Test case generation

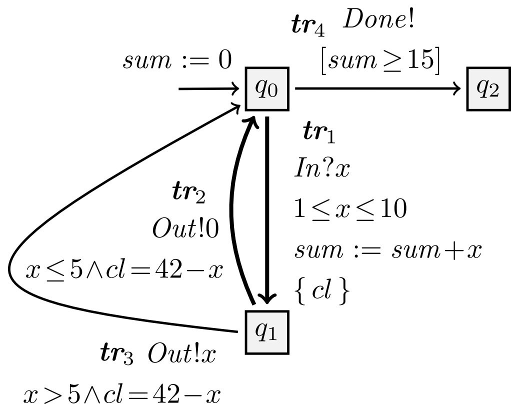
The construction of the test case is obtained by applying dedicated symbolic execution techniques to the reference timed symbolic automaton, in order to derive a symbolic subtree restricted to the test purpose, i.e., a path represented as a sequence of transitions of the reference automaton. In the following, we **first provide an overview of these test-oriented symbolic techniques**, and **then describe the actual test case generation**, obtained by applying specific transformations to this subtree (mirroring and constraint simplification). Finally, we show **how to use SPTG to generate the test cases**.

Table of content

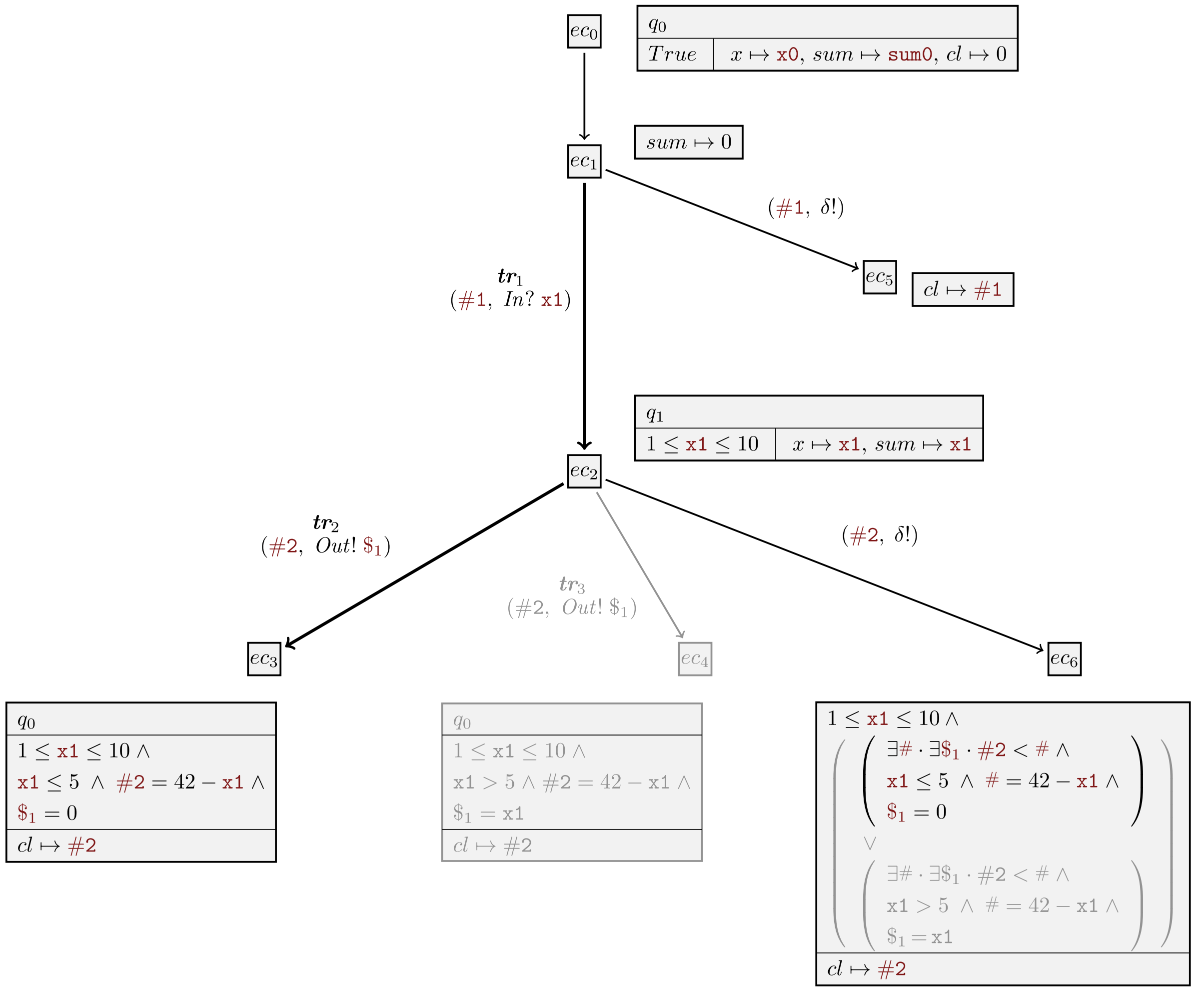
Test-oriented Symbolic Execution Techniques

