MarQ: Monitoring At Runtime with QEA

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in collaboration with

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Outline

Runtime Monitoring

Quantified Event Automata

Efficient monitoring

Using MarQ

Motivation

- See lots of other talks for why we want formal guarantees about correctness of software systems

- Static verification has many successes but
  - It can have scalability issues
  - It often works with abstractions of the real system
  - It often needs to make assumptions about the environment and input data

- Runtime verification is a complementary technique that tackles these issues by ‘verifying’ a single run of the system
- Additionally, if performed at runtime it can be used to *stop* or *correct* bad behaviour

Runtime Monitoring Problems

Runtime Monitoring

Checking whether an execution trace τ produced at runtime satisfies a given a (typically temporal) specification ϕ

Online Runtime Monitoring

Performing runtime monitoring alongside the running system.

Offline Runtime Monitoring

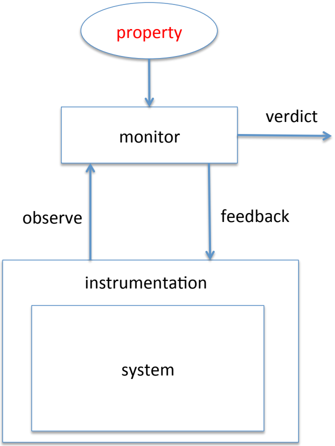
Performing runtime monitoring on a log file after running the system.

Parametric Runtime Monitoring

Runtime monitoring with *first-order* specifications i.e. ones that deal with data-carrying events

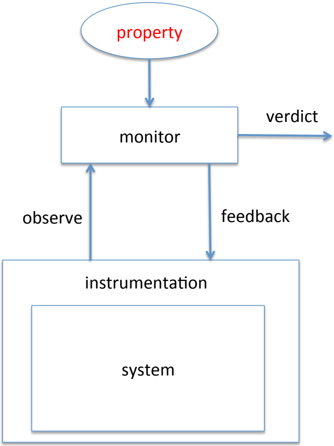
Online Runtime Monitoring Setup

Instrument the system to observe a trace of relevant events



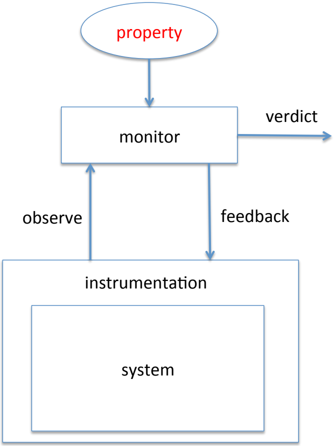
Online Runtime Monitoring Setup

The monitor uses the given property . . .



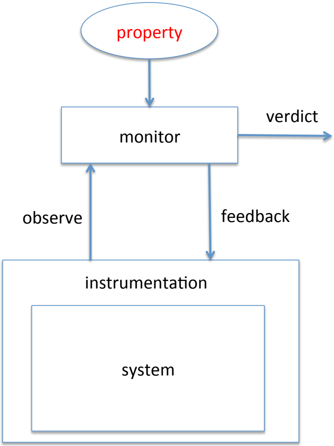
Online Runtime Monitoring Setup

. . . to process each event . . . possibly providing feedback. . .



Online Runtime Monitoring Setup

. . . and finally computing a verdict - did the system pass?



Online Runtime Monitoring in Practice

- Lots of pragmatic considerations
  - Instrumentation
  - Overhead
  - Interference
- Commonly shown to be useful for checking usage of libraries - successful application to large open source projects
- Recent industrial successes in the banking industry for monitoring reliability and correctness
- Applicable to safety-critical systems i.e. aerospace, automotive, medical.

Offline Runtime Monitoring in Practice

- Idea: record behaviour and check afterwards
  - Gives minimal/predictable overhead
  - Applies to more general domains/settings
  - Only get what is recorded
- Offline RV successes at NASA's JPL
  - Used on the LADEE mission to check command sequences sent to the spacecraft as part of a daily testing regime
  - Used daily on the MSL mission to check rules against Spacecraft telemetry logs sent from Curiosity

Parametric (or first-order) Properties

- Originally runtime verification considered properties over event names i.e. using propositional LTL or automata
- A *parametric event* consists of a name and a list of data values
- Examples:
  - An iterator i created from a collection c should not be used after c is updated
  - Every `start`(t) should have a corresponding `stop`(t)
  - If locks l_1 and l_2 are taken in one order by a thread t then later they should not be taken in the reverse order by any thread
- Introduces new challenges in terms of specification languages and monitoring algorithms

Contributions

- We introduce the MarQ runtime monitoring tool
- MarQ stands for Monitoring at runtime with QEA
- Quantified Event Automata (QEA) is a previously introduced specification language for parametric specifications

MarQ

- Can be used *offline* and *online*
- Supports all features of the QEA language
- Is efficient
    - Won the Offline and Java tracks of the CRV14, the first international competition on runtime verification.
    - Incorporates novel indexing, redundancy elimination and structural specialisation techniques

Outline

The Slicing idea

- Based on the notion of *parametric trace slicing*
  - Turns a quantified problem into a set of unquantified problems
- The basic idea of QEA
  1. Use a list of *quantifications* to define *trace slices* relating to separate valuations of quantified variables
  2. Use an *extended finite state machine* to check properties over those slices
  3. The quantifications define which trace slices need to be accepted by the state machine

Quantified Event Automata

Definition (Event Automaton)

An Event Automaton $\langle Q, \mathcal{A}, \delta, q_0, F \rangle$ is a tuple where

- Q is a set of states,
- $\mathcal{A} \subseteq \mathit{SymbolicEvent}$ is a alphabet of events,
- $\delta \subseteq (Q \times \mathcal{A} \times \mathit{Guard} \times \mathit{Assign} \times Q)$ is a set of transitions,
- q_0 is an initial state, and
- $F \subseteq Q$ is a set of final states.

