CS 6156 Runtime Verification

Events, Traces, Properties, and Specification Languages

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Spring 2022

Some logistics

- Reading 2 is in progress (due 2/3 at 7:59am ~~AoE~~ Eastern)
- Homework 1 will likely be released on 2/3 (due 2/8 at 7:59am AoE)
- Three PhD students are yet to talk to me about projects
- Project proposals are due 2/8

Concepts discussed in this class

- RV checks traces of system events against properties that are specified in some language

- But, what do the terms in blue mean?

- These terms occur a lot in the RV literature

Let's discuss…

- What is an event?

something that we can observe during system exec
most atomic "thing"

- What is a trace?

One path through a CFG
a sequence of events that happened during exec

- What is a property?

certain sequences of events
a way to describe a set of traces

What is an Event?

- A mathematical (formal languages) view
  - An event as a symbol *e* in an alphabet Σ, where Σ is a finite set of such symbols
- A logical view
  - An event as an atomic predicate in a logical formula
- A practical view
  - An event as a state/step during system execution

When/how you'll see these views

- View of events as symbols is common when defining concepts or proving theorems in RV

- View of events as atomic predicates is often used when specifying properties

- View of events as execution state/steps is required for defining what to observe in system executions

Instrumentation

Example: CSC spec from last class

https://docs.oracle.com/javase/7/docs/api/java/util/Collections.html#synchronizedCollection(java.util.Collection)

synchronizedCollection

```
public static <T> Collection<T> synchronizedCollection(Collection<T> c)
```

It is imperative that the user manually synchronize on the returned collection when iterating over it:

```
  Collection c = Collections.synchronizedCollection(myCollection);
     ...
  synchronized (c) {
      Iterator i = c.iterator(); // Must be in the synchronized block
      while (i.hasNext())
         foo(i.next());
  }
```

Obtain lock
release lock

iterator Obtain
iterator Close

Failure to follow this advice may result in non-deterministic behavior.

What events (execution states/steps) do we care about?

Example: events in the CSC spec

Demo

What view(s) of events are in CSC?

Logical

Practical

Events as execution states/steps

- Examples: method calls, field/variable access, lock acquisition/release
- One often must define the conditions under which to observe the execution step → instrumentation

```
event syncCreateIter after(Object c)
        returning(Iterator iter) :
        call(* Collection+.iterator())
        && target(c) && if(Thread.holdsLock(c)){}
```

- Events can carry data, or they can be parametric

What view of events is this? (1)

- A property is a logical formula over a set of events[1]

[1] Legunsen et al., Techniques for Evolution-Aware Runtime Verification, ICST 2019

What view of events is this? (2)

An RV tool instruments the program based on the properties so that executing the instrumented program generates events and creates monitors that listen to events and check properties?[1]

[1]Legunsen et al., Techniques for Evolution-Aware Runtime Verification, ICST 2019

What view of events is this? (3)

- A bad prefix is a finite sequence of events which cannot be the prefix of any accepting trace.[2]

[2]d'Amorim et al., Efficient Monitoring of ω-Languages, CAV 2005

Takeaway message on events

- Events are fundamental in RV theory and practice
- But RV literature will often mix the different views of events
- So, when you read papers on RV, be careful to distinguish these views

Any questions about events?

?

What is a trace?

There are many notions/views of traces in RV, e.g.,

What Is a Trace? A Runtime Verification Perspective

Giles Reger[1(✉)] and Klaus Havelund[2]

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[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

http://havelund.com/Publications/traces-isola-2016.pdf

What is a trace? Some views..

- A trace is a sequence of events
  - In practice: sequences are finite
  - In theory: we reason about infinite sequences (why?)

- If events are symbols in an alphabet Σ, traces are strings (or words) in Σ *
  - So, we can talk about (in)finite prefixes/suffixes of traces

What is a trace? (A definition)

Let Σ be a set of events. A Σ**-trace** (or simply a **trace** when Σ is understood or not important) is any finite sequence of events in Σ, that is, an element in Σ^*. If event $e \in \Sigma$ appears in trace $w \in \Sigma^*$ then we write $e \in w$.[3]

[3]Rosu and Chen, Semantics and Algorithms for Parametric Monitoring, LMCS 2012

Example 1: events and traces

Consider a resource (e.g., a synchronization object) that can be acquired and released during the lifetime of a procedure (i.e., between when the procedure begins and when it ends).