Symbolic execution explores a model by representing both data and time with symbolic variables instead of concrete values. It unfolds the automaton while generating constraints over symbolic variables, producing a **symbolic execution tree** . The tree's nodes are **execution contexts**, and its edges represent symbolic steps such as initialization, transition firing, or **quiescence completion**.

Consider the following dummy automaton example:



The symbolic execution tree (restricted by test purpose transitions sequence $\mathbf{tr}_1.\mathbf{tr}_2$):



Execution Contexts

An **execution context** $ec = (q, \pi, \lambda, ev, pec)$ consists of:

- The current state q.
- The **path condition** π (accumulated constraints).
- The mapping λ of variables and clocks to symbolic terms.
- The triggering event ev.
- The predecessor context pec.

The **root context** ec_0 starts in q_0, with clocks at zero, variables assigned fresh symbols, $\pi = True$, and ev and pec undefined. Initialization produces the first successor, ec_1.

Symbolic Variables: Fresh symbolic variables are introduced:

`x0`, `x1`, ... represent successive values of a data variable x (with `x0` being the initial value).

`#1`, `#2`, ... denote **symbolic delays**.

`$1`, `$2`, ... denote **emitted values** typed according to their channels.

Symbolic Paths

Contexts ec_2, ec_3, and ec_4 illustrate the symbolic execution of transitions $\mathbf{tr}_1$, $\mathbf{tr}_2$, and $\mathbf{tr}_3$.

1. **Edge from ec_1 to ec_2 ($\mathbf{tr}_1$)**:
   - Transition from q_0 to q_1 via input In.
   - x is updated to x1. Clock cl is reset to 0.
   - Edge label: symbolic action $In?$x1 and delay #1.
   - **Path condition**: 1 $\leq$ x1 $\leq$ 10 (from guard $1 \leq x \leq 10$).
   - Update: $sum \mapsto$ x1.

2. **Edge from ec_2 to ec_3 ($\mathbf{tr}_2$)**:
   - Transition from q_1 to q_0, emitting on channel Out.
   - #2 is elapsed time, and $1 is the emitted value. Clock value becomes #2.
   - **Path condition**: x1 ≤ 5 and #2 = 42 - x1 (from guard $x \leq 5$ and $cl = 42 - x$), and $1 = 0.

The symbolic path $ec_1 . ec_2 . ec_3$ corresponds to model path $\mathbf{tr}_1 . \mathbf{tr}_2$, yielding the symbolic trace (#1, $In?$x1).(#2, $Out!$$1).

The **path condition** for this trace (#1 is unconstrained) is:

1 $\leq$ x1 $\leq$ 10 $\wedge$ x1 $\leq$ 5 $\wedge$ #2 = 42 - x1 $\wedge$ $1 = 0

This is **satisfiable** e.g. with x1 $\mapsto$ 1, $1 $\mapsto$ 0, #1 $\mapsto$ 0, #2 $\mapsto$ 41, producing the **timed trace** $(0, In?1).(41, Out!0)$. This trace shows the system receives $In?1$ after initialization and emits $Out!0$ 41 time units later.