Definition (Quantified Event Automaton)

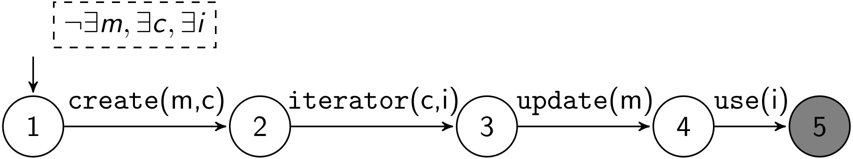
A QEA is a pair $\langle \Lambda, \mathrm{E} \rangle$ where

- $\Lambda \in (\{\forall, \exists\} \times \texttt{variables}(\mathrm{E}) \times \mathit{Guard})^*$ is a list of quantified variables with guards, and
- E is an Event Automaton

UnsafeMapIterator Example

Property : UnsafeMapIterator

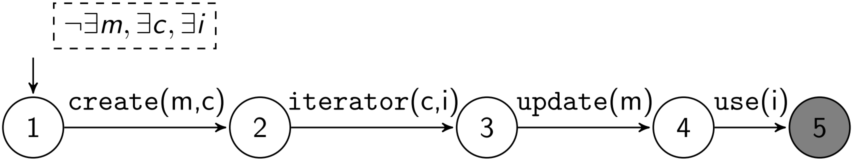
An iterator created from a collection created from a map should not be used after the map is updated.



Demonstrating slicing

$\texttt{create}(M, C1).\texttt{iterator}(C1, I1).\texttt{use}(I1).\texttt{update}(M).\texttt{create}(M, C2).$
$\texttt{iterator}(C2, I2).\texttt{iterator}(C2, I3).\texttt{use}(I3).\texttt{update}(M).\texttt{use}(I2)$

There are six possible bindings



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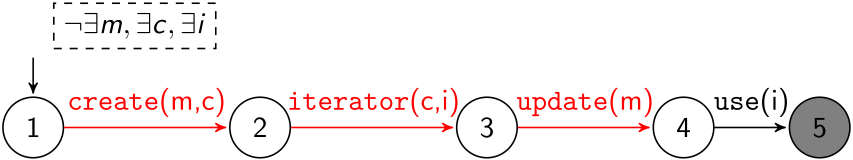
For $m = M$, $c = C1$, $i = I1$



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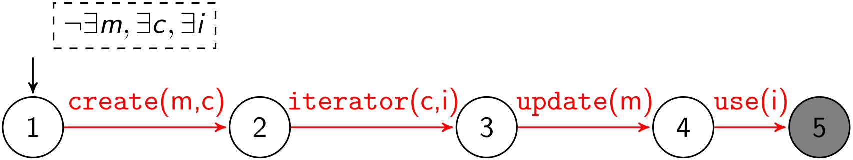
For $m = M$, $c = C2$, $i = I2$



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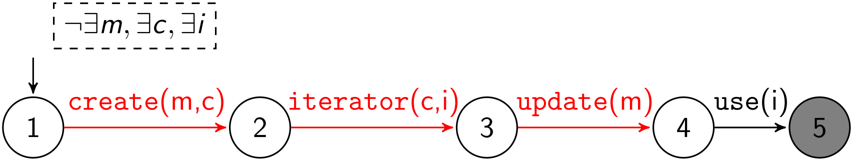
For $m = M$, $c = C2$, $i = I3$



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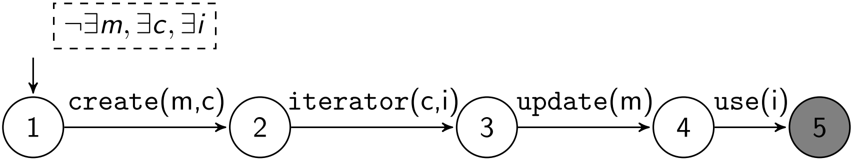
There exists a slice that reaches a final state. The quantifications mean that the trace violates the property.



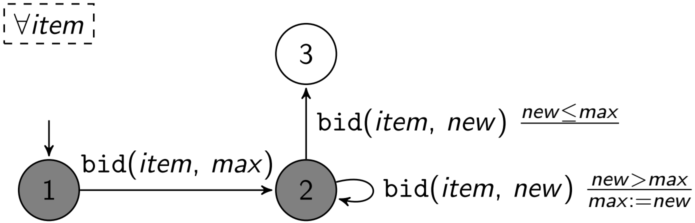
Free Variables

- Some variables in the Event Automaton may not be quantified
- These are called free variables
- Free variables are (re)bound as the trace is processed
- Allowing us to capture changing data values

Auction Bidding Example

Property : Auction Bidding

Amounts bid for an item should be strictly increasing.



