Runtime Verification of Hash Code in Mutable Classes

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1 **Object equality and hash code**

2 **Runtime Verification and RML**

3 **Specification of safe hash sets**

Contract for equality and hash code

Features of most object-oriented languages

- two different notions of equality
    - by reference, predefined (==)
    - weaker equality, user-defined (equals)
- hash code associated with an object

General contract in java.lang.Object

If two objects are equal, then the same hash code must be computed for them

Reason

Classes as HashSet or HashMap rely on equals and hashCode:

- hashCode is used to identify a bucket
- equals is used to find an element in a bucket identified by hashCode

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Contract for equality and hash code

RML

A stricter contract in `java.util.Set`

Great care must be exercised if mutable objects are used as set elements.

The behavior of a set is not specified if the value of an object is changed in a way that affects equals comparisons while the object is an element in the set.

A special case of this prohibition is that it is not permissible for a set to contain itself as an element.

Comments

- rather imprecise specification
    - affected only sets and maps implemented with hash tables
    - no problem if `hashCode` is not redefined
    - mutable objects must not be modified while in a hash table

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Contract for equality and hash code

A simple example

```
var sset = new HashSet<Set<Integer≫();
var s = new HashSet<>(asList(1)); // s is {1}
sset.add(s); // sset is {{1}}
assert sset.contains(s);
s.remove(1);
assert sset.contains(s);
s.add(1);
assert sset.contains(s);
```

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Contract for equality and hash code

A simple example

```
var sset = new HashSet<Set<Integer>>();
var s = new HashSet<>(asList(1)); // s is {1}
sset.add(s); // sset is {{1}}
assert sset.contains(s); // success
s.remove(1);
assert sset.contains(s); // failure
s.add(1);
assert sset.contains(s); // success
```

Contract for equality and hash code

Another example

```
var sset = new HashSet<Set<Integer>>();
var s = new HashSet<>(asList(0)); // s is {0}
sset.add(s); // sset is {{0}}
assert sset.contains(s);
s.remove(0);
assert sset.contains(s);
s.add(0);
assert sset.contains(s);
```

Contract for equality and hash code

Another example

```
var sset = new HashSet<Set<Integer>>();
var s = new HashSet<>(asList(0)); // s is {0}
sset.add(s); // sset is {{0}}
assert sset.contains(s); // success
s.remove(0);
assert sset.contains(s); // success!
s.add(0);
assert sset.contains(s); // success
```

Issues

- almost unpredictable code behavior
- non-deterministic behavior if hashCode depends on object references
    - object references may change from one execution to another
    - hash code needs not remain consistent from one execution to another

Theory versus practice

RML

Theory

- mutable classes should not redefine `equals`
- weaker contract: `hashCode` should not depend on "mutable" fields

Practice

- mutable classes of `Collection` do not satisfy such a contract
- same problem in Kotlin and Scala, but not in C#

Aims

- verify that `Collection` objects are not modified while in a hash table
- proposed solution: Runtime Verification (RV)
- related work: study of `Collection` contracts in Java collections [NelsonPearceNoble@TOOLS2010]

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Runtime verification

CRML

Definition

Runtime Verification (RV) is a verification technique that allows for checking whether a run of a system under scrutiny (SUS) satisfies or violates a given correctness property.

Main ingredients

- run = possibly infinite event trace
- instrumentation = generates the relevant events
- formal specification = a set of event traces
- monitor = generated from a specification, dynamically checks finite prefixes of a run

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Runtime verification

Why RV?
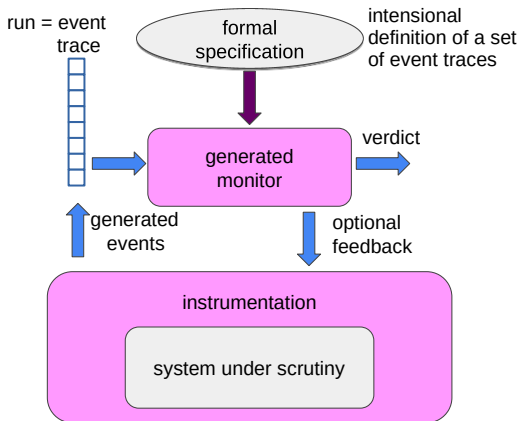
RV bridges the gap between formal verification and testing

- as in formal verification
    - properties defined with a formalism
    - runs abstracted by event traces
- as in testing
    - scalable solution although non exhaustive
    - exploitation of information available only at runtime
- other features
    - error recovery, self-adaptation, cast-iron guarantees
    - runtime verification of control-oriented properties

