PROGRAM YOUR OWN RV SYSTEM

an exercise in DSL design

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for Reliable Software

Definition of "Runtime Verification"

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

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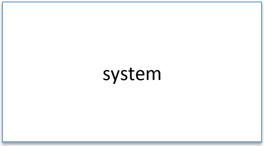
Runtime Verification is the discipline of computer science dedicated to the analysis of system executions, including checking them against formalized specifications.

Other variations:

- analysis with algorithms (no specs): data race and deadlock analysis
- specification learning
- trace visualization
- fault protection: changing behavior

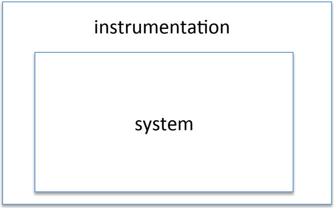
Runtime verification

- Start with a system to monitor.



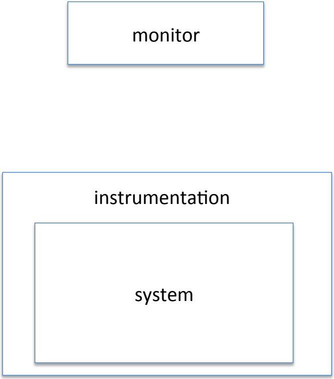
Runtime verification

- *Instrument* the system to record relevant events.



Runtime verification

- *Provide* a monitor.



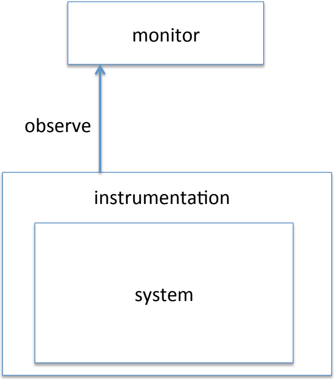
monitor

instrumentation

system

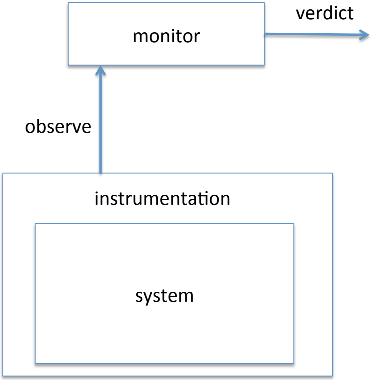
Runtime verification

- *Dispatch* each received event to the monitor.



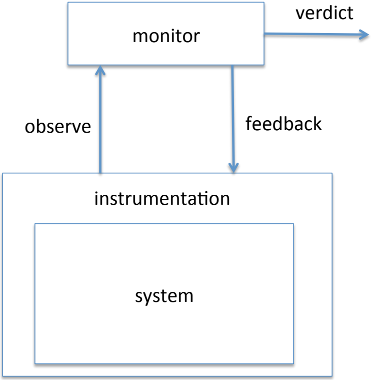
Runtime verification

- Compute a *verdict* for the trace received so far.



Runtime verification

- Possibly generate *feedback* to the system.



monitor

verdict

observe

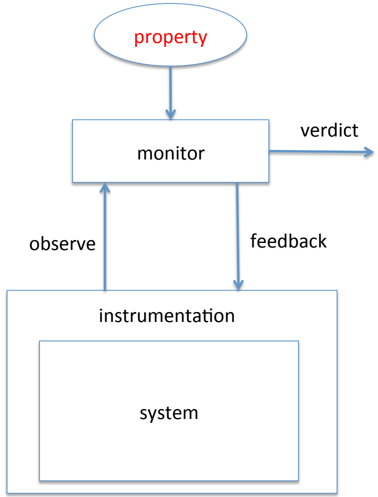
feedback

instrumentation

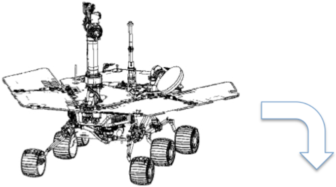
system

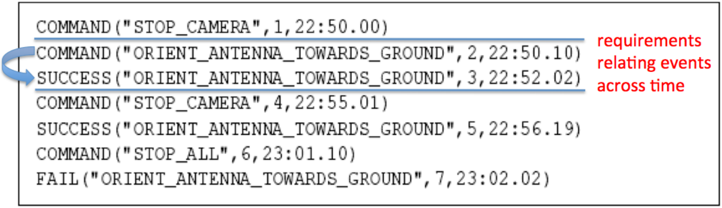
Runtime verification

- We might possibly have synthesized monitor from a *property*.



