CS 6156
Events, Traces, and Properties

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Fall 2020

Some logistics

- Homework-0 is assigned, due 9/15 11:59pm AoE
  - Goal: getting your hands wet with RV

- Reading for next class is assigned
  - Goal prepare for more foundational topics in RV

- Thanks for submitting reading 1; we'll discuss some of your responses in class

Concepts discussed in this class

- Runtime verification checks traces of system events against properties

- But what do the terms in blue mean?

- These terms occur a lot in the RV literature

Let's discuss…

- What is an event?

  observable change of state

  abstract set of things we care about

- What is a trace?

  series of ordered events

  can be p.o., purpose is to describe execs

- What is a property?

  set of traces that meet some condition

  x ?

  membership.

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 in system/software execution

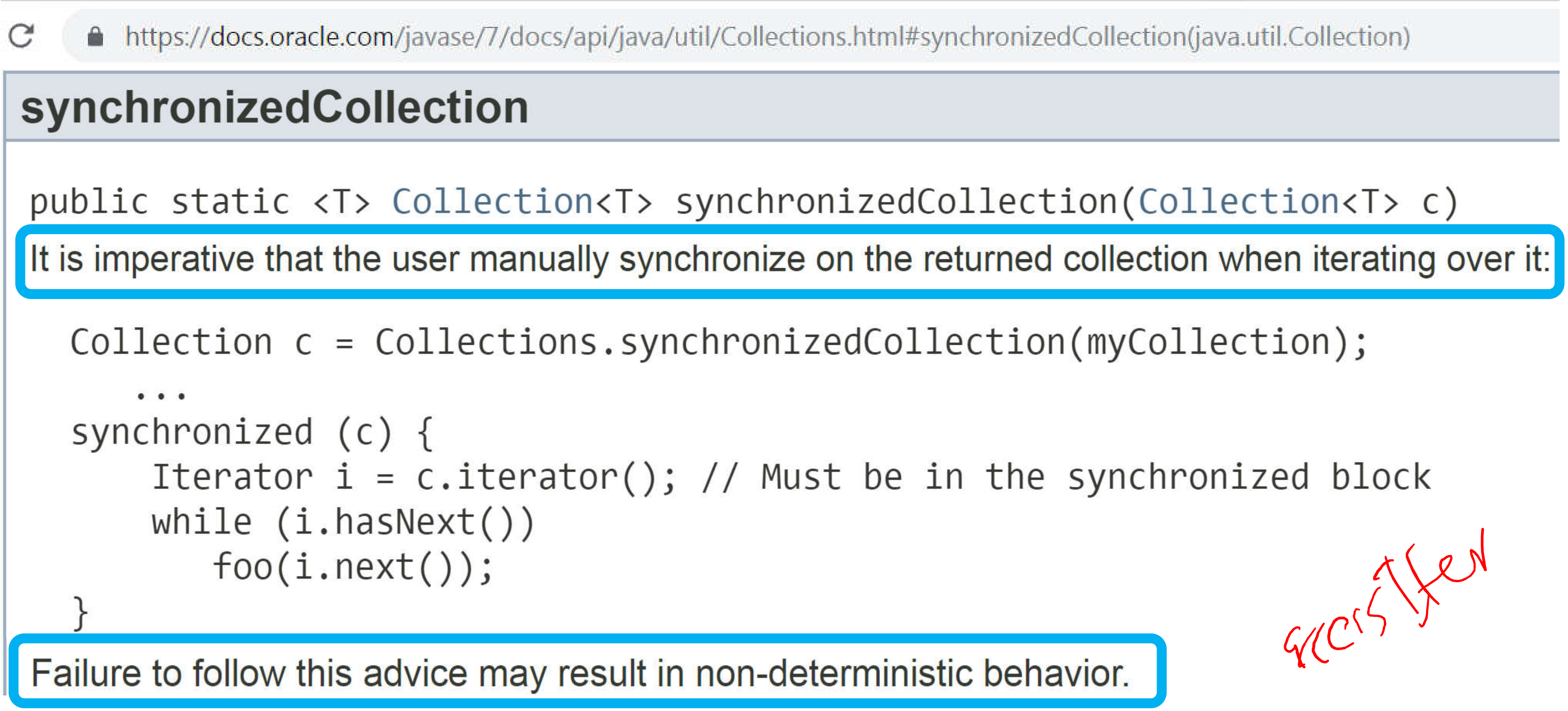
When/how you’ll see these views

- 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 steps is required when defining what to observe during system execution

