Traces Properties

Semantics and applications to verification

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Program of this first lecture

Studied so far:

- **semantics:** operational, denotational...
- **typing:** "well typed programs do not go wrong"
- **proof by Hoare logic:** reasoning about programs step by step

Today's lecture: we look back at program's properties

- **families of properties:**
  what properties can be considered "similar" ? in what sense ?
- **proof techniques:**
  how can those kinds of properties be established ?
- **specification of properties:**
  are there languages to describe properties ?

A high level overview

- In this lecture we look at **trace properties**
- A property is **a set of traces**, defining the **admissible** executions

Safety properties:

- **something (e.g., bad) will never happen**
- proof by invariance

Liveness properties:

- **something (e.g., good) will eventually happen**
- proof by variance

Some interesting program properties do not fit this classification

State properties

As usual, we consider $\mathcal{S} = (\mathbb{S}, \rightarrow, \mathbb{S}_{\mathcal{I}})$

First approach: properties as sets of states

- a property $\mathcal{P}$ is **a set of states** $\mathcal{P} \subseteq \mathbb{S}$
- $\mathcal{P}$ is satisfied if and only if all reachable states belong to $\mathcal{P}$, i.e., $[\![\mathcal{S}]\!]_{\mathcal{R}} \subseteq \mathcal{P}$ where $[\![\mathcal{S}]\!]_{\mathcal{R}} = \{s_n \in \mathbb{S} \mid \exists \langle s_0, \ldots, s_n \rangle \in [\![\mathcal{S}]\!]_{\mathcal{R}},\ s_0 \in \mathbb{S}_{\mathcal{I}}\}$

Examples:

- **absence of runtime errors**:

$$\mathcal{P} = \mathbb{S} \setminus \{\Omega\} \quad \text{where } \Omega \text{ is the error state}$$

- **non termination** (e.g., for an operating system):

$$\mathcal{P} = \{s \in \mathbb{S} \mid \exists s' \in \mathbb{S}, s \rightarrow s'\}$$

Trace properties

Second approach: properties as sets of traces

- a property $\mathcal{T}$ is **a set of traces** $\mathcal{T} \subseteq \mathbb{S}^{\propto}$
- $\mathcal{T}$ is satisfied if and only if all traces belong to $\mathcal{T}$, i.e., $[\![\mathcal{S}]\!]^{\propto} \subseteq \mathcal{T}$

Examples:

- obviously, **state properties** are trace properties
- **functional properties**
  e.g., "program P takes one integer input x and returns its absolute value"
- **termination**: $\mathcal{T} = \mathbb{S}^{\star}$ (i.e., the system should have no infinite execution)

Monotonicity

Property

Let $\mathcal{P}_0, \mathcal{P}_1 \subseteq \mathbb{S}$ be two state properties, such that $\mathcal{P}_0 \subseteq \mathcal{P}_1$.
Then $\mathcal{P}_0$ **is stronger than** $\mathcal{P}_1$, i.e. if program $\mathcal{S}$ satisfies $\mathcal{P}_0$, then it also satisfies $\mathcal{P}_1$.

Let $\mathcal{T}_0, \mathcal{T}_1 \subseteq \mathbb{S}$ be two trace properties, such that $\mathcal{T}_0 \subseteq \mathcal{T}_1$.
Then $\mathcal{T}_0$ **is stronger than** $\mathcal{T}_1$, i.e. if program $\mathcal{S}$ satisfies $\mathcal{T}_0$, then it also satisfies $\mathcal{T}_1$.

Proof: straightforward application of the definition of state (resp., trace) properties

Outline

Safety properties

Informal definition: safety properties

A safety property is a property which specifies that some (bad) behavior **will never occur**

- **absence of runtime errors** is a safety property ("bad thing": error)
- **state properties** is a safety property ("bad thing": reaching $\mathbb{S} \setminus \mathcal{P}$)
- **non termination** is a safety property ("bad thing": reaching a blocking state)
- **"not reaching state** ***b*** **after visiting state** ***a*****"** is a safety property (and **not** a state property)
- **termination** is **not** a safety property

Towards a formal definition

We intend to provide a **formal definition** of safety.

How to refutate a safety property ?

- we assume $\mathcal{S}$ does **not** satisfy safety property $\mathcal{P}$
- thus, there exists a **counter-example trace** $\sigma = \langle s_0, \ldots, s_n, \ldots \rangle \in [\![\mathcal{S}]\!] \setminus \mathcal{P}$;
  it may be finite or infinite...
- the intuitive definition says this trace **eventually exhibits some bad behavior**
- thus, there exists a rank $i \in \mathbb{N}$, such that the bad behavior has been observed before reaching s_i
- therefore, trace $\sigma' = \langle s_0, \ldots, s_i \rangle$ violates $\mathcal{P}$, i.e. $\sigma' \notin \mathcal{P}$
- we remark σ' **is finite**

A safety property that does not hold can always be refuted with a finite counter-example

Limit

Definition: upper closure operator (uco)

Function $\phi : \mathcal{S} \to \mathcal{S}$ is an **upper closure operator** iff:

- **monotone**
- **extensive:** $\forall x \in \mathcal{S},\ x \sqsubseteq \phi(x)$
- **idempotent:** $\forall x \in \mathcal{S},\ \phi(\phi(x)) = \phi(x)$

Definition: limit

The **limit operator** is defined by:

$$\begin{array}{rrcl} \mathbf{Lim} : & \mathcal{P}(\mathbb{S}^{\propto}) & \longrightarrow & \mathcal{P}(\mathbb{S}^{\propto}) \\ & X & \longmapsto & X \cup \{\sigma \in \mathbb{S}^{\propto} \mid \forall i \in \mathbb{N},\ \sigma_{\lceil i} \in X\} \end{array}$$

Operator **Lim** **is an upper-closure operator**

Proof: exercise!