Completion by Quiescence

Contexts ec_5 and ec_6 model **quiescence** (system silence). Symbolic variables are reused across sibling contexts (e.g., #1 for ec_2 and ec_5).

- **Quiescence context** ec_5: Derived from ec_1. The edge is labeled with the quiescence event (#1, $\delta!$). The system may remain silent indefinitely, reflected by $\pi = True$ and unconstrained delay #1.

- **Quiescence context** ec_6: Derived from ec_2's output successors (ec_3 and ec_4). Its path condition is a disjunction of existential constraints (e.g., $\exists$ # $\cdot$ $\exists$ $1 $\cdot$ #2 < # $\wedge \ldots$), capturing that quiescence persists until an output is possible.

- **Trace-determinism and pruning**: For a chosen Test Path (TP) $ec_1 . ec_2 . ec_3$ (which implies x1 $\leq$ 5), context ec_4 (which implies x1 > 5) **conflicts** and is removed (grayed out). This simplifies ec_6's path condition.

A **witness timed trace** $(0, In?1) \cdot (40, \delta!)$ covers ec_6 (with x1 $\mapsto$ 1, #2 $\mapsto$ 40), demonstrating that after $In?1$, the system can remain silent for 40 time units, expecting the next output at 41.

SPTG Workflow

For a model $\mathbb{G}$, the **Symbolic Path-guided Test Generation (SPTG)** workflow restricts symbolic exploration to a **model path** $p = \mathbf{tr}_1 \cdots \mathbf{tr}_n$, chosen as a **test path (TP)**.

Starting from the initial state q_0, the workflow performs **symbolic execution along** p, using the SMT solver **Z3** to verify:

- satisfiability of execution contexts,
- trace-determinism, and
- conflict detection.

The workflow proceeds through the following five main steps:

1. **Symbolic execution along the path**

    - From the current execution context ec_1, all successor contexts are computed (Custom Symbex).
    - For each transition $\mathbf{tr}_i$, the workflow checks whether it can be fired.
    - If the transition is fireable, exploration continues exploring the remaining suffix $p' = \mathbf{tr}_{i+1} \cdots \mathbf{tr}_n$ from the successor produced by $\mathbf{tr}_i$, .
    - Otherwise, the exploration stops.

2. **Conflict removal**

    - Any conflicting contexts detected during symbolic execution are removed.

3. **Trace-determinism verification**

    - The workflow verifies that no two sibling contexts on the same channel could be covered by the same trace.
    - Exploration halts if nondeterminism is detected.

4. **Incorporation of quiescence contexts**

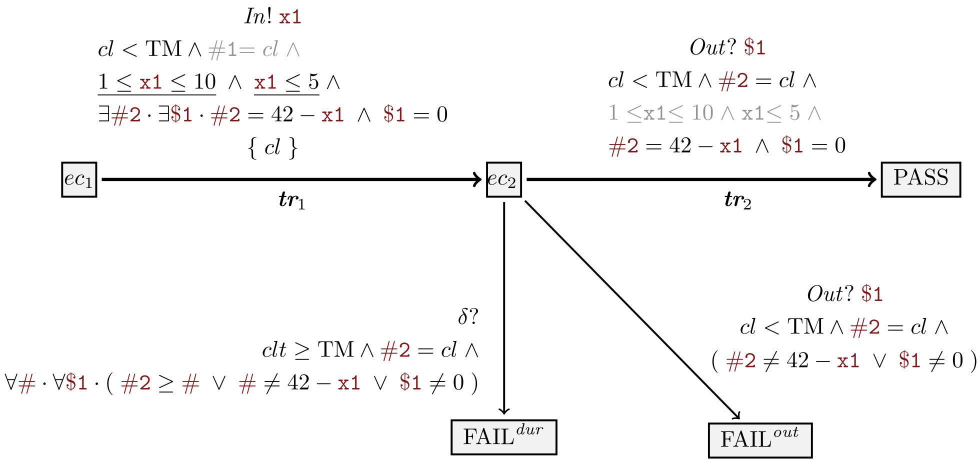
    - Quiescence contexts are added, producing a restricted, deterministic, quiescence-augmented symbolic execution tree $SE(\mathbb{G})^{\delta}_{/p}$, which contains the path and its immediate trace-deterministic divergences.