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());
  }
```

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

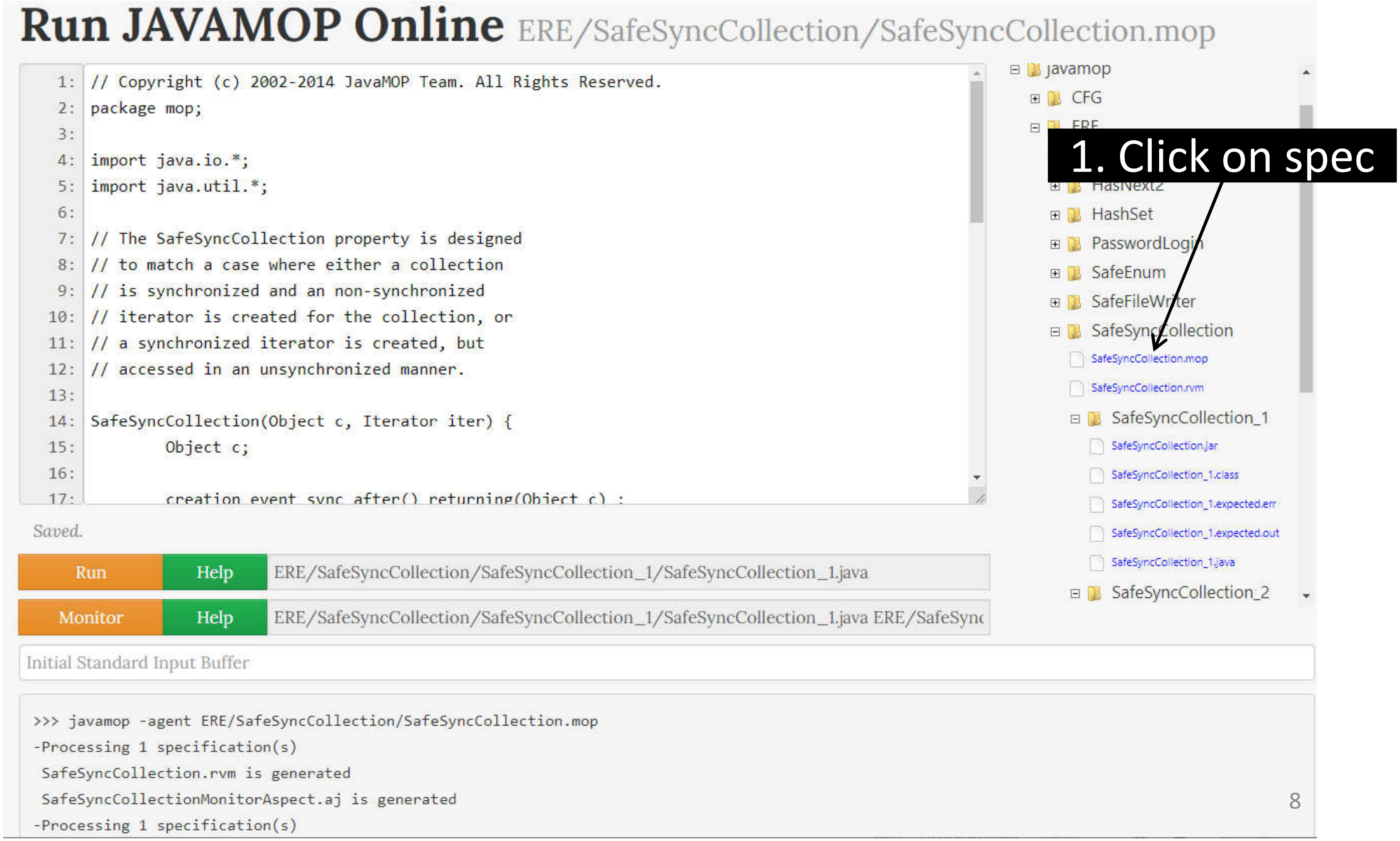
accessIter

- What events (execution states) do we care about?

syncCreate ~~begin~~ ~~exit~~ createIter

Example: events in the CSC spec

http://www.kframework.org/tool/run/javamop



Run JAVAMOP Online ERE/SafeSyncCollection/SafeSyncCollection.mop

```
// Copyright (c) 2002-2014 JavaMOP Team. All Rights Reserved.
package mop;

import java.io.*;
import java.util.*;

// The SafeSyncCollection property is designed
// to match a case where either a collection
// is synchronized and an non-synchronized
// iterator is created for the collection, or
// a synchronized iterator is created, but
// accessed in an unsynchronized manner.