1. *What events do we care about?*

   acquire, release
   begin, end

2. *What is an example trace over events in 1?*

   begin end acquire release X
   end begin X

“Good” and “bad” traces

- From example 1, are these good or bad traces:
  - begin acquire release end
  - begin acquire acquire release end
  - begin acquire acquire release release end

- Properties formalize notion of “good” or “bad” traces

- Intuition: traces validate or violate a property depending on how the property is specified

What is a property?

- A property is a set of traces
  - may include "good" traces and exclude "bad" traces
  - or, it may exclude "good" traces and include "bad" traces CSC

- Alternately, a property is a language of acceptable or unacceptable traces (a subset of Σ^*).

- In practice, can you think of why set/language inclusion/exclusion may be insufficient for RV?

Are these definitions sufficient?

- If “good” properties in example 1 are those in which an acquired resource is released before the procedure ends. Are these “good” or “bad” traces?
  - begin acquire release ~~acquire~~ end
  - begin acquire acquire
- Partial traces may be in “don’t know” category
  - future events may lead to including/excluding the trace
- We need to build on the idea of partitioning traces into categories

Properties: another definition

A monitor realizes P

An Σ-**property** P (or simply a **property**) is a function $P : \Sigma^* \to C$ partitioning the set of traces into (verdict) categories C.

Partial or total function?

- This definition is a better basis for monitoring
  - C can be any set, e.g., {validating, violating, don't-know}
  - C is chosen depending on the specification language and the property being specified

Properties partition sets of traces (1)

- Let regular expressions (RE) be the spec language and choose C = {match, fail, dont-know}

- Then an RE, E, specifies property P_E, defined as:
  - **$P_E(w)$ = match** iff w is in the language of E
  - **$P_E(w)$ = fail** iff $\nexists$ w' $\in$ Σ^* s.t. ww' is in the language of E
  - **$P_E(w)$ = dont-know** otherwise

- This is the semantics of monitoring RE in JavaMOP

Properties partition sets of traces (2)

- Let regular expressions (RE) be the spec language and choose C = {match, dont-care}
- Then for any RE, E, its property P_E can be defined as
  - **$P_E(w)$ = match** iff w is in the language of E
  - **$P_E(w)$ = dont-care** otherwise
- This is the semantics of monitoring RE in tracematches[4]

Same spec language, different semantics

[4]Allan et al., Adding Trace Matching with Free Variables to AspectJ, OOPSLA 2005

Examples: CSC-related traces

- CSC specifies “bad” traces as a regular expression:
  - (sync asyncCreateIter) | (sync syncCreateIter accessIter)
- One matching trace:
  - sync asyncCreateIter accessIter accessIter accessIter accessIter
- Another matching trace:
  - sync syncCreateIter accessIter accessIter accessIter accessIter accessIter

Properties: other things to know

- Can all interesting system behavior be defined as "sets of traces"?
  - No. Hyperproperties[5] are "sets of sets of traces".
- Properties are sometimes called "trace properties"
  - In contrast with "state properties", which are defined in terms of program values at a point in an execution
  - xUnit Assertions are examples of "state properties"

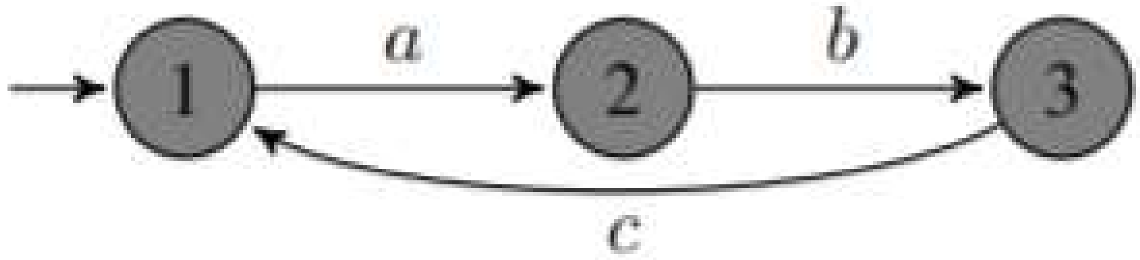
[5] Clarkson and Schneider, Hyperproperties, CSF 2008

Questions about traces/properties?

