Information Extraction for Run-time Formal Analysis

Moonjoo Kim

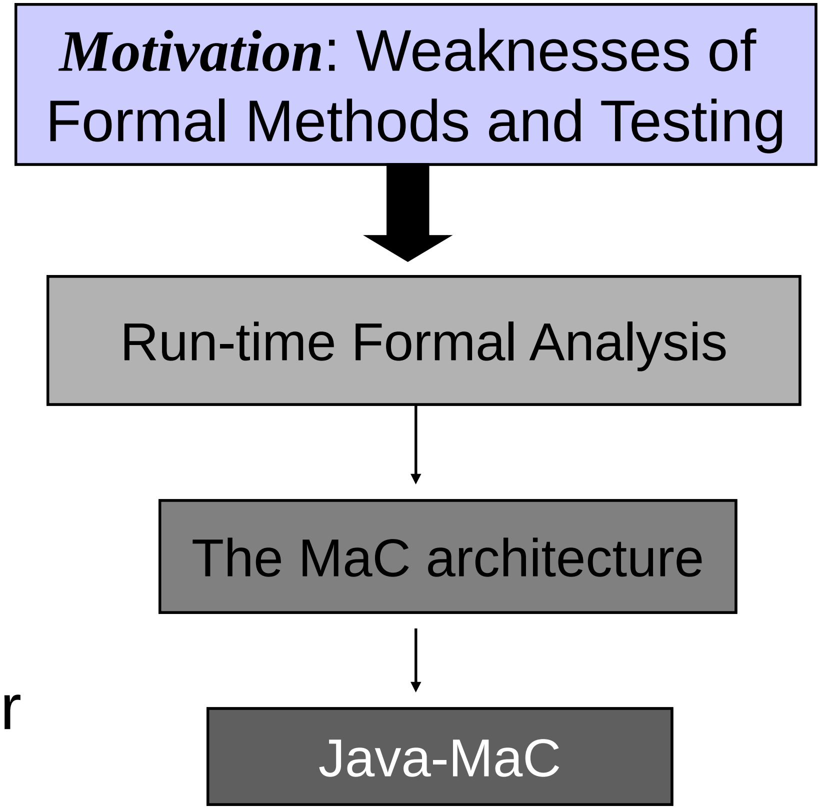
Advisors: Prof. Kannan and Prof. Lee

CIS Department

University of Pennsylvania

Outline

- WHY?
  - –Motivation
- WHAT?
  - –Run-time Formal Analysis
- HOW?
  - –High-level: the Monitoring and Checking (MaC) Architecture
  - –Low-level: a MaC Prototype for Java programs (Java-MaC)

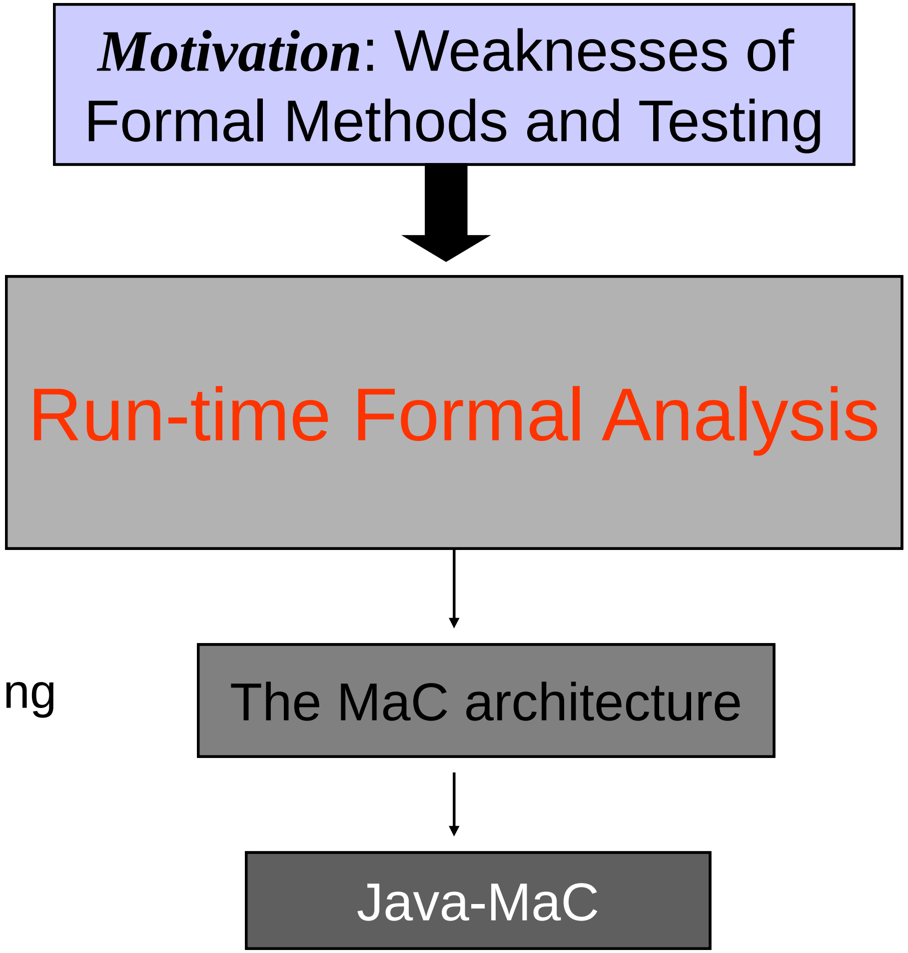


Motivation

- Weaknesses of formal verification and testing
  - formal verification:
    - gap between an abstract model and the implementation
    - lack of scalability
  - testing:
    - lack of complete guarantee

