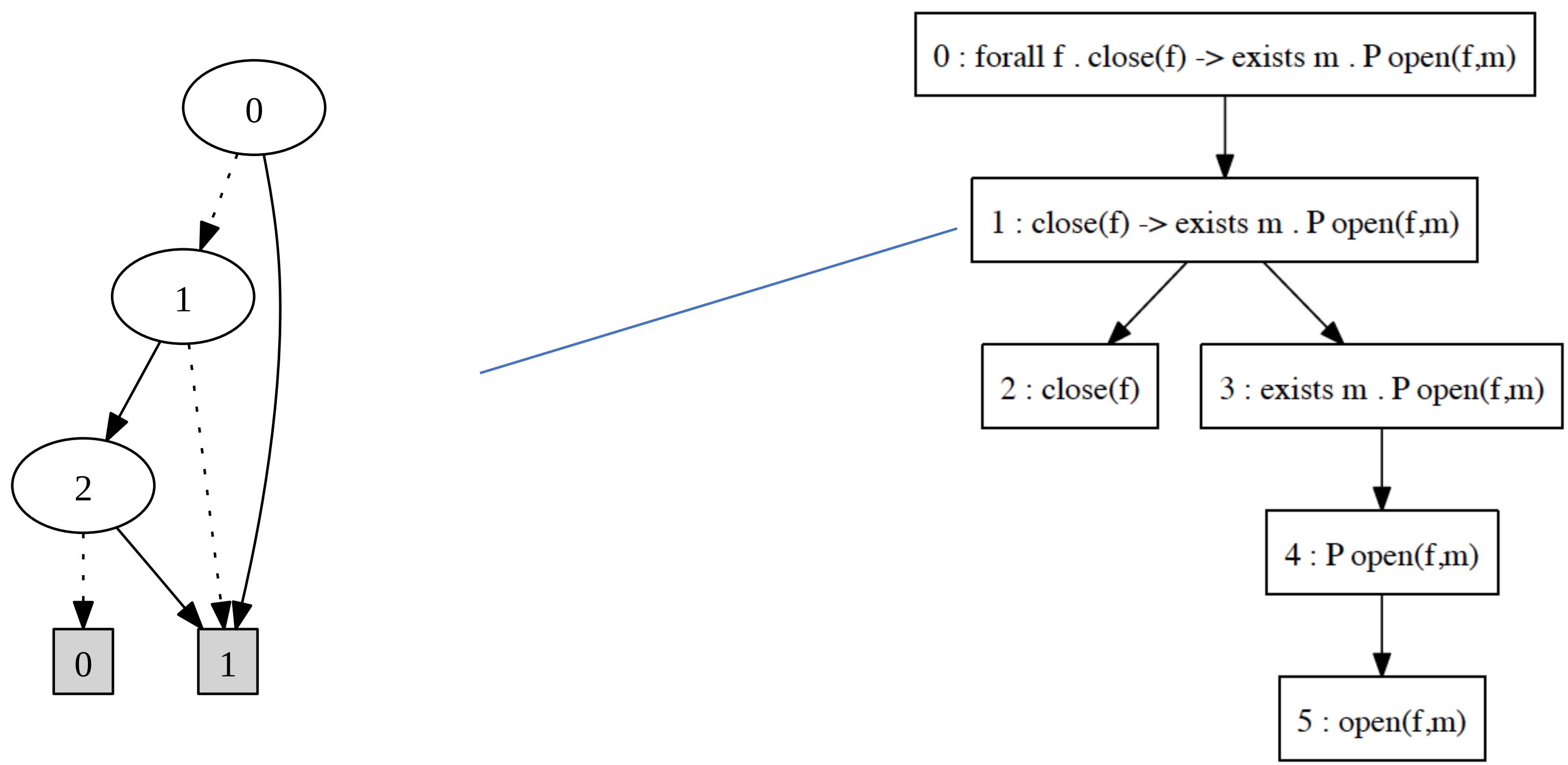
$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)





```
open,input,read
open,output,write
close,out
```