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

        creation event sync after() returning(Object c) :
```

Saved.

ERE/SafeSyncCollection/SafeSyncCollection_1/SafeSyncCollection_1.java

ERE/SafeSyncCollection/SafeSyncCollection_1/SafeSyncCollection_1.java ERE/SafeSync

Initial Standard Input Buffer

```
>>> javamop -agent ERE/SafeSyncCollection/SafeSyncCollection.mop
-Processing 1 specification(s)
 SafeSyncCollection.rvm is generated
 SafeSyncCollectionMonitorAspect.aj is generated
-Processing 1 specification(s)
```

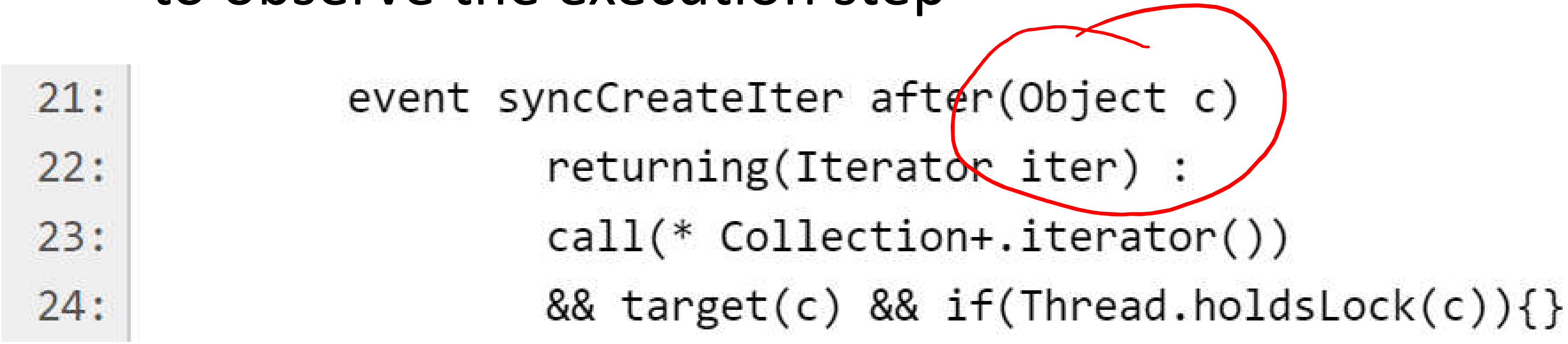
1. Click on spec

What (view of) events are in CSC?

- Logical view
- Practical view

Events as execution states

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



```
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]

logical

[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]

practical

[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]

math view

[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

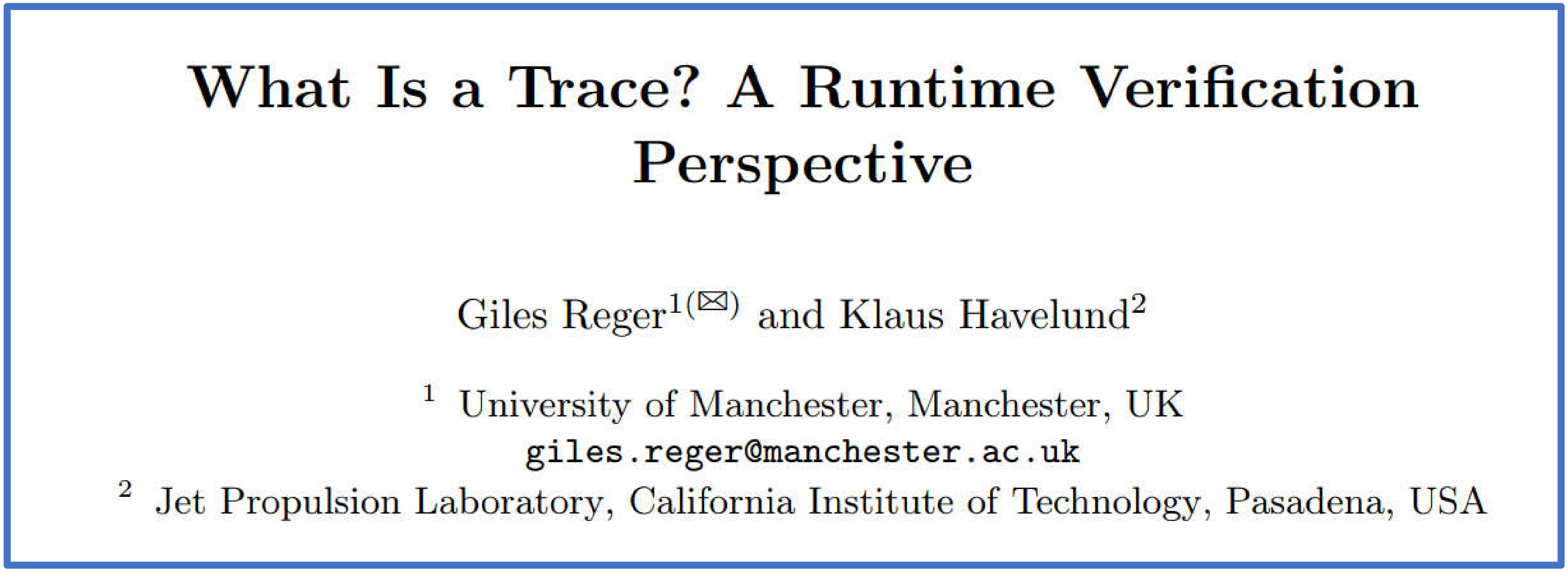
- So, when you read papers on RV, be careful to distinguish these views