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RML

RML Web page: https://rmlatdibris.github.io/

RML

Main features of RML

- inspired by global session types
- based on formal languages: extension of deterministic CF grammars
- usability: developers are familiar with regular expressions and grammars
- expressive power: more expressive than deterministic CF grammars
- interoperability: separation between specification and instrumentation

Structure of RML specifications

Four layers

- event types: relevant events
- trace expressions: primitive and derived operators on sets of traces
- parametricity: existential quantification w.r.t. data carried by events
- genericity: enhanced modularity, reuse and expressive power
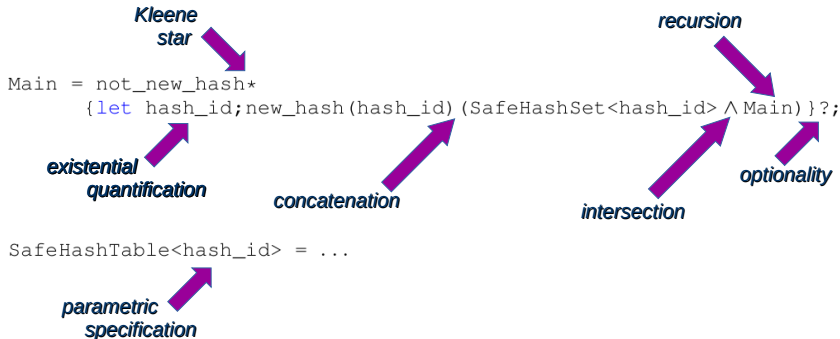
Events and event types in RML

An event trace

```
...
{"event":"func_pre","name":"add","targetId":5,"argIds":[13]}
{"event":"func_post","name":"add","res":true,"targetId":5,"argIds":[13]}
{"event":"func_pre","name":"remove","targetId":5,"argIds":[9]}
{"event":"func_post","name":"remove","res":true,"targetId":5,"argIds":[9]}
...
```

Event type declarations

```
add(hash_id,elem_id) matches {event:'func_post', targetId:hash_id, name:'add',
    argIds:[elem_id], res:true};
remove(hash_id,elem_id) matches {event:'func_post', targetId:hash_id,
    name:'remove', argIds:[elem_id], res:true};

modify(targ_id) matches add(targ_id,_) | remove(targ_id,_);
```

RML specifications


```
Main = not_new_hash*
       {let hash_id;new_hash(hash_id)(SafeHashSet<hash_id> ∧ Main)}?;

SafeHashTable<hash_id> = ...
```

Kleene star

existential quantification

concatenation

recursion

intersection

optionality

parametric specification

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RML semantics

In a nutshell

- based on the notion of Brzozowski derivative
- defined by a labeled transition systems with rewriting rules
- labels are the events
- the initial state is the specification of the property

RML semantics

$$\text{(par-t)} \frac{t \xrightarrow{e} t'; \sigma}{\{\text{let } x; \ t\} \xrightarrow{e} \sigma_{|x} t'; \sigma_{\setminus x}} \ x \in dom(\sigma)$$

$$\text{(par-f)} \frac{t \xrightarrow{e} t'; \sigma}{\{\text{let } x; \ t\} \xrightarrow{e} \{\text{let } x; \ t'\}; \sigma} \ x \notin dom(\sigma)$$

$$\text{(app)} \frac{\sigma t \xrightarrow{e} t'; \sigma'}{(\langle x_1, \ldots, x_n \rangle . t)\langle d_1, \ldots, d_n \rangle \xrightarrow{e} t'; \sigma'} \ \sigma = \{x_1 \mapsto ev(d_1), \ldots, x_n \mapsto ev(d_n)\}$$

$$\text{(cond-t)} \frac{t_1 \xrightarrow{e} t; \sigma}{\text{if } (d) \ t_1 \text{ else } t_2 \xrightarrow{e} t; \sigma} \ ev(d) = true$$

$$\text{(cond-f)} \frac{t_2 \xrightarrow{e} t; \sigma}{\text{if } (d) \ t_1 \text{ else } t_2 \xrightarrow{e} t; \sigma} \ ev(d) = false \qquad \text{(n-par)} \frac{t \xrightarrow{e}}{\{\text{let } x; \ t\} \xrightarrow{e}}$$

$$\text{(n-app)} \frac{\sigma t \xrightarrow{e}}{(\langle x_1, \ldots, x_n \rangle . t)\langle d_1, \ldots, d_n \rangle \xrightarrow{e}} \ \sigma = \{x_1 \mapsto ev(d_1), \ldots, x_n \mapsto ev(d_n)\}$$

$$\text{(n-cond-t)} \frac{t_1 \xrightarrow{e}}{\text{if } (d) \ t_1 \text{ else } t_2 \xrightarrow{e}} \ ev(d) = true$$

