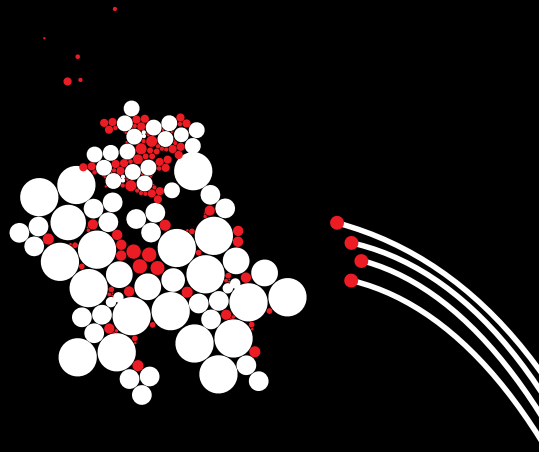
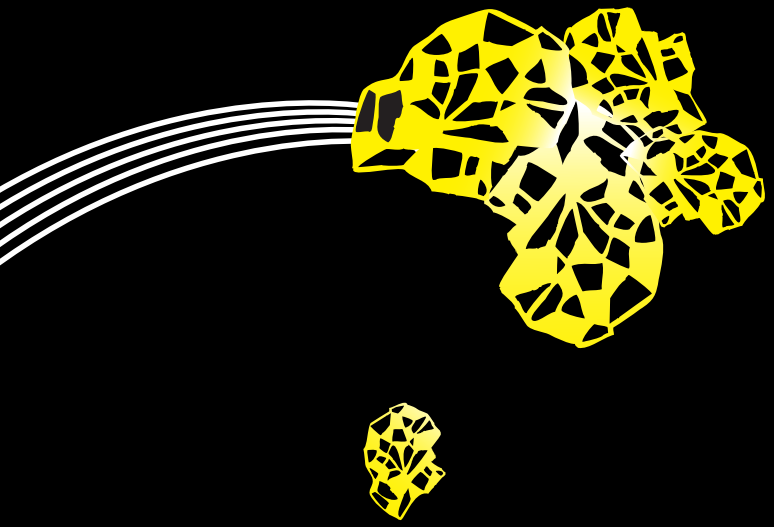
UNIVERSITY OF TWENTE.



Test generation & ioco

Software Testing and Risk Assessment

Lecture 5



Today

- after and test cases (revisited)
- Batch test generation
- On-the-fly Test generation
- Test assumptions
- ioco
- Sound and exhaustive test suites
- Underspecification
- uioco

after

- Let $S = (Q, L_I, L_U, T, q_0)$ be an LTS.
- Let $L = L_I \cup L_U \cup \{\delta\}$.
- Let $q \in Q$ be a state, $\mu \in L$ a label, and $\rho \in L^*$ a sequence of labels.
- A state q is quiescent, denoted $\delta(q)$, if:
  $\forall x \in L_U, \forall q' \in Q : (q, x, q') \notin T$
- *after* : $Q \times L^* \to \mathbb{P}(Q)$
- q *after* $\epsilon = \{q\}$
- q *after* $\mu\rho = Q'$ *after* ρ where
  $Q' = \{q' \in Q \mid (q, \mu, q') \in T\} \cup \{q \mid \delta(q) \wedge \mu = \delta\}$
- Extend to *after* : $\mathbb{P}(Q) \times L^* \to \mathbb{P}(Q)$

after

- Let $S = (Q, L_I, L_U, T, q_0)$ be an LTS.
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- Extend to *after* : $\mathbb{P}(Q) \times L^* \to \mathbb{P}(Q)$
- Let $Q' \subseteq Q$.
- Q' *after* $\rho = \bigcup_{q \in Q'} q$ *after* ρ

Example for *after*

- q *after* $\mu\rho = Q'$ *after* ρ where
  $Q' = \{q' \in Q \mid (q, \mu, q') \in T\} \cup \{q \mid \delta(q) \wedge \mu = \delta\}$
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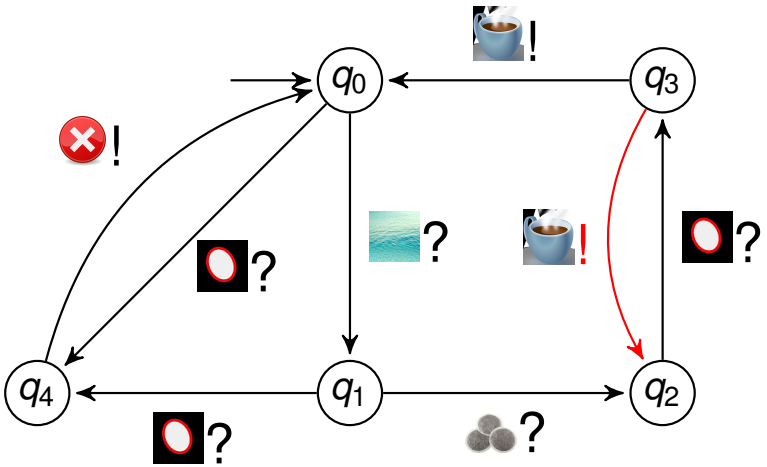

- q_3 *after* ☕!🍩? =

Example for *after*

- q *after* $\mu\rho = Q'$ *after* ρ where
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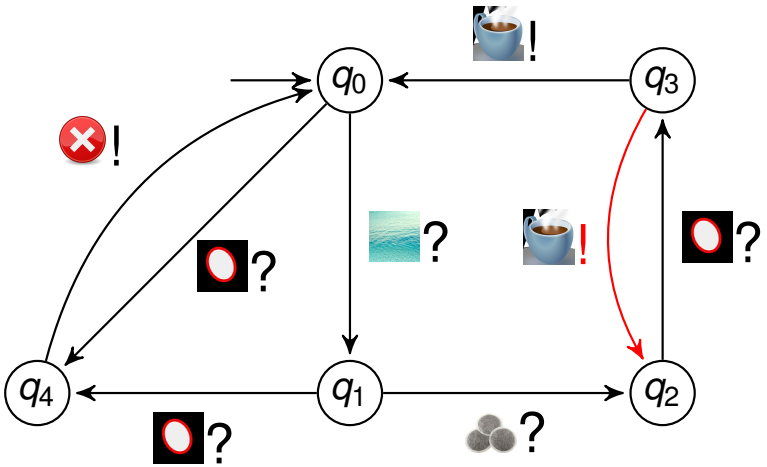

- q_3 *after* coffee! cup? =
  $(\{q' \in Q \mid (q_3, \text{coffee}!, q') \in T\} \cup \{q_3 \mid \delta(q_3) \wedge \text{coffee}! = \delta\})$ *after* cup? =

Example for *after*

- q *after* $\mu\rho = Q'$ *after* ρ where
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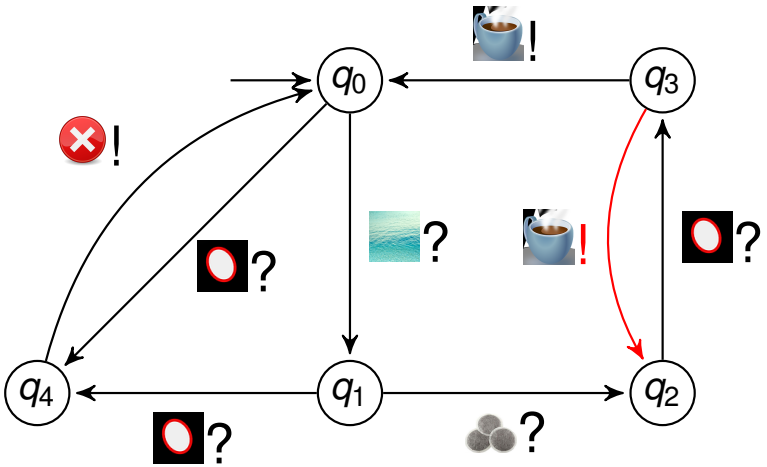

- q_3 *after* ☕!🍩? =
  $(\{q' \in Q \mid (q_3, ☕!, q') \in T\} \cup \{q_3 \mid \delta(q_3) \wedge ☕! = \delta\})$ *after* 🍩? =
  $(\{q_0, q_2\} \cup \emptyset)$ *after* 🍩? =

Example for *after*

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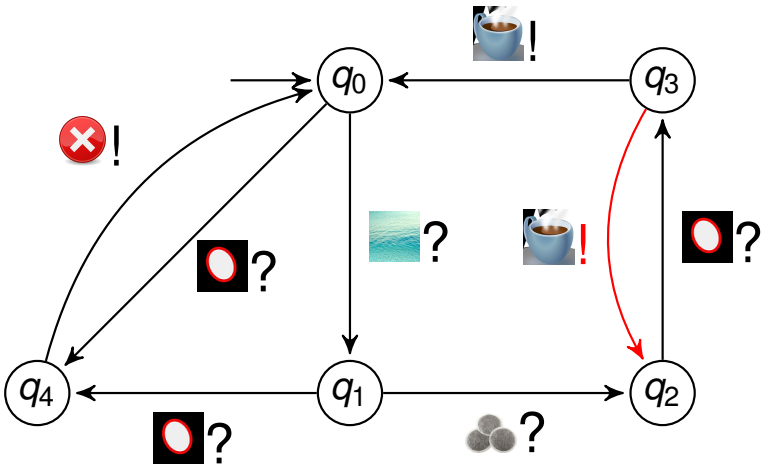
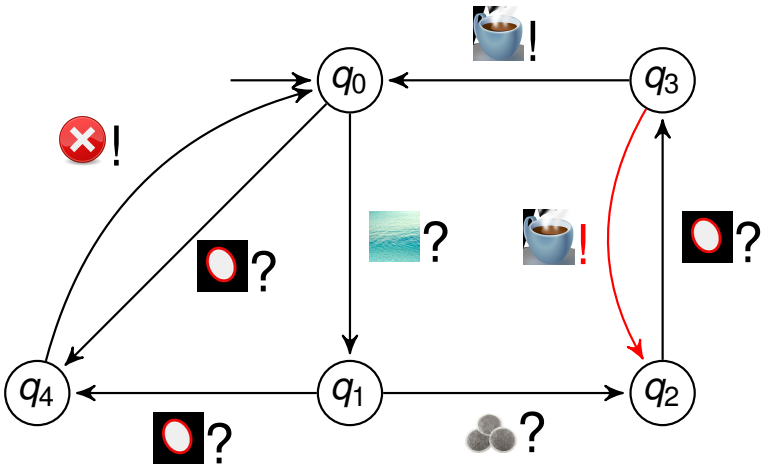


- q_3 *after* ☕!🍩? =
  $(\{q' \in Q \mid (q_3, ☕!, q') \in T\} \cup \{q_3 \mid \delta(q_3) \wedge ☕! = \delta\})$ *after* 🍩? =
  $(\{q_0, q_2\} \cup \emptyset)$ *after* 🍩? =
  (q_0 *after* 🍩?) $\cup$ (q_2 *after* 🍩?) =

Example for *after*

- q *after* $\mu\rho = Q'$ *after* ρ where
  $Q' = \{q' \in Q \mid (q, \mu, q') \in T\} \cup \{q \mid \delta(q) \wedge \mu = \delta\}$
- Q' *after* $\rho = \bigcup_{q \in Q'} q$ *after* ρ