Trace evaluation





```
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

Trace evaluation

- The type of events E
- A trace is a finite sequence of events: $Trace = E^*$
- A *property* ϕ denotes a *language* $\mathcal{L}(\phi) \subseteq Trace$:
- On the fly evaluation, say current trace is τ:

$\tau \in \mathcal{L}(\varphi)$	:	true	$\wedge$	no extension	can make it false
	:	true_{sofar}	$\wedge$	some extension	can make it false
$\tau \notin \mathcal{L}(\varphi)$	:	false	$\wedge$	no extension	can make it true
	:	false_{sofar}	$\wedge$	some extension	can make it true

How is the monitor specified?

- Program (built-in algorithm focused on specific problem)
    - data race detection
    - deadlock detection
- Programming language
- Design by contract (pre/post conditions), JML for example
- Temporal formalism (expressing ordering of events)
    - state machines
    - regular expressions
    - grammars (context free languages)
    - linear temporal logic (past time, future time)
    - rule-based logics

Some instrumentation techniques

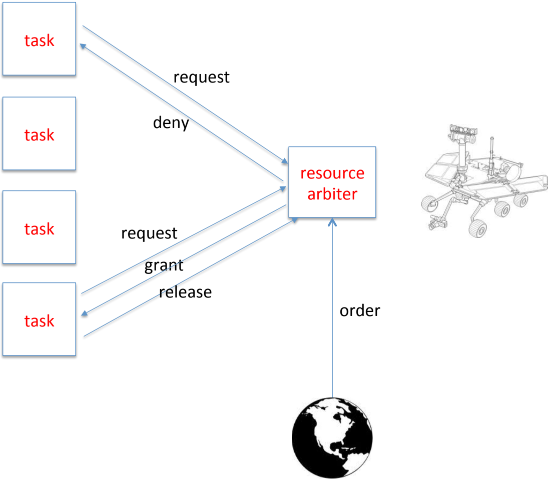
- Instrumentation of *byte/object code*
  - Valgrind (C) `http://valgrind.org`
  - BCEL (Java) `http://jakarta.apache.org/bcel`
- Instrumentation of *source code*
  - CIL (C) `http://sourceforge.net/projects/cil`
- Aspect-oriented programming (AOP):
  - AspectC (C) `https://sites.google.com/a/gapp.msrg.utoronto.ca/aspectc`
  - AspectC++ (C++) `http://www.aspectc.org`
  - AspectJ (Java) `http://www.eclipse.org/aspectj`

Data Automata

(Daut)

MSL

System architecture



task

task

task

task

request

deny

resource arbiter

request

grant

release

order

Resource allocation requirements

Requirement R_1

A grant of a resource to a task must be followed by a release of that resource by the same task, without another grant of that resource in between (to the same task or any other task).

Requirement R_2

A resource cannot be released by a task, which has not been granted the resource.

A state machine

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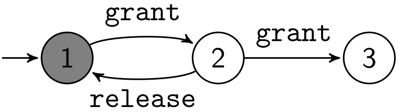

A state machine with parameters

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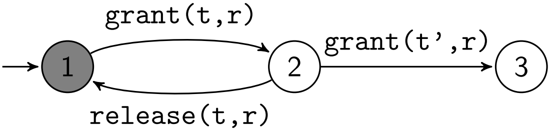

A restriction in MOP

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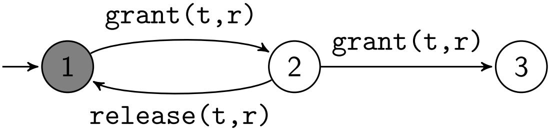
A grant of a resource to a task must be followed by a release of that resource by the same task, without another grant of that resource in between (**to the same task** or any other task).

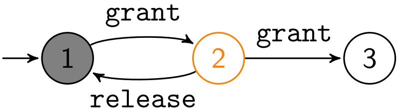


Consider trace

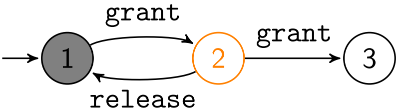
$$\langle grant(t_1, antenna), grant(t_2, motor_2), grant(t_3, motor_4)\rangle$$

MOP: monitor state is a map from parameters to states

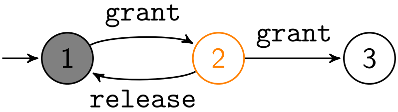
$(t_1, antenna) \mapsto$



$(t_2, motor_2) \mapsto$



$(t_3, motor_4) \mapsto$



DAUT: monitor state is a set of records

$$\{S2(t_1, antenna), S2(t_2, motor_2), S2(t_3, motor_4)\}$$

Design of a DSL

References

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  1. small language with focused functionality
  2. specialized parser programmed using parser generator

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- as an **internal** DSL
  1. API in SCALA
  2. using SCALA's infra-structure (compiler, IDEs, ...)
  3. advantages:
     1. expressive, the programming language is never far away
     2. easier to develop/adapt (although, sometimes not)
     3. allows use of existing tools such as type checkers, IDEs, etc.

An external DSL

Recall the two resource allocation requirements

Requirement R_1

A grant of a resource to a task must be followed by a release of that resource by the same task, without another grant of that resource in between (to the same task or any other task).

Requirement R_2

A resource cannot be released by a task, which has not been granted the resource.

R_1 and R_2 as a state machine in DAUT

```
monitor R1R2 {
  init always Start {
    grant(t, r) → Granted(t,r)
    release(t, r) :: ¬Granted(t,r) → error
  }

  hot Granted(t,r) {
    release(t,r) → ok
    grant(_,r) → error
  }
}
```

top level abbreviation

```
monitor R1R2 {
  grant(t, r) → Granted(t,r)
  release (t, r) :: ¬Granted(t,r) → error

  hot Granted(t,r) {
    release (t,r) → ok
    grant(_,r) → error
  }
}
```

Requirement R_1