5. **Test case synthesis**

    - The final step synthesizes from $SE(\mathbb{G})^{\delta}_{/p}$ the timed symbolic test case $\mathbb{TC}_p$.

In the following, we detail the construction of $\mathbb{TC}_p$, illustrated below for our running dummy example, and explain how SPTG generates it from the given model path p, which serves as the test purpose.

The test case $\mathbb{TC}_{\mathbf{tr}_1.\mathbf{tr}_2}$ which corresponds to the test purpose path $\mathbf{tr}_1.\mathbf{tr}_2$ (partial view):



Symbolic Path-guided Test Case

The test case $\mathbb{TC}_p$ is defined as a **timed symbolic transition system** equipped with a **single clock** `cl`, which measures the elapsed time before each action it performs.

The **data variable set** of $\mathbb{TC}_p$ includes all symbolic variables used to produce the execution contexts covering the path p.
These variables represent the information known and manipulated by the test case as execution progresses, including:

- **Input values** to stimulate the SUT with (e.g., `x1`) and their associated **submission durations** (e.g., `#1`).
- **Output values** expected from the SUT (e.g., `$1`) and their corresponding **observation times** (e.g., `#2`).

Clock constraint

- The clock satisfies:

  $$cl < \mathrm{TM}$$

  where TM denotes the maximal waiting time before either:

  - applying a stimulation, or
  - observing an output.

This timing mechanism, combined with quiescence detection ($cl \geq \mathrm{TM}$), ensures that the test case can be implemented in a real-time environment.

Test case general structure

The test case mirrors $SE(\mathbb{G})^{\delta}_{/p}$ and is used to **check the conformance** of the SUT to $\mathbb{G}$ along the symbolic path p.

Roughly speaking, test case structure is obtained as follows:

- The execution contexts related to path p form the **main branch** leading to the verdict PASS.
  The target context is replaced by PASS.

- Any deviation from this branch triggers a verdict state:
  - FAIL if the behavior violates expectations.
  - INC (inconclusive) if no clear verdict can be determined.

Test case guard derivation

The **guard** of the test-case transition from ec_1 to ec_2 is derived from the target of the test path (TP), denoted ec_3.
It guides the selection of the stimulation $In!x_1$ along this path.
The guard is expressed as:

cl < TM ∧ 1 ≤ x1 ≤ 10 ∧ x1 ≤ 5 ∧ ∃ #2 · ∃ $1 · (#2 = 42 - x1 ∧ $1 = 0)

At this stage:

- x1 and its duration #1 are determined.
- #2 and $1 remain undetermined.

The variable x1 is constrained by the path condition of ec_3 (corresponding to small input values), whereas #1 is unconstrained and can therefore be omitted (shown as grayed out in the explanatory figure of the test case $\mathbb{TC}_{\mathbf{tr}_1.\mathbf{tr}_2}$).

Conditions producing ec_3 are, by default, under existential quantifiers: ∃ #2 · ∃ $1 · (x1 ≤ 5 ∧ · #2 = 42 - x1 ∧ $1 = 0). Since #2 and $1 do not occur freely in x1 ≤ 5, this constraint is moved outside the quantifiers, yielding the final guard.

Following the test path, the test case expects an observation $Out?$$1 on channel Out, storing it in $1.
It transitions from ec_2 to PASS under the following guard:

cl < TM ∧ #2 = cl ∧ 1 ≤ x1 ≤ 10 ∧ x1 ≤ 5 ∧ #2 = 42 - x1 ∧ $1 = 0

- The formulas 1 ≤ x1 ≤ 10 and x1 ≤ 5 appear *grayed* because they are inherited from earlier transitions.
- The remaining guard ensures that:
  - the observed value $1 matches the expected output 0 for small inputs (x1 ≤ 5), and
  - the measured duration #2 recorded by cl equals 42 - x1.