Prefix closure

We write $\sigma_{\lceil i}$ for the prefix of length i of trace σ:

$$\begin{array}{rcl} \langle s_0, \ldots, s_n \rangle_{\lceil 0} & = & \epsilon \\ \langle s_0, \ldots, s_n \rangle_{\lceil i+1} & = & \left\{ \begin{array}{ll} \langle s_0, \ldots, s_i \rangle & \text{if } i < n \\ \langle s_0, \ldots, s_n \rangle & \text{otherwise} \end{array} \right. \\ \langle s_0, \ldots \rangle_{\lceil i+1} & = & \langle s_0, \ldots, s_i \rangle \end{array}$$

If σ is finite, of length n, $|\sigma|i = \min(n, i)$; if σ is infinite, $|\sigma|i = i$.

Definition: prefix closure

The prefix closure operator is defined by:

$$\begin{array}{rccl} \mathbf{PCl}: & \mathcal{P}(\mathbb{S}^{\propto}) & \longrightarrow & \mathcal{P}(\mathbb{S}^{\star}) \\ & X & \longmapsto & \{\sigma_{\lceil i} \mid \sigma \in X, i \in \mathbb{N}\} \end{array}$$

Properties:

- **PCl** is monotone
- **PCl** is idempotent, i.e., $\mathbf{PCl} \circ \mathbf{PCl}(X) = \mathbf{PCl}(X)$

Safety properties: formal definition

An upper closure operator

Operator **Safe** is defined by $\mathbf{Safe} = \mathbf{Lim} \circ \mathbf{PCl}$.
It is an upper closure operator over $\mathcal{P}(\mathbb{S}^{\propto})$

Proof:

- **Safe** is monotone as **Lim** and **PCl** are
- **Safe** is extensive; indeed if $X \subseteq \mathbb{S}^{\propto}$ and $\sigma \in X$, we can show that $\sigma \in \mathbf{Safe}(X)$:
  - if σ is a finite trace, it is one of its prefixes, so $\sigma \in \mathbf{PCl}(X) \subseteq \mathbf{Lim}(\mathbf{PCl}(X))$
  - if σ is an infinite trace, all its prefixes belong to $\mathbf{PCl}(X)$, so $\sigma \in \mathbf{Lim}(\mathbf{PCl}(X))$

Safety properties: formal definition

Proof (continued):

- **Safe** is idempotent:
  - as **Safe** is extensive and monotone $\mathbf{Safe} \subseteq \mathbf{Safe} \circ \mathbf{Safe}$, so we simply need to show that $\mathbf{Safe} \circ \mathbf{Safe} \subseteq \mathbf{Safe}$
  - let $X \subseteq \mathbb{S}^{\propto}, \sigma \in \mathbf{Safe}(\mathbf{Safe}(X))$; then:

$$\begin{array}{rll} & \sigma \in \mathbf{Safe}(\mathbf{Safe}(X)) & \\ \Rightarrow & \forall i,\ \sigma_{\lceil i} \in \mathbf{PCl} \circ \mathbf{Safe}(X) & \text{by def. of } \mathbf{Lim} \\ \Rightarrow & \forall i,\ \exists \sigma', j,\ \sigma_{\lceil i} = \sigma'_{\lceil j} \wedge \sigma' \in \mathbf{Safe}(X) & \text{by def. of } \mathbf{PCl} \\ \Rightarrow & \forall i,\ \exists \sigma', j,\ \sigma_{\lceil i} = \sigma'_{\lceil j} \wedge \forall k,\ \sigma'_{\lceil k} \in \mathbf{PCl}(X) & \text{by def. of } \mathbf{Lim} \\ \Rightarrow & \forall i,\ \exists \sigma', j,\ \sigma_{\lceil i} = \sigma'_{\lceil j} \wedge \sigma'_{\lceil i} \in \mathbf{PCl}(X) & \text{with } i = j \end{array}$$

    - ★ if σ is finite, we let $i = |\sigma|$, thus j has to be equal to n as well and $\sigma = \sigma'_{\lceil i} \in \mathbf{PCl}(X)$, thus $\sigma \in \mathbf{Lim}(\mathbf{PCl}(X))$
    - ★ if σ is infinte, $|\sigma_{\lceil i}| = i$ and we may let $i = k$ so

$$\forall i,\ \sigma_{\lceil i} = \sigma'_{\lceil i} \in \mathbf{PCl}(X)$$

      thus $\sigma \in \mathbf{Lim}(\mathbf{PCl}(X))$

Safety properties: formal definition

Safety: definition

A trace property $\mathcal{T}$ is a **safety** property if and only if $\mathbf{Safe}(\mathcal{T}) = \mathcal{T}$

Theorem

If $\mathcal{T}$ is a trace property, then **$\mathbf{Safe}(\mathcal{T})$ is a safety property**

Proof: straightforward, by idempotence of **Safe**

Example

We assume that:

- $\mathbb{S} = \{a, b\}$
- $\mathcal{T}$ states that a **should not be visited after state** b **is visited**; elements of $\mathcal{T}$ are of the general form

$$\langle a, a, a, \ldots, a, b, b, b, b, \ldots\rangle \textbf{ or } \langle a, a, a, \ldots, a, a, \ldots\rangle$$

Then:

- **PCl**($\mathcal{T}$) elements are all finite traces which are of the above form (i.e., made of n occurrences of a followed by m occurrences of b, where n, m are positive integers)
- **Lim**(**PCl**($\mathcal{T}$)) adds to this set the trace made made of infinitely many occurrences of a and the infinite traces made of n occurrences of a followed by infinitely many occurrneces of b
- thus, **Safe**($\mathcal{T}$) $=$ **Lim**(**PCl**($\mathcal{T}$)) $= \mathcal{T}$

Therefore $\mathcal{T}$ is indeed formally **a safety property**.