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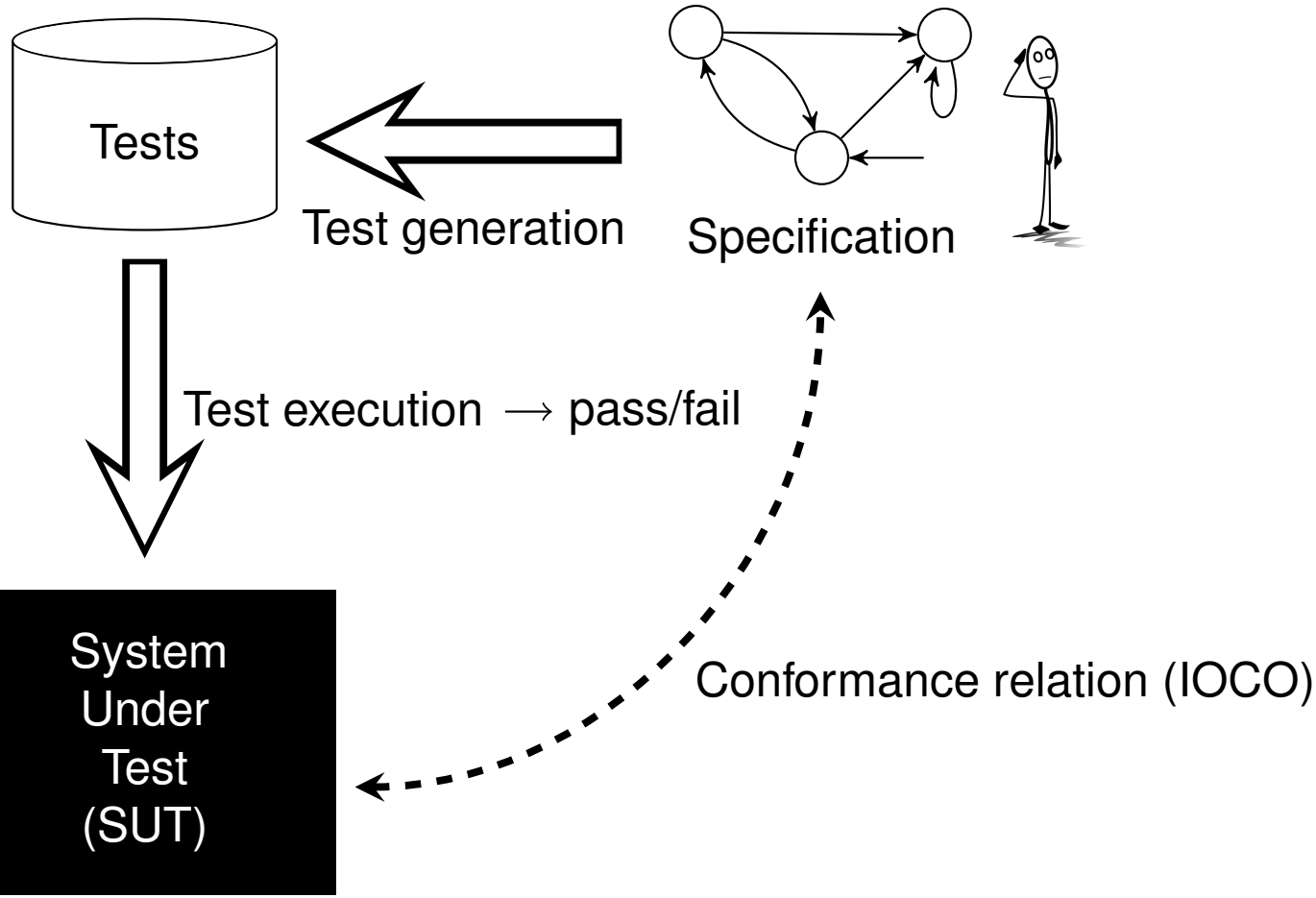
  $(\{q' \in Q \mid (q_3, \text{coffee}!, q') \in T\} \cup \{q_3 \mid \delta(q_3) \wedge \text{coffee}! = \delta\})$ *after* cup? =
  $(\{q_0, q_2\} \cup \emptyset)$ *after* cup? =
  $(q_0$ *after* cup?$) \cup (q_2$ *after* cup?$) =$
  $\{q_4\} \cup \{q_2\} = \{q_2, q_4\}$

Formal definition of test cases

- A test case for an LTS S is an LTS $t = (Q^t, \underline{L_I, L_U}, T^t, q_0^t)$ s.t.:
  - $\underline{t \text{ uses the same labels as } S}$
  - There are two special states *Pass*, *Fail*$\in Q^t$
  - States *Pass* and *Fail* have self-loops for all outputs (incl. δ): $\forall x \in L_U \cup \{\delta\} : \textit{Pass after } x = \{\textit{Pass}\}$ and $\textit{Fail after } x = \{\textit{Fail}\}$
  - States *Pass* and *Fail* have no transition for inputs: $\forall a \in L_I : \textit{Pass after } a = \textit{Fail after } a = \emptyset$
  - t has no cycles except those in *Pass* and *Fail*
  - t is deterministic
  - Every state enables all outputs L_U, and either one input or δ: $\forall q \in \underline{Q^t} : (|in(q)| = 0 \wedge out(q) = L_U \cup \{\delta\}) \vee (out(q) = L_U \wedge |in(q)| = 1)$

Model-Based Testing



Test generation (batch)

- Algorithm *batchGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' \subseteq Q$
  - **Output:** a test case for S

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- $batchGen(S, Q') =$ take either of the following steps:

End test case	pass

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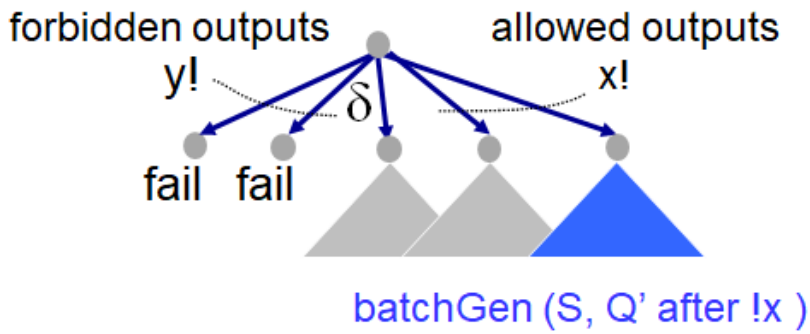
End test case	pass
Observe output	

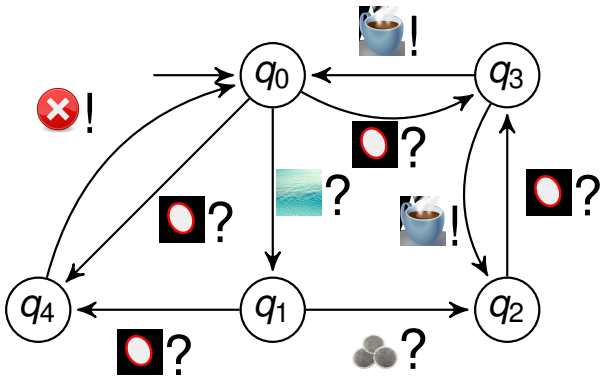
Test generation (batch)

- Algorithm *batchGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' \subseteq Q$
  - **Output:** a test case for S
- $batchGen(S, Q') =$ take either of the following steps:

End test case	pass
Observe output	forbidden outputs y! δ fail fail allowed outputs x! batchGen (S, Q' after !x)
Supply input a? where Q' *after* $a? \neq \emptyset$	forbidden outputs y! a? fail fail allowed outputs x! batchGen(S, Q' after a?)

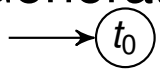
Batch test generation example

- Input LTS:



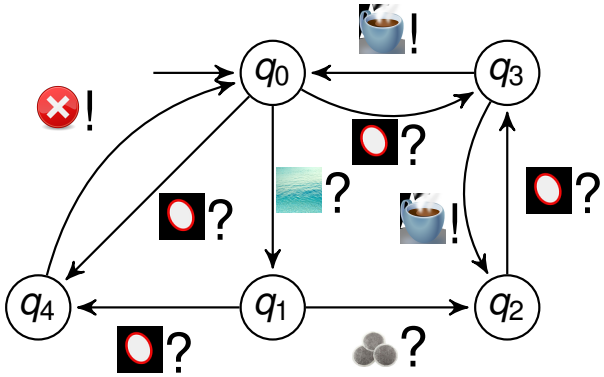
- Current states in t_0: $\{q_0\}$

- Generated test case:



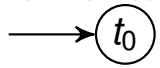
Batch test generation example

- Input LTS:



- Current states in t_0: $\{q_0\}$
- Choose input: ?

- Generated test case:



Batch test generation example

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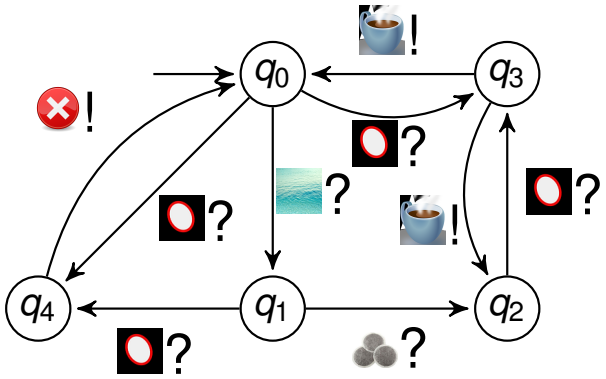
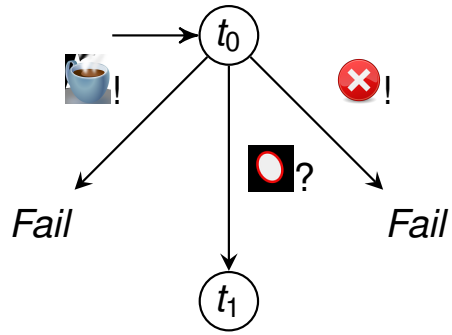


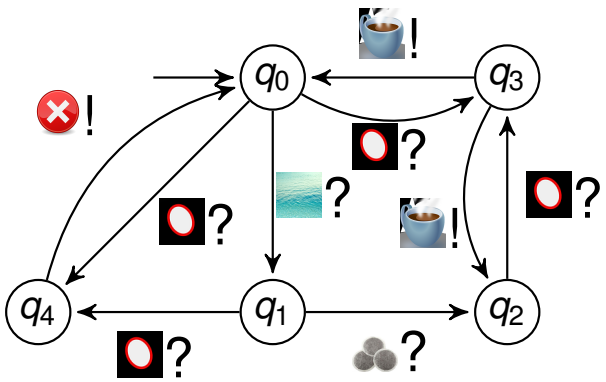
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$

- Generated test case:



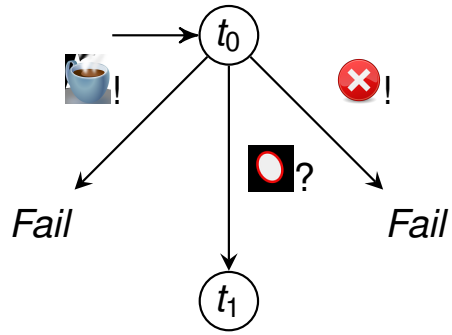
Batch test generation example

- Input LTS:



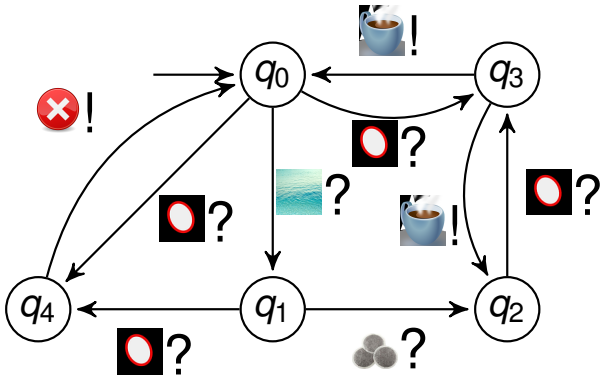
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs

- Generated test case:



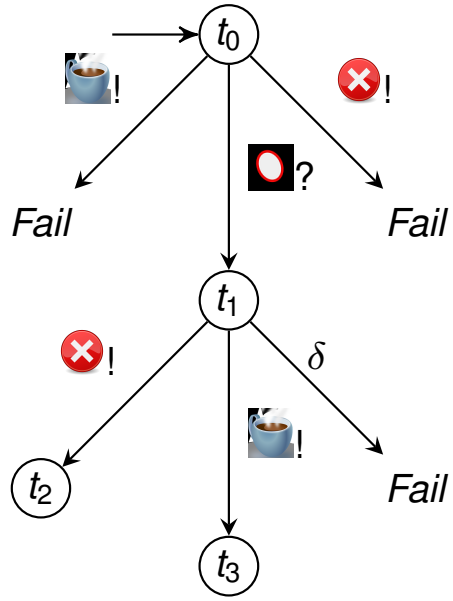
Batch test generation example

- Input LTS:



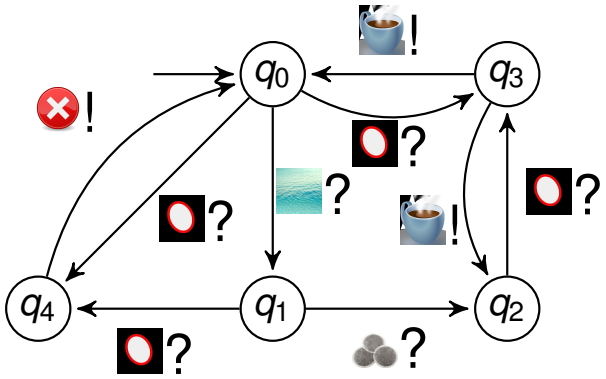
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs
- Current states in t_2: $\{q_0\}$

- Generated test case:



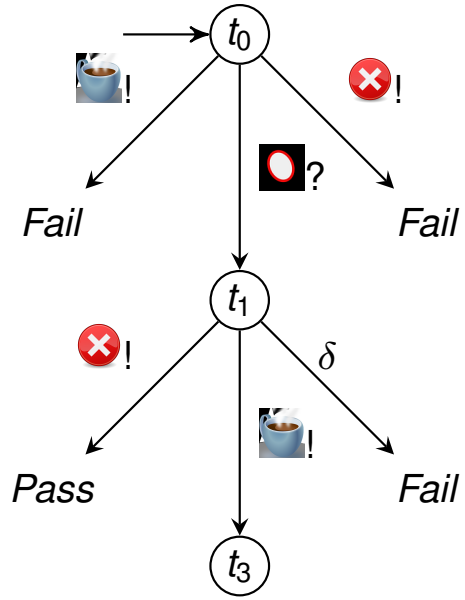
Batch test generation example

- Input LTS:



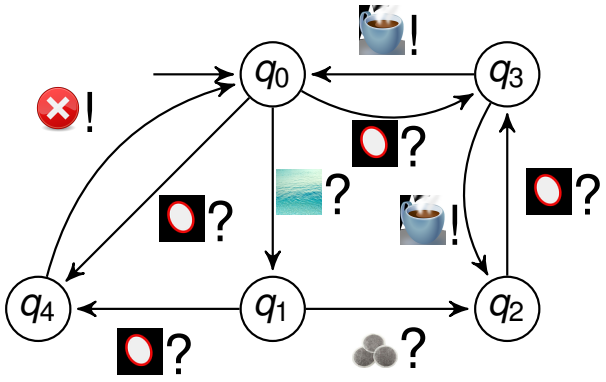
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs
- Current states in t_2: $\{q_0\}$
- Stop

- Generated test case:



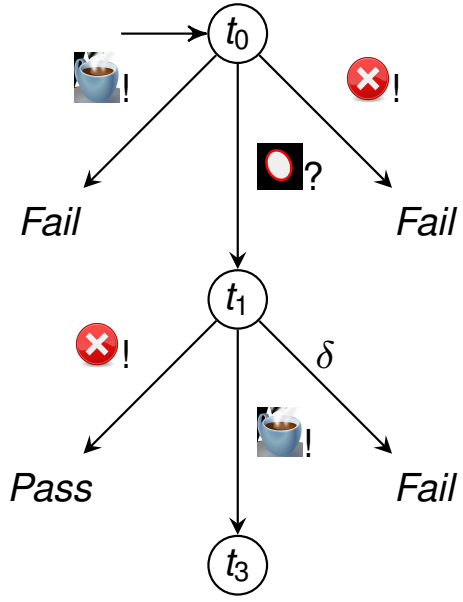
Batch test generation example

- Input LTS:



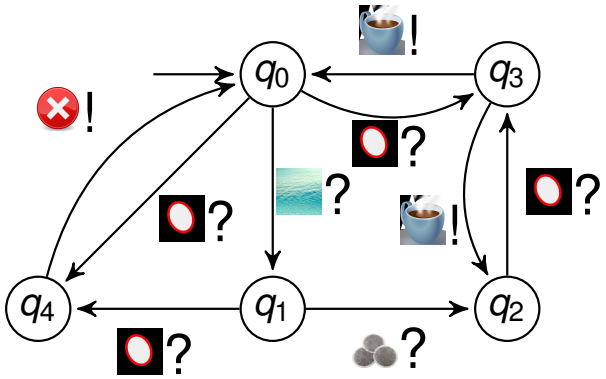
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs
- Current states in t_2: $\{q_0\}$
- Stop
- Current states in t_3: $\{q_0, q_2\}$

- Generated test case:



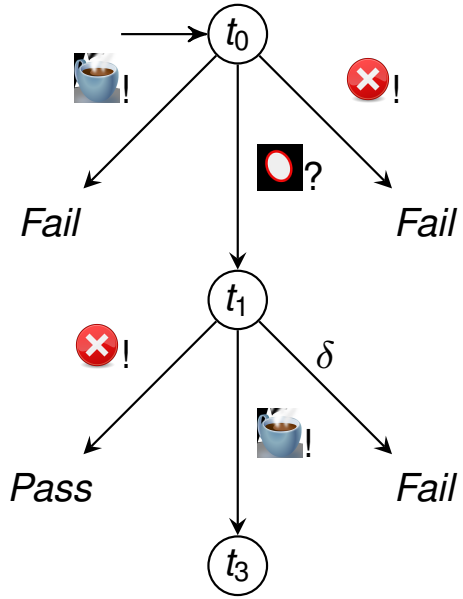
Batch test generation example

- Input LTS:



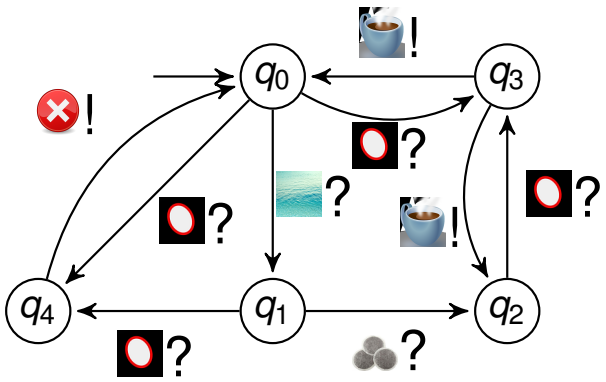
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs
- Current states in t_2: $\{q_0\}$
- Stop
- Current states in t_3: $\{q_0, q_2\}$
- Choose input: ?

- Generated test case:



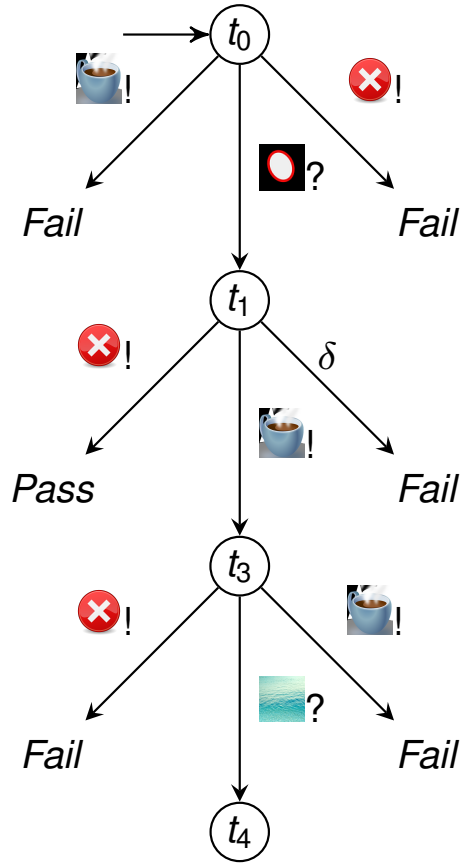
Batch test generation example

- Input LTS:



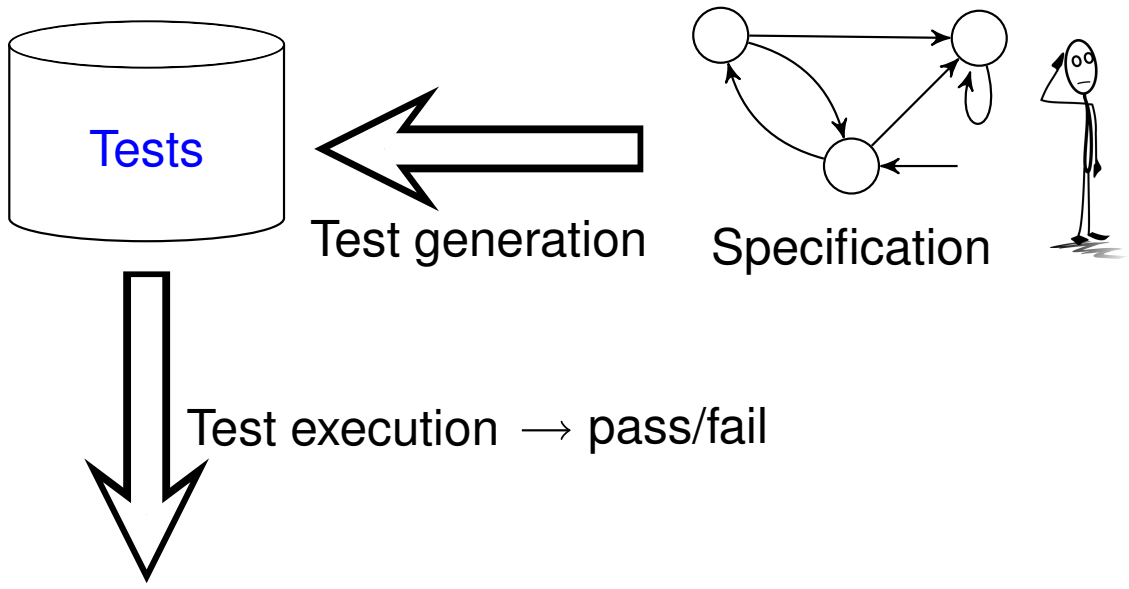
- Current states in t_0: $\{q_0\}$
- Choose input: ?
- Current states in t_1: $\{q_3, q_4\}$
- Observe outputs
- Current states in t_2: $\{q_0\}$
- Stop
- Current states in t_3: $\{q_0, q_2\}$
- Choose input: ?
- Current states in t_4: $\{q_1\}$ and ?

- Generated test case:



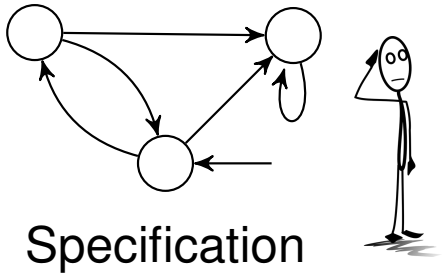
Test generation (batch)

- *batchGen* is a nondeterministic algorithm
  - Outputs different test cases
- Store test cases for execution



On-the-fly test generation

- *OnTheFlyGen* is also a nondeterministic algorithm
  - Outputs different test cases
- Generates a test step and executes it right away



Specification

Test generation and execution

pass/fail

System Under Test (SUT)

On-the-fly test generation

- Algorithm *onTheFlyGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' = \{q_0\}$
  - **Output:** a verdict *Pass* or *Fail*

On-the-fly test generation

- Algorithm *onTheFlyGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' = \{q_0\}$
  - **Output:** a verdict *Pass* or *Fail*
- *onTheFlyGen*$(S, Q') =$ take either of the following steps:

End test case	return verdict *Pass*

On-the-fly test generation

- Algorithm *onTheFlyGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' = \{q_0\}$
  - **Output:** a verdict *Pass* or *Fail*
- *onTheFlyGen*(S, Q') = take either of the following steps:

End test case	return verdict *Pass*
Observe output $x!$	if $x! \in out(Q')$: *onTheFlyGen*$(S, Q'$ *after* $x!)$ else: return *Fail*

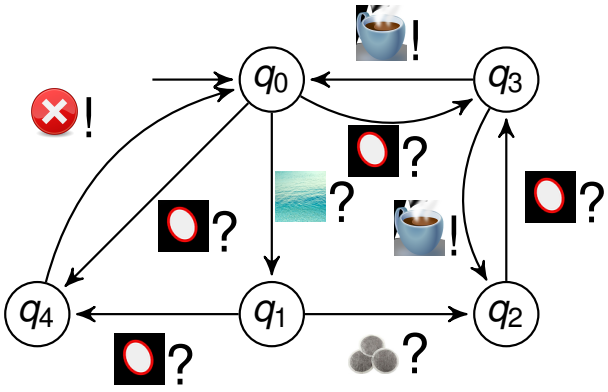
On-the-fly test generation

- Algorithm *onTheFlyGen*:
  - **Input:** LTS $S = (Q, L_I, L_U, T, q_0)$, and current states $Q' = \{q_0\}$
  - **Output:** a verdict *Pass* or *Fail*
- $onTheFlyGen(S, Q') =$ take either of the following steps:

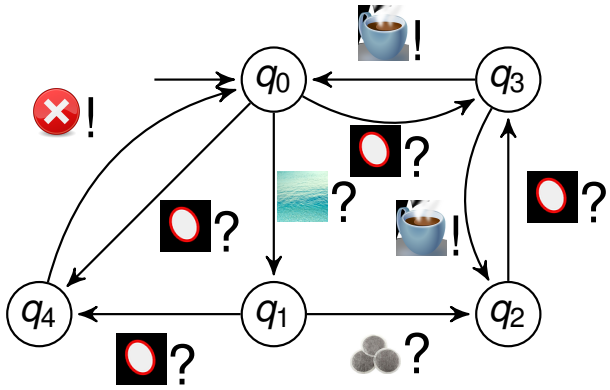
End test case	return verdict *Pass*
Observe output $x!$	if $x! \in out(Q')$: $onTheFlyGen(S, Q'\ after\ x!)$ else: return *Fail*

Choose input $a?$
where $Q'\ after\ a? \neq \emptyset$
	if SUT provides output $x!$ already:
	  handle output observation (as above)
	else:
	  supply $a?$ and continue with
	  $onTheFlyGen(S, Q'\ after\ a?)$

On-the-fly test generation example

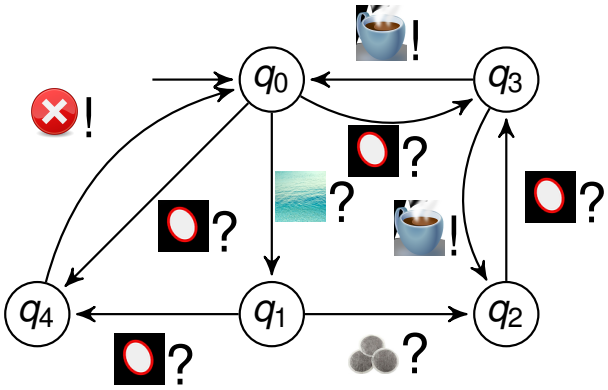


On-the-fly test generation example



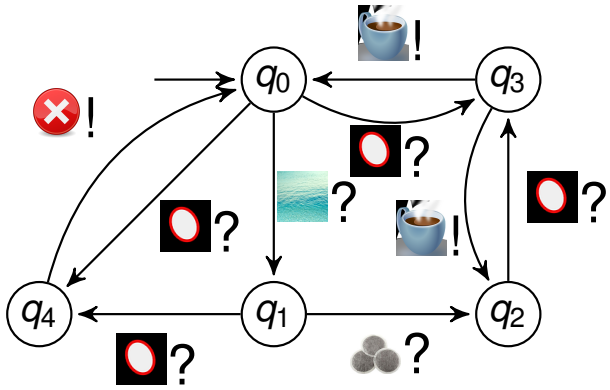
- Choose ?