```
monitor R1 {
  grant(t,r) → hot {
    release (t,r) → ok
    grant(_,r) → error
  }
}
```

syntax

$\langle \mathit{Specification} \rangle ::= \langle \mathit{Monitor} \rangle *$

$\langle \mathit{Monitor} \rangle ::= \textbf{monitor}\ \langle \mathit{Id} \rangle\ `\{\text{'}\ \langle \mathit{Transition} \rangle *\ \langle \mathit{State} \rangle *\ `\}\text{'}$

$\langle \mathit{State} \rangle ::= \langle \mathit{Modifier} \rangle *\ \langle \mathit{Id} \rangle\ \lceil\ (\langle \mathit{Id} \rangle **)\ \rceil\ \lceil\ `\{\text{'}\ \langle \mathit{Transition} \rangle *\ `\}\text{'}\ \rceil$

$\langle \mathit{Modifier} \rangle ::= \textbf{init} \mid \textbf{hot} \mid \textbf{always}$

$\langle \mathit{Transition} \rangle ::= \langle \mathit{Pattern} \rangle\ `{:}{:}\text{'}\ \langle \mathit{Condition} \rangle\ `{\rightarrow}\text{'}\ \langle \mathit{Action} \rangle **$

$\langle \mathit{Pattern} \rangle ::= \langle \mathit{Id} \rangle\ `(\text{'}\langle \mathit{Id} \rangle **`)\text{'}$

$\langle \mathit{Condition} \rangle ::= \langle \mathit{Condition} \rangle\ `{\wedge}\text{'}\ \langle \mathit{Condition} \rangle$
$\quad \mid\ \langle \mathit{Condition} \rangle\ `{\vee}\text{'}\ \langle \mathit{Condition} \rangle$
$\quad \mid\ `{\neg}\text{'}\ \langle \mathit{Condition} \rangle$
$\quad \mid\ `(\text{'}\langle \mathit{Condition} \rangle`)\text{'}$
$\quad \mid\ \langle \mathit{Expression} \rangle\ \langle \mathit{relop} \rangle\ \langle \mathit{Expression} \rangle$
$\quad \mid\ \langle \mathit{Id} \rangle\ \lceil\ `(\text{'}\langle \mathit{Expression} \rangle **`)\text{'}\ \rceil$

$\langle \mathit{Action} \rangle ::= \textbf{ok}$
$\quad \mid\ \textbf{error}$
$\quad \mid\ \langle \mathit{Id} \rangle\ \lceil\ `(\text{'}\langle \mathit{Expression} \rangle **`)\text{'}\ \rceil$
$\quad \mid\ \textbf{if}\ `(\text{'}\ \langle \mathit{Condition} \rangle\ `)\text{'}\ \textbf{then}\ \langle \mathit{Action} \rangle\ \textbf{else}\ \langle \mathit{Action} \rangle$
$\quad \mid\ \langle \mathit{Modifier} \rangle *\ `\{\text{'}\ \langle \mathit{Transition} \rangle *\ `\}\text{'}$

Semantics

Basic concepts

- An environment: $env \in Env = Id \xrightarrow{m} V$

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- A trace: $\sigma \in Trace = Event^*$

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Basic concepts

- An environment: $env \in Env = Id \xrightarrow{m} V$
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- A trace: $\sigma \in Trace = Event^*$
- A particular state $s \in State = id(v_1, \ldots, v_n)$ represents an instantiation of the formal parameters
- Environment of a state: $s.env = [id_1 \mapsto v_1, \ldots, id_n \mapsto v_n]$

Labeled Transition System

- $LTS = (Config, Event, \rightarrow, i, F)$.
    - $Config \subseteq State$
    - $Event$ is a set of parameterized events
    - $\rightarrow \subseteq Config \times (Event \times \mathbb{B}) \times Config$
    - $i \subseteq Config$ is the set of initial states
    - $F \subseteq Config$ is the set of final states
- Result of transitions will hence be pairs of the form $(flag, con) \in \mathbb{B} \times Config$
- $\perp$ indicates that an evaluation has failed

Semantics part 1/3

$$\boxed{\mathsf{E}}\ \frac{con, con \overset{e}{\hookrightarrow} b, con'}{con \xrightarrow{e,b} con'}$$

$$\boxed{\mathsf{E\text{-}ss_1}}\ \frac{}{con, \{\} \overset{e}{\hookrightarrow} (true, \{\})}$$

$$\boxed{\mathsf{E\text{-}ss_2}}\ \frac{\begin{array}{c} con, s \overset{e}{\longmapsto} res \\ con, ss \overset{e}{\hookrightarrow} res' \end{array}}{con, s \cup ss \overset{e}{\hookrightarrow} res \oplus res'}$$

Semantics part 2/3

$$\boxed{\text{E-s}_1}\ \frac{con, s.env, s.ts \overset{e}{\Longrightarrow} \bot}{con, s \overset{e}{\longmapsto} true, \{s\}}$$

$$\boxed{\text{E-s}_2}\ \frac{con, s.env, s.ts \overset{e}{\Longrightarrow} res}{con, s \overset{e}{\longmapsto} res}$$

$$\boxed{\text{E-ts}_1}\ \frac{}{con, env, Nil \overset{e}{\Longrightarrow} \bot}$$

$$\boxed{\text{E-ts}_2}\ \frac{\begin{array}{c} con, env, t \overset{e}{\rightharpoondown} res_\bot \\ con, env, ts \overset{e}{\Longrightarrow} res'_\bot \end{array}}{con, env, \langle t\rangle^\frown ts \overset{e}{\Longrightarrow} res_\bot \oplus_\bot res'_\bot}$$

Semantics part 3/3

$$\boxed{\text{E-t}_1}\ \frac{\begin{array}{c} t\ \textbf{is}\ `pat :: cond \to rhs' \\ [\![pat]\!]^P env\ \ e = \bot \end{array}}{con, env, t \overset{e}{\rightharpoondown} \bot}$$

$$\boxed{\text{E-t}_2}\ \frac{\begin{array}{c} t\ \textbf{is}\ `pat :: cond \to rhs' \\ [\![pat]\!]^P env\ \ e = env' \\ [\![cond]\!]^C con\ env' = false \end{array}}{con, env, t \overset{e}{\rightharpoondown} \bot}$$

$$\boxed{\text{E-t}_3}\ \frac{\begin{array}{c} t\ \textbf{is}\ `pat :: cond \to rhs' \\ [\![pat]\!]^P env\ \ e = env' \\ [\![cond]\!]^C con\ env' = true \\ [\![rhs]\!]^R con\ env' = res \end{array}}{con, env, t \overset{e}{\rightharpoondown} res}$$

Semantic functions