State properties are safety properties

Theorem

Any **state property** is also a **safety property**.

Proof: Let us consider **state property** $\mathcal{P}$.
It is equivalent to **trace property** $\mathcal{T} = \mathcal{P}^\propto$:

$$\begin{array}{rcl} \textbf{Safe}(\mathcal{T}) & = & \textbf{Lim}(\textbf{PCl}(\mathcal{P}^\propto)) \\ & = & \textbf{Lim}(\mathcal{P}^\star) \\ & = & \mathcal{P}^\star \cup \mathcal{P}^\omega \\ & = & \mathcal{P}^\propto \\ & = & \mathcal{T} \end{array}$$

Therefore $\mathcal{T}$ is indeed a safety property.

Intuition of the formal definition

Operator **Safe saturates** a set of traces S with

- prefixes
- infinite traces all finite prefixes of which can be observed in S

Thus, if **Safe**$(S) = S$ and σ is a trace, to establish that **σ is not in S**, it is sufficient to discover a **finite prefix of σ** that cannot be observed in S.

Alternatively, if all finite prefixes of σ belong to S or can observed as a prefix of another trace in S, by definition of the limit operator, **σ belongs to S** (even if it is infinite).

Thus, our definition **indeed captures properties that can be disproved with a counter-example**.

Outline

Proof by invariance

- We consider transition system $\mathcal{S} = (\mathbb{S}, \rightarrow, \mathbb{S}_{\mathcal{I}})$, and safety property $\mathcal{T}$. Finite traces semantics is the least fixpoint of $F_{\star}$.
- We seek a way of **verifying that $\mathcal{S}$ satisfies $\mathcal{T}$**, i.e., that $[\![\mathcal{S}]\!]^{\propto} \subseteq \mathcal{T}$

Principle of invariance proofs

Let $\mathbb{I}$ be a set of finite traces; it is said to be an **invariant** if and only if:

- $\forall s \in \mathbb{S}_{\mathcal{I}},\ \langle s \rangle \in \mathbb{I}$
- $F_{\star}(\mathbb{I}) \subseteq \mathbb{I}$

It is stronger than $\mathcal{T}$ if and only if $\mathbb{I} \subseteq \mathcal{T}$.

The **"by invariance"** proof method is based on finding an invariant that is stronger than $\mathcal{T}$.

Soundness

Theorem: soundness

The invariance proof method is **sound**: if we can find an invariant for $\mathcal{S}$, that is stronger than $\mathcal{T}$, then $\mathcal{S}$ satisfies $\mathcal{T}$.

Proof:

We assume that $\mathbb{I}$ is an invariant of $\mathcal{S}$ and that it is stronger than $\mathcal{T}$, and we show that $\mathcal{S}$ satisfies $\mathcal{T}$:

- by induction over n, we can prove that $F_\star^n(\{\langle s\rangle \mid s \in \mathbb{S}\}) \subseteq F_\star^n(\mathbb{I}) \subseteq \mathbb{I}$
- therefore $[\![\mathcal{S}]\!]^\star \subseteq \mathbb{I}$
- thus, $\mathbf{Safe}([\![\mathcal{S}]\!]^\star) \subseteq \mathbf{Safe}(\mathbb{I}) \subseteq \mathbf{Safe}(\mathcal{T})$ since **Safe** is monotone
- we remark that $[\![\mathcal{S}]\!]^\propto = \mathbf{Safe}([\![\mathcal{S}]\!]^\star)$
- $\mathcal{T}$ is a safety property so $\mathbf{Safe}(\mathcal{T}) = \mathcal{T}$
- we conclude $[\![\mathcal{S}]\!]^\propto \subseteq \mathcal{T}$, i.e., **$\mathcal{S}$ satisfies property $\mathcal{T}$**

Completeness

Theorem: completeness

The invariance proof method is **complete**: if $\mathcal{S}$ satisfies $\mathcal{T}$, then we can find an invariant $\mathbb{I}$ for $\mathcal{S}$, that is stronger than $\mathcal{T}$.

Proof:

We assume that $[\![\mathcal{S}]\!]^{\propto}$ satisfies $\mathcal{T}$, and show that we can exhibit an invariant.

Then, $\mathbb{I} = [\![\mathcal{S}]\!]^{\propto}$ is an invariant of $\mathcal{S}$ by definition of $[\![.]\!]^{\propto}$, and it is stronger than $\mathcal{T}$.

Caveat:

- $[\![\mathcal{S}]\!]^{\propto}$ is most likely **not** a very easy to express invariant
- it is just a convenient completeness argument
- so, completeness does not mean the proof is easy !