On-the-fly test generation example



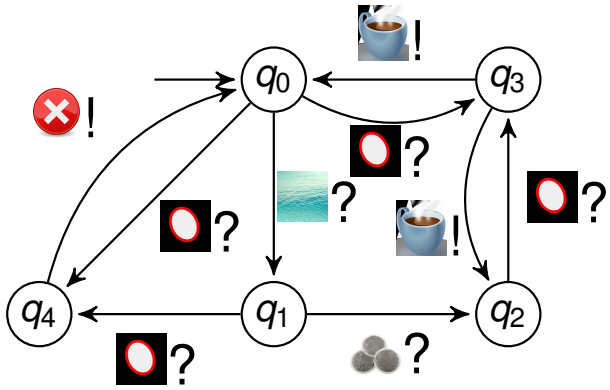
- Choose ?
- SUT accepts input

On-the-fly test generation example



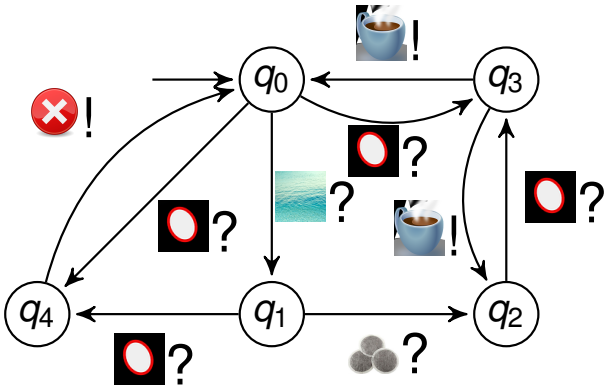
- Choose ?
- SUT accepts input
- Current states: $\{q_3, q_4\}$

On-the-fly test generation example



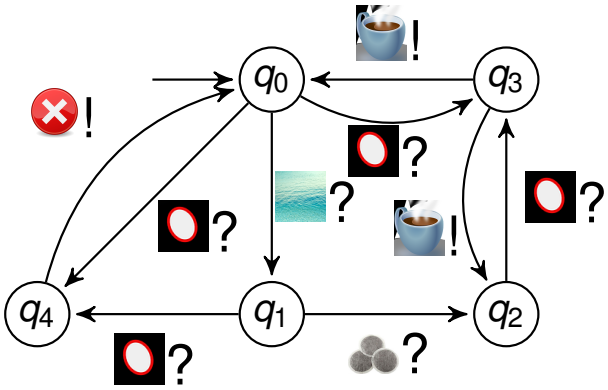
- Choose ?
- SUT accepts input
- Current states: $\{q_3, q_4\}$
- Observe output

On-the-fly test generation example



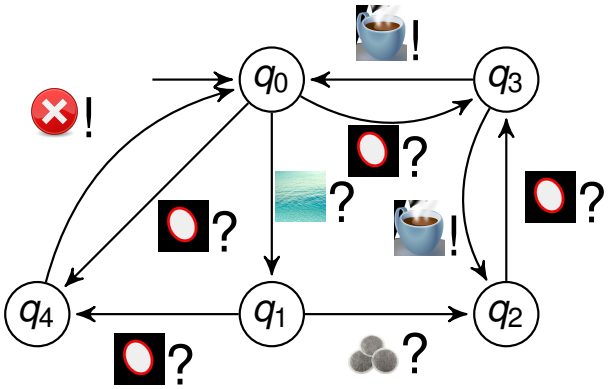
- Choose ?
- SUT accepts input
- Current states: $\{q_3, q_4\}$
- Observe output
- SUT provides !

On-the-fly test generation example



- Choose ?
- SUT accepts input
- Current states: $\{q_3, q_4\}$
- Observe output
- SUT provides !
- Current states: $\{q_0, q_2\}$

On-the-fly test generation example



- Choose ?
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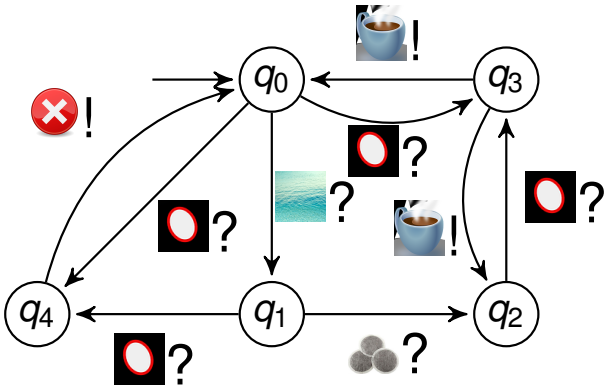

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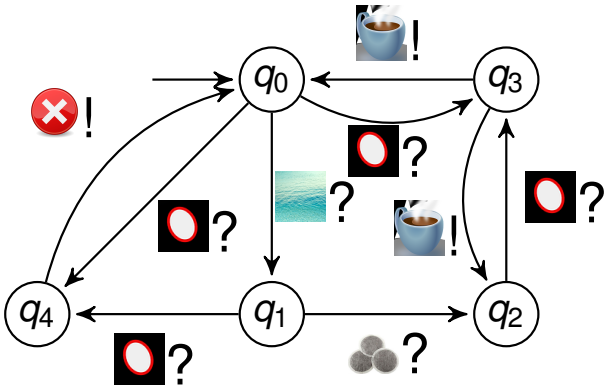
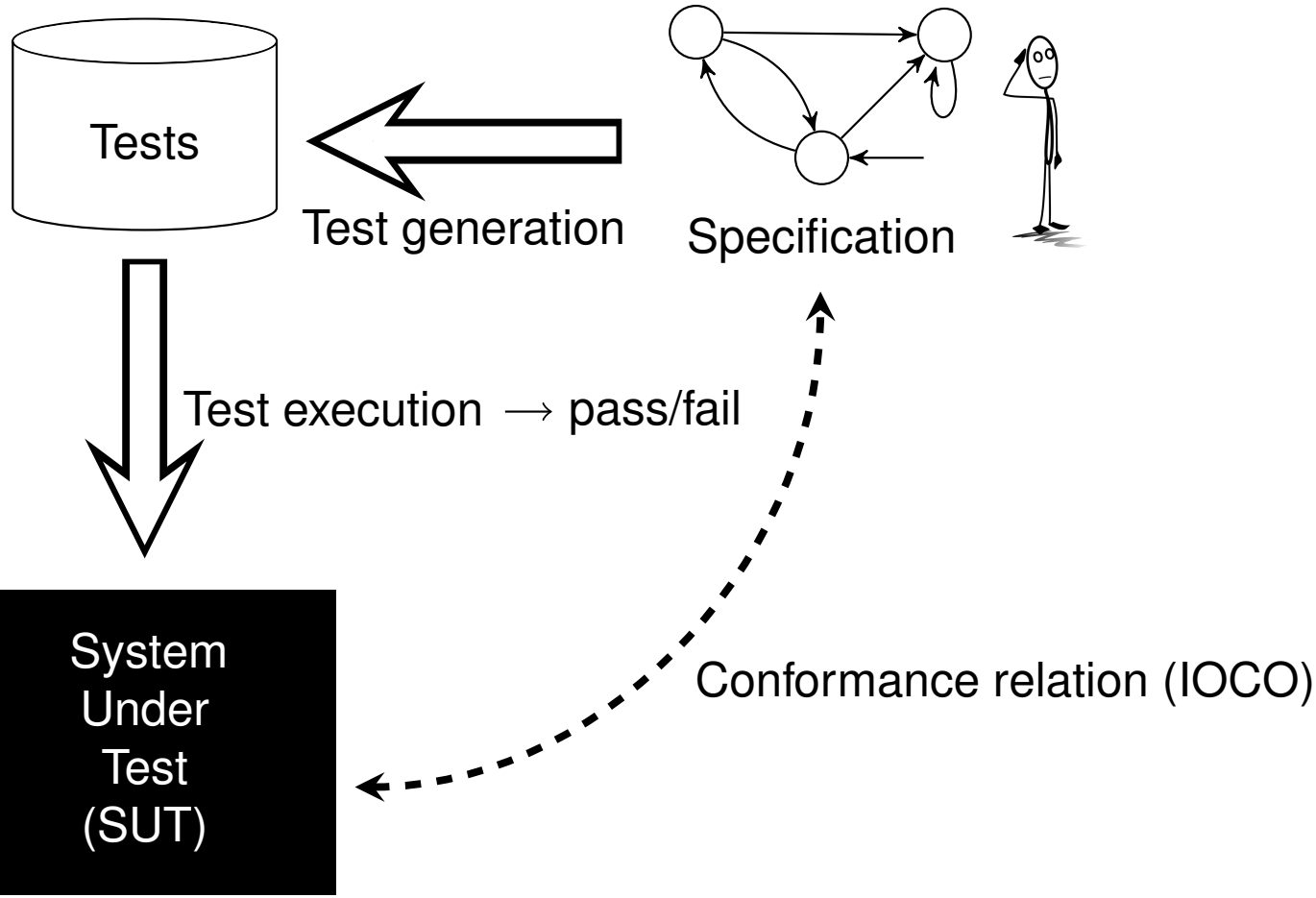
- SUT provides !