Transition to FAIL^{out} is triggered when #2 is within the time limit (TM), but either the duration or the observed value $1 violates the guard from ec_2 to PASS:

cl < TM ∧ #2 = cl ∧ 1 ≤ x1 ≤ 10 ∧ x1 ≤ 5 ∧ (#2 ≠ 42 - x1 ∨ $1 ≠ 0)

Transition to FAIL^{dur} captures invalid quiescence, defined by:

cl ≥ TM ∧ #2 = cl ∧ ∀ # · ∀ $1 · (#2 ≥ # ∨ # ≠ 42 - x1 ∨ $1 ≠ 0)

Other test case transitions are shown in (complete) test case image generated by SPTG.

Example verdicts (for $\mathrm{TM} = 60$)

Verdict	Trace	Description

Verdict	Trace	Description
PASS	$(0, In?1).(41, Out!0)$	Valid output and timing
FAIL^{out}	$(0, In?1).(40, Out!0)$	Incorrect timing
FAIL^{out}	$(0, In?1).(41, Out!1)$	Output mismatch
FAIL^{dur}	$(0, In?1).(60, \delta!)$	Quiescence beyond allowed duration

The last trace shows quiescence exceeding the allowed duration, with only $(41, Out!0)$ as a valid output after $(0, In?1)$, resulting in a FAIL^{dur} verdict.

Using SPTG

Navigate to the `/path/to/SPTG/examples/example02_dummy/` directory, then run:

```
cd /path/to/SPTG/examples/example02_dummy/
./run-sptg-h2.sh
```

Script `run-sptg-h2.sh` invokes `sptg.exe` using the workflow configuration file:

File `/path/to/SPTG/examples/example02_dummy/workflow_4_testcase_generation_h2.sew`

An excerpt from this file:

```
workspace [
        root   = "example02_dummy"
        launch = "example02_dummy"
        output = "output_h2"
] // end workspace
...
project 'path of input model' [
  source = "."
    model  = "example02_dummy.xlia"
] // end project
...
path#guided#testcase#generator testcase_genertor {
    ...
    trace [
      //Sequence of elements characterizing the test purpose.
      transition = "tr1"
      transition = "tr2"
    ] // end trace
    vfs [
        file#tc       = "testcase.xlia"
        file#tc#puml  = "testcase.puml"
    ] // end vfs
    ...
}
...
```

SPTG generates the resulting **test case automaton** in the following formats:

- **Graphical format: PlantUML**
  File `/path/to/SPTG/examples/example02_dummy/output_h2/testcase.puml`
  Comment: This file provides a visual representation of the test case automaton, which can be rendered using PlantUML.

- **Specification language: XLIA**
  The same language used to express the reference model.
  File `/path/to/SPTG/examples/example02_dummy/output_h2/testcase.xlia`
  Comment: This file can be explored using the symbolic execution platform Diversity.

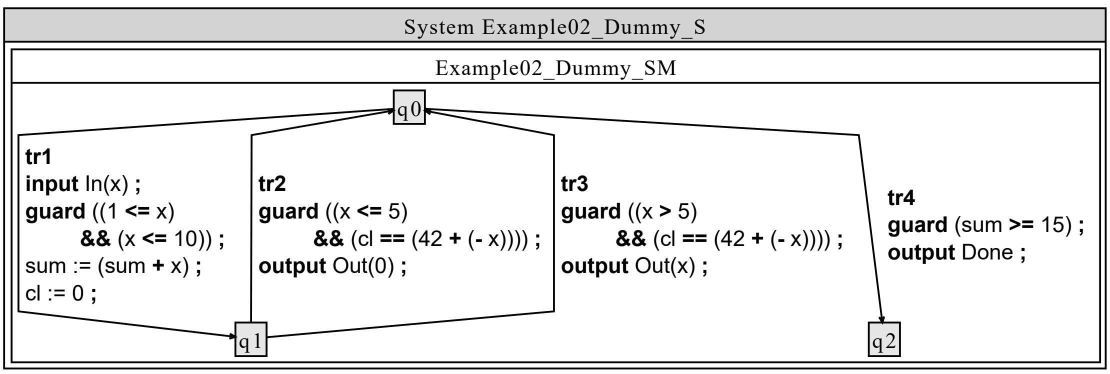
- **JSON format with SMT-LIB guards**
  File `/path/to/SPTG/examples/example02_dummy/output_h2/testcase_smt.json`
  Comment: This JSON file encodes the test case automaton, including guards in SMT-LIB format, suitable for automated execution againt system under test (SUT) using an SMT-solver (e.g. Z3).