Example

We consider the proof that the program below **computes the sum of the elements of an array**, i.e., when the exit is reached, $\mathtt{s} = \sum_{k=0}^{n-1} \mathtt{t}[k]$:

$$
\begin{array}{ll}
 & \mathtt{i}, \mathtt{s} \text{ integer variables} \\
 & \mathtt{t} \text{ integer array of length } n \\
\ell_0: & (\!|\mathbf{true}|\!) \\
 & \mathtt{s} = 0; \\
\ell_1: & (\!|\mathtt{s} = 0|\!) \\
 & \mathtt{i} = 0; \\
\ell_2: & (\!|\mathtt{i} = 0 \wedge \mathtt{s} = 0|\!) \\
 & \mathbf{while}(\mathtt{i} < n)\{ \\
\ell_3: & (\!|0 \leq \mathtt{i} < n \wedge \mathtt{s} = \sum_{k=0}^{\mathtt{i}-1} \mathtt{t}[k]|\!) \\
 & \quad \mathtt{s} = \mathtt{s} + \mathtt{t}[\mathtt{i}]; \\
\ell_4: & (\!|0 \leq \mathtt{i} < n \wedge \mathtt{s} = \sum_{k=0}^{\mathtt{i}} \mathtt{t}[k]|\!) \\
 & \quad \mathtt{i} = \mathtt{i} + 1; \\
\ell_5: & (\!|1 \leq \mathtt{i} \leq n \wedge \mathtt{s} = \sum_{k=0}^{\mathtt{i}-1} \mathtt{t}[k]|\!) \\
 & \} \\
\ell_6: & (\!|\mathtt{i} = n \wedge \mathtt{s} = \sum_{k=0}^{n-1} \mathtt{t}[k]|\!)
\end{array}
$$

Principle of the proof:

- for each program point ℓ, we have a **local invariant** $\mathbb{I}_\ell$ (denoted by a logical formula instead of a set of states in the figure)
- the global **invariant** $\mathbb{I}$ is defined by:

$$\mathbb{I} = \{\langle(\ell_0, m_0), \ldots, (\ell_n, m_n) \mid \forall n,\ m_n \in \mathbb{I}_{\ell_n}\}$$

Outline

Liveness properties

Informal definition: liveness properties

A liveness property is a property which specifies that some (good) behavior **will eventually occur**.

- **termination** is a liveness property
  "good behavior": reaching a blocking state (no more transition available)
- **"state *a* will eventually be reached by all execution"** is a liveness property
  "good behavior": reaching state *a*
- the **absence of runtime errors** is *not* a liveness property

Intuition towards a formal definition

We intend to provide a **formal definition** of liveness.

How to refutate a liveness property ?

- we consider liveness property $\mathcal{T}$ (think $\mathcal{T}$ **is termination**)
- we assume $\mathcal{S}$ does **not** satisfy liveness property $\mathcal{T}$
- thus, there exists a **counter-example trace** $\sigma \in [\![\mathcal{S}]\!] \setminus \mathcal{T}$;
- let us assume σ is actually finite...
  the definition of liveness says some (good) behavior should eventually occur:
  - how do we know that σ cannot be extended into a trace $\sigma \cdot \sigma'$ that will satisfy this behavior ?
  - maybe that after a few more computation steps, σ **will reach a blocking state...**

Intuition towards a formal definition

To refutate a liveness property, we need to look at infinite traces.

Example: if we run a program, and do not see it return...

- should we do `Ctrl+C` and conclude it does not terminate ?
- should we just wait a few more seconds minutes, hours, years ?

Towards a formal definition: **we expect any finite trace be in $\mathcal{T}$**
as finite executions cannot be used to disprove $\mathcal{T}$

Definition

Formal definition

Operator **Live** is defined by $\mathbf{Live}(\mathcal{T}) = \mathcal{T} \cup (\mathbb{S}^\propto \setminus \mathbf{Safe}(\mathcal{T}))$. Given property $\mathcal{T}$, the following three statements are equivalent:

(*i*) $\mathbf{Live}(\mathcal{T}) = \mathcal{T}$

(*ii*) $\mathbf{PCl}(\mathcal{T}) = \mathbb{S}^\star$

(*iii*) $\mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T}) = \mathbb{S}^\propto$

When they are satisfied, $\mathcal{T}$ is said to be a **liveness property**

Example: **termination**

- the property is $\mathcal{T} = \mathbb{S}^\star$
  (i.e., there should be no infinite execution)
- clearly, it satisfies (*ii*): $\mathbf{PCl}(\mathcal{T}) = \mathbb{S}^\star$
  thus termination indeed satisfies this definition

Proof of equivalence

Proof of equivalence:

- (i) **implies** (ii):
  we assume that $\mathbf{Live}(\mathcal{T}) = \mathcal{T}$, i.e., $\mathcal{T} \cup (\mathbb{S}^{\propto} \setminus \mathbf{Safe}(\mathcal{T})) = \mathcal{T}$
  therefore, $\mathbb{S}^{\propto} \setminus \mathbf{Safe}(\mathcal{T}) \subseteq \mathcal{T}$;
  let $\sigma \in \mathbb{S}^{\star}$, and let us show that $\sigma \in \mathbf{PCl}(\mathcal{T})$; clearly, $\sigma \in \mathbb{S}^{\propto}$, thus:
  - either $\sigma \in \mathbf{Safe}(\mathcal{T}) = \mathbf{Lim}(\mathbf{PCl}(\mathcal{T}))$, so all its prefixes are in $\mathbf{PCl}(\mathcal{T})$ and $\sigma \in \mathbf{PCl}(\mathcal{T})$
  - or $\sigma \in \mathcal{T}$, which implies that $\sigma \in \mathbf{PCl}(\mathcal{T})$
- (ii) **implies** (iii):
  if $\mathbf{PCl}(\mathcal{T}) = \mathbb{S}^{\star}$, then $\mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T}) = \mathbb{S}^{\propto}$
- (iii) **implies** (i):
  if $\mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T}) = \mathbb{S}^{\propto}$, then
  $\mathbf{Live}(\mathcal{T}) = \mathcal{T} \cup (\mathbb{S}^{\propto} \setminus (\mathcal{T} \cup \mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T}))) = \mathcal{T} \cup (\mathbb{S}^{\propto} \setminus \mathbb{S}^{\propto}) = \mathcal{T}$