Outline

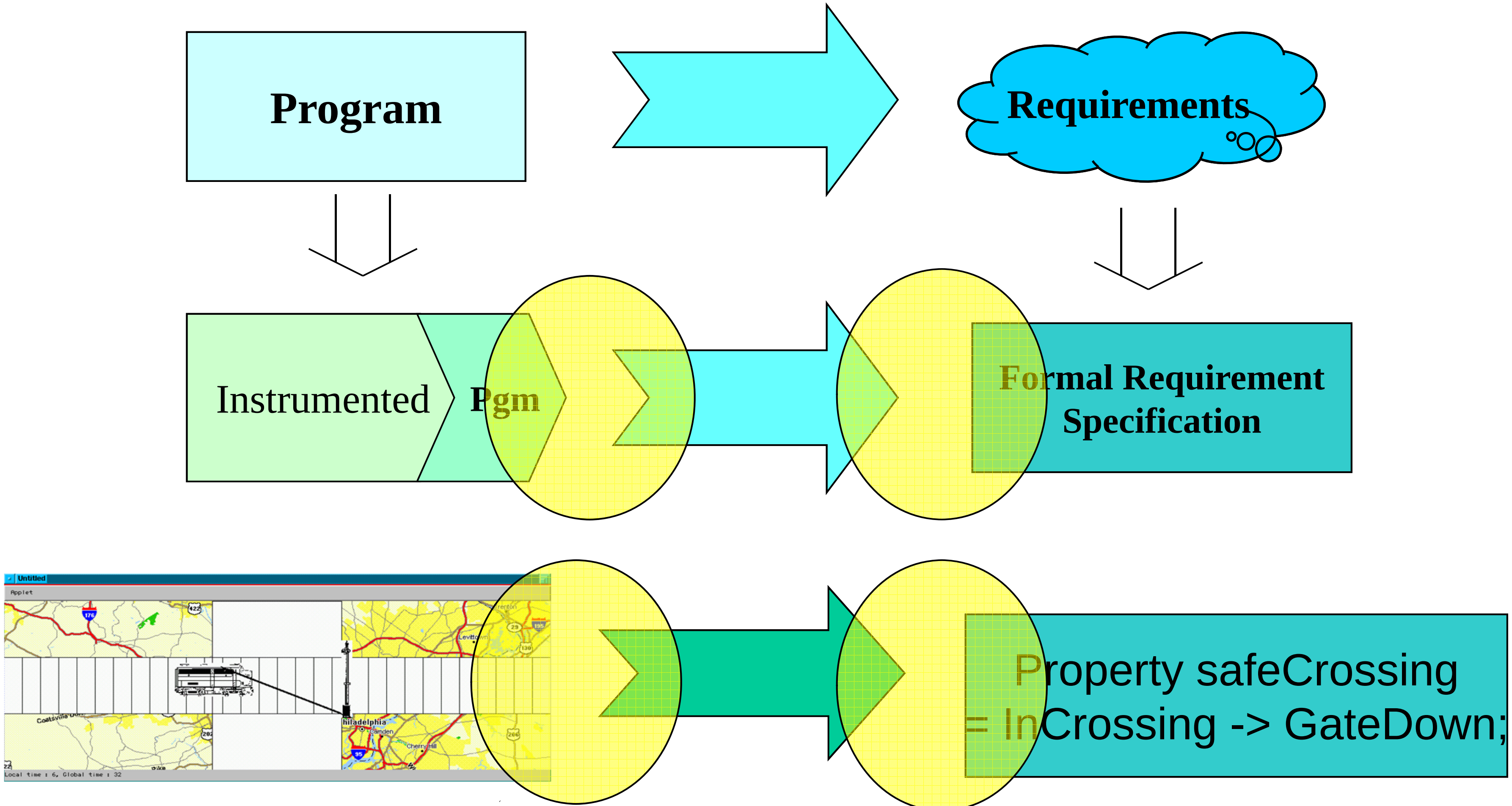
- WHY?
  - Motivation
- **WHAT?**
  - **Run-time Formal Analysis**
- HOW?
  - High-level: The Monitoring and Checking (MaC) Architecture
  - Low-level: a MaC Prototype for Java programs
- Summary



Run-time Formal Analysis

- Motivation:
  - Run-time correctness is not guaranteed
- The goal of run-time formal analysis
  - to give confidence in the run-time compliance of an execution of a system w.r.t formal requirements
- The analysis validates properties on the *current* execution of application.
- Run-time formal analysis helps user to detect errors and prevent system crash.

Relation Between Execution and Requirements



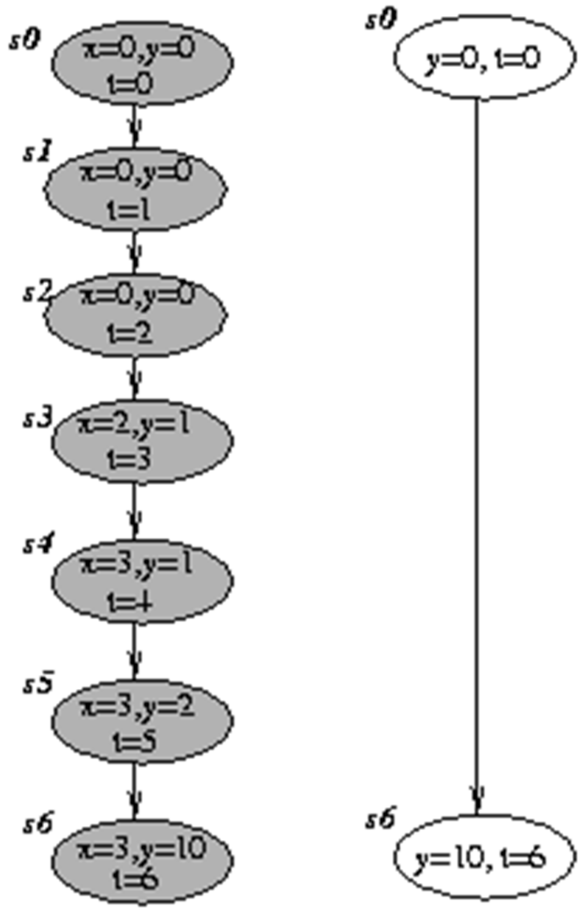

```
train_pos :20.5
crossing_pos:50
gate_angle:15
```

InCrossing =
```
  train_pos > crossing_pos;
```
GateDown =
```
  gate_angle == 0;
```