$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)



```
open,input,read
open,output,write
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```
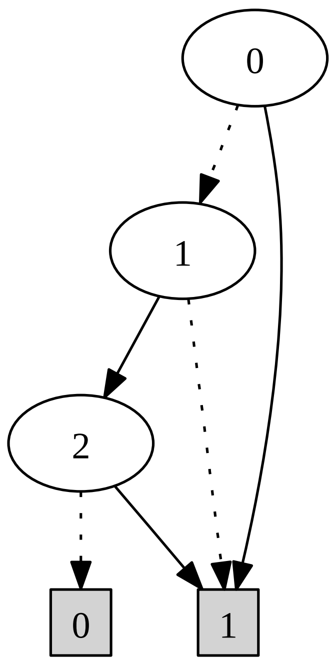
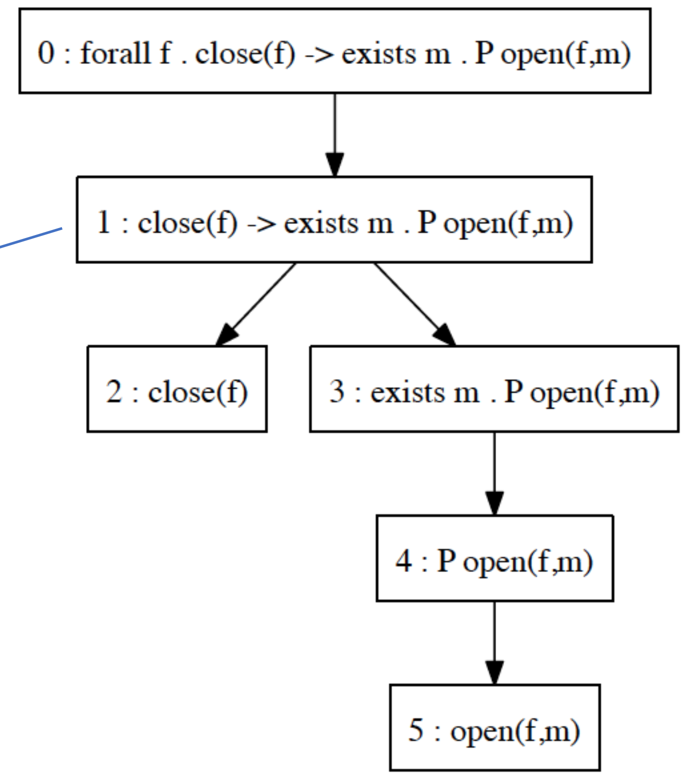

$\models$ **prop** p: **forall** f . close(f) $\rightarrow$ **exists** m . **P** open(f,m)



FALSE



Evaluation Properties in QTL

prop access : **forall** u . **forall** f .
  access(u,f) → [login(u),logout(u)) & [open(f),close(f))

prop file : **forall** f .
  close(f) → **exists** m . @ [open(f,m),close(f))

prop fifo : **forall** x .
  (enter(x) → ! @ **P** enter(x)) &
  (exit(x) → ! @ **P** exit(x)) &
  (exit(x) → @ **P** enter(x)) &
  (**forall** y . (exit(y) & **P** (enter(y) & @ **P** enter(x))) → @ **P** exit(x))

Evaluation Properties in MonPoly

```
/* access */ FORALL u. (FORALL f.
  ( access(u,f) IMPLIES
    ((( NOT logout(u)) SINCE login(u)) AND (NOT close(f) SINCE[0,*] open(f)))))

/* file */ FORALL f .
  (close(f) IMPLIES (EXISTS m . PREVIOUS ( NOT close(f) SINCE[0,*] open(f,m) )))

/* fifo */ FORALL x. (
 (enter(x) IMPLIES NOT PREVIOUS ONCE[0,*] enter(x)) AND
 ( exit (x) IMPLIES NOT PREVIOUS ONCE[0,*] exit(x)) AND
 ( exit (x) IMPLIES PREVIOUS ONCE[0,*] enter(x)) AND
 FORALL y.
   (( exit (y) AND ONCE[0,*] (enter(y) AND PREVIOUS ONCE[0,*] enter(x)))
     IMPLIES PREVIOUS ONCE exit(x)))
```

Evaluation Results

Table 1: Evaluation of QTL and MONPOLY

Property	Trace length	MONPOLY (sec)	QTL (sec) bits per var.: 20 (40, 60)
ACCESS	11,006	**1.9**	**3.1** (3.3, 3.2)
	110,006	**241.9**	**6.1** (9.1, 10.9)
	1,100,006	**58,455.8**	**36.8** (61.9, 88.8)
FILE	11,004	**61.1**	**2.8** (2.8, 3.0)
	110,004	**7,348.7**	**6.3** (6.5, 8.6)
	1,100,004	**DNF**	**30.3** (43.9, 59.5)
FIFO	5,051	**158.3**	**195.4** (OOM, ?)
	10,101	**1140.0**	**ERR** (?, ?)

Pros

- Compact.
  - With k bits we can represent 2^k values
  - V values can be represented by $\log_2(V)$ bits
- We expect to pay little for “surplus” bits.
- We can extend the BDDs with additional bits dynamically if needed.
- Complementation is efficient (just switching the 0 and 1 leaves).
- Values not yet seen are represented by unused bit patterns (avoid using all bit patterns).

Cons

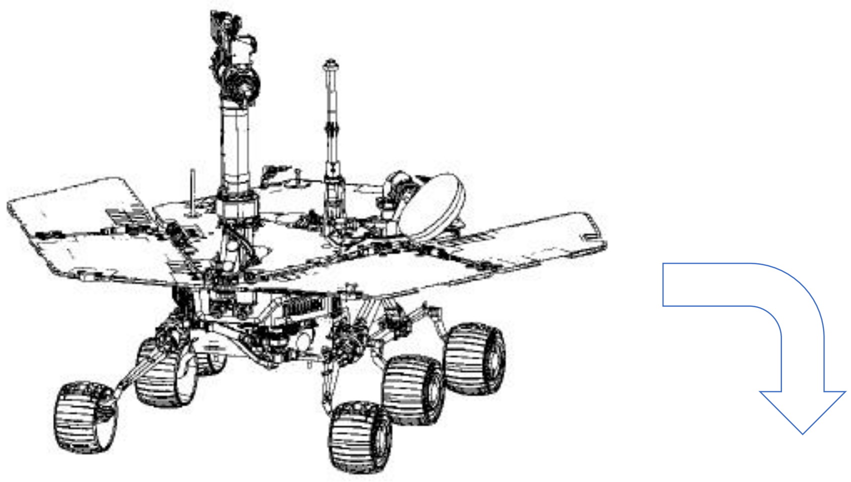
- We cannot compare variables beyond equality
- We cannot perform computations on values

Prop allAnswersOk :
forall t_2 . **forall** a .
answer(t_2,a) ->
exists t_1 . **exists** q .
P question(t_1, q) $\wedge$
$t_1 < t_2$ $\wedge$ rightAnswer(q) = a

TraceContract

An internal Scala DSL for monitoring

generation of logs