Example

We assume that:

- $\mathbb{S} = \{a, b, c\}$
- $\mathcal{T}$ states that b **should eventually be visited, after** a **has been visited**; elements of $\mathcal{T}$ can be described by

$$\mathcal{T} = \mathbb{S}^\star \cdot a \cdot \mathbb{S}^\star \cdot b \cdot \mathbb{S}^\propto$$

Then $\mathcal{T}$ **is a liveness property:**

- let $\sigma \in \mathbb{S}^\star$; then $\sigma \cdot a \cdot b \in \mathcal{T}$, so $\sigma \in \mathbf{PCl}(\mathcal{T})$
- thus, $\mathbf{PCl}(\mathcal{T}) = \mathbb{S}^\star$

A property of **Live**

Theorem

If $\mathcal{T}$ is a trace property, then **Live**$(\mathcal{T})$ **is a liveness property** (i.e., operator **Live** is **idempotent**).

Proof: we show that $\mathbf{PCl} \circ \mathbf{Live}(\mathcal{T}) = \mathbb{S}^\star$, by considering $\sigma \in \mathbb{S}^\star$ and proving that $\sigma \in \mathbf{PCl} \circ \mathbf{Live}(\mathcal{T})$; we first note that:

$$\begin{array}{rcl} \mathbf{PCl} \circ \mathbf{Live}(\mathcal{T}) & = & \mathbf{PCl}(\mathcal{T}) \cup \mathbf{PCl}(\mathbb{S}^\omega \setminus \mathbf{Safe}(\mathcal{T})) \\ & = & \mathbf{PCl}(\mathcal{T}) \cup \mathbf{PCl}(\mathbb{S}^\omega \setminus \mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T})) \end{array}$$

- if $\sigma \in \mathbf{PCl}(\mathcal{T})$, this is obvious.
- if $\sigma \notin \mathbf{PCl}(\mathcal{T})$, then:
  - $\sigma \notin \mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T})$ by definition of the limit
  - thus, $\sigma \in \mathbb{S}^\omega \setminus \mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T})$
  - $\sigma \in \mathbf{PCl}(\mathbb{S}^\omega \setminus \mathbf{Lim} \circ \mathbf{PCl}(\mathcal{T}))$ as **PCl** is extensive, which proves the above result

Outline

Termination proof with ranking function

- We consider only **termination**
- We consider transition system $\mathcal{S} = (\mathbb{S}, \rightarrow, \mathbb{S}_{\mathcal{I}})$, and liveness property $\mathcal{T}$
- We seek a way of **verifying that $\mathcal{S}$ satisfies termination**, i.e., that $[\![\mathcal{S}]\!]^{\propto} \subseteq \mathbb{S}^{\star}$

Definition: ranking function

A **ranking function** is a function $\phi : \mathbb{S} \rightarrow E$ where:

- $(E, \sqsubseteq)$ is a **well-founded ordering**
- $\forall s_0, s_1 \in \mathbb{S},\ s_0 \rightarrow s_1 \Longrightarrow \phi(s_1) \sqsubset \phi(s_0)$

Theorem

If $\mathcal{S}$ has a ranking function ϕ, it satisfies termination.

Example

We consider the termination of the array sum program:

$$
\begin{array}{ll}
 & \texttt{i}, \texttt{s} \text{ integer variables} \\
 & \texttt{t} \text{ integer array of length } n \\
l_0: & \texttt{s} = 0; \\
l_1: & \texttt{i} = 0; \\
l_2: & \textbf{while}(\texttt{i} < n)\{ \\
l_3: & \quad \texttt{s} = \texttt{s} + \texttt{t}[\texttt{i}]; \\
l_4: & \quad \texttt{i} = \texttt{i} + 1; \\
l_5: & \} \\
l_6: & \ldots
\end{array}
$$

Ranking function:

$$
\begin{array}{rlcl}
\phi: & \mathbb{S} & \longrightarrow & \mathbb{N} \\
 & (l_0, m) & \longmapsto & 3 \cdot n + 6 \\
 & (l_1, m) & \longmapsto & 3 \cdot n + 5 \\
 & (l_2, m) & \longmapsto & 3 \cdot n + 4 \\
 & (l_3, m) & \longmapsto & 3 \cdot (n - m(\texttt{i})) + 3 \\
 & (l_4, m) & \longmapsto & 3 \cdot (n - m(\texttt{i})) + 2 \\
 & (l_5, m) & \longmapsto & 3 \cdot (n - m(\texttt{i})) + 1 \\
 & (l_6, m) & \longmapsto & 0
\end{array}
$$

Proof by variance

- We consider transition system $\mathcal{S} = (\mathbb{S}, \rightarrow, \mathbb{S}_{\mathcal{I}})$, and liveness property $\mathcal{T}$; infinite traces semantics is the least fixpoint of F_ω.
- We seek a way of **verifying that $\mathcal{S}$ satisfies $\mathcal{T}$**, i.e., that $[\![\mathcal{S}]\!]^\propto \subseteq \mathcal{T}$