CIS department
University of Pennsylvania

Program Execution

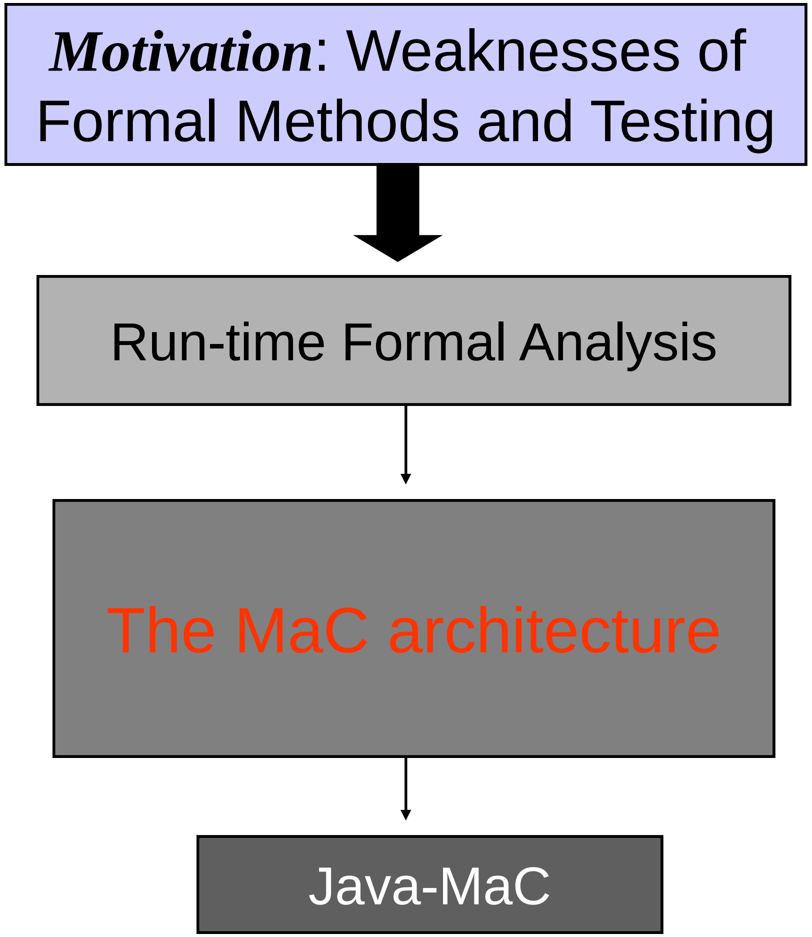
- A program execution σ is a sequence of states $s_0 s_1 \ldots$
  - A state s consists of
    - an environment ρ_s:V-> R
    - a timestamp t_s s.t. $t_{s_i} < t_{s_{i+1}}$
- We may abstract out state information unnecessary to detect requirements.