```
$[\![\_]\!]^P : Pattern \rightarrow Env \rightarrow Event \rightarrow Env_\perp$
$[\![pat]\!]^P env\ id(v_1, \ldots, v_n) =$
    case $pat$ of
        "_" $\Rightarrow env$
        $id(id_1, \ldots, id_n) \Rightarrow$
            let $env' = \{id_1 \mapsto v1, \ldots, id_n \mapsto v_n\}$ in
                if $(\forall id \in (dom(env) \cap dom(env')) \bullet env(id) = env'(id)))$
                    then $env \oplus env'$
                    else $\perp$
        $id'(\ldots)$ where $id \neq id' \Rightarrow \perp$  // event names do not match

$[\![\_]\!]^C : Cond \rightarrow Config \rightarrow Env \rightarrow \mathbb{B}$
$[\![cond]\!]^C con\ env =$
    case $cond$ of
        $id(exp_1, \ldots, exp_n) \Rightarrow id([\![exp_1]\!]env, \ldots, [\![exp_n]\!]env)) \in con$

$[\![\_]\!]^E : Exp \rightarrow Env \rightarrow \mathbb{B}$
```

Semantic functions

$$
\begin{array}{l}
[\![\_]\!]^R : Action^{**} \rightarrow Config \rightarrow Env \rightarrow Result \\
[\![act_1, \ldots, act_n]\!]^R con\ env = \\
\qquad \textbf{let} \\
\qquad\qquad results = \{[\![act_i]\!] con\ env \mid i \in 1..n\} \\
\qquad\qquad status = \bigwedge\{b \mid (b, con') \in results\} \\
\qquad\qquad con'' = \bigcup\{con' \mid (b, con') \in results\} \\
\qquad \textbf{in} \\
\qquad\qquad (status, con'')
\end{array}
$$

$$
\begin{array}{l}
[\![\_]\!]^A : Action \rightarrow Config \rightarrow Env \rightarrow Result \\
[\![act]\!]^A con\ env = \\
\qquad \textbf{case}\ act\ \textbf{of} \\
\qquad\qquad \textbf{ok} \Rightarrow (true, \{\}) \\
\qquad\qquad \textbf{error} \Rightarrow (false, \{\}) \\
\qquad\qquad id(exp_1, \ldots, exp_n) \Rightarrow (true, \{id([\![exp_1]\!]env, \ldots, [\![exp_n]\!]env)\}) \\
\qquad\qquad \textbf{if}\ (cond)\ \textbf{then}\ act_1\ \textbf{else}\ act_2 \Rightarrow \\
\qquad\qquad\qquad \textbf{if}\ ([\![cond]\!] con\ env) \textbf{then}\ [\![act_1]\!] con\ env\ \textbf{else}\ [\![act_2]\!] con\ env
\end{array}
$$

Semantic functions

$$
\begin{aligned}
&\mathit{res}_\perp \oplus_\perp \mathit{res}'_\perp = \\
&\qquad \textbf{case } (\mathit{res}_\perp, \mathit{res}'_\perp) \textbf{ of} \\
&\qquad\qquad (\perp, r) \Rightarrow r \\
&\qquad\qquad (r, \perp) \Rightarrow r \\
&\qquad\qquad (r_1, r_2) \Rightarrow r_1 \oplus r_2
\end{aligned}
$$

$$
\begin{aligned}
&(b_1, \mathit{con}_1) \oplus (b_2, \mathit{con}_2) = \\
&\qquad (b_1 \wedge b_2, \mathit{con}_1 \cup \mathit{con}_2)
\end{aligned}
$$

Summarized outcome

- *false* : if **error** reached, otherwise:
- *true* : if config contains no states
- *false sofar* : if config contains at least one non-final state
- *true sofar* : if config contains only final states, one or more

Implementation of external DSL

Scala is 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
- Lively growing community

Abstract syntax

```
case class Specification (automata: List[Automaton])
case class Automaton(name: Id, states: List[StateDef])

case class StateDef(
  modifiers: List[Modifier],
  name: Id,
  formals: List[Id],
  transitions: List[Transition])

case class Transition(
  pattern: Pattern,
  condition: Option[Condition],
  rhs: List[StateExp])

trait Pattern
case class FormalEvent(name: Id, formals: List[Id]) extends Pattern
case object Any extends Pattern
```

Abstract syntax