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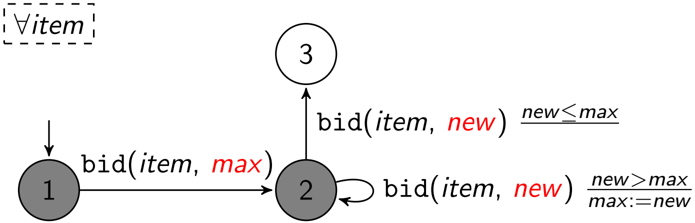
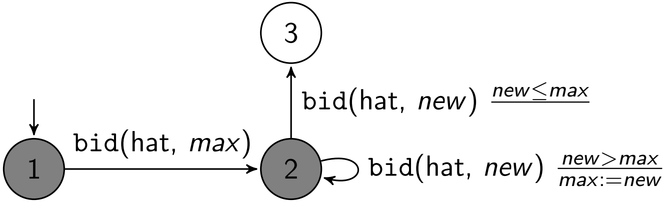


Bidding For A Hat

bid(hat, 5).bid(hat, 10).bid(hat, 7)



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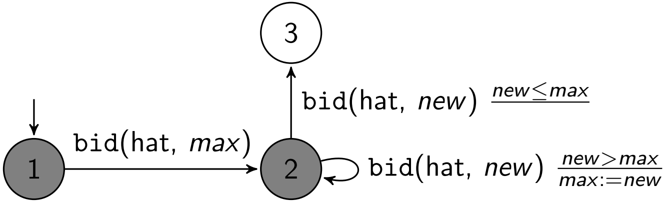

$\langle 1, [\ ]\rangle$

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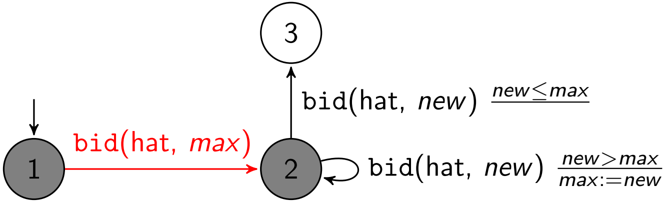

$\langle 1, [\,]\rangle \xrightarrow{\texttt{bid}(\text{hat},5)} \langle 2, [max \mapsto 5]\rangle$

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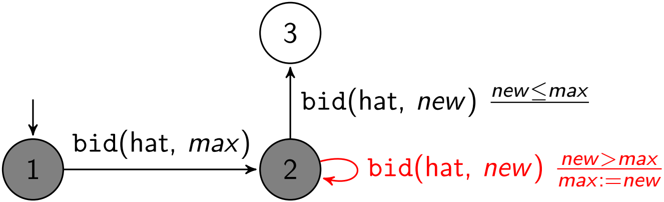

$$\langle 1, [\ ]\rangle \xrightarrow{\texttt{bid}(\text{hat},5)} \langle 2, [max \mapsto 5]\rangle$$

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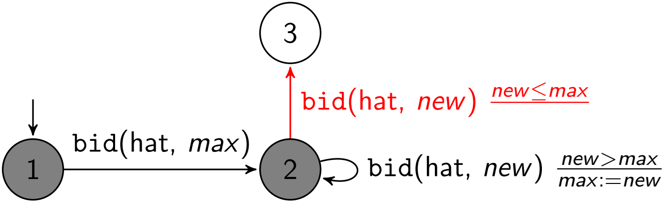

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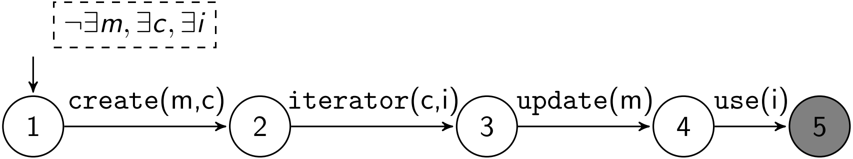

Monitoring algorithm

The monitoring algorithm is organised as follows

- There is a map M from bindings (of quantified variables) to sets of configurations (reached by that slice)
- For each incoming event
  - Decides if new bindings need to be created, possibly extending existing bindings
  - Updates configurations related to existing relevant bindings
  - Produces a verdict based on the quantifications and M

bindings		configurations
m=M1,c=C1	$\longrightarrow$	{ 2 }
m=M1,c=C1,i=I1	$\longrightarrow$	{ 3 }

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- For each incoming event `update(M1)`
  - Decides if new bindings need to be created, possibly extending existing bindings
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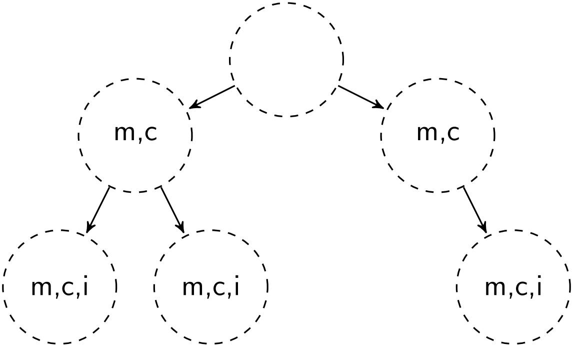
Efficient monitoring with MarQ

- Obviously for *online* monitoring *overhead* and *interference* are very important
- For *offline* monitoring we still need practically efficient trace processing

- MarQ achieves efficient monitoring in three ways
  - Indexing
  - Redundancy elimination
  - Structural specialisation
- We give a flavour of these techniques here