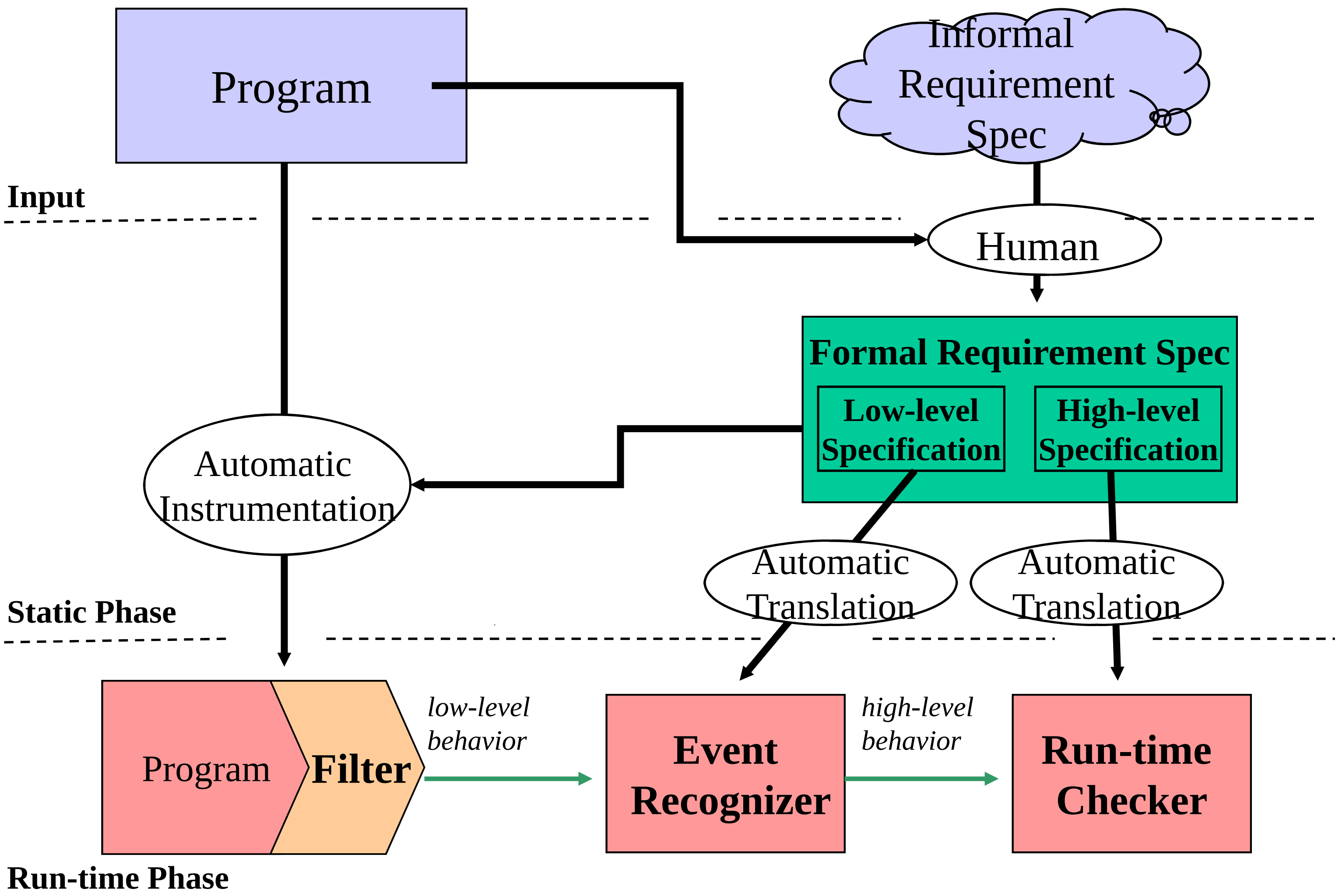

```
property p =
  3 < y && y < 11
```

Outline

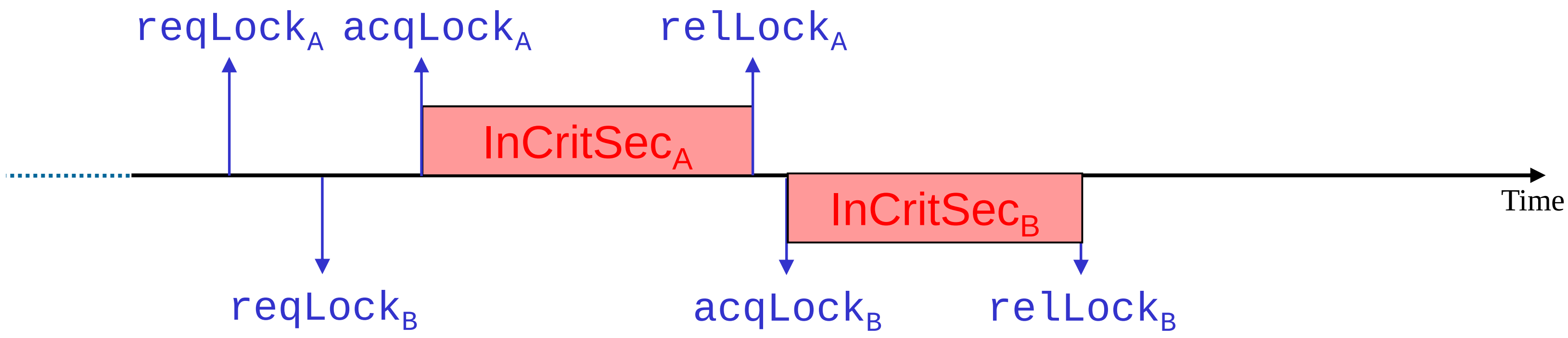
- WHY?
  - Motivation
- WHAT?
  - Run-time Formal Analysis
- HOW?
  - High-level:
    - the Monitoring and Checking (MaC) Architecture
  - Low-level: a MaC Prototype for Java programs
- Summary



Overview of the MaC Architecture



Design of the MaC Languages



- Must be able to reason about both time instants and information that holds for a duration of time in a program execution.
- Need temporal operators combining events and conditions in order to reason about traces.

Logical Foundation

$$C \ ::= \ c \ |\text{defined}(C) \ | \ [E_1, E_2) \ | \ \neg C \ | \ C_1 \vee C_2 \ | \ C_1 \wedge C_2$$

$$E \ ::= \ e \ | \ \text{start}(C) \ | \ \text{end}(C) \ | \ E_1 \vee E_2 \ | \ E_1 \wedge E_2 \ | \ E \text{ when } C$$

- conditions interpreted over 3 values
  - true, false and undefined.
- $[\cdot,\cdot)$ pairs a couple of events to define an interval.
- start and end define the events corresponding to the instant when conditions change their value.

The MaC Languages

- Meta Event Definition Language(MEDL)
  - Describes the *safety requirements* of the system, in terms of conditions that must always be true, and *alarms* (events) that must never be raised.
  - Target program implementation independent.
- Primitive Event Definition Language (PEDL)
  - Defines primitive events/conditions in terms of program entities
    - Provides primitives to refer to values of variables and to certain points in the execution of the program.
  - Depends on target program implementation

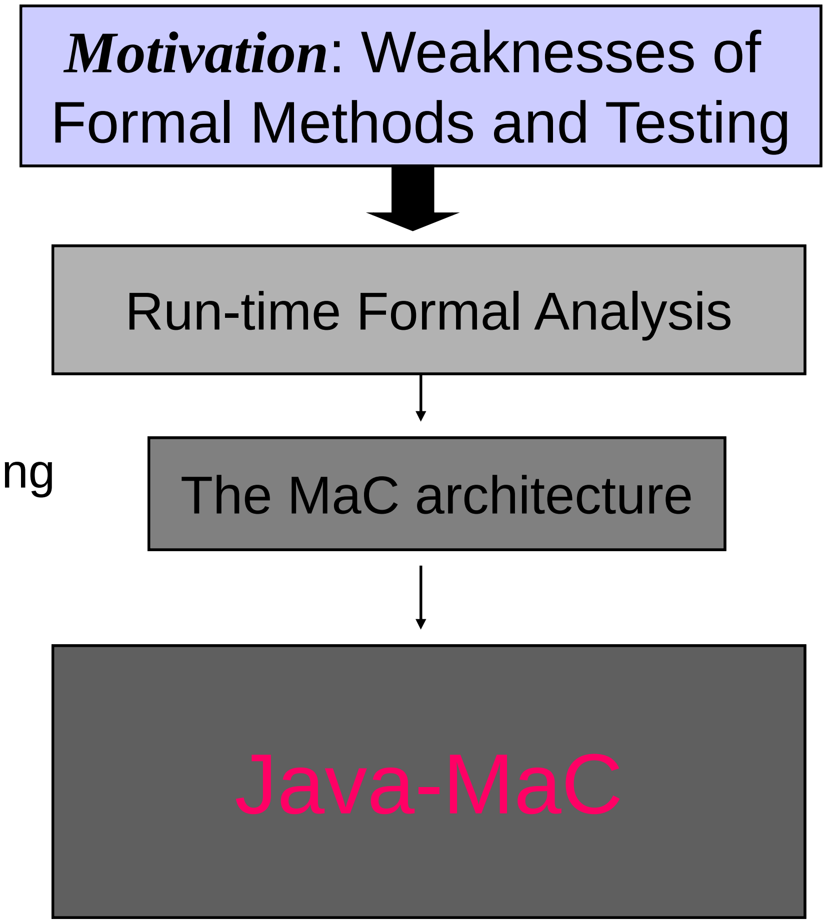
Meta Event Definition Language (MEDL)

- Expresses requirements using the events and conditions
- Expresses the subset of safety languages.
- Describes the *safety requirements* of the system
  - property safeRRC **= IC -> GD;**
  - alarm violation = start (!safeRRC);
- *Auxiliary variables* may be used to store history.
  - endIC-> { num_train_pass' = num_train_pass + 1; }

```
ReqSpec <spec_name>

  /* Import section */
  import event <e>;
  import condition <c>;

  /*Auxiliary variable */
  var int <aux_v>;

  /*Event and condition */
  event <e> = ...;
  condition <c>= ...;

  /*Property and violation */
  property <c>  = ...;
  alarm <e> = ...;

  /*Auxiliary variable update*/
  <e> -> {  <aux_v'> := ... ; }
End
```

Outline

- WHY?
  - Motivation
- WHAT?
  - Run-time Formal Analysis
- HOW?
  - High-level: The Monitoring and Checking (MaC) Architecture
  - Low-level: a MaC Prototype for Java programs
- Summary