```
trait Condition
case class Relation(exp1: Exp, op: RelOp, exp2: Exp) extends Condition
case class StatePredicate(name: Id, exprs: List[Exp]) extends Condition
case class BinCond(cond1: Condition, op: BinCondOp, cond2: Condition)
  extends Condition
case class Negation(cond: Condition) extends Condition
case class ParenCond(cond: Condition) extends Condition

trait StateExp
case object ok extends StateExp
case object error extends StateExp
case class NewStateExp(name: Id, values: List[Exp]) extends StateExp
case class IfStateExp(
  cond: Condition, stateExp1: StateExp, stateExp2: StateExp) extends StateExp
case class InlinedStateExp(
  modifiers: List[Modifier], transitions : List[Transition]) extends StateExp
```

Parser

```
object Grammar extends JavaTokenParsers {
  def  specification  :  Parser[ Specification ]  =
    rep(automaton) ^^ {
      case automata ⇒transform( Specification (automata))
    }

  def automaton: Parser[Automaton] =
    "monitor" →ident ~ ("{" → rep( transition ) ~ rep( statedef ) ← "}") ^^
      {
        case name ~ ( transitions  ~  statedefs ) ⇒
          if  ( transitions .isEmpty)
            Automaton(name, statedefs)
          else  { // derived  form
            val   initialState   =
              StateDef( List ( init ,  always ),  "StartFromHere", Nil,  transitions )
            Automaton(name,  initialState  ::   statedefs )
          }
      }
```

Parser

```
  def statedef : Parser[StateDef] =
    rep(modifier) ~ ident ~ opt("(" → repsep(ident, ",") ← ")") ~
    opt("{" → rep( transition ) ← "}") ^^
      {
        case modifiers ~ name ~ formals ~ transitions ⇒
          StateDef(modifiers, name, toList(formals), toList( transitions ))
      }

  def transition : Parser[ Transition ] =
    pattern ~ opt("::" → condition) ~ ("->" →rep1sep(stateexp, ",")) ^^
      {
        case pat ~ cond ~ rhs ⇒
          Transition(pat, cond, rhs)
      }
  }
   ...
}
```

Interpreter interface

```
trait Monitor[Event] {
  def verify (event: Event)
  def end()
}
```

Preliminaries

```
object Preliminaries {
  type Id = String
  type Value = Any

  type Env = Map[Id, Value]

  def mkEnv(ids: List[Id], values: List[Value]): Env =
    (ids zip values).toMap
}
```

Interpreter

```
class Observer(fileName: String) {
  var monitors: List[Monitor[Event]] = Nil

  parse(fileName) match {
    case None ⇒ assert(false, "syntax error")
    case Some(spec @ Specification(automata)) ⇒
      for (automaton ∈ automata) {
        monitors ++= List(new MonitorImpl(automaton))
      }
  }

  def verify(event: Event) {
    monitors foreach (_.verify(event))
  }

  def end() {
    monitors foreach (_.end())
  }
}
```

Interpreter

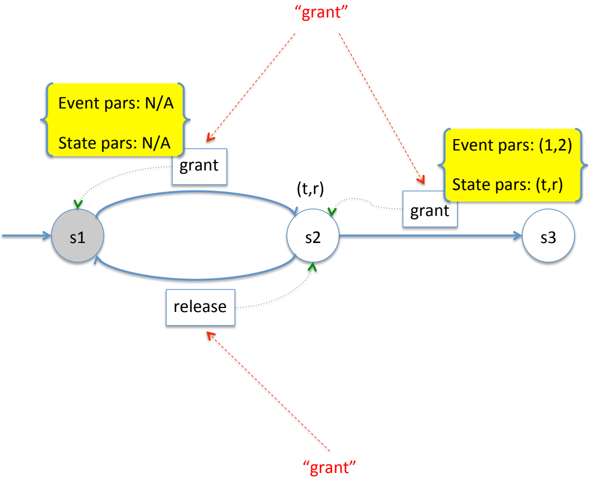
```
class MonitorImpl(automaton: Automaton) extends Monitor[Event] {
  case class State(name: Id, values: List[Value]) {
    var env: Env = null
  }

  type Config = Set[State]
  type Result = (Boolean, Config)

  var currentConfig: Config = initialConfig(automaton)

  def verify(event: Event) {
    val (status, con) = eval(currentConfig)(event)
    if (!status) println("*** error")
    currentConfig = con
  }
  ...
}
```

Interpreter

```
def evalTransition(con: Config, env: Env, transition: Transition)
                  (event: Event): Option[Result] =
{
  val Transition(pat, cond, rhs) = transition
  val optEnv = evalPat(pat)(env, event)
  optEnv match {
    case None ⇒None
    case Some(env_) ⇒
      if (evalCond(cond)(con, env_))
        Some(evalRight(rhs)(con, env_))
      else
        None
  }
}
```

Optimization with indexing

State nodes and event nodes



Indexed monitor

```
class MonitorImpl(automaton: Automaton) {
  val config = new Config(automaton)
   ...
  def verify(event: Event) {
    var statesToRem: Set[State] = {}
    var statesToAdd: Set[State] = {}
    for (state ∈ config.getStates(event)) {
      val (rem, add) = execute(state, event)
      statesToRem ++= rem
      statesToAdd ++= add
    }
    statesToRem foreach config.removeState
    statesToAdd foreach config.addState
  }
}
```

Indexed monitor