```
COMMAND("STOP_CAMERA",1,22:50.00)
COMMAND("ORIENT_ANTENNA_TOWARDS_GROUND",2,22:50.10)
SUCCESS("ORIENT_ANTENNA_TOWARDS_GROUND",3,22:52.02)
COMMAND("STOP_CAMERA",4,22:55.01)
SUCCESS("ORIENT_ANTENNA_TOWARDS_GROUND",5,22:56.19)
COMMAND("STOP_ALL",6,23:01.10)
FAIL("ORIENT_ANTENNA_TOWARDS_GROUND",7,23:02.02)
```

requirements relating events across time

CommandMustSucceed:

"An issued command must succeed, without a failure to occur before then".

```
monitor CommandMustSucceed {
  always {
    Command(n,x) => RequireSuccess(n,x)
  }

  hot RequireSuccess(name,number) {
    Fail(name,number) => error
    Success(name,number) => ok
  }
}
```

user reaction

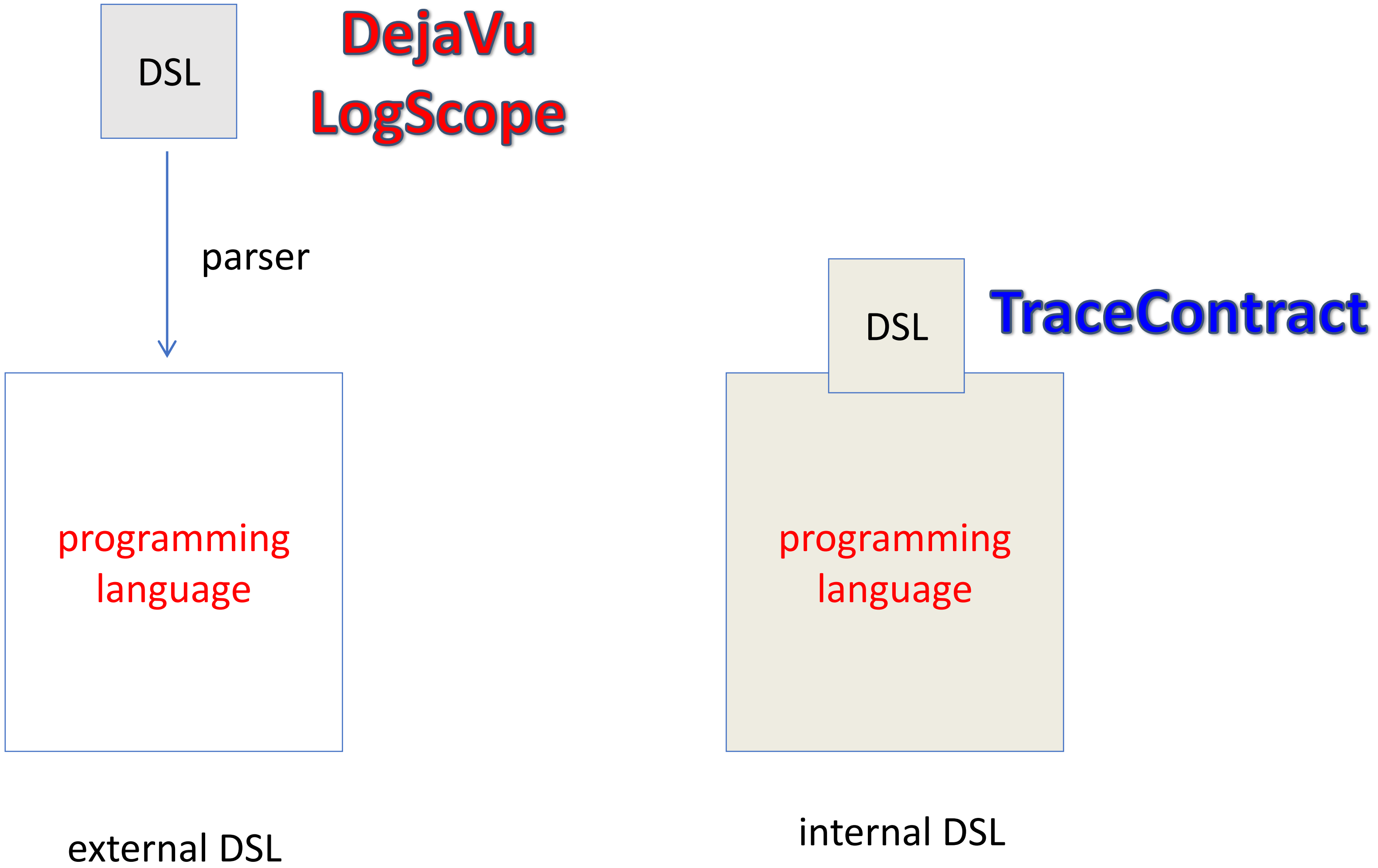
excellent

- I read the manual and was up an running, all before lunch
- my first spec had no errors and just worked

but (2 days later)

- can I define a function and call it in a formula?
- is it possible to re-use formulas?

external versus internal DSL



pros and cons for internal DSL

pros

- decreases development effort
- increases expressiveness
- allows use of existing IDE, debuggers, etc.

cons

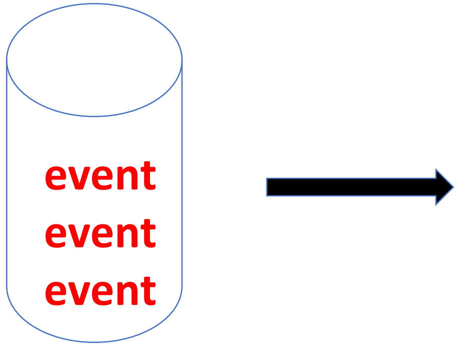
- steep learning curve for non-Scala programmers
- limited analyzability (for shallow internal DSLs)

Modeling in Scala: a high-level unifying language

- Object-oriented + functional programming features
- Strongly typed with type inference
- Script-like, semicolon inference
- Sets, list, maps, iterators, comprehensions
- Lots of libraries
- Compiles to JVM
- A "better Java"

events

```
abstract class Event