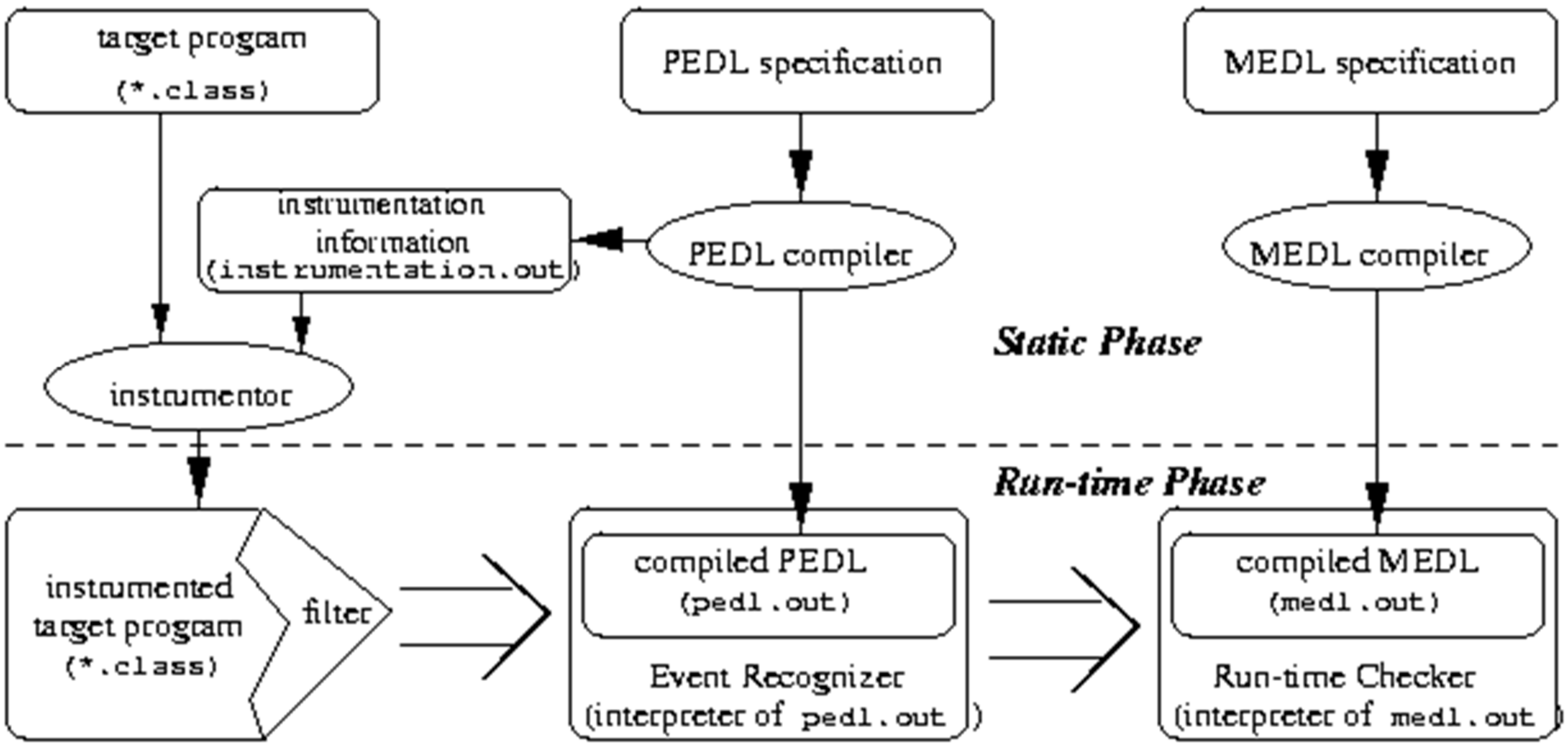


Java-MaC

- Overview of Java-MaC
- Monitoring Java programs
  - Monitoring objects
  - PEDL for Java
- Static components
  - Instrumentor, PEDL/MEDL compilers
- Run-time components
  - Filter, event recognizer, run-time checker
- Overhead reduction
- Case study

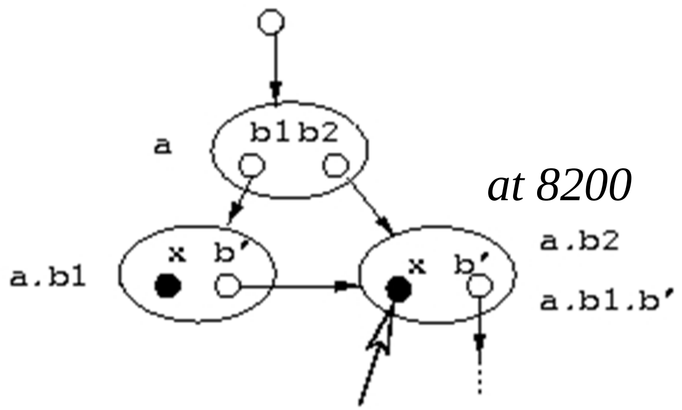
CIS department
University of Pennsylvania

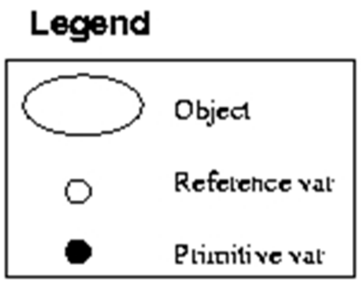
The MaC Prototype for Java Programs



Monitoring Objects

- Specifying monitored objects
  - There can be several instances (objects) of the same class.
- Monitoring objects
  - A monitored object can be updated by several references.
- To test references, we need a globally accessible table (*address table*) containing pairs of *addresses* of monitored objects and monitored object *names*
  - Assumption: *no* primary reference to a monitored object is changed





Address Table

Address	Var Name
8200	a.b2

PEDL for Java

- Provides primitives to refer to
  - primitive variables
  - beginnings/endings of methods
- Primitive conditions are constructed from
  - boolean-valued expressions over the monitored variables
    - ex> condition IC = (position == 100);
- Primitive events are constructed from
  - update(x)
  - startM(f)/endM(f)
    - ex>event raiseGate= startM(Gate.gu());

```
MonScr <spec_name>
  /* Export section */
  export event <e>;
  export condition <c>;

  /* Monitored entities */
  monobj <var>;
  monmeth <meth>;

  /* Event and condition*/
  event <e> = ...;
  condition <c>= ...;
End
```