Principle of variance proofs

Let $(\mathbb{I}_n)_{n\in\mathbb{N}}$, $\mathbb{I}_\omega$ be elements of $\mathbb{S}^\propto$; these are said to form a variance proof of $\mathcal{T}$ if and only if:

- $\mathbb{S}^\propto \subseteq \mathbb{I}_0$
- for all $k \in \{1, 2, \ldots, \omega\}$, $\forall s \in \mathbb{S}$, $\langle s \rangle \in \mathbb{I}_k$
- for all $k \in \{1, 2, \ldots, \omega\}$, there exists $l < k$ such that $F_\omega(\mathbb{I}_l) \subseteq \mathbb{I}_k$
- $\mathbb{I}_\omega \subseteq \mathcal{T}$

Proofs of soundness and completeness: exercise

Outline

The decomposition theorem

Theorem

Let $\mathcal{T} \subseteq \mathbb{S}^{\propto}$; it can be decomposed into the **conjunction** of **safety property** $\mathbf{Safe}(\mathcal{T})$ and **liveness property** $\mathbf{Live}(\mathcal{T})$:

$$\mathcal{T} = \mathbf{Safe}(\mathcal{T}) \cap \mathbf{Live}(\mathcal{T})$$

- Reading:
  Recognizing Safety and Liveness.
  Bowen Alpern and **Fred B. Schneider**.
  In Distributed Computing, Springer, 1987.
- **Consequence of this result:**
  the proof of any trace property can be decomposed into
  - a proof of safety
  - a proof of liveness

Proof

- **safety part:**
  Safe is idempotent, so $\mathbf{Safe}(\mathcal{T})$ is a safety property.
- **liveness part:**
  Live is idempotent, so $\mathbf{Live}(\mathcal{T})$ is a liveness property.
- **decomposition:**

$$\begin{array}{rcl}
\mathbf{Safe}(\mathcal{T}) \cap \mathbf{Live}(\mathcal{T}) & = & (\mathbb{S}^{\propto} \setminus \mathbf{Safe}(\mathcal{T}) \cup \mathcal{T}) \cap \mathbf{Safe}(\mathcal{T}) \\
& = & (\mathbb{S}^{\propto} \setminus \mathbf{Safe}(\mathcal{T}) \cap \mathbf{Safe}(\mathcal{T})) \cup (\mathcal{T} \cap \mathbf{Safe}(\mathcal{T})) \\
& = & \mathcal{T}
\end{array}$$

Example: verification of total correctness

$\mathtt{i}, \mathtt{s}$ integer variables
$\mathtt{t}$ integer array of length n

$$
\begin{array}{ll}
\ell_0: & \mathtt{s} = 0; \\
\ell_1: & \mathtt{i} = 0; \\
\ell_2: & \textbf{while}(\mathtt{i} < n)\{ \\
\ell_3: & \quad \mathtt{s} = \mathtt{s} + \mathtt{t}[\mathtt{i}]; \\
\ell_4: & \quad \mathtt{i} = \mathtt{i} + 1; \\
\ell_5: & \} \\
\ell_6: & \ldots
\end{array}
$$

Property to prove:
total correctness

1. the program **terminates**
2. and it **computes the sum of the elements in the array**

Application of the decomposition principle

Conjunction of two proofs:

1. proved with a **ranking function**
2. proved with **local invariants**

Outline

Notion of specification languages

- Ultimately, we would like to **verify or compute** properties
- So far, we simply describe properties with **sets of executions** or worse, with English / French / ... statements
- Ideally, we would prefer to use a **mathematical language** for that
  - to **gain in concision**, **avoid ambiguity**
  - to **define sets of properties to consider**, fix **the form of inputs for verification tools...**

Definition: specification language

A **specification language** is a set of terms $\mathbb{L}$ with an interpretation (or semantics)

$$[\![.]\!] : \quad \mathbb{L} \quad \longrightarrow \quad \mathcal{P}(\mathbb{S}^{\propto}) \qquad (\text{resp., } \mathcal{P}(\mathbb{S}))$$

- We are now going to consider specification languages **for states**, **for traces**...

A state specification language

A first **example** of a (simple) specification language:

A state specification language

- **Syntax:** we let terms of $\mathbb{L}_{\mathbb{S}}$ be defined by:

$$p \in \mathbb{L}_{\mathbb{S}} ::= @\ell \mid \mathrm{x} < \mathrm{x}' \mid \mathrm{x} < n \mid \neg p' \mid p' \wedge p''$$

- **Semantics:** $\llbracket p \rrbracket \subseteq \mathbb{M}$ is defined by

$$\begin{array}{rcl} \llbracket @\ell \rrbracket & = & \{\ell\} \times \mathbb{M} \\ \llbracket \mathrm{x} < \mathrm{x}' \rrbracket & = & \{(\ell, m) \in \mathbb{S} \mid m(\mathrm{x}) < m(\mathrm{x}')\} \\ \llbracket \mathrm{x} < n \rrbracket & = & \{(\ell, m) \in \mathbb{S} \mid m(\mathrm{x}) < n\} \\ \llbracket \neg p \rrbracket & = & \mathbb{S} \setminus \llbracket p \rrbracket \\ \llbracket p \wedge p' \rrbracket & = & \llbracket p \rrbracket \cap \llbracket p' \rrbracket \end{array}$$

Exercise: add $=$, $\vee$, $\Rightarrow$...