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]

[1] University of Manchester, Manchester, UK
giles.reger@manchester.ac.uk
[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

- If events are symbols in an alphabet Σ, traces are strings (or words) in Σ*
  - We can talk about finite prefixes or 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 ∈ Σ appears in trace w ∈ Σ* then we write $\mathrm{e} \in \mathrm{w}$.[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?*

ϵ

acquire begin release end

“Good” and “bad” traces

- In example 1 context, 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

- Terminology: traces validate or violate a property depending on how the property is expressed

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

- 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

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

- This definition is more general (in a sense)
  - 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 for any RE, E, its property P_E can be defined as
  - $P_E(w)$ = match iff w is in the language of E
  - $P_E(w)$ = fail iff $\nexists\ w' \in \Sigma^*$ 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}

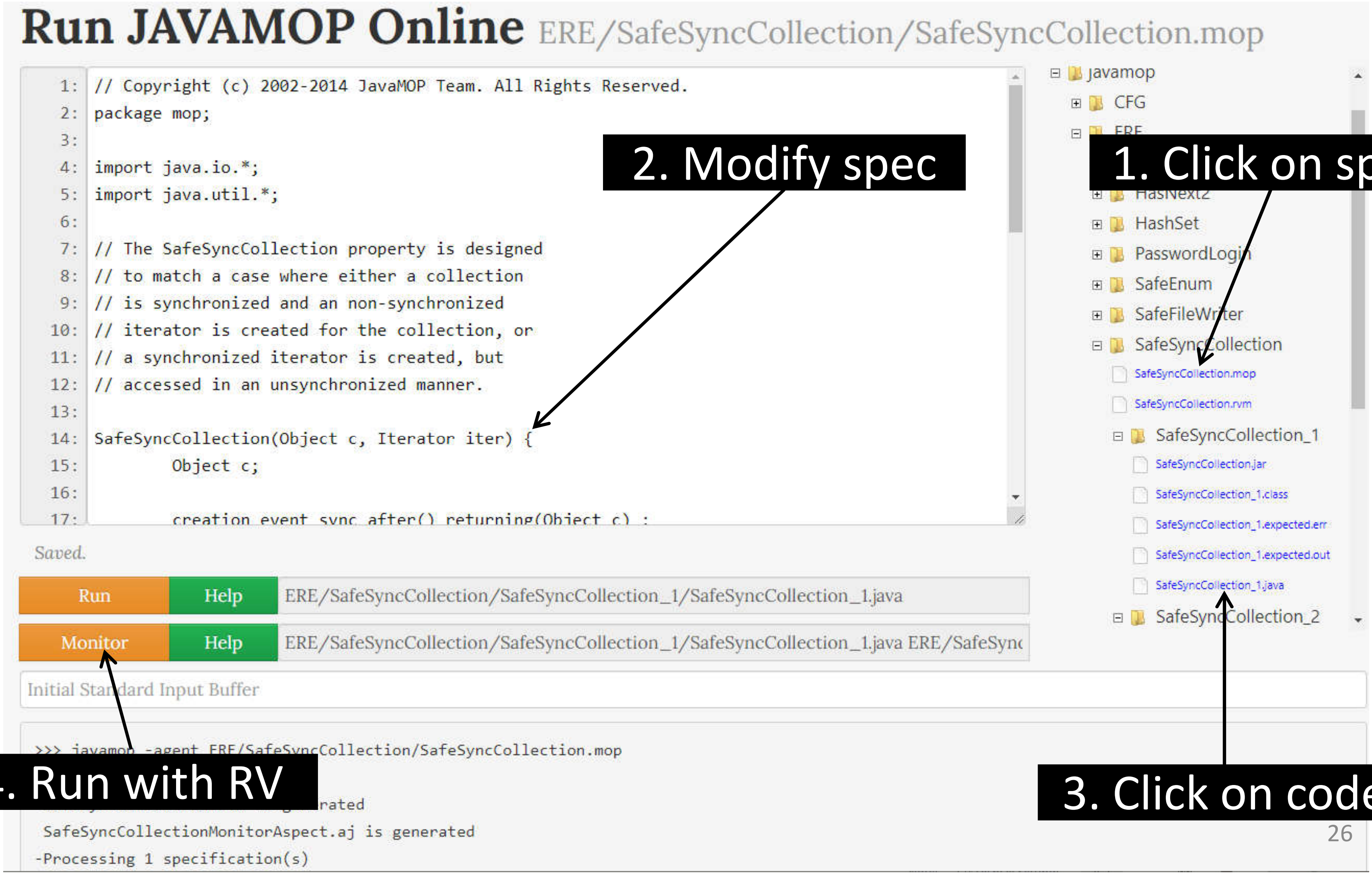
- Then for any RE, E, its property P_E can be defined as
  - $P_E(w)$ = match iff w is in the language of E
  - $P_E(w)$ = dont-care otherwise