Indexing

- The monitor needs to track the status of different valuations of quantified variables
- Given an event it needs to *quickly* find what needs to be updated. This is the indexing problem.
- MarQ uses *symbol-based indexing*



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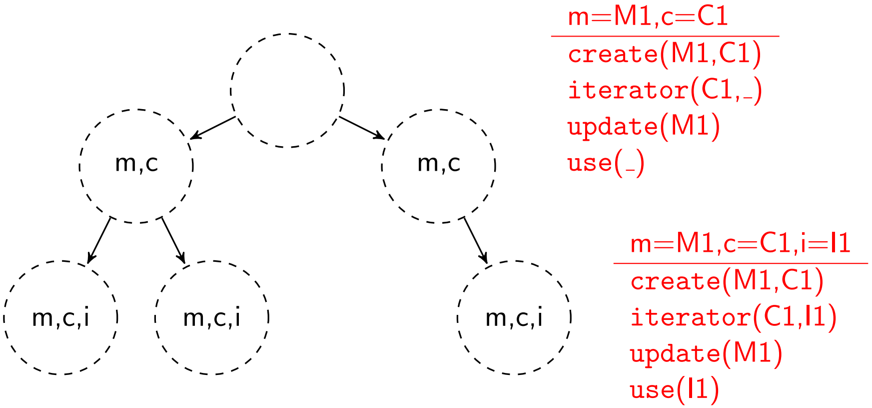

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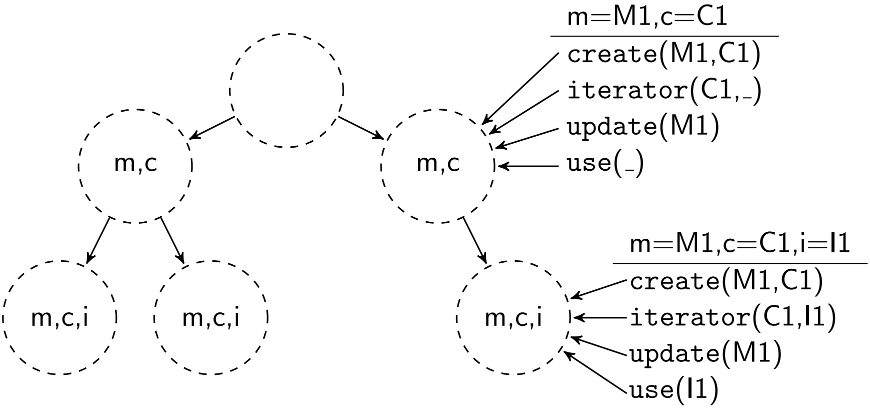

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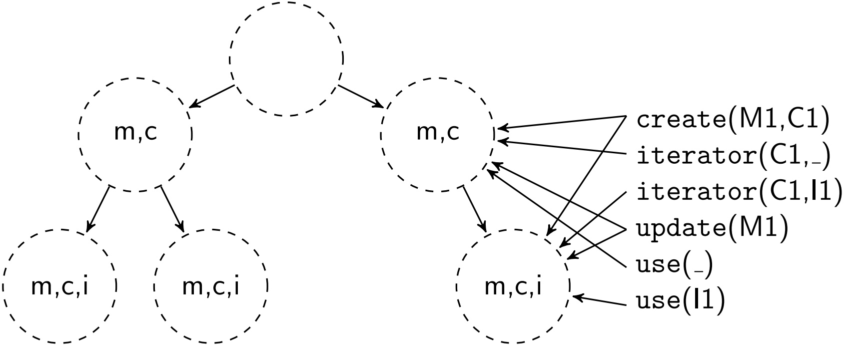

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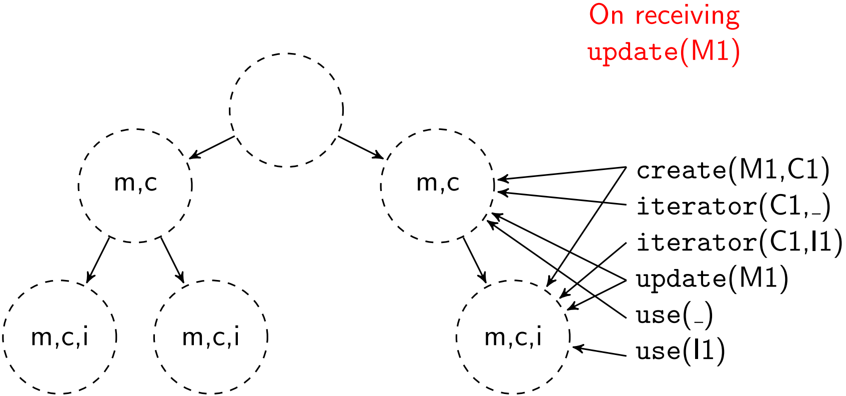

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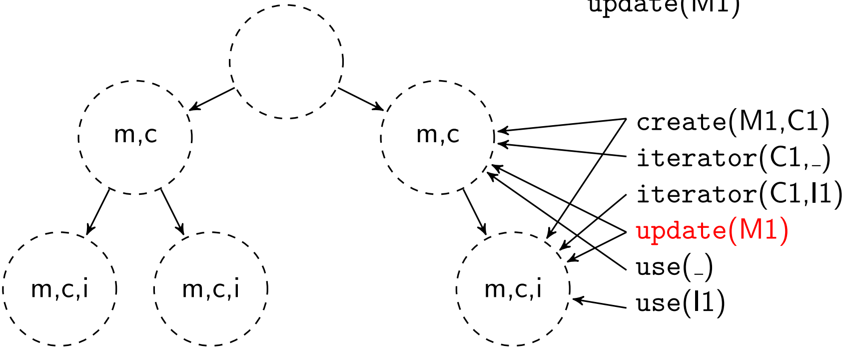
On receiving
update(M1)