Propositional temporal logic: syntax

We now consider the **specification of trace properties**

- **temporal logic:** specification of properties in terms of events that occur at distinct points in the execution of programs (hence, the name "temporal")
- there are **many** such logics
- we consider a compact one: **Pnueli's Propositional Temporal Logic (PTL)**

Definition: syntax of PTL

Properties over traces are defined as terms of the form

$$
\begin{array}{rcll}
t (\in \mathbb{L}_{\mathbf{PTL}}) & ::= & p & \text{state property, i.e., } p \in \mathbb{L}_{\mathbb{S}} \\
& \mid & t' \vee t'' & \text{disjunction} \\
& \mid & \neg t' & \text{negation} \\
& \mid & \bigcirc\, t' & \text{"next"} \\
& \mid & t' \,\mathfrak{U}\, t'' & \text{"until", i.e., } t' \text{ until } t''
\end{array}
$$

Propositional temporal logic: semantics

A "tail" operator $\cdot_{i\rceil}$ on traces:

- $(\langle s_0, \ldots, s_i \rangle \cdot \sigma)_{i\rceil} ::= \sigma$
- if $|\sigma| < i$, $\sigma_{i\rceil} = \epsilon$

Semantics of temporal logic formulae:

$$\begin{array}{rcl}
[\![p]\!] & = & \{ s \cdot \sigma \mid s \in [\![p]\!] \wedge \sigma \in \mathbb{S}^{\propto} \} \\
[\![t_0 \vee t_1]\!] & = & [\![t_0]\!] \cup [\![t_1]\!] \\
[\![\neg t_0]\!] & = & \mathbb{S}^{\propto} \setminus [\![t_0]\!] \\
[\![\bigcirc\, t_0]\!] & = & \{ s \cdot \sigma \mid s \in \mathbb{S} \wedge \sigma \in [\![t_0]\!] \} \\
[\![t_0 \,\mathfrak{U}\, t_1]\!] & = & \{ \sigma \in \mathbb{S}^{\propto} \mid \exists n \in \mathbb{N},\ \forall i < n,\ \sigma_{i\rceil} \in [\![t_0]\!] \wedge \sigma_{n\rceil} \in [\![t_1]\!] \}
\end{array}$$

Temporal logic operators as syntactic sugar

Many useful operators can be added:

- **Boolean constants:**

$$\begin{array}{l}\textbf{true} ::= (\mathtt{x} < 0) \vee \neg(\mathtt{x} < 0) \\ \textbf{false} ::= \neg\textbf{true}\end{array}$$

- **Sometime:**

$$\Diamond\, t ::= \textbf{true}\, \mathfrak{U}\, t$$

  intuition: there exists a rank n at which t holds

- **Always:**

$$\Box\, t ::= \neg(\Diamond(\neg t))$$

  intuition: there is no rank at which the negation of t holds

Exercise: what do $\Diamond\,\Box\, t$ and $\Box\,\Diamond\, t$ mean ?

Examples

We consider the program below:

$$
\begin{array}{ll}
\ell_0: & \textbf{int}\; \mathtt{x} = \textbf{input}(); \\
\ell_1: & \textbf{if}(\mathtt{x} < 8)\{ \\
\ell_2: & \qquad \mathtt{x} = 0; \\
\ell_3: & \}\,\textbf{else}\,\{ \\
\ell_4: & \qquad \mathtt{x} = 1; \\
\ell_5: & \} \\
\ell_6: & \ldots
\end{array}
$$

Examples of properties:

- "when ℓ_4 is reached, $\mathtt{x}$ is positive"

$$\square(@\ell_4 \Longrightarrow \mathtt{x} \geq 0)$$

- "if the value read at point ℓ_0 is negative, and when ℓ_6 is reached, $\mathtt{x}$ is equal to 0"

$$(@\ell_1 \wedge \mathtt{x} < 0) \Longrightarrow \square(@\ell_6 \Longrightarrow \mathtt{x} = 0)$$

Outline

Security properties

We now consider other interesting properties of programs, and show that they do not all reduce to trace properties

Security

- collects many kinds of properties
- so we consider just one:

  an unauthorized observer should not be able to guess anything about private information by looking at public information

- **example:** another user should not be able to guess the content of an email sent to you
- we need to **formalize this property**

A few definitions

Assumptions:

- we let $\mathcal{S} = (\mathbb{S}, \rightarrow, \mathbb{S}_{\mathcal{I}})$ be a transition system
- states are of the form $(\ell, m) \in \mathbb{L} \times \mathbb{M}$
- memory states are of the form $\mathbb{X} \rightarrow \mathbb{V}$
- we let $\ell, \ell' \in \mathbb{L}$ (program entry and exit) and $\mathrm{x}, \mathrm{x}' \in \mathbb{X}$ (private and public variables)

Security property we are looking at

Observing the value of x' at ℓ' gives no information on the value of x at ℓ.

We consider the **transformer** Φ defined by:

$$\begin{array}{rrcl} \Phi : & \mathbb{M} & \longrightarrow & \mathcal{P}(\mathbb{M}) \\ & m & \longmapsto & \{m' \in \mathbb{M} \mid \exists \sigma = \langle (\ell, m), \ldots, (\ell', m') \rangle \in [\![\mathcal{S}]\!]\} \end{array}$$

Non-interference

Definition: non-interference

There is **no interference** between (ℓ, x) and (ℓ', x') and we write $(l', x') \not\rightsquigarrow (l, x)$ if and only if the following property holds:

$$\forall m \in \mathbb{M}, \forall v_0, v_1 \in \mathbb{V}, \\ \{m'(\mathrm{x}') \mid m' \in \Phi(m[\mathrm{x} \leftarrow v_0])\} = \{m'(\mathrm{x}') \mid m' \in \Phi(m[\mathrm{x} \leftarrow v_1])\}$$

Intuition:

- if two observation at point ℓ differ only in the value of x, there is no difference in observation of x' at ℓ'
- in other words, observing x' at ℓ' (even on many executions) gives no information about the value of x at point ℓ...