$$\text{(n-cond-f)} \frac{t_2 \xrightarrow{e}}{\text{if } (d) \ t_1 \text{ else } t_2 \xrightarrow{e}} \ ev(d) = false \qquad \text{(e-par)} \frac{E(t)}{E(\{\text{let } x; \ t\})}$$

$$\text{(e-app)} \frac{E(\sigma t)}{E((\langle x_1, \ldots, x_n \rangle . t)\langle d_1, \ldots, d_n \rangle)} \ \sigma = \{x_1 \mapsto ev(d_1), \ldots, x_n \mapsto ev(d_n)\}$$

$$\text{(e-cond-t)} \frac{E(t_1)}{E(\text{if } (d) \ t_1 \text{ else } t_2)} \ ev(d) = true$$

$$\text{(e-cond-f)} \frac{E(t_2)}{E(\text{if } (d) \ t_1 \text{ else } t_2)} \ ev(d) = false \qquad \text{(ne-par)} \frac{NE(t)}{NE(\{\text{let } x; \ t\})}$$

$$\text{(ne-app)} \frac{NE(\sigma t)}{NE((\langle x_1, \ldots, x_n \rangle . t)\langle d_1, \ldots, d_n \rangle)} \ \sigma = \{x_1 \mapsto ev(d_1), \ldots, x_n \mapsto ev(d_n)\}$$

$$\text{(ne-cond-t)} \frac{NE(t_1)}{NE(\text{if } (d) \ t_1 \text{ else } t_2)} \ ev(d) = true$$

$$\text{(ne-cond-f)} \frac{NE(t_2)}{NE(\text{if } (d) \ t_1 \text{ else } t_2)} \ ev(d) = false$$

Specification of safe hash sets

Declaration of event types

```
new_hash(hash_id) matches
  {event:'func_post', name:'HashSet', resultId:hash_id};
not_new_hash not matches new_hash(_);

add(hash_id,elem_id) matches
  {event:'func_post', targetId:hash_id, name:'add',
   argIds:[elem_id], res:true};
not_add(hash_id) not matches add(hash_id,_);

remove(hash_id,elem_id) matches
  {event:'func_post', targetId:hash_id, name:'remove',
   argIds:[elem_id], res:true};

modify(targ_id) matches add(targ_id,_) | remove(targ_id,_);

not_modify_remove(hash_id,elem_id) not matches
  modify(elem_id) | remove(hash_id,elem_id);
op(hash_id,elem_id) matches
  {targetId:hash_id} | {targetId:elem_id};
```

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Specification of safe hash sets

Whole specification

```
Main = not_new_hash*
  {let hash_id;new_hash(hash_id)(SafeHashSet<hash_id> ∧ Main)}?;

SafeHashSet<hash_id> = not_add(hash_id)*
  {let elem_id;add(hash_id,elem_id)(SafeHashElem<hash_id,elem_id> ∧
    SafeHashSet<hash_id>)}?;

SafeHashElem<hash_id,elem_id> = not_modify_remove(hash_id,elem_id)*
    (remove(hash_id,elem_id) all)?;
```

Monitor at work

Events

- **new** hash set with id 5
- **new** hash set with id 9
- **insertion** of set with id 9 into set with id 5

Reached state

```
(SafeHashElem<5,9> ∧ SafeHashSet<5>) ∧ (SafeHashSet<9> ∧ Main);
```

Monitor at work

Preliminary experiments

- aim: validation of the specification
- on event traces that simulate the execution of simple Java programs

Monitor at work

RML

Preliminary experiments: example

```
var sset = new HashSet<Set<Integer>>();
var s1 = new HashSet<Integer>();
var s2 = new HashSet<Integer>();
s1.add(1);
s2.add(2);
sset.add(s1);
s1.contains(1);
s1.add(1);
sset.add(s2);
sset.remove(s1);
//s2.remove(2);
s1.remove(1);
s2.remove(1);
sset.remove(s2);
s1.add(1);
s2.add(2);
```

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Generalization of the specification

RML

Extension to other methods and classes

```
new_hash(hash_id) matches {event:'func_post', name:'HashSet' |
    'HashMap', resultId:hash_id};

add(hash_id,elem_id) matches // addition to a set
  {event:'func_post', targetId:hash_id, name:'add',
   argIds:[elem_id], res:true}
 |    // addition to a map
  {event:'func_post', targetId:hash_id, name:'put',
   argIds:[elem_id,_]};

clear(hash_id) matches  {event:'func_pre', targetId:hash_id,
    name:'clear'};
```

Remark:

- with `put` and `clear` is not possible to monitor modification accurately false positives are possible
- the same specification can be reused for Kotlin and Scala

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Assessment of the approach

Experiments with real Java applications

- scalability
- effective bug detection

Thank you!

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