CS 6156

Safety Properties and Monitoring

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Some Logistics

- Homework was due today
  - Any problems?

- Reading 3 will be assigned (due 11:59pm AoE on 2/14)

- You will start leading the discussion in ~2 weeks

Intro to RV: what we talked about

- Events
- Traces
- Properties
- Specification languages
- Specifications

Intro to RV: today

- Safety Properties
- Monitors
- Monitorability

Let’s start with some reminders

- Alphabets
- Words
- Languages

A conversation from CS6156 Fa’20

- Owolabi: In theory, RV can force the system to always be correct

safety

- Student 1: but… doesn’t that depend on how “correctness” is specified, i.e., bad things will never happen, or good things will eventually happen?

liveness

- Owolabi: ☺

More conversation from Fa’20

- Owolabi: Partial traces may be in “don’t know” category. So, notions of set or language membership should be extended for RV.

- Students 2 & 3: Wait… are you relaxing the notion of a safety property?

- Owolabi: ☺

Some goals…

- Formalize the intuition of “correctness” from the previous classes and reading

- Provide a framework for answering similar questions in the future

- Such formalization and framework are important for a deeper understanding of RV

What we'll discuss

- A synopsis of this paper

Scientific Annals of Computer Science vol. 22 (2), 2012, pp. 327–365
doi: 10.7561/SACS.2012.2.327

On Safety Properties and Their Monitoring

Grigore ROŞU[1]

- Goal: give you the intuition you'll need to read it on your own (if interested)

What kinds of correctness properties have you heard about?

- ? Safety props
- ?? Liveness props
- ??? partial correctness & termination
- ???? time and space complexity

fairness (distr. systems)

Give examples of these kinds of properties?

Q1: Which of these kinds of correctness properties can RV check?

- Your answer:

- Why?

Intuition: what is a safety property?

- Your answers:

Questions that the paper answers

- What are some formal definitions of safety properties?
- Do all the definitions of safety properties agree?
- How many safety properties are there?
- What's the complexity of monitoring safety properties?
- Is there a formalism that can express all safety properties?

Recall: properties as sets of traces

- In practice, traces are always finite
- In theory, traces can be infinite, e.g., the ideal reactive system
- Traces are strings over Σ, so we can talk about their prefixes

Def 1: safety property

- A safety property is a prefix-closed set of “good” finite traces. Let the set of all such finite-trace prefix-closed properties be **Safety***

- L is prefix-closed if for all prefixes u of w, $\mathrm{w} \in L \rightarrow u \in L$.

- Let P ∈ **Safety***
    - If !P(w), then ∄u s. t. P(wu), where w, u ∈ Σ*
    - Equivalently, if P(wu) then P(w)

Implication of Def 1

- Once a “bad” event occurs, the resulting trace cannot be extended to be in P ∈ **Safety***
- So, as soon as a “bad” event is concatenated with a trace that is in P ∈ **Safety***, RV can report a violation and stop checking

Illustrating Def 1 (1)

- Safety property: a one-time-access key issued to a client can be activated, then used at most once, then closed

- Prefix-closed set: {ϵ, *activate, activate close, activate use, activate use close*}

- Any trace that is not in this prefix-closed set is a violation of the safety property

Illustrating Def 1 (2)

- Safety property: a one-time-access key issued to a client can be activated, then used multiple times, then closed
- The prefix-closed set now has infinitely many finite traces: $\{\epsilon\} \cup \{activate\} \cdot \{use^n \mid n \in \mathbb{N}\} \cdot \{\epsilon, close\}$
- RV can still detect traces that are not in this set, e.g., {*activate activate, activate use close use, …*}

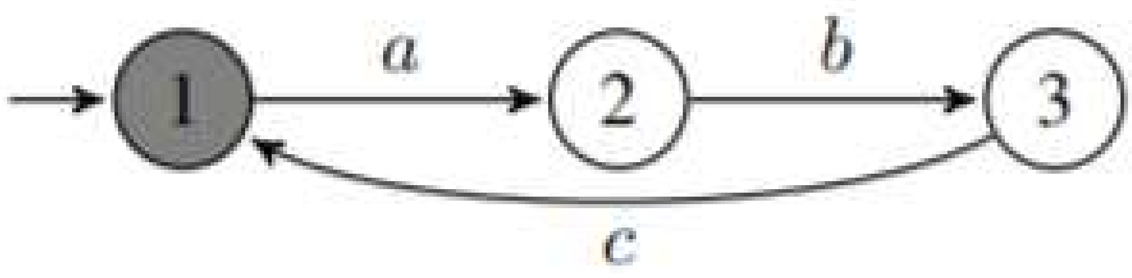
A practical implication of Def 1

A "convenient" translation of the FSM to RE

Grey node is accepting state
white node is rejecting state

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

Translation to FSM



Should JavaMOP print a violation **as soon as** it sees [a], [ab]?

Is prefix closure sufficient?

- **Safety*** contains the safety properties {} and all prefix-closed ~~*finite*~~ set of traces

- Any reactive system will eventually violate such safety properties even if no "bad" event occurs (reactive systems should run "forever")

- So, we need more than prefix closure

Def 2: persistent safety properties

- We need prefix closure, but we also want (reactive) systems to be able to progress safely

- **PersistentSafety*** is the set of all safety properties that allow a system in a safe state to continue execution onto the next safe state

$$\textbf{PersistentSafety}^{\star} = \{ P \in \textbf{Safety}^{\star} \mid P(w) \rightarrow \exists a \in \Sigma \text{ s.t. } P(wa) \}$$

On Safety* and PersistentSafety*

- **PersistentSafety*** provides a way of thinking about infinite behaviors in terms of finite traces

- $|$**Safety**$^\star| = |$**PersistentSafety**$^\star| = c$

- $\forall$P $\in$ **Safety*** $\exists$P$^\circ$ $\in$ **PersistentSafety*** s.t. P$^\circ$ is the largest persistent safety property in P

- See paper for more details and proofs

Any questions so far?