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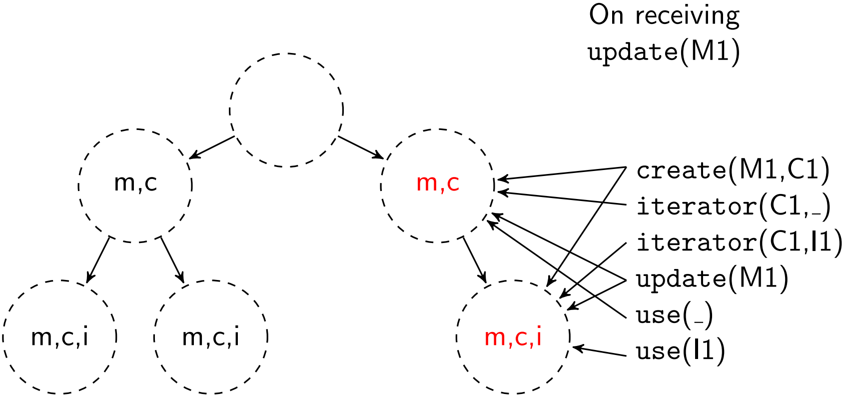

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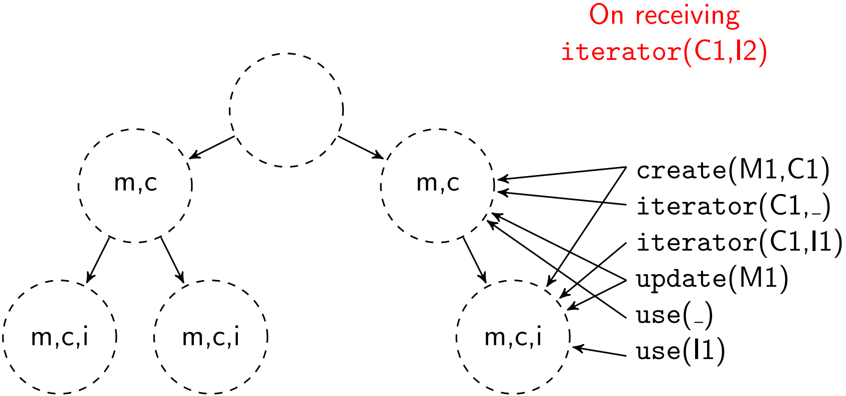

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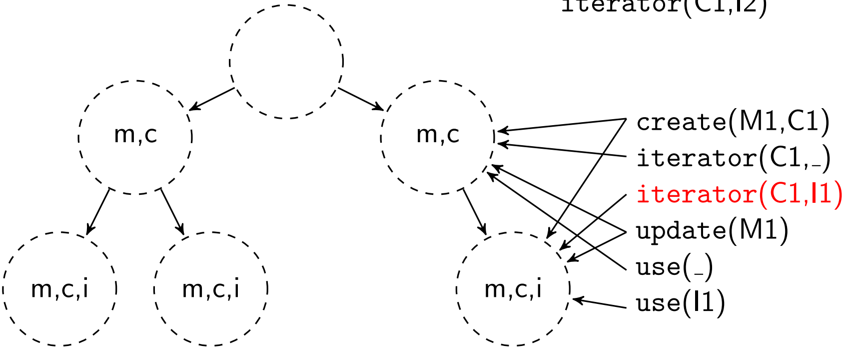
iterator(C1,I2)



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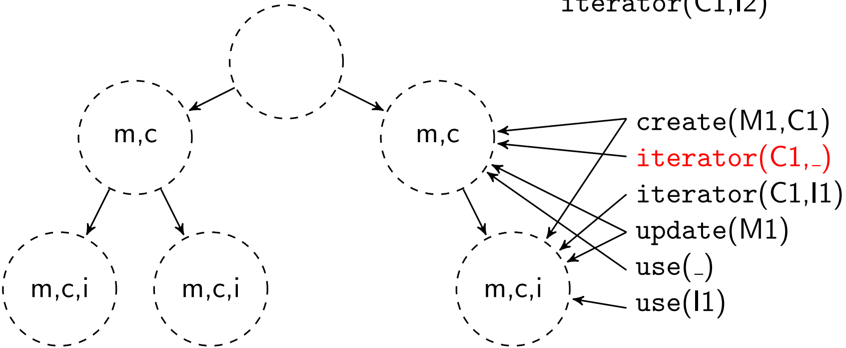

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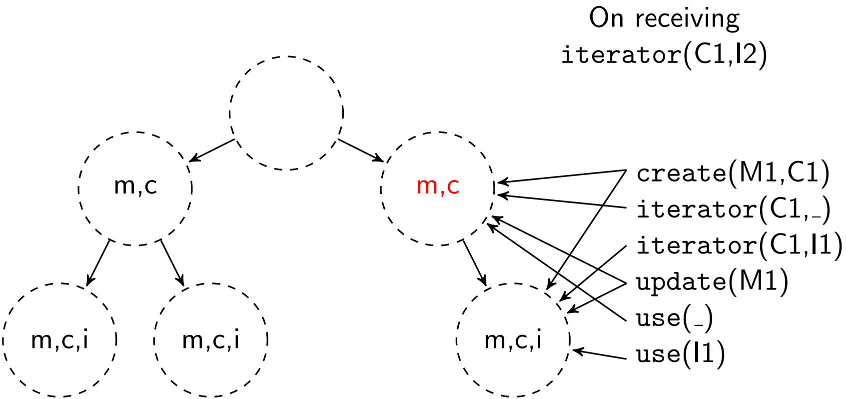