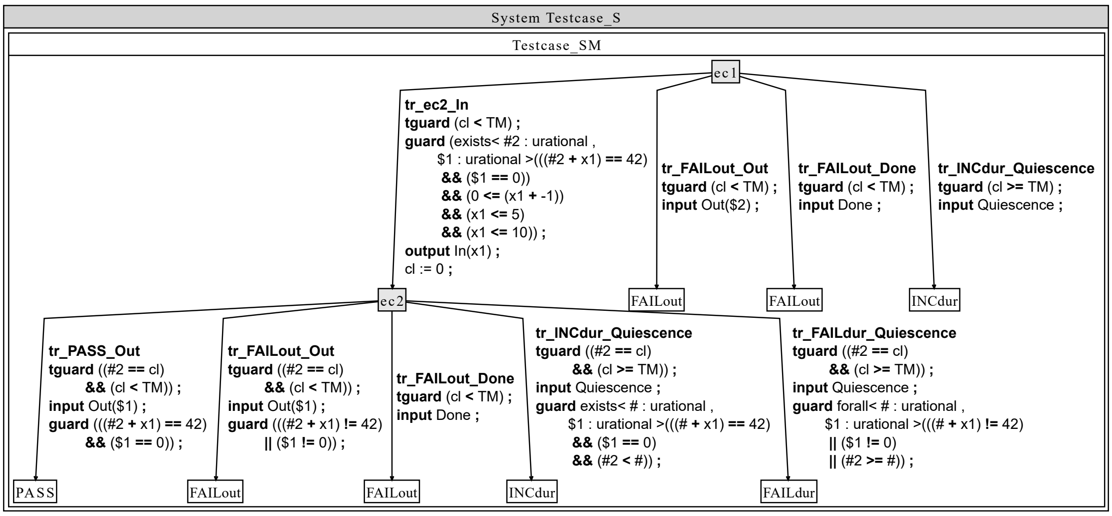
> **Note:** The script also generates the graphical **PlantUML** file for the reference automaton:
> **File** `/path/to/SPTG/examples/example02_dummy/output_h2/example02_dummy.puml`
> *Comment:* This file provides a visual representation of the reference automaton.

> **Note:** You can visualize `.puml` files using PlantUML or the online tool PlantText. You can convert a file `.puml` to a file `.svg` (see the PlantUML Conversion Guide).

> **Note:** If the **PlantUML JAR** and the Graphviz `dot` executable are located in `/path/to/SPTG/bin`, the script automatically produces:
> **File** `/path/to/SPTG/examples/example02_dummy/testcase.svg`.

The table below summarizes the inputs and outputs for generating the **test case** with SPTG. The figures shown are **visual representations** obtained by converting the corresponding **PlantUML** files into **SVG** format.