?

Problems with Defs 1 & 2?

- Another view of safety: a “bad” infinite trace must have a finite “bad” prefix

- **Safety*** and **PersistentSafety*** seem not to say anything about “bad” infinite traces

- Is there a relationship between this view, **Safety*** , and **PersistentSafety***?

Def 3: safety properties on infinite traces

- Let **Safety**$^{\omega}$ be the set of infinite trace properties Q $\in \mathcal{P}(\Sigma^{\omega})$ s.t. if u $\notin$ Q then there is a finite trace w $\in$ $\mathrm{prefixes}(\mathrm{u})$ s.t. wv $\notin$ Q for any v $\in \Sigma^{\omega}$.

- Probably the most common definition of safety[1]

- **Safety**$^{\omega}$ and **Safety*** agree (see proof in the paper):

  |**PersistentSafety***|=|**Safety**$^{\omega}$|=c

[1]Alpern and Schneider, Defining Liveness, IPL 1985

Notice a common theme?

- **Safety***: the sequence of past events in a “good” trace must be in the property

- **PersistentSafety***: to proceed to a new safe state, the sequence of past events must have been safe

- **Safety**$^\omega$: an infinite trace becomes “bad” after a finite sequence of past events

"Always past" characterization

- A safety property as an arbitrary (not necessarily prefix-closed) property on finite traces s.t. all finite prefixes of "good" traces are in the property

- Bijection to **Safety*** and **Safety**$^\omega$ (proof in paper)
  - any safety property can be expressed as "always past"

- Connects very nicely with past-time LTL
  - one reason why LTL is a popular spec language in RV

We saw an example before…

- Property: keys must be authenticated before use
- LTL spec: $\forall k.\Box(\text{use} \rightarrow \Diamond\text{authenticate})$
- "always (b implies eventually in the past a)"
- $\Box(b \rightarrow \Diamond a)$ compactly represents this set:

$\{wsw's' \mid w, w' \in \Sigma^*, s, s' \in \Sigma, a(s) \text{ and } b(s') \text{ hold}\} \cup$

$\{ws \mid w \in \Sigma^*, s \in \Sigma, b(s) \text{ does not hold}\}$

There are more notions of safety

- The paper discusses at least two other notions that we omit

- They all refer to the same set of safety properties, even though they are expressed differently

Why go through all the math?

- 1: “something bad will not happen”
- 2: “always in the past, something bad did not happen”
- Math showed a bijection between 1 & 2
- RV can check properties expressed as 2, but not 1

Revisiting fa’20 conversation

- Owolabi: Partial traces may be in “don’t know” category. So, notions of set or language membership should be extended for RV.

- Students 2 & 3: Wait… are you relaxing the notion of a safety property?

- Owolabi: No, we are expressing safety properties in a checkable way that has a bijection to other notions of safety properties

Monitoring safety properties

- Checking safety properties as sets of traces is hard
  - Those sets can contain infinitely many traces
  - Analyzing those sets can be inconvenient

- We need to specify safety properties in formalisms that are easier to represent and reason about

Recall definition from lecture 2

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

- RV operationalizes P through a monitor

Def 4: What is a monitor?

- A Σ-**monitor** is a triple $\mathcal{M} = (S, s_0, M : S \times \Sigma \rightharpoondown S)$, where S is a set of events, s_0 is the initial event and M is a deterministic partial transition function

- Notes:
  - No final state, allows checking reactive systems
  - $\mathcal{M}$ is driven by events generated by the observed system
  - Each event drives the monitor from one state to another
  - If M is undefined for the current state and current event, $\mathcal{M}$ declares a violation

Why is Def 4 important?

- A property is monitorable if it can be specified as a monitor

- All safety properties can be specified by their monitor (see paper for proof)
  - But transition function M may be undecidable

- Synthesizing monitors from compact specifications of safety properties is critical in RV

The complexity of monitoring (1)

- Let P be a safety property

- The complexity of monitoring P is the complexity of checking if $w \in \text{prefixes}(P)$, where $w \in \Sigma^*$

- Problem: assumes that we can always store w, and ignores complexity due to online monitoring

The complexity of monitoring (2)

- Let P be a safety property

- The complexity of monitoring P is a function of the size of a finite specification or representation of P

- Problems:
  - P may have different sizes in different spec languages
  - Spec of P may take more space than needed to monitor P (“every 2^{n}-th event is *a*” as FSM with 2^{n} states)

The complexity of monitoring (3)

- Let P be a safety property
- Complexity of monitoring P is the functional complexity of M in a "best" $\mathcal{M}=(S, s_0, M{:}S \times \Sigma \rightarrow S)$
- Good: complexity of processing each event is important
- Bad: ignores the accumulating cost of M with time

Monitoring is arbitrarily hard

- Proof is in the paper
- Implication 1: P is monitorable does not always imply that monitoring P is feasible
- Implication 2: One needs to carefully choose P and to design efficient monitor synthesis algorithms

Review

- Formalizations of notions of safety properties and their consensus
- "Always past" characterization allows us to express safety properties in ways that we can check
- Monitoring safety properties is arbitrarily hard

Next class

- Instrumentation (how to observe events)
  - There will likely be live coding in class
- Reading(s) will be released soon

Also next week…

- Assign paper presentations