```
class Config(automaton: Automaton) {
  var stateNodes: Map[String, StateNode] = Map()
  var eventNodes: Map[String, List[EventNode]] = Map()
   ...
  def getStates(event: Event): Set[State] = {
    val (eventName, values) = event
    var result : Set[State] = Set()
    eventNodes.get(eventName) match {
      case None ⇒
      case Some(eventNodeList) ⇒
        for (eventNode ∈ eventNodeList) {
          result ++= eventNode.getRelevantStates(event)
        }
    }
     result
  }
}
```

Indexed monitor

```
case class EventNode(stateNode: StateNode,
  eventIds: List[Int], stateIds: List[String]) {
  ...
  def getRelevantStates(event: Event): Set[State] = {
    val (_, values) = event
    stateNode.get(
      stateIds,
      for (eventId ∈ eventIds) yield values(eventId)
    )
  }
}
```

Indexed monitor

```
case class StateNode(stateName: String, paramIdList: List[String]) {
  var index: Map[List[String], Map[List[Value], Set[State]]] = Map()
   ...
  def get(paramIdList: List[String], valueList : List[Value]): Set[State] =
  {
    index(paramIdList).get( valueList ) match {
      case None ⇒ emptySet
      case Some(stateSet) ⇒  stateSet
    }
  }
}
```

Another example

```
monitor R3 {
  grant(t, r) → Granted(t,r)

  hot Granted(t,r) {
    release (t,r) → ok
    cancel(r) → ok
  }
}
```

Indexing for this example

Suppose we observe the events:

$$\langle \mathit{grant}(t_1, a), \mathit{grant}(t_2, a) \rangle$$

Index after this trace:

$$\begin{array}{lcl} \langle t, r \rangle & \mapsto & [\ \langle t_1, a \rangle \mapsto \{\mathit{Granted}(t_1, a)\},\ \langle t_2, a \rangle \mapsto \{\mathit{Granted}(t_2, a)\}\ ] \\ \langle r \rangle & \mapsto & [\ \langle a \rangle \mapsto \{\mathit{Granted}(t_1, a), \mathit{Granted}(t_2, a)\}\ ] \end{array}$$

An internal DSL

Event type modeled in internal DSL

```
trait Event
case class grant(task: String, resource: String) extends Event
case class release(task: String, resource: String) extends Event
```

Properties modeled in internal DSL

```
class R1R2 extends Monitor[Event] {
  Always {
    case grant(t, r) ⇒ Granted(t, r)
    case release(t, r) if !Granted(t, r) ⇒ error
  }

  case class Granted(t: String, r: String) extends state{
    Watch {
      case release(‘t‘, ‘r‘) ⇒ ok
      case grant(_, ‘r‘) ⇒ error
    }
  }
}
```

Properties modeled in internal DSL

```
class R1 extends Monitor[Event] {
  Always {
    case grant(t, r) ⇒ hot {
      case release(‘t‘, ‘r‘) ⇒ ok
      case grant(_, ‘r‘) ⇒ error
    }
  }
}
```

Properties modeled in internal DSL

```
object Main {
  def main(args: Array[String]) {
    val obs = new R1R2

    obs.verify(grant("t1", "A"))
    obs.verify(grant("t2", "A"))
    obs.verify(release("t2", "A"))
    obs.verify(release("t1", "B"))
    obs.end()
  }
}
```

amazon.com

S. Hallé and R. Villemaire,
"Runtime enforcement of web service message contracts with data",
IEEE Transactions on Services Computing, vol. 5, no. 2, 2012. –
formalized in $\mathrm{LTL\text{-}FO}^{+}$.

XML based client server communication

XML

client

server

Example of XML message

```
<CartAdd>
  <CartId>1</CartId>
  <Items>
    <Item>
      <ASIN>10</ASIN>
    </Item>
    <Item>
      <ASIN>20</ASIN>
    </Item>
  </Items>
</CartAdd>
```

Amazon E-Commerce Service

ItemSearch(txt)	→	search items on site
CartCreate(its)	→	create cart with items
CartCreateResponse(c)	←	get cart id back
CartGetResponse(c, its)	←	result of get query
CartAdd(c, its)	→	add items
CartRemove(c, its)	→	remove items
CartClear(c)	→	clear cart
CartDelete(c)	→	delete cart

Definition of events

```
case class Item(asin : String )

 trait Event
case class ItemSearch(text : String ) extends Event
case class CartCreate(items: List [Item]) extends Event
case class CartCreateResponse(id: Int ) extends Event
case class CartGetResponse(id: Int , items: List [Item]) extends Event
case class CartAdd(id: Int , items: List [Item]) extends Event
case class CartRemove(id:Int, items: List [Item]) extends Event
case class CartClear( id : Int ) extends Event
case class CartDelete( id : Int ) extends Event
```

From XML to objects