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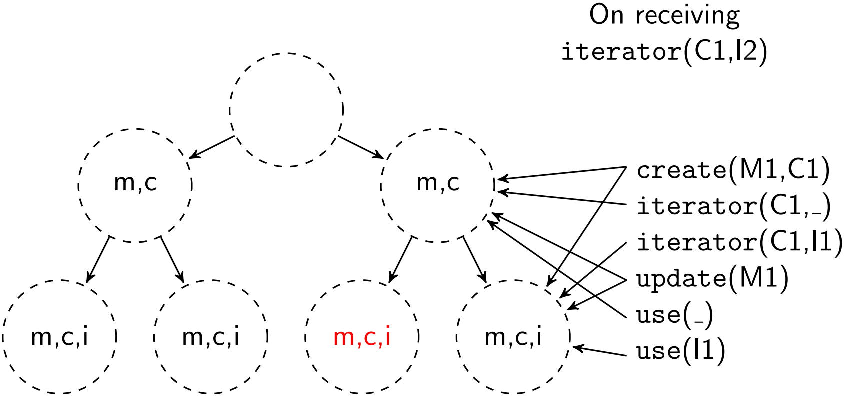
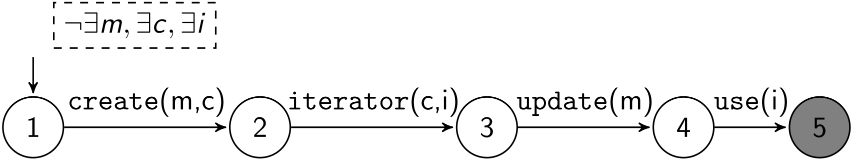


Redundancy elimination



- Given this specification there are two observations
  1. A binding m=M,c=C does not need to be extended for use(I) as this does not tell us anything new
  2. If a monitored object is garbage collected it can no longer contribute to a failing trace slice
- Generalising these gives us a theory of *redundancy elimination* that ignores or removes bindings of quantified variables

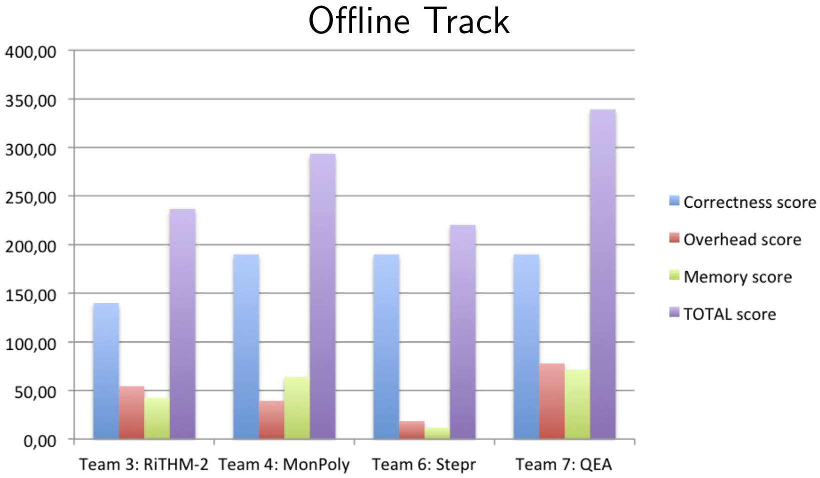
Structural specialisation

- Not all features of the QEA specification language are needed for every specification i.e. non-determinism, free variables
- However supporting these features makes the monitoring algorithm more complex

- Structural specialisation produces a monitoring algorithm based on the structure of the specification using special data structures

- Motivation: monitoring is the frequent repetition of the same small bit of code

Results of the 1st compeititon on Runtime Verification



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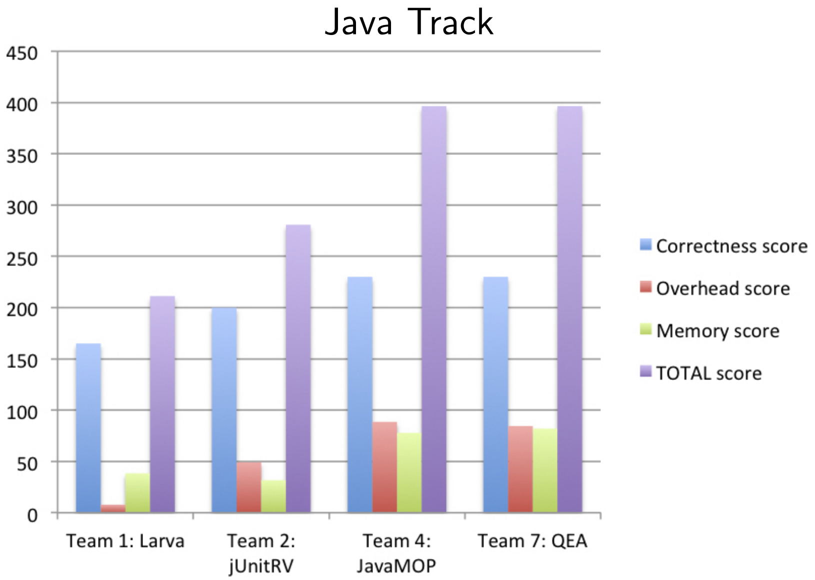