On-the-fly test generation example

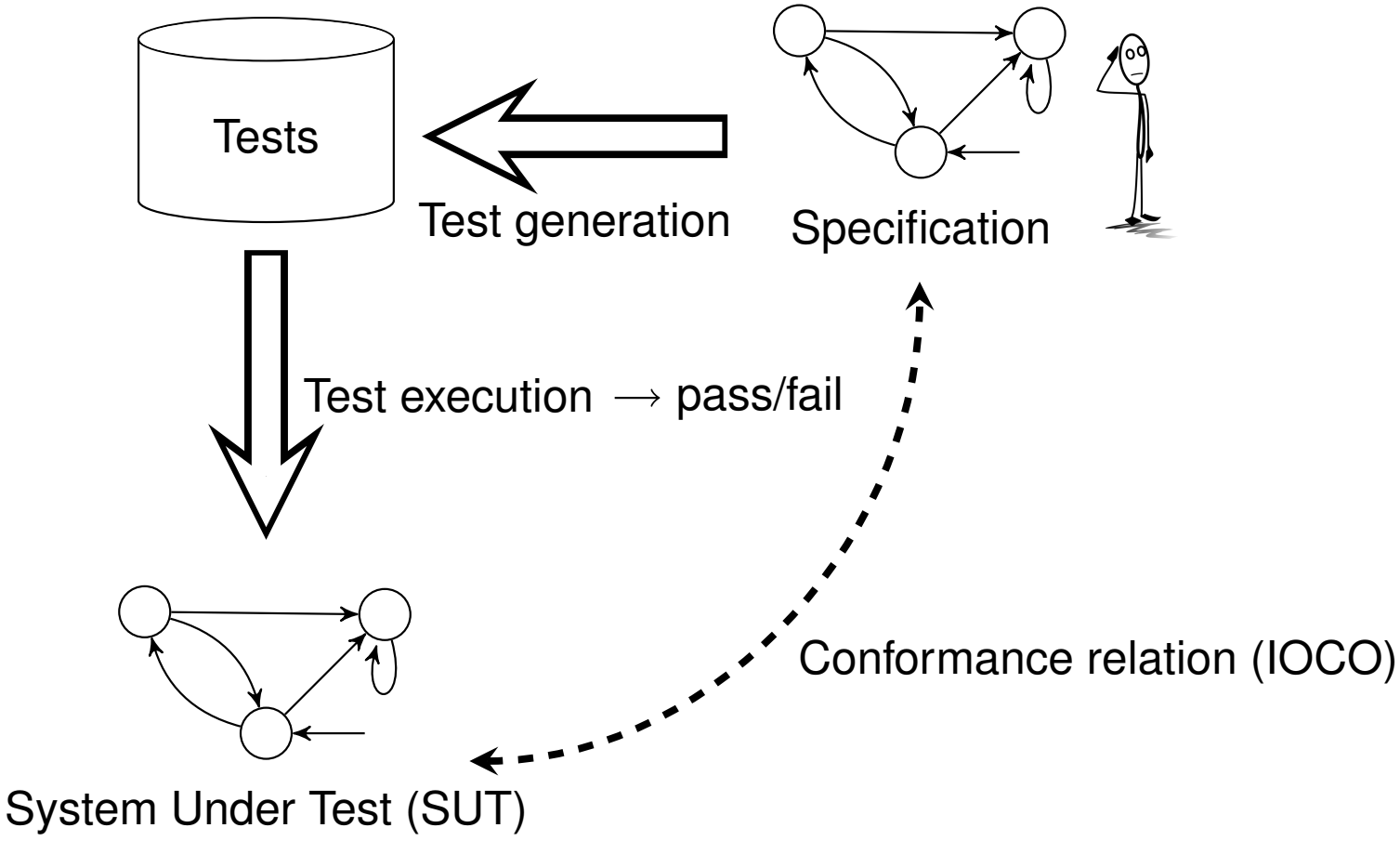


- Choose ?
- SUT accepts input
- Current states: $\{q_3, q_4\}$
- Observe output
- SUT provides !
- Current states: $\{q_0, q_2\}$
- Observe output
- SUT provides !
- Stop with verdict *Fail*

Model-Based Testing

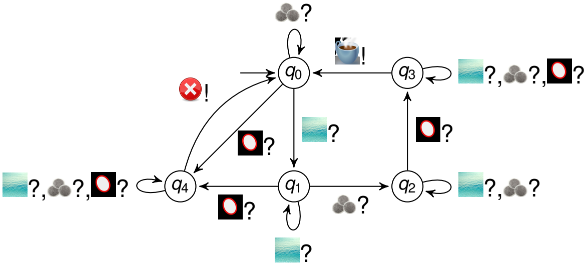


Test hypothesis



Test assumptions on SUT for ioco

- Test hypothesis: the SUT can be modeled as an LTS (or STS)
- The SUT accepts any input (unless it is providing an output)
  - Model SUT with IELTS: input-enabled LTS, e.g.:



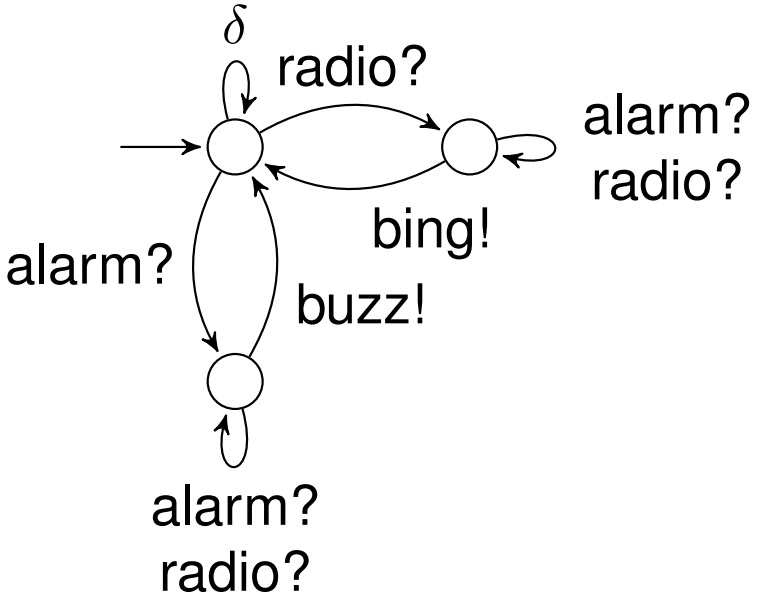
  - Formally: An LTS $S = (Q, L_I, L_U, T, q_0)$ is input-enabled if $\forall q \in Q : in(q) = L_I$
- Optional:
  - Fairness: if the SUT can provide an output, it will eventually

ioco

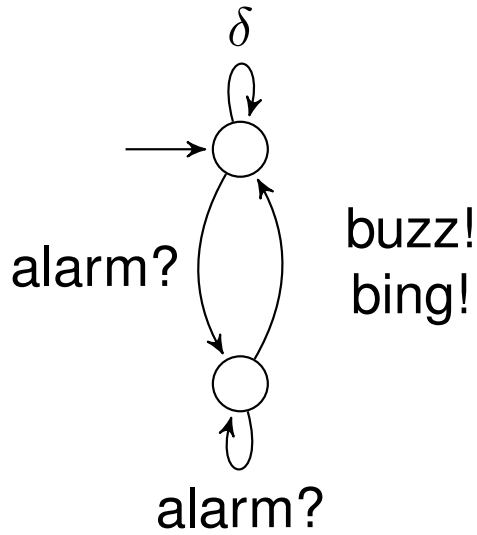
- IOCO: Input Output COnformance
- ioco : IELTS $\times$ LTS $\rightarrow$ Bool
- Write: *I* ioco *S*
- Intuition: what does *I* ioco *S* mean?
  - *I* allows the same or more inputs than *S*
  - *I* provides the same or fewer outputs than *S*

More inputs and fewer outputs for ioco

Implementation



Specification



Write S instead of q_0

- Let $S = (Q, L_I, L_U, T, q_0)$ be an LTS, $\rho \in L^*$
- $Straces(S) = Straces(q_0)$
- $S \text{ after } \rho = q_0 \text{ after } \rho$
- $out(S) = out(q_0)$
- $in(S) = in(q_0)$

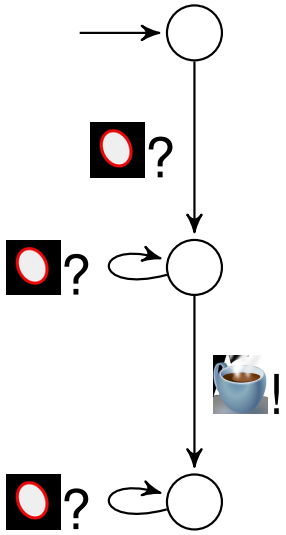
Formal definition for ioco

- Let $S = (Q^s, L_I, L_U, T^s, q_0^s)$ be an LTS
- Let $I = (Q^i, L_I, L_U, T^i, q_0^i)$ be an IELTS
  - Note: same label sets!
- Then ioco : IELTS $\times$ LTS $\rightarrow$ Bool is defined as:
  I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$
  - Note '$\subseteq$': If I can produce an output $x!$ after ρ then S can produce the output $x!$ after ρ as well

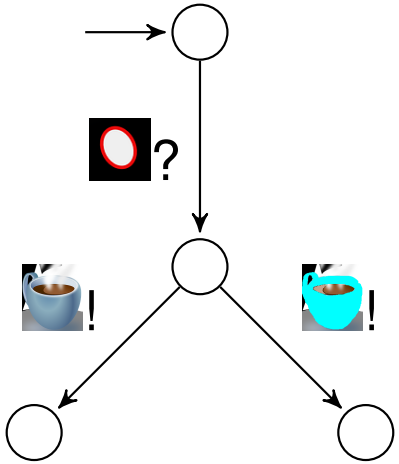
Example 1: ioco?

- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



Specification S



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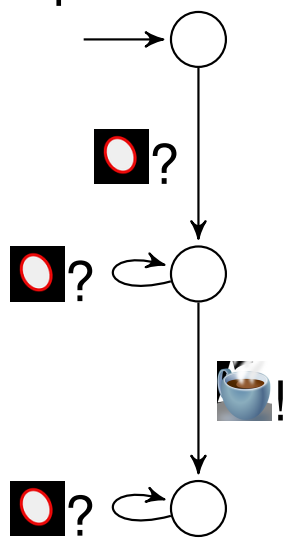
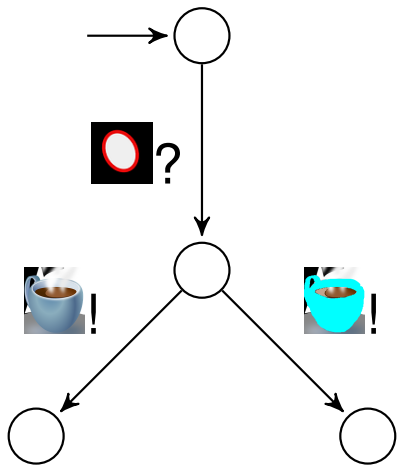
Implementation I



$out(I \text{ after } ?) = \{!\}$

Specification S



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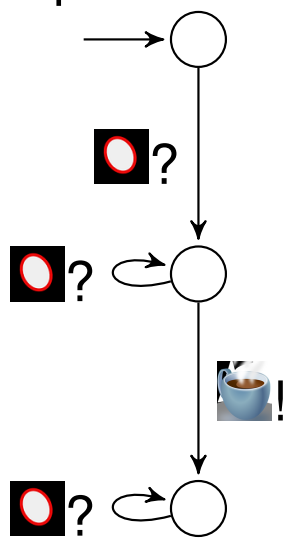
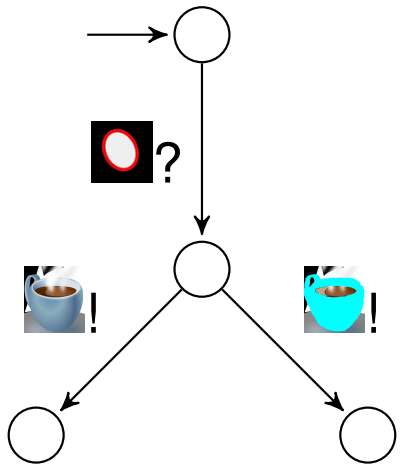


$out(I \text{ after } ?) = \{!\} \subseteq$

ioco

Specification S



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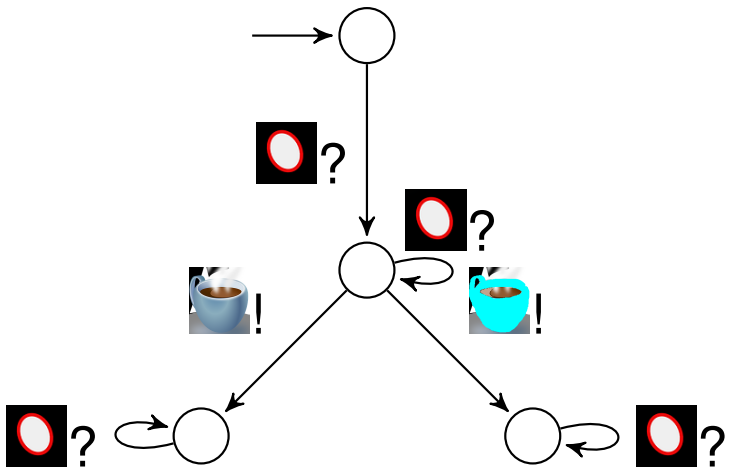
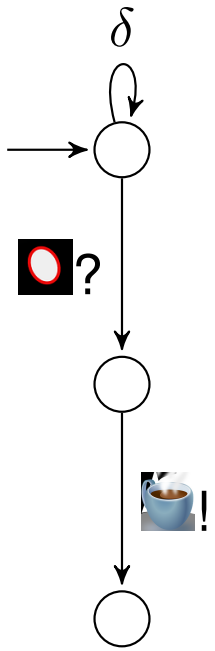
Implementation I