```
def xmlToObject(xml:scala.xml.Node):Event =
  xml match {
    case x @ <CartAdd>{ _* }</CartAdd> ⇒
      CartAdd(getId(x), getItems(x))
     ...
  }

def xmlStringToObject(msg:String):Event = {
  val xml = scala.xml.XML.loadString(msg)
  xmlToObject(xml)
}

def getId(xml:scala.xml.Node):Int =
  (xml \ "CartId").text.toInt

def getItems(xml:scala.xml.Node):List[Item] =
  (xml \ "Items" \ "Item" \ "ASIN").
     toList.map(i ⇒ Item(i.text))
```

Properties

- **Property 1** - *Until a cart is created, the only operation allowed is ItemSearch.*
- **Property 2** - *A client cannot remove something from a cart that has just been emptied.*
- **Property 3** - *A client cannot add the same item twice to the shopping cart.*
- **Property 4** - *A shopping cart created with an item should contain that item until it is deleted.*
- **Property 5** - *A client cannot add items to a non-existing cart.*

Properties formalized

```
class  Property1 extends Monitor[Event] {
  Unless  {
    case ItemSearch(_) ⇒ ok
    case _  ⇒ error
  } {
    case CartCreate(_) ⇒ ok
  }
}

class  Property2 extends Monitor[Event] {
  Always {
    case CartClear(c)  ⇒  unless  {
      case CartRemove(‘c‘,  _) ⇒  error
    } {
      case CartAdd(‘c‘,  _) ⇒ ok
    }
  }
}
```

```
class Property3 extends Monitor[Event] {
  Always {
    case CartCreate(items) ⇒ next {
      case CartCreateResponse(c) ⇒ always {
        case CartAdd(‘c‘, items_) ⇒ items disjointWith items_
      }
    }
  }
}

class Property4 extends Monitor[Event] {
  Always {
    case CartAdd(c, items) ⇒
      for (i ∈ items) yield unless {
        case CartGetResponse(‘c‘, items_) ⇒ items_ contains i
      } {
        case CartRemove(‘c‘, items_) if items_ contains i ⇒ ok
      }
  }
}
```

```
class Property5 extends Monitor[Event] {
  Always {
    case CartCreateResponse(c) ⇒ CartCreated(c)
    case CartAdd(c, _) if !CartCreated(c) ⇒ error
  }

  case class CartCreated(c: Int) extends state {
    Watch {
      case CartDelete(‘c‘) ⇒ ok
    }
  }
}
```

Recall property 3

- **Property 3** - *A client cannot add the same item twice to the shopping cart.*

Property 3 made less strict

```
class  Property3Liberalized  extends Monitor[Event] {
  Always {
    case CartCreate(items) ⇒ next {
      case CartCreateResponse(c) ⇒ CartCreated(c, items)
    }
  }

  case class CartCreated(id: Int, items: List[Item]) extends state {
    Watch {
      case CartAdd(‘id‘, items_) ⇒
        val newCart = CartCreated(id,items + items_)
        if (items disjointWith items_) newCart else error & newCart
      case CartRemove(‘id‘, items_) ⇒ CartCreated(id, items diff items_)
    }
  }
}
```

Property 4 formulated on XML messages directly

```
class Property4_XML extends Monitor[scala.xml.Elem] {
  Always {
    case add @ <CartAdd>{_∗}</CartAdd> ⇒
      val c = getId(add)
      val items = getItems(add)
      for (i ∈ items) yield
        unless {
          case res @ <CartGetResponse>{_∗}</CartGetResponse>
            if c == getId(res) ⇒ getItems(res) contains i
        } {
          case rem @ <CartRemove>{_∗}</CartRemove>
            if c == getId(rem) &&
             (getItems(rem) contains i) ⇒ ok
        }
  }
}
```

Creating and applying a monitor

```
class  Properties  extends Monitor[Event] {
  monitor(
    new Property1(), new Property2(), new Property3(),
    new Property4(), new Property5())
}

object Main {
  def main(args: Array[String]) {
    val m = new Properties
    val  file :  String  = "..."
    val xmlEvents = scala.xml.XML.loadFile( file )

    for  (elem ∈ xmlEvents \ "_") {
      m. verify (xmlToObject(elem))
    }
    m.end()
  }
}
```

Implementation

Implementation

```
class Monitor[E <: AnyRef] {
  val monitorName = this.getClass().getSimpleName()

  var states : Set[state] = Set()

  var monitors : List[Monitor[E]] = List()

  def monitor(monitors:Monitor[E]*) {
    this.monitors ++= monitors
  }

   ...

}
```

Implementation

```
type Transitions = PartialFunction[E, Set[state]]

def noTransitions : Transitions = {
  case _ if false ⇒ null
}

val emptySet : Set[state] = Set()
```

Implementation

```
class state {
  var transitions : Transitions = noTransitions
  var isFinal : Boolean = true

  def apply(event:E):Set[state] =
     if (transitions.isDefinedAt(event))
        transitions(event) else emptySet

  def Watch(ts: Transitions) {
     transitions = ts
  }

  def Always(ts: Transitions) {
     transitions = ts andThen (_ + this)
  }

  def Hot(ts: Transitions) {
    Watch(ts); isFinal = false
  }
```

Implementation

```
  def Wnext(ts: Transitions ) {
    transitions  = ts orElse {
        case _ ⇒ ok
     }
  }

  def Next(ts : Transitions ) {
    Wnext(ts); isFinal = false
  }

  def Unless(ts1 : Transitions )(ts2 : Transitions ) {
    transitions  = ts2 orElse
      (ts1 andThen (_ + this))
  }

  def Until (ts1 : Transitions )(ts2 : Transitions ) {
    Unless(ts1 )(ts2 ); isFinal = false
  }
}
```

Implementation