case class  Command(name: String, nr: Int)  extends  Event
case class  Success    (name: String, nr: Int)  extends  Event
case class  Fail           (name: String, nr: Int)  extends  Event
```




```
val trace : List[Event] =
    List(
        Command("STOP_DRIVING", 1),
        Command("TAKE_PICTURE", 2),
        Success("TAKE_PICTURE", 2),
        Success("TAKE_PICTURE", 2)
    )
```

```
monitor CommandMustSucceed {
  always {
    Command(n,x) => RequireSuccess(n,x)
  }

  hot RequireSuccess(name,number) {
    Fail(name,number) => error
    Success(name,number) => ok
  }
}
```

LogScope


```
class CommandMustSucceed extends Monitor[Event] {
  require {
    case Command(n,x) => RequireSuccess(n,x)
  }

  def RequireSuccess(name: String, number: Int) =
    hot {
      case Fail(`name`, `number`) => error
      case Success(`name`, `number`) => ok
    }
}
```

TraceContract

```
monitor CommandMustSucceed {
  always {
    Command(n,x) => RequireSuccess(n,x)
  }

  hot RequireSuccess(name,number) {
    Fail(name,number) => error
    Success(name,number) => ok
  }
}
```

LogScope

INLINING A STATE


```
class CommandMustSucceed extends Monitor[Event] {
  require {
    case Command(n, x) =>
      hot {
        case Fail(`n`, `x`) => error
        case Success(`n`, `x`) => ok
      }
  }
}
```

TraceContract

LogScope

```
monitor CommandMustSucceed {
  always {
    Command(n,x) => RequireSuccess(n,x)
  }

  hot RequireSuccess(name,number) {
    Fail(name,number) => error
    Success(name,number) => ok
  }
}
```

USING SOME LINEAR TEMPORAL LOGIC

pattern LTL formula