Non-interference is not a trace property

- we assume $\mathbb{V} = \{0, 1\}$ and $\mathbb{X} = \{\mathrm{x}, \mathrm{x}'\}$ (store m is defined by the pair $(m(\mathrm{x}), m(\mathrm{x}'))$, and denoted by it)
- we assume $\mathbb{L} = \{\ell, \ell'\}$ and consider two systems such that all transitions are of the form $(\ell, m) \rightarrow (\ell', m')$
(i.e., system $\mathcal{S}$ is isomorphic to its tranfsormer $\Phi[\mathcal{S}]$)

$$\Phi[\mathcal{S}_0] : \begin{array}{ccc} (0,0) & \longmapsto & \mathbb{M} \\ (0,1) & \longmapsto & \mathbb{M} \\ (1,0) & \longmapsto & \mathbb{M} \\ (1,1) & \longmapsto & \mathbb{M} \end{array} \qquad \Phi[\mathcal{S}_1] : \begin{array}{ccc} (0,0) & \longmapsto & \mathbb{M} \\ (0,1) & \longmapsto & \mathbb{M} \\ (1,0) & \longmapsto & \{(1,1)\} \\ (1,1) & \longmapsto & \{(1,1)\} \end{array}$$

- $\mathcal{S}_1$ has fewer behaviors than $\mathcal{S}_0$: $[\![\mathcal{S}_1]\!]^\star \subset [\![\mathcal{S}_0]\!]^\star$
- $\mathcal{S}_0$ **has the non-interference property**, but $\mathcal{S}_1$ **does not**
- if non interference was a trace property, $\mathcal{S}_1$ should have it (monotony)

Thus, the non interference property is not a trace property

Dependence properties

Dependence property

- many notions of dependences
- so we consider just one:

what inputs may have an impact on the observation of a given output

- **Applications:**
  - **reverse engineering:** understand how an input gets computed
  - **slicing:** extract the fragment of a program that is relevant to a result
- This corresponds to the **negation** of non-interference

Interference

Definition: interference

There is **interference** between (ℓ, x) and (ℓ', x') and we write $(l', x') \rightsquigarrow (l, x)$ if and only if the following property holds:

$$\begin{array}{l} \exists m \in \mathbb{M},\ \exists v_0, v_1 \in \mathbb{V}, \\ \quad \{m'(\mathrm{x}') \mid m' \in \Phi(m[\mathrm{x} \leftarrow v_0])\} \neq \{m'(\mathrm{x}') \mid m' \in \Phi(m[\mathrm{x} \leftarrow v_1])\} \end{array}$$

- This expresses that there is at least one case, where the value of x at ℓ has an impact on that of x' at ℓ'
- It may not hold even if the computation of x' reads x:

$$\begin{array}{ll} \ell : & \mathrm{x}' = 0 \star \mathrm{x}; \\ \ell' : & \ldots \end{array}$$

Interference is not a trace property

- we assume $\mathbb{V} = \{0, 1\}$ and $\mathbb{X} = \{\mathrm{x}, \mathrm{x}'\}$ (store m is defined by the pair $(m(\mathrm{x}), m(\mathrm{x}'))$, and denoted by it)
- we assume $\mathbb{L} = \{\ell, \ell'\}$ and consider two systems such that all transitions are of the form $(\ell, m) \to (\ell', m')$
  (i.e., system $\mathcal{S}$ is isomorphic to its tranfsormer $\Phi[\mathcal{S}]$)

$$\Phi[\mathcal{S}_0] : \begin{array}{rcl} (0,0) & \longmapsto & \mathbb{M} \\ (0,1) & \longmapsto & \mathbb{M} \\ (1,0) & \longmapsto & \{(1,1)\} \\ (1,1) & \longmapsto & \{(1,1)\} \end{array} \qquad \Phi[\mathcal{S}_1] : \begin{array}{rcl} (0,0) & \longmapsto & \{(1,1)\} \\ (0,1) & \longmapsto & \{(1,1)\} \\ (1,0) & \longmapsto & \{(1,1)\} \\ (1,1) & \longmapsto & \{(1,1)\} \end{array}$$

- $\mathcal{S}_1$ has fewer behavior than $\mathcal{S}_0$: $[\![\mathcal{S}_1]\!]^\star \subset [\![\mathcal{S}_0]\!]^\star$
- $\mathcal{S}_0$ **has the interference property**, but $\mathcal{S}_1$ **does not**
- if interference was a trace property, $\mathcal{S}_1$ should have it (monotony)

Thus, the interference property is not a trace property

Outline

Summary

To sum-up:

- **trace properties** allow to express a large range of program properties
- **safety = absence of bad behaviors**
- **liveness = existence of good behaviors**
- trace properties can be **decomposed** as conjunctions of safety and liveness properties, with **dedicated proof methods**
- some interesting properties are **not trace properties**
- notion of **specification languages** to describe program properties

Next lectures:

- another family of properties: **equivalences** of programs
- tools to **compute** proofs of programs