- This is the semantics of monitoring RE in tracematches[4]

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

Demo: generating CSC traces

http://www.kframework.org/tool/run/javamop



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ERE/SafeSyncCollection/SafeSyncCollection_1/SafeSyncCollection_1.java ERE/SafeSync

Initial Standard Input Buffer

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                          rated
 SafeSyncCollectionMonitorAspect.aj is generated
-Processing 1 specification(s)
```

1. Click on spec

2. Modify spec

3. Click on code

4. Run with RV

What we ~~saw~~ would have seen during the demo

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

- Matching trace from SafeSyncCollection_1.java:
  - sync asyncCreateIter accessIter accessIter accessIter accessIter ✓ @ match

- Matching trace from SafeSyncCollection_2.java:
  - sync syncCreateIter accessIter accessIter accessIter accessIter accessIter ✓ @match

Properties: other things to know

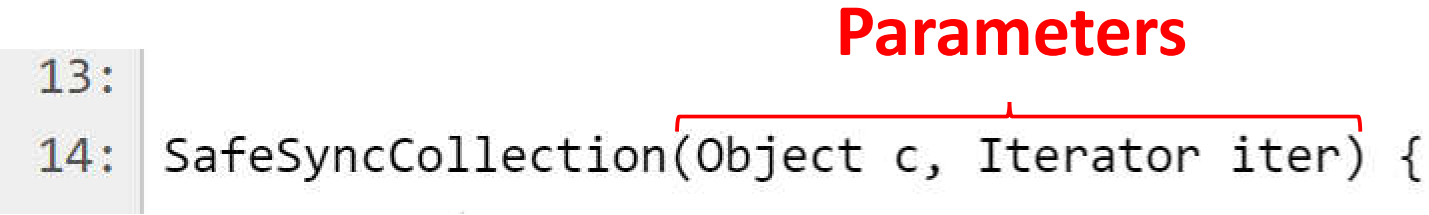
- Can all interesting system behavior be defined as "sets of traces"?
  - No. Hyperproperties[5] are "sets of sets of traces".

- 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

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

@match

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: fail
  - Reason:

r_2 in first invocation of procedure is not released

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‹›

⇩

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 TBD

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 $[X \rightharpoonup V]$. 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
- Correct locking

Example: authenticate before use

- Property: keys must be authenticated before use
- LTL spec: $\forall k.\square$(use → ⟐authenticate)
- 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 today

- 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?

?