```
class CommandMustSucceed extends Monitor[Event] {
  require {
    case Command(n, x) =>
      not(Fail(n, x)) until (Success(n, x))
  }
}
```

TraceContract

```
monitor CommandMustSucceed {
  always {
    Command(n,x) => RequireSuccess(n,x)
  }

  hot RequireSuccess(name,number) {
    Fail(name,number) => error
    Success(name,number) => ok
  }
}
```

LogScope

USING ALL LINEAR TEMPORAL LOGIC

LTL formula LTL formula


```
class ACommandMustSucceed extends Monitor[Event] {
  property {
    globally(
      Command("A",42) implies
        not(Fail("A", 42)) until (Success("A", 42))
    )
  }
}
```

TraceContract

```
monitor CommandMustSucceed {
  always {
    Comm[illegible] x) => Requi[illegible]ess(n,x)
  }

  hot Requir[illegible]mber) {
    Fail([illegible]ber) [illegible]
    Succes[illegible]ame,number) =>[illegible]
  }
}
```

LogScope

first 10 commands must succeed


```
class CommandMustSucceed extends Monitor[Event] {
  var count = 0
  require {
    case Command(n, x) if count < 10 =>
      count += 1
      not(Fail(n, x)) until (Success(n, x))
  }
}
```

TraceContract

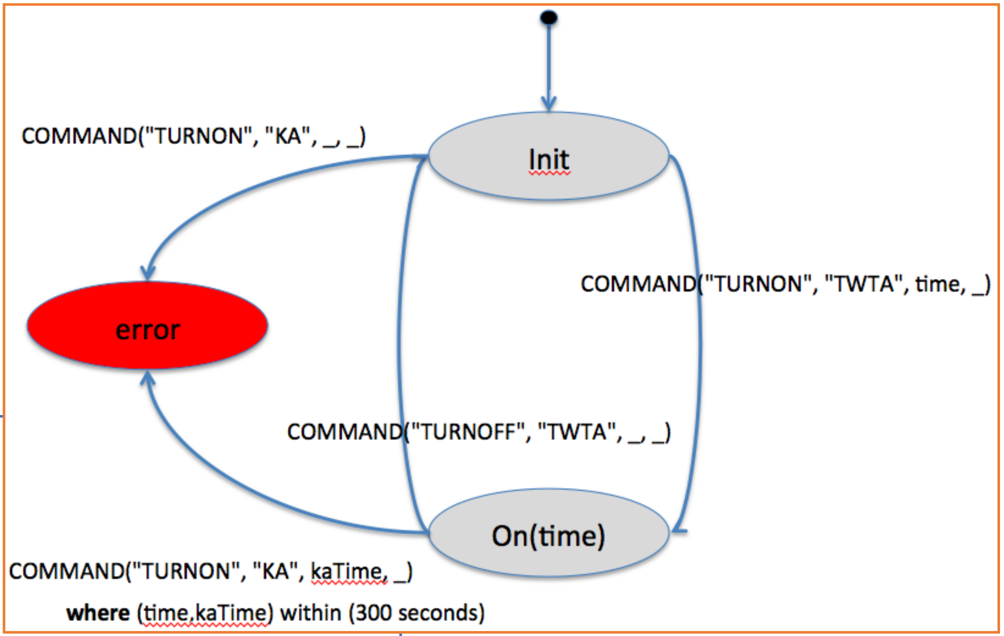
the state function

CommandMustSucceed:

"An issued command can succeed at most once".

```
class MaxOneSuccess extends Monitor[Event]
{
 require {
  case Success(_, number) =>
   state {
    case Success(_, `number`) => error
   }
 }
}
```

state machines




```
class TWTA_Ka extends Monitor[Event] {
 property { Init }

 def Init: Formula =
  state {
   case Command("TURNON", "TWTA", time, _) => On(time)
   case Command("TURNON", "KA", _, _) => error
  }

 def On(time: Int): Formula =
  state {
   case Command("TURNOFF", "TWTA", _, _) => Init
   case Command("TURNON", "KA", kaTime, _)
        if (time,kaTime) within (300 seconds) => error
  }
}
```

TraceContract

rule-based system
for expressing past time logic

Success Has a Reason:

"A command success must be caused by an issued command".