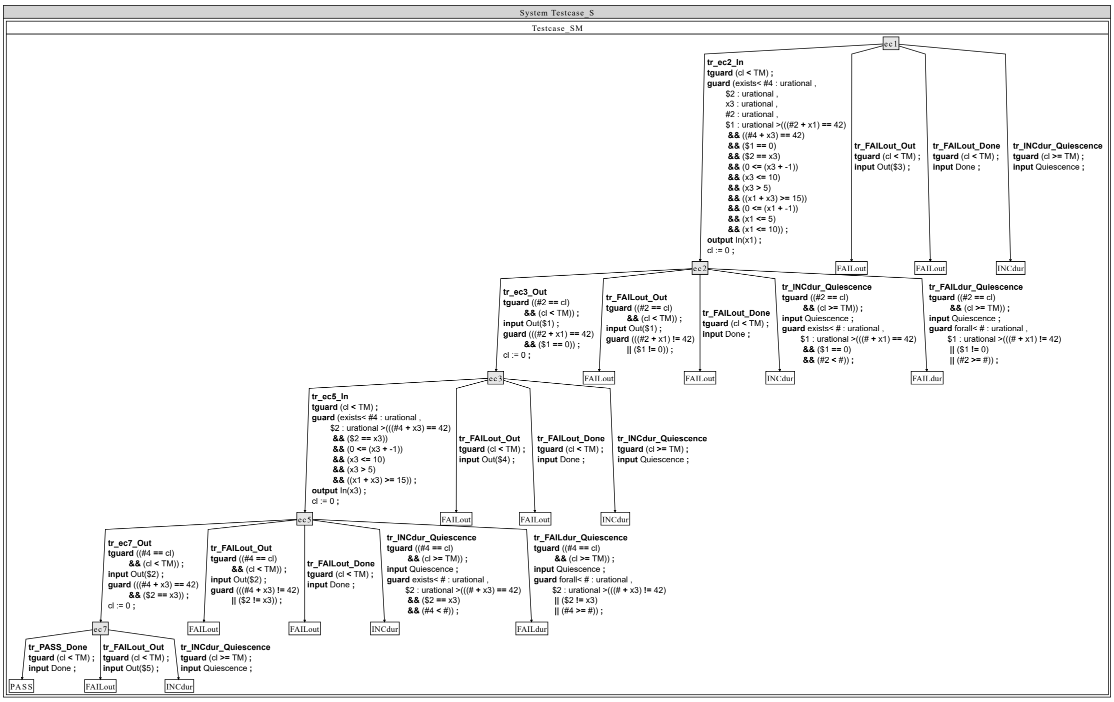
Description	Content
Input 1: *Reference system model (Timed Symbolic Automaton)*	
Input 2: *Test purpose (Sequence of transitions)*	`tr1; tr2`

Description	Content
Output: *Generated test case (Deterministic Timed Symbolic Automaton)*	

To generate another test purpose of length 5 for the same reference model, run:

```
cd /path/to/SPTG/examples/example02_dummy/
./run-sptg-h5.sh
```

This script executes the workflow configured for a longer test purpose (length 5). As a result, you obtain the following generated test case:

Description	Content
Input 2: *Test purpose (Sequence of transitions)*	`tr1; tr2; tr1; tr3; tr4`
Output: *Generated test case (Deterministic Timed Symbolic Automaton)*	

PlantUML: PUML to SVG Conversion Guide

A concise reference for converting `.puml` files to `.svg` images via the command line.
PlantUML requires **Graphviz** for diagram rendering.

Prerequisites

1. **Java Runtime Environment (JRE):** Required to execute PlantUML.
2. **PlantUML JAR File:** The standalone PlantUML application.
3. **Graphviz:** Used internally by PlantUML for layout and rendering.
   After installation, Graphviz will be available in your system path.

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a. Installation

Install Graphviz

On Debian/Ubuntu-based systems, install Graphviz with:

```
sudo apt install graphviz
```

After this, the `dot` executable will be available system-wide.

b. Download PlantUML

Get the latest stable release of `plantuml.jar` from:
👉 https://github.com/plantuml/plantuml/releases

Ensure both `java` and `dot` commands are available:

```
java -version
dot -V
```

c. Conversion Command

Navigate to the folder containing both `plantuml.jar` and your `.puml` file.

Use the `-tsvg` flag to generate an SVG image:

Command	Action
`java -jar plantuml.jar -tsvg yourfile.puml`	Converts the input file (`.puml`) to an SVG output (`.svg`).

Example

```
# Generates 'MyDiagram.svg'
java -jar plantuml.jar -tsvg MyDiagram.puml
```