```
case object ok extends state
case object error extends state

def error(msg:String): state = {
  println("\n*** " + msg + "\n")
  error
}
```

Implementation

```
def watch(ts: Transitions) = new state {Watch(ts)}
def always(ts: Transitions) = new state {Always(ts)}
def hot(ts: Transitions) = new state {Hot(ts)}
def wnext(ts: Transitions) = new state {Wnext(ts)}
def next(ts: Transitions) = new state {Next(ts)}

def unless(ts1: Transitions)(ts2: Transitions) =
  new state { Unless(ts1)(ts2) }

def until(ts1: Transitions)(ts2: Transitions) =
  new state { Until(ts1)(ts2) }
```

Implementation

```
def  initial (s: state) { states += s }

def Always(ts: Transitions) {  initial (always(ts)) }

def Unless(ts1: Transitions)(ts2: Transitions) {
   initial (unless(ts1)(ts2))
}

...
```

Implementation

```
implicit def stateAsBoolean(s: state ): Boolean =
  states contains s
```

Implementation

```
def stateExists(p: PartialFunction[state,Boolean]): Boolean = {
  states exists (p orElse { case _ => false })
}
```

Implementation

```
implicit def ss1(u:Unit):Set[state] = Set(ok)

implicit def ss2(b:Boolean):Set[state] = Set(if (b) ok else error)

implicit def ss3(s:state):Set[state] = Set(s)

implicit def ss4(ss:List[state]):Set[state] = ss.toSet

implicit def ss5(s1:state) = new {
  def &(s2:state):Set[state] = Set(s1, s2)
}

implicit def ss6(set:Set[state]) = new {
  def &(s:state):Set[state] = set + s
}
```

Implementation

```
var statesToRemove : Set[state] = Set()
var statesToAdd : Set[state] = Set()
```

Implementation

```
def verify (event:E) {
  for (sourceState ∈ states) {
    val targetStates = sourceState(event)
    if (! targetStates.isEmpty) {
      statesToRemove += sourceState
      for (targetState ∈ targetStates) {
        targetState match {
          case ‘error‘ ⇒ println ("*** " + monitorName + " error!")
          case ‘ok‘ ⇒
          case _ ⇒ statesToAdd += targetState
        }
      }
    }
  }
  states −−= statesToRemove; states ++= statesToAdd
  statesToRemove = emptySet; statesToAdd = emptySet
  for (monitor ∈ monitors) {monitor.verify (event)}
}
```

Implementation

```
def end() {
  val hotStates = states filter (!_.isFinal)
  if (!hotStates.isEmpty) {
    println ("hot " + monitorName + " states:")
    hotStates foreach println
  }
  for (monitor ∈ monitors) {
    monitor.end()
  }
}
```

Evaluation

Results

trace nr.	1	2	3	4	5	6	7
memory	1	1	5	30	100	500	5000
length	30,933	2,000,002	2,100,010	2,000,060	2,000,200	2,001,000	1,010,000
parsing	3 sec	45 sec	47 sec	46 sec	46 sec	46 sec	24 sec
LogFire	26 1:190	42 47:900	41 50:996	34 58:391	23 1:27:488	8 3:55:696	1 15:54:769
Rete/UL	38 816	109 18:428	75 28:141	41 48:524	14 2:26:983	4 8:25:867	0.4 43:33:366
Drools	10 3:97	8 4:1:758	9 3:47:535	9 3:34:648	8 4:14:497	7 4:36:608	3 5:4:505
Ruler	95 326	138 14:441	78 27:77	8 4:5:593	0.8 41:39:750	0.034 977:20:636	DNF
LogScope	17 1:842	15 2:11:908	7 4:54:605	2 21:42:389	0.4 76:17:341	0.09 369:25:312	0.01 2074:43:470
TrContract	48 645	69 28:851	37 57:428	6 5:58:497	0.9 36:29:594	0.036 919:5:134	DNF
Daut	49 631	84 23:847	86 24:338	89 22:432	90 22:298	86 23:287	80 12:612
Daut^{sos}	102 302	192 10:435	79 26:438	24 1:22:727	8 4:19:697	2 16:27:990	0.18 92:2:26
Daut^{int}	233 133	1715 1:166	770 2:729	373 5:368	195 10:236	54 36:929	5 3:6:560
Mop	595 52	1381 1:448	1559 347	1341 1:491	7143 280	7096 282	847 1:193

Conclusion

Conclusion

- We have seen the concept of data automata
- implemented as an external as well as an internal DSL
- internal DSL is simple but hard to optimize if shallow

Will programming and specification merge?

- Modern programming languages, such as Python, Scala, Fortress have many things in common with specification language such as VDM.
- I see a trend in this direction: specification and programming will merge.
- We see programming constructs such as:
  - functional programming combined with imperative programming
  - algebraic datatypes
  - sets, list and maps as built in data types with mathematic notation
  - predicate subtypes ($\mathbb{N} = \{i \in \mathbb{Z} \mid i \geqq 0\}$)
  - design by contract: pre/post conditions, invariants on state
  - session types
  - predicate logic, quantification over finite sets (as functions)
  - verification systems built around programming languages
  - meta programming for defining DSLs
  - integration of visualization and programming

The end