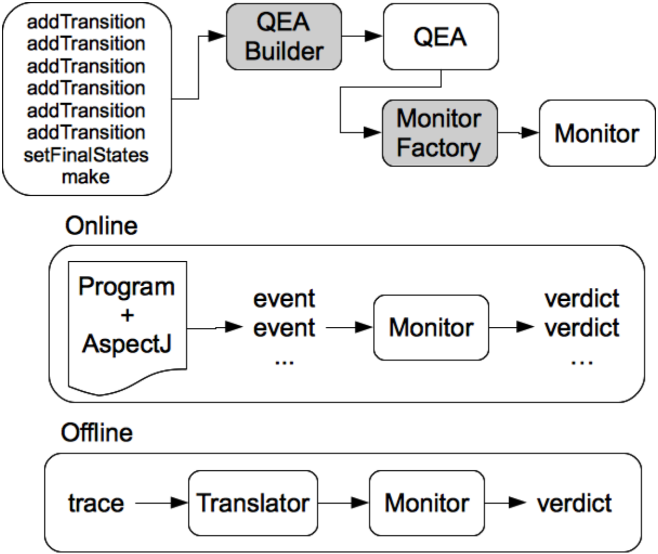
Writing specifications with efficiency in mind

- Efficiency of the monitoring algorithm depends on the *structure* of the specification
- Therefore the way the specification is written matters

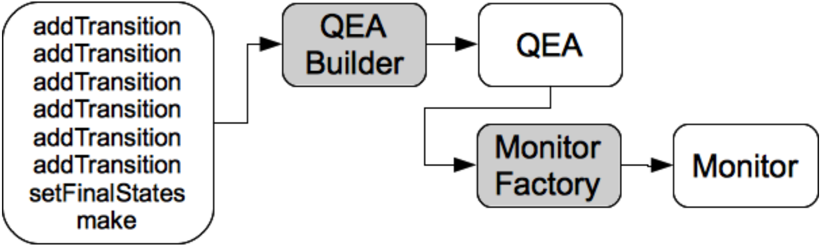
- Can achieve an order of magnitude speedup by changing the way the property is expressed

Outline

Separating specification and usage



Writing QEA specifications in MarQ



- The QEA Builder uses an API to construct a QEA
- The MonitorFactory constructs a monitor from that specification

The QEA Builder

```
QEABuilder q = new QEABuilder("safeiter");

int ITERATOR = 1; int NEXT = 2;
final int i = -1; final int size = 1;
q.addQuantification(FORALL, i)

q.addTransition(1,ITERATOR, i, size, 2);
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The QEA Builder

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QEABuilder q = new QEABuilder("safeiter");

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The Monitor Factory

```
public interface Monitor{
    public Verdict step(int name, Object[] args);
}
```

```
Monitor monitor = MonitorFactory.create(
    qea,
    GarbageMode.LAZY,     //Optional
    RestartMode.REMOVE); // Optional
```

- A monitor is an object accepting events and producing verdicts
- The factory will analyse the specification and produce the best monitor it can (i.e. using *structural specialisation*)
- Optional modes
  - Garbage: handling monitored objects that are garbage collected
  - Restart: what to do when a violation occurs

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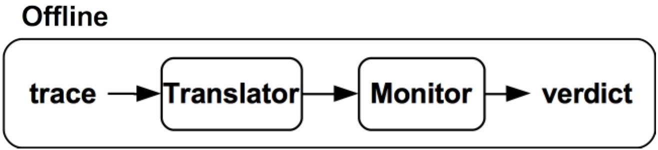
Offline monitoring with MarQ



- We first create a `Translator` object for the trace
- Then using a `QEA` object and trace string we create a monitor
- Finally we call `monitor` to get a result

Offline monitoring with MarQ

```
OfflineTranslator translator =
    new DefaultTranslator(``a'', ``b'',``c'');
String trace = ``trace_dir/trace.csv'';
QEA qea = builder.make();
CSVFileMonitor m =
    new CSVFileMonitor(trace_name, qea, translator);
Verdict v = m.monitor();
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Trace formats

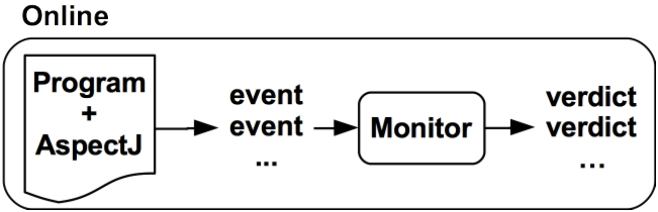
- We support three trace formats proposed by the RV competition
    - CSV
    - JSON
    - XML
- We also provide tools for translating between formats
- Parsing is surprisingly important.
    - MarQ has an optimised parser for the CSV format
    - Also aparallel option that separates trace processing and monitoring.
- Parsers produce abstract event objects handled by translators before being passed to the monitor

Translators

- Translators map abstract events to monitor `step` calls
- They tackle three pragmatic issues