PEDL for Java *(cont.)*

- Events can have two attributes - time and value
- time(e) gives the time of the last occurrence of event e
  - used for expressing temporal properties
- value(e,i) gives the i th value in the tuple of values of e
  - value of update(var) : a tuple containing a current value of var
  - value of startM(f) : a tuple containing parameters of the method f
  - value of endM(f) : a tuple containing parameters and a return value of the method f

Instrumentation

- Java-MaC instruments Java executable code
- Java-MaC instrumentor detects instructions
  - variable updates
    - putstatic/putfield for field variable updates
    - <T>store and iinc for local variable updates
  - execution points
    - instruction located at the beginning of method definition
    - return of method definition
- At the each detected instruction, Java-MaC instrumentor inserts a probe

Sample Probe

- Monitoring a field variable Var.val

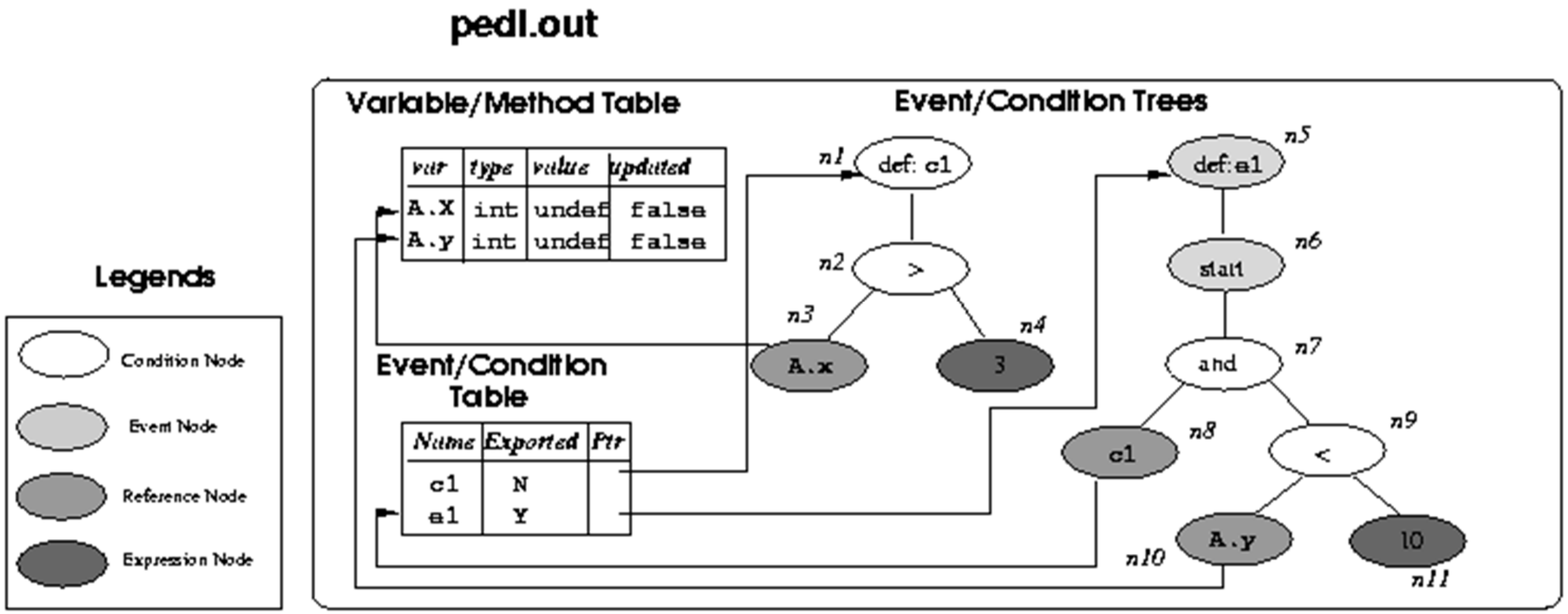
```
; >> METHOD 8 <<
.method public run()V
    .limit stack 4
    .limit locals 2
    ...
    getfield DigitalVar.v I
    putfield Var.val I
     ...
.end Method
```

```
; >> METHOD 8 <<
.method public run()V
    .limit stack 7
    .limit locals 2
    ...
    getfield DigitalVar.v I
    getstatic mac.filter.Filter.lock Ljava.lang.Object;
    monitorenter
    dup2
    ldc “val”
    invokestatic mac.filter.SendMethods.sendObjMethod(
        Ljava/lang/Object;ljava/lang/String;)V
    putfield Var.val I
    getstatic mac.filter.Filter.lock Ljava.lang.Object;
    monitorexit
     ...
.end Method
```

PEDL/MEDL Compilers

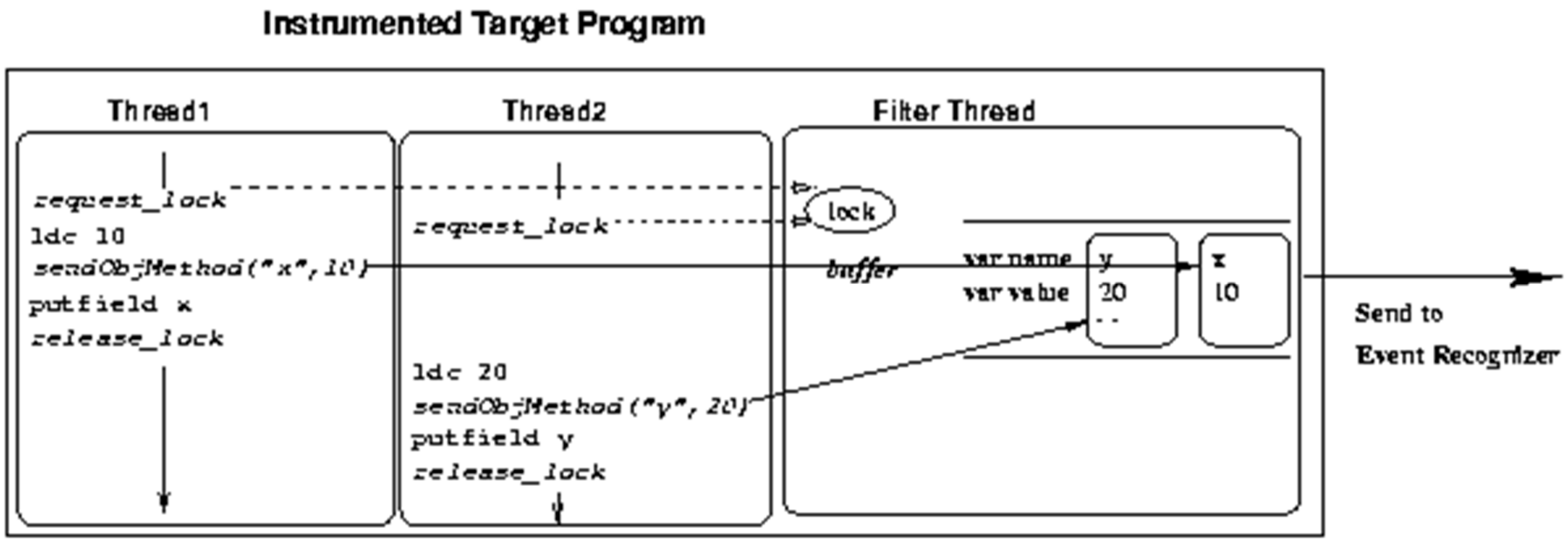
- Compiles PEDL/MEDL scripts into pedl.out/medl.out respectively
- Ex> condition c1 = A.x > 3;