```
class SuccessHasAReason extends Monitor[Event] {
  case class Commanded(name: String, nr: Int) extends Fact

  require {
    case Command(n,x) => Commanded(n,x)  +
    case Success(n,x)     => Commanded(n,x)  ?-
  }
}
```

analyzing a trace

```
class Requirements extends Monitor[Event] {
  monitor(
    new CommandMustSucceed,
    new MaxOneSuccess
  )
}
```

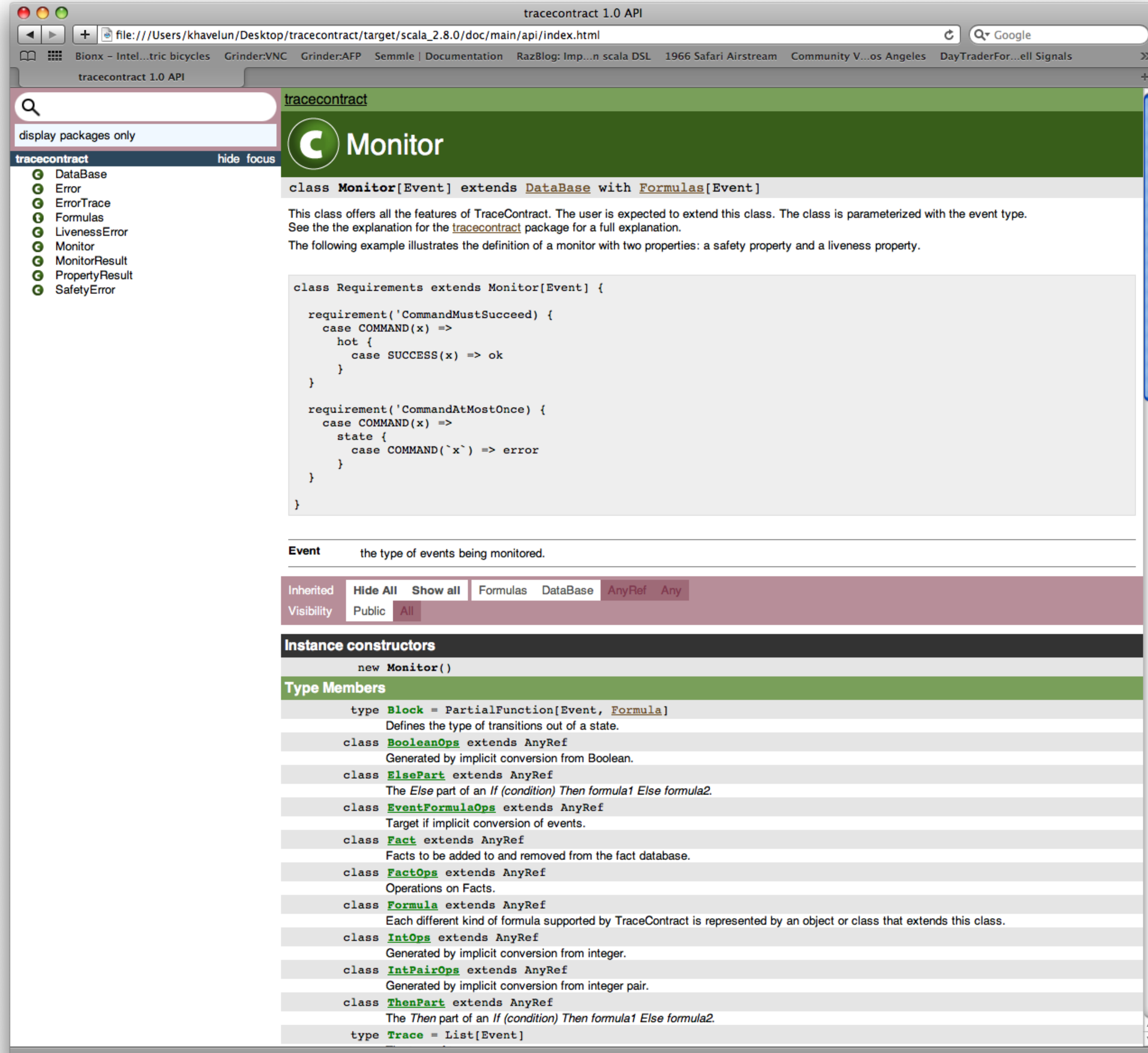
compose

run

```
object Apply {
  def readLog(): List[Event] = {...}

  def main(args: Array[String]) {
    val monitor = new Requirements
    val log = readLog()
    monitor.verify(log)
  }
}
```

result

```
Monitor: CommandMustSucceed

Error trace:
  1=Command(STOP_DRIVING,1)


---------------------------------


Monitor: MaxOneSuccess

Error trace:
  2=Command(TAKE_PICTURE,2)
  3=Success(TAKE_PICTURE,2)
  4=Success(TAKE_PICTURE,2)
```



tracecontract 1.0 API

file:///Users/khavelun/Desktop/tracecontract/target/scala_2.8.0/doc/main/api/index.html

display packages only

tracecontract hide focus

- DataBase
- Error
- ErrorTrace
- Formulas
- LivenessError
- Monitor
- MonitorResult
- PropertyResult
- SafetyError

tracecontract

Monitor

`class Monitor[Event] extends DataBase with Formulas[Event]`

This class offers all the features of TraceContract. The user is expected to extend this class. The class is parameterized with the event type. See the the explanation for the tracecontract package for a full explanation.

The following example illustrates the definition of a monitor with two properties: a safety property and a liveness property.