1. Name mappings
   - Map between event names used in the trace and specification
   - May not be one-to-one
2. Reordering parameters
   - The events recorded in the trace may not have the same structure as in the specification
   - Parameters may be reordered or removed
3. Interpreting values
   - Data values in events may need to be treated semantically
   - i.e. parsing into integers
   - May need to ensure values are *interned*

Online monitoring with MarQ



- Currently MarQ supports monitoring `Java` programs via `AspectJ`
- Instrumentation should handle verdicts
- However, we do not yet automatically generate `AspectJ`
- This is work in process, along with targetting other languages

Instrumentation with AspectJ

```
public aspect SafeIterAspect {

  private int ITERATOR = 1; private int NEXT = 2;
  private Monitor monitor;

  SafeIterAspect(){
    QEA qea = SafeIter.get();
    monitor = MonitorFactory.create(qea);
  }

  ...
```

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Instrumentation with AspectJ

```
pointcut iter(Collection c) :
  (call(Iterator Collection+.iterator()) && target(c));
pointcut next(Iterator i) :
  (call(* Iterator.next()) && target(i));

after (Collection c) returning (Iterator i) : iter(c) {
    synchronized(monitor){
      check(monitor.step(ITERATOR,i,c.size()));
    }
}
before(Iterator i) : next(i) {
    synchronized(monitor){
      check(monitor.step(NEXT,i));
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}
```

Instrumentation with AspectJ

```
 ...

 private void check(Verdict verdict){
     if(verdict==Verdict.FAILURE){ <report error here> }
 }
}
```

Future work

- External specification language
- Automated generation of instrumentation code
- Transformations from other Runtime Monitoring specification languages into QEA i.e. temporal logics, rule-based systems
- Automated transformations into syntactic classes with better efficiency guarantees
- Violation explanation

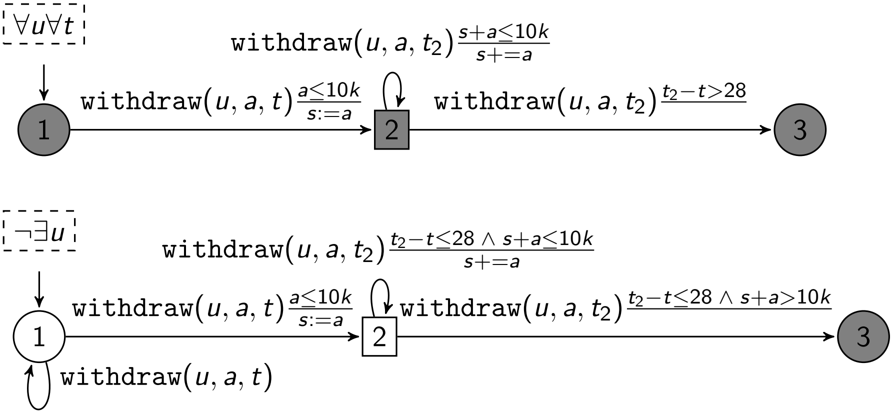
And finally...

- The tool is available online

  `https://github.com/selig/qea`

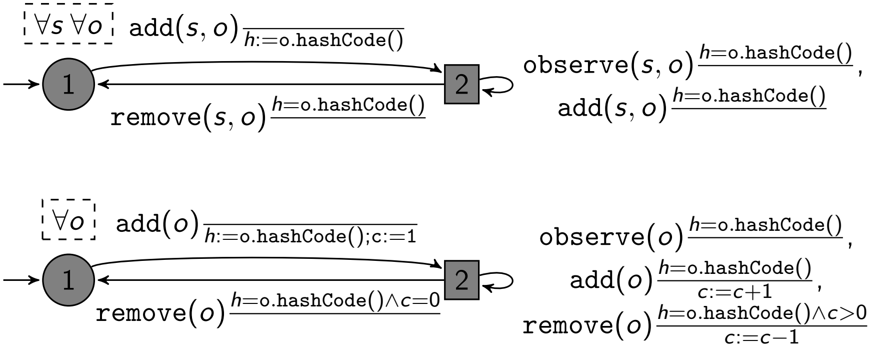
- Thanks for listening

Non-determinism



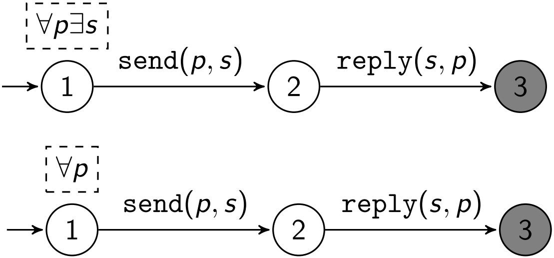
- By introducing non-determinism we can remove a quantifier
- The idea is to have a path through the automata for each t
- There is a trade-off between complexity in quantification and non-determinism

Counting



- By making certain assumptions about how trace slices for a quantifier are related we can track instances with a counter
- Transformation needs more information than is in the specification

Quantifier stripping



- Existential quantifiers on the right can be stripped
- This is a trivial case, more complex cases involve the introduction of guards and non-determinism

Big impact

Property	Trace length	Runtime (milliseconds)		Speedup
		Original	Translated	
withdrawal	150k	3,050	2,106	1.44
persistenthash	4M	12,267	864	14.12
publishers	200k	355	37	9.59

- Can achieve an order of magnitude speedup
- A phenomenon not often talked about in RV papers
- Further work: automate these transformations