?

Properties: what specification language should we use?

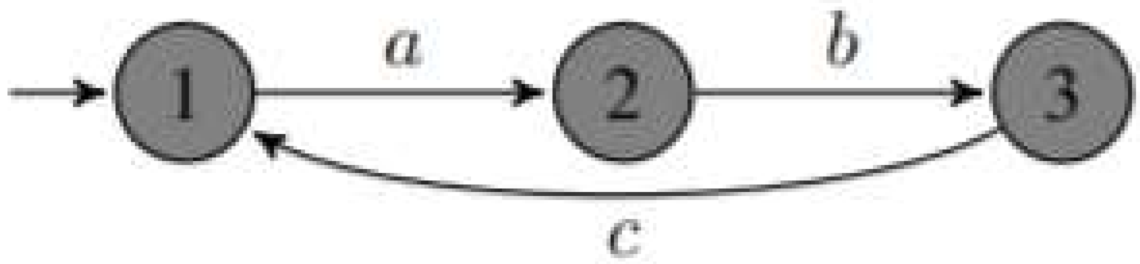
Grey node is accepting state
White node is rejecting state



Write the property specified by this FSM using RE

Properties: what specification language should we use? (2)

Grey node is accepting state
white node is rejecting state



Write the property specified by this FSM using RE

$$(a\, b\, c)^*(\epsilon \mid a \mid a\, b)$$

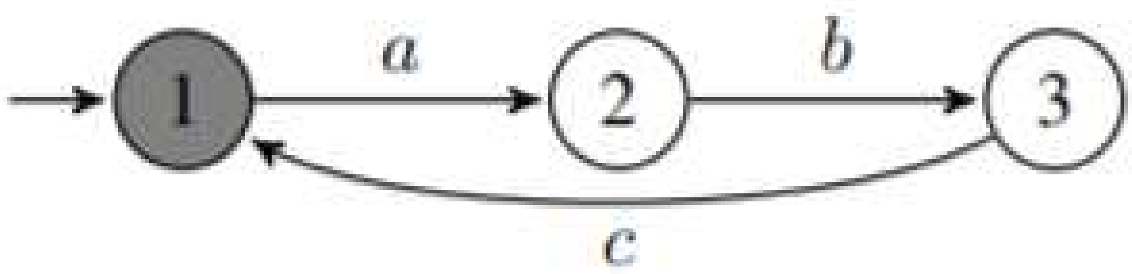
Properties: what specification language should we use? (3)

Grey node is accepting state
White node is rejecting state

A “convenient” translation of the FSM to RE

$$(a\ b\ c)^*$$

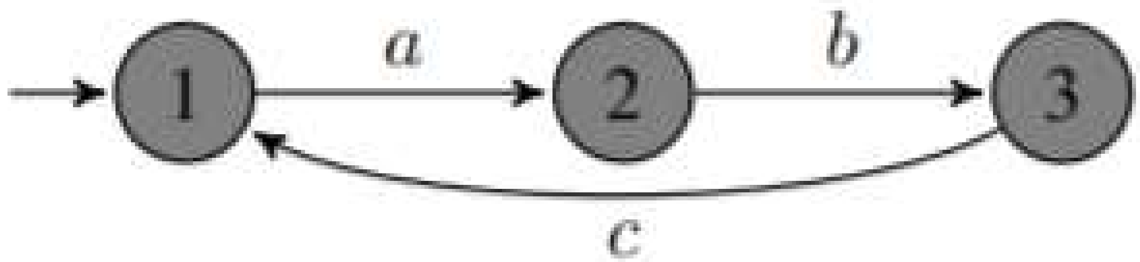
But is this what we really mean? (rejects traces **[a b]**, **[a]**)



It seems that what we really want is ***closure((a b c)*)***

Closure(E) ≡ E and all its prefixes

Properties: what specification language should we use? (4)



Wait… how does this FSM reject a trace like **[a a]** ?

Properties: what specification language should we use? (5)

- Some factors to consider:
  - How expressive is the language?
  - How “convenient” is that language for RV users?
  - Does the language’s semantics need to be adapted for RV?
  - If semantics is adapted for RV, what is the new semantics?
  - How expensive are the monitors that are synthesized?