  event e1 = start(c1 && A.y < 10);



Filter

- A filter consists of
  - *a communication channel* to the event recognizer
  - *probes* inserted into the target system
  - a *filter thread* which flushes the content of communication buffers to the event recognizer
- Filter uses global lock for consistent snapshot ordering in spite of arbitrary preemption



Event Recognizer/Run-time Checker

- Event recognizer
  - evaluates `pedl.out` whenever it receives snapshots from the filter.
  - If an event or a condition changing its value is detected, the event recognizer sends the event or the condition to the run-time checker
- Run-time checker
  - evaluates `medl.out` whenever it receives events and conditions from the event recognizer.
  - detects a violation defined as alarm or property and raises a signal.

Reduce Overheads

- Less snapshot, less overhead
- Not every snapshot affects requirement properties
  - Evaluates *simple* expressions to check whether current snapshot *may* affect requirements

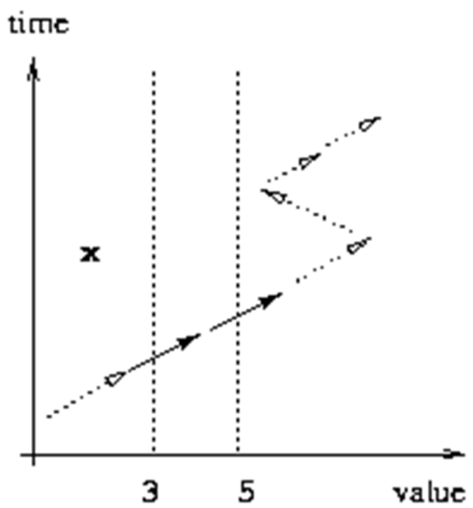
•Ex>

condition c1 =

(3 < x && x < 5) || y > 10;

condition c2 = w > z;

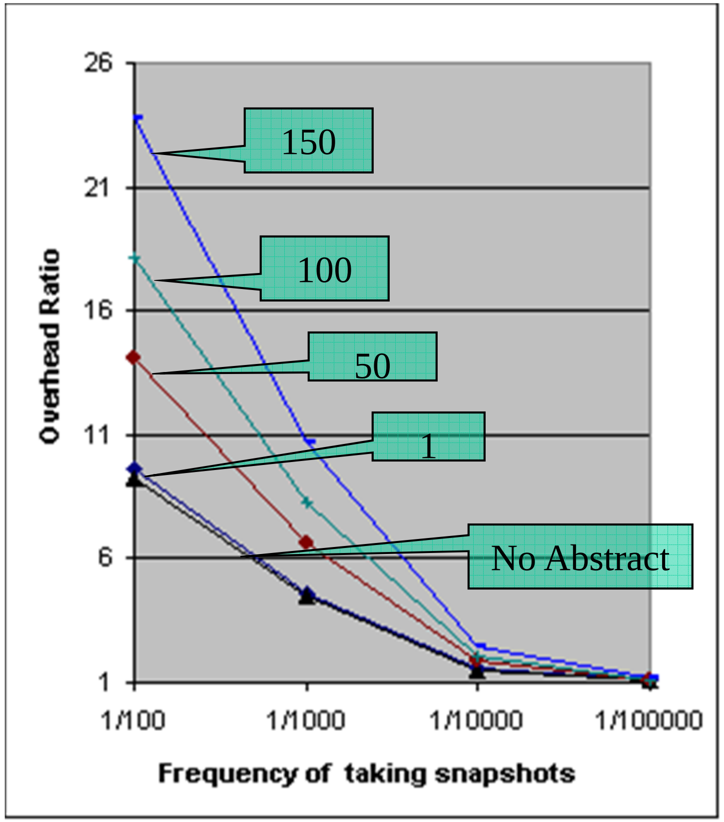
property req = c1 -> c2;