Specification S



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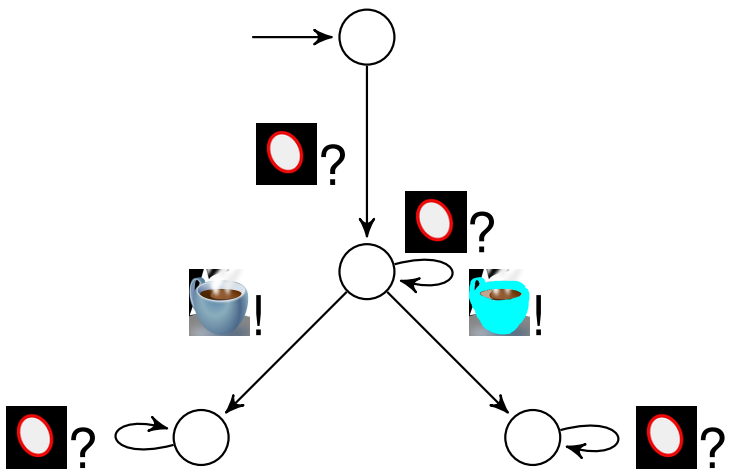
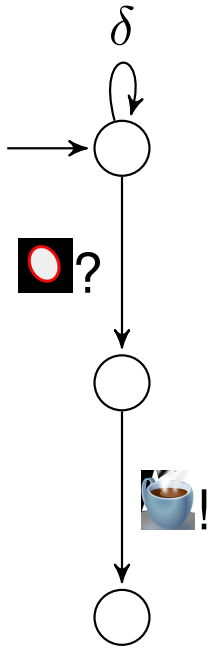
Implementation I



$out(I \text{ after } ?) = \{!, !\}$

Specification S



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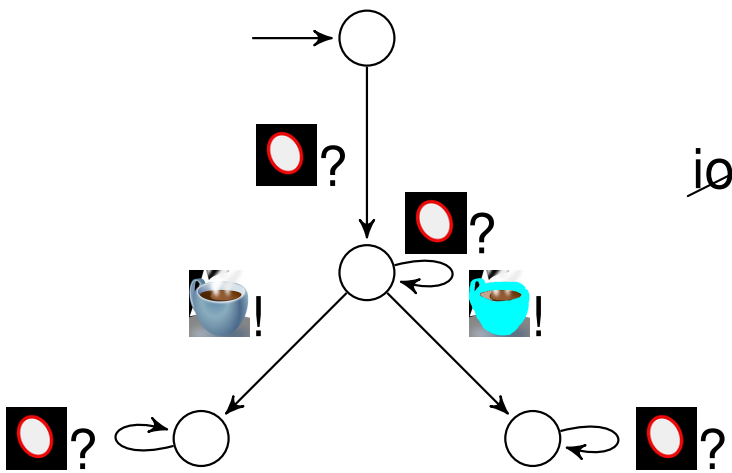
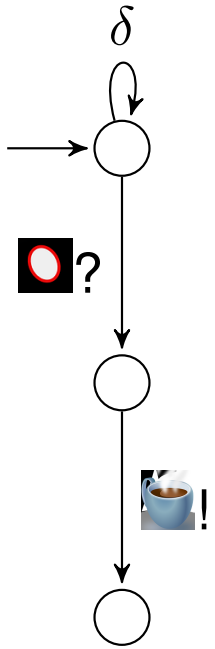
Implementation I



$out(I \text{ after } ?) = \{!, !\} \not\subseteq$

ioco

Specification S



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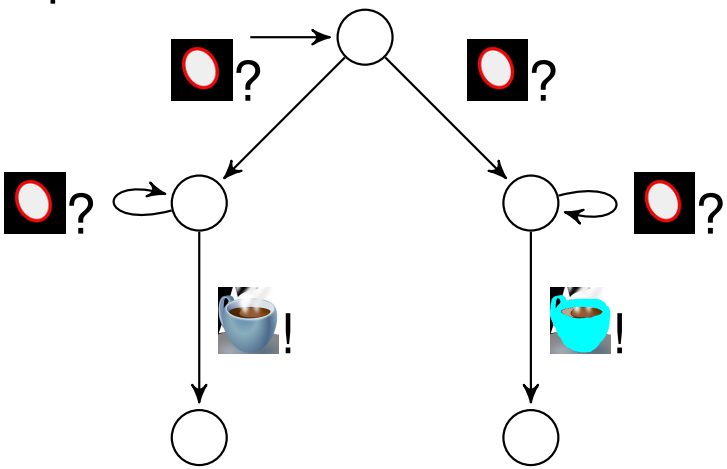
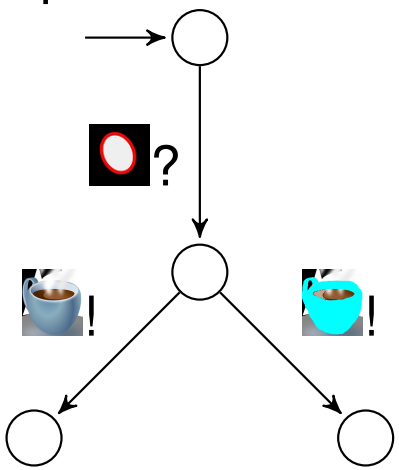
Example 3: ioco?

- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



Specification S



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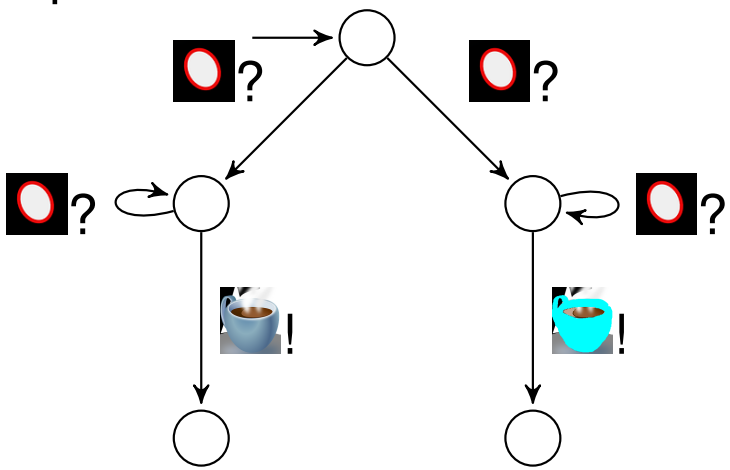
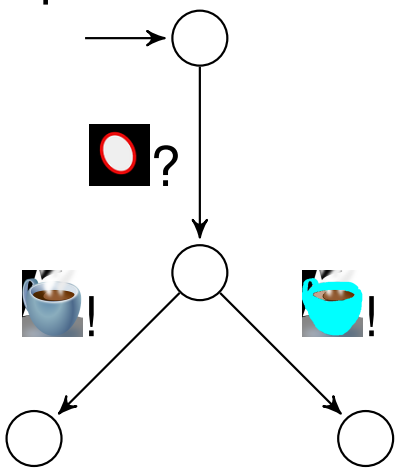


$out(I \text{ after } ?) = \{!, !\}$

Specification S



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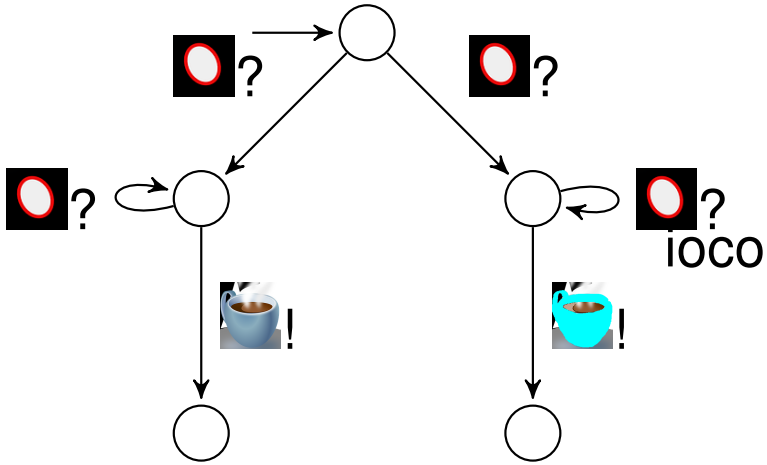
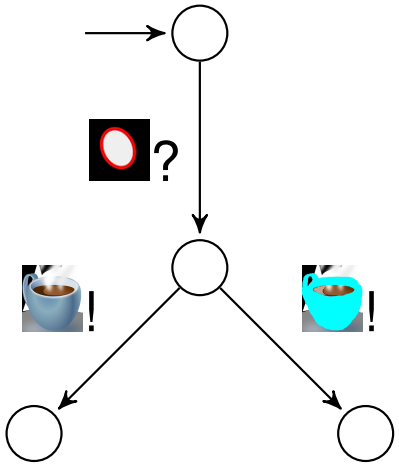


ioco

Specification S

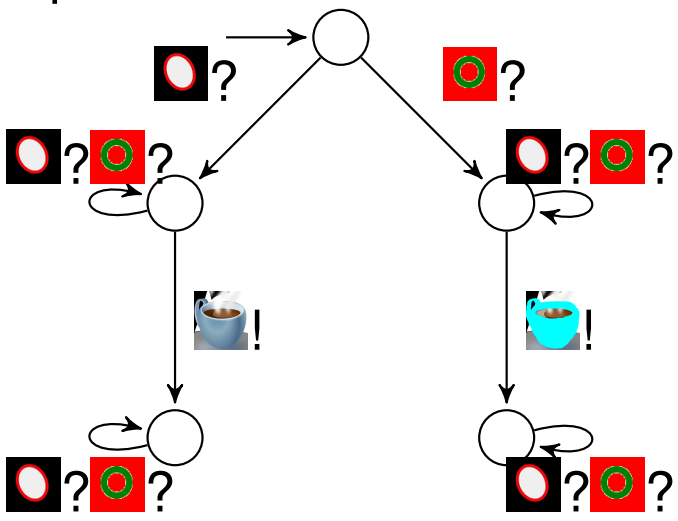


$out(I \text{ after } ?) = \{!, !\} \subseteq out(I \text{ after } ?) = \{!, !\}$

Example 4: ioco?

- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



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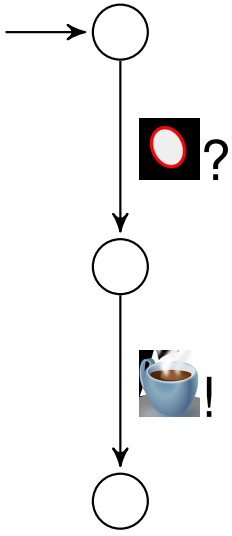
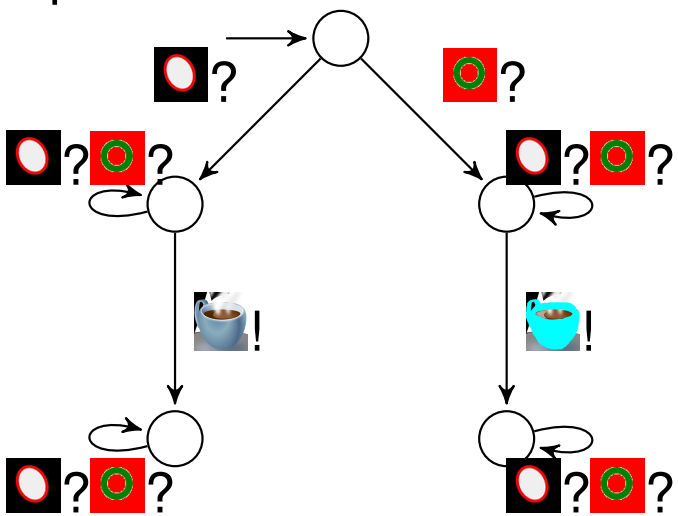


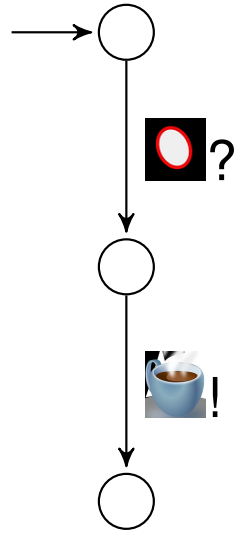
Example 4: ioco?

- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



Specification S



$out(I \text{ after } ?) = \{!\}$

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$out(I \text{ after } ?) = \{!\}$

$out(I \text{ after } ?) = \emptyset$

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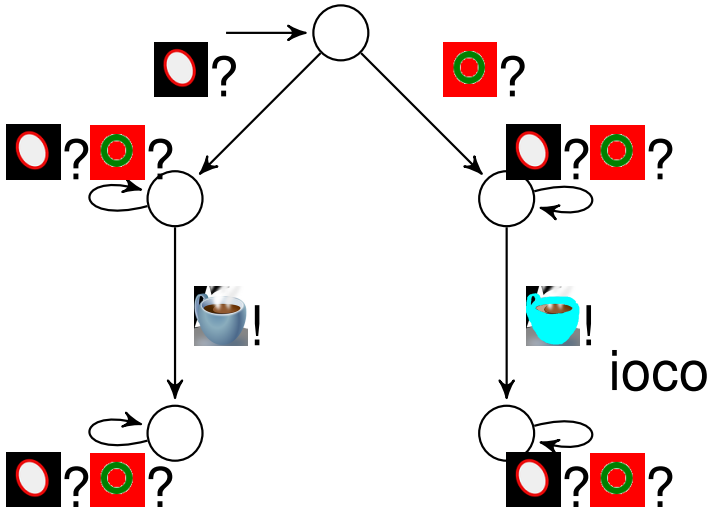
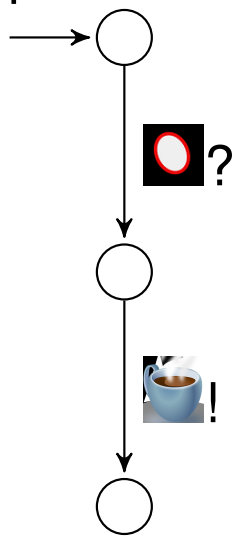
- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



ioco

Specification S



$out(I \text{ after } ?) = \{!\}$

$out(I \text{ after } ?) = \{!\} \not\subseteq$

but ? $\notin Straces(S)$

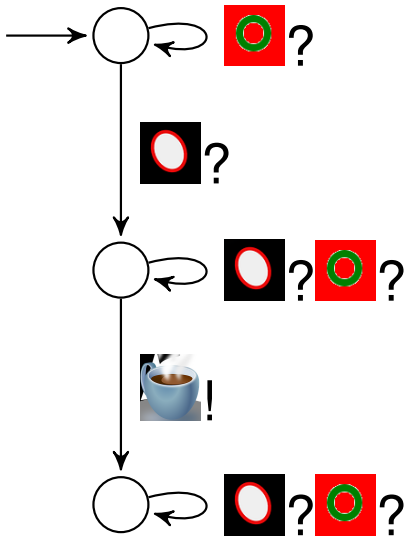
$out(I \text{ after } ?) = \{!\}$

$out(I \text{ after } ?) = \emptyset$

Example 5: ioco?

- I ioco $S = \forall \rho \in Straces(S) : out(I \text{ after } \rho) \subseteq out(S \text{ after } \rho)$

Implementation I



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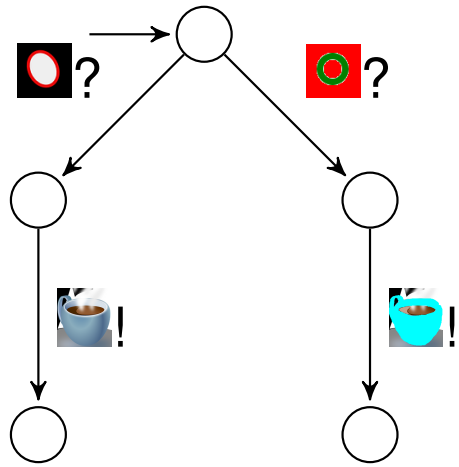

Example 5: ioco?

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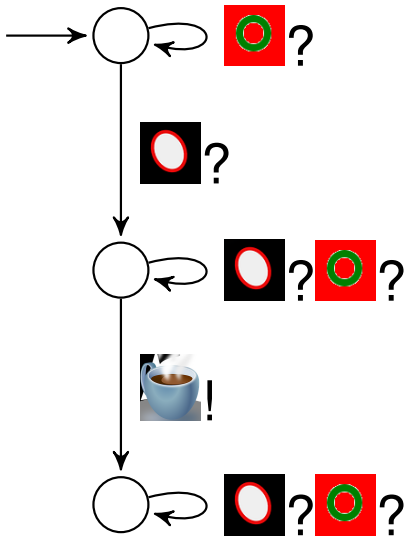
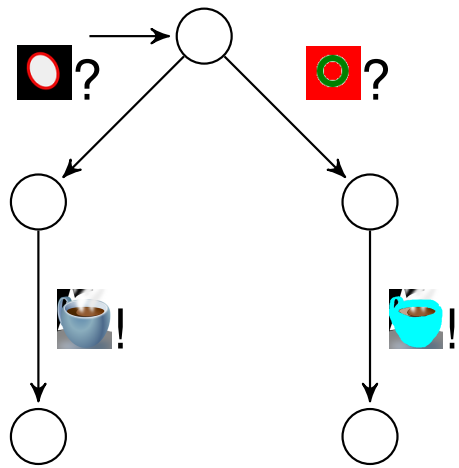
Implementation I



$out(I \text{ after } ?) = \{!\}$

$out(I \text{ after } ?) = \{\delta\}$

Specification S



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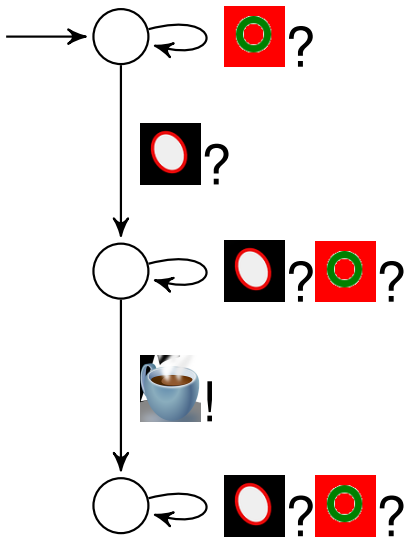
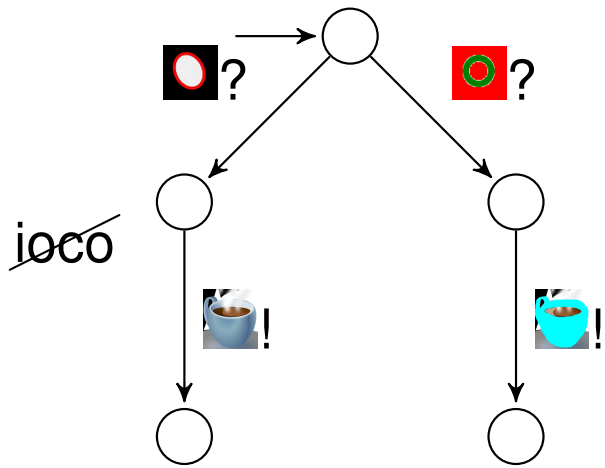
Implementation I



$out(I \text{ after } ?) = \{!\}$

$out(I \text{ after } ?) = \{\delta\} \not\subseteq$

Specification S



$out(I \text{ after } ?) = \{!\}$

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Soundness

- When to put *Pass* or *Fail* at end node of test case?

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- A test case t for an LTS S is sound if:
  for any IELTS I:
  I ioco S implies that execution of t on I yields *Pass*

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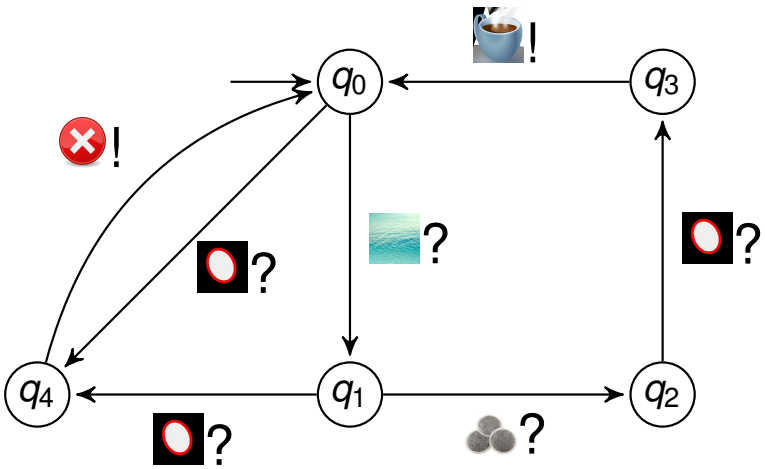
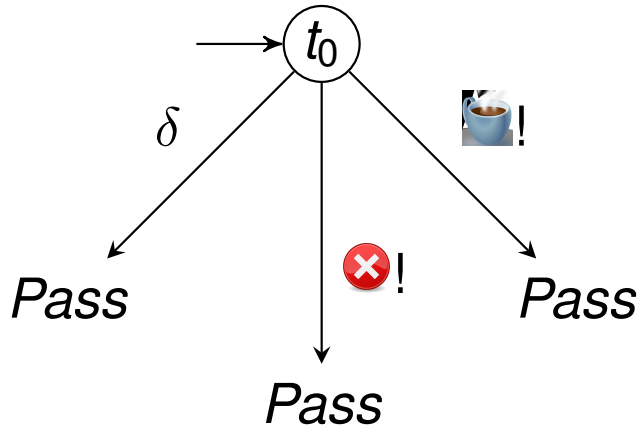
  for any IELTS *I*:
    I ioco *S* implies that execution of *t* on *I* yields *Pass*
- Or alternatively formulated as follows:
  for any IELTS *I* :
    execution of *t* on *I* yields *Fail* implies that *I* ~~ioco~~ *S*

Soundness

- When to put *Pass* or *Fail* at end node of test case?
- A test case t for an LTS S is sound if:
  for any IELTS I:
  I ioco S implies that execution of t on I yields *Pass*
- Or alternatively formulated as follows:
  for any IELTS I :
  execution of t on I yields *Fail* implies that $I \not\text{ioco}\ S$
- A test suite TS is sound if all its test cases $t \in TS$ are sound

Is this test case sound?





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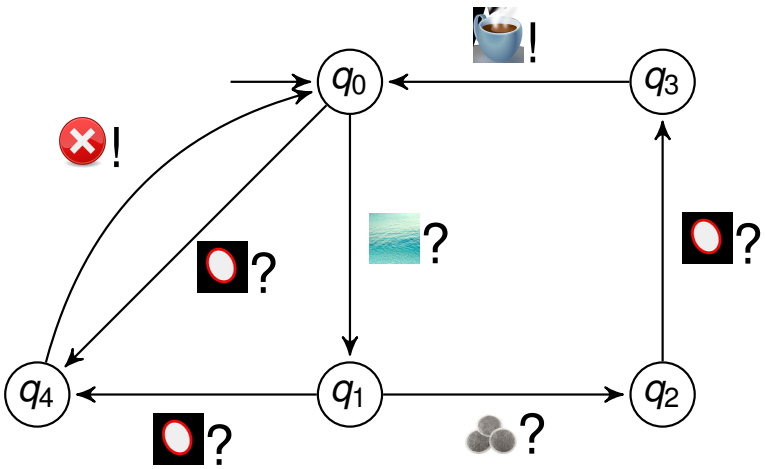

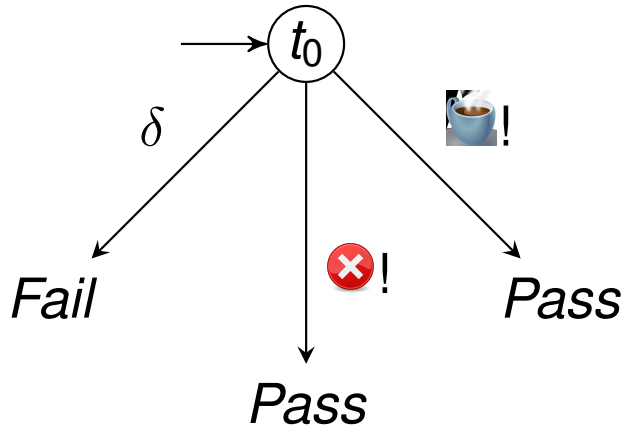

Exhaustiveness

- A test suite *TS* for LTS *S* is exhaustive if:
  for any IELTS *I* :
  I ~~ioco~~ *S* implies that:
  there is a $t \in TS$ such that execution of *t* on *I* yields *Fail*

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- Q: how many test cases in an exhaustive test suite?
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- A test suite *TS* is complete for LTS *S* if it is sound and exhaustive for *S*

Making underspecification explicit

- Let $S = (Q, L_I, L_U, T, q_0)$ be an LTS.
- Then $a? \in L_I$ is underspecified in $q \in Q$ if $a \notin in(q)$

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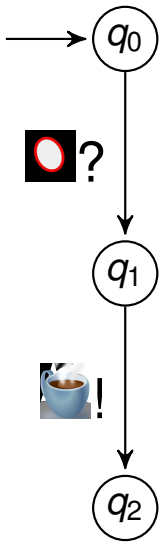
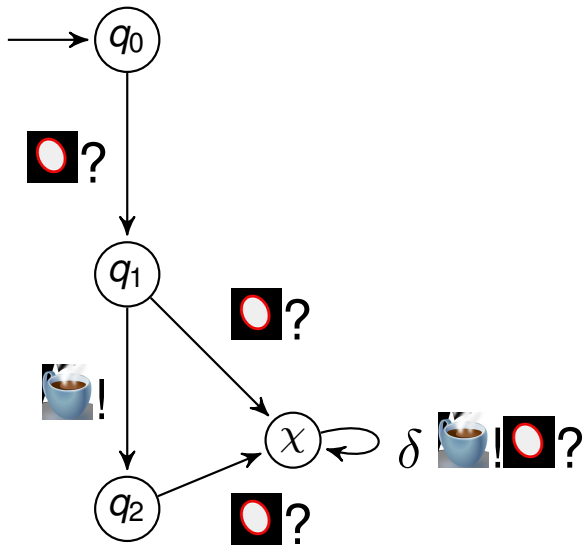
- Demonic completion:
  - Add χ-state (chaos, where anything is allowed)
  - Add a transition to χ for all underspecified inputs

Demonic completion example



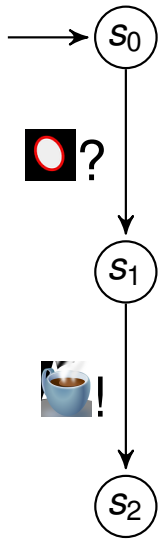
Demonic completion example



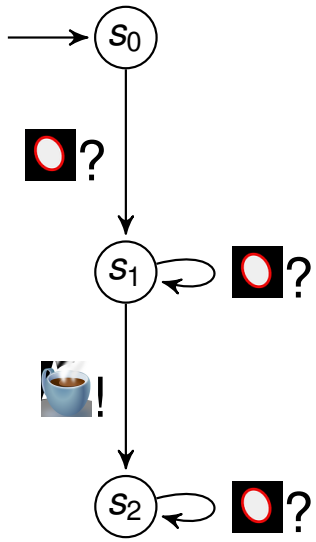
Angelic completion

- Add a self-loop for all underspecified inputs
- Does not preserve ioco!