A mini-survey of spec languages

Runtime Verification Logics
A Language Design Perspective

Klaus Havelund[1*] and Giles Reger[2**]

[1] Jet Propulsion Laboratory, California Inst. of Technology, USA
[2] University of Manchester, Manchester, UK

Questions on specification languages?

?

Recall: events can be parametric

- Events in real programs occur on different “objects”

Parameters

```

SafeSyncCollection(Object c, Iterator iter) {
```

- RV tools must be able to handle parametricity to correctly partition traces at runtime
  - Let’s look at an example

Acquire/release revisited

- Property: procedures must release acquired resources

- Spec: (begin(ϵ|(acquire(acquire|release)*release))end)*
  - Multiple “acquire” or “release” have the effect of acquiring or releasing the resource exactly once

- Categorize as a match, fail, or don’t-know (JavaMOP):

begin acquire acquire acquire release end begin acquire release end

Acquire/release revisited

- Same trace, but two different resources (r_1 and r_2):

begin‹› acquire‹r_1› acquire‹r_2› acquire‹r_1› release‹r_1› end‹›
begin‹› acquire‹r_2› release‹r_2› end‹›

- Categorize this parametric trace (JavaMOP)
  - Your answer:
  - Reason:

Monitoring a parametric trace (1)

- Intuition: split into two trace slices, one per resource

begin‹› acquire‹r_1› acquire‹r_2› acquire‹r_1› release‹r_1› end‹›
begin‹› acquire‹r_2› release‹r_2› end‹›

$$\Downarrow$$

begin‹› acquire‹r_1› acquire‹r_1› release‹r_1› end‹› begin‹› end‹›

&

begin‹› acquire‹r_2› end‹› begin‹› acquire‹r_2› release‹r_2› end‹›

Monitoring a parametric trace (2)

- Then, check the trace slices non-parametrically:

begin acquire acquire release end begin end

begin acquire end begin acquire release end

Parametric trace slicing

- Essential for monitoring real software

- Future discussion: definitions and algorithms for efficient trace slicing

- Defining parametric trace slicing and parametric monitoring needs definitions of
    - parametric events
    - parametric traces
    - parametric properties

Parametric events and traces

Let X be a set of **parameters** and let V be a set of corresponding **parameter values**. If Σ is a set of events, then let Σ⟨X⟩ denote the set of corresponding **parametric events** e⟨θ⟩, where e is an event in Σ and θ is a partial function in [X→V]. A **parametric trace** is a trace with events in Σ⟨X ⟩, that is, a string in Σ⟨X⟩*.

- Revisit these definitions in the class on trace slicing
- You now have an intuition for when you see these terms in RV papers

Parametric properties: examples

- Releasing acquired resources ✓
- Authenticate before use
- Safe iterators

Example: authenticate before use

- Property: keys must be authenticated before use
- LTL spec: $\forall k.\Box$(use $\rightarrow$ ◈uthenticate)
- Parametric trace:

authenticate‹k_1› authenticate‹k_3› use‹k_3› use‹k_2› authenticate‹k_2› use‹k_1› use‹k_2› use‹k_3›

- k_1 trace slice:
- k_2 trace slice:
- k_3 trace slice:

Example: safe iterators

- **Property:** when an iterator is created for a collection, do not modify the collection while its elements are traversed using the iterator
- **Events:** create‹*c, i*› creates iterator *i* from collection *c*, update‹*c*› modifies *c*, and next‹*i*› traverses *c*'s elements using *i*
- **RE Spec:** $\forall c, i.\, create\ next^{\,*}\ update^{\,+}\ next$
- **Parametric trace:**

create‹c_1, i_1› next‹i_1› create‹c_1, i_2› update‹c_1› next ‹i_1›

Example: safe iterators (your turn)

- **RE Spec:** $\forall c, i. create\ next^{\,*}\ update^{\,+}\ next$
- **Parametric trace:**

create‹c_1, i_1› next‹i_1› create‹c_1, i_2› update‹c_1› next ‹i_1›

- Questions:
  - Is there a trace slice that violates the spec?
  - If "yes", which pair(s) of parameters are in the slice?

What we discussed this week

- What is an event?
- What is a trace?
- What is a property?
- What are parametric events, traces, and properties?
- Intro to parametric trace slicing (to be continued…)

Any questions about events, traces, and parameters?

?