CIS department
University of Pennsylvania

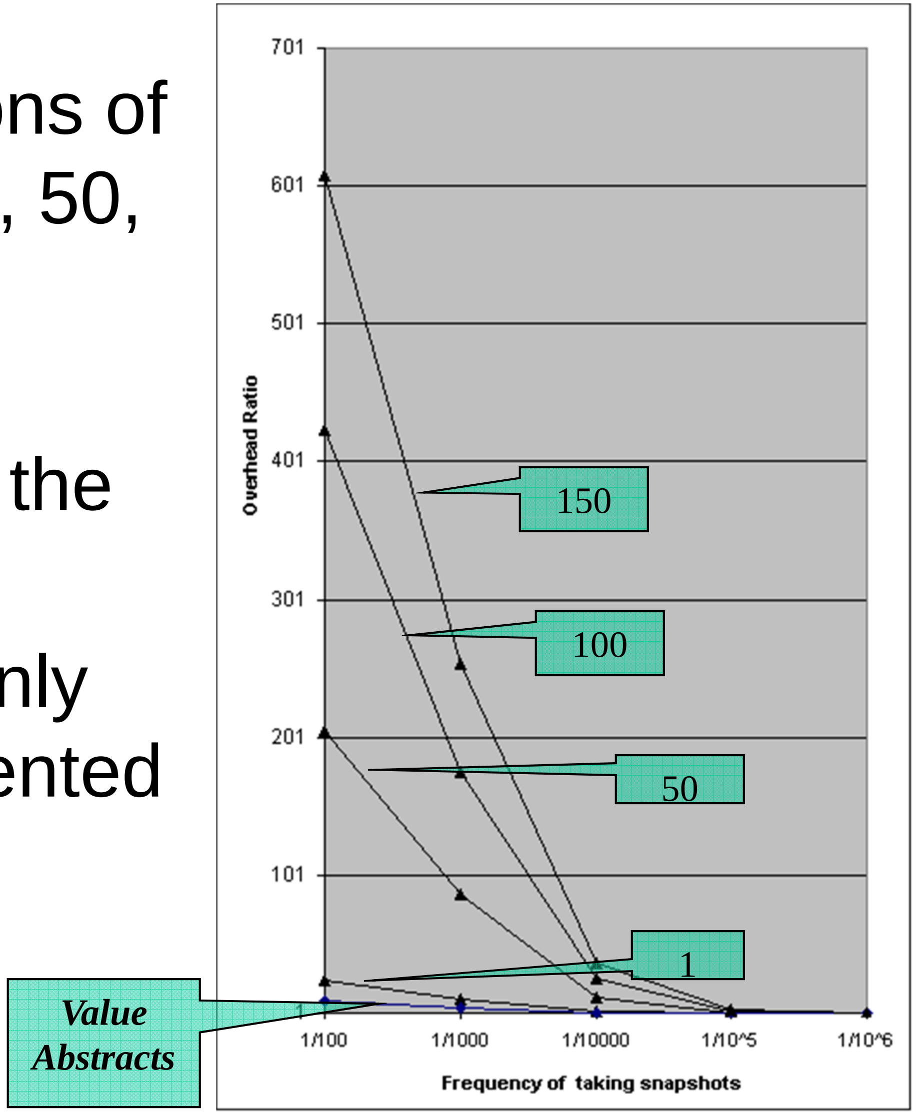
Probe Overhead

- Measure overhead over various frequency of updating a monitored integer variable by the target program
- Value abstraction with 1,50,150,200 *simple expressions* to check



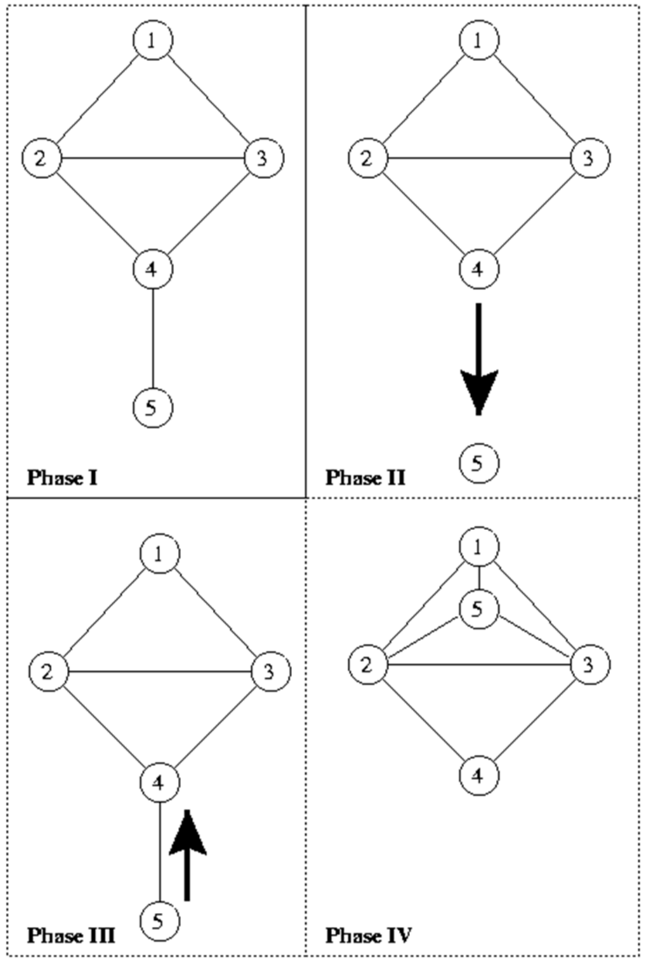
Overall Overhead

- Evaluating expressions of 4 different lengths (1, 50, 100, 150)
- Value abstraction significantly reduces the overhead
- The overhead is mainly due to the object-oriented implementation of `pedl.out`



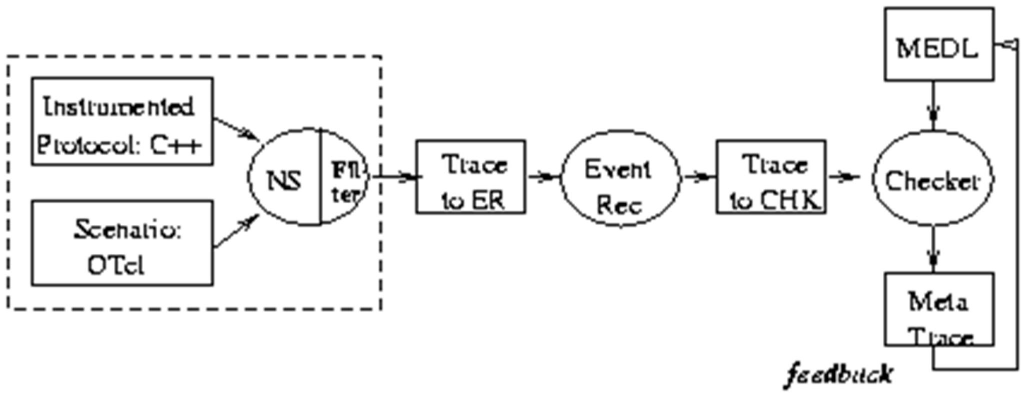
Case Study: Routing Protocol Validation

- Ad-hoc On Demand Vector (AODV) routing protocol used in packet radio networks consisting of mobile nodes
- Detect violations of properties such as loop invariant in AODV routing protocol implemented using NS2 simulator [Bhargavan,etc]



Case Study: Routing Protocol Validation (*cont.*)

- NS2 simulator is used instead of target Java program
- Execution trace containing packets delivered among nodes is analyzed repeatedly with different property descriptions without running the simulation again



Contributions

- Main contribution
  - Confirming the idea that run-time formal analysis can assure a user of the correctness of program execution in a *practical* manner through the implementation of the MaC architecture.
- Technical contributions
  - Rigorous analysis
  - Flexibility
  - Automation
  - Easy of use

Future Works

- Loosen the restriction on monitoring objects
  - Combined approach of instrumenting classfiles and modified Java virtual machine
- Apply value abstraction in more general way to gain the benefit of abstraction broadly
- Real-time extension of Java-MaC
- Application areas