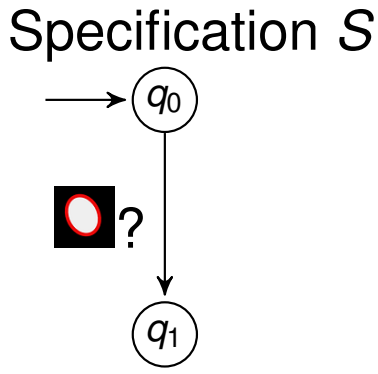
Angelic completion example



Angelic completion example



Angelic completion counterexample for ioco



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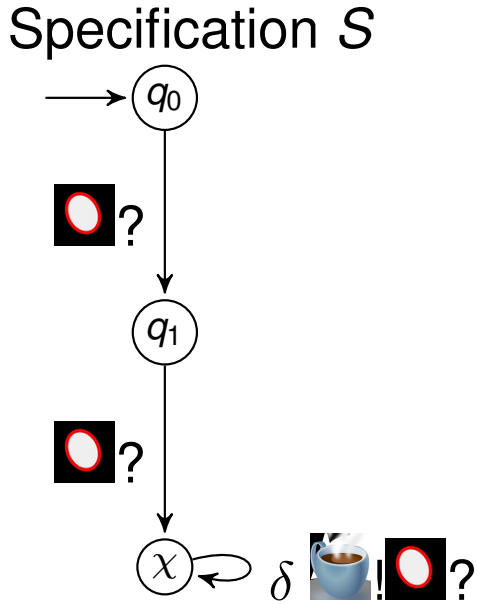

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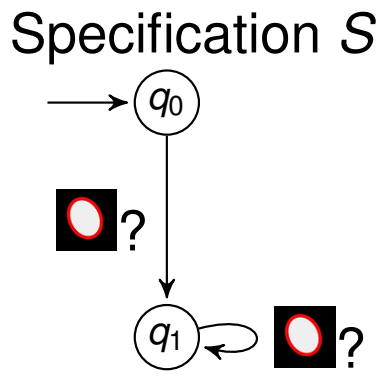
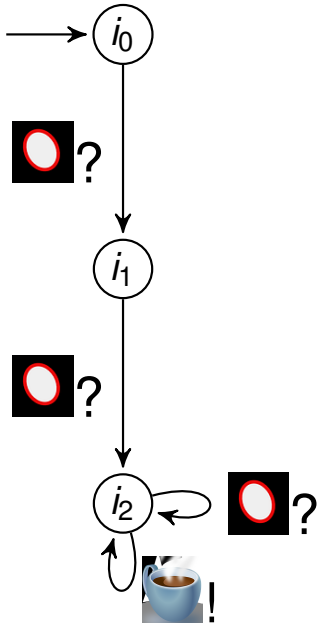
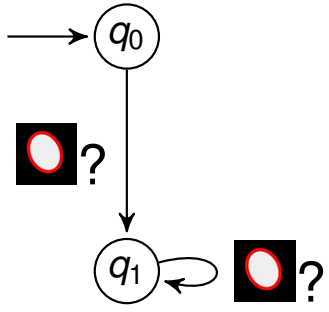


Angelic completion counterexample for ioco

Implementation *I*



Specification *S*



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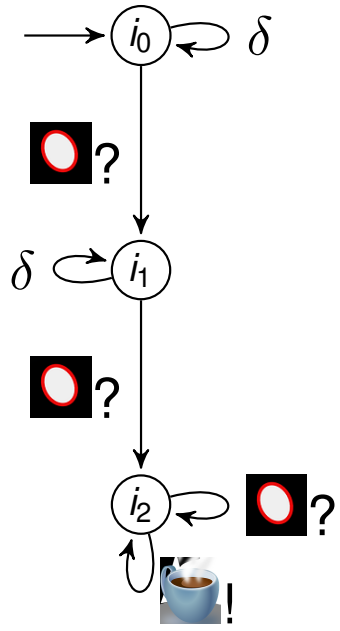
Implementation *I*



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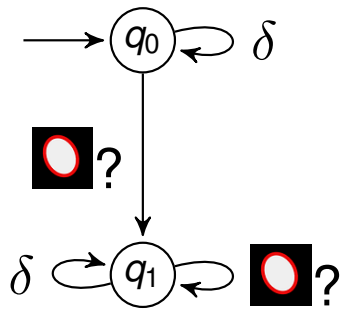

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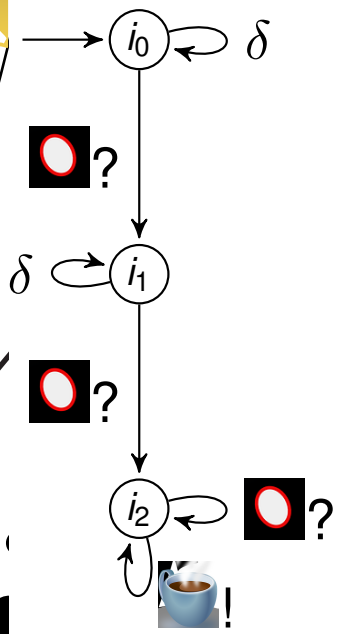

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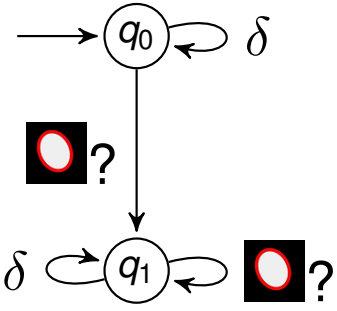

~~ioco~~

$out(S \text{ after } ??) = \{!\}$

$out(S \text{ after } ??) = \{\delta\}$

Angelic completion counterexample for ioco

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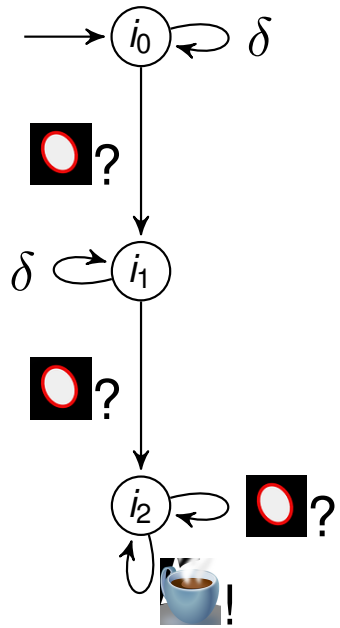

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ioco

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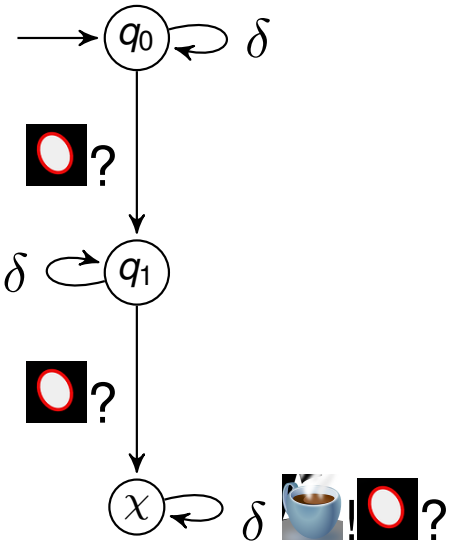

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ioco is not input-universal [1]

- Edge case of ioco: combine nondeterminism and underspecification

[1] R. Janssen, F. W. Vaandrager, J. Tretmans: Relating Alternating Relations for Conformance and Refinement. https://doi.org/10.1007/978-3-030-34968-4_14

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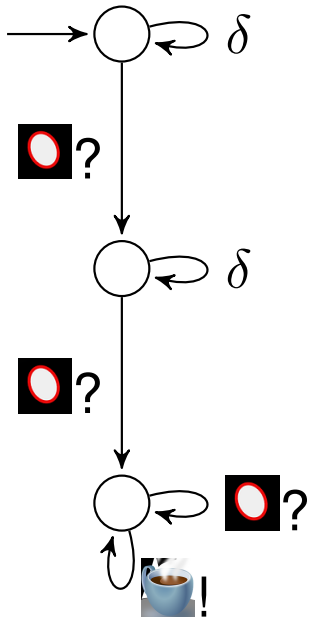

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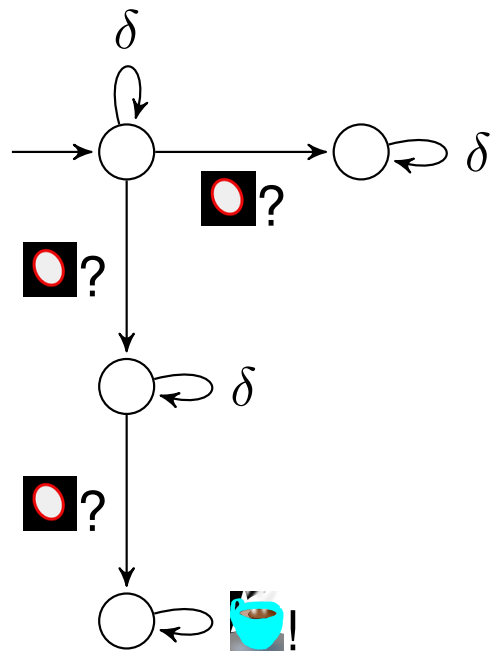

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uioco

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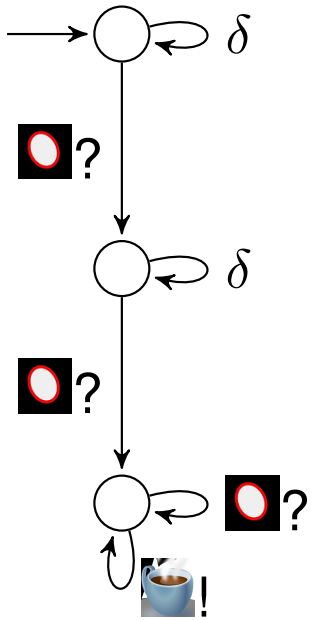

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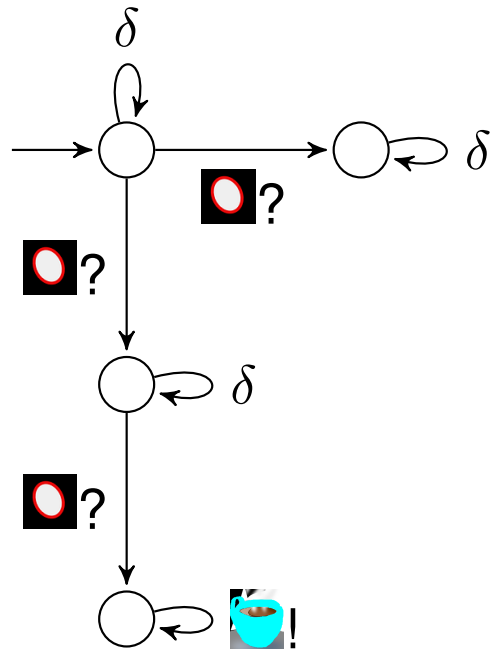

~~ioco~~

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- *I uioco S* = $\forall \rho \in$ *Utraces*(*S*) :*out*(*I after* ρ) $\subseteq$ *out*(*S after* ρ)
- ?? $\notin$ *Utraces*(*S*)

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Next times

- Tutorial next Monday
- Lecture next Wednesday: Symbolic Transition Systems