```
class Requirements extends Monitor[Event] {

  requirement('CommandMustSucceed) {
    case COMMAND(x) =>
      hot {
        case SUCCESS(x) => ok
      }
  }

  requirement('CommandAtMostOnce) {
    case COMMAND(x) =>
      state {
        case COMMAND(`x`) => error
      }
  }

}
```

Event	the type of events being monitored.

Inherited: Hide All | Show all | Formulas | DataBase | AnyRef | Any

Visibility: Public | All

Instance constructors

`new Monitor()`

Type Members

`type Block = PartialFunction[Event, Formula]`
Defines the type of transitions out of a state.

`class BooleanOps extends AnyRef`
Generated by implicit conversion from Boolean.

`class ElsePart extends AnyRef`
The *Else* part of an *If (condition) Then formula1 Else formula2.*

`class EventFormulaOps extends AnyRef`
Target if implicit conversion of events.

`class Fact extends AnyRef`
Facts to be added to and removed from the fact database.

`class FactOps extends AnyRef`
Operations on Facts.

`class Formula extends AnyRef`
Each different kind of formula supported by TraceContract is represented by an object or class that extends this class.

`class IntOps extends AnyRef`
Generated by implicit conversion from integer.

`class IntPairOps extends AnyRef`
Generated by implicit conversion from integer pair.

`class ThenPart extends AnyRef`
The *Then* part of an *If (condition) Then formula1 Else formula2.*

`type Trace = List[Event]`

def **eventuallyGt**(n: Int)(formula: Formula): Formula

Eventually true after *n* steps.

def **eventuallyLe**(n: Int)(formula: Formula): Formula

Eventually true in maximally *n* steps.

def **eventuallyLt**(n: Int)(formula: Formula): Formula

Eventually true in less than *n* steps.

def **factExists**(pred: PartialFunction[Fact, Boolean]): Boolean

Tests whether a fact exists in the fact database, which satisfies a predicate.

def **getMonitorResult**: MonitorResult[Event]

Returns the result of a trace analysis for this monitor.

def **getMonitors**: List[Monitor[Event]]

Returns the sub-monitors of a monitor.

def **globally**(formula: Formula): Formula

Globally true (an LTL formula).

def **hot**(m: Int, n: Int)(block: PartialFunction[Event, Formula]): Formula

A hot state waiting for an event to eventually match a transition (required) between *m* and *n* steps.

def **hot**(block: PartialFunction[Event, Formula]): Formula

A hot state waiting for an event to eventually match a transition (required). The state remains active until the incoming event *e* matches the *block*, that is, until *block.isDefinedAt(e) == true*, in which case the state formula evaluates to *block(e)*.

At the end of the trace a *hot state* formula evaluates to False.

As an example, consider the following monitor, which checks the property: *"a command x eventually should be followed by a success"*:

```
class Requirement extends Monitor[Event] {
  require {
    case COMMAND(x) =>
      hot {
        case SUCCESS(`x`) => ok
      }
  }
}
```

block	partial function representing the transitions leading out of the state.
returns	the *hot state* formula.

definition classes: Formulas

def **informal**(name: Symbol)(explanation: String): Unit

Used to enter explanations of properties in informal language.

def **informal**(explanation: String): Unit

Used to enter explanations of properties in informal language.

def **matches**(predicate: PartialFunction[Event, Boolean]): Formula

Matches current event against a predicate.

def **monitor**(monitors: Monitor[Event]*): Unit

Adds monitors as sub-monitors to the current monitor.

def **never**(formula: Formula): Formula

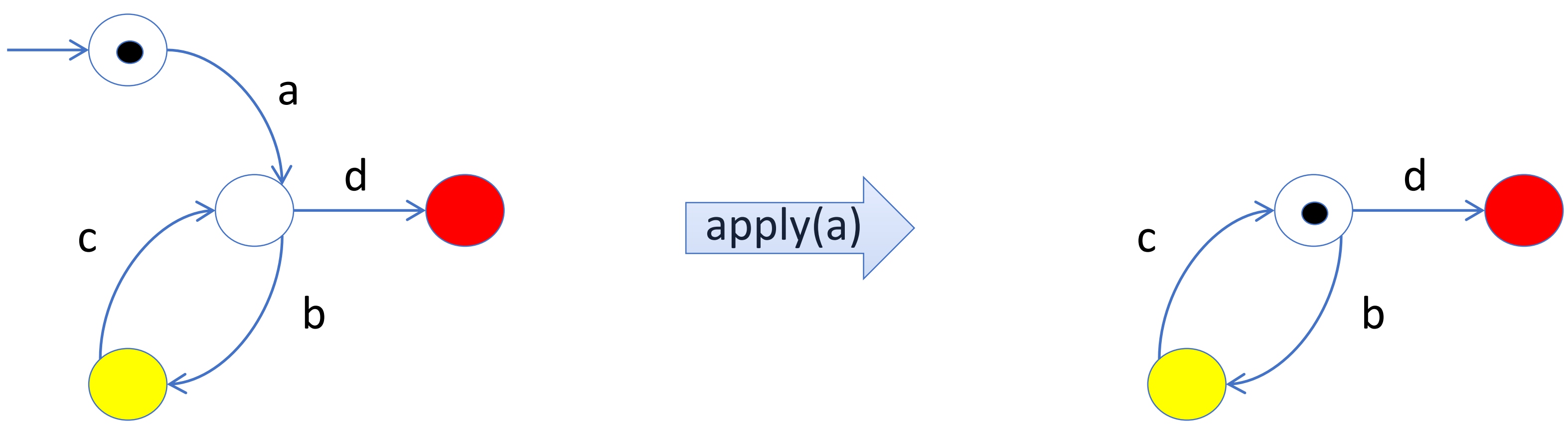
Never true (an LTL-inspired formula).

IMPLEMENTATION

how does it work?

formulas

```
abstract class Formula {
  def apply(event: Event): Formula
  def reduce(): Formula = this
  ...
}
```



basic formulas (single time point)

```
case object True extends Formula {
  override def apply(event: Event): Formula = this
}


case class Now(expectation: Event) extends Formula {
  override def apply(event: Event): Formula =
    if (expectation == event) True else False
}
```

```
...
not(Fail(n, x)) until (Success(n, x))
...
```

```
implicit def Event2Formula(event: Event): Formula = Now(event)
```

and

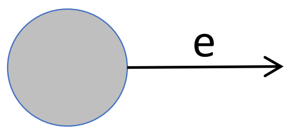
```
case class And(formula1: Formula, formula2: Formula) extends Formula {
  override def apply(event: Event): Formula =
    And(formula1(event), formula2(event)).reduce()

  override def reduce(): Formula = {
    (formula1, formula2) match {
      case (False, _) => False
      case (_, False) => False
      case (True, _) => formula2
      case (_, True) => formula1
      case (f1, f2) if f1 == f2 => f1
      case _ => this
    }
  }
}
```

until

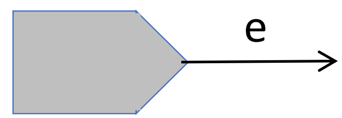
$$f_1 \cup f_2 = f_2 \vee (f_1 \wedge \bigcirc(f_1 \cup f_2))$$

```
case class Until(formula1: Formula, formula2: Formula) extends Formula {
  override def apply(event: Event): Formula =
    Or(formula2(event), And(formula1(event), this).reduce()).reduce()
}
```

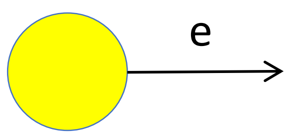
states

state 

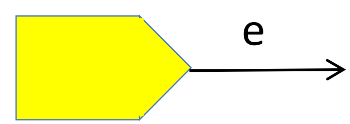
e'≠e : stay
at end : ok

hot 

e'≠e : stay
at end : error

weak 

e'≠e : error
at end : ok

strong 

e'≠e : error
at end : error

```
case class State(block: Block) extends Formula {
  override def apply(event: Event): Formula =
    if (block.isDefinedAt(event)) block(event) else this
}

case class Weak(block: Block) extends Formula {
  override def apply(event: Event): Formula =
    if (block.isDefinedAt(event)) block(event) else False
}
```

// Hot the same

// Strong the same

at the end

```
def end(formula: Formula): Boolean =
  formula match {
    case State(_)   => true
    case Hot(_)     => false

    case Weak(_)   => true
    case Strong(_) => false

    case Until(_,_)    => false

    case And(formula1, formula2) => end(formula1) && end(formula2)
    ...
  }
```

observations

- high expressive power, easy to develop
- hard to analyze, learning curve for non-Scala programmers

what state
are we in?

what events
are enabled?

```
class CommandMustSucceed extends Monitor[Event] {
  require {
    case Command(n,x) => RequireSuccess(n,x)
  }

  def RequireSuccess(name: String, number: Int) =
    hot {
      case Fail(`name`, `number`) => error
      case Success(`name`, `number`) => ok
    }
